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DOCTORAL THESIS

ARCHITECTURAL ASPECTS OF MASSIVE TIMBER

Structural Form and Systems

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Luleå University of Technology
Department of Civil and Environmental Engineering
Division of Structural Engineering - Timber Structures

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This thesis was set in Palatino with headlines in Helvetica.
Photos on the front cover: Staircase in a school building in St Peter, Switzerland, by the architect Conradin Clavuot (left) and model of a tower structure with plate tensegrity (right). Photo, model and model photo by the author.

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"For me, knowledge of two languages
doesn't mean the possession of a repertory
of synonyms; it doesn't mean knowing
that in Spanish you say *ancho*
and in English *wide* or *broad*.
What is important is to learn to think
in two different ways, and to have access
to two literatures.

If a man grows up within a single culture,
if he gets used to seeing other languages
as hostile or arbitrary dialects,
his mental development will be constricted.
If, however, he gets used to thinking
in two languages and to the idea that his mind
has developed from two great literatures,
that must surely benefit him."

The Argentinean writer Jorge Luis Borges (1899-1986)
interviewed by Rita Guibert 1968

PREFACE

Some words…

Several times I have been asked why I as an architect show interest in studies of structural engineering and material properties. Every time the reason stands clear to me. That I am curious by nature is part of it but only half the reason. Architecture is the art of building; it is my opinion that the knowledge of materials, techniques and technologies is the basis for this work to reach a satisfying result. Without knowing the nature of materials, techniques and technologies there will be no freedom in architectural design, except in the world of drawings and sketches.

Fully unrestricted visionary work must have its place and time, even if the designs never leave the state of lines on a paper or shapes of a small-scaled model. But to reach a solid result in a built reality the architect must know the properties and technology associated with the material he or she is to use. Some may say that this knowledge limits the architectural freedom and creativity. I say that it inspires it, and enables it to result in a both aesthetically and functional as well as rational built reality.

Timber is a challenging material, simple as well as complex; soft and workable as well as sustainable and strong; rich in its raw state as well as potentially beautiful when aged. There are many examples of fine structures and items in timber in the history of man's everyday life, timber building and handcraft and still, new uses, products, forms and appearances are possible to create. I find interest in the continuation and transformation of tradition and the possibilities to take advantage of the industrial means that today steadily gain importance in construction. Architecture must deal with this, both in house construction and in more advanced structural contexts. To suddenly discover and then to develop and study a new matter, as an extension of this, has furthermore meant sheer fascination. It was a thrilling moment when the new idea of plate tensegrity dawned on me and working with this has even increased my curiosity.

…of acknowledgement.

From the depth of my heart I would like to thank professor emeritus Sture Samuelsson, who has been my supervisor since 2000, i.e. from the very beginning of my PhD-studies. Sture awoke and has steadily deepened my interest in timber construction – and what projects, ideas and visions have we not discussed during meetings, lunches and coffee breaks? It has been most instructive and indeed these have been invaluable years when the inspiration has been without limits, laughter never far away.

I am grateful to professor Lars Stehn at Luleå University of Technology for several years of encouraging contacts during the Wood Technology Programme and for offering the last resort when it was more than needed and for supervising me with interest and dedication along the finish.

PhD Dan Engström was engaged in the project as a nice, pedagogic, always positive and dedicated co-supervisor in the beginning and has followed my work at a distance, however most encouraging, since 2002. …I think this is the beginning of a beautiful friendship. And I miss Kajsa – Kajsa is extremely rarely seen in Humlegården nowadays, I check every passing Schnauzer, but no…

PhD. Anders Rosenkilde opened the relieving possibility for me to move to SP Trätek in Stockholm, where so many colleagues have offered advice, support, joy and encouragement. It has meant much to me, both professionally and socially to have had a room there for more than two years. I am also glad that I got to know the colleagues at the Division of Structural Engineering – Timber Structures in Luleå, who enriched both my work and my spare time in a flash.

Professor Ture Wester at the Royal Academy of Fine Arts in Copenhagen and Professor Gerhard Schickhofer at Graz University of Technology have both welcomed me to very interesting, fruitful and nice stays in Copenhagen and Graz, which have made me touch upon threads that would be very exciting to continue following.

The work has been funded by the Wood Technology Programme.
Stockholms Byggnadsförening, Ångpanneföreningen and Skogsindustrierna, the Swedish Forest Industries Federation, have enabled me to spend valuable time abroad during the last two years.

My old friend Rickard helped me with the proofreading. Ulf and Maria at the Glenn Miller Café in Stockholm run an invaluable place in the best of ways, that steadily provides me restful, soothing and musically thirst quenching moments.

Friends, fellow aikidokas and dear islanders,
of course words cannot repay your company!

Bosse and Karin!

Andreas Falk
Brandbergen 30. October 2005

ABSTRACT

The hypothesis *of this thesis is that there are rational, technical and architectural gains to be made from interactively developed architectural and structural utilisation of massive timber plates.*

The aim is to study and describe architectural features of structural applications of massive timber and ways to utilise and develop timber-based plates in building applications by combining an architectural and a structural engineering perspective.

The work presented in this thesis concerns the fields of architecture and structural engineering, their interrelations and interaction in building systems based on cross-laminated timber products. Characteristic of the entire work is the search for advantages from material- and product-specific features and how to utilise these architecturally and structurally, unified in a holistic perspective. The work contains two case studies and a theoretical extension. The studies and discussions on development of the utilisation have lead in two directions: towards industrialised residential building construction and towards timber plate structures in combination with steel rods or cables for wide spans.

For building systems production, erection methods and system-action are of main importance for the result and a case study comprising four Swedish and two Austrian projects on medium- and high-rise residential blocks has been performed. For advanced structures it is the material and product properties that are of main importance and a case study on timber-structures for wide spans has been performed. One Swedish project has been considered aligned with four Austrian examples.

Two- and three-dimensional structures for wide spans of the type treated in the thesis are not yet in production. The results from the case studies and a discussion on form finding, the study of and search for the interplay between force and structural form, have been developed into a theoretical extension of advanced structures with timber-plates in combination with steel rods, cables and trestle structures. The theoretical extension has resulted in a new type of structural element based on timber plates.

Keywords: massive timber, surface-elements, system-action, holism, architectural language, form finding, tensegric structures

SAMMANFATTNING

Hypotesen *i avhandlingen är att det går att dra fördelar, i fråga om rationalitet, konstruktion och formspråk, av massivträapplikationer som utvecklats genom interaktion mellan arkitektur och konstruktion.*

Syftet har varit att studera och beskriva arkitektoniska aspekter av massivträkonstruktioner, samt sätt att utnyttja och utveckla träbaserade skivelement (plattor och skivor) i byggnader genom att anlägga ett kombinerat arkitektoniskt och konstruktivt perspektiv.

Arbetet som presenteras i denna avhandling rör områdena arkitektur och konstruktion samt dessas inbördes relationer och interaktion i byggsystem baserade på krysslimmade träbaserade konstruktionselement. Genomgående i avhandlingen är att diskussionerna kretsar kring material- och produktspecifika egenskaper och hur dessa kan utnyttjas arkitektoniskt och konstruktivt, sammanfört i ett holistiskt perspektiv. I arbetet ingår två fallstudier och en teoretisk del. Studier av och diskussioner kring utvecklingen av utnyttjandet har lett i två rikningar: mot industrialiserad produktion av flerbostadshus och mot kombinationer av träskivor och dragstål eller kablar för stora spännvidder.

I fallet med flerfamiljshus är produktion, byggmetoder och systemverkan av stor betydelse för resultatet. En fallstudie har genomförts omfattande fyra svenska och två österrikiska projekt med flerfamiljshus. I det andra fallet är framför allt material- och produktegenskaper av stor betydelse och en fallstudie har genomförts, omfattande ett svenskt projekt och fyra österrikiska referensobjekt.

Två- och tredimensionella konstruktioner för stora spännvidder, av den typ som behandlas i avhandlingen, är ännu inte i produktion. Resultaten från fallstudierna och en diskussion kring *form finding*, studiet av samspelet mellan krafter och konstruktiv form, har utvecklats i ett teoretiskt avsnitt om avancerade konstruktioner med träskivor i kombination med dragstål, kablar och bockkonstruktioner. Det teoretiska utvidgningen har resulterat i ett nytt konstruktionselement.

Nyckelord: massivträ, ytelement, systemverkan, holism, arkitektoniskt språk, form finding, tensegriska konstruktioner

Contents

Short Definitions

Aspect denotes an appearance, or in another sense, a particular side of a many sided situation, idea or subject.[1] In this context it is used to deal with different perspectives put on the main subject of timber building, different themes or parts of the same matter.

Brettstapelbau can be compared to parallel laminated or stapled boards; sawn and planed boards are assembled to form plane elements that are glued, nailed or doweled together or spanned with rods in predrilled holes.

Co-action means that two or more parts (people, companies, building-parts, structural systems etc.) work together and support each other.

Component A product, which is produced for a specified place or function in a building-part or a building-system, which decides its measures and design.[2]

Context The surrounding physical or theoretical conditions of something, through which an object or issue can be understood, by which it can be influenced and on which it can have influence.

Cross-laminated timber is used for elements built up by layers of boards in two or more directions locking each other.

Element A product, which is not specified at the production for a certain place or function. Elements are designed to be part of building-parts and components.[3]

Flexibility denotes ability to change or to be changed in order to suit certain needs and/or changed conditions.[4]

Form finding is a field of research for the study of and search for the interplay between force and structural form.

Glulam is a composite of timber and glue. It denotes laminated timber of four or more boards/lamellas glued together. The most common products are columns and beams.

Holism (adj. holistic) A theory based on the perspective that a whole thing is more than just a collection of parts.

Interaction The phenomenon of items/matters/players influencing, having effect on each other, by working closely together.

Light timber construction denotes stud-framed timber structures, commonly in the range of the widely spread "two by four" system. The structure is then minimised concerning material volume, and built up by several layers with specific functions.

Massive implies great size, strength and weight. Structures in massive timber are normally characterised by being built up by a small number of layers, each one being able to fulfil more than one function.

Medium-rise building refers to a building with three to four storeys.

Module An independent part or unit, which can be combined with others to form a structure or arrangement. [5]

Multi-storey building refers to a building with five or more storeys.

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[1] Longman Dictionary of Contemporary English 1987, p. 52
[2] Samuelsson, S. 1979, p. 2
[3] Samuelsson, S. 1979, p. 2
[4] Longman Dictionary of Contemporary English 1987, p. 391
[5] Longman Dictionary of Contemporary English 1987, p. 672

Mutuality Parts/matters that influence each other to an equal extent based on the relationship between them.

Plates Surface-elements active in taking care of loads/forces. Within statics one differs between *plates* and *diaphragms (shear-plates)* depending on the direction of the imposed loads. Thus, the technical behaviour of plates can be termed either plate action or shear-plate (diaphragm) action.

Structural morphology can be defined as the study of structural form.

Surface-element An element with its main extension in two dimensions.

Sub-system a group of parts related to each other on a specific level. The group is related to other groups as well as to (a) governing system(-s) on a higher level.

Synergy Another word for co-action, often denoting an effect with a result being more than the sum of its parts.

System a group of related parts which work together as a whole.[6]

System effect can be noted when relations between different parts of a group get developed to work well. Simultaneous co-action between a number of parts in a system.

A Reading Guide

Chapter 1 Opening

The first chapter opens up the aim, context and method of this thesis. It gives an outline of the work and the prerequisites given by industry and society. The background of the author is presented and a number of central terms are described.

Chapter 2 Reasoning Essays

The second chapter gives an overview of the history, tradition, and development of timber usage and modern approaches to industrial production and systemisation. It is an extended overview of subjects related to the context of the hereby-presented work.

Chapter 3 Plates: Elements and Structures

The third chapter describes the timber-based element types that have been studied. It furthermore sorts out a number of properties of timber-based plates that are deciding for application in architectural and structural purposes.

Chapter 4 Building Systems

The fourth chapter deals initially with the nature and utility of systems in construction. Timber-based plates in construction are then described followed by brief sections on environmental matters. The chapter is to be seen as a theoretical introduction to Chapter 5.

Chapter 5 Case Study on Building Systems

The fifth chapter contains a multiple-case study on building system applications of timber-based plate elements. The study contains six cases and uses a comparative and exploratory approach to investigate the use of timber-based plates for construction of residential blocks.

[6] Longman Dictionary of Contemporary English 1987, p. 1075

Chapter 6 Advanced Structures

The sixth chapter gives an introduction to advanced structures and theoretical work that has already been carried out on the subject. Secondly it presents a sketch study on different possible advanced element designs. The chapter provides an introduction to Chapter 7 and a theoretical starting point for Chapter 8.

Chapter 7 Case Study on Advanced Structures

The seventh chapter contains a single-case study on advanced structural applications of timber-based plate elements. The study contains one case with reference to four examples of related structural designs. It uses a descriptive and explanatory approach to investigate advanced applications for long spans.

Chapter 8 Theoretical Extension

The eighth chapter presents a study on hypothetical new applications of timber-based plates in advanced large span structures. It describes prerequisites, development and architectural effects of a developed new structural element.

Chapter 9 Closing

This chapter closes the thesis with a discussion on the results from the performed studies. It summarises the work and evaluates it on a number of levels, both in detail and on a contextual level. After the discussion conclusions are drawn as well as proposed guidelines for future work.

References

Published and unpublished sources of literature and figures are listed.

Appendix

There are four appendices:

I	Questionnaires used in the case studies
II	Drawings from development project on cases #3 and #4
III	Paper on installation systems
IV	Calculations on the theoretical study in Chapter 8

1 OPENING

1.1 Introduction

1.1.1 A Descriptive Outline

This thesis treats timber building, i.e. timber based architecture and construction. Timber building includes many products and methods and among these the rather recently developed product called massive timber is in focus. The term *massive timber* refers to structural plate elements, a product type developed since the early 1990's, which can be assembled in different ways. Here the method of glued cross-laminated boards is of primary interest. This type of product provides properties allowing other structures than those possible in other timber building techniques, e.g. the currently well-established and common timber building techniques with light frames, as has been shown in the works by e.g. Falk (2002). Thus it is interesting to study the products, their usage and their potential development.

The core of this thesis is the hypothesis that there are rational, technical and architectural gains to be made from interactively developed architectural and structural utilisation of massive timber plates.

The aim is to study and describe architectural features of structural applications of massive timber and ways to utilise and develop timber-based plates in building applications by combining an architectural and a structural engineering perspective. The approach stems from a close relationship between architecture and structural engineering, and thereby also a close relation to the utilised material(s), in the context of this thesis i.e. timber.

1.1.2 The Perspective of Industry and Society

In Sweden during most of the 20th century timber was not allowed for load-bearing structures of more than two storeys. In 1994, however, the Swedish fire regulations were changed from prescriptive to performance based[7], thereby opening for an increased variety of applications for timber. From that point, knowledge and technique has had to develop to suit the new application types[8], e.g. structural systems for multi-storey houses.

In Sweden as in Austria there was in the early 1990's a wish to find new timber-based products for the building market, suiting the needs for adequate structures for multi-storey houses and other more advanced structural systems.[9]

The timber industry has suffered from lack of standardised systems similar to those developed for e.g. steel and concrete.[10] The situation has been the same in Sweden[11] as in Austria, where methods vary from company to company and financial means and understanding of the necessity of common initiatives such as system development and co-ordination for increased competitiveness often are missing.[12]

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[7] Östman, B. Et al. 2002, p. 8
[8] von Platen, F. 2004, p. 78
[9] Pischl, R. et al. 1998; Samuelsson, S. 2000, p. 18
[10] von Platen, F. 2004, pp. 63
[11] Alsmarker, T. 2001, p. 5
[12] Jöbstl, R.A. 2002, p. 8

The field of construction in massive timber has so far in most cases been surveyed from a purely technical point of view and several technically oriented research- and experiment projects have been undertaken in different parts of Europe, primarily Germany, Switzerland and Austria.[13] The technique has become highlighted in different projects also in Sweden[14] and has been approached with ecological, recycling and timber utilising perspectives by communities and timber producing companies.[15] However, the technique needs further development on several levels from material utilisation to applications in construction, and concerning a system approach to the development of new structures.

In several Swedish projects the aims to prepare the market for increased use of massive timber have not really been reached, in most cases for economic reasons.[16] When new techniques and products are to be introduced on the market the initial economic gains are small, but will increase when the production gets more effective and the technique/product are modified by momentary experience of performance in situ, which is generated by increased demand.[17] The different parts of a building can be developed separately and made better and better, but the quality, function and usability of the end result will depend on how the different parts work together, and how the issues of production and system are worked through.[18]

Competitiveness on the market

The building market is a place for competing. Today all activities include decisions based on qualitative and economic judgements of products and services that are regarded needed. Different companies compete and different material industries compete, which make systemised technology and know-how decisive. During recent years in Sweden reports have been published on the essence of systemising efforts in the timber industry and on the competitiveness of timber.

Early in the year 2001 the Swedish Business Development Agency[19] published a report on interface relations in timber building systems.[20] An initial statement is made on the potential competitiveness of timber as a building material, but also concerning the growth of other material industries having brought them ahead of timber. A basic condition for competing is to fulfil demands of function and security, which is therefore first priority in the development of a system. A potential gain with a system is that it is easy to grasp and overview. This makes it attractive on the market and also effective to deal with. The hypothesis in the report is that the use of timber in the building industry can be motivated on economic grounds.

The discussion supporting this hypothesis concerns an increased use of standards, which is stated to lead to several gains for industry and society.[21] Such long-term, general gains are always theoretically interesting, but the market of today tends to react to guaranteed direct, short-term economic gains only. This makes it very

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[13] Johansson, L. et al. 2000; Schickhofer, G. and Winter, W. et al. 2001

[14] Industrikonsortiet Massivträ 2002; Östman, B. et al. 2002

[15] *Växjösamtalet 2004, symposium on the future social structure in Sweden, with one session focusing on the future of the Swedish timber building market, held in Växjö, Sweden, 04-06.02.2004*

[16] *Aims can for example be "to show economic effects of massive timber building" and "to increase the efficiency of the building process to support the introduction of a competitive material on the market".* Gagner I. 2004, pp. 3 *(Translation by the author.)*

[17] Kaufmann, H. 2004, p. 14

[18] Engström, D. and Samuelsson, S. 2000; Falk, A. and Engström, D. 2002

[19] *Vinnova (Verket för Innovationssystem), the Swedish Agency for Innovation Systems.*

[20] Alsmarker, T. 2001

[21] *Note that the motives for standardising e.g. lowered building costs and increased number of vacant jobs are currently the same as those considered in the mid 1900, when the first industrial efforts were made on the Swedish building market.* Adler. P. 2001, p. 7

difficult to realise new large-scaled systematic changes. There is a catch 22 in the situation, where individual companies do not dare to spend money on development for the market since they cannot be sure of gaining from it until some examples already have been developed, realised and sold on the market.

The striving towards sustainable construction cannot be the task for only one or few players, but a joint venture for producers, builders and proprietors. What is needed is a major centralised effort to co-ordinate the players and to develop the prerequisites for a stable development of the building industry.[22]

The national strategy for timber building

Governmental initiatives have been requested to form the future of construction and a long-term strategy for the building development.[23] Such an initiative came concerning the future of timber building industry in Sweden in 2003 when the Swedish government commissioned a thorough investigation of the timber industry and its prerequisites on both the national and the international market. The investigation was published in 2004 as a national strategy for timber building.[24]

Among the terms of reference for the strategy were that forestry is an important industry for Sweden, the growth in the forests exceeds the yearly harvested volume and architecture and design are important for the competitiveness. There is also an importance of increased awareness of this among the current players.[25] The harvested volume has steadily increased since 1990 and in 2002 it reached the largest volume ever.[26] To harvest and utilise more timber is regarded as fully possible, considering the forest being a renewable material-source. To promote the use of timber on the building market defined as comprising apartment blocks, public buildings, other built structures such as bridges and small houses, the strategy aimed at processes within education, research and development.[27]

The published strategy was followed by a series of seminars on the subject, where the effects from increased refining of timber products within the country were discussed[28] along with the need for joint actions on the national level to strengthen the competitiveness in different steps: national market, Nordic market, European market.

Needs and development

Industrialisation is currently a strong trend on the Swedish building market and the relation between structural systems and production is important to deal with[29], as well as the relation between prefabricated structural system and architectural design.[30] A mutual understanding and interest, and an interactive approach to development issues on the building market were dealt with by Falk (2002), where the importance of a close cooperation between architects and engineers was stressed.

From an architectural point of view building systems, prefabrication of built structures and computer programs aiding the manufacturing of houses have been

[22] von Platen, F. 2004, p. 15
[23] Adler, P. 2001, p. 16
[24] von Platen, F. 2004
[25] von Platen, F. 2004, p. 15
[26] von Platen, F. 2004, p. 34
[27] von Platen, F. 2004, p. 22
[28] Växjösamtalet 2004, p. 11
[29] Alsmarker, T. 2001; von Platen, F. 2004
[30] *The subject of Design in industrialised building production was discussed at a seminar held in Stockholm on May 18. 2005, initiated by Vinnova.*

criticized and from time to time seen as a threat.[31] The tools have also often been developed and used without consideration of the architectural perspective but solely regarded automation and reduction of production costs.

Techniques and systems can be developed along different lines, e.g. to optimise the production process and the on site erection, or to optimise the structural utilisation from a static point of view. When production gets industrialised there has to be a tight interplay with the utilisation, architectural design and development of technical systems.[32] The demands on efficient handling and transportation rise, and so do the demands on system action in the finished building, in case of volume module manufacturing even during handling and transportation.

System action is also crucial for advanced structural applications such as cases with few widely spaced supports or in minimised structures eventually using combinations of materials. Such applications are also strongly dependent on material properties. With increased structural demands it gets more and more important to follow the nature of the utilised material, and to let the structural design follow the patterns of force distribution.

In building systems the architectural aspects have, to some extent, to make use of standardised prerequisites.[33] In structures with long spans the load-bearing structure plays a decisive role for the architectural result. In both examples the interplay between architecture and structure is tight, but also in need of further studies.

1.1.3 Academic Background

The work in this thesis concerns architecture (often approached as a hermeneutic field of knowledge) and architecturally relatable matters where subjectivity is always present to some extent. Therefore, the background of the author and the way leading to the results are of importance for the reader's understanding.

The work stems from the work at the division of Building Engineering at the Royal Institute of Technology, KTH School of Architecture (KTH-A) in Stockholm. This division is responsible for education and research on structural systems in architecture. The architecture that originates from materials, techniques and structural systems is related to an iterative process. This iterative process is included in the study of materials and techniques for a proper rational function, economic and environmental sustainability and aesthetically gainful appearance.

From this field of work, the author has pulled two terms of current interest: *form finding* and *structural morphology*. These two terms are subject to thorough work in the IASS, the International Association for Shells and Spatial Structures, where the author is a member. The work in this thesis crosses the border between Architecture and Structural Engineering and the research has been carried out as an interactive search for potential development of synergies combining architectural and structural aspects on timber building. Ideas and discussions generated from theories on form-finding and structural morphology have strongly influenced the hereby-presented work.

The trend of development and use of massive timber products in Central Europe in the early 1990's was soon recognised by professor Sture Samuelsson at Building Engineering, and since 1994 several study trips have been made to the region to analyse this timber-based trend in construction. A number of related issues have been dealt with at the division.

[31] Janols, H. 2005, paper III, p. 4
[32] Kaufmann, H. 2004, p. 15
[33] Krippner, R. 2001, p. 605

Nordic Wood, a Nordic effort to stimulate and develop timber building, has resulted in several Danish, Finnish, Norwegian and Swedish reports and documentary studies on timber building.[34] One phase on multi-storey timber building, described by Hansson (1997), concerned the initiation of medium-rise to multi-storey applications of light timber frame construction in the Nordic countries after 1994.

A second phase within Nordic Wood, described in Sjöberg and Samuelsson (2002), was concentrated on massive timber construction, aiming at developing massive timber into a competitive and price-worthy alternative for building structures. The documentation of the Swedish built examples was published by the Division of Building Engineering and treated the architectural result obtained in six projects.

A second report on this part of Nordic Wood was published by Heikkilä (2002) at the department of Architecture at the University of Oulu. It is documenting the Scandinavian massive timber tradition, i.e. historic log building construction and modern applications of this technique. It describes both handicraft and industrial approaches to modern log building.

With funding from the national research school named the Wood Technology Programme[35] this research project started in January 2000.[36] The first part of the work resulted in a licentiate thesis in 2002.[37] In the licentiate thesis potential architectural and structural gains and problems with massive timber construction were mapped and described.

The main topics that were pointed out in the licentiate thesis, as being in need of continued research, were:

- *Structural systems and their interplay with, and prerequisites for, technique-specific architectural design-features for different types of buildings.*
- *Complex 2- and 3-dimensional structural elements for advanced structures.*
- *Treatment and location of installations in a structural system based on massive timber.*

From these concluding lines, the lines for the work between 2002 and 2005 were drawn, and the results are thus presented in this thesis.

In the search for funding for the completion of this project the author has changed affiliations, left the KTH-A and moved the project to the Division of Structural Engineering at Luleå University of Technology in November 2004. The new affiliation is with the Division of Structural Engineering – Timber Structures. The Timber Structures research group studies three topics: Timber engineering, Industrialised production technology and Business and construction management. This gives support for the work concerning technique and production issues.

Since the project was launched from the academic field of architecture aiming at the integration/interaction of architecture and structural engineering, the change of affiliations to a civil engineering division has been very interesting and the Division of Structural Engineering a most suitable landing field.

The work has been assembled into a monograph. The material has, along the way, been presented at international conferences. In all, seven papers concerning the research project have been submitted and accepted to conference venues:

[34] Hansson, T. 1997, pp. 6; Nordisk ministerråd 2003, pp. 25
[35] *With support from the Strategic Research Foundation (SSF)*
[36] *The title of the project, mentioned in the original application, was "Architecture for medium-rise buildings with a massive timber frame". The project was presented in Engström, D. and Samuelsson, S. 2000*
[37] Falk, A. 2002

2000	WCTE 2000, 6th World Conference on Timber Engineering "Engineered Timber Technology for the New Millennium", Whistler, Canada (Engström and Samuelsson)
	Nordic Association for Architectural Research, "Nordic Research Symposium on Architecture and Materials", Oulu, Finland (Engström, Samuelsson and Falk)
2001	IABSE 2001, International Association for Bridge and Structural Engineering "Innovative Wooden Structures and Bridges", Lahtis, Finland (Falk and Engström)
2002	WCTE 2002, 7th World Conference on Timber Engineering "Timber Construction in the New Millennium", Shah Alam, Malaysia (Falk and Engström)
2004	WCTE 2004, 8th World Conference on Timber Engineering, Lahtis, Finland (Falk and Samuelsson)[38]
	IASS 2004, International Symposium on Shells and Spatial Structures "From Models to Realisation", Montpellier, France (Falk and Samuelsson)
2005	IASS 2005, International Symposium on Shells and Spatial Structures "Theory, Technique, Valuation, Maintenance", Bucharest, Romania (Falk and Tibert)[39]

1.1.4 Aim

To study and describe architectural features of structural applications of massive timber and ways to utilise and develop timber-based plates in building applications by combining an architectural and a structural engineering perspective.

The chosen approach to architectural features of structural applications of massive timber stems from a preferred close relation between architecture and structural engineering. This implies a close relation to the utilised material(s), in the context of this thesis i.e. timber. The form for this initiative is holistic in search of architectural and structural possibilities with timber-based plate-products in focus. It concerns both utilised and not yet fully explored and developed features of massive timber construction.

The approach is holistic rather than narrowly deep, dealing with system effects between the aspects of architectural and structural design. The work seeks to point out a not yet fully exploited potential and to point at some steps of development concerning the chosen aspects, rather than to cover a complete system.

There is the need for investigating architectural potentials within material and technique through an inter-disciplinary approach. This need has become apparent to the author during the duration of the project. Literature studies and contacts with sawmills, glulam manufacturers, builders, engineers, architects and end-users have pointed in the same direction. The potential of material and technique should be analysed thoroughly, not focusing on how to build as before, but on what the new technology makes possible. Gains might as well be architectural and structural as rational upon construction. It is to this recognised need that this work tries to respond.

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[38] *See Appendix III*

[39] *An excerpt of the paper containing a structural analysis made by Tibert has been appended. See Appendix IV.*

1.1.5 Research Questions

The main unit of analysis concerns the question "How can structural applications of timber-based plate-elements be utilised and developed by combining an architectural and a technical perspective?" It is here divided into two separate but linked questions:

How can the use of timber-based plate-elements be developed in

- *building systems for multi-storey building construction in industrial production?*
- *advanced structural applications making use of material and product properties?*

1.1.6 Scope and Limitations

The product type focused on in this thesis was chosen since it is a relatively new product. It is a timber-based product type, which has been refined through an industrial process that provides the product with a set of characteristics, static features and potential utility, which distinguishes it from other timber-based products.[40] These characteristics also make structures possible that are not achievable in any other material, considering e.g. weight to stiffness ratio, thermal inertia and adaptability.

In this thesis the glued cross-laminated timber-plate is of primary interest. There are also other kinds of laminated build-ups, as well as structural elements with hollow box-sections, but these are with a few exceptions not regarded here.

The thesis deals with the architectural and structural results and effects of the application of these timber-based surface elements. The title of the thesis pinpoints the terms Architecture, Structural form and Systems. These aspects have been chosen for their close interrelations in the design of buildings and for the effect of the nature of these interrelations on the finished result.

A complete system implies a great number of sub-systems[41], except for architectural and structural systems also installations, flows of physical communication, systems concerning organisation and production etc. Other aspects than architectural and structural ones are however not dealt with in this context, except for a few being briefly considered, e.g. fire-safety, installations, comfort and stability. A discussion on installations is presented separately in an appended conference-article (*see Appendix III*). Issues like sound and thermal insulation, acoustics and cost are mentioned but not considered specifically and exact.

One reason for not looking deeper into them is a wished focus on the two aspects regarded as having the most wide effect on experience and use of a built structure. Each one of the aspects are furthermore potential subjects for research actions why it is not reasonable to include them in the scope of this thesis.

Furthermore, there are many architectural conveyors of value. Those aspects of architecture that not specifically concerns timber-structures are not dealt with. To provide concrete examples of all aspects has not been an aim in the work, which rather has dealt with discussions on principles.

Concerning method, this thesis uses case study methodology, which gives findings that are not possible to generalise. At this stage, however, it is found not to be

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[40] Schickhofer, G. and Winter, W. et al. 2001, p. 111
[41] Samuelsson, S. 1979, pp. 30; Engström, D. and Samuelsson, S. 2000

interesting to generalise statistically. The case studies have been used to explore, compare and explain contemporary use of a relatively new technique and to investigate its architectural and structural potential. The main approach is holistic and to exemplify the state of the art as a foundation for further work.

Timewise, this work relates in large to the development of timber-products during the 1990's in Central Europe and what has happened in Sweden since 1994. The studied products have been manufactured in Sweden and Austria and the studied applications are located in the same two countries.

The production of massive timber products started in Austria in 1996 and in Sweden in 2003. The applications chosen for the current study were erected in Sweden in 2001, 2004 and 2005, and in Austria during 2004 and 2005.

There is a polarity in the scope, between house construction and large span structures, a polarity caused by the holistic view of the products and the interest in different possibilities. Two types of structures have been studied where cross-laminated timber plates have been used. These two are a bit disparate and have been chosen deliberately for being so. They have been decided upon to study different possible developments/extensions of the material technique, the following construction and the resulting structures: the one towards multi-level system issues and rationality of production, the other towards plate and material properties, material combination and co-action.

One type is multi-storey residential buildings, where both technical and aesthetical demands on the structure are high, to secure an acceptable living environment. The issue concerns element production, structure and function. *What is the essence of these systems?* Stability, thermal and sound insulation, fire safety, layout and production rationality have during the last years been repeatedly highlighted as problematic key-issues.[42] The area of multi-storey building was addressed in the original project description at KTH-A from 1999, for the studies and development of material potential.

The second type is advanced structures for long-span spatial structures, where utilisation and optimisation of utilised products and techniques get primary priority. This issue originates from an idea on how to be more extreme when discussing the capacity of material and technique. *What is the essence of these products?* "What would they like?" to refer to a saying by the American architect Louis I. Kahn.[43]

High-tech architecture and construction[44] is a steadily growing field with an ever-increasing number of products. The common use of cable stayed beams and columns, for roofs and large glass-structures has in the work presented in this thesis lead to proposed prototype designs for applications on timber-plates. These structural types tend to break new ground concerning utilisation of timber and show new characteristics, though they are made possible by the basic physical and mechanical properties of the timber material. This theoretical experimental part constitutes the last part of the thesis.

[42] Hansson, T. (ed.) 1997; Andreasson, S. 2000; Östman, B. et al. 2002, and others.
[43] Engström, D. et al. 2004
[44] *"High-tech" commonly denotes utilisation of advanced structural techniques and elements in buildings, and architectural design making use of these features. Steel and glass are for example used in quite technical ways in wall and roof structures.*

1.2 Research Methodology

1.2.1 To Choose and Handle Complexity

Architecture

Architecture is an interdisciplinary subject. The area of building, the issue of building systems and the industrialisation of the building process are complex aggregates, both theoretically and practically. The very essence of architecture is to be a multi-faceted subject. Theoretically, architecture can be described as a circle consisting of different sectors, which can be labelled e.g. structure, installations, layout, choice and treatment of materials etc.[45] A well working built result – i.e. a functional architecture – demands that it inscribes that full circle, no sectors missing. A full circle (Architecture) is only possible to reach if all the sectors are equally worked through, matched and developed in an interactive way.

To encircle architecture is not easily done, and to penetrate architectural features tends to result in studies more wide than they are deep. Research has dealt with architecture many times, but often from the point of view of a single sector or a neighbouring subject. An architect deals with a multitude of factors and issues concerning each approached project. Some regard it impossible to do research on architectural matters, since architecture in itself so easily becomes a complex field with the scope of the intricate web it actually is in reality instead of a clearly defined and easily limited issue. Many subjects are tightly linked to each other. However, in order to utilise and develop these relationships to their full extent, the author considers it necessary to approach the complexity of architecture and structural engineering as a research issue.

Architecture and structural engineering

It is however a deliberate choice to look into the matters of timber construction from an architectural point of view. The areas of architecture and structural engineering are entwined and strongly linked to each other. To study one without considering the other may be done but many features will then pass unnoticed and, as stated in the hypothesis of the author, many gains will not be revealed, i.e. the effects that architecture and structural engineering have on each other and may potentially produce will not be taken into account.

By choosing architecture and the sector of structural engineering as subjects the main receivers of the text are automatically defined. To combine the fields of architectural and structural design means that language and material have to be chosen so that both architects and engineers may read and follow the discussion. Some things may then be written, which are obvious to one discipline but not so evident or understandable to the other. And vice versa. Some things may not have been treated or only briefly touched upon. Some things may be missed by one discipline, whereas the other does not even consider it. And vice versa. A balance has had to be obtained so that both disciplines can gain from the work.

[45] Falk, A. 2002, p. 35

Polarity

In this thesis massive timber building is viewed as a system and in this complex context, the two aspects of architectural and structural design have been put in focus for a study of the effect of utilisation of material and technical properties on the built result and its utility.

To scope the field of timber-based plate construction two different application types have been studied, one in structural systems for residential buildings and one in advanced applications for long-span structures. Both types show potential for increased use of massive timber and are dependent on the material properties of the product.

The two application types stretch the limits of massive timber building in two partly different ways: one towards the material in the process (in the direction of production, logistics and system action); the other towards the performance of the material (in the direction of utilisation of material and product properties). In this way the diversity of potential applications can be explored and tested.

1.2.2 Methodological Description

Methodological choice

To divide and sort products, functions and relations of any phenomenon in a systematic way helps to reveal gains and weaknesses and provides a simplified overview of the focus matter. In this way a problem, a studied task, can be broken down into handy pieces. Two aspects of a building have been chosen and studied more or less separated from the rest, to concentrate on internal relations, on different levels. A holistic main approach is, however, kept by considering the focused aspect, sub-system, part or level in relation to the main system, surrounding parts or other levels.

To investigate the current utilisation of massive timber construction in architecture and to investigate the interplay between architecture and structural engineering recently erected projects were chosen for study. Along the way towards this study the work has consisted of literature studies, studying of technical reports, interviews, study visits and sketch analyses.

The studied matter does not have a long history and it is currently changing. The interest concerns the contemporary use of a relatively new technique. The investigation has therefore been focused on contemporary phenomena within their real-life contexts and looking into interrelations, interplay and contextual conditions.

The nature of the studied phenomena is that the boundaries are not clearly evident. With these prerequisites, the case study as an empirical inquiry is found to be suitable.[46] There have also been a number of available sources of information (technical documentation, drawings, interviews and observations during on-site visits), and to handle these circumstances a case study design is useful.[47]

Two different case studies have been performed, one on building systems and one on advanced structures.

[46] Yin, R.K. 2003, p. 13
[47] Yin, R.K. 2003, p. 14

Research strategy

The technique of massive timber is fairly new in Sweden and the number of built Swedish projects is still relatively low. Four Swedish cases were chosen for the study on building systems. There are different types of massive timber building construction following different trends in industrial building production. They can be generalised into two main categories: those with plane elements and those with volume elements. Two of the chosen Swedish cases are based on plane elements and two are based on volume elements.

Since the structural technique is so new two cases were chosen from the Austrian building market for comparison and cross-case analysis. Austria started developing timber-based plate-structures some years earlier than Sweden and in comparison with Sweden a greater number of projects have been erected, and thus more experience has been gained in Austria. The Austrian cases have been used to compare and test the findings from the Swedish cases.

Advanced structures are even fewer in number in Sweden than building system applications. One unusual, advanced application has been erected in Sweden during 2005 and this was chosen for a single-case study. Briefly referred to, four Austrian examples align the Swedish project.

It is considered too early to make a statistic generalising study. For the same reason it is not regarded as fruitful to make a survey. It is rather a question of expanding and generalising theories (analytical generalisation)[48] based on a small number of cases. The main approach is furthermore holistic to reach a comprehensive contextual understanding, which implies a rather complex set of data from each case. This points towards a qualitative rather than towards a quantitative method.[49]

Design of the case studies

The studied cases are listed in the table below.

Nr:	*Case:*	*Location:*	
#1	Vetenskapsstaden I	Stockholm,	Sweden
#2	Vetenskapsstaden II	Stockholm,	Sweden
#3	Sundsvall I	Sundsvall,	Sweden
#4	Sundsvall II	Sundsvall,	Sweden
#5	Impulszentrum	Graz,	Austria
#6	Spöttlgasse	Vienna,	Austria
#7	Flyinge	Flyinge,	Sweden

The Swedish cases on building systems are numbered according to and presented in the chronological order of their finishing dates. They are tightly related two and two.

The cases with volume elements are two separate projects even though one team has produced both of them within the same development venture. The first, case #1, was finished in 2001 and the second, case #2, was finished in 2005. These two cases constitute an example of structural development.

[48] Yin, R.K. 2003, p. 37
[49] Miles, M.B. and Huberman, A.M. 1994

The venture resulting in cases #1 and #2 is a thoroughly researched project with an ambitious development aim with several sub-systems. It has been followed closely by the KTH Division of Building Engineering since 1998. To use these cases has therefore been close at hand.

The cases with plane elements are two phases of the same project and to some extent merely seen as one. The first phase was started in 2003 and the second and last phase is not yet finished. A division during the project, into two parts for reasons of receiving the building permits in two steps, and a shift in structural design, make it reasonable to deal with them as two separate cases, cases #3 and #4. The shift makes the cases provide an example of structural development from other reasons than the aforementioned.

The project comprising cases #3 and #4 is the first large-scale project on multi-storey residential building in massive timber where the products have been industrially manufactured in Sweden. The project has been and is currently still studied by the LTU Division of Structural Engineering.

Time did not allow a large number of additional cases, nor was it regarded necessary. An Austrian manufacturer of massive timber products was contacted and provided a list of projects in massive timber already built or under construction. Among eight contemporary projects the two most interesting were chosen. Case #5 is built with volume elements and case #6 with plane elements.

The Swedish case on advanced structural applications is unique in Sweden and was designed and erected by Swedish and Austrian companies in co-operation. Between 2004 and 2005 the project was taken from the design stage to a finished building. There have been close contacts with the involved companies since before the current project, case #7. The project was chosen for its uniqueness; for brief comparison of its structural principle four Austrian projects with some similarity were added to the study for brief reference.

Two types of case studies[50] have been performed to investigate the two structural polarities:

For building systems for residential blocks:

- *A comparative/exploratory embedded multiple-case study.*

For advanced structures:

- *A descriptive/explanatory holistic single-case study.*

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[50] *With terminology used by Yin (2003)*

Design of case study on building systems

The case study on building systems deals with a number of factors in six cases:

Nr:	*Case:*	*Type:*
#1	Vetenskapsstaden I	Student apartments
#2	Vetenskapsstaden II	Student apartments
#3	Sundsvall I	Residential blocks
#4	Sundsvall II	Residential blocks
#5	Impulszentrum	Office building
#6	Spöttlgasse	Residential blocks

The cases have been chosen to illustrate the utilisation of timber-based plate-elements in house building system applications. The approach is exploratory and tries to investigate how the massive timber building technique has been utilised architecturally and structurally. It is also comparing the findings from the different cases.

To some extent the cases predict similar results, to some extent, for predictable reasons, they predict contrasting results. Based on this a replication logic has been possible to use. When the cases differ partly, theory has been used for the validation.

The main unit of analysis is the architectural and structural utilisation of massive timber systems. The study contains embedded units of analysis: the use of 2D elements in building systems; the use of 3D elements in building systems; differences in the use of massive timber in Sweden and Austria.

Design of case study on advanced structures

The case study on advanced structures deals with a number of factors in a single case:

Nr:	*Case:*	*Type:*
#7	Flyinge	Equestrian hall

In an international perspective the project in the case study on advanced structures is unusual. In Sweden it is a unique case. This makes it interesting to describe and explain the case.

The findings from the single case have been matched against theoretical findings. To enable comparison of some structural features four loosely related examples of current interest are regarded in conjunction with the case.

The main unit of analysis is the architectural and structural utilisation of material and product properties of massive timber in a long-span structure.

Data collection

The collected data concerns the architectural and structural design and features of the finished result in each case. These are caused by intentions, production and use of massive timber leading to the built result, the course of events design-production-erection-use. To cover the cases as thoroughly as possible multiple sources have been used for the data collection, which also helps to construct validity.

Sources of data have in both case studies been technical documentation, drawings, interviews and observations at on-site visits. The technical documentation has comprised written reports and meeting protocols. Drawings imply architectural, construction and manufacturing drawings. Interviews were performed at meetings and via telephone; complementary information was collected via telephone and e-mail. Each building site has been visited at least once for direct observations.

The collection of data has been carried out in varying orders. Interviews have in most cases been performed after having studied data from other sources. In cases with an early interview, before studying other data, the interviewees have been contacted again after further data studies.

Interviews based on the questionnaires (*see Appendix I*) have been used to get information about the planning and production of the studied structures, to get material for analyses, to sort and evaluate syntheses and conclusions and to discuss further development. The multiple sources of data are used for data triangulation as a means for evaluation to secure validity.

The data collection has influenced the data collection e.g. in that way that the questions have been put open-ended, giving an interview more the character of a conversation or a narrative. This has been intentional since it enables the interviewee to answer questions that are not even put, and cast light on matters not yet thought of or known by the interviewer. It provides flexibility and openness to the study and minimises the subjectivity and the interviewer's intrusion into the analysis.[51] The interviews have been recorded in writing.

Also other data sources have been used in varying order as an effect of uneven and irregular access to the sources and the data collection phase has continued with a simultaneous analysis, an overlapping and flexible approach dealt with and supported by Eisenhardt (1989).[52] Due to differences in the available material between the cases, there are differences in the amount of collected findings.

Sampling parameters

The theoretical foundation consists of technical reports and descriptions, results of structural and material analyses of cross-laminated timber plates and applications of this product type. Multiple sources of evidence are used as a case study tactic to construct validity.[53] Available sources have been documentation, interviews, direct observations and on two occasions participant-observations.

Documentation consisting of drawings, protocols and technical analyses is fruitful to use, since it is stable (can be reviewed repeatedly), unobtrusive and exact, but may on the other hand be retrievable and biased. Interviews are targeted but are impaired by the risk of biases. Direct observations and participant-observations have their strengths in the direct covering of reality and context, but run the risk of momentary selectivity.[54] By comparing the findings from different sources the weaknesses of each source is believed to be parried. To some extent the sources are complementary, as stated by Yin (2003).[55]

[51] Strauss, A. and Corbin, J. 1998, p. 43
[52] Eisenhardt, K. 1989, p. 539
[53] Yin, R.K. 2003, p. 34
[54] Yin, R.K. 2003, p. 86
[55] Yin, R.K. 2003, p. 85

In the table below the interviewed professionals for each case are listed. The full-length designation for each case is used along with the utilised abbreviation.

Nr:	*Case:*	*Abbr:*	*Interviewees:*		
#1	Vetenskapsstaden I	VET1	architect	engineer	
#2	Vetenskapsstaden II	VET2	architect	engineer	
#3	Sundsvall I	SVA1	architect	engineer	
#4	Sundsvall II	SVA2	architect	engineer	
#5	Impulszentrum	IMZ	architect	engineer	
#6	Spöttlgasse	SPG	architect	engineer	builder
#7	Flyinge	FLY	architect	engineer	producer

Projects for reference:	*Abbr:*
Katsch an der Mur	KAT
Studenzen	STU
Unzmark	UNZ
Bau Technik Zentrum	BTZ

The interviewees have been chosen for being responsible for the architectural or structural design or for the practical production and erection.

Analysis of case studies

The multiple-case study has been made to enable an analysis of the use, methods, production and design work, efficiency, gains and utilisation of the studied products. Concerning building systems the analysis has comprised comparisons of the findings from the different cases on three levels *(Fig. 1.1)*:

1) VET1 with VET2 and SVA1 with SVA2
2) VET with IMZ and SVA with SPG
3) 3D with 2D

On each level a number of related factors have been noted and compared, such as level of prefabrication, level of finish, measures of utilised elements etc.

A possibility opened up by a multiple-case study is cross-case analysis[56], an approach, which may also strengthen the findings from the study. The cases have been used for a comparative cross-case analysis and for evaluation of the theories formed under way working with the project.

[56] Yin, R.K. 2003, pp. 133

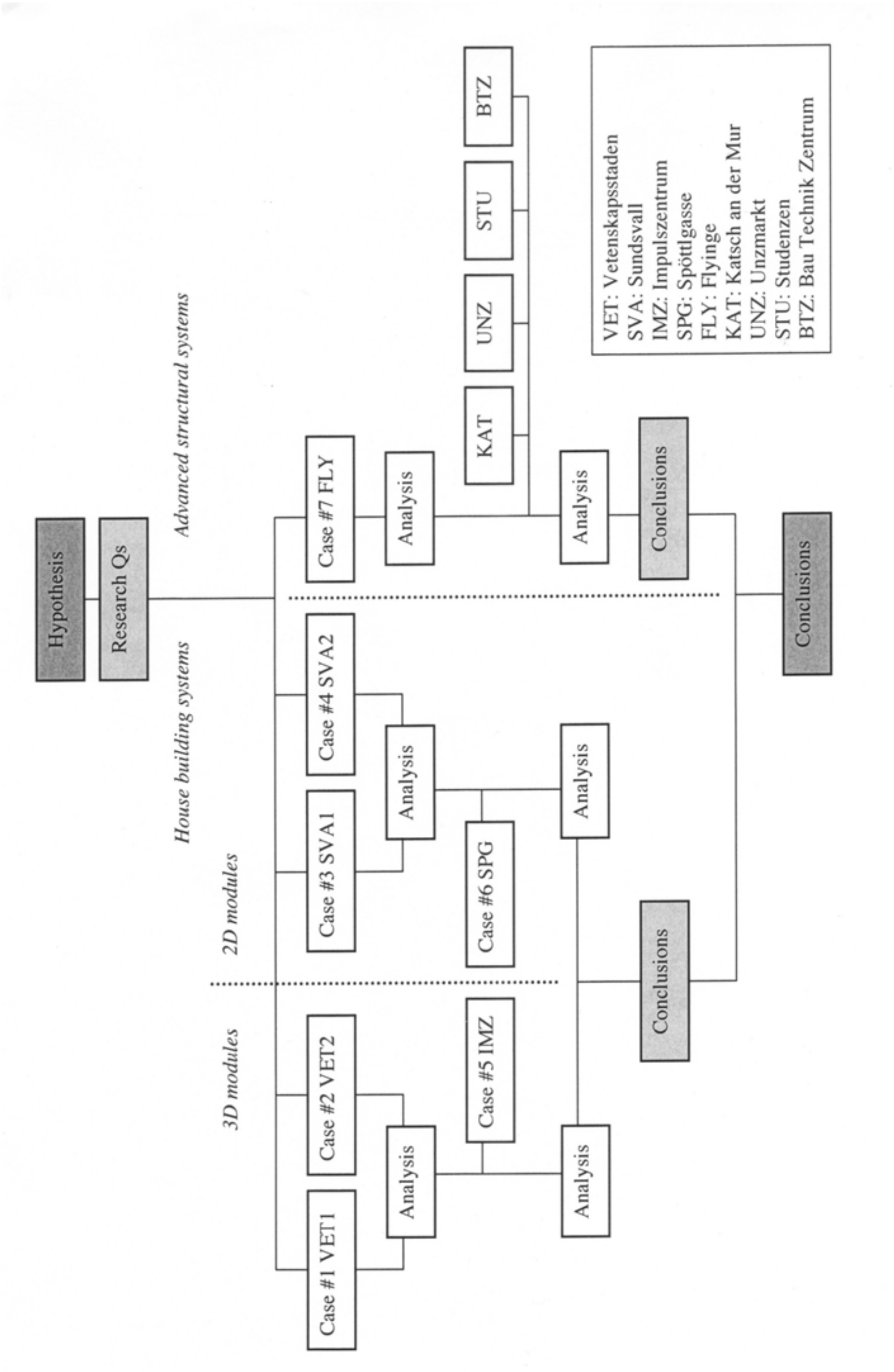

Fig. 1.1 Layout of the case-study design.

Initially there has been a compilation of findings from each case. Then findings have been summarised for comparisons, initially within and between the Swedish cases in twos. On the second level the Swedish cases have been compared in a cross-wise manner with the technically corresponding Austrian cases. On the third level the different techniques of 2D and 3D have been compared.

In the single-case study the findings have been compared with experience previously gained by the author and the chosen similar smaller projects. The case has been chosen to illustrate current advanced use of plate structures and describes development of structural design and erection methods concerning high performing plate elements. It has provided a background for further comparisons and development of possible new structural applications.

In both case studies findings have been structured to build up a picture of the cases, how they were intended, planned, produced and finished. It has been done in an iterative manner.[57] The analyses are based on observations of e.g. element measurements, element orientation, floor-span, montage, joint solutions and interplay between architecture and structural design. The analyses of the built results have then been considered in the light of the production conditions.

Sketching has been used as an analytic tool to test ideas and theories systematically, and to sort them, as well as to seek new solutions and applications. Previously gained experience of massive timber in different applications and the prerequisites given by material and technique in different scales from literature, photo documentation and site-visits have been matched with technical descriptions and modelling of the product type, which has resulted in sketches on related structures.

Structural principles, which have been utilised in already built projects or have been described in research reports and papers, have been considered. The technical potential of processed timber products has been synthesised. Then sketching render forms, which are possible to analyse, draw preliminary conclusions from, put in a development matrix and thereafter decide whether to continue with or not. It is a phase in a form finding process.

These sketched results have been discussed from architectural, static and rational points of view in the search for possible prerequisites of further development.

This method has been used both considering case #7 and when dealing with the theoretical development presented in Chapters 6 and 8 where hypothetical new structures have been proposed.

[57] *Yin has discussed the iterative nature of explanation building.* Yin, R.K. 2003, pp. 120

Research strategy: reliability and quality

Four tests to establish quality of empirical research have been listed by Yin (2003):[58]

- *External validity*[59] at the research design stage can be obtained through the use of theory in single-case studies and replication logic in multiple-case studies.
- It is possible to reach *construct validity*[60] during data collection by using multiple sources of evidence or establishing a chain of evidence.
- To secure *reliability*[61] during data collection a case study protocol can be used or a case study database be developed.
- *Internal validity*[62] during data analysis can be obtained in four ways: pattern-matching, explanation building, addressing rival explanations or use of logic models.

In this thesis the cases have been approached in two ways. The cases on building systems bear relative similarities in prerequisites, use and structural approach. Replication has been possible to use to some extent when dealing with these cases. The case on advanced structures is unique and therefore theory has mainly been used to validate it.

However, since the total number of buildings erected with the products of interest is low, there have been reasons to look at all the chosen cases as unusual to some extent. It has therefore been interesting to use theory in all cases, to validate them. To cast a widened beam of light on the advanced structure a few examples have been added for comparison, and thereby the use of replication logic has been made possible, though to a very limited extent.

Several sources of evidence have been available, these have been partly complementary, partly overlapping. During the collection of data the findings have been used to build up a chain of evidence, an analysable pattern. Since the sources may not give a complete picture, despite their being multiple, the chain of evidence-action helps to arrange the findings and interpolate between them.

A case study protocol has been used during data collection, even though it has been loosely kept. It was formed not beforehand but during iterative data collection as a guide in the work. The openness to where the findings may lead has made the relation to the study protocol less strict, or rather it has made the study protocol quite inclusive.

The internal validity has been more difficult to achieve during analysis of data. Both case studies are impure however, and imply parts of explanatory character, which has enabled the use of explanation building as a means in a hypothesis-generating process.[63]

[58] Yin, R.K. 2003, pp. 34
[59] *For generalisation of findings.*
[60] *For establishment of operational measures.*
[61] *For repeatability of the study.*
[62] *For establishment of casual relationships.*
[63] Glaser, B. and Strauss, A. 1967

1.3 General Approach to Central Concepts

In this section the most important terms are described. The descriptions should be used as guide lights when following the work presented in this thesis. The descriptions and definitions mirror the viewpoint of the author and the theoretical foundation for the overall approach and the following discussions.

Massive timber

Massive timber and massive timber construction are in this work used as major terms for all kinds of structural plate-like elements in construction based on solid timber-products such as boards, planks and logs. Massive timber can be given several meanings and definitions, much depending on trademark-registered principles of production. In this thesis, this term is used also for layered plate-elements with air spaces between the layers. Other English terms are “solid wood”, “heavy timber” and “laminated timber”. “Massivträ” is the proposed term to be used in Swedish, even though other words like “solidträ”, “tungträ” and “trämassivt” appear. In German the term “Massivholz” is common, but also “Brettsperrholz” appear for plate-like elements of different designs.

Architecture

Architecture stems from the Greek words *Arke*, which means the first, superior, and *Tekton*, which means carpenter, builder, or even the art of timber building. *Tectonics* can be described as design based on the structural properties of materials[64]. Another description reads ”the rules for artistic treatment of the materials of architectural and handcrafted products”[65]. Tectonic can also denote a readable structural function in e.g. a building, as the opposite of *stereotomic*, denoting the homogenous appearance of mass, where the parts are visually non-separable.[66] The adjectives *architectural* and *architectonic* are synonymous.

Architecture is the art of building. It is also the physical result of a creative process involving the coordination of a great number of different physical parts and their relations in a way that the result is more than the sum of its parts. Thereby it can be said to be a synergistic effect, a synergy.

One could speak of aesthetical and functional awareness. A basic reason for erecting a building is the need for a room with a certain function. To raise a building one needs a structure to create, enclose and protect this room. Fundamental for an engineer are structures making buildings rise above the ground. The structures in themselves, the physical structure and its ability to fulfil its load carrying and stabilising task, are of primary interest.

Fundamental for an architect are the spaces created by the building action. A building without a function looses its architectural meaning, and therefore the physical structure is seen as something supporting the function of the room. The void and the experienced impact on it from the surrounding structure are given the highest priority. The work of the architect is overviewing, combining, concluding, synthesising. Thereby it can be said to be holistic.

[64] Svenska Akademiens Ordlista 1987, p. 580 *(Translation by the author)*
[65] Nordisk Familjebok, Malmö 1948, Vol. 19, p. 59 *(Translation by the author)*
[66] *Frampton has written: ”the tectonics of the frame, in which lightweight, linear components are assembled so as to encompass a spatial matrix, and the stereotomics of the earthwork, wherein mass and volume are conjointly formed through the repetitous piling up of heavyweight elements.”* Frampton, K. 1995, p. 5.

"Architecture as an art form is essentially such, that its entire meaning appears only when we see its aesthetical and its practical sides as being jointly and inseparably belonging to the whole."[67] Architecture is not purely art. It is primarily a functional sustainable result of design with aesthetical awareness, a composition of a great number of parts. In a sense it is a system of pieces and like a puzzle the system/picture is incomplete until the last piece is put in place. In this way of approaching a building the parts and the whole are of equal importance. When studying the whole one cannot neglect what it is built up by. The individual parts can on the other hand not manage the overall function by themselves.

The work of the architect bridges the gap between what is and what is not yet physical reality, designing a built environment ex nihilo[68]. An architect is to deliver a proposal for something to fill a gap, suit a need; an architectural drawing is an image of something that does not exist, yet. Architecture should also bridge the gap between art and technology, since the artistic and synthetic work of the architect has to be transferred to a concrete, sustainable appearance by the means of material and structure to become realised architecture.

Architecture, in its widest sense, concerns a built structure, its technical function, its usability, its aesthetical qualities, its environmental impact on its surroundings and its enclosed space. Well working architecture consists of a full circle built up by different sectors. If some of the sectors are missing, the function will not be optimal and it is reasonable to ask if it is still architecture. This is a highly philosophical critique, applicable on practically all subjects. In "Zen and the Art of Motorcycle Maintenance", Robert M. Pirsig[69] asks if a motorcycle is still to be called a motorcycle if a single, very important screw is taken away. Of course it is a motorcycle, someone says, but is it? If the motorcycle does not start, after a screw has been removed, is it still a motorcycle? In the average sense: yes. If the term motorcycle implies the proper function of the bike: no! A built structure that lacks any aspect of proper function as a result of a missing part, or e.g. failing structural detailing, will hardly end up with a synergic effect. It could then be questioned if it really is architecture.

The Roman architect Vitruvius in the first century B.C. stated *Firmitas, Utilitas, Venustas* as the three tightly linked aspects of the art of building. By this he meant that the art of building is dependent on the three equally important parts Durability, Convenience and Beauty.[70] What he addressed was the importance of stability, utility and aesthetics being for architecture what each of the legs on a three-legged stool is for the stool to stand. Take away one leg and the stool will topple over.

The interdisciplinary character of Architecture has lead other authors to the subject of highlighting different aspects. In 1880 the English architect John Ruskin wrote the book "Seven Lamps of Architecture". He then chose the themes sacrifice, truth, power, beauty, life, memory and obedience.[71] He had another aim, poetic and romantic, than that which is presented here, but his fundamental view should be recognisable. There are many threads in this weave.

The tie between architecture and structure has in some respects grown stronger during the last decades, when new generations of architects seek their own styles, freed from the structural shapes of past times.[72] The striving for unique features tends to lead to, by current standards extreme structural solutions. Whether the

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[67] Cornell, E. 1966, p. 9 *(Translation by the author.)*
[68] *Latin for* out of nothing
[69] Pirsig, R.M. 1974
[70] Vitruvius p. 17
[71] Ruskin, J. 1880
[72] Eekhout, M. and Lockefeer, W. 2004

architects desire it or not the dependence on structural engineering is inevitable. But then again also high-tech has established itself as a visual expression, or style, of its own[73].

The lowest common denominator is the material. The material that is chosen for the structure will decide the architectural characteristics of the created room. Julius Natterer, professor at EPFL in Lausanne, has written that "the choice of material, the joining technique, the structural concept, the structural design and the design of the detailing are of particular importance for the quality of a timber structure."[74] What he argues are rational relations between material cost and action, i.e. architectural goal, functional and structural demands, and between material cost and total cost. Knowledge about materials and what they can do, their properties and what one can use them for and how, is decisive for the result of both architectural and structural practice.

Architecture and its language

Architecture is physically and visually composed by building parts, geometric forms, materials, textures and colours, etc. There are a great many ways to combine the different parts and different approaches, principles and methods can be applied. When a certain obvious approach or code is used to bring e.g. visual and/or functional order, it is possible to refer to it as an architectural language, denoting a label for its characteristic features, the formal expression of a built structure. In the point of view of form finding and structural morphology the chosen material, treated with a chosen technique, generates the design and expression. This can be called an architectural language of the chosen material, or a material language. To seek the character of this language, it is of great interest to study the characteristics of the material properties and their performance in built structures. The character and the potential of the material are possible to describe by looking into the nature of the limitations provided by the material. What can this material do?[75]

A material language concerns the close physical experience, tactile values of surface properties, for example texture. These properties imply smoothness, fibre patterns, surface grain, thermal interaction with the surrounding climate etc.

Material properties e.g. density, stiffness, bending strength, annual ring width, knots and capacity to buffer moisture and heat decide design possibilities. The properties are the prerequisites for what can be made, constructed and gained from, as well as for the climate experienced in the finished building. Timber show a relatively high stiffness and bending strength in relation to its density, its properties may vary between elements since growing environment has effect on the quality of timber from individual trees, and if left uncovered timber take up and release moisture and heat in long cycles. The material properties are then strongly influencing the final result, both technically, functionally, aesthetically, and concerning building physics. The properties of a certain material lead to certain ways of optimisation and if followed closely they lead to a characteristic design.

In a recently published book on the topic of structural design and architecture[76], there is a quote by the American architect Louis I Kahn. "You say to brick, 'What do you

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[73] *Eekhout states the erection of Centre Pompidou in Paris, by Renzo Piano and Richard Rogers 1972-76, as the dawn of high-tech architecture. This trend lingers on in the later era of IT and exceeds it in computed design, where the geometries can be formed completely digitally, referred to as BLOB architecture (Binary Large Objects). This leads to a gap between "free-form designing architects and engineering, producing and building industry".* Eekhout, M. and Lockefeer, W. 2004 *This approach is thus opposed to the one used in this thesis.*

[74] Natterer, J. et al. 1991, p. 66 *(Translation by the author.)*

[75] *See Chapter 3 for a description of material properties.*

[76] Engström, D. et al. 2004

want brick?' Brick says to you, 'I like an arch.' If you say to brick, 'Arches are expensive, and I can use a concrete lintel over an opening. What do you think of that, brick?' Brick says, 'I like an arch.'" By studying the limitations and trying to widen the possible use, the material specific properties must be regarded more and more thoroughly and the design must follow the material more and more closely. This purifies the experienced character of the material and its architectural language.

Structure

The term structure can denote phenomena in several different contexts, from theory and organisation to woven textiles, the character of the surface of a leaf or load-carrying elements. A common replacing term is order. The hierarchical structure of a company brings order into the making and following up of decisions; the post and beam structure brings order into the force transference through a building.

In order to the architecture to be constructed, to leave the paper state of the original drawings, there is a need for an organisation of physical members. Order brought to organisational or physical phenomena results in a *structure*. A built structure can create a space by either defining a surrounding area or separating an inside from an outside defining a room, or both. In a building the load bearing structure is of primary importance, since it is the prerequisite for the building to stand up. But the term and its appearance imply different things for the architect and the engineer.

The term structure can be used on several levels with different scopes then accompanied by a prefix, like roof, load bearing, stabilising or architectural structures. An architectural structure can be defined as a structure with both technical/mechanical and architectural/spatial aspects put upon it. The Norwegian engineer Bjørn Normann Sandaker defines in his thesis an architectural structure[77] as a structure that is part of an architectural work. What he denotes is any structural part of an architectural work. He furthermore refers to a characteristic set of problems caused by the relationship between "a structure and an architectural space". Thereby he addresses a challenge in dealing with architectural aspects as obstacles in working with structural design.

In the vocabulary of our everyday language there are words that we commonly use without reflecting about the specific use. We use them in a way we are familiar to, when talking to people we know and/or whose frames of reference we know. When we meet people with differing frames of reference we notice that our words no longer denote the same. In some cases the differences may be marginal and only concern the periphery of the vocabulary. In some cases central terms are interpreted differently and here we have a problem.

Both architects and engineers use the term material in the same way, but they care for different aspects of it. The engineer is mainly interested in the load bearing capacity, the sustainability and rational treatment of the material; the architect cares about e.g. the visual expression and the tactile experience. The engineer often stresses the production rationality and structural behaviour whereas the architect stresses the experience of the building during the lifespan, the utility phase. Both perspectives are indeed needed and do not need to oppose each other in practice.

[77] Sandaker B.N. 2000, p. 12

Structural morphology

"Form follows function"[78] is a well-known expression. This is, however, a highly simplified relation, and only partly true, as can be noted by a quick look at the path from idea to result. It reveals a dependence that is a bit more complicated than a strict polar one.

A product needed for a certain purpose, a certain function, will have to follow certain demands on form put forth by this function (Form follows function). But to fulfil those demands, to let the form of the product follow the function, one has to choose a material, a material whose properties fulfil the demands in question, has the right properties for good function and allows for the demanded form in the best way. Different materials have different properties and allow different forms; not every form is possible in every material (Form follows material). This material will have to be treated and refined to result in the sought product and for this a certain technique has to be chosen. To get the desired shape and design properties the material in question requires certain tools and techniques (Form follows technique).

Every step on this way from idea/function to finished realisation/product /form will decide some properties of the final result and in case of a failure along this way the result will not be obtained satisfactorily. Even if the function is the main deciding factor, form will in this aspect depend quite heavily on the success and characteristics of the applied technique.

The key to reach a good form in designing a product is a combination of the features of the function and the material properties. In this work the inventiveness of the designer will be crucial as a third factor, and this inventiveness is depending on the designer's knowledge and experiences of function and material. For a specific use one needs a product/structure with specific properties and one is to choose material and technique to suit these properties. For a certain use a certain material and a certain technology normally provide an optimal solution; how to utilise the basic properties of a material in the best way is invaluable knowledge. The properties of a material can furthermore to some extent also be developed through tailoring of its composition, like choosing specific grades of timber in different layers of plywood or composite materials such as composites of wood fibre and plastic possible to extrude.

Structural morphology can be defined as the study of structural form. Many professional groups, e.g. mathematicians, engineers and architects approach structural morphology and form finding from different angles and use both physical and computer modelling to search for suitable forms for combined structural and architectural function.

Within the IASS[79] there are several working groups active in different topics. The Structural Morphology Group (SMG) was founded in Copenhagen in 1991 aiming among other things to bridge the gap between disciplines of engineers, architects, technicians and artists in the work with structural design. Another aim was to bring to the front the design-mutuality of force-patterns, material-utilisation and architectural form.

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[78] *The dictum form follows function was coined by the American architect Louis Sullivan in an article on high rise buildings "The Tall Office Building Artistically Considered" published in 1896. He wrote: "All things in nature have a shape, that is to say, a form, an outward semblance, that tells us what they are, that distinguishes them from ourselves and from each other. Unfailingly in nature these shapes express the inner life, the native quality, of the animal, tree, bird, fish, that they present to us; they are so characteristic, so recognizable, that we say, simply, it is 'natural' it should be so. (...) Unceasingly the essence of things is taking shape in the matter of things, and this unspeakable process we call birth and growth.(...))"* Sullivan, L. 1947

[79] *The International Association for Shells and Spatial Structures.*

to the front the design-mutuality of force-patterns, material-utilisation and architectural form.

One reason for the formation of the SMG has been a noted desire for a revival of the structural expression and a fascination for structural work as a means for architectural design, "yet without leaving the poetry, symbolism and artistic attitude of good architecture"[80]. Material, technique, structural function and utility should meet and result in a sustainable architectural design.

Practically all IASS working groups study structural form, but the SMG has concentrated on structures of more unconventional, breathtakingly complex and experimental designs, as well as on interactivity and interdisciplinary work. The topics for the SMG's activities range from timber lattice shells to membranes and concrete structures with vast variety.

Characteristic morphology

The main traditional building forms follow two typologies, one of stone and one of wood. The language of stone is smooth, characterised by plane unbroken surfaces, either bare stone or brick, or plastered, whereas the language of wood is characterised by the visibility of the individual trunks, poles and/or boards.

The traditional treatment of materials for building follows rules decided by fairly simple tools. The visible character of raw cut stone remains in the mason wall and the trunk still shows a curved profile when put into a wall structure. Man's treatment of materials is the result of the material properties and the available techniques. The development of tools and techniques has gradually offered new treatments and ways to transform the materials' natural appearance. With sharp axes the sides of trunks can be flattened and with saws trunks can be cut into boards.

The language of wood has in this way changed into a dialect that was not originally typical for timber. The sawn boards came into use to protect the inner load-bearing members in a wall, but has also been usual in history to simulate what was regarded as more noble materials, to make the timber look like e.g. stone, brick, plaster or copperplate.

When even surfaces are to be created, normally the basic classical features of the timber, like the rounded surface of the trunk or the grain direction on the board, disappear. This happens when wooden claddings are polished and painted. Timber decks clad with gypsum boards are another use where the timber in most cases is possibly exchangeable. However, defining and developing material-characteristic ways to treat timber even in plate-form, taking e.g. its relative lightness or the possibility of curved elements as a point of departure, opens up for new characteristics that are unmistakably timber-specific. Then one can once again recognise a material-based language and the design as material-specific.

System

The use of a system is to bring superior order to a set of phenomena, e.g. products, parts, items, or issues etc. above all to gain rationality in the process of manufacturing and assembling. A system concerns a defined set of two or more related parts creating a whole and their abstract or concrete interrelations, the interplay between them. Systems are possible to describe on different levels and also as composed by other systems i.e. sub-systems. *Sub-systems* are systems on lower levels that are dependent on but also influence the systems on higher levels and the main overall system.

[80] Wester, T. 1997, p. 149

A system can be open or closed, which is decided by its relations to other systems. The concept of an *open building system* for example, implies a system where the components are interchangeable and can be supplied by different manufacturers. Any component, which is to be used in this building system, must adapt to a standardised set of joints. Apart from that, it can have any design, as long as it meets the requirements for safety and serviceability.

A *closed building system* is built up by parts that work well together within the system. It is however not compatible with any other system, i.e. its parts will not fit in other systems and parts originating in other systems will not work in the closed system. A *level* refers to the location of a sub-system's in a hierarchy of dependence and influence.

System action is a term for the co-action between different parts in a structure, or members in a part of a structure. When the parts/members work together and have an effect on each other they can be said to display a system action. A system can be organisational and thereby immaterial, it can also be highly physical as in a built structure. On a higher level it may be both physical and organisational, concerning e.g. both a product and the production process resulting in the product.

In this thesis the term mainly denotes physical elements and their functional and static relations and mutual influence. A building is dependent on a system, structural and functional order and interrelations. In a building system there are a large number of sub-systems that are to be coordinated and adapted to each other. All sub-systems have an effect on each other and on the system as a whole.

2 REASONING ESSAYS

This chapter contains three sections dealing with subjects related to and of importance for the main subject of the thesis. The sections provide overviews forming the context for the chapters following Chapter 2.

A Technical-Historical Perspective

"There is no law, no principle, based on past practice, which may not be overthrown in a moment, by the arising of a new condition, or the invention of a new material; [...]"[81]

History

In Sweden there is a long historical tradition of using timber for many purposes. It has been an available and cheap material, easy to work and easily given many shapes. The basic reason is not any romantic, aesthetical or structural idea, but pure rationality. In all times man has used materials that have been available in the nearby surroundings. Rare materials and materials fetched far away have been sought after, but they have always been rather expensive and luxurious and therefore rarely used. But then the very rareness is a strong reason for them to be sought after. Sweden has a foresting history and timber has been treated and given shapes with tools that have varied over time.

Fig. 2.1 Corner of log building in Skellefteå, Sweden (left) and column with rebates for inclined braces, Museo Chillida Leku, Spain (right).

[81] Ruskin, J. 1880, p. 5

In Scandinavia log building with horizontally oriented logs was the most commonly used building-method for hundreds of years. (*Fig. 2.1*) The technique was used for several different kinds of buildings. Logs were processed by hand into more or less complex designs of innumerable local varieties. The radial shrinkage of the logs when drying has been taken advantage of, making the building tight.[82] The fitting of the logs put high demands on skilled craftsmen.

When using only axe and saw in construction the range of possible cuts is limited, resulting in certain designs following the nature of the material.[83] This has caused similar traditions to appear and develop in different parts of the world.[84] In areas with similar climates and thereby similar species of wood, similar kinds of timber construction are recognisable.

The material has been the foundation and the prerequisite for many aspects of society, not only for the small red-painted house that has become a well-known attribute of Swedish culture. The basic importance of timber has been expressed differently in different regions[85]: log cabins, decorative carpentry, in half-timber work as frames for masonry etc. (*Fig. 2.1-2*) Trends and matters of taste have also been important factors for changes in choices of materials and techniques, but have always been subordinate.

Fig. 2.2 Corner detail of a log-structure, protected by a board cladding. An old sawmill at Bråfall, Sweden (left) and a timber framed structure in St. Peter, Switzerland (right).

Timber has often been used instead of more expensive materials, and then treated to look like something else than wood e.g. brick, marble or metal. Thus the red colour has paradoxically often been used not only for protection and spontaneous decoration but also in an effort to make the timber look like brick, which has been valued more highly.[86] In the beginning the red paint was an expensive product as well and only used in the wealthier parts of society. It was not until the early 1800's that the use became more widely spread and gained popularity in the countryside

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[82] *Logs in such a structure actually act as a plate, a behaviour normally secured in long wall sections and in gables by wooden dowels, even though the jointing mainly relies on gravity.* Werne, F. 1993, p. 133
[83] Boëthius, G. in Paulsson, G. 1938, p. 395
[84] Lundberg, E. 1971
[85] Broström, I. in Byggförlaget 2001
[86] Fried, K. in Jansson, E. (ed) 1986, p. 121

among those who were not so well situated. But then it rapidly turned the long tradition of weathered grey houses[87] into the tradition of the red façade.

Log houses have also been built with logs oriented vertically[88], which has resulted in different forms and detailing than those mentioned above. An early example is the Norwegian stave churches built in the period of roughly 1000-1100.[89] In the 18th century a modified version of this method appeared in Sweden as an effort to reach more freely shaped plans, free from the dimensioning log module, and lesser need for skills when working with the logs.[90] The flaw with vertically oriented logs/wood is that the swelling-shrinking movements cannot be taken advantage of but will lead to a lack of tightness varying with the moisture content in the air. Different types of tongue-and-groove joints have been used to obtain tightness.

Since the end of the 19th century, hybrids between horizontal and vertical log structures have been used and the dimensions of the used timbers have varied. Timber boarded houses[91] can be seen as a development of the log houses where sawn planks – two and a half to four inches thick – are used instead of logs. Vertically oriented plank structures, with plank thickness between two and three inches, came into use in Sweden in the middle of the 19th century. To increase tightness the planks for vertical structures were dried in beforehand.

The timber-boarded house was further developed and different plank based systems stemming from log structures have been described.[92] The system closest to the log type was built up floor by floor, with a course of horizontal members between the storeys. A further developed kind was built up with continuous planks with only the floor beams penetrating the wall-surface. During the 1940's and -50's most of the plank-based structures were abandoned for timber frames and further experimental projects on prefabricated small houses were launched. [93] One example is the Swedish company AB Elementhus, which in 1953 started production of entire houses, all-inclusive, from foundation to interior complements and installations. Everything was to be prefabricated to reduce the work on site to mere simple montage by a small group of unspecialised workers.[94]

Restrictions

In many parts of Sweden houses and whole cities have been built mainly in timber throughout history with exception for roughly the scope of the 20th century. Exploitation of the forests, and big fires in cities like Borås and Norrköping awakened the need for regulating the building of houses and cities in the early 19th century. From 1750 there was a rapid growth of the population and the cities became more dense. In an attempt to achieve national building regulations the Swedish parliament made in 1823 a building regulating effort concerning the risk of city fires. This trial failed, however, as a consequence of severe local diversities. Most Swedish cities then consented to building ordinances, and e.g. in the town of Hudiksvall the ordinance was revised in 1828, with a prohibition of buildings taller than two storeys in timber.[95]

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[87] *Which are still to be seen locally in the Nordic countries.*
[88] *The Swedish term is* restimmer *or* resvirke.
[89] Boëthius, G. in Paulsson, G. 1938, pp. 398; Lundberg, E. 1971, pp. 63
[90] Lind, S.I. in Paulsson, G. 1938, p. 177
[91] *The Swedish term is* plankhus.
[92] Lind, S.I. in Paulsson, G. 1938, pp. 179
[93] *Several prefab industries started in the late 1940's and developed to be important players in the area of single-family house construction.*
[94] Bergvall, L. in Engfors, C. and Rudberg, E. 1995, pp. 89
[95] Rentzog, S. 1967, pp. 40

From the late 18th century fire regulations were formed and developed stepwise, initiated by a fire insurance company. They included guidelines for city plans as well as building heights. During the 19th century the regulations came to be accepted in the entire country and after the last big city fires in 1888 the new practice is obvious. In 1888 the cities of Umeå and Sundsvall to a large extent burnt down. Umeå was rebuilt with two-storied timber houses along streets that were much wider than before. Sundsvall was rebuilt in stone, in a compact manner with narrow streets.[96] Since then buildings in timber were restricted to two stories until 1994.

During this time industrialisation was progressed greatly and steel and concrete took big parts of the building market.[97] Also the timber industry developed in the field of house construction, but the prevailing product for the timber building companies was the single-family house[98], where the restrictive influence of the fire regulations was small. Whereas single-family houses in timber have flourished, multi-storey houses have been developed in techniques based using other materials.

The urban environment has changed the demands on visual appearance of buildings. Timber buildings were sometimes not even regarded as real houses, but simple buildings without any long-term value. The modernist movement appearing in the 1920's preferred plastered walls of concrete or masonry for symbolic reasons to attribute and promote a clean and healthy way of living.[99] The stone appearance is sometimes preferred in our time, even though for other reasons. In 2001, for example, a pilot project in massive timber had to be plastered to fit the city plan of Stockholm, which prescribed the preservation of the stone town appearance in the area (*Fig. 2.3*) (*see Chapter 5, case #1*).

Fig. 2.3 Residential building in massive timber with a plastered façade, Stockholm.

[96] Hogdal, L. in Jansson, E. (ed) 1986, pp. 51
[97] von Platen, F. 2004, p. 64
[98] von Platen, F. 2004, p. 66
[99] Grandelius, L. et al. in Byggförlaget 2001, p. 222

In 1994 the fire regulations were changed. Before, they prohibited combustible materials in structures with more than two stories. Since 1994 the regulations are performance based and allow timber in all types of buildings as long as the performance of the structure in case of fire is secured. To manage this timber may be clad, covered with protective paint or the structure can be sprinkled. The development has been similar in all the Nordic countries, where Sweden so far has the most allowing regulations[100], even if the number of erected projects still is low.

Modern trends

A trend during most of the 20th century was to optimise structures and structural elements through material minimising, to increase the strength and behavioural capacity and reduce the volume of consumed material. This poses high demands on the material quality; the less timber used, the higher the demands on its strength and stiffness. The production at the sawmills today is largely set on supplying the building-market with timber matching light timber-frames (*Fig. 2.4*), popularly known as the two by four system, which was adopted from the US after World War II.

Fig. 2.4 Stored sawn and planed boards at a sawmill in Furudal, Sweden.

Steel can be considered as an engineered material. The raw bedrock is treated and refined, melted down and in some respects designed concerning its content and properties. Timber is not an engineered material in this sense. Timber can be ground and refined to similar degrees resulting in e.g. fibreboards and particleboards where the timber is ground and mixed with glue.[101] These products show evened out properties and homogeneity. In sawn studs, beams and laminated boards knots, cracks, differences in annual ring width and other factors give the individual members far from identical properties. To deal with these heterogeneities timber is graded, knots can be cut away and beams can be finger-jointed.

[100] Östman, B. et al. 2002, pp. 11

[101] *Engineered wood products are used for e.g. sheathing and stabilising and in composite beams.*

The optimising efforts have lead to diversified layered wall sections, providing an overall quite severe sensitivity to failure of individual layers. The performance of each layer has been modified and made better, but the overall structure has shown to be sensitive. If one layer is damaged, the whole structure is in danger of failing. The reason can be the intrusion of water or air.

There are, however, examples of other approaches to construction today. Heavy structures in timber can be noted of many kinds. For heavy loads, large spans and high-rise structures a material-minimised technique is not always the most efficient one and when the supply of timber is not a problem, relatively heavy, massive timber-techniques have appeared as a possible alternative.

Development of massive timber structures in the US

With the wide extension of railroad tracks in the 19th century, an emphasised need for bridges arose in the US. From 1830 onwards timber bridges were constructed in rapidly increasing numbers. The bridges before the turn of the 19th century seldom spanned longer distances than those allowed by the lengths of single logs. The higher demands on railroad bridges were met with truss and arch designs.[102] The earliest designs were often not carried out following calculations and strict engineering work, but were produced via trial and error by local craftsmen.

Except for fasteners, bridges consisted entirely of wood until about 1840, when cast iron and later steel and reinforced concrete came into use in structural components. This introduction lead to a decrease of timber as a structural material for bridges.

Small individual members make wooden trusses easy to transport and erect, but the production is relatively expensive and the maintenance costly, which made massive decks competitive. The first more massive bridge-structures were decks of nail-laminated lumber. The type consisted of vertically oriented sections nailed to each other to form a continuous surface. It appeared in the 1920's as an improvement of simple structures of sawn planks placed flat-wise on beams and was common until the 1960's when glulam became a reasonable alternative.[103] Glue-laminated timber can be used with longitudinal or transverse orientation on supporting beams, either with or without interconnections, e.g. steel dowels.

Another way to increase the capacity of wooden decks is to combine the timber with e.g. concrete, resulting in a double structure with concrete in the compressed upper part and wood in the lower part in tension. Timber can act as mould for the casting[104] – a sandwich-type of structure where the concrete in the upper layer improves both acoustic and fire performances[105] – or be designed as beams fixed with bolts or steel plates to a concrete slab, a T-shaped section[106] (*Fig. 2.5*).

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[102] Ritter, M.A. 1990, p. 1-6
[103] Duwadi, S.R. and Ritter, M.A. 2001, p. 165
[104] Natterer, J. et al. 1991; Gutkowski, R. et al. 2000
[105] *The method can be used for restoration of buildings as well, where concrete is cast on site on top of the existing timber floor.*
[106] Ritter, M.A. 1990, p. 2-22; Bathon, L.A. and Graf, M. 2000

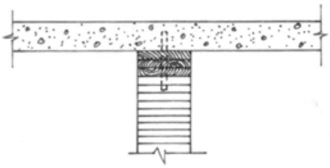

Fig. 2.5 Composite floor design with T-section.

Like concrete, timber can be stressed before loading, a technique first developed for bridges in Ontario, Canada, in the mid-1970's.[107] Such stressing can be carried out both in longitudinal and transverse direction, most commonly through the deck with drilled in steel rods (*Fig. 2.6*). These types are variations on laminated timber, either single-piece or multiple-piece laminations[108] depending on the expected loads.

Fig. 2.6 Early timber plate designs for bridge decks.

Development in Central Europe

In the case of bridges, timber is competitive both on a first-cost basis and a life-cycle basis.[109] It is however not only in bridges that timber results in an advantageous life cycle cost (LCC), and the LCC is not only about financial economy. In Austria in the early 1990's as well as in Sweden about five years later[110], overproduction of low quality timber at the sawmills and a need for alternate timber-building systems – more suitable than light frames for high-rise construction – were primary arguments for studying possibilities to utilise timber in new ways.[111]

Thus, the original reasons for exploring the processing of sawn products were financial, but there were promising outcomes even in other areas. The experimental projects turned out to show other advances as well, with regards to rational construction, effects on indoor climate, new characteristics of plan layouts and main design features.[112]

[107] Ritter, M.A. 1990, p. 9-3
[108] Ritter, M.A. 1990, p. 8-4
[109] Thelandersson, S. et al. 2004, pp. 4
[110] Falk, A. and Sjöberg, H. 2001; von Platen, F. 2004, p. 78
[111] Pischl, R. et al. 1998
[112] Falk, A. 2002

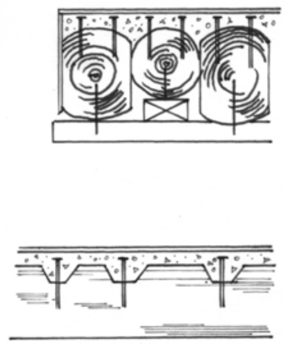

Fig. 2.7 Round timber with concrete topping. Section perpendicular to (above) and along (below) the logs.

Initial development of massive timber-based systems for residential buildings was seen in Switzerland in the early 1990's[113], e.g. at the technical universities in Lausanne and Zurich. Several designs with timber combined with concrete have been presented by professor Julius Natterer in Lausanne.[114] Vertical Nailed Planks (VNP), i.e. piled planks nailed together, is used either as a wooden deck, or in combination with concrete. Natterer has also presented element types with round timber (*Fig. 2.7*).

The performance of these composite elements is dependent on the shear connection between the two material-layers. Several types of connections have been tested, skewed screws and cut grooves being the most common principles.[115] Grooves can be cut perpendicular to the direction of the planks in the main spanning direction, or obtained by shifting the depth of every second lamella, resulting in a ribbed upper surface against the concrete (*Fig. 2.8*). Techniques with piled, mechanically fixed[116] planks have been further developed concerning nailing patterns and also by using screws instead of nails[117].

Fig. 2.8 An example of composite sections of floors/decks.

During the 1990's several companies in Europe have started production of plate-like structural components of timber for the house-building market. The products range from surface-elements to industrially produced logs of glulam, different varieties of rather highly processed structural members. In the case of glulam logs the

[113] Schickhofer, G. 1994, p. 4-22; Johansson, L. et al. 2000, p. 138
[114] Natterer, J. 2000
[115] Gutkowski, R. et al. 2000
[116] *Mechanical fasteners, e.g. nails, screws, dowels, are distinguished from glued joints. The difference is above all performance-based since mechanical joints are ductile and allow a certain slip or movement, whereas glued joints are regarded as stiff, rigid connections.*
[117] Meierhofer, A.U. 1998

combination between old timber-traditions and newer rationale is obvious, whereas surface-elements show characteristics that are completely new for timber.

In the Austrian region of Styria in 1996 the foresting companies entered a joint venture on product development together with Graz University of Technology. The project resulted in the realisation of a production line for two developed timber-based plate products: laminated timber (Brettstapelbau) and cross-laminated timber.[118]

The Middle-European three-layered product (Dreischichtsplatte), is another cross-laminated type of plate available in varying thicknesses. Products of this kind are suiting needs for interior design, scaffolding, façade cladding and as visible layers on floors (*Fig. 2.9*).

Fig. 2.9 A three-layered plate as facade cladding on a building laboratory in Graz, Austria (left) and a partition wall in a fire station in Triessenberg, Austria (right).

Development in Sweden

The interest in timber as a structural material has re-awakened and architectural experiments with new versions of old techniques have been introduced. In 1999, for example, a prototype for a modern log cabin called Vistet[119] was presented in Stockholm. The aim was to show how values in log construction can be utilised with a modernised aesthetical and functional expression. The project tried to deal with building tradition in new ways and showed un-conventional ways to treat log-systems, concerning the location and orientation of openings.

The need for architectural studies concerns not only massive timber-techniques but also timber-building at large today, especially high-rise construction. New techniques, new products and new contexts need new designs to match old and new needs. The development of the built environment place altered and new demands on both functional and aesthetical design. The red-painted log house differs from the industrial production unit or the multi-storey office building. (*Fig. 2.10-11*)

[118] Pischl, R. et al. 1998

[119] *Designed by Anders Landström, Bertil Harström och Thomas Sandell 1997-99.*

During the 1990's timber building has been subject to increased development on the Swedish building market. At first it was a slow reaction, but by the year of 2005, projects on high-rise and massive timber construction have been launched. The timber-producing companies are also showing interest in delivering new products as well as in the development of products, production and knowledge. In Sweden, massive timber structures have until the year 2005 been proposed and planned for three to eight storeys in different projects.[120] The constructed projects have been erected in three to six storeys.

Fig. 2.10 Office building with massive timber floors, Skellefteå, Sweden.

Fig. 2.11 Residential building in massive timber construction, Judenburg, Austria.

[120] *The planned but never constructed project Woodfront in Skellefteå, Sweden, was designed with eight storeys.*

The Nordic Wood Programme was run 1993-2000 as a joint venture engaging trade associations, companies, universities and research institutes in the Nordic countries. During the active period 85 projects were initiated, e.g. concerning bridges in timber, fire-safety in timber buildings, multi-storey timber houses and new markets for Nordic timber products. [121] Within the Nordic Wood Programme several buildings have been erected.

A first phase of the programme was dedicated to multi-storey construction in timber.[122] In 1994 the residential project Kvarngården was erected with three storeys in light timber construction. In 1995-96 the four-storied residential block Orgelbänken was erected with a light timber-frame. In 1996 Wälludden outside Växjö (*Fig. 2.12*) became the first Swedish timber-framed building project that was constructed with one part in five stories, which meant a breakthrough concerning fire-safety, since there is a leap in the general restrictions[123] between four and five stories.[124]

Fig. 2.12 Plastered façades on a light timber-frame structure, Wälludden, Växjö, Sweden.

A second phase of Nordic Wood treated massive timber construction for medium-rise and multi-storey buildings. 15 projects were erected in the Nordic countries within this phase – most of them in Sweden – where the technique to use large plate elements was beginning to gain attention.[125]

Two other recently published projects on massive timber are a handbook in massive timber construction, published on the Internet by an industrial consortium[126] and a documented development project on volume element construction[127] (*see Chapter 5, Cases #1 and #2*) Both projects provide examples of realised projects constructed with industrially produced massive timber elements. The projects referred to in the handbook were erected 1997-2001 and the projects in the documentation were erected 2001-2005.

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[121] Nordisk ministerråd 2003, pp. 25-28
[122] Described in Hansson, T. 1997
[123] *The leap is from REI60 for four storeys to REI90 for five storeys. In REIxx, R = load bearing capacity; E = integrity (tightness); I = isolation (temperature); xx = required minimum number of minutes to failure.*
[124] Persson, S. 1998, p. 7; Östman et al. 2002, p. 11
[125] Described in Sjöberg, H. and Samuelsson, S. 2002
[126] *Industrikonsortiet Massivträ 2002 (Industry Group Solid Wood Construction). See http://www.solidwood.nu*
[127] Vetenskapsstaden 2005

Comments

Throughout history methods and techniques have changed and thereby changing the properties and appearance of materials. The fundamental matter, i.e. materials, decides what is possible to achieve, but through technology the limits can be pushed forward and the possibilities concerning construction can be widened. Science, technology and society interact in this development by matching needs, visions, demands and experience.

The development concerning construction can be viewed as a pendulum swinging from one extreme to the other and light, minimised and complex structural designs can be regarded as one extreme opposed to heavy, massive structures as another. In that respect the trend in society and on the building market now seems to promote the latter type of construction. Massive, "heavy" timber products provide the option of interaction between structure and indoor climate. The development of timber-based construction techniques provides new possibilities and this changes the prerequisites for timber as a structural material. New products are possible to use in new designs with visual results. The utilisation of these has not been fully researched and the effect of this step cannot yet be fully evaluated.

An Industrial-Productional Perspective

"There is inertia in the construction sector caused by cultural and administrative hindrance that makes the introduction of new building systems hard."[128]

"Is industrial production biologically suitable for man? – Since the answer is not obvious, the question is worth asking."[129]

Industry

The industrial revolution was a slow but sure and a very far-reaching turn for society.[130] Its prerequisites were both a material and an organisational development. Knowledge about how to treat materials to be able to create tools and mechanical means to manufacture items, made it possible to develop new techniques, which have lead to new products, new needs, the search for new techniques and so on.

Industrialisation can be carried out mainly in two ways: either for the sake of the industrialisation itself or for the sake of the product. The first way is most often a cul-de-sac.[131] When the industrial production becomes a goal in itself the production may very well get swift and efficient but it will easily result in products with reduced meaning and use. The development and adjustments of the production technique and equipment need the perspective of the product's features to be of any useful meaning.

Technical means to reach controllable productivity

Traditionally craftsmanship has been concerned with the production of more or less unique items. An analogous example is the production of books. When manuscripts were first to be duplicated each copy was made by hand, syllable by syllable. It was a very time consuming work, and making a thing out of the handcraft became a fashion. Illuminating the texts with small-scale pictures and coloured initials became both a way to amuse the writer at work and a way to make the text attractive to the reading eye and mind.

The technique to print made books more easily duplicated and the uniqueness of books came to be more rarely seen. The text production turned from production of unique objects into series production. A book is a means to transfer information and the readability is therefore of great importance. A printing technique, no matter how fast, is worth nothing if one cannot read the copies it produces.[132] Transferred to building construction: If the industrialisation of building construction leads to uninhabitable homes, the production loses its meaning.

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[128] von Platen, F. 2004, p. 16 *(Translation by the author.)*
[129] Citation by Georg Henrik von Wright. *(Translation by the author.)* Bergvall, L. in Engfors, C. and Rudberg, E. 1995, p. 91
[130] Cornell, E. 1967, pp. 66
[131] Bergvall, L. in Engfors, C. and Rudberg, E. 1995, pp. 88
[132] *Books, which are printed to be just beautiful pieces of art without claiming the necessity of transferring other experiences to the consumer than the pure aesthetical one, can be left aside in the current discussion.*

A building is to be used and therefore the entire production should be subordinate to the utility function of the building. A building is a part of a surrounding society and should be adapted to this. The finished product is essential and its function, use and life cycle economy are thereby the goal for the industrialisation process.[133] The knowledge about what the goal is and how to use available means to reach it is the basis for any producing activity.

Not only economic and technical rationality are important. The usability decides the value of a product and is strongly linked to both practical/functional and aesthetical matters. Architectural design needs to be studied, as well as system-issues, to make the resulting products/environments durable.

Time of production, construction and erection has become an important factor for the building-economy and the raising of speed is a central issue. Economy may decide the useful life of a building today and even decrease the importance of the sustainability of the used material. High speed puts high demands on accuracy in the process and this is not easily obtained. When industrialisation craftsmanship the means and their result are to some extent bound to follow uniform rules and standards. Standardisation strives to draw lines for a product and its parts making them more simple to obtain in long series. Though, the paradox is that the new technical means provide easily achieved variety.

During the early years of construction systemisation, detailing was often very little regarded. Using the method of industrial production as an excuse a poor level of detail design was carried out, which would not have been accepted within handcrafted house construction.[134] After the early years of modernism, when the wellbeing of man was in focus, the aim shifted from the quality of the result to the efficiency of the means. The means have now been developed to a completely different level. With new machines it is possible to get close to achieving the finish of surfaces and detailing created with hand tools until about a hundred years ago. Above all it is possible to handle complexity and unique products in rational and economic ways.

Computerised production

The development of computerised production has taken the industry another step from the traditional handcraft but makes it, in a sense, possible to close the circle. The precision and repeating capacity of CNC-machines turns the production process into exact mass tailoring, or mass customisation with the possibility to combine capacity of quantity and ability of quality.

With CAD/CAM-software each part and element can be designed in every detail. Digital drawings are produced with measures and dimensions and can be accompanied by listings of parts and details. Every part of the process can be prepared and planned and through digital communication an order can easily be delivered to CNC-machines for the production. With the CNC-machines the programmed manoeuvres are carried out repetitively or one time only; shifts between different programmed design patterns are swift, thus different individually designed elements can be produced with both precision and speed.

The demands on operative systems and even flows of information are huge.[135] The situation is however different for different actors in the building sector, different

[133] Jacobsson, M. 1965, p. 11
[134] Bergvall, L. in Engfors, C. and Rudberg, E. 1995, p. 88
[135] Samuelsson, S. in Engfors, C. and Balgård, S. 1999, p. 74

professions utilise information technology to much varying extents.[136] Every part of the process needs regular control, adjustments and calibration.

A difference can be made between inner and outer rationality[137], where inner rationality denotes the way technical solutions fulfil technical demands, and outer rationality denotes their relation to non-technical demands, i.e. relations to political priorities, economical interests and a multitude of varying demands of the end users. This is the duality of the context where the product is manufactured and to which it is delivered: One logical part, which is possible to design, standardise and rationalise. One part affected by culture, tradition, history etc. tied to a more or less specific time and place.

Different system generations

The systemised building efforts grew from big, urgent needs of dwellings after World War II. The Swedish building standardisation organisation (BST[138]) initiated in the 1940's the publishing of an inquiry on modularisation[139], founded on a vision about systematic co-ordination of measures for all structural elements. The leading Swedish architects of that time considered the industrialisation as the users' and architects' servant and tool. "Real rationalising leads to cheaper products with retained or increased quality or better products at retained cost, or both! Lower cost with less quality is merely product deterioration."[140]

The first systems to be utilised were closed ones, meant to compete and thereby produce rich and variable built results. Only a few, big companies were active, possessing the required machinery, and information about system properties was regarded as trade secrets. Instead of great variety long series of few types were required, since the companies optimised the technical function of the production and avoided most deviations from a chosen set of measurements and properties.

The typical project of this stage was the large-scaled residential area with repetition of giant apartment blocks with only a minor part of prefabricated products. The introduction of cranes on the building sites enabled construction with big, heavy elements. There was a large-scaled production of big, generalised structures and element systems in concrete. This has later become the most common picture of prefab, which is often regarded as cheap, dull and unattractive by the man on the street.[141] In Sweden this strategy resulted, and ended, in a boom between 1965-1975, whereas the development in Denmark and Finland followed lines of open systems and a wider use of prefabrication and lasted until the late 1980's.[142]

The closed systems gained the development of precise control of the production, but the inability to change became a disadvantage, for which they also were heavily criticised. The technique was not flexible enough, not resource efficient and not adaptable to local conditions. The built projects were too large-scaled and the moving of the production from the sites to factories lead to changes of materials and methods that in most cases lowered the quality.[143]

Co-ordination of measurements became a current theme when smaller projects attracted interest and the closed systems started to be opened up. There had to be a

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[136] Cigén, S. 2003, pp. 16
[137] Adler, P. 2001, p. 6
[138] *"Byggstandardiseringen" with the motto: "Standardisation – an indispensable tool for industrial production" (Translation by the author.)*
[139] Bergvall, L. and Dahlberg, E. 1946
[140] Bergvall, L. in Engfors, C. and Rudberg, E. 1995, p. 87 *(Translation by the author.)*
[141] von Platen, F. 2004, p. 63
[142] Adler, P. 2001, p. 9
[143] Samuelsson, S. in Engfors, C and Balgård, S. 1999, p. 71

steady flow of information concerning the building parts and products on an open market to allow this, and with an increased flow and a larger variety of products, above all the design of layouts was more freely developed. This also influenced the exteriors and the surrounding environments. Focus was kept on flexibility and small scales. The typical project of this stage was the small-scaled, tightly built area with high density where the design was kept closer to the needs of the users and the local conditions.[144]

The next stage of systems and techniques to be reached has in the late 1990's and early 2000's been featured by aspects of sustainability, management, ecology and exchange of products, services and information.[145] This is to a large extent indebted to the means provided by increased computer capacity and the development of information technology. The production methods are once again to be flexible, technical solutions should allow alternate layouts and adaptability to changed needs and uses, and both techniques and materials should be evaluated concerning sustainability and life cycle analysis (LCA)[146].

In small-scale production, product design can be worked to fit a common standard project by project, whereas in production of big volumes and varying co-players/co-producers this will generate a growing problem. A closed system is an element standard for a specific project or company, which enables combinations and assemblies within the system, but not with other elements from other systems. The element and joint design can be specifically optimised for a certain project or to work in a row of projects with the same type of elements.

The key to a closed system is kept inside the companies. The production achieved through long series of units for big projects easily gets stuck, since they often get specialised without ability to allow changes. Long series of units big projects spontaneously demand big companies, which nurtures the development of even less adaptable systems and a development difficult to shift; the situation with few dominating companies and a strict focus on separate material industries is still to be seen today in Sweden.[147]

Open systems allow small companies to take part in the production, even in co-operation in big projects. The key to an open system is kept outside the companies as a common framework. This allows for competition between companies, which run the risk of loosing the competition and being exchanged. The exact features of the product are kept flexible and adaptable to varying geographical, technical, organisation and project specific prerequisites.

An open system is based on a universal set of joints, making its members adaptable to a variety of other elements. The joining points/lines are alike but the elements between the interfaces may be designed differently – it allows different manufacturers to design their own elements and building parts without other restrictions than the jointing principle. Main measurements, distances and jointing technique are kept and more general limits concerning acoustic integrity and allowed vibrations are regarded. The principles of open systems are meant to open up and simplify the adaptation of elements, components, techniques and systems. The key to mass production can today be stated as complete and consistent interchangeability of parts and the simplicity of attaching them to each other.[148] This approach was applied

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[144] Adler, P. 2001, p. 13; Beim, A. 2005
[145] Adler, P. 2001, p. 14
[146] *I.e. analysis of the chain from raw material over production and use, to recycling. i.e. "[…] the environmental aspects and potential impacts throughout a product's life (i.e. cradle to grave) from raw material acquisition through production, use and disposal."* Borg, M. 2001, p. 5
[147] von Platen, F. 2004, p. 64
[148] Crowley, A. 1998, p. 398

in 2001 in a Swedish systemisation effort on interface relations concerning a Wood Interface System[149].

Development of an open system for timber construction has been discussed in the context of the COST[150] action E5. This program action was run 1995-2000 to promote sharing of research results, transfer of knowledge between European research institutions and between research and practice concerning timber-building systems. Referring to the fairly new performance based fire regulations, the action was aimed at strengthening the position of lightweight timber frame building systems on the European market.[151]

In practice this was realised by means of workshops, conferences etc. and exchange of researchers as well as documentation. A Finnish proposal for a pan European open timber construction system[152] focusing on an industrial standard may exemplify these efforts. The proposal can be summed up in three main parts: dimensional standards (building parts, building components), type solutions (structures and joints, technical systems) and operational procedures (design, manufacture, installations). The presumed gains were further developed competitiveness and a broadened market share.

Uniformity and variety

The market provides with numerous products and alternative solutions. By dividing products into x types and y models the number of variations is much increased. Choice is for the sake of the customer and the end user. Without differing tastes and likings concerning aesthetical values and comfort, one single model of one single type would be needed and one single apartment design could prevail; production would, hypothetically, be possible to reduce and economise to its extreme.

The production does not let the freedom of choice be unlimited and it demands reduction of variability. But diversity of customers and ideals do exist and production has to meet these differences of demands. The producer must take into account the needs and demands of the market but also perform developing actions in a way that gains the acceptance of the market for the product. The entire market can be described as dependent on a steady flow from producer to customer.[153] Developed products must be presented and explained to the market[154] in a very clear, almost over-explicit way to convince regarding its reliability and good function.

The relation between manufacturing and construction at a lean production approach[155] has been discussed by several authors. It can be argued that construction is a complex production process, which depends on the relation between producer and customer. This relation cannot be optimised as linearly as other production. Construction is by Bertelsen and Koskela characterised as "a complex production of a one-of-a-kind product undertaken mainly at the delivery point by co-operation with a multi-skilled ad-hoc team"[156].

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149 Alsmarker, T. 2001

150 *COST (European Co-operation in the field of Scientific and Technical Research) is an intergovernmental framework co-ordinating nationally funded research.*

151 COST 253/95

152 Viljakainen, M. 1999, p. 50

153 Bertelsen, S. and Koskela, L. 2004, p. 6

154 von Platen, F. 2004, p. 108

155 *Lean production is a way to maximise efficiency in production by minimising waste along the production chain.*

156 Bertelsen, S. and Koskela, L. 2004, p. 5

In the 1930's, the Swiss architect Pierre Jeannerret, known as Le Corbusier, commented on the production in the Ford factories[157]. "This is the dramatic conflict which holds back architecture and keeps it out of the main line of progress. In Ford's factory everyone works to one end, all are in agreement, all have the same objective and all their thoughts and actions flow along the same channel. In the building industry there is nothing but contradictions, hostility, pulling in opposite directions, differences of opinions, working at cross purposes and marking time. We pay dearly for this – to build is a luxury and consequently society is badly housed. On the other hand when we do drain our financial resources to build, the result is always precariously discouraging. And what architecture does produce bears no relation to the needs of our time."[158]

The above-cited comment by Le Corbusier, as well as reflections made by the German architect Konrad Wachsmann[159], deal with possible similarities between the building industry and other industrial lines of business. In production some fundamental aspects are the very same no matter what the product is. The conditions at the beginning of the 20th century that made Le Corbusier and Wachsmann speak as they did are, however, still recognised today. Even if the preconditions have changed, the lack of co-ordination, interactivity and holism still causes problems and large costs. Apparently there are differences that are very hard to overcome or put aside. What makes building actions so different from any other production that it could not learn from these?

Much of the manufacturing theory during recent years relate to ideas inspired by Japanese car industry, where striving for efficiency and economic gains has lead to thorough work on minimising waste. The engagement of individual workers along the production line has been considered important for dealing with production complexity and the solving of problems.[160] The adaptation to technological change in the building industry has, however, been slow and the over all characteristics have been labour intensive low-tech methods.[161]

A stated difficulty within construction compared to other kinds of production is the forming of the preconditions in parallel with the solutions during the design phase, which is often propagated to the construction phase as lack of information or even defective design solutions[162], met by the workers with a deeply rooted practice to find solutions on site.[163] This makes the adoption of lean difficult. The chain from raw material to production to end user needs to be clarified to release the potential increase of values of the manufactured product, thereby defining and securing the economic and rational gains from the production.

Prefabrication

Today the building industry is capable of delivering more and more complete products to the building sites. To protect an entire building during construction is difficult and therefore it is gainful to reduce construction time on site to a minimum. Parts of the building process are moved inside to protect the building materials

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[157] *A well-known slogan approaching the freedom of the customer is the line from an early Ford advertisement: "You may choose any colour as long as it is black."*
[158] Jacobsson, M. 1965, p. 32, *citation from Le Corbusier, Jeannerret, P. "Œvre complète 1934-38" p. 24*
[159] Wachsmann, K. 1959 *Konrad Wachsmann moved to the USA where he from 1941 worked with development of building systems.*
[160] Bertelsen, S. and Koskela, L. 2004, p. 4
[161] Crowley, A. 1998, p. 397
[162] Bertelsen, S. and Koskela, L. 2004, p. 7
[163] *The saying "LPP – Löses på platsen" [to be solved on site] is a well-known approach among workers on the construction site.*

during the building process. The wish for good working-conditions, rational use of tools, machines and manpower, production control as well as shelter for materials and building-parts results in increased degrees of prefabrication. Dry construction and concentration of working-capacity are thus attractive gains of prefabrication. In a factory temperature, light and working-postures can be optimised and machines can easily and economically be utilised for heavy lifts and difficult manoeuvres to ease the conditions of the workers.

Modules for multi-storey residential buildings are e.g. provided with interior detailing, surface finishing, wallpaper and complete bathroom installations already in the factory (*Fig. 2.13*). The work on site is then largely reduced to the joining of the different modules why these must be designed to provide for a swift completion of a working entity. Prefabrication is a technical solution to rationalise building actions, to allow transportation of building parts and dismantling of built structures.

Fig. 2.13 “Su-si Fertighaus” on the road (left) and “Fred Fertighaus” in use (right). KFN Kaufmann Project GmbH.

Different approaches to prefabrication are noticeable,[164] e.g. modularity, lightness and thoroughly elaborated joint solutions as optional features. The concepts of assembly dismantling and re-erection have even been stated as being of importance during the planning of the production of buildings.[165] The elements can be plane (2D) or volumes (3D). Volume modules with close to finished interiors are gainful for the working conditions and time saving on the building site. Light timber-frame systems are today produced in this way on a regular basis. The actual building site may not be big enough to allow assembling of products on site, since this often demands spaces for working, loading and unloading of material and storage of delivered material and products pre assembly. Complete volume elements can in these cases be produced with high interior finish and exterior insulation and cladding.

But volume elements put high demands on joints during handling/transport and easily cause complicated and expensive transport conditions. Transportation raises specific demands and may limit the degree of prefabrication. The sizes of transported products must follow current road regulations and the products must stand transport. A balance is needed between working economy, rationality and conditions on site.

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[164] Bahamón, A. 2002
[165] Crowley, A. 1998, p. 398

Field factories

A third production method exists in-between complete prefabrication and full on-site construction (*Fig. 2.14*). Transporting big volume elements leads both to environmentally and economically costly handling, since actually large volumes of air are transported. Volume-modules mean increased number of transported packages, which may thereby lead to greater disturbances around the building site. It places rather high demands on the access routes, which must be quite wide. Big trucks have to be taken close to the site, to deliver the modules within reach of cranes at the foundation. High degree of finish also demands more careful handling which may be impractical.

Fig. 2.14 A light timber frame during production in a field factory, Wälludden, Sweden.

If the available area around the building site is large enough, an alternate production method can be obtained in a factory temporarily located close to the site. A field factory is used for assembling big modules for instant incorporation, a kind of build-on-demand at the very site.[166] Such semi-manufactured articles require a production in two steps – 1) production in a factory (then transport), 2) assembly and finishing in a field-factory (then integration). The raw material can vary from elementary boards, posts and beams, to prefabricated plane elements. Plane elements can be transported in packages of high density, which reduces the transport action.

[166] *Treated by* Samuelsson (2005) *in an unpublished paper.*

Comments

It is of fundamental importance for the development of building systems and means of production to regard the customer and the utilised material. Gains from e.g. industrial production and standardisation are out of reach unless the customer is willing to pay or the prerequisites given by the material are followed. When new techniques are offered they should be utilised to serve the production according to these factors and adapted to the specific conditions at each project and on each site. This concerns all players along the chain of production; everybody must share the same awareness of origin and goal in the process.

The same can be said about material development and use, which must proceed along lines decided by its properties and not be steered by principles utilised for other materials and products. Production puts demands on logistics, techniques, tools and methods. So it has done for innumerable years. To increase productivity man has explored new tools and methods to become better, to increase efficiency and to reach higher degrees of processing and thereby skill has developed, and still develops. The industrial revolution began as early as in the late 18th century but still today there are fields where industrialisation has not been realised to its full extent. Habits and tradition hold back the development, at the same time as they are the indispensable launching pad to take off from.

An Architectural-Constructional Perspective

"New material, new design and new knowledge are sources for new architectural expressions. The introduction of them is a very slow process."[167]

Motifs in architecture

In architecture structural motifs, such as material-character, method of treatment, jointing and function of the structural parts, have been used in composition throughout history. Different methods of treatment result in different textures, which give both visual aesthetic experiences and information indicating how the material has been treated i.e. handcraft, tools, machines involved in its production. The function of a structure can be utilised for designed expressions e.g. the carrying performed by a column or the suspension of a roof, expressing strength and lightness respectively.

Contributing motifs act as the opposing types, using associations to say something about the building, not having anything to do with the structure. Motifs can be plane sections and neutral details to bring out other elements, or they can be taken from nature such as vegetation or caves.[168] The use of metaphoric terms is also common, where e.g. *organic* normally denotes structures that take spontaneous, undulating, unordered asymmetrical forms.

The relation between structural and contributive motifs is not always clear. Walls, floors and roofs are the main building-parts, which have clearly defined structural and sheltering purposes and act as main features of the visual/aesthetic expression. The structure represents a form, which through varying designs can result in numerous versions and different expressions.

New designs can be created from imagination or be composed by items/designs transferred from one area, one context, one meaning, to another. In art history *readymade* is a term of late date denoting a manufactured item designed for a special use, which is taken from its planned context and put on a pedestal or in a frame and is referred to as art[169]. The method is still used but the nuisance of the use in performing arts has vanished; once done it will never be as surprising and revolutionary again.

The term readymade is in a way possible to recognise in the building history, in the use and borrowing of structural form, technical detailing and building methods in architectural design. The architect uses building materials and techniques to create designs, but furthermore has the possibility to take part in the forming of the structural elements, if he or she is willing to take it.

There is a similar striving in architecture to create new, unique expressions. But more obviously than in other visual arts, borrowing and copying occur in architecture. The use of attributes like the antique Doric column or the marine detailing of early

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[167] Vanggaard, O. 1998, p. 187
[168] Cornell, E. 1966, p. 24
[169] *It was the French artist Marcel Duchamp (1887-1968) who originated the concept of the readymade. A well-known example is his "Fountain" from 1917, a porcelain urinal that was signed and then exhibited as a piece of art.*

modernism, e.g. boat bridges or gunwales, is often possible to recognise in new buildings, in different combinations and in varied contexts. One can see it as plain plagiarism, or as tributes to built icons of the past.

One of the most extreme examples of borrowing and playing with attributes is seen in buildings from the 1980's when the -ism of post-modernism became a fashion. It was a widespread eclecticism acting as a protest against (however, as well as an inheritor to) the modernistic era.[170] An earlier example is the eclecticism of Neo-Gothicism in the 19th century, where new technology of that time was mixed with features of the Middle Ages to achieve buildings rhyming with romantic ideals. Buildings and their structural components are in this way always very active in conveying messages and meaning.

One can see plane wall-surfaces as abstract compared to columns with their visually obvious purpose to support and carry[171]. Plates can have more or less complicated inner structures but they still show a plain appearance as its main feature. The plate has in its basic form a simple planar extension and increases the distance between element interfaces, i.e. lowers the number of dividing joints, edges etc. on the surface of a building part.

The change of construction method from a post and beam system to a plate-based system changes the view of the wall into an architect's way to approach the composition of surfaces in a building.[172] The architect defines the surfaces and the positions of openings. As noted by e.g. Vanggaard (1993) members of the Dutch movement De Stijl already in the 1920's used plates in their architectural design[173], presented in axonometric projections of three-dimensional, spatial studies.[174]

Joints as architectural detailing

Through an ever-higher degree of prefabrication, the architectural meaning of joints and interfaces between elements becomes more important. [175] If the industrialisation of construction follows the development of aeroplane- and car-industry the jointing in the long run can become the main design feature and intermediary of design-styles.

Joints themselves can be given a certain structurally efficient design, eventually fully visible and salient, which can be used repetitively for a certain visual effect, to frame a room or an exterior, but it is still a question whether the joint area should be revealed or concealed.[176] A joint designed without any aesthetical care taken makes the defining of an aesthetically as well as a technologically rational/logic[177] design for building-products difficult. The possibility to read and understand the structural function is furthermore a matter of experienced safety in a building, which should not be neglected. To ignore connection-design means that the potential of a very effective expressional feature is left out.

Architecture can be regarded as primarily defined by the joints between its surfaces, between the elements it is composed of, the boundaries of the experienced space.

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[170] *Charles Jencks has classified post-modernism in three phases: a first pluralistic one in the early 1970's, a second eclectic one in the late 70's and early 80's, and a classicistic phase in the late 80's. This is referred to in* Werne, F. 1998, p. 162. *It is a good example of how quickly trends have changed during the recent decades.*

[171] Cornell, E. 1966, p. 30

[172] Affentranger, C. 2001

[173] *E.g. Cornelius van Eesteren and Theo van Doesburg.*

[174] Vanggaard, O. in Lillman, E. (ed.) 1993, p. 433

[175] Interview with Richard Horden, Detail 2001:4, pp. 614

[176] *A built in, hidden joint or joint zone is just another aesthetical standpoint on how to treat an element connection.*

[177] Sandaker B.N. 2000, pp. 51, 54

When the structure is to be covered with sheeting materials, such as gypsum boards, wooden panels or plywood boards, the jointing technique is a purely technical matter. The joining solutions can be of any kind and it will not make any visible difference with exception for one aspect, indirectly noticeable. In case of a visible load-carrying structure the type of jointing becomes directly deciding for the appearance of any room. In the same way as the edges define an element, the interfaces between different surfaces/elements define a room, or a spatial entity, or even the exterior of a building.

Connections should be studied and developed as parts of a system. Degree of co-action, magnitude and direction of loads, visibility and effect on the architectural design should be regarded when dealing with joint solutions and joint design. On a drawing the architectonic expression can be symbolised by lines between plane elements. In three-dimensional practice on the other hand, this is not the case.

Architecturally this means a consideration of how to treat the interfaces regarding necessary structural detailing, in a structure with an in other respects simple expression. In architecture as in structural design the detailing influences the design as a whole. With its senses the human mind notices more than usually thought of or reflected upon. Often a small detail can be crucial without one being able to tell what really decides the impression.

Industrial prefabrication in itself does not secure rational production throughout the process but needs supporting systematic design and co-ordination, of measures and of jointing. Joints in timber are decisive for the behaviour and capacity of the structure. Timber structures often consist of several parts but whereas steel can be welded and concrete can be cast, timber has to be cut and provided with additional fittings. Jointing appears in many varieties much due to timber being so easily worked. Joint design thereby becomes even more important to study and standardise.

Element architecture

Plane elements, and even orthogonal volume elements represents a surface-based expression. A common use of surface-elements in society since the 1970's is seen in prefabricated multi-storey buildings in concrete. The elements are left visible and remind of a patchwork, originally a play between different shades of grey. (*Fig. 2.15*) The density of concrete implies a limit for transport and handling of elements, which leads to relatively small elements and a forced, rather small-scale repetition of the surface modularity.

Industrialised production has many times so far resulted in repetitive design, uniform solutions and cheap detailing. E.g. when prefabricated elements are utilised for temporary structures and only the first impression at a distance is of importance. The modularity of the elements is utilised for the over all design with the rhythm of joints and element edges are fully visible.

Volume elements in timber have been commonly utilised for cheap temporary solutions, such as school pavilions, simple youth hostels, barracks for hosting refugees etc. In these cases too the modular rhythm is obvious and often not regarded as some special positive design feature but simply an untreated result of a chosen rational technique. These structures often show poor acoustic quality, cheap materials and low finish, which results in a negative subjective impression colouring the common view of both prefab and timber building.[178]

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[178] *In many countries timber buildings are still by some associated with poor living conditions, e.g. reminding of emergency barracks built in ruined cities after the second world war, which lowers the attractiveness.*

Fig. 2.15 Element architecture in concrete 1970-72, Brandbergen, Sweden.

In an exterior position the façade cladding is applied to shield the insulation and the load carrying structure behind it, but during transportation the façade can easily be damaged. Insulated volumes without cladding, covered with fabric for protection during transport are in this respect advantageous.

Another issue is the final visible expression. If the façade is mounted in the factory either the separate façade elements will be definable on the final result, or special solutions for joining the separate façade elements on site will be needed. To protect the structural interfaces the distances between elements are often covered with battens, in a way that leaves the rhythm of the prefabricated volumes unchanged and just as obvious. (This may in some designs, of course, be a deliberate expression.) Jointing volumes with prefabricated façades can be a tricky task since varying precision is a common phenomenon. The higher the degree of prefabrication, the more refined the joining methods needed on site will be. Imperfection earlier during the manufacturing process can be very difficult to deal with at a late stage.

The degree of prefabrication decides the element effect/modular expression of the final resulting architecture. If the façade is applied on site it can be fixed in larger elements, each element covering more of the wall area than only one unit. It is then also easier to correct and repair the climate insulation and to control the joining of the volumes. The façade elements can be fixed so that each element covers a load-bearing element. The joints can also be shifted, providing the same frequency of joint rhythm, but not the exact positions of joints in the load bearing structure. The façade can even be delivered as bigger elements, letting each element cover more than one structural element.

Style and fashion

The world of the 20th and 21st century has taken a path more and more outspokenly sensitive to trends. Through the entire history of culture fashion has influenced the choice of design and there is a constant flow of styles. Most often terms like *style* and *-ism* point at trends during a specific scope of time or in a specific region and concern the prevailing expression and/or methods in use there and then. Styles and -isms become fashions on many fields and may very well be a label put on clothing, furniture, architecture and art, literature and music. Even in mercantile contexts –isms occur, such as professionalism, economism or rationalism. It is more or less an attitude to the world, conditioned by the technology and science, politics and religion i.e. a sum of the current society, in a spiral of mutual exchange.

Styles are sometimes dismissed as phenomena without actual importance and without practical meaning. And to some extent they can be regarded as manifestations of man's ambition, beliefs and myths, be it profound or superficial or even arbitrary.[179] But two aspects point at the opposite. Since styles grow from prerequisites given by available materials and techniques they are in one aspect an expression for the theoretical and practical knowledge at hand. Since the recipient of most information and the end user of most products are subjective individuals, styles and what they try to convey become important tools for the results of producing activities. The critique of rapid changes of trends may be reasonable, but not critique of the design efforts to follow the trends.

The Enlightenment during the 18th century deprived the divine of the most important influencing symbolic essence in architecture and instead opened up for reason and logic. The new materials of the industrial revolution gained a symbolic value within themselves.[180] With developed technical prerequisites the changes have come more rapidly and with quick and effective means for communication, styles and trends spread much more easily today than during earlier times. The flow of styles and changing of trends have been constant, but the frequency has changed.

A striving can be noted in art, to seek the outskirts of customs and traditions, to break borderlines and question convention, to extend experiences into the so far not yet seen. In this aspect artistry is closely related to research, with exception for the demand for reference, documentation and repeatability that is put on scientific research.

The definition of architecture and its meaning depend on prevailing conventions and traditions, on how we choose to regard it. (Which is influenced by social context and of course by professional culture and frames of reference.) Architectural work is not mainly developed at institutes or universities, but is influenced by its context of social and political changes.[181] One can see architecture as art or aesthetic artefact or technical system, as shelter or social manifestation, as building or symbol. Thereby it carries the potential function of expressing e.g. status, political gestures or environmental awareness.

The message/meaning and its interpretation are possible to choose. Effects of this relation can be both an advantage and a problem on the building market, which is obvious in both the case of timber building and the case of prefab products and modular construction.

The repetition of modular façade elements on concrete blocks from the 1960's and 1970's is well known to most people. But the use of and play with rhythm was a well-known architectural means already in ancient Greece and long before that.[182] Prefabrication is not a new phenomenon either, but is, as mentioned above, clearly seen in e.g. the log building tradition in the Nordic countries, where log houses were by the standards of their time movable, by taking them down, marking them log-by-log, then storing them or transporting them to a new site for re-erection.

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[179] Cornell, E. 1967, p. 81, 85
[180] Cornell, E. 1967, pp. 82
[181] Werne, F. 1998, p. 10
[182] Lundberg, E. 1945, pp. 301, pp. 422

Today there are trendy publications on industrial production as an architectural fashion, illustrated by numerous almost objectified projects for a multitude of aims. The features of prefab can be concealed in the finished product, but can also be used as a sought after identity, a style, a trademark. Prefab can be treated as specialised production of exquisite, project oriented objects aiming at either luxurious production of singular units. It can be a summerhouse where high degree of prefabrication lowers the need for adaptation on site to a minimum (*Fig. 2.13, right*). It can be a swiftly erected apartment block with high finish and elaborate detailing. Rational building methods can be combined with possibilities of adaptation and provide individuality and rather small series.[183]

Prefabrication and industrial building production are simply ever developing means to reach the goal of a sustainable built environment and should therefore be developed and used in a way securing enrichment and value of the built result. It is all about the knowledge and experience of using the tools currently available. With a concerted effort this is fully possible to deal with and obtain.

Comments

The tension between curiosity about what is new and the affection concerning what is well known is a paradox in architectural work. New phenomena may thrill the senses and attract some, whereas tradition stands for the reliable social foundation. New expressions are also often regarded with suspicion by the man on the street and new methods are in the same way viewed as risky tasks to deal with on the market, since no one can guarantee the economic gains.

Therefore the development is slow and to keep the pace or even speed it up requires realisation of pilot projects of experimental and searching character. Initially, good quality is of high priority since the good example is the only reliable advertisement. There is a worthwhile task to produce good quality with a salient, characteristic design that follows sustainable relationship between material, design and knowledge.

[183] *The versatility of prefab construction is for example illustrated in* Bahamón (2002), *where several built and planned projects are described in an order following a row of basic, characterising properties of prefabricated structures.*

3 PLATES: ELEMENTS AND STRUCTURES

Timber-based plate-elements show a set of properties and features that signify the technical, functional and aesthetical possibilities that they provide. The technical properties and tactile and aesthetic features stem from the material on the cellular level but in this context the description starts at the level of logs and sawn boards. A description of structural plates and timber-based plate-elements is given but the main focus is concentrated on glued laminated timber plates and some element-linked aspects

3.1 General Properties

Plates appear in two main structural cases depending on their orientation and direction of loads, normally i.e. as floor and wall structures. In the first case, a plate is loaded perpendicular to its plane and relies on plate-action and stiffness perpendicular to its plane.

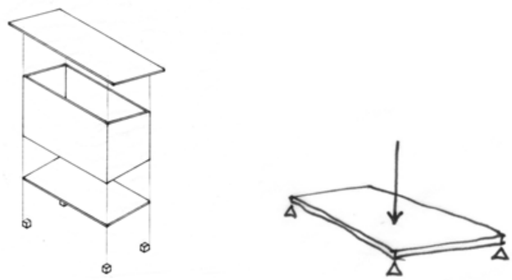

Fig. 3.1 Principles of plate action.

Plate-action (*Fig. 3.1*) appears in horizontally oriented elements e.g. in floors and roofs, where the plate is supported along three or more edges and shows an inner bending and torsional stiffness, gained through its massiveness.

In the second case, a plate is loaded in its plane and relies on shear-plate action[184] (*Fig. 3.2*) and in-plane stiffness. As with columns the strength of a plate in in-plane loading is dependent on the slenderness ratio[185]. In tension it is more easily optimised since influence from slenderness is low. Shear-plate action is most obvious in vertically oriented elements e.g. in walls where the plate will work as a very deep beam. In compression it will tend to buckle resulting in a bending moment or torsional deformation, depending on the distribution of the load.

[184] *This behaviour is based on shear within the member. A shear force is a pair of oppositely directed parallel forces of equal magnitude and with zero distance between them.*
[185] *Slenderness of a member is defined as the ratio (distance between supports):(thickness of the member).*

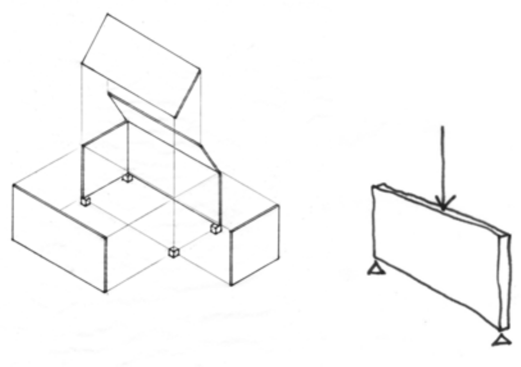

Fig. 3.2 Principles of shear-plate action.

Shear-plate action is used to secure the stability of the entire building, whereas plate-action is utilised to transfer wind and service loads to the stiffening shear-plates. Forces with horizontal direction require shear-plate action in the floors (*Fig. 3.3*), so that they can act like deep beams and the walls can spread and transfer forces through plate-action.

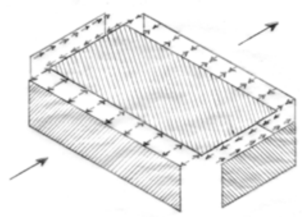

Fig. 3.3 Principles of horizontal force distribution between walls and floors.

In architectural design it is more relevant to treat plates as one type of form, disregarding the differences that occur in technical actions or behaviour. This is not far from the technical definition of plates and shear-plates as surface-elements that are active in load-carrying structures. Since a building cannot rely solely on resistance to shear in walls, but will need such a capacity also in the floors, the difference between definitions of plate- and shear-plate action will be useful only when discussing the technical behaviour, not the appearance of the physical elements.

3.2 Timber-Based Plates

A single piece of wood shows properties varying across its section. This is caused by the nature of the living tree, and is well known and studied.[186] Trees have evolved a complex inner structure to carry the load of their own weight and also to resist outer forces such as winds and other loads. Knots, varying fibre-angles, growth rings, compression-wood, orthotropy etc. are necessary in the living tree, but cause

[186] Dinwoodie, J.M. 1989

problems when utilising timber in a building, where all the properties in an engineering sense should be well known, exactly determined and homogenous. By sawing the lumber into thin lamellas and gluing these displaced in layers, one can overcome these "defects" by spreading them and thereby creating very strong products with a more homogenous quality. Glued timber-products have existed for a long time, e.g. plywood and beams of glulam.[187]

The problems connected to the properties of wood are at least partially caused by the wish to use wood as a completely engineered material. Steel and concrete show negligible variation of properties over a section, and in that respect it would be very comfortable to be able to look at timber in the same way. Properties determined from so-called small clear specimens[188] cannot easily be used as characteristics for full-size beams since these properties are altered by the variability in the timber and depending on the sawing pattern of the log[189]. Grading and engineered timber-products are important subjects of research within the timber-industry. The former aims at sorting timber in as exactly described quality-classes as possible, the latter aims at creating building-products with well-defined and better utilised properties.

3.2.1 Processed Timber Products

Engineered timber-products are developed to create strong building-members with tailored properties – which in some cases are totally new – and several different types are available on the market. The three main groups are structural composites, structural plates and glued beam products. In the first group one finds e.g. Parallam, LVL, glued joint and timber/concrete and fibre-composites of wooden fibres mixed with plastic. In the second one finds OSB, plywood and more recently widely used products like laminated plates and cross-laminated timber. In the third group glulam, I-beams and sawn timber are to be found.

Round timber possesses an advantage compared to sawn timber since the fibres of the log are uncut, which gives the structural product higher strength and stiffness[190]. A problem with round timber is the risk of cracking, which can be reduced by longitudinally cut grooves.

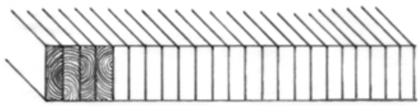

Fig. 3.4 Principle for the cross-section of laminated plates.

As a principle the laminated plate is the simplest plate-type (*Fig. 3.4*). It is similar to a glulam beam only with a much bigger depth and not intended to be used only for in plane loading. The method creates an element out of smaller identical pieces. When loading a single beam, one can observe a certain deflection. This deflection depends

[187] Johansson, L. et al. 2000; *E.g. the curved beams at the Stockholm Central were constructed in 1925 as glued elements.* Cornell, E. 1979, p. 287
[188] *I.e. small pieces of wood free from knots and with even growth rings, for test and experimental use.*
[189] *The probability of a weakness or a defect in a piece of timber increases with increased volume/size. This phenomenon is called the volume effect or the size effect.* Serrano, E. 2001
[190] Natterer, J. et al. 1991, pp. 94

on the stiffness of the material and depth of the beam – the stiffer the material and/or deeper the beam, the smaller the deflection.

The depth is the most crucial geometrical factor for the stiffness, but increasing the width by doubling the beam and fixing two (or more) beams together also leads to a reduced deflection. This is a result of load sharing where the deflection in one member under a point load is transferred to and taken up by the neighbouring member(s) (*Fig. 3.5*). These kinds of plates can be nailed, dowelled, glued or pre-stressed with drilled-in rods.

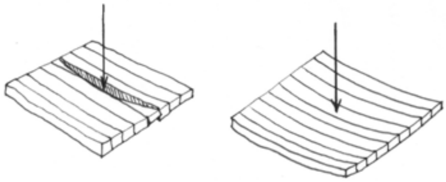

Fig. 3.5 Load sharing in a laminated plate.

This type of beam build-up can also be jointed with nails, screws or dowels. The manufacturing can be both prefabrication and assembling on site. In glued elements the joints are stiff, whereas the plate-action in mechanically assembled elements depends on a ductile joint behaviour. Elements can also be stressed with drilled in rods.

Multi-layered timber can be produced in a great variety of designs, tailored for specific uses (*Fig. 3.6*). The different layers can all be oriented in one direction or in two or more, all layers can be out of boards of one or differing thickness but boards can also be combined with other products, e.g. fibreboards.[191] The timber normally used is softwood. Species that are used in Sweden are Norwegian spruce and Scots pine[192], but in Germany, Switzerland and Austria also larch and white spruce[193] are in use, and tests have been carried out on e.g. the behaviour of beech[194] in glued elements.

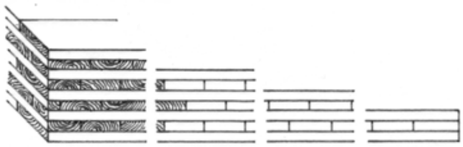

Fig. 3.6 Principle for the cross-section of cross-laminated plates.

Visible surface-layers may also be chosen as e.g. oak or other species regarded as more exclusive, for varying the visual appearance of the elements. The boards can be nailed, stressed with drilled-in rods or glued. Glues in use are today normally polyurethane, phenol-resorcinol resins or melamine resin.

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191 Industrikonsortiet Massivträ 2002, 2.2.2.1

192 *Norwegian spruce:* Picea abies *and Scots pine:* Pinus sylvestris

193 *Larch:* Larix deciduas *and White spruce:* Picea glauca

194 *Beech:* Fagus sylvatica

The most widely used plate-types today are cross-laminated products. Each layer consists of laminated boards of 14 – 33 mm thickness[195] planed on all sides, which are finger-jointed.

The boards are normally taken from the outer zone of the log. Material from these zones often get deformed from inner tension forces, which makes them hard to use as studs, beams and single boards. Tensile strength, tensile module of elasticity and density for example tend to increase with the distance to the pith.[196] (*Fig. 3.7*) Tests on low-quality timber have been performed in many places. In Norway tests have been carried out on sorted out spruce timber for glulam production and low-graded fir timber for pulp. In both cases the mass effect gave good results for short floors-spans of about 5 m.[197]

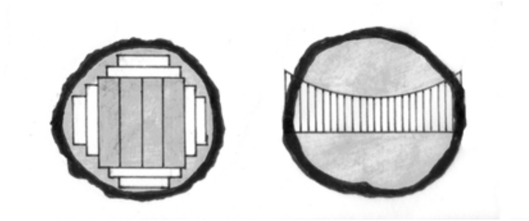

Fig. 3.7 Common principle sawing pattern for logs (left) and general principle distribution of mechanical properties of timber from a log (right).

It is important to adapt the moisture content to the intended service conditions.[198] If the moisture content of the timber is far from matching the relative humidity in the intended environment forces may be induced that will break the joints. Deformations may also follow. For interior use moisture content of 8% and for exterior use in sheltered locations about 15% are suitable.[199] The matching of moisture contents is important for the use and in some cases for the curing process with adhesives curing through loss of or chemical reaction with water.[200]

Edge-wise gluing is optional. For optimal tightness the edges need to be glued, at least in the inner layers. A problem may occur with edge-glued surface layers, caused by swelling and shrinking in wood surfaces exposed to indoor climates with varying air humidity.[201] With wide edge-glued elements the movements of each board result in big movements at the element edges, which may cause too big tension forces during drying leading to cracking of the surface layer. To avoid or minimise the risk of cracking, the element width can be reduced, or only the unexposed or middle-layer(s) can be edge-glued. The boards in the surface-layer are then allowed to move individually.

An uneven number of layers (3, 5, 7, 9…) are assembled cross-wise with flat-wise gluing. The uneven number of layers gives the plates one main, stronger direction and one weaker. According to research carried out at Graz University of Technology three layers will not give enough stiffness perpendicular to the main direction. Neighbouring perpendicular layers fix longitudinally oriented layers, but will not

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195 *With increasing board thickness the risk of cracking from drying increases and it gets difficult to obtain an even pressure at gluing resulting in uneven thickness of the glue joint.*

196 Schickhofer, G. 2001

197 Norwegian Institute of Wood Technology 2003, p. 17

198 Jönsson, J. 2005

199 Raknes, E. 1988, p. 67

200 Davis, G. 1997, p. 251

201 Eriksson, J. 2004

increase their load-carrying capacity. Hypothetically, a three-layered plate is too weak since there is only one crossing layer.

Depending on the usage the different layers can consist of different qualities of timber. The choice of quality also depends on the desired quality of the surface, if it is to be visible or provided with cladding.[202] The layers that are assembled symmetrically[203] can be oriented at different angles to each other (e.g. 0-90-0-90-0-90º or 0-45-90-45-90º) leading to different properties of stiffness.[204] The analogy with the build-up of plywood has been discussed by Schickhofer (1994, 2001). The maximum size of the panels is mainly decided by means of transportation. The largest plate-elements produced today are today 2.95 × 16.50 m^2 with 60 to 500 mm thickness when they leave the factory, but whole elements can be finger-jointed to lengths of 30 m.[205] Timber plates can be manufactured in various shapes.

3.2.2 Assembling Methods

Plate action as shown by a concrete slab relies on an isotropic behaviour. In large spans the isotropy is not totally reached but through effective load distribution the stresses are evenly spread. Isotropy is not a characteristic for raw timber. When assembled into products like glulam beams or plates, the isotropy is still not guaranteed – the type of connection between the timber members decides the load-sharing capacity.[206]

Pre-stressing of laminated plates is used to increase their stiffness and their capacity to span and carry loads, without unacceptable bending. Cross-laminated timber-plates can be assembled with mechanical joints like nails, screws, dowels or chemical joints like glue.

Mechanically jointed plates show a ductile behaviour under load, with small slips at each nail; under load in the plane nailed plates exhibit in-plane buckling failure since the nailed joints are ductile and thereby introduce weakness in the plane.

Chemical joints are regarded ras igid and the resulting plates show a stiffer behaviour than e.g. nailed types. Glued elements rely on rigid joints; during load in the plane they fail from much higher loads and they fail out of the plane.[207] If elements are produced with small measures to be assembled into large plates later or even on site the joints between the elements must be carefully designed and securely fixed. Gluing is common and effective in industrial environments, but today no established methods exist for control of gluing joints on site.

Curves can be the result of gluing of boards in bending, like curved glulam beams assembled in jigs, of application of post-stressing with tension-rods, or rods and trestles, or as a result of a combination of those. The curve can be achieved in two steps by first gluing a curved plate in a jig and then increasing the curvature by rod stressing. Either the stressing rods are fixed in advance or a number of elements can be joined together on site and the stressing be carried out afterwards. The radius of

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[202] *An Austrian producer of massive timber products categorises the surface qualities* Nichtsichtqualität, Industriesichtqualität, Wohnsichtqualität *and* Sonderoberflächen. (http://www.klh.at)

[203] *The behaviour of asymmetrical sections has been studied in wall structures and results show unstable behaviour.* Bosl, R. 2001, pp. 94

[204] Schickhofer, G. and Winter, W. et al. 2001, p. 113

[205] *In Sweden wall elements are produced up to 3.6 m in width (tongue and grooved assemblies of 1.2 m modules) with exceptions possible up to 4 m (restricted by heights allowed for transport) lengths of up to 12 m. Thickness of the plates is between 60 and 120 mm. Tolerances in length: 2 mm, in width; 2 mm and in thickness: 0.5 mm. Floor elements are produced in Sweden with thicknesses between 115 and 215 mm thickness for rod stressed plates and between 95 and 154 mm for glued cross-laminated plates.*

[206] Schickhofer, G and Guggenberger, W. 1996, p. 16

[207] Haller, P. and Pannke, K. 1998, vol 2 p. 234

the curve is decided by the thickness of the individual layers and by the combination of layers with different orientation. [208] There is, however, a restriction to single-curved plates, since double-curved elements are not possible to create by tension in timber.

Glued joints

Depending on the conditions during which the product will be used, different adhesives are required. For exterior use with exposure to weathering and rainfall, polyurethane or phenol-resorcinol resins are used. For indoor use, varieties of melamine resins are most common.[209] The glued joints appear in finger jointing of single boards, in edge jointing of single-layered assemblies and flat-side jointing in the layered assembly.

As finished product glued cross-laminated timber contains about 12-15 kg/m^3 of adhesive (about 0.2 kg adhesive per m^2 joint area). The risk of emissions from adhesives has been discussed for many years. Formaldehyde is a common component and during the late 1970's it was presumed being carcinogenic. It has not proven as such[210], but like several other chemical components for industrial use and production of adhesives it irritates skin, eyes, throat and mucous membranes[211] and sensitive people react already at low concentrations. Most of the emissions disappear after hardening. Good working-conditions, with good ventilation and protection during production are important. If carried out correctly, health and environmental risks at production can be minimised, if not totally avoided.

All adhesives for structural use are to be approved by the Swedish organisation for quality control of glulam.[212] Furthermore all gluing of joints must be carried out in factories, where the conditions are fully controllable and the quality of the glue-joint can be ensured.

- Polyurethane utilizes isocyanates for hardening, substances that imply health risks at inhalation of dust, aerosol and vapour. At production efficient ventilation is needed. In the state of the finished product this kind of adhesive will not have any effects on the environment, but when burnt the products will emit toxic fumes. The joints are very durable regarding moisture and temperature. The strength of the adhesive decreases with the thickness of the joint, which should be less than 0.3 mm.[213] The glue has a pale colour.
- Phenol-resorcinol resins utilize formaldehyde for hardening. Formaldehyde can cause allergic as well as respiratory problems. At the hardening process formaldehyde is emitted to the air, but the bonding to phenol is strong and the initial emission[214] is relatively low. Phenol-resorcinol resins are used for load-carrying glulam and finger jointing of structural timber. Pure resorcinol resins can be used for the same purposes, but are expensive, so up to 50%phenol is added. The joints are of a dark brown colour and are both weatherproof and moisture-proof.

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[208] Schickhofer, G. and Winter, W. et al. 2001, p. 113
[209] Raknes, E. 1988, pp. 36
[210] Bosl. R. 2001, p. 27
[211] Raknes, E. 1988, p. 150
[212] Svensk Limträkontroll
[213] Bosl, R. 2001, p. 26
[214] *VOC (Volatile Organic Compounds) is a common term when discussing emissions.*

- Melamine resins are composed by melamine and formaldehyde and are often used in combinations with urea-formaldehyde. The joints of the type most common in Sweden are not weatherproof and the adhesive[215] is therefore used for products indoors. Compared to phenol-resorcinol resins, melamine resins initially give high emissions of formaldehyde. It gives colourless or very light coloured joints.

The shear modulus of the joint varies with the choice of adhesive, but is for most adhesive types higher than that of timber. The shear modulus also varies with the joint thickness and gets higher with thicker glue joint.[216]

3.2.3 Rolling Shear

The differences in strength in different directions of timber not only implies a reduced load-carrying capacity in one of the directions, but also that if loaded perpendicularly to its plane the perpendicular timber-layer(s) of a cross-laminated plate means a weakness in the plate. Shear forces that appear perpendicular to the grain is termed rolling shear.[217]

The tubular cell-structure of wood results in high strength in the longitudinal direction but low strength perpendicular to this, where the internal bonding between the individual cells tends to fail when forces are increased. The inner microstructure of softwood is built up by layers of weaker non-load carrying cells (early wood) produced by the living tree during spring, and stronger load carrying cells (late wood) produced during summer.

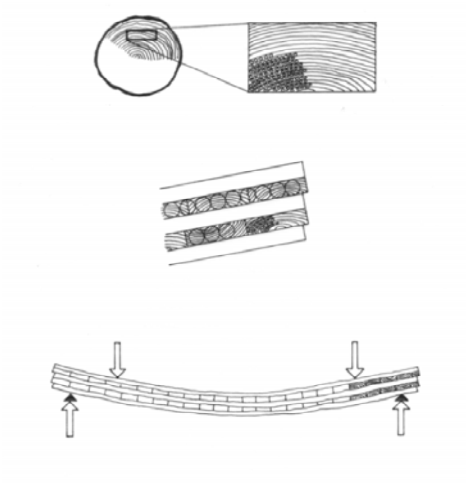

Fig. 3.8 Overview of the phenomenon of rolling shear from trunk to processed product.

[215] *There are different types of melamine resins, with different ways of hardening. Melamine resins hardened by heat are regarded as weathering-proof for outdoor use.*
[216] Bosl, R. 2001, p. 26
[217] Schickhofer, G. and Guggenberger, W. 1996; Fellmoser, P. and Blass, H.J. 2004

The phenomenon is noticed both on the cellular level and in the layered structure of plywood and multi-layered cross-laminated timber (*Fig. 3.8*). The rolling shear modulus is however not a material parameter, but appears in structural elements depending on elasticity, geometry and measuring parameters and production.

The rolling shear phenomenon significantly affects the overall stiffness of a plate-structure. If only one of the layers is oriented perpendicularly to the spanning direction there is an obvious reduction of the stiffness. Also the capacity to distribute normal stresses will be reduced.[218] What happens on this macro-level is that the longitudinally oriented layers in the plate tend to roll off from the perpendicularly oriented layers.

This can also appear as a result of failure in the adhesive layers between the planks. When the shear capacity of the glue is passed there will be a failure either in the glue or in the wood close to the joint (*Fig. 3.9*). The quality of the glue and the precision of the glued joint decide the degree of wood failure.

To reduce this reaction the boards of the intermediate layers need a relation of width: thickness 4:1 to 8:1. The phenomenon of rolling shear has been noted, thoroughly studied and verified at Graz University of Technology.[219]

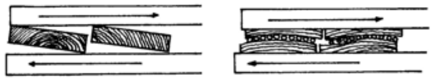

Fig. 3.9 Shear failure in glued joint (left) and in the annual ring structure (right).

There is a considerable difference in strength between these layers and if loaded perpendicularly to the growth-direction the weaker layer can fail and let the stronger layer be displaced, resulting in a fracture. Shear forces perpendicular to the direction of grain are referred to as rolling shear. Tests on glued cross-laminated plates have shown that failure in bending in most cases appears as a combination of failure in the glue joint of the lamellas and a rolling off phenomenon, through slip between late wood and early wood in the annual rings.[220]

A chain is not stronger than its weakest link. The Weibull-theory (the Weakest Link Theory)[221] is founded on this assumption and is used for computer-modelling and calculating properties of e.g. beams. By fixing a weak section or member to a strong one, the weakness in a single cross section is reduced. The higher stiffness of the stronger member is also reduced, but the effect is a more even strength in the element.

[218] Fellmoser, P. and Blass, H.J. 2004, p. 7
[219] Schickhofer, G. and Guggenberger, W. 1996
[220] Schickhofer, G. and Winter, W. et al. 2001, p. 125
[221] Weibull 1939. *The probability of finding a severe defect is greater in a large volume than in a small one, and therefore strength decreases with increasing size.* Described by e.g. Serrano, E. 2001

3.3 Timber-Based Elements

3.3.1 Elements and Prefabrication

Due to larger components prefabrication makes the matter of transportation and transportability important. Sizes of prefabricated elements can be chosen almost freely today. Industrialised production possesses the capacity to make elements of almost any length, leaving the dimensioning factor to the means of transportation.

There is a contradictory relation between joints and element-sizes in prefabrication. On the one hand there is often a striving for as large an element as possible to minimise the number of joints, since joints are expensive and constitute weak zones in a structure and since large elements allow a more rational construction. On the other hand there are practical reasons for as small an element as possible, to increase the possibilities of combination and adaptation to different uses and layouts. In Denmark several projects have been built with massive timber elements of storey height and widths of 300 mm for the possibility of one worker handling them.[222]

Surface-elements

In a plate based building system, the basic characterising members are the plane elements. The structural properties and the in-plane geometry differ, depending on the demands of and location and orientation in individual projects.

Plane elements in massive timber are most often produced in the desired shape and used directly with no further treatment before assembling. Available product types can be divided into plane elements, box elements and composite elements with co-action, in most cases between timber and concrete[223]. For floors all these element types are used, in walls only the plane elements appear.

Surface element construction gains from the elements being fairly robust and easy to store. They can be loaded in flat packages which makes it possible maximise utilisation of the means for transport. In its most simple state a raw timber element can be transported to the site, cut to size, perforated for openings, provided with cladding and eventual insulation and put in place.

The raw element is neutral in that sense that it can be used for any purpose in a small building, be it wall, floor or roof. Delivered to the site they can be adapted to exact measures. Holes for windows, doors, stairs and installations can be cut on site. Adaptations and corrections to measurements are rather swift to make with drill, saw and chainsaw. Other gains are the effect of low weight on transportation both to and on site.[224] They can be refined and provided a high degree of finish, making them more fragile and circumstantial to handle, but decreasing the time of treatment on site.

Volume-elements

For three-dimensional modules, the plane elements are assembled into box-like volume elements. The properties of the volume decide the usage. The most simple combination consists of complete boxes with walls and both floor and ceiling. But the boxes can also be designed to make up a part of a room, with one or two sides open for combination with other modules. The primary limiting factor in this case is stability during transport – the volume must resist deformation on its own until the building is assembled.

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[222] Associerede Ingeniører ApS 2001, p. 43
[223] Industrikonsortiet Massivträ 2003, 2.2.1
[224] Industrikonsortiet Massivträ 2002, 3.5.2; Falk, A. 2002, pp. 94

Volume-elements are composed of surface-elements and may stay similar in appearance to those. The basic character of volume-elements is the same as the architectural character of surface-elements: the plane surfaces of the elements.

Composite structures

By combining a great number of plain volume elements with volume-elements and other structural parts adaptable, complex structures can be created. A large number of rigid boxes can be put together and fixed to each other, installations plugged-in, wrapped in a weathering and climatic shielding envelope. It is basically a principle comparable to a drawer or containers placed on top of each other for a transatlantic shipping. The most simple case is a hotel or a residential building for students, containing a large number of identical small units. This system is also reasonable for use in an office building, or a hospital, with similar needs for the repetition of room cells.

Wet areas can be prefabricated with a high finish. On site they can be built into a structure constructed on site with assembled plane elements and/or volume elements (*see Appendix III*). Apartments can be prefabricated as volume-elements and complemented by the addition of plane elements for staircases, lofts, balconies and serving areas. Additions like balconies and mezzanine floors are uses where massive timber can be suitable also for main structures of other materials like masonry or concrete, with relatively low demands on new joints and new and/or reinforced foundation.

Massive timber can also be utilised to add storeys to an existing structure, providing a stable and stiff structure with relatively low weight. The need reinforcements can in many cases be reduced or avoided. The massive timber is lighter than concrete, but manage wider spans than light timber floors in general, which means easier adaptation to existing support spacing. Additions to an already existing building has e.g. been carried out in Umeå in northern Sweden where a hotel has been extended through the addition of storeys in light timber-frame and in a massive timber extension of a small hotel outside Vienna. In common for those examples is that the timber is not necessarily visible in the finished result.

3.3.2 Aspects of Light and Massive Structures

In light timber-frame construction layer after layer needs to be added to make the building stable, tight, insulated and enclosing a comfortable environment for living. In plate construction these layers can be reduced in number since the plate in itself can serve as a stable and airtight, moisture-inert and to some extent heat- and sound-insulating structure (*Fig. 3.10*).

Fig. 3.10 Model of a principle section of a massive timber wall.

For comparison two wall-structures can be used to illustrate the properties of these different approaches to construction (*Fig. 3.11*). If a section through a wall is divided into three layers these can be labelled: F) façade as outdoor wall-surface and weathering-shelter for the insulation, I) insulation sheltering for differences in temperature and L) structural zone as carrier of loads, moisture barrier and indoor wall-surface, C) indoor cladding. [225]

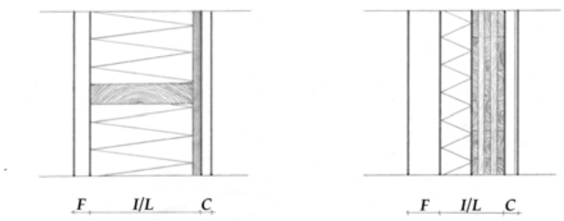

Fig. 3.11 Sections of a light and a massive timber wall structure. ***F****açade;* ***I****nsulation/****L****oad-bearing;* ***C****ladding.*

The facade can be the same in the two examples, i.e. boards, thin plates, plaster etc. The indoor cladding can be the same, with extra insulation if needed, gypsum boards, panel, thin plates or wallpaper. The massive wall gives the additional possibility of leaving the carrying structure uncovered, in it self-constituting the visible interior surface.

In the middle layer the difference in principles is noticable. The insulation in the light wall is integrated with the load-carrying structure, with insulation between carrying posts, whereas the insulation in the massive wall is added on the outside of the load-carrying plate.

The light structure is based on minimising the load-carrying material, whereas the massive one is based on the opposite, material-maximisation. It is very difficult to optimise something for more than one task while minimising its main structure. Therefore, minimising the main structure leads to reduced capacity to fulfil more tasks than load carrying. While the load-carrying structure is minimised the need for additional insulation tends to be maximised instead. To obtain thermal comfort indoors with only timber, about 350 to 400 mm thick wall-elements would be needed and these dimensions are rather rarely seen[226]. Thus, maximising the structural layer normally means that insulation is added, but less insulation will be needed than in the light example.

The light structure is based on several material-layers, each fulfilling one purpose and the optimisation of the layers is also carried out layer by layer. In the above used theoretical division into three zones each zone will thus contain more than one layer. The result is a complex inner design with an obvious weakness in the fact that failure of one layer affects the whole structure by, so to speak, disturbing the technical balance. Perforation of the moisture-barrier in a light wall may for example lead to air leakage. Thereby convection can transport water from the interior to the insulating layer, with the risk for mould.

[225] Schickhofer, G. and Hasewend, B. 2001

[226] *The Austrian company Thoma-holz (see http://www.alpenholz.at) offer products fulfilling the current Austrian regulations concerning thermal insulation.*

The massive structure in itself fulfils several purposes and is as an element not so sensitive as the multi-layered one. The massiveness has effects on the inner climate if left exposed. According to measurements carried out at the KTH Department of Building Sciences, the Division of Building Physics, only the surface zone of the timber-plate is active in the moisture cycling during normal living conditions in an apartment[227]. Timber of such dimensions as those treated here thus provides a moisture-barrier, bringing the question of the necessity of plastic films to the fore.[228]

There are architectural visions about the massive timber that are not so easy to make real. Massive timber can be overestimated as a material fulfilling all required functions in a building. The traditional log cabins had at early stages one single layer of one single material in both walls and floors. These structures were not very tight and not very well insulated. Through time (as described in *Chapter 2*), external cladding has been added to increase the tightness and to protect the exterior of the log structure from weathering. In modern timber structures massive timber floors have been difficult to provide with accurate sound insulation, (*see Chapter 5*) with the visibility of the upper surface remaining. As decks with exterior exposure the upper surface of the timber deck has to be protected from weathering, either with a rubber sheet or with e.g. deck plating.

In Sweden the main approach to massive timber is to leave visible as much as possible. Floors are without questioning left with visible upper surface. The possibility to leave the lower surface visible has also been mentioned[229] but must be regarded unrealistic if not for use in single-family houses. An unprotected horizontal surface exposed to fire from below implies a big risk, and without the space provided by a suspended ceiling installations will in most cases be difficult to place. Walls are in most cases covered with gypsum boards but may be left visible through technical exchange[230].

The main reason for covering is the fire regulations limiting the area of combustible materials indoors. Another reason is to give the walls another expression than that of untreated timber with knots and annual ring patterns. The possibility to use paint is so far rarely seen, but has been tried in a recently finished project in Stockholm (*see Chapter 5, case #2*). To use wallpaper is not advisable, since the movements in the timber surface from varying moisture content will tear the wallpaper. The company Ekologibyggarna AB in Vadstena, Sweden has exhibited examples of massive timber walls with wallpaper where the cracking is obvious.

3.4 Fire and Combustibility

3.4.1 Prerequisites

Until 1994 the use of combustible materials was prohibited in load-carrying structures of more than two storeys. Since 1994 the codes are performance based which means that combustible materials are allowed in multi-storey buildings if it is designed and protected to resist fire during a certain time.

Timber is combustible and when exposed to sufficient heat thermal degradation occurs, resulting in loss of weight and dimensions. But after the initial degradation-phase the properties of timber keep the burning rate fairly low. When it burns the

[227] Hameury, S. 2004, pp. 45
[228] Further discussed by Achtziger, J. 2002
[229] Industrikonsortiet Massivträ 2002, 3.4.1.1
[230] *Technical substitution is a term used for exceptions from the fire regulations allowed by e.g. installation of sprinkling systems in a building. See Section 3.4.3*

timber gets momentarily protected by its own charring, which creates an insulating charcoal layer that reduces the speed of charring.

This means that a timber structure, being well designed, will remain capable of carrying the load it has been designed for, even when having been exposed to fire for quite a long time. The charring rate for timber can be estimated to 0.5-1.0 mm per minute[231], in average 0.65 mm per minute for deep sections with single-side exposure to the fire[232].

Old timber-structures are often noticed to be over-dimensioned for the intended load. It can in most cases be explained by the lack of means of calculating with the accuracy of our time. This makes them, however, in the aspect of fire, more safe than the material-minimised structures that are dimensioned with computers and mathematical precision.

The combustibility of timber, however, makes it predisposed to add to the risk of flash-over in a room, if wooden surfaces are exposed.[233] Therefore the use of timber in construction is important to study in detail concerning load carrying, stability and use of visible wooden surfaces indoors and on façades. The solutions and designs are to be approved by the local rescue service. Thus, regulations in practice are not co-ordinated. Tests on both light and massive timber structures have shown that massive structures do not increase temperature in the immediate surroundings compared to a light timber-structure, but that unprotected massive structures may cause larger flames through windows in case of flash-over. [234]

Fig. 3.12 Cement-based plates and wooden cladding restricted to certain areas. Kv. Räven, Stockholm, Sweden.

[231] *The burning rate depends on dimensions of the timber, airflow (i.e. available oxygen) and the effect further on number of edges exposed to the fire.*
[232] Östman, B. et al. 2002, p. 59, 79; *This value is also referred to in Eurocode*, Industrikonsortiet Massivträ 2003, 5.1.6.2
[233] Industrikonsortiet Massivträ 2003, 2.4.2
[234] Östman, B. et al. 2002, p. 16

Façades is another sensitive location for timber, since fire can spread on the outside of the building and thereby travel from one apartment to another. Cladding is a critical location for timber, since it most often is fixed at a distance from the wall to let moisture from rain and snow dry out. This distance can easily work as a channel for fire inside the façade structure, leading it up along the building.

The use of wooden cladding on facades is commonly restricted to narrow sections between windows with incombustible materials between the windows vertically to prevent the spreading, under balconies, which work as shields, and just below the eaves[235] (*Fig. 3.12*).

3.4.2 Design for Fire-Safety

The building-codes consider load-carrying capacity, development and spreading of fire and fumes, possible spreading to neighbouring buildings, evacuation and the safety of the rescue team.[236] A complete fire-safety documentation contains the intended use of the building, aimed at users, potential fire-development, structural (passive) fire-protection, fire detection and sprinkling systems (active), fire-exhausting equipment, evacuation strategy and resources of the rescue service.[237]

In the building-codes, demands concerning performance in case of fire are summarised as a certain required amount of time with the retained capacity to carry loads, to seal and to insulate. Structures and elements are given a certain set of values shortened as *REIxx*, where R = load bearing capacity; E = integrity (tightness); I = isolation (temperature); xx = required minimum number of minutes to failure. The value depends on the building-type and use and on the element's location in the structure.

Different principles and technical devices are developed to provide built structures with a reliable fire-protection. Methods to handle fire-safety are either passive or active. One of the most common ways is passive, to use gypsum boards to cover the timber. The gypsum boards protect during the early phase of fire, and retard the charring of the timber.[238]

Other examples of passive methods are e.g. impregnating with fire-protecting agents or using protective paint, using fireproof windows, using fire barriers like protruding, horizontal battens or balconies. Active methods are e.g. window-shutters that close in case of fire and residential sprinkling systems or sprinkled facades, means that can enable more or less unrestricted use of wood in the exterior cladding.

Structures with big redundancy allow forces to be redistributed when one or more parts have reached the ultimate limit state. As long as E and I are secured within each fire compartment, the overall structure can act as a load-carrying reserve.[239] The function of plate action for lateral force transference must be secured as well. The knowledge of the behaviour of massive timber under fire load is so far rather limited.

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[235] Östman, B. et al. 2002, p. 97
[236] Östman, B. et al 2002, p. 17
[237] Industrikonsortiet Massivträ 2003, 5.1.2
[238] *For a light wall structure EI60 can be obtained with 13 mm gypsum + 70 mm mineral wool + 13 mm gypsum, EI90 can be obtained with 15+13 mm gypsum + 95 mm mineral wool + 15+13 mm gypsum.* Östman, B. et al. 2002, p. 49*; For massive wall structures EI60 can be obtained with 66 mm glued cross-laminated massive timber and EI90 can be obtained with 110 mm glued cross-laminated massive timber.* Industrikonsortiet Massivträ 2003, 5.1.5*; For massive wall structures REI60 can be obtained with 175 mm cross-laminated massive timber or 110 mm cross-laminated massive timber + 15 mm gypsum. For massive floor sections the values are for REI60 obtained with 133 mm cross-laminated massive timber or with 133 mm cross-laminated massive timber + 13+15 mm gypsum.* Industrikonsortiet Massivträ 2003, 5.1.6.2
[239] Industrikonsortiet Massivträ 2003, 5.1.6.1

The normal structural behaviour of massive timber is determined by its rolling shear capacity. In case of fire the symmetry of the cross-laminated build-up is changed and the behaviour of asymmetrical sections can so far only be estimated theoretically.[240]

There are several matters to consider in a building exposed to fire, such as air tightness, the effect on installations and the effect of their perforations, insulation materials, window types, façade material and design. Glued and rod stressed elements are considered tight. Glued cross-laminated elements glued both edge- and flat-wise[241] are tighter than elements that are glued only flat-wise. Other elements that are mechanically jointed must be provided with a covering on the built in surface, either with paper or plate cladding. The elements must be jointed tightly to meet the demands of integrity either with tongue and groove, or with battens covering the joints.

Massive timber structures show a more robust behaviour in case of fire than light timber structures. They are not as sensitive to collapse but must be designed carefully considering joints and interfaces. Because of larger volume of combustible material massive timber can cause a more lasting fire, if it is not correctly designed and the fire gets widespread.

In nailed elements the nail joint may be affected by the increase of temperature, which must be regarded by using a reduction coefficient when calculating the fire-resistance of this type of element.[242]

3.4.3 Sprinkling Systems

Residential sprinklers were introduced in the U.S. the early 1970's and their performance is considered good with a reliability of 90-95% with less volumes of water needed than with manual actions.[243] The introduction concerned small houses but technique and practice were successively developed. In 1989 the Swedish regulations and recommendations were revised and opened up for use of sprinklers in apartment blocks up to four storeys.[244]

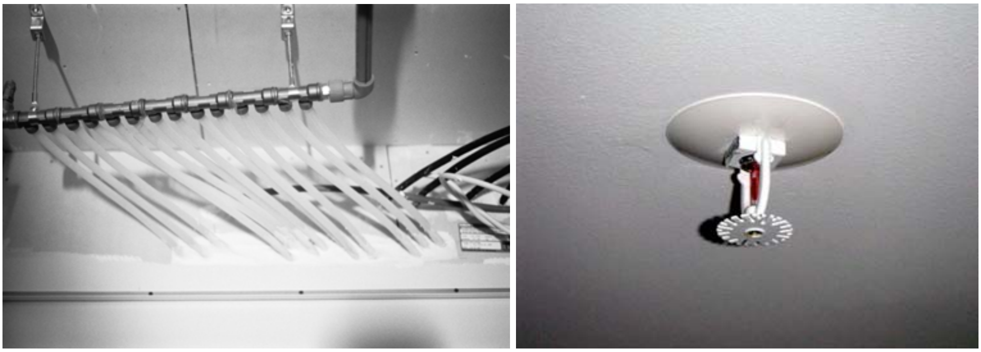

Fig. 3.13 Connections of PEX pipes in the suspended ceiling outside an apartment (left) and a spray nozzle on a finished ceiling surface (right).

[240] Industrikonsortiet Massivträ 2003, 5.1.6.2
[241] *The general value of burning-rate at elements with open edge-joints is 0.8 mm/min.*
[242] Östman, B. et al. 2002, p. 81
[243] Östman, B. et al. 2002, p. 16
[244] Arvidson, M. 1998, p. 13

Sprinkler systems have been developed to extinguish fires at early stages, which earlier sprinkler types for industrial environments did not manage. Quick activation is crucial to reduce fire prior to exceeding of threshold values. Reduction of installation cost lead to change in materials in the pipes from iron and steel to copper or plastic and reduced endurance of the water source has been accepted[245] (*Fig. 3.13*). The most common systems residential blocks on the market today are connected to the tap-water system and the spray nozzles can be visible or covered (*Fig. 3.14*).

Fig. 3.14 A spray nozzle left visible (left) and covered by a lid (right).

In the case of residential sprinklers the possibility to use wood in a less restricted way depends on the term *technical substitution*. If a residential sprinkler system is installed one ore more restrictions can be reduced. Then the following examples may be allowed: combustible façade in more than two stories, reduced restrictions considering the risk of fire-spreading through windows, reduced restrictions concerning surface layers in residential buildings and increased lengths of escape routes.[246] The decision lies in a balance between design of fire-protection, cost and demands from society and client.

[245] Arvidson, M. 1998, p. 9
[246] Industrikonsortiet Massivträ 2003, 2.4.2.2 *Further exceptions than the above mentioned can be made, but require analytical dimensioning.*

4 BUILDING SYSTEMS

To study the optimisation of the material of and production techniques for timber plate elements this chapter focuses on the use of engineered timber-products in building systems for residential buildings and what structural and architectural possibilities that are and could be allowed.

4.1 A Systematic Approach

4.1.1 Systems Featuring Order

The term system denotes a set of at a minimum two parts, and their mutual relations. Since a system implies both the phenomena and the relations between them the complexity of a system increases quickly with increasing number of included phenomena. There are fundamental organising and hierarchical patterns that build up the immaterial cores needed for all phenomena that include more than one item.

The complexity may also differ depending on the level of study. A system can be a description of dependence or a linear process, more or less one-dimensional, e.g. a chronological order of production steps from raw material to finished product, with only one active actor at each step. A system can describe situations where every part has direct relations to more than two other parts, which results in a two-dimensional structure. A system can consist of a structure of dependence/hierarchy/chronology of a three-dimensional kind with several levels. Each level in such a system can be viewed as a separate inferior system, and can be related to as a sub-system. Thus, a system can be illustrated as a layered three-dimensional structure built up by levels consisting of two-dimensional sub-structures.

A system can be defined/described either upwards or downwards, by using one of its end points as a point of departure, following and describing its relations and related parts onwards to the other end. Any intermediate point can be chosen when mapping relations in different directions.

In its widest meaning a building system contains both organisational and physical sub-systems; organisational systems for function, decision-making, production, transport and assembling, physical sub-systems for adaptability, assembling, co-action and flexibility. There are multitudes of relations in every case on every level and around every detail and the degree of complexity varies with the thoroughness and the width of the scope. There are several more or less clearly defined functional/physical sub-systems appearing – structure, layout, installations, building physics, functional design (closely related to layout and physical communication) and architectural co-action and aesthetic design. These sub-systems can be dealt with as parts of a unity and elaborated for swift adaptation to a good overall practical, visual, environmental and static function as well as a high rationality and sustainable economy. A building system deals with the relations between matters related to the production, management, utilisation and life cycle of any built structure, be it theoretical organisation or physical manufacturing.

4.1.2 Systems and Utility

The focus of structural engineering connected to material, technique and application is in a generalised view mainly on the production phase and the long-term static behaviour. Everything has to fit, match and adapt in the forming of a structure, which is to be built in and often fully covered at the finishing of the pre-usage phase.

The structure is a prerequisite for the usage phase and its characteristics and its lifetime is of course the same as the rest of the built product, but structural engineering is mostly occupied with the production phase and will later only be indirectly visible. Architectural work aims at serving the utilitarian point of view and at the visible result in the finished building. The architectural design merges with the structural engineering in the production phase, deciding spatial and utilitarian features, but architecture is mostly occupied with the usage phase.

The architectural use of a building system is sometimes questioned, since a latent conflict can be noted between strict regulations and the freedom of art, design and individuality. This conflict is partly based on pure artistic/expressional aspects, concerning the architects' wish to create without restrictions, but also concerning the wishes and needs of the end users – there are many different personalities in the society and different people have different tastes and urges to express their individuality.[247]

There are also differences between physical needs concerning layout, number, orientation and properties of rooms such as measurements and openings. Variability implies a problem, since the wider the freedom of choice becomes, the more complex the system will be, and thereby more intricate and demanding to handle.

Systems and standards are closely related. Standards concern basic measures and design agreed upon as common objectives of properties of a product. They should denote properties as ideal prerequisites for a convenient, practical and economic use. Often however they have been written and viewed as an allowed minimum of dimensions, utilised to build as compactly and economically gainful as possible, which makes them unattractive and seen as something almost negative.

Actions of systematising have through recent history resulted in poor environments, where few types of modular elements have been used and steadily repeated and where the rationality of machines during construction has decided orientation and spacing of buildings.[248]

There is however potential positive aspects of systemising that must not be neglected when discussing prefabricated architecture. Good architecture should imply good function as well as good aesthetical and structural design. Systemising is a tool for dealing with materials and techniques and since materials and techniques are means to create architecture, systematising work should be a suitable tool for architectural design (*Fig. 4.1*).

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[247] *A common scenario is e.g. that residential areas where only a limited set of colours has been initially allowed on the exteriors show big changes with repainted façades in a wide variety of colours once the restrictions are taken away.*

[248] Falk, A. 2002, pp. 68

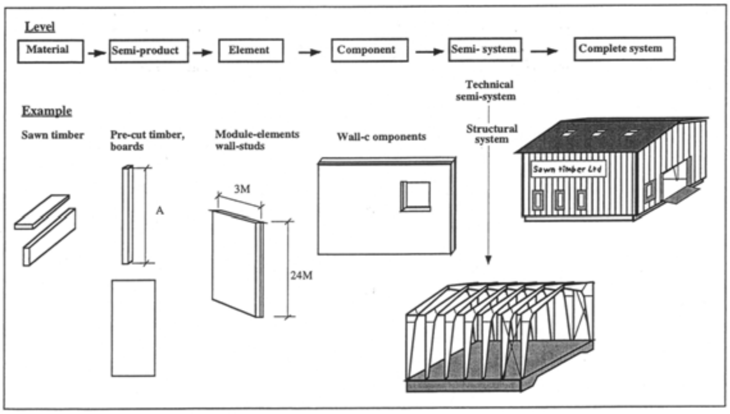


Fig. 4.1 Levels of a building system as described by Samuelsson.

A building system must rely on a hierarchical order, with superior factors deciding inferior ones, but not without the inferior being able to guide the setting of the superior ones. In defining the relation between the included parts of the system a mutual adaptation of the parts should guide to the final solution. Technical applicability must be combined with prerequisites for utilitarian design utilitarian design, i.e. functional and aesthetical design aspects.

The system works as a frame of reference and a guideline through the process. The use of a system demands a lot of initial thorough work, of matching parts and optimising relations. Once the system is in use it may put specific demands on storage, transport and well working communication.

High degree of prefabrication means needs for thorough planning of parts, details and process in the factory, which put specific needs for systemisation and well defined system levels. Low prefab degree means on site production, possibilities to deal with problems and detail work late in the process, which means that supplementary work can compensate for a low systemisation level (*Fig. 4.2*).

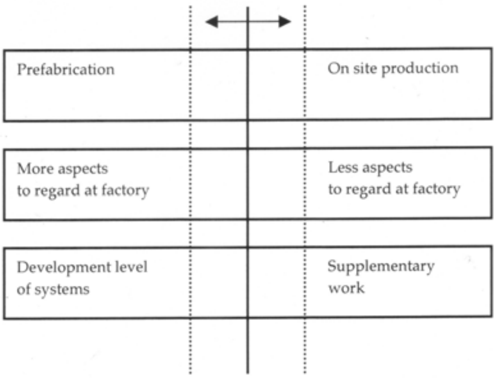


Fig. 4.2 Effects from prefabrication degree on production.

4.2 Building Systems in Timber

4.2.1 Basic Properties

There are a number of theoretical levels of a building system, with different degrees of abstraction. The term building system is not bound to a specific material. The term building system deals with any material and is in that sense still general. It includes building parts and the prerequisites for their function, joints and their function and the transference of forces, but not the specific joint-design. With the specification building system *in timber* a less abstract level is entered. The more specific the term, the more rules there are to follow, since more prerequisites are defined.

4.2.2 Deciding Factors

A building system depends on several factors, which to different degrees decides its design and assembly. The key to the system is the basic unit and its properties. On the basic unit, demands are put concerning function and use:

Prefab

Production of elements (design, measures and dimensions), assembling technique and inter-element joining technique is the starting point. The properties of the elements and their finishing degree decide the entire production chain and the demands on information flow and interfaces and adaptability between the different stages of construction.

There are also limits imposed by the production line, which have maximum lengths and/or widths initially constructed for certain standardised measurements. The geometry of the planned building then decides the dimensions of the element.

Structure

Co-action and technical function are fundamental to built structures. With a certain sub-division of a structure and concerning construction, de-construction, replacement and maintenance the function of the elements, their interfaces and joints gain importance. To satisfy requirements concerning stability a structure has to contain rigid elements and joints that manage to transfer forces between the elements. Accurate design of edge zones and the location and orientation of load carrying and load transferring elements is crucial for the structural behaviour.

Architecture

Structure and synergy between architecture and structure is important for efficient overall and detail design of a building; utility and rationality during construction and usage phase relay on this interaction. Openings and other penetrations such as doors, windows, light shafts and shafts for installations affect both stability and co-action in the modules and what can be allowed is decided by the individual element design – material, assembly and geometry are related.

Further factors are the layout, dimensions of the plan and number of storeys of the proposed building. The layout and the height of the building are important for the potential stability within and between modules.

Planning

The building and the units that it consists of must be planned for the desired structural system to reach a good structural and architectural utilisation and function.

Installation and prefabrication degree have effect on prerequisites for handling and assembling the elements. The higher the degree of prefabrication, the more sensitive the elements and the more thoroughly the joint design has to be studied.

Location of installations has effect on layouts and types of surfaces on floors, walls and ceilings in rooms. If concentrated to central shafts the installations leave most of the plan for free layouts, but is then dependent on pipes and cords in elements. If the installations are placed inside the elements the original surface in unaffected, if placed on the surfaces of elements covering claddings may be considered necessary.

Living

Environment and qualities concern surface materials and treatments and the finishing of the building. There are a number of aspects that affect the comfort and utility of built structures: light conditions in the rooms; light reflection, acoustic and tactile qualities of surfaces; climatic conditions relating to temperature of the air and surfaces; moisture and emissions in the air.

4.3 Plates in Construction

Force transferring properties of a plate structure allows for a number of interesting uses, such as floor-structures with wide spans and wall-structures working as deep beams. Cuts and openings can be orientated rather freely and columns can be used as supports without main beams (*Fig. 4.3*); foundation can be simple e.g. plinths or columns with a free span of the wall acting as a deep beam between them (*Fig. 4.4*).

Fig. 4.3 A tourist office in Murau during construction utilising shear-plate action (left) and a plate-based villa-structure in Schladming, Austria, with cut-outs and cantilevering floors (right).

The applications and behaviour discussed below depend on the rigidity of the elements. If an element is composed of a number of smaller plates, these have to be rigidly joined e.g. by gluing, drilled in rods or addition of top and bottom plates. As rigid surfaces the plates are then to be assembled into a stable structure.

Fig. 4.4 A plate floor deck supported on steel columns.

A floor can be put directly on columns or plinths without carrying beams because of the effective potential of spreading point-loads. Cantilevering all the way around as a bridge is also a possibility. The potential is similar with roof-structures, in which the plate can span without roof trusses or rafters. The plate-floor can lead to a freedom of placing inner walls. The functional benefits of this will not be so obvious in a small one- or two-storied house, though it can be architecturally interesting (*Fig. 4.5*), but is an interesting advance in the multi-storey house, where walls do not have to be placed or oriented in the same way on different floors. This means that different layouts can be used, serving differing needs of e.g. commercial activities on one floor and varying demands of households on other floors[249].

Fig. 4.5 An example of a villa with different utilisations of the plate action. Schladming, Austria.

[249] Falk, A. et al. 2001

Outdoor exposed structures have to resist uplift forces from wind loads. In massive buildings in stone this is not a problem since the self-weight of the structure is enough to hold down the structure. In lighter building types like e.g. light or massive timber frames the structure is not heavy enough. The lightness must then be completed with anchoring structures and an otherwise light structure gains weight through the need of big volumes of concrete in the foundation. The effect of lateral and uplift forces can however be decreased by thoroughly analysing the plan of the load-bearing structure. By arranging load-bearing walls and securing co-action with floor decks the over all structure can be made to act as a stiff unit, to stand the lateral deformations and reduce the uplifting effect (*see Chapter 5, case #3*).

4.3.1 Stability

The primary function of the load-bearing structure is to handle the vertical loads from self-weight, variable service-loads, snow-loads and wind-loads. Stability is needed against lateral and/or torsional forces, which normally occur as a result of wind and/or of eccentric action/displacements of loads. The transmittance of lateral forces through the structure down to the foundation can be secured by connections to force-resisting building-members and bracing.

An unbroken line is needed to take care of loads and forces in a building. Vertical elements are needed to transfer forces to horizontal ones and other vertical elements and horizontal elements transfer loads to vertical ones. A floor can transfer loads to interfacing walls. A wall can in the same way act as a plate and transfer the reaction to horizontal forces along its interfaces into neighbouring elements.

Uplift forces are a critical issue for timber buildings since relatively low weight makes them sensitive to wind-pressure resulting in forces pushing upwards. To secure the wall its in place the uplift resistance force must be bigger than the uplift force.

The uplift resistance is composed by the resultant force from storeys above, forces from dead weight and from load displacement around openings in walls on the current storey, the capacity of hold-down connections between the current storey and the storey or foundation below.

Connections to the foundation can be carried out as continuous rods reaching from the top floor down to the foundation, or as bracing connecting floor to floor all the way down. Hold-down connections are required at each end and between the openings in perforated segments.[250] The self-weight can be enough to resist uplift if the structure is heavy enough, but combinations of outer forces such as wind-load and asymmetrical temporary loads such as snow may become very big. Increased length of the shear wall increases the resistance to lateral forces. The shorter the wall is, the greater the need for hold-down connections.

[250] Ni, C. et al. 1999, p 1

Types of element function

Load-carrying building parts take up vertical loads in shear-plates as well as forces in and perpendicular to plates and shear-plates and are to transfer the forces to the ground. They also act as stiffeners in co-action with other load-carrying walls and floors.

The primary functions of stiffening walls are to prevent buckling in load-carrying walls and to transfer wind-loads to load-carrying walls. Stiffening walls show the most efficient performance with wide extension and few openings. Load carrying and stiffening floors take up vertical forces perpendicular to the surface and horizontal wind-forces in their plane. Columns and beams can be utilised for local stiffness and stability, but they only take care of point and line loads.

Bracing

Bracing of a structure can be achieved principally in two ways:

- A complete bracing of an orthogonal main structure can be obtained by adding diagonals. Diagonal bracing is applied and fixed to an already built main structure, e.g. cross-bracing rods – K-, W-, N- or X-shape – added to a post and beam structure, or in flat slab construction.
- The main structure can be self-supporting against lateral in-plane forces (*Fig. 4.6*). Such integrated bracing takes advantage of plate and shear-plate action. The plate is able to distribute and redistribute forces within its mass. Cross-laminated elements distribute both point loads and evenly spread loads in its plane.

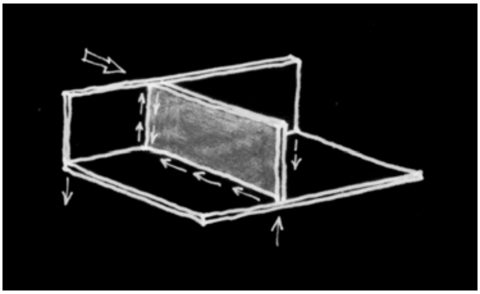


Fig. 4.6 Force distribution in a three-dimensional structure.

In lightweight timber building thin sheeting-materials such as gypsum boards or plywood are also very often used for stabilisation. These are nailed or screwed to the timber frame, totally or partially covering the area between the members to obtain shear-plate action.[251] In a conventional sheeted stud-frame there is a potential for co-action between the studs and the sheeting. The studs and the sheeting have their own tasks separated from each other. While the studs carry the vertical loads and transfer lateral forces applied perpendicular to the wall, sheeting transfers the lateral, in-plane forces[252]. The sheeting is chosen thin since it will not have to take up forces in

[251] *The function relies on co-action of sheeting and frame, for which the fixing is crucial.*
[252] *For load-transfer, the sheeting is dependent on the nailing to the studs.*

any other direction. In flat slab construction with massive timber decks cross bracing is the main stabilising principle.

With the use of plates 0-dimensional joints loose their crucial importance; plates are basically 2-dimensional and are able to transfer forces along their edges (1-dimensional joints). Vertically oriented plates obtain stabilising action against lateral forces and transference of forces to the foundation is offered along the bottom line of the same plates.

Lateral stability of plate systems

Stability should be dealt with from the beginning of the design work. It is important to decide already during the planning phase which structural elements to utilise for load bearing and load-transfer, and which to utilise for stiffening only.[253] The building system gives the limitations and possibilities for structure and layout, why it is necessary to plan both structure and architecture with a certain building system in mind.

A minimum of three stabilising walls is needed on every floor. When arranging elements of a structure the reaction lines of the walls must not be parallel or cross each other in the same point (*Fig. 4.7*). A distance as large as possible to the mid-point of the plan is advantageous.

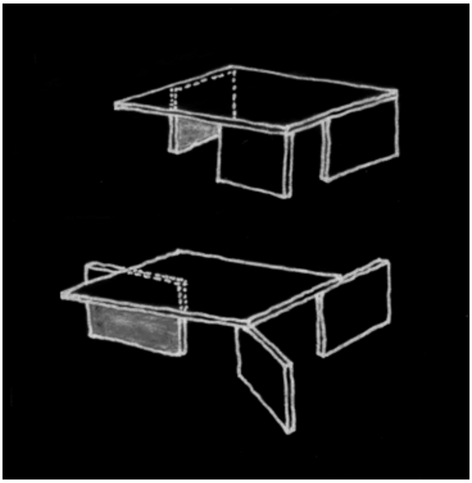


Fig. 4.7 Stability and spaces obtained in a plate-structure.

Symmetric orientation of the stiffening walls is advantageous from the point of view of stabilisation. A symmetric static plan will show a centre of resistance that coincides with the centre of load-pressure. Asymmetry in the static plan layout easily leads to addition of torsional forces, which may be difficult to take care of.

Plates and shear-plates provide more stiffness than the corresponding elements in a frame construction. This means that number of stiffening walls and the length of those may be reduced but the effects must be analysed.[254]

[253] Lignum Research 2001, 1-8
[254] Lignum Research 2001, 1-12

The structural co-action between horizontal and vertical plates can also be utilised in flags (*Fig. 4.8*). With large recesses in surface elements changes and effects on continual support and the stiffening structure in the building will be caused by the operation.

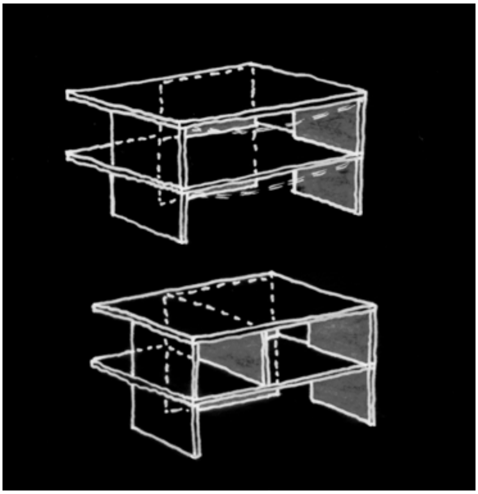


Fig. 4.8 Flag action in a plate structure.

In a multi-storey building there is normally a play between more open and more closed parts, e.g. between apartments as more or less closed boxes and staircases as more or less open shafts. The shafts can be cast in concrete as in SH-Holz, the Swiss forestry school building in Biel[255], finished in 1999. There the asymmetrically located concrete shafts stabilise the timber floor decks of box-elements. In a system with staircases in massive timber construction beams and plates may transfer lateral loads across the staircases between the apartment sections.[256] Staircases can be utilised for transversal stabilisation of a longitudinally oriented plan layout pattern of the apartments.

System performance

Shear walls and diaphragm floors provide lateral stability in a structure by transferring loads between each other and to horizontal elements. It is the interplay between them and other elements that ensure a reliable structure. The appearance of synergic effects has to be been taken into account in the modelling and design of buildings and their performance. The co-action and stability issues need to be studied in three dimensions to benefit from the capacity of the complete structure.[257]

Applied forces are seldom purely horizontal or vertical, which in a three-dimensional structure means that they induce stresses out of the plane of a single member. Most design techniques today assume a rigid behaviour of all horizontally oriented shear-plates, which leads to a hypothetical equal behaviour of all walls. If however these shear-plates are regarded as flexible the shear walls will act independently resulting

[255] *With structural design by Jürg Conzett.* Described by Sigrist, C. 2000.
[256] Lignum Research, 2001, 1-10
[257] Andreasson, S 2000, p. 17

in a completely different behaviour.[258] In e.g. a structure with nailed floor decks without drilled in rods the horizontal slabs should be viewed and dealt with as flexible.[259]

Each member can be illustrated separately as two-dimensional but when put into a building they become parts of the three-dimensional system and the combined action of lateral and vertical loads has to be taken into account.

In light timber-frames a wall with a window is regarded as discontinuous; the part with the opening does not count as active. With glued cross-laminated timber plates the basic elements are fully rigid and the properties of the plates allow a wall-structure to transfer forces over its entire area. This brings a hypothetical freedom to create openings; even walls active in shear can be perforated, i.e. for doors and windows (*Fig. 4.9*).

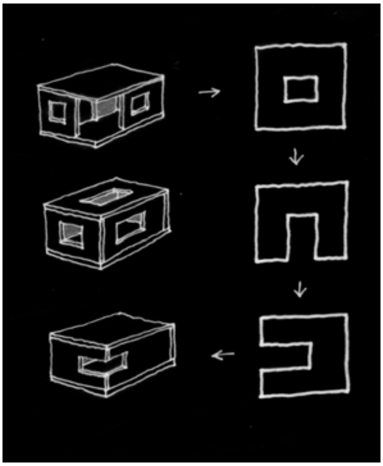


Fig. 4.9 Plate structure with cut-outs.

The total active section will be reduced, but the active beam-depth of the plate can be preserved. If the outer edges are kept continuous, openings can be oriented and placed in almost any way since the plate will provide alternative paths for the forces around the openings. Cuts can be made in floors for staircases and installation shafts, chimneys etc. and in walls for windows and doors.

A cut made at the edge will reduce the active depth. It will then act e.g. by co-action with a floor-plate if the connections are designed in the right way. If the opening is made at the end of the plate, towards a corner of a building, one can see the plate as a vertical cantilever capable of transferring loads from an unsupported to a supported part. Depending on the magnitude of the loads, the size of the opening and the composition of the plate this can make open corners possible, i.e. windows reaching around corners, without supporting columns.

However, recesses in the walls such as doors and windows limit the possible transfer-routes of forces and risk to reduce the shear-plate action[260]; openings may reduce the rigidity and flexible joints may alter the prerequisites and the behaviour.

[258] Andreasson, S. 2000, p. 18
[259] Industrikonsortiet Massivträ 2003, 4.5.2
[260] Schickhofer, G. and Winter, W. et al. 2001, p. 117.

Doors normally break the load-transferring active frame, and thorough jointing may be needed to restore the stabilising capacity of the wall surface. Positions of walls in the layout, openings for windows in exterior walls and doors inside e.g. apartments have to be designed and placed cautiously to support an efficient overall performance. Openings placed directly over each other, for example, leads to less rigid behaviour than an altered placing (*Fig. 4.10*), especially concerning lateral forces. An altered placing increases the wall's resistance to racking.[261]

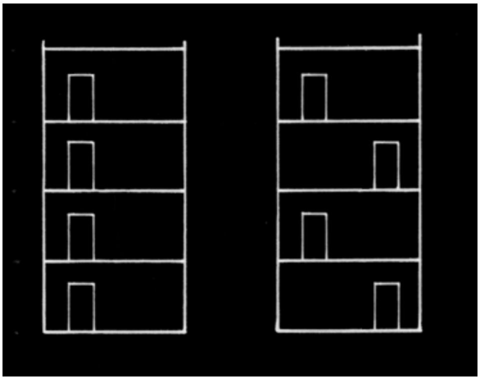


Fig. 4.10 Location of openings in a multi-storey plate structure.

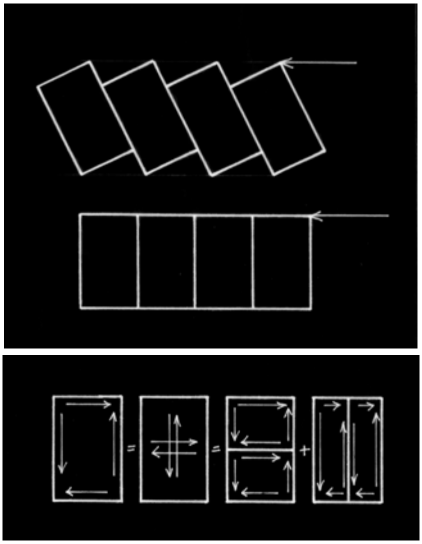
4.4 Joints and Detailing

Joint-design enables standardisation. One main advantage of a standardised set of joints is that it clearly defines the interfaces between the different parts of the building, thus facilitating the development of prefabricated systems. Prefabrication and industrial production are gaining importance today since they reduce the number of man-hours on site. This is made possible through connections within a component that withstand transportation, and connections between components designed for swift assembly[262].

Within an element stability depends on the properties of its material to transfer loads and forces, and on the way the different members that build up the element are fixed to each other, i.e. how the element is assembled. Shear strongly influences the capacity of wall elements to carry loads.

[261] Andreasson. S 2000, p.
[262] Schickhofer G. and Hasewend B. 2000, p. 3

The shear modulus is decided by the method of assembling the plate. Small elements can build up a larger element with remaining shear-resistance capacity as long as sufficient jointing is provided (*Fig. 4.11*). Such a composite element can be designed with e.g. a steel rod at the lower side or glued tongue and groove joints between the element parts.



4.11 Members constituting a shear-plate element and the effect of insufficient jointing.

The joints determine the co-action in the element system. Floors meet interior and exterior walls and floor-elements meet each other; walls meet roof-elements, interior walls meet exterior ones and wall-elements meet each other in-plane. Thus the stability of a plate-structure depends on both orientation and jointing.

Joints not only signify the interface-zones in a structure but also outline an object and enclose a volume. Even if joints should be understood as technical functions[263] the architectural aspect of joints defining objects and rooms should not be underestimated. Their location is decided by material and method, structural principle, standard and modular order, but an initial choice is possible and free - and important - to influence since it to a wide extent affects the experienced environment.

4.4.1 Joint Types

An element can be defined by its borders and bordering conditions, where it is to fulfil the demands of compatibility. Even if the expression of the system is characterised by lines, load-carrying plates will demand a certain thickness in a physical model or a building for the material to be able to take care of occurring load-situations. Joint types have to be designed considering:

[263] Wachsmann, K. 1959, p. 74

- A jointing area consisting of either the edges or the sides at the edges
- Possible depth for jointing, e.g. screws, bolts, nails, dowels
- Direction and magnitude of introduced forces
- Angle between force and grain direction

Jointing techniques are of two kinds: those utilising the edge-surfaces and those utilising the sides. With edge-joining the jointing technique is not visible when the members have been fixed to each other, whereas joints mounted on the element sides will have to be covered if not to be seen. Side-joints can also be applied to the elements in cut grooves.

The demands on and design of these joints differ depending on the principle of support, if the floor is hung in or supported on walls of storey-height. When hung in, floors transfer vertical forces from self-weight and variable loads, and horizontal forces from e.g. wind-loads. If supported on the walls, roof and walls above bring down an addition of vertical loads to the wall-floor joint-zone.

Shear forces appear along horizontal edges as a result of lateral forces and along vertical edges as a result of uplift forces and/or lateral forces, and shear between elements puts high demands on jointing. At the edges of an element the forces must be transferred to a bordering element or building-part.

Joints should be designed to transfer forces, but depending on the location also to stand fire, to act as fire-barriers and to prevent sound transmission. At the same time as loads must be transferred sound must not, and this makes the situation complicated. The design of joints also depend on whether one wishes to be able to deconstruct surfaces and elements, or to replace if needed, without breaking the element or tearing it down.

4.5 Linked Aspects

4.5.1 Moisture and Heat

Effects on indoor climate

Sensed experiences are difficult to measure, but when we experience discomfort we normally try to do something about it, e.g. if we feel cold, we try to raise the temperature. Time is important for climatic experience and the cyclic variations of temperature and moisture in the indoor climate strongly affect our sense of wellbeing. To design a good convenient climate is therefore economically gainful.

Quick changes of temperature and humidity in the air will be obvious and not so comfortable. Therefore a material with the capacity to even out the fluctuations in the air during a 24-hour period can provide to both a comfortable climate as well as lowered energy consumption gaining a good life cycle economy (LCE).

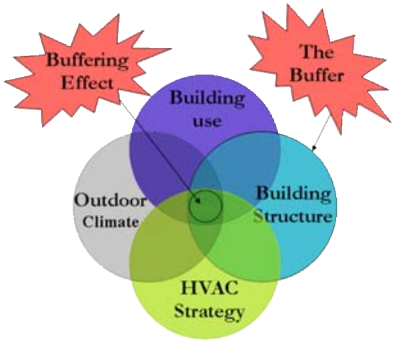


Fig. 4.12 Factors affecting the indoor climate as described by Hameury.

Heat and moisture have been shown to co-act in the indoor environment, this evens out the effects of temperature changes and shifts in moisture load from indoor activities. Indoor humidity and temperature and the variations of those have big effect on comfort, health and energy consumption. It has been proposed that timber as a hygroscopic material can be utilised for its heat and moisture storage capacity, or buffering effect, to add positively to the experienced indoor climate and to lower the need for heating and cooling systems (*Fig. 4.12*).[264] This has also been preliminarily confirmed at tests on a massive timber structure in Stockholm (*treated in Section 5.1*). The need for ventilation is however not reduced to the same extent as the need for temperature regulating.

Hygroscopic properties of the material give timber the ability to absorb, buffer and desorb moisture. The timber can take up and let out moisture in quite long cycles, not letting moisture through the wall from inside to outside but returning it to the indoor air.

For temperature the active zone[265] is shown to be about 70 mm deep. More stored heat is released to the indoor environment from partition walls than from exterior walls.[266] For moisture the active zone during a yearly period is 20 mm, during a daily cycle it is about 1 mm.[267] Variations of moisture has been found so slow that the effect of ventilation rate is more decisive for the indoor conditions than the interplay with bare timber surfaces. The contribution of the structure on the indoor moisture level is, however, shown to remain.[268]

The close relationship between the heat and moisture transport in the building structure and the indoor environment[269] depends on the surface treatment of the timber. With a wooden surface that is uncovered, or unsealed with a surface treatment like paint, the indoor climate interacts with the building structure. But already with a permeable coating the buffering effect decreases.

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[264] Hameury, S. 2004, paper I, p. 282
[265] *Penetration depth, defined as the distance from surface where variations are one third of the indoor variation.*
[266] Hameury, S. 2004, p. 49
[267] *In the zone between surface and 3 mm depth the study referred to here could not measure the moisture variations. At 3 mm the variations were negligable and the behaviour therefore defined as a surface phenomenon in need of further studies.* Hameury, S. 2004, paper II, p. 1006
[268] Hameury, S. 2004, p. 65
[269] Hameury, S. 2004, p. 27

Effects of partly covered or sealed timber surfaces, i.e. reduced active areas in a room, have not yet been studied. With high ventilation rate, the size of areas active in the climatic balance do not play any important role, but studies have shown that the importance increases with lower ventilation rate.[270]

During construction

It is important that the raw material is dried and conditioned to the right moisture-content before use. When it is to be assembled to surface elements and built in it should have a moisture-content corresponding to the equilibrium in the intended environment.[271]

The construction can be carried out swiftly and during "dry" conditions, but if the timber is well conditioned even some time of exposure to rain or snow during erection will not have any durable effects.[272] The timber takes up the added moisture slowly and what is taken up will be evaporated as soon as it gets protected.

4.5.2 Living Environment

Acoustics and sound insulation

Acoustics, sound environment and reverberation rate depend on properties of surfaces. The choice of materials and the treatment of these decide the perceived sound environment.

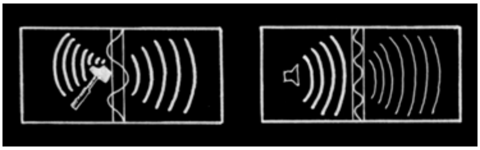

Fig. 4.13 Impact sound (left) and airborne sound (right).

Two types of sound transmittance occur: airborne sound (through the material of a structure) and footfall (in the material of a structure) (*Fig. 4.13*). The problems concerning sound insulation in timber structures can be summarised in three points: airborne sound, impact sound and flank transmission.

Sound is basically shifts of pressure in the air. In a material it gets transmitted as vibrations (*Fig. 4.14*). When a sound wave meets a structural element some of it will be reflected back into the room. Some of the energy will be absorbed by the material and some will tend to be transmitted in the material to the neighbouring structural elements and further on into a neighbouring room via e.g. a perpendicularly oriented wall or a floor structure. The remaining energy will cause sound waves on the other side of the first wall.

[270] Hameury, D. 2004, p. 62

[271] *For indoor housing environments a relative humidity of 8 to 9% is suitable.* Trätek 1998 *For production of e.g. laminated timber plate floors for residential buildings a moisture content as low as 6% preferable.*

[272] Industrikonsortiet Massivträ 2002, 2.3.2.2

Fig. 4.14 Sketch of principle routes for sound transmission in and through a structure.

To prevent sound transmission floors can be provided with suspended ceilings (common build up: gypsum boards on spaced boarding). These act as flexible layers damping the vibrations and are also used for installations. The lower surfaces can be designed for specific acoustic properties. These solutions often result in rather big depths to compensate for the low weight of the floor, which is a critical property concerning vibrations.

A suspended ceiling prevents the vibrations from passing directly into the storey below, but a visible upper surface means that vibrations reach the load-bearing structure and can be transferred in the material. This puts demands on damping solutions at the floor to wall interfaces. To prevent vibrations to be transmitted in plane to neighbouring apartments the floor slab must not cover wider spans than one apartment.

The ceilings can either be hung in the upper floor structure or, if better performance is required the ceiling can be completely separated from the load-bearing floor and be self-supported.

Another way to deal with sound damping in floors is to add a wearing surface e.g. a parquet floor on a flexible, damping layer on the upper side. This means that the vibrations are reduced or totally absorbed before they reach the load-bearing structure and that the entire structural floor is built in. If the upper surface is covered the floor deck may be continuous over the partition walls and floor decks be manufactured in bigger sizes. The two principles are illustrated in *Fig. 4.15*. Combinations are plausible as well.

Fig. 4.15 Damping principles for floors, suspended ceiling (left) and upper floor covering (right).

The transmission of vibrations in massive timber floor plates also depends on the sub-division of the floor surface and the jointing between the combined elements.[273] A problem with timber-based floor-structures is the lightness, the low weight of the floor as mentioned above. Low weight leads to low eigenfrequency, which demands rather much work to overcome. A heavy floor-deck shows a more gainful behaviour concerning disturbing vibrations than a light one, why addition of weight increasing material, tiles for example, is a possible functional solution, as shown in e.g. Falk et al. (2001).

The low density compared to e.g. concrete has been regarded as positive while hypothetically reducing the amount of foundation work.[274] The relative lightness of massive timber in comparison with other massive structural types can on the other hand cause problems with stability, as an effect of the mass not being of the magnitude to act against the uplift forces caused by lateral wind pressure.

Flank transmission is more obvious in floors of massive timber than in concrete floors and if no measures are taken most of the sound is transmitted through flank transmission.[275] To reduce the flank transmission the connection between floor and the lower wall structure is designed to break the vibrations. This can be carried out in different ways, most common to use are battens of synthetic rubber with flexibility adapted to intended load conditions.

Load-bearing wall structures can be single or double. For exterior walls single layer wall structures are used with exterior thermal insulation and exterior cladding. Partition walls between apartments are normally of a double design, with two massive timber elements on either side of intermediate insulation. An asymmetrical cross-section is often preferable for a good acoustic result.[276]

Thermal insulation

The air tightness is crucial for the behaviour of a building from the perspective of building physics. It decides the function of the insulating action of the wall, and controls the indoor climate.

Thermal inertia and the capacity to store heat have effects on the need of additional insulating material. The insulating capacity of massive timber walls may reduce the need for insulation, but insulating materials are still needed for exterior wall thicknesses suiting the load bearing requirements.

For normal load-bearing conditions a massive timber structure of 80 mm is a minimum requirement. Thicker timber-structures can be produced, for higher demands of load-bearing and thereby also increased insulating capacity, but a wall thickness of more than 300 mm is however not reasonable.[277] For normal indoor thermal climate a wall thickness of 100 mm needs addition of thermal insulation of about 100-150 mm, depending on surrounding climatic conditions and acceptable indoor climate.

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[273] Industrikonsortiet Massivträ 2002, 5.2.3.1
[274] Industrikonsortiet Massivträ 2002, pp. 14
[275] Industrikonsortiet Massivträ 2002, 5.2.3.1
[276] *With an asymmetric cross-section the eigenfrequency of the wall-structure will differ over the section and vibrations will me more easily be prevented from reaching through.*
[277] Schickhofer, G. and Winter, W. et al. 2001, p. 131

Tactile values

To use man as point of departure in design work has been common throughout history. The way to deal with the reactions from human senses has varied though. The Swiss architect Le Corbusier based his entire method for proportions and scale on the measures of man (*Fig. 4.16*) even if many projects of his reached a monumental overall scale. The definite measures are easily defined and adjusted to. What is experienced with the senses is on the other hand not at all easily defined and therefore difficult to deal with technically.

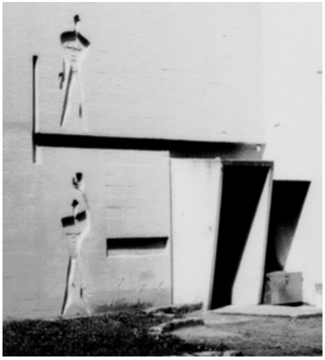

Fig. 4.16 Le Modulor, the measures of man, as a relief in concrete at an entrance to Unité Habitation, an apartment block in Berlin.

Rasmussen (1959) has written about the different ways in which we experience our built environment.[278] There are a great number of parameters concerning buildings and environment often regarded as soft, immeasurable an imprecise qualities. The experiences of voids and solids, of colour and shape, of surface patterns and characters, of smell and temperature; all these and more concern the volumes of air that man enters, lives and acts in and the materials that enclose the volumes.

In many environments, above all in residential buildings, the treatment of materials becomes very influential. Where the inhabitants come close to and touch materials and surfaces the experience and the individual evaluation turns to being governed by the impressions conveyed by other senses than eyesight and hearing.

Much of what is sensed is normally referred to as *soft values*, which to a large extent are subjective. The experience of measured values of e.g. volume of sound and temperature may differ from person to person, from one moment or context to another. These soft values are difficult to estimate the effect of and evaluate, which, however, does not decrease their impact on our reactions on the experienced environment.

Characteristics of surfaces can be experienced by eyesight, hearing and by touch. The surface reflects light or may be matted to absorb it. The surface's structure reflects sound in different ways. The feeling when moving one's hand over a surface reveals the material and its treatment. A central term is *materiality*.

[278] Rasmussen, S.E. 1959

The feeling can convey something else than its visual appearance when e.g. a material with a smooth, warm surface is formed with sharp edges, or when a hard material is given a soft, rounded design. Historically, these effects have been used in different ways and can be used for contrasting effects in the same object.[279]

There are many values that cannot be confirmed scientifically, which are of importance for the choice of the customer and end-user, thereby of importance for the evaluation of the finished result. A project on residential blocks in the northern part of Sweden was divided in two parts, one with a massive timber structure and one constructed in concrete. Most of those people that were to live there wanted an apartment in the timber house. Those who moved in have been very satisfied with the timber house compared to own earlier experiences of light timber structures and concrete construction. They have also referred to experiences made by friends and relatives visiting them.[280]

There are many ways to compose the message to the experiencing mind. There are many possibilities to steer the impression given by the built environment. The experiences differ between a sawn timber-surface and a planed one, between a surface treated with glazing paint and a surface covered with a coating paint. The experience of a panelled wall with visible screws or nails differs from that of a wall where the jointing is carried out from the backside. Visible edges, joints and obvious surface treatment will convey a description of how the element was made. An even, plain surface without traces of the treatment and jointing will be experienced as abstract and more or less material neutral.

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[279] Rasmussen, S.E. 1959, p. 23

[280] *The residential project called Gammfällan.* Industrikonsortiet Massivträ 2002

5 CASE-STUDY ON BUILDING SYSTEMS

The multiple-case study presented below has been performed to explore and compare how massive timber products are used today in building systems, primarily for medium- and high-rise residential blocks. Six cases have been studied, four Swedish and two Austrian; three cases have been constructed with surface-elements and three with volume-elements. The cases are listed below:

Nr:	*Case:*	*Abbr:*	*Type:*	*Location:*
#1	Vetenskapsstaden I	VET1	Stud apartments	Stockholm, Sweden
#2	Vetenskapsstaden II	VET2	Stud apartments	Stockholm, Sweden
#3	Sundsvall I	SVA1	Residential	Sundsvall, Sweden
#4	Sundsvall II	SVA2	Residential	Sundsvall, Sweden
#5	Impulszentrum	IMZ	Office building	Graz, Austria
#6	Spöttlgasse	SPG	Residential	Vienna, Austria

Under the headline *Players,* the companies/people responsible for each project are mentioned. Where a group of people has been responsible only the company's name is mentioned.

5.1 Case #1: Vetenskapsstaden I (VET1)

5.1.1 Background

The case comprises an apartment block for guest researchers in Stockholm. One of the issues that the initiating client dealt with was providing apartments for guest researchers in the Stockholm area; another issue was to stimulate interdisciplinary research. The project started with a preliminary study on potential development of a timber-based building method for apartment blocks, carried out in co-operation with a number of departments at the Royal Institute of Technology KTH. The driving force was the need of new apartments.

Among the project aims were to increase utilisation of timber in construction, to provide better indoor living environment, lower energy consumption and reduce costs for construction and maintenance.[281] A timber-based plate structure was chosen and the project that was used for application of the results was an apartment block providing apartments to guest researchers at three universities in Stockholm (*Fig. 5.1*).

During an experimental second phase two prototype apartments, produced by two house building companies[282], were assembled in a building laboratory at KTH, where tests were carried out on acoustic, thermal and moisture related properties and behaviour of the massive timber structure.[283] KTH has continued measuring campaigns concerning temperature and moisture in the load-bearing structure in situ

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[281] Svensk Byggtjänst 2005, p. 15

[282] *Lindbäcks bygg AB and Flexator AB*

[283] *During this phase the author was engaged in the project and performed studies on insulating solutions and façade design as a part of his diploma work at the KTH School of Architecture.*

Fig. 5.1 The apartment block at Roslagstull, Stockholm, Sweden.

after the finishing of the project.[284] The project was used for development and testing of a new type of energy recycling system for sewage and ventilation.[285]

A volume-module based system was chosen for the good acoustic potential of a double structure, which is obtained when incorporating volumes in a structure. The original project plan comprised 24 apartments for guest researchers only. This was changed during the project and the finally realised version consists of 36 apartments: 24 apartments of 34 m^2 and 12 apartments of 50 m^2 (*Fig. 5.2*). The use has changed as well and the building is currently partly serving the needs of the universities and partly offered on the public market.

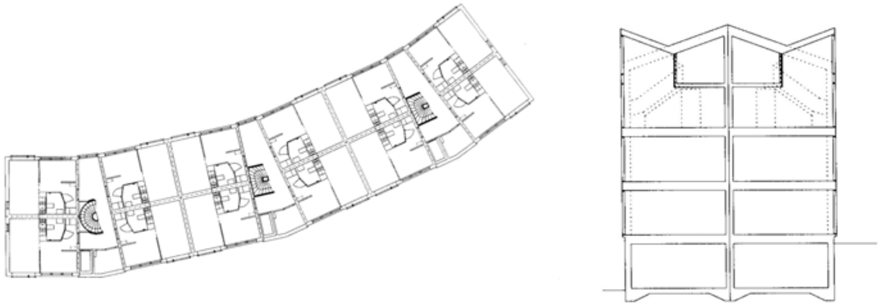

Fig. 5.2 Layout for Vetenskapsstaden I, 1st and 2nd floor and section.

5.1.2 Structure

The project was constructed as complete prefabrication with volume elements[286]. The structure was erected with three storeys (above a subterranean floor under half of the block) with an additional integrated fourth floor resulting in duplex apartments on the third storey (*Fig. 5.3, left*). The layout is the same on the first and second storeys and is thus changed on the third storey.

[284] Hameury, S. 2004
[285] Södergren, D. 2003
[286] *Produced by Pluss Hus AB and Ekologibyggarna AB.*

The entire building is sprinkled, which has allowed for unclad, visible timber in the walls in apartments and staircases.[287]

Fig. 5.3 Interior view of the living room area in a duplex apartment (left) and detail of joints in the massive timber structure and the additional cladding (right).

5.1.3 Wall Elements

The wall structure consists of cross-laminated timber plates of 90 mm thickness built up with three layers. The two outer layers (34 mm) are vertical and the middle layer (22 mm) is placed spaced with horizontal orientation, resulting in cavities in the inner structure. The cavities in the wall elements were originally meant for saving timber, but turned out to provide heat insulation gains. The enclosed air show good insulating properties in the structure.

The elements were produced with storey-height and 1200 mm width. The production line for the massive timber elements was developed for the project and was based on gluing under hydraulic pressure. The outer board layers were edge glued for aesthetic reasons. The element width in combination with edge gluing in the outer layer has resulted in cracking of several element surfaces in the finished building, caused by moisture-induced stresses. The cracking does not affect the static performance, but is viewed as an aesthetic defect in the interior. The problem was approached in the following project (*Section 5.2, case #2*) by changing the element width.

On the outside the exterior walls were covered with vapour barrier[288], 120 mm sawn studs with mineral wool, 9 mm plywood, 50 mm hard mineral and as weathering surface 20 mm plaster was applied (*Fig. 5.4*). On the inside of the exterior walls 18 mm glued joint was added at 10 mm distance to obtain better sound insulation (*Fig. 5.3, right*). On the interior, glazing paint of different colours, from white to dark brown, was applied on the wall elements. The total thickness of the exterior wall structure is about 320 mm.

[287] *The sprinkling system uses fireproof pipes of C-PVC, which were very expensive and hard to work with.*
[288] *For an experimental study the vapour barrier was left out in the exterior wall of one apartment.*

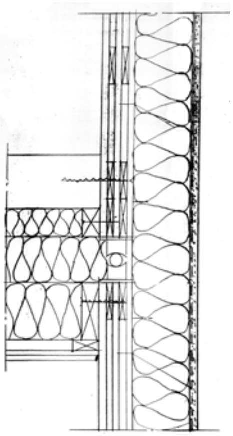

Fig. 5.4 Principle vertical section through the wall-floor joint zone in Vetenskapsstaden I.

The apartment dividing partition wall structure was built up as a double structure: 90 mm cross-laminated timber, 70 mm mineral wool, air gap, 70 mm mineral wool and 90 mm cross-laminated timber. The total thickness of the apartment dividing partition wall structure is about 330 mm. Walls that are not load-bearing have been produced as light timber frame.

5.1.4 Floors

The floors were constructed as a double structure, formed by the floor in one volume and the ceiling in the volume below. Each volume module was provided a load-carrying floor slab consisting of 145 mm glued laminated timber. It was covered on the upper side with 12 mm tongued and grooved timber board floor. The suspended ceiling consists of 145 mm joists, 28 mm spaced boarding and 13 + 13 mm gypsum boards. The distance between the floor element and the suspended ceiling was filled with mineral wool and is utilised as the main horizontal zone for the installations, which were placed in the volumes in the factory. The total depth of the floor structure is about 500 mm.

The floors were delivered with untreated surfaces, which were provided the timber board floor on site. Several combinations of flexible sylomer battens were tried to break the flank transmission between the floors. The aging behaviour and shear capacity of the battens is not documented in Sweden, which motivated a development venture to find new damping solutions for the chosen building. Two types of new dampers were tested and finally utilised in the full-scaled project. One type was timber-based[289] and the other was designed in steel (*see Section 5.2.4*). The steel type developed and tested in the project gave very efficient with promising results and has been patented.

[289] *The timber-based type consisted of two small timber plates of hardwood (aspen) with four pieces of hardwood (birch) in between. Through vacuum compression aspen gains flexible properties, which were utilised for damping effects.*

5.1.5 Detailing

On the exterior the plaster covers all joints in the prefabricated structure. Sections with windows are clad with hard boards, painted in the same colour as the plaster.

All the interior floors and walls are left with visible timber and horizontal joints are emphasised with covering battens whereas the vertical element joints are left visible (*Fig. 5.5*). The edges are sharply cut leaving the interfaces as narrow slots, varying in width with the air humidity. The tactility is characterised by planed wooden surfaces with different treatments, leaving the structure with knots and annual ring-pattern visible.

Fig. 5.5 Interior view of an apartment with glazing paint and detail of radiator pipes and profiled wood in a corner.

5.1.6 Prefabrication and Erection

The building was produced in prefabricated volumes. The cross-laminated timber was delivered to the factory as elements of 1200 mm width and storey height (2890 mm). In the factory they were assembled into wall elements with tongued and grooved joints. The floor elements were nailed together into the measures of the prefabricated modules (3000 × 5600 mm and 3600 × 5600 mm). The floor decks were delivered by a company producing nailed laminated plates for one- and two-storied houses. The layout was sub-divided in three types of volume-modules.

The volume elements were assembled in a factory and transported on trailers to the site where they were lifted with straps around each module. This lifting method left no traces on the volumes, but was problematic concerning the disconnection after mounting. The volume-modules were protected with plastic covers during transport.

The wet areas (bathrooms with shower and water closet) were prefabricated as units, provided with clinker floors. They were placed in the modules in the factory. Installations were concentrated to shafts with central location in the apartments. This lead to logistical problems during construction, when several activities interfered with each other. The sprinkler pipes have been placed in the suspended ceilings with visible sprinkler nozzles.

The project has generated valued experience of systemised construction, planning and production of modularised timber-construction.

5.1.7 Vetenskapsstaden I in Short

The principle for production is complete prefabrication of volume-modules. The layout is not subordinated to the production rationality. There are different types of modules. The timber structure is visible in the interior design; in the exterior both the structural principle and the structural material is covered. The timber-structure has been utilised for the development of a rational structural system, possible to adapt to any environment. There is no architectural utilisation of material-specific form-features.

5.1.8 Players

Client and initiator: The Vetenskapsstaden foundation

Research and development: Royal Institute of Technology KTH
Bengt Hidemark, architect

Planning: Architectural design: Rolf Bergsten, FFNS
Structural design: Tore Möller

Production: Norrfog Enroco, Pluss Hus AB and Ekologibyggarna AB

Erection: Skanska Nya Hem

5.2 Case #2: Vetenskapsstaden II (VET2)

5.2.1 Background

The experiences from VET1 showed gains with the developed system but also a need of changes and further modifications. To be able to offer a well studied system and to enable competing capacity on the market the pilot project had to be followed up and improved. Another project was searched for.

Case #2 comprises a project on apartments for students at the campus of the Royal Institute of Technology KTH in Stockholm (*Fig. 5.6*). The case is the second part of the development project on building system development, described in VET1. This second part was opened with a new research and development phase, where changes were proposed based on the experiences from VET1. The floor structure of VET1 was changed, primarily for reasons of production, from a nailed laminated to a glued cross-laminated floor deck with reduced thickness. The wall elements have been modified to obtain better static performance, by increasing the number of layers while retaining the total element thickness.

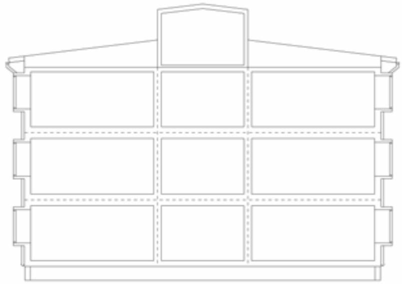

Fig. 5.6 One of the three student apartment blocks at KTH's campus, Stockholm.

5.2.2 Structure

The layout consists of three three-storied blocks, each with two rows of equal room volumes of 20 m^2; the entire project consists of 72 student apartments (*Fig. 5.6-7*). To reduce the experienced height of the building the roof ridge is low with a small slope of the saddle roof. An elevated part at the western gable of each block has been added for installations. The foundation is carried out as an unventilated, warm crawl space, with the massive floor plate above uninsulated.

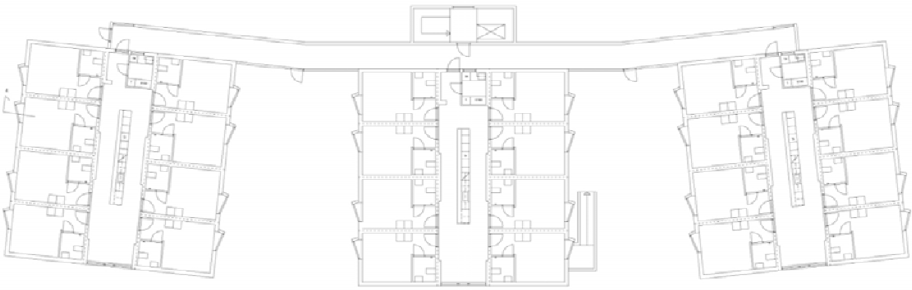

Fig. 5.7 Layout for Vetenskapsstaden II, the 1st floor.

The blocks are entered from an access balcony in timber construction. Common areas for the inhabitants of each floor are placed between the apartments. The common area contains a kitchen (*Fig. 5.8*), a living-room area and a room for washing machines.

Fig. 5.8 Interior view of the common kitchen and living room.

The structural system utilised in VET1 was studied in the light of experience gained from that project and the system was further developed. The design of the volume-modules was reduced to one single type. The installation systems developed for and tested in VET1 had proven efficient and gainful and were also utilised in VET2. One of the flank transmission damper types tested in VET1 was used in VET2.

The entire building is sprinkled[290], which has allowed for uncovered timber in the walls in apartments and staircases and a wooden façade cladding with boards.

5.2.3 Wall Elements

The walls were constructed with cross-laminated timber plates with five layers of equal thickness (18 mm), three vertically oriented and two intermediate layers of spaced horizontal boards (*Fig. 5.9, left*). The plate thickness is 90 mm as in the walls in VET1. Studs (145 mm) are placed every 900 mm on the outer side of the massive timber plate, to secure load-bearing in case of fire. The exterior was covered with 145 mm mineral wool, air barrier, 28 mm spacers and 22 mm wooden board cladding.

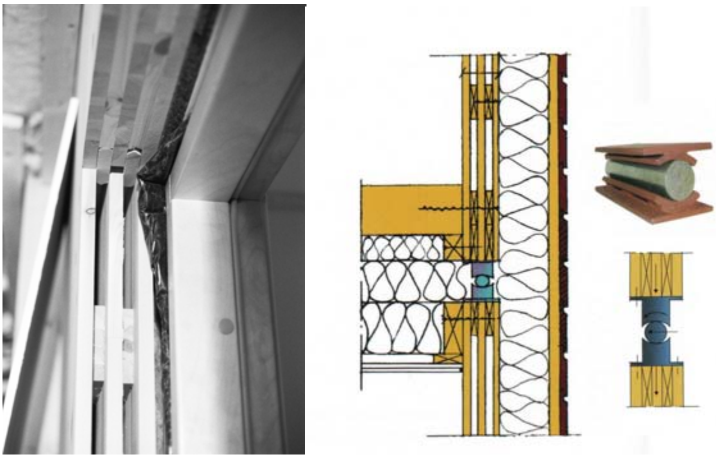

Fig. 5.9 Cross-section of the wall structure during construction and a vertical section of an exterior wall with a flank transmission damper in steel.

[290] *The sprinkling system uses PEX pipes, which has replaced the C-PVC in VET1.*

The elements were glued under hydraulic pressure and produced with storey height and 900 mm width and were jointed with vertical tongued and grooved joints (*Fig. 5.9, right*). The total thickness of the wall structure is about 285 mm.

Apartment dividing partition walls consist of a double structure: 90 mm cross-laminated timber, 70 mm mineral wool, air gap, 70 mm mineral wool and 90 mm cross-laminated timber. The total thickness of the apartment dividing partition wall structure is about 330 mm. Walls that are not load-bearing were produced as light timber-frame.

The five-layered wall showed less sensitivity to moisture induced stresses and less cracking than the three-layered wall in VET1.

5.2.4 Floors

The floors were built up as a double structure, formed by the floor in one volume and the ceiling in the volume below. Each volume module was provided a load-carrying floor slab consisting of 130 mm cross-laminated timber plates and a ceiling with joists. The suspended ceiling consists of 145 mm joists 28 mm spaced boarding, 13 mm gypsum boards and 13 mm board cladding (*Fig. 5.9*). The distance between the floor element of one volume and the ceiling of another was filled with mineral wool (70 + 120 + 145 mm) and is utilised as the main horizontal installation-zone. The total depth of the floor structure is about 530 mm.

To prevent flank transmission the steel-based damping device tested in VET1 was used (*Fig. 5.9*). The damper consists of a steel roll placed between concave steel fittings fixed with screws on the massive timber structure of the upper and the lower volume. The damper reduced the vertical transmission of vibrations between the storeys. Whereas flexible battens are continuous, the steel dampers are separate fittings and each module rests on seven devices.

The floor structure in the common areas consist of an upper cross-laminated plate and a suspended ceiling with 145 mm insulation, 28 mm spaced boarding and 12 mm acoustic boards, carried by 145 mm joists. The total depth of this structure is 390 mm.

5.2.5 Detailing

On the exterior, the modules were covered with a wooden panel in the factory and the joint zones were to be covered on site. The vertical joints were covered with battens on the outside. The horizontal joints were covered with panel boards to obtain an unbroken surface (*Fig. 5.10*). The horizontal joint boards are somewhat narrower than the rest and are possible to recognise. The exterior is also provided with additional bay windows, which were designed in light timber construction and fixed on the massive timber elements.

In the interior the massive timber structure is left visible on all surfaces except for in the ceilings, where gypsum boards cover installations that run between the modules. The main jointing type for the massive timber is screwed, tongued and grooved joints in plane and screwed and glued joints between walls and between walls and floors. All joint zones are covered. The edges of the massive timber elements are sharply cut leaving the interfaces as narrow slots, varying in width with the air humidity. In a small number of the apartments different types of diffusion open paint of different colours have been applied for testing. To benefit from moisture

Fig. 5.10 Bay windows and vertical and horizontal joints in the façade.

buffering and interaction between the timber-structure and the indoor air, the paint type must be moisture diffusive. Tests on untreated timber have shown gained benefits from the moisture diffusivity and specific heat capacity of the timber.[291]

Indoors, the tactility is characterised by planed wooden surfaces with different treatments, leaving the structure with visible knots and annual ring-pattern. In the exterior, timber is used as enclosing surfaces in the two semi-closed courtyards that are formed between the three blocks. The exterior cladding is plain and provided a pale coloured paint contrasting to a brown glazing paint on the access balconies.

The sprinkling system has been completely built in and the spray nozzles, covered by plastic lids, are revealed when activated.

5.2.6 Prefabrication and Erection

The buildings have been erected with a combination of volume and surface elements. One single type of complete volume-modules has been prefabricated complemented on site with plane surface-elements. The structure consists of uniform, room-sized volume elements in rows with plane elements mounted between them. The volume-modules were provided surface finish, installed wet areas, insulation and façade cladding in the factory (*Fig. 5.11*). The upper surfaces of the floors were planed and lacquered in the factory.

For transport and incorporation the modules were lifted with straps fastened in holes drilled at four points on the upper part of the modules. This method left holes on the placed volumes, but they were possible to fill with dowels and built in after erection. The volumes were protected during transport by reusable covers. The roof of each building was constructed in two sections on site, which were used to cover the structure during the erection. One roof section covered half of the block during the incorporation of the modules in the other part of the block (*Fig. 5.11*). The stiff box-modules were jointed together storey-by-storey. When the last module had been put in place the roof was fixed and provided.

[291] Hameury, S. 2004, p. 65

Fig. 5.11 Delivery of a volume module to the site. The prepared roof elements lie in the background.

Delivery of wet areas to the site would have made the work in factory more swift, since less moments would have been carried out there. However, the cost would have been the same and it was chosen to do the work in the factory. The finishing of wet areas in factory saved one lift for each module on site. There have been ideas about increasing the efficiency of the transport by producing volume-elements for delivery with complementary material stowed inside, to utilise the transported volume.

Fig. 5.12 An installation shaft during construction and electric rods at a wall socket.

The installations in the volumes were finished in the factory and the only thing left to install in the volumes on site were electric rods in the ceiling and spray nozzles for the sprinkling system. The vertical installations have been concentrated to shafts on the walls towards the common area. Ventilation, sewage and water pipes are connected to the vertical shafts and the electric rods run in the ceiling and inside the massive timber walls (*Fig. 5.12*).

The number of storeys has been regarded reasonable. The structural system is suitable for three to four storeys, considering the load-bearing capacity and resistance to lifting forces.

5.2.7 Vetenskapsstaden II in Short

The principle for production is complete prefabrication of volume-modules. The layout is subordinated to the production rationality. There is one single type of volume-modules, with complements of surface-elements. The timber structure is visible in the interior design; in the exterior the structural principle is visible and the cladding is timber-based. The timber-structure has been utilised for the development of a rational structural system, possible to adapt to any environment. There is no architectural utilisation of material-specific form-features.

5.2.8 Players

Client: Familjebostäder

Planning: Architect: Rolf Bergsten
Structural design: Tore Möller

Production: Norrfog Enroco, Martinsons Trä AB and Pluss Hus AB

Erection: Pluss Hus AB

5.3 Case #3: Sundsvall I (SVA1)

5.3.1 Background

The case comprises three apartment blocks for the public market in the inner harbour of Sundsvall, Sweden (*Fig. 5.13*). The project aimed at promoting timber on the multi-storey building market and to develop methods and production for massive timber construction. The original project comprised five buildings, but it was divided into two phases with building permits received in two parts. The first phase, here described as SVA1, includes three apartment blocks (apartment blocks 1-3) and the second phase, here described as case #4: SVA2, includes two apartment blocks (apartment blocks 4-5). During the time between the receiving of the building permits the production prerequisites were changed. The massive timber-based wall-structure in apartment blocks 1-3 had shown to be uneconomic and it was exchanged for a light timber frame for apartment blocks 4-5. The entire project has been thoroughly studied and documented from the start by Ylva Sardén, Luleå University of Technology.[292]

[292] Fredriksson, Y. 2003

Fig. 5.13 Sundsvall I, apartement block 1 and 2, in the inner harbour in Sundsvall.

An information and development project has been initiated to study, document and evaluate the work, results and experiences during production and construction. This project has been run as a joint venture by NCC Construction Sverige AB and Luleå University of Technology. Among the aims are treatment and handling of the massive timber elements, working methods, degree of prefabrication and communication/ interaction between suppliers and contractor. The author has been engaged in this project since the start of 2005, to provide architectural and functional aspects to the study and to enable a structural-architectural co-action.

One of the tasks in the development project has been to study the structural design of the building project. There have been problems with the stability of the structure under lateral loads, why it has been of interest to propose other structural solutions for a better performance. Evaluations of the project during construction were used as a basis for a modified layout for the buildings. The layout was developed from the projected layouts of SVA1 and SVA2 to the final proposal that will be presented in a concluding report[293] (*see Appendix II*).

5.3.2 Structure

The apartment blocks have been constructed with surface-elements. The buildings consist of five-storied blocks with an additional integrated sixth floor turning the apartments on the fifth storeys into duplex apartments under steep saddle roofs. There are four apartments on each storey (*Fig. 5.14*). The entire building is sprinkled, which has allowed for a wooden façade in six storeys.

[293] *To be presented in December 2005.*

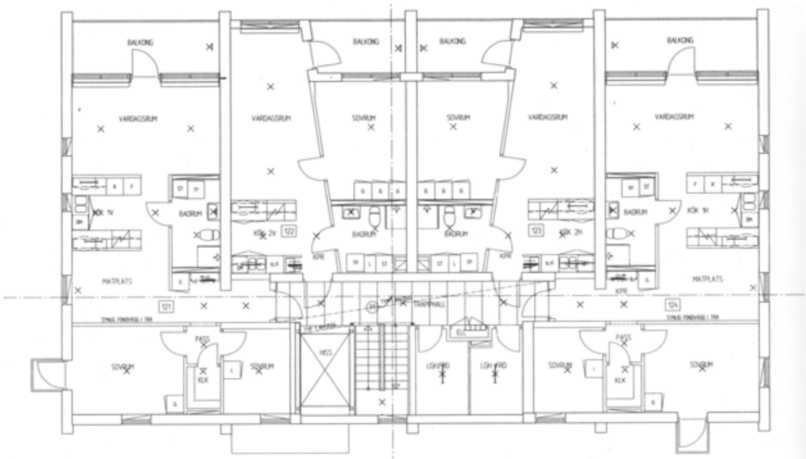

Fig. 5.14 Layout for Sundsvall I, apartment block 1-3, floor 1-4 in case #3.

5.3.3 Wall Elements

The wall structure is composed of five-layered massive timber plates that are clad with gypsum boards on both sides. An exception has been made for one wall[294] in two of the apartments on each storey. There the timber has been left visible on one side.

The exterior walls consists of 95 mm cross-laminated timber boards with 15 mm gypsum board on the inner side. On the outer side the timber is covered with 170 mm mineral wool, 34 mm air gap and 28 mm glued joint. The total thickness of the exterior wall is about 340 mm (*Fig. 5.15*). The exterior walls to the north are constructed as light timber frame.

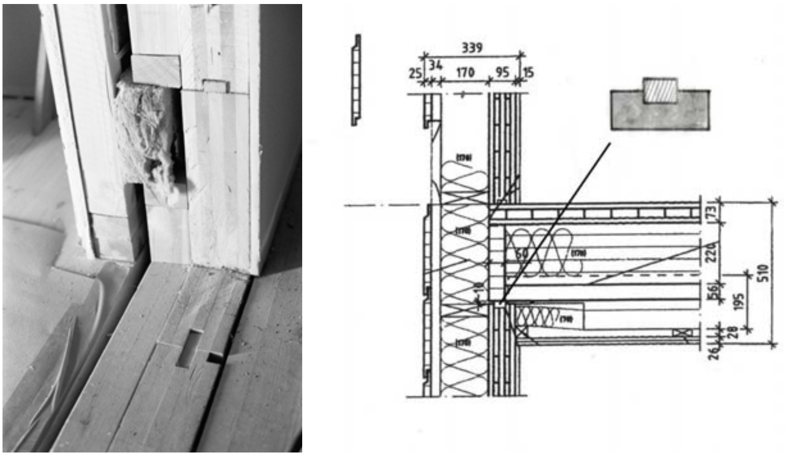

Fig. 5.15 Wall section of an apartment dividing partition wall between an apartment and the staircase during construction and vertical section at wall-floor joint-zone. A separate board is placed on site to cover the horizontal element joints.

[294] *It had to be a wall inside an apartment. The fire-regulations did not allow visible timber in an apartment dividing partition wall.*

Apartment dividing partition walls are built up as a double structure: 15 mm gypsum board, 95 mm massive timber, 70 mm mineral wool, 10 mm air gap, 70 mm mineral wool, 95 mm massive timber and 15 mm gypsum board. The total thickness of the load-bearing apartment dividing partition walls is 370 mm.

The load-bearing wall structure take down the loads on the floor of each storey and a load-distributing binder integrated in the floor structure. Horizontal glulam beams frame the floor decks close the box-section (*as can be seen in Fig. 5.15 and Fig. 5.22*). The walls that are not load-bearing are produced in light construction.

5.3.4 Floors

The floors consist of semi-closed box-elements built up with an upper cross-laminated timber plate flange and of glulam beams as webs jointed with HF-cured glue on the lower side. A suspended ceiling constitutes the lower surface and provides vertical sound-insulation. The upper part consists of 73 mm thick three-layered cross-laminated timber plates and glulam beams 220 × 42 mm with additional glulam beams as lower flange. The lower part consists of 195 mm sawn joists partly overlapping the webs of the upper floor elements. The joists carry 70 mm insulation on spaced boarding and 13 + 13 mm gypsum boards. The total depth of the floor section is 510 mm.

The space between upper and lower floor part is utilised for horizontal sewage pipes, water pipes and ventilation. The spans (up to 5700 mm) are decided by the wish for visible upper timber surface: For accurate sound-insulating performance the floor plates have been cut over each apartment dividing partition wall. To reduce flank transmission flexible battens of sylomer are placed between the floor elements and the supporting wall elements. The sylomer batten is fixed in a cut groove in a wooden lintel (*Fig. 5.15*).

The integrated balcony-structure (*Fig. 5.13 and 5.16*) consists of the extended load-carrying walls carrying cross-laminated floor plates of 150 mm thickness. (The plate-thickness in small balconies, which also can be seen in *Fig. 5.13*, is 110 mm.) The same thickness is used for the floors in the staircases.

Fig. 5.16 Façade with integrated balconies between extended load-carrying walls (left) and detail of joint zone between wall and floor structure at a balcony (right).

5.3.5 Detailing

The cross-laminated timber is covered, apart from the upper floor surfaces shown in the integrated balconies and in one wall in two apartments on each storey and as separately added plates in small balconies and as cantilevering roofs over entries (*Fig. 5.17*). The panel boards of glued joint in the façade are 250 mm wide to suit the big scale of the building. They are not applied in full lengths but cut about every 2000 mm where the joints have been covered with narrow battens**.** The panels have been entirely treated with distemper paint except for a small area at each window (*Fig. 5.17, left*) and at the protruding parts of the load-bearing wall structure at the corners and along the façades (with the regularity of the inner structure).

Fig. 5.17 Exterior details and drawing of a cantilevering roof-structure.

Fig. 5.18 Grooves cut for electric installations in the timber wall (left) and nail-plate reinforcement of the core-wall (right).

The interior wall cladding is gypsum and it covers the structural joints. The structural jointing comprises a great variety of steel fittings (*Fig. 5.18, right*) and a lot of physically tiring work has been carried out placing and fixing them. Vertical electric cables run in cut grooves in the timber surfaces (*Fig. 5.18, left*), behind the gypsum boards, from the main installation zone in the suspended ceiling. Vertical pipes run in shafts integrated in light structure walls.

The acoustic environment is characterised by massive timber. The experienced frequency of vibrations in the floor-structure is higher than in a conventional light timber-framed structure. The tactile benefits are, however, few. The timber in the floors is experienced by vision and hearing but the massiveness is not obviously expressed. The texture and structure in the exterior is given by the wooden panel with distemper paint and the panelled protruding edges of the plate-structure.

5.3.6 Prefabrication and Erection

The original elements were produced 1200 mm in width and with storey height (3010 mm). These elements were delivered from the producer to a factory, where they were assembled into walls of six to seven elements for lengths up to 6000 mm with tongued and grooved, screwed and glued joints. Exterior wall elements were provided insulation and exterior cladding in the factory.

The cross-laminated floor elements were produced 1200 mm in width and up to 5700 mm length. The plates were combined with glulam beams into a T-section by gluing. These elements were assembled with glued tongued and grooved joints into elements 2400 mm in width, combined with webs and suspended ceilings where installations were placed. Compact packages were delivered to the site where they were jointed into a continuous floor structure in place. The elements were pushed together and pipes, perpendicular to span, were connected.

During erection, the building has been protected with a deployable tent structure on fixed cranes, which has meant good and dry working conditions on site (*Fig. 5.19*).

Fig. 5.19 The covering tent structure during construction work on case #4.

During the project, the massive timber structure showed to cause several unexpected problems. The layout did not suit the structural requirements for stability and a rigid behaviour. This lead to increased need for more extensive jointing and steel fittings, especially on the core walls (*Fig. 5.18, right*). It also caused more extensive foundation work than expected. The company erecting the structures on site found the production speed being too low and demanded faster deliveries of the massive timber elements. The supplier regarded it impossible to deliver at the requested speed and proposed a change of the wall-structure to the second part of the project (SVA2).

The object is unique in its scale and a new challenge for most of the players. Much development work had to be carried out during the production and areas of responsibility[295], techniques and methods have had to be adapted, which has slowed down the production,. The building system was not complete and finished at the project start and the time for planning has been estimated to twice the normal time. The erection of apartment block 1 was the most laborious phase, since much development had to be performed during the construction. The production of apartment block 2 and 3 went much faster.

The problems with the stability were partly caused by the wish for six storeys, which brought much increased loads (wind, torsion and uplift). With three to four storeys the problems would have been less and easier to deal with.

5.3.7 Sundsvall I in Short

The principle for production is semi-prefabrication of surface-elements. The layout is not subordinated to the production rationality. There are different types of surface-elements. In the exterior the character of the timber structure is visible in the balconies and in small additional balconies and roofs. The structure is clad with a wooden panel. In the interior the timber structure is used as visible floors whereas the walls have been covered, except for a partition wall in two of the apartments. The timber-structure has been utilised for the development of a rational structural system, but few advantages have been made, except from the floor structure which is regarded competitive. There is little architectural utilisation of material-specific form-features.

5.3.8 Players

Client:	Mitthem AB
Planning:	Architect: White Arkitekter AB
	Structural design of the foundation: WSP Byggprojektering
	Structural design of the timber structure: Martinsons Trä AB
Production:	Martinsons Trä AB and Pluss Hus AB
Erection:	NCC Construction Sverige AB

5.4 Case #4: Sundsvall II (SVA2)

5.4.1 Background

The case comprises two apartment blocks for the public market in the inner harbour in Sundsvall, Sweden (*Fig. 5.20*). It is a continuation of SVA1, with changed prerequisites concerning layout and production.

The layout for SVA2 contains three apartments per storey, to compare with SVA1. To increase stability, the layout in SVA1 had to be modified and for reasons of production the wall-structure had to be changed.

[295] *Especially between producer and builder.*

Fig. 5.20 Sundsvall II, apartment block 4 during construction.

5.4.2 Structure

The buildings consist of five-storied blocks with an additional integrated sixth floor turning the apartments on the fifth storey into duplex apartments. The character at large is the same as in SVA1. The differences from SVA1 are that the load-bearing wall structure has been changed into a light timber-frame, prefabricated as surface-elements and that there are three apartments on each storey. The structural plan has also been changed into a layout with a load-bearing northern exterior wall (*Fig. 5.21*). As in SVA1, the entire building is sprinkled, which has allowed for a wooden façade in six storeys.

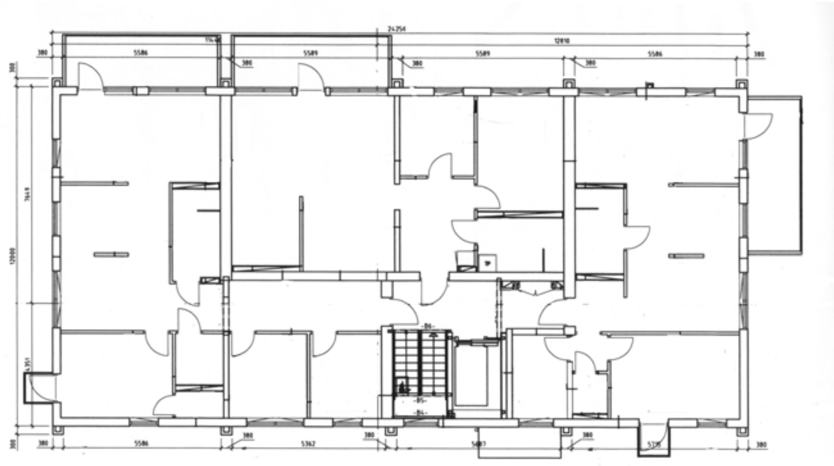

Fig. 5.21 Layout for Sundsvall II, apartment block 4-5, 2nd to 5th floor.

5.4.3 Wall Elements

The walls are produced in light timber frame construction (*Fig. 5.22*), except for three partition walls (*marked grey in Fig. A2 in Appendix II*), where massive timber elements have been used. These massive timber elements were produced with a thickness of 150 mm and were clad with 15 mm gypsum on both sides. The insulation thickness was increased from 170 mm mineral wool in the massive timber structure of SVA1 to 170 + 45 mm mineral wool in the light timber frame of SVA2. The exterior cladding is the same in SVA2 as in SVA1, but the surface treatment has been changed to a covering paint.

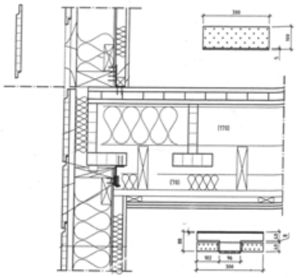

Fig. 5.22 Placing of wall elements (left) and a cross-section of the wall structure (right) A separate board is placed on site to cover the horizontal element joints.

5.4.4 Floors

The floors are of the same construction as in SVA1 (*Fig. 5.22-23*) with the same type of flank transmission damper.

Fig. 5.23 Placing of a floor element.

5.4.5 Detailing

The visible detailing is the same as in SVA1, except for on the northern façade, where the light infill walls with integrated balconies have been replaced by a continuous load-bearing timber wall in light timber-frame construction. The light timber frame wall elements were assembled into walls of three to four elements in length in factory and delivered to the site in the same way as the massive timber elements.

In the interior, the massive timber floors are visible, but the three wall elements in massive timber construction are covered.

The sprinkling system is built into the ceiling with visible spray nozzles.

5.4.6 Prefabrication and Erection

The co-ordination, techniques and methods continued according to the same principles as in SVA1. The project has been followed, studied and documented by Ylva Sardén.[296]

5.4.7 Sundsvall II in Short

The principle for production is semi-prefabrication of surface-elements. The layout is subordinated to the requirements of structural stability. There are different types of surface-elements. In the exterior the load-bearing timber structure is not visible; the structure is clad with a wooden panel. In the interior the timber structure is used as visible floors whereas the walls have been covered. The massive timber floor-structure utilised in SVA1 is regarded competitive but are combined with light timber-frame walls in SVA2 to reach an acceptable production economy, since the massive timber wall-elements could not be produced rationally enough. There is a limited use of massive timber and no architectural utilisation of material-specific form-features.

5.4.8 Players

Client:	Mitthem AB
Planning:	Architect: White Arkitekter AB
	Structural design of the foundation: WSP Byggprojektering
	Structural design of the timber structure: Martinsons Trä AB
Production:	Martinsons Trä AB and Lövångerstugan
Erection:	NCC Construction Sverige AB

5.5 Case #5: Impulszentrum (IMZ)

5.5.1 Background

The case comprises a block providing office areas for small, newly started companies in Graz, Austria (*Fig. 5.24*). The initiator of the project, the Styrian Business Promotion Agency, supports co-operation between academic research and companies, as well as the establishment of new small companies. Impulszentrum is a block of office and laboratory premises for newly started and expanding companies erected with aiming to set high standards regarding economy, ecology, energy, functionality and flexibility.

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[296] *The work is to be published as a doctoral thesis entitled* Complexity and Learning in Timber Frame Housing – The case of a solid wood pilot project. *It will be presented at Luleå University of Technology in December 2005.*

Fig. 5.24 The courtyard at Impulszentrum, Graz.

5.5.2 Structure

The project is constructed with volume-elements in massive timber added to a surrounding structure in concrete. The timber units contain office spaces of ca 80 m^2, which are possible to both sub-divide and extend. The concrete structure surrounds an inner yard where the timber volumes have been placed in three-storied office units.

The hybrid structure suits safety-prescriptions through the location of escape routes to the concrete parts. It also suits production since installations can be located to the concrete parts and enables the timber volumes to be free from sewage and water pipes. The concrete structure contains laboratory and workshop spaces, most of the communication, wet areas and installations (*Fig. 5.25*). A garage is located a storey below ground.

Fig. 5.25 Section and layout of the entire block.

5.5.3 Wall Elements

The walls consist of five-layered cross-laminated timber elements of 162 mm thickness. They are insulated with 100 mm mineral wool, wind barrier, 30 mm vertical battens/air gap and 19 mm exterior cladding of larch wood (*Fig. 5.26*). On the inner side they are clad with 15 mm gypsum boards. The total thickness of the exterior wall structure is about 240 mm.

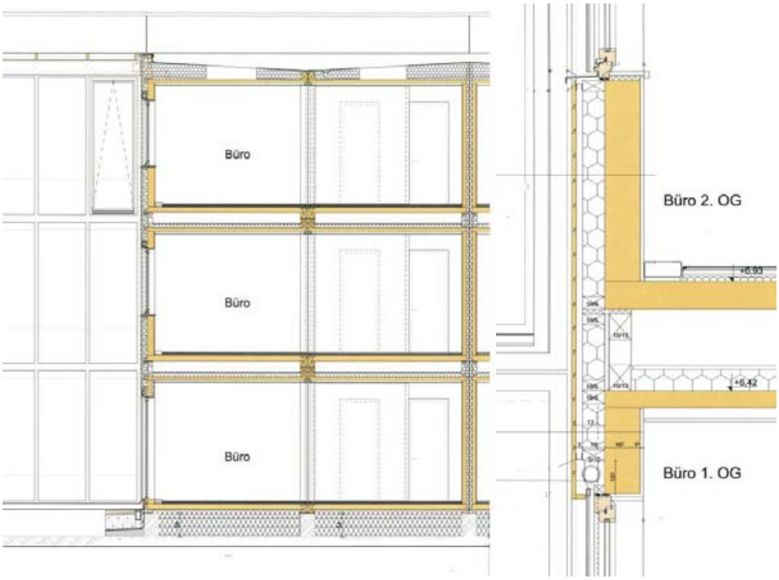

Fig. 5.26 Vertical section of office block and a detail section of the structure.

Apartment dividing partition walls are built as a double structure: 78 mm cross-laminated timber, 60 mm mineral wool, 3-10 mm air gap, 60 mm mineral wool and 78 mm cross-laminated timber (*Fig. 5.26*). The total thickness of the apartment dividing partition wall structure is about 280 mm.

5.5.4 Floors

The floor structure is constructed as a double structure with the floor of the upper volume and the ceiling of lower one. The floor consists of 128 mm cross-laminated timber plates, 25 mm mineral wool (footstep insulation), 10 mm gypsum boards, 20 mm gypsum with floor heating, 10 mm gypsum boards and 5 mm linoleum. An installation zone runs on the floor along the wall (*Fig. 5.27*).

The lower part consists of 78 mm cross-laminated timber covered on the upper side with 100 mm mineral wool and 15 mm gypsum boards. On the lower side there is an air gap of 50 mm and 15 mm gypsum board as ceiling surface. Battens of sylomer have been placed between the volumes to reduce flank transmission.

Fig. 5.27 Installation of floor heating and the finished floor with installation frieze.

5.5.5 Detailing

On the exterior, planed, high finish panelling is used. Joints between the modules in the wall surface are revealed as marked lines; the vertical joints are covered in level with the surface with vertical boards, whereas the horizontal joints are covered with protruding elements meant as fire-stoppers (*Fig. 5.28*). On the upper side these are clad with steel sheets. The exterior environment is characterised by a high finish of the wooden panels, with planed surfaces and precision. In the courtyard the timber is used as enclosing surfaces providing a fine structure and texture.

In the interior the timber is clad with gypsum boards (on the walls) and cement based topping (on the floors). The reminiscence of the timber structure is the coupled timber columns along the central axis in the office rooms (*Fig. 5.29*).

Fig. 5.28 Vertical and horizontal joints in the façades.

Fig. 5.29 The interior view of a finished office volume.

5.5.6 Prefabrication and Erection

The project was constructed with prefabricated volume-elements transported to the site on trailers. The volume-modules were provided insulation and exterior cladding in the factory (*Fig. 5.30*). On site they were mounted in pairs and provided with floor-heating, electric installations and additional inner cladding.

Fig. 5.30 Incorporation of a prefabricated volume.

5.5.7 Impulszentrum in Short

The principle for production is semi-prefabrication of simple volume-modules. The layout is subordinated to the production, but coupling modules in pairs provide spaces wider than the individual modules. There is one single type of volume-modules. In the exterior the structural principle is visible but the massive timber is covered both in the exterior (wooden panel) and in the interior (gypsum). The shear-plate capacity of massive timber has been utilised architecturally to obtain spanning structures.

5.5.8 Players

Client:	The Styrian Business Promotion Agency
Planning:	Architect: Architekturbüro Dipl.-Ing. Hubert Riess, Graz
	Structural engineer: JR Consult, Graz
Production:	KLH Massivholz GmbH, Katsch an der Mur
Erection:	Kulmer Holzleimbau GmbH, Pischelsdorf

5.6 Case #6: Spöttlgasse (SPG)

5.6.1 Background

The case comprises an apartment block for social housing in Vienna, Austria (*Fig. 5.31*). It is constructed as a combination of timber elements and parts in concrete. The regulations concerning timber building vary from region to region in Austria. At the start of SPG the regulations in Vienna allowed up to four storied buildings in timber if the first floor was built and escape routes were located to building-parts in concrete. This settled the structural solution for the project at Spöttlgasse. The client preferred a massive timber structure to a conventional one.

Fig. 5.31 One of the outer façades of Spöttlgasse, during construction.

5.6.2 Structure

The project is comprises 154 apartments and is constructed with surface-elements in massive timber placed on an underground garage and a ground floor in concrete and with a concrete structure for communication, access, wet areas and most installations serving as a spine (*Fig. 5.32*). The fire-regulations state oak as the only wooden material allowed on façades. Oak is fairly expensive and the façades in SPG are plastered. The timber-surfaces in the loggia-structures, covering one long wall of each block, are clad with timber-based products.

The structure is held down with threaded steel rods fixed with nuts between each storey. Three storeys are regarded as the maximum number of storeys possible to hold down this way.

Fig. 5.32 Timber structures with communication zones in concrete.

5.6.3 Wall Elements

The walls consist of cross-laminated timber plates. The dimensions of the massive timber wall elements differ between different positions in the structure, from three-layered plates with 95 mm thickness in the walls towards balconies and gables, to 128 mm (five-layered) in interior walls between apartments, to 170 mm (five-layered) in the load-carrying structure for the loggias. The loggia-structure is designed to secure load-bearing in case of fire. The walls in the loggia structure are covered with three-layered board cladding.

The plates in the exterior walls are stopped on the outside, insulated with 120 mm mineral wool and 20 mm plastered façade on a fibre glass net fixed with screwed fittings. On the inner side the structure is covered with a vapour barrier, 10 mm air gap, 50 mm light studs of steel with mineral wool in between and 15 + 15 mm gypsum boards (*Fig. 5.33*). The entire wall section measures about 320 mm. Wall that are not load-carrying are constructed with light studs in steel clad with gypsum boards.

Walls between apartments are constructed with cross-laminated timber plates of 128 mm thickness with five layers. The wall elements have asymmetrical cross-section. The plate elements were provided 22 mm insulation, 13 mm gypsum, 35 mm insulation and 15 mm gypsum board (in all 85 mm) on one side and 47 mm insulation, 13 mm gypsum boards, 35 mm insulation and 15 mm gypsum boards (in all 110 mm) on the other side. The apartment dividing partition wall elements were delivered to the site in this state. On site additional layers are mounted on both sides: Three gypsum boards with shifted joints and mineral wool.

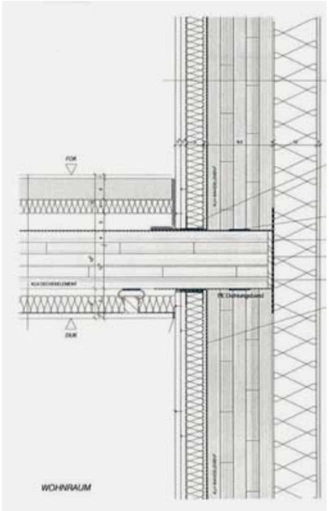

Fig. 5.33 Vertical detail section of the exterior wall and a partition floor.

5.6.4 Floors

The floor structure consists of load-carrying cross-laminated timber plates with 162 mm thickness and five layers. The construction is described upwards and downwards from the timber plate. On the upper side they are covered with membrane, 50 mm mineral wool (footstep insulation), 42 mm mineral wool, 60 mm cement-based topping (Estrichbeton) and 5 mm linoleum. On the lower side there are steel-profiles carrying 50 mm insulating felt on 15 mm gypsum boards. The total thickness of the floor is about 410 mm.

The topping on the upper side of the floor decks enables the floor decks to be continuous over apartment dividing partition walls and span more than one apartment.

The loggia floors consist of 120 mm thick plates with three-layers, on the upper side covered with Kerto-plates and on the lower side covered with three-layered board cladding.

5.6.5 Detailing

The exterior shows two main surface-types: plaster and timber-based board cladding. In the interior, all timber-surfaces are clad with gypsum. The load-bearing structure is not revealed. The structural detailing is built in, e.g. steel fittings to secure shear stiffness between wall elements. The approach in the façades is plain surfaces and the large-scaled rhythm of elements in the loggia-structure. It shows the module-size but has its own load-carrying purpose and expresses itself as a separately added structure (*Fig. 5.34*).

In the interior the visual expression is material neutral. With the concrete in the access balconies the material of the load-bearing structure is difficult to associate with timber. The loggia-structure differs from the overall experience and provides timber surfaces and timber-based detailing.

Fig. 5.34 Shear-stabilising steel joint between wall elements, before exterior cladding (left) and wooden windows and load-bearing structure for the balconies (right).

5.6.6 Prefabrication and Erection

The timber units were assembled on site and mounted on the ground floor in concrete. A section comprising two apartments was erected in three to four storeys and then installations were placed. The vertical installations have been concentrated to shafts constructed as steel cages placed in connection to the wet areas storey-by-storey (*Fig. 5.35*). Radiator pipes have been placed on the upper side of the timber floor, under the topping.

The partition wall plates have been delivered with double gypsum boards and insulation from the producer. Additional cladding, insulation and façade have been mounted on site. The floor elements have been delivered in lengths up to 16 m.

Fig. 5.35 Erection of wall elements and placing of installation cages.

5.6.7 Spöttlgasse in Short

The principle for production is to use surface-elements of low prefabrication degree. The layout is subordinated to the requirements of structural stability. There are different types of surface-elements. In the exterior the timber structure is not visible. The structure is covered with a plaster façade. In the interior the timber structure has been covered on all surfaces. The massive timber has been utilised architecturally in a loggia-structure covering the long walls on one side of each building, whereas access balconies on the opposite side of each block are constructed in concrete. The massive timber in the loggias is clad, but express the scale and measurements of the structural material.

5.6.8 Players

Client: Sozialbau AG, Wien
Planning: Architect: Architekturbüro Dipl.-Ing. Hubert Riess, Graz
Structural engineer: JR Consult, Graz
Erection: Kulmer Holzleimbau GmbH, Pischelsdorf and Gerstl Bau GmbH, Wien

5.7 Analysis

5.7.1 Analysis on 3D Modules

Vetenskapsstaden I and II

In the VET projects, complete prefabrication has been the goal and the theoretical framework. The major difference between VET1 and VET2 is the location of the wet areas. In VET1 they are located centrally in the apartments, whereas they are located outside the apartments in VET2. This location is possible since the apartments are so small. In VET1 a lot of work was still carried out on site, above all in the apartments on the third storey and in the staircases. The location of the shafts may decide the finishing degree.

The structural system has been developed from VET1 to VET2. The wall structure was changed for structural reasons from a three-layered to a five-layered cross-laminated plate. The performance of the wall structure under fire load and the risk of progressive collapse still needs further studies. The floors in VET2 have been constructed with the same principle as in VET1 but the laminated timber plate in the upper part of the section, has been replaced by a five-layered cross-laminated plate.

The VET cases have been clearly aimed at rational production of an efficient and competitive structure. In VET2 rationalising measures have been taken to improve the production and performance of the system developed and tested in VET1. The volume-modules for VET2 have been produced with a simpler geometry and the structural integration of installations has been adapted to improve rationality of construction, erection and installation work in practice, to ease and rationalise the work on site.

In VET1 the roof structure was integrated in the volume-elements of the last storey. This meant that temporary shelters had to be used during the construction of the lower storeys. In VET2 the roof was constructed as two separate elements used to protect the structure during the erection and finally integrated as the permanent roof after integration of the last volume.

The lifting method was developed from VET1 to VET2. The solution in VET2 had not been possible to apply on a light timber structure without further measures taken, such as steel rods in the corners. The massive timber structure provides enough stiffness for this without additions. The stiffness also enabled the development of nodal flank transmission dampers.

The exterior design of VET1 does not reveal the modularisation of or the timber in the structure. It is experienced as a concrete or a masonry building, to suit the demands stated in the city plan. It solves the frequently faced problem with strict modularisation of the façade on a prefabricated structure. VET1 makes use of the massive timber as a structural system possible to clad with anything.

The exterior design of VET2 reveals both the modularisation and timber in the structure. It is provided a wooden façade that lets the prefabricated box-like appearance remain. The middle gable part of each block constructed with surface-elements is marked with wooden cladding of a darker colour. VET2 makes use of the massive timber as a competitive structural system for a functional, pragmatic result.

The massive timber has not been utilised in the architectural form, which could have been obtained with other structures/materials in both VET1 and VET2. No difference in treatments has been made between visible massive timber and massive timber in a clad state.

The massive timber has been utilised for rational production and construction and for visual and sensory effects on the indoor environment and climate. The technique has primarily been refined to suit economic productional means. In VET1 a wider freedom concerning layout was allowed, at the experienced expense of rationality. Within a strict technical framework, layout and material finish has been worked into a continuity of spaces and surfaces, comparable to the pragmatic exterior.

Vetenskapsstaden and Impulszentrum

VET and IMZ are based on 3D-modules. All three projects are adapted to rational production and swift construction using massive timber plates. The structural utilisation of the plates is very similar, but the environmental utilisation differs.

The uses of the final buildings differ, since VET1 and VET2 are residential blocks and IMZ provides office spaces. This has caused rather small differences in the utilisation of the building system though, since VET1 provides installations of high standard to the guest researchers that were the intended end users, enabling them to work at home. IMZ provides office spaces of high installation standard to new, small companies. The main difference is the wet areas that are integrated in the modules of VET whereas they have been placed outside the volumes in IMZ.

Between VET1 and VET2 the element sizes have been optimised to suit rational construction of a regular structure and a plain layout that both technically and architecturally reveals the rationalized construction. The massive timber has been utilised to serve as stable, robust frames protecting volumes with relatively high interior finish of complements, installations and surfaces.

The thickness of the surface layer is enough to provide buffering of heat and moisture but it has been regarded weak concerning fire safety. The hollow section of the elements used in VET1 and VET2 have been questioned concerning performance in case of fire, since the surface layer may burn off and then reveal a hollow part. The shown insulating gains also depend on air tightness of the surface layers, which thus is a reason for prescribing edge gluing for this element type.

The sprinkling system is a central factor in VET, since the main approach is to leave the timber structure visible. The effects of this can be questioned for aesthetic reasons, since the pattern of the timber to a large extent is prevailing on the surfaces.

It gives the possibility, though, to benefit from the building physical properties of the timber and it is also shown in VET that different types of paint can be an option to change the visual expression with retained building physical properties.

The exterior of IMZ is elaborated to a high finish that visually stresses the difference in material between the serving concrete frame and the served timber additions. In IMZ there is no interior use of visible massive timber, which suits the fire-safety regulations. The covering of the timber in IMZ results in a material neutral indoor environment. The cladding means that the surface-quality of the timber-plates is of no importance.

In IMZ the flexibility in the finished result with larger rooms has lead to less complete volumes with low interior finish at the delivery and open volumes. The coupling of the modules benefits from semi-prefabrication since it is easy to cover the joint zones on site after jointing. The approach to installations is apart form the floor heating similar to the approach in VET2, with shafts removed from the timber volumes.

The plates in use in VET are manufactured in widths of 1200 and 900 mm and then joined into bigger elements. The massive timber has been utilised with structural, building physical and tactile benefits, but the structural form bears no characteristic features of massive timber. The elements used in IMZ are big-sized to manage to constitute entire walls. The principle with large plates brings higher and more easily achieved stiffness in the structure and enables more plate-specific form features. IMZ shows no tactile benefits from the massive timber, but the structural form provides the architecture with plate-specific features.

In IMZ the massive timber elements have been used structurally in two ways. In the separate office units the timber elements serve as stable framed volumes. The modules are not closed but the plate structure is combined with columns to enable coupling of the modules in pairs for wider continuous floor areas. In the surrounding structure along the enclosing concrete structure, massive timber plates have been utilised as beams. In this way, the modules span over the entries to the courtyard (*Fig. 5.24*). The wall elements in the modules act as deep beams carrying the weight of two module storeys, which shows architectural utilisation of the massive timber properties in the structural form.

5.7.2 Analysis on 2D Modules

Sundsvall I and II

The development between SVA1 and SVA2 mainly concerns the load-bearing wall structure. For productional and economic reasons it was changed from a massive timber structure to a light timber frame. The massive floor structure was, however, kept. One problem that occurred with the massive timber structure in situ was sensitivity to lateral loads and torsion. The main cause was found in the fact that the layout of SVA1 does not follow the structural criteria for stability.

For the floor-structure in SVA1, a rather thin timber-plate has been combined with glulam beams into a T-section to reach a wide span. The floor structure has shown to be efficient and is utilised also for SVA2. The small thickness of the plate could be questioned concerning acoustics, since a hollow, thin-walled section can be sensitive to resonance. The total thickness of the floor structure is rather big, which may affect the competitiveness compared to concrete structures.

The construction was planned as a concrete project, not designed for timber. The location and orientation of the walls decide the forces in stabilising walls and thereby also the demands on the foundation and eventual piling.

Leaving one exterior wall without load-carrying structure has lead to severe sensitivity to wind loads caused by torsional weakness. Lack of load-bearing elements along the northern façade increased the static demands on the core wall. Big nailing plates had to be applied to stiffen the core wall to resist the turning moment. The in-plane joints were glued with tongued and grooved joints, partly on site. Steel fittings connect floors and walls. The overall jointing was very laborious.

In SVA2 the layout has been changed for better performance. The relatively small plate elements made precision during integration on site difficult despite the use of a guide rail along the bottom. In SVA2 the elements used for the assembly of the walls were reduced in number.

The timber character is obvious in the exterior design, where the wooden façade has been used for advertising purposes, whereas the interior is mostly material anonymous. The timber in the floors are utilised as visible surface.

Architecturally, few benefits have been made from the massive timber structure. The buildings are rather uniform and closed, with no cantilevering parts except for balconies and small window openings in the walls with massive structure. The long wall to the north, now missing, had been possible to construct with plate elements, which with fairly large openings would have acted to stabilise the overall structure as stiff frames. The architectural form could have been obtained with another structure/material.

Sundsvall and Spöttlgasse

SVA and SPG are based on 2D-modules. The three projects utilise surface-elements in massive timber but in different ways structurally and environmentally.

The overall principle concerning elements in SVA is to utilise few element thicknesses (one element-type for walls and two types for floors[297]). In load-bearing apartment dividing partition walls this and the wish to show the timber surface lead to a double timber structure with insulation in between. The obtained double structure of the apartment dividing partition walls (also to be seen in VET and IMZ) increases the sound-insulating properties. The massive timber walls have, except for two walls per storey in SVA1, been clad on the interior with gypsum boards. In SVA2 the retained massive timber walls are clad.

In SPG the utilisation of tailored products is more outspoken. The utilised element sections differ in width and layers with their location in the structure (five element-types for walls and four element-types for floors).

In SPG there have been big gains and positive experiences among the workers on site. The workers were not used to work with timber construction. There are presumed good feelings about the timber structure, but those are hard to define and evaluate with accurate precision. In SVA the workers on site had no experience of massive timber, which caused problems during construction.

The possibility to design windows relying on frame action in the plate structure has not been fully utilised in any of the projects. Where window openings appear in the structures they are relatively small. Where larger openings have been placed, the plate has been cut away in its entire height and replaced by light timber infill walls (SVA1) or lintels (SPG).

In SPG the layout is repetitive with a layout approach similar to the one in VET2: to obtain an apartment solution inside a stiff frame suiting structural demands. Because of the cement-based topping the floors have been possible to produce for double spans, to be continuous over supports, which makes rigidity more easily obtained.

[297] *The number of elements of different measurements in length and with additional treatment is however large.*

In SVA the wooden structure is presented with a timber façade whereas SPG is plastered. To obtain the required fire-safety in SVA the appearance of timber on the façades has required sprinkling of the apartments, which enabled the balconies with visible timber surfaces to be left without sprinkling. However, the massive timber is only visible on the floors, since the walls are covered with the exterior board cladding.

In SVA benefits have been gained from the massive timber in the floor structure, which is efficient and economically competitive and also utilises the timber surface to provide to the visual environment sensed environment indoors. The form and spans are, however, conventional and could have been obtained with another structure/material. Only a few architectural details make use of a material-characteristic structural form.

Except for the loggias, the blocks at SPG could have been obtained with another structure/material. In SPG the loggias are the most visually obvious architectural gains made from the massive timber. Even if the structure is clad here as well, the form of the load-bearing structure is salient and made characteristically plain.

The structural utilisation of massive timber is similar in SVA and SPG. The main difference is the difference in sizes of utilised elements; whereas SVA have been constructed with small-sized elements joined into bigger ones partly on site, SPG has been constructed with elements manufactured in one piece. In SVA the layout is formed following functional demands from the client, which means that the structure originally was given a form that does not suit a good structural behaviour. In SPG the material-specific features of massive timber has been utilised in the loggias for a characteristic structural form.

5.7.3 Analysis on 2D- and 3D-Modules

In the cases with surface-elements (2D-modules) the structures allow variations in plan. In e.g. SPG several types of plate elements have been used to tailor the structure for local structural demands. The structure is thus optimised concerning structural action on site in the finished building. The structural concept can be referred to as limited optional freedom concerning layout design within rigid frames obtained with element-structures assembled on site.

As long as the object is planned for the structural system it can provide an efficient productional and structural solution. The acoustic performance of the structure demands thorough work, which has lead to two different principle solutions in the cases: double wall- and floor-structures on the one hand and single-plate structures with several additional layers on the other.

The box-principle of volume-elements leads to an efficient solution for sound insulation between apartments, since a gainful double structure is inherent and obtained automatically. The double structure of the apartment dividing partition walls and the floor spans of a single apartment in SVA mean a division between the load-carrying structure of two neighbouring apartments and show the same principle as in volume-module construction.

The other solution can be seen in SPG where the floor-plate is completely built in. This leads to the possibility to let the plates be continuous over the supports, which can speed up the erection and add to the rigidity of the finished structure. The layered structure causes a lot of work with the floor on site, since it demands a complex layered structure for accurate performance.

In the cases with volume-elements (3D-modules) the structures are optimised for rational production and more or less for few variations in layout. In VET1 a small number of different volume-modules were used but it turned out to be disadvantageous for the wished rational production of an economically reasonable result. Volume-elements strictly designed for prefabrication are to be compact. The potential of massive timber that can be utilised in such states is rigidity of assembled volumes and cut-outs for windows. A wider freedom of layouts and more varied element-specific form require surface-elements.

The consequence of this has been drawn in VET2, combining volume-elements with surface-elements. In SVA two combinations are shown: A massive timber floor-structure has been combined with massive timber wall-elements (SVA1) and with a light timber-framed structure (SVA2). In SVA2 wall-elements of massive timber have been utilised to increase the stability of the light timber-frame. Optimisation of a structure may result in a mixed structure with different components and structural properties in different parts.

Volume-elements can be produced as parts of a larger volume/room as in IMZ. In IMZ each room is divided into two modules, leaving one side of each module open with column supports. If the division into parts is taken further, stable modules are more difficult to obtain, e.g. two sides are to be left open. Columns can be utilised and also temporary supports, but the stiffness of the volumes required for transport is harder to achieve and more work has to be carried out on site.

Surface-elements can be utilised for variable degrees of prefabrication and allow more variations in the final result. Rigidity of the overall structure must be constructed on site and depends on well-designed and simple jointing. Production pace and stability in the finished building gain from big plate-sizes, both with surface- and volume-elements. A wall consisting of one single element simplifies the construction, speeds up erection and implies stability without further measures taken. If oriented horizontally a big-sized element can form an entire wall on a storey in platform construction.

6 ADVANCED STRUCTURES

To investigate utilisation of the material properties of timber and performance of timber plate elements, some existing structures in different technologies are used as a point of departure for a discussion. A number of sketched proposals for further developed advanced uses are presented.

6.1 Aspects of Production and Form

6.1.1 From 1D to 3D

Building products in our surroundings can easily be related to geometrical terms. A point in an orthogonal geometric system is through its coordinates a definition of a specific location and has 0 dimensions (0D). In a building system the 0D-member refers to a node, or a nodal joint. A line in the same geometric system can be defined as the distance between two points, i.e. a 1D-member or a beam between two nodal joints. A surface connecting lines at an angle to each other, describes an area, a plane of 2D, which can be illustrated by a plate. Surfaces at angle to each other define a volume, a 3D arrangement and a spatial structure – a room or a volume module, is obtained.

The capacity of handling forces is quite clearly developed from a one-dimensional element like a tension rod to a two-dimensional element like a plate. The rod can only take up tension forces; in compression the rod will be relaxed and offer no activity. The bar can take up compression, which the rod cannot, but also tension like the rod. The plate can take up shear, which neither the rod nor the bar can, but also both tension and compression. These differences in behaviour make different designs, and different ways of minimisation possible.

To minimise is to reduce as much as possible without loosing some specific, desired properties. To minimise a structure by taking away material, and maybe even elements, means that the requirements on the remaining material/elements are increased and it becomes more and more crucial to use materials and/or elements in a way and in a position and orientation that makes them suit their purpose in the best way. The more minimised, the closer the design of a structure must get to the theoretical shape or pattern of the lines and the distribution of forces. Thus, the more minimised, the more the design closes to the ideal form of force-transference for that specific material and that specific technique. So, less material and structure means more obvious expressions of the play and action of forces.

In nature this principle is constantly in use and the phenomenon can be observed in the internal structure of bones[298], for example, where the mass by natural evolution is localised to the zones and in a pattern that gives the best capacity to take up the loads and the load direction that the bone is normally exposed to.

[298] Wester, T. in Gabriel, J.F. (ed.) 1997 pp. 323-324

6.1.2 Vertices and Facets

In the work of Professor Ture Wester at the Royal Danish Academy of Fine Arts, one finds thorough studies of relations between lattice structures and plate structures. Statically there is a dual relation between force transmittance through one-dimensional elements such as bars, and two-dimensional elements such as plates. Within the elements the forces to be transferred react on the current existence and distribution potential of available material, where bars act as links connecting two nodal (0-dimensional) joints, in the shortest possible way, i.e. concentrating the forces to the joints. Plates act as links connecting line-shaped (1-dimensional) joints, edges, in a partly opposite way by spreading the forces along its edges, its joint-zones.

By spreading the forces along its interfaces a pure plate-structure relies upon shear-strength in the material and on friction, which depends on continuous joints. There are possible hybrids though, that utilise the plate as a deep beam for transference of in-plane forces to or between nodal joints/supports. There is however a great difference between nodal joints and shear joints.

In the theorising and modelling of spatial structures as described by Wester, vertices[299] and facets are crucial. The numbers of vertices and facets can vary, but have a minimal number of three in each case. The lowest number of edges of a facet circumscribed by a node and bar system is three; in a three-dimensional space no plate structure can show a vertex with less than three adjacent edges.[300]

Bars, shear lines, nodes and plates are surface-active membrane structures, which makes them free of bending moments. Bending moments are secondary to lattice and plate action, but are however utilised for transference and resolution of external loads into a plate-active or lattice-active surface.[301] This discussion is based on principles of force distribution, relations between and the behaviour of different members.

Fig. 6.1 Model and full-scale model of different types of faceted plate structures.

[299] *The points where three or more plates/edges meet are called* vertices
[300] Wester, T. in Gabriel, J.F. (ed), 1997, p. 308
[301] Wester, T. in Gabriel, J.F. (ed), 1997, p. 315

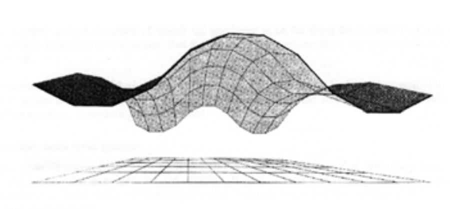

Fig. 6.2 A three-dimensional plate-shell (left) and a folded paper-model (right).

At the Royal Academy of Fine Arts, Copenhagen, other projects are carried out on similar topics, like faceted shell structures of other than polyhedral geometries (*Fig. 6.1*).[302] Different surface-based structures have been proposed[303] (*Fig. 6.2, left*). Origami deals with folding of a single sheet of paper after different geometric patterns, resulting in shapes of animals, plants etc (*Fig. 6.2, right*).

6.2 Tension and Compression

6.2.1 Zero Weight, Infinite Span

The aforementioned architect Lois I. Kahn was active at the University of Pennsylvania, where he worked together with the engineer Robert Le Ricolais from the late 1950's. Kahn could be described as an earthbound phenomenologist, and may be quoted as saying "When you have a room, something happens, the building program opens by itself." Le Ricolais was engineer and rationalist and could be quoted as saying "Zero weight, infinite span – You know it can't be done, but at least it's a limit that we could try to go to."[304] Zero weight and infinite span is the utopic goal of material minimisation (*Fig. 6.3*). By refining a structure all the way to that extent it would be utterly efficient, from a technical point of view. But if technology and materials would be possible to take that far, the structure would probably be so expensive that it would be impossible to afford, at least more than once.

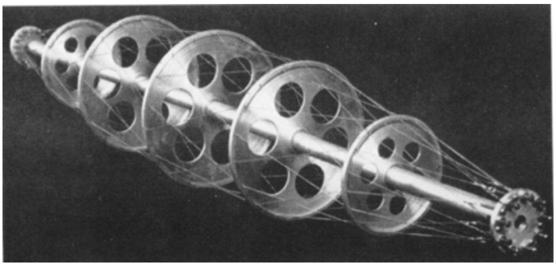

Fig. 6.3 Cable reinforced column design by Le Ricolais.

[302] Almegaard, H. and Vanggaard, O. 2004
[303] Tarnai, T. 2001
[304] Vanggaard, O. 1998, p. 22

Nature often ends up in a balance between structural capacity and resource economy. Le Ricolais studied and commented on natural phenomena like soap films and buckling performances of columns and beams to find orders for construction in the order of destruction. In an article he stated, "The time is not too far distant when to use steel as a compression member will be as unthinkable as to use concrete for tension."[305]

He addressed the replacement of bending in a beam by tension in the lower part and compression in the upper part, explicitly shown in a king and queen post and theoretically he opened up for refining the tasks for different structural members (*Fig. 6.4*).

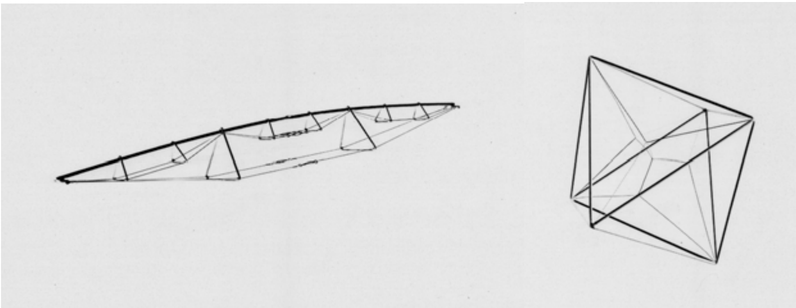

Fig. 6.4 King and queen post and a model of an internally cable stressed bar octahedron.

The first quote of Le Ricolais above is an extreme definition of lightweight structures. In long span structures the dead load of the structure becomes important for its behaviour. Palaeontologists have discussed that some species of dinosaurs reached the limit for the size of living creatures on this earth. The magnitude of Earth's gravity decides how big our bones can become. The bigger a structure or a skeleton becomes, the heavier its structural members/bones have to be to be able to carry its own weight. There is a limit, where the structure cannot grow more without collapse, unless bending in its members can be transferred into tension and/or compression. The challenge lies in the design of a structure as light and statically efficient as possible. "[…] the more stiffness it produces from least weight the better"[306], to cite Jörg Schlaich, engineer and professor emeritus at the Institute for Lightweight Structures and Conceptual Design in Stuttgart.

But lightness is not a pleasing one-way lane without problems to deal with; the lighter the better is not necessarily the case. Light structures easily become unstable and they often deform to a certain degree before they take loads. Tension structures, which may look slender and light enough, also demand heavy anchoring systems or abutments to manage the forces they will be exposed to. This makes the entire system quite heavy and also expensive. Reduction of material also places high demands on the design and structural detailing, which have to provide more efficient and precise performance.

Erik Reitzel, former professor at the Royal Academy of Fine Arts and the Technical University of Denmark, has worked with structural form based on the study of

[305] Vanggaard, O. 1998, p. 24
[306] Schlaich, J. 2004, p.157

failure patterns of materials and elements.[307] His work has resulted in several minimised structures and tension rod and cable-stayed structures. Buckling patterns as generators for the design has also been described by e.g. Yoshimura in the 1950's.[308]

Means and needs may thus go hand in hand. In 1921 Karl Ioganson, Russian constructivist, was the first to patent structures later called tensegric (*Fig. 6.5*). He stated his credo as "From painting to sculpture, from sculpture to construction, from construction to technology and invention – this is my chosen path, and will surely be the ultimate goal of every revolutionary artist."[309]

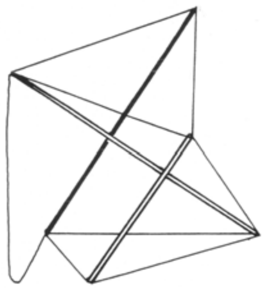

Fig. 6.5 Karl Ioganson's "Study in balance".

High-tech has become an expression, a style, associated with technical delicacy and visual, readable, more or less advanced technical solutions. It can be used as a visual means, but is based on the minimising of structures, increasing the demands on the performance of the remaining members. If mass is taken away, the joints still remain largely irreducible.

6.3 1D-2D-3D

To search for different ways to develop timber elements for advanced architectural and structural use different methods for theoretical development have been used. One way has been to look at existing structures based on other materials and to transfer their structural principles to timber-based plates. Another has been to take existing timber-based structures and structural elements into consideration to sketch further extension of their properties.

6.3.1 Development of Conventional Thinking Towards Complexity

Beams are conventionally used in combinations with rods to obtain stability and to fulfil demands of certain spans and supports. Additional structures are needed, such as sheeting materials, for functions as covering and protecting structures e.g. roofs with large spans, wall structures in large halls or as bridges. The covering can be of steel plates, glass elements, thin concrete slabs as well as timber or timber-based boards, or fabric.

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[307] Reitzel, E. 1979

[308] *The so-called Yoshimura pattern concerning buckling mechanisms of cylindrical shells under axial compression.* Tarnai, T. 2001

[309] Robbin, T. 1996, p. 25

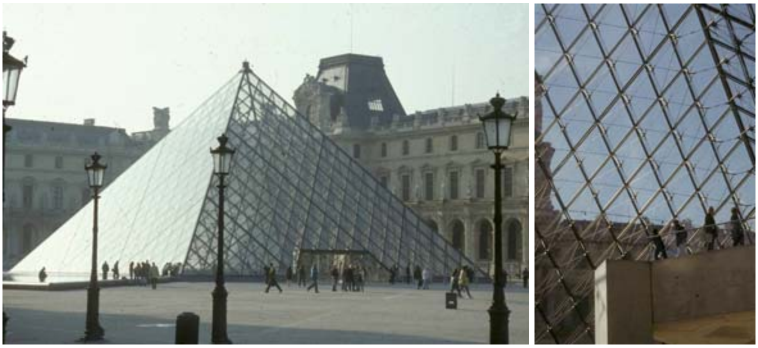

Fig. 6.6 The entrance pyramid at the Louvre.

Close at hand is to consider e.g. glass structures, where for the glass panes obvious reasons are wished to be kept as visually undisturbed as possible. The brittleness of glass put high demands on the joints and connections to supports. The utilisation of glass for structural purposes are to be seen as early as in Chrystal Palace built 1851 with design by Joseph Paxton. The load-bearing structure is made of iron, but the glass sheets provide the lateral stability in the iron frames. The shear stiffness of cross-laminated timber is easier to utilise and the sizes of the timber-plates surpass by far the normally used glass panes, from practical and rational reasons. But principles are possible to transfer from one material to another.

In large roof structures, such as the entrance pyramid at the Louvre in Paris (designed by I.M. Pei 1985-89) (*Fig. 6.6*) and the covering of the central railway and bus terminal in Chur, Switzerland, (designed by Brosi/Orbist and P. Rice 1988-92) (*Fig. 6.7*), glass is used with high-tech joining in steel to create the volume of the obtained space. A similar case (designed by F.O. Gehry and J. Schlaich in 1998) is the atrium of DZ Bank in Berlin[310] where a free form glass roof is stabilised by steel rods oriented like a fan (*Fig. 6.8*).

Fig. 6.7 The terminal roof in Chur and one of its rod joints.

[310] Schlaich, J. and Bergermann, R. 2003 pp. 125-130

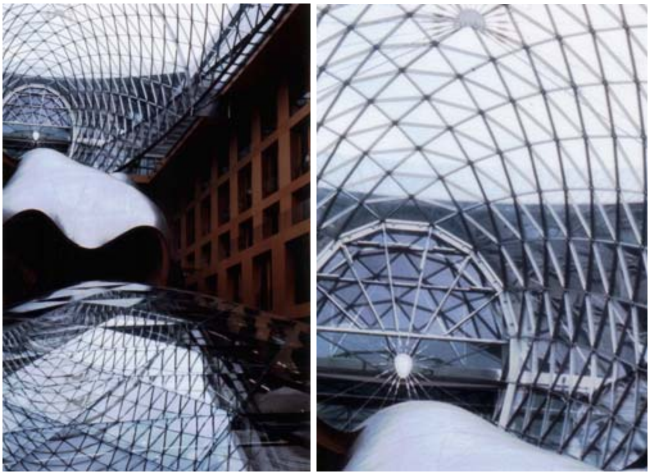

Fig. 6.8 Atrium in the office building of DZ Bank in Berlin.

These cases could be transformed into timber-based plate structures. The existing pyramid at the Louvre consists of a great number of small elements connected to a network of steel joints and rods. Each of its sides could be made out of a single assembled timber plate, resulting in a structure where four triangular plates lean against and thereby support each other (*Fig. 6.9)*.

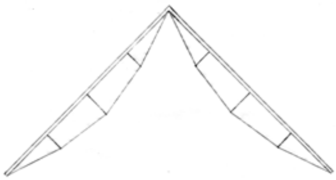

Fig. 6.9 Plane plate-elements.

In such a pyramid structure with plates the continuous joints along the edge interfaces between the plates would take care of tension and compression. In a linear elongation of the section in *Fig. 6.9*, forces to take into consideration would be those converging towards the centre, above all in the upper part of the structure, which are taken up by counter reactions in the opposite plates. Others would be the diverging forces in the lower part of the structure, taken up by e.g. steel rods or by rigid joints to the foundation. In a case with steel rods, the foundation would not need to take up lateral forces from the structure's own weight and the foundation could be made relatively simple. The timber plates can span between the corners, where the foundation work can be concentrated. The use of post-stressed plates could result in curved walls of the pyramidal shape, transforming it into the shape of a dome, or a bud of a plant.

In Chur, glass sheets with joints and rods of steel are used to cover the terminal area in a vault shape where radial rods stabilise the structure by tension. A timber-plate structure can span the distance in a similar way, though not as transparent, of course.

An example of a large curved structure acting partly in an opposite way, though also with a curved result, is to be found in the roof of Bau Technik Zentrum, Graz University of Technology in Austria, shown in *Fig. 6.10* (*see also Section 7.2.4*) The technique with a plate curved with trestles in compression is here utilised for a span of about 20 m.[311] The trestle structure increases the depth of the spanning members and takes care of the lateral forces at the supports, resulting in only vertical loads to transfer into the walls.

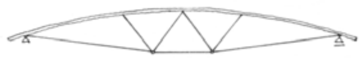

Fig. 6.10 Roof structure for BTZ laboratory hall at TU-Graz.

Fig. 6.11 Curved plates with tension rods.

Fig. 6.12 Plane plates in a faceted assembly with tension rods.

The material properties and the joints decide the performance. On the first most basic level the material relies on co-action between small members by gluing. On the second level the elements need to be connected to each other. The connecting issues concern in-plane joints for the individual plate-members acting as a unit, and in directions out of the plane to keep the curved shape. A principle based on a bicycle wheel, similar to the one in Chur can be applied, with the radial rods securing the curved shape from deformation caused by lateral and/or unevenly spread loads. The principle could be applied both on curved elements and on plane ones (resulting in a faceted shape) (*Fig. 6.11-12*).

The length of the rods decides the distance between plates and centre joint. Chur shows a version with the centre joint above the support level, whereas DZ Bank shows a version with the centre joint below the support level. Anchoring with rods pulling the structure downwards is then needed (*Fig. 6.13*).

More structures can be created in rather simple ways, increasing the capacity of plate structures considerably. Plates with trestles and tension rods in one direction on the

[311] Schickhofer, G. and Hasewend, B. 2000

lower element side are already in use. A satisfying structural depth is in this way easily obtained and it provides with a cheap method to produce high-performance elements. The principle described above concerning the Louvre can be utilised in roof structures covering sports-hall or equestrian.

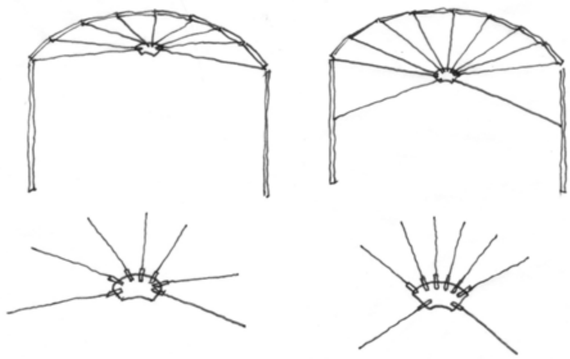

Fig. 6.13 Different principles for joint location in relation to the supports in Chur (left) and Berlin (right).

The two sides of a saddle roof are then composed with single planes (like the section in *Fig. 6.9*, extended longitudinally, perpendicular to the drawing). Since a cross-laminated timber-plate is capable of spanning in two directions utilising pre- or post-stressing in more than one direction is a short step development, either in a crossing orthogonal way or diagonally, serving any desired use of the plate (*Fig. 6.14*). The pre- or post-stressing can be applied on either the lower or the upper side of the element.

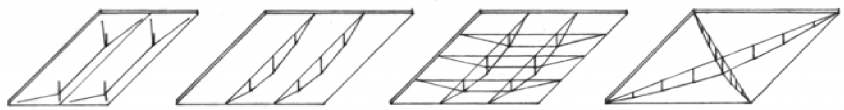

Fig. 6.14 Principle designs for plane plate elements with tension structures on the lower side.

6.1.2 Development from Simple Elements and Structures

Stiff cross-laminated timber plates can be combined in a plane on tightly spaced supports of different designs (*Fig. 6.15*). Supports, such as simple timber or steel columns, can be placed tightly and four plates can be supported directly on a column or on a forked column head. Depending on the space to be covered the thickness and build up of the plate can be tailored for bigger spans and the plates can be combined with a rod and trestle structure on the lower (or the upper) side.

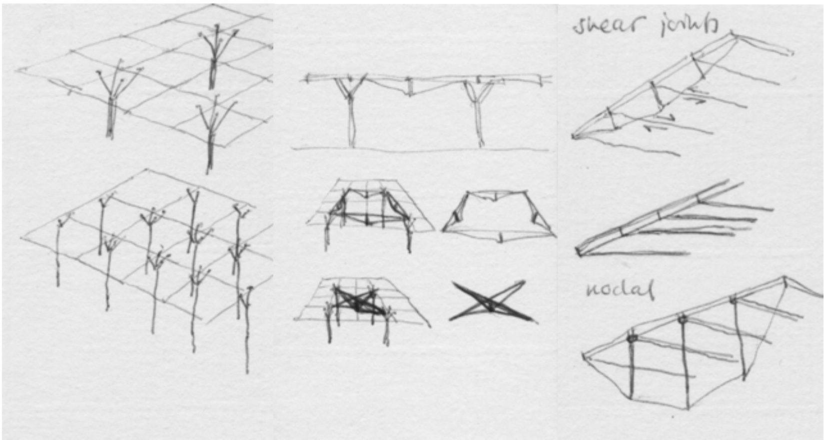

Fig. 6.15 Sketches for plane assemblies of regular plates.

Plates can be inclined and combined into roof structures supporting each other along the edges (*Fig. 6.16*). As long as the edge joints can be regarded stiff the resulting pyramid shaped and truncated[312] geometrical structures will only require quite simple column supports, since lateral forces from the structure itself are taken absorbed by the plate joints.

One of the structural types sketched in *Fig. 6.16* is the single-truncated pyramid roof (seen in the middle). This structural unit consists of a flat plate pyramid on which the top has been cut away, resulting in a lantern. Turned upside-down the element works as a cantilevering structure from a central support.

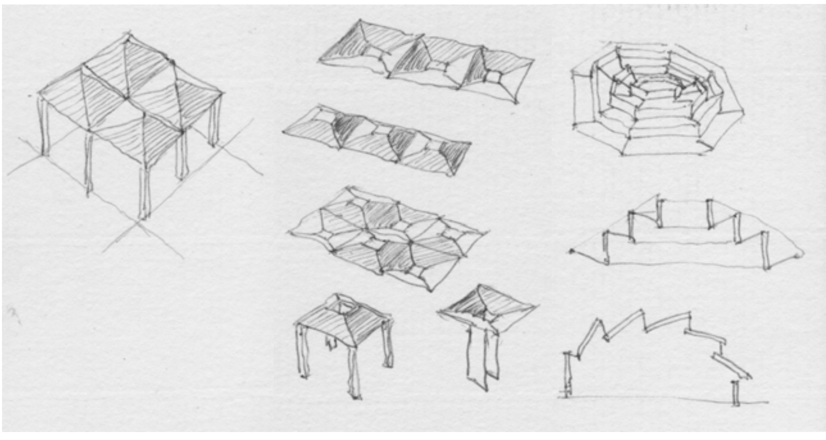

Fig. 6.16 Sketches for plate combinations and variations on this theme.

[312] Truncation *implies to cut off the vertices on a polyhedra. The holes are normally closed as faces in a new polyhedron.* Wester, T. 1984, p. 22. *In the current context the hole is utilised as a lantern.*

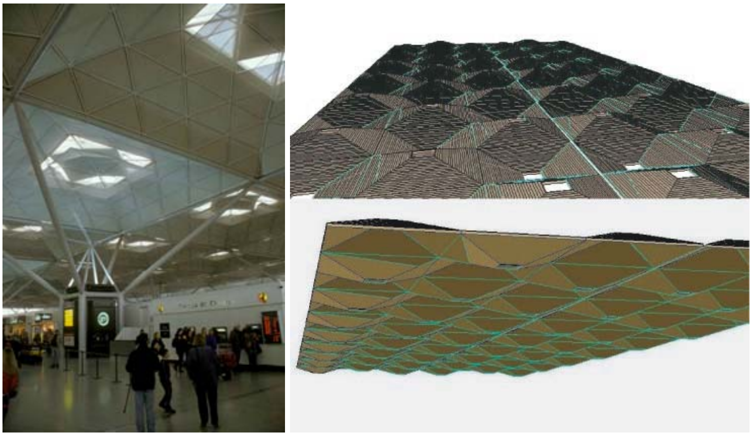

Fig. 6.17 The roof structure at Stansted Airport, London (left) and sketches for a roof solution for e.g. a transit hall (right).

With a stiff unit repetitive structures can be generated for the purpose to cover big areas like transit halls at airports (*Fig. 6.17*). Either the elements can be repeated with only one orientation, either cantilevering units or "lanterns", or they can be combined. Then the cantilevering units support the intermediate "lanterns".

Cross-laminated timber plates can also be used for curved structures, like in the examples shown above in *Fig. 6.11-13*, both with and without and rods and trestles (*Fig. 6.19*). In most designs hanging structures do not take care of lateral forces from self-weight. This places high demands on the fixation and rigidity of the supports. There are already examples to be seen of roofs hung in between existing or newly constructed buildings, which provide sufficient stability as supports. By combining the curved structures with rods the lateral forces can be handled in rational ways, even in hanging structures and several hypothetical structural solutions can be sketched (*Fig. 6.18-19*).

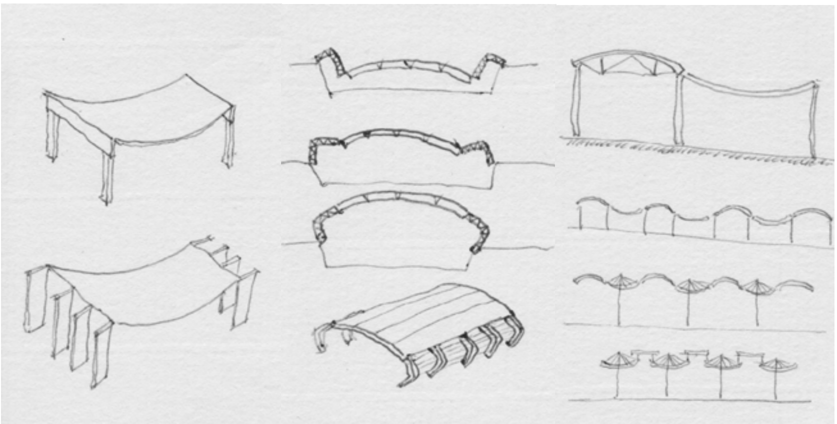

Fig. 6.18 Sketches for curved timber-based plate structures.

By refining the relation between tension and compression and to work with effects from nodal and continuous joints, timber plate-based structures of further increased structural and visual complexity can be obtained (*Fig. 6.19*). The cable-stayed column is an example of a similar refining of the performance of structures and structural members, which has been utilised by e.g. Johan Otto von Spreckelsen for the elevator structures at La Grande Arche in Paris and by Sir Norman Foster in glass structures in the subway in Copenhagen (*Fig. 6.20*). The different structural principles and solutions for timber structures that have been dealt with so far can be displayed in a table in *Fig. 6.21*, showing the step-by-step development of complexity in form and increase of structural performance. The structure of the table is developing from basic, simple surface-elements to more complex elements and structures in one, two and three dimensions. In the following two chapters (*Chapter 7 and 8*) different advanced timber-based structures for wide spans, both constructed and hypothetical ones, will be further treated.

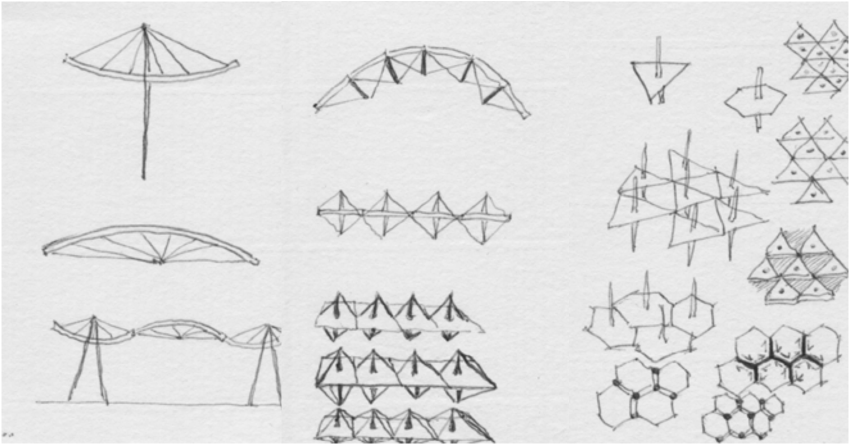

Fig. 6.19 Sketches for curved and plane plate-assemblies in combinations with rods, cables and struts.

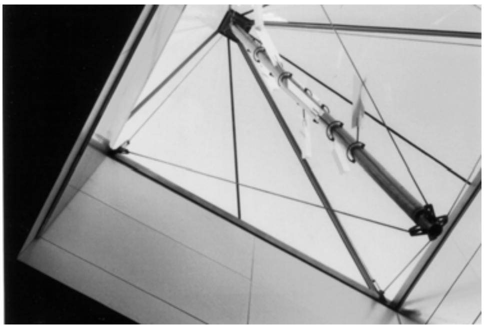

Fig. 6.20 A lantern at a subway station in Copenhagen; a glass roof with a central cable-stayed post.

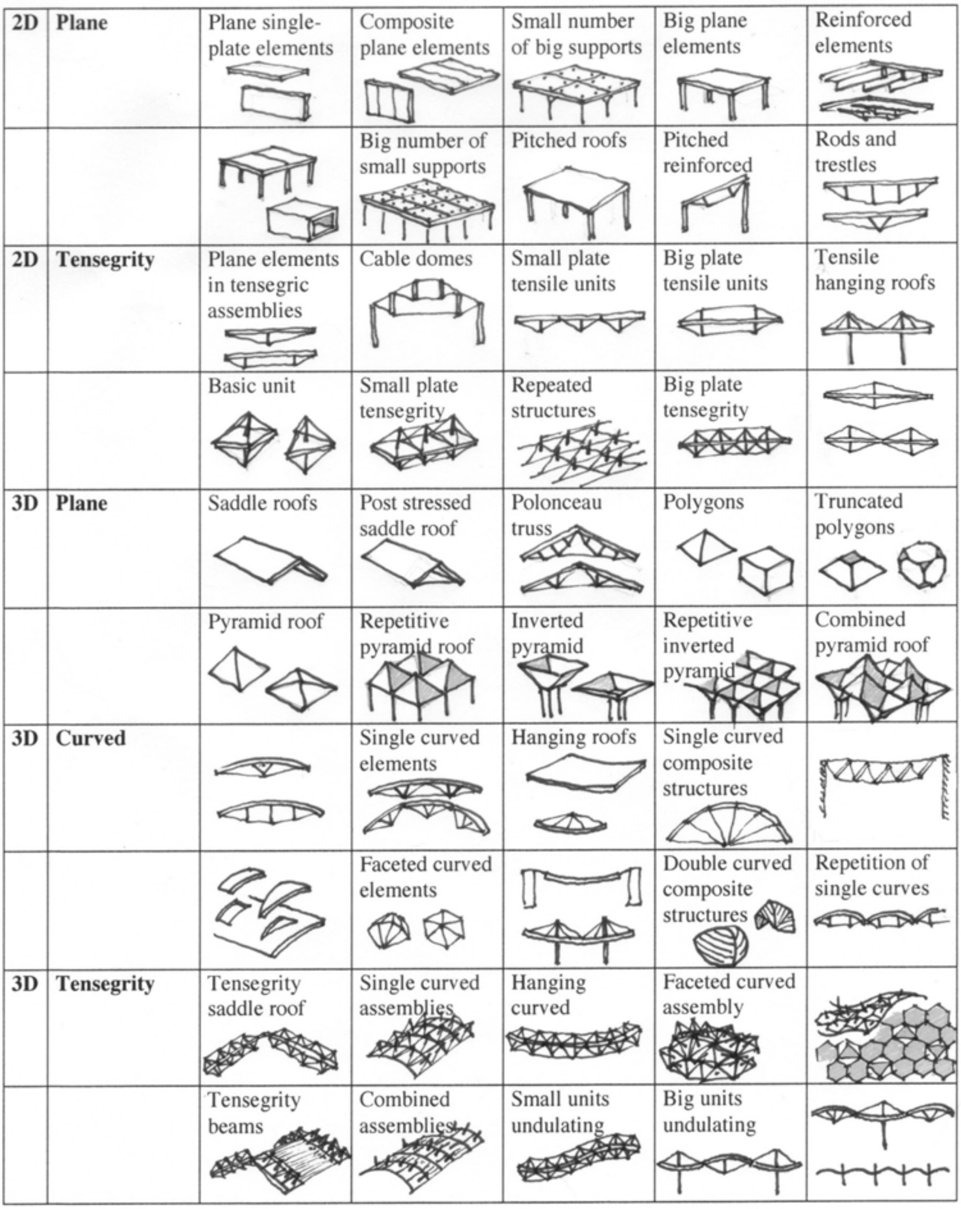

Fig. 6.21 Sketched table presenting an over-view of possible development of different plate-based structural elements.

7 CASE STUDY ON ADVANCED STRUCTURES

The single-case study presented below has been performed to describe and explain the use of massive timber elements for an advanced structure with a long span. Four related building projects have been added to widen the theoretical framework for advanced utilisation of structural plates.

Nr:	*Case:*	*Abbr:*	*Type:*	*Location:*
#7	Flyinge	FLY	Equestrian	Flyinge, Sweden

Projects for reference:	*Abbr:*	*Type:*	*Location:*
Katsch an der Mur	KAT	Car port	Katsch a.d. Mur, Austria
Studenzen	STU	Sports hall	Studenzen, Austria
Unzmarkt	UNZ	Storage	Unzmarkt, Austria
Bau Technik Zentrum	BTZ	Building lab.	Graz, Austria

7.1 Case #7: Flyinge (FLY)

7.1.1 Flyinge State Demesne

The project is located at the equestrian centre of the State demesne Flyinge outside Lund in southern Sweden (*Fig. 7.1*). The site is historic ground for horse riding, breeding and education and the area is today a historic building site. A new equestrian hall was needed but regarded as being a difficult issue to deal with considering the protective regulations for the area. Three architectural offices were invited for a competition and a submitted proposal for a plate-based roof structure was chosen. The actual planning started in 2004.

Fig. 7.1 The outer courtyard at Flyinge with the equestrian hall at the northern side.

Similar and historic structures

The chosen principle is derived from the historical Polonceau truss, developed in the mid 19th century by the French engineer Camille Polonceau (1813-1859). In his truss design he made use of then newly developed steel with tensile strength and reinforced beams of timber and cast iron with steel rods. An example of the Polonceau truss is to be seen in an old equestrian hall at Flyinge (*Fig. 7.2*), which can be compared with the corresponding view of the new structure (*Fig. 7.3*). The old equestrian hall was designed by the Swedish military engineer Fredrik Blom (1781-1853), who has designed several of the old buildings at Flyinge.[313]

Fig. 7.2 Polonceau truss in the old equestrian hall at Flyinge.

Fig. 7.3 Polonceau's principle with plates in the new building.

He developed structural systems utilising tension in the construction, e.g. dismountable and movable prefabricated houses, where the roof was constructed as two inclined surface-elements, held together at the base with an iron rod.[314] (*Fig. 7.4*) The principle used by Blom was to prevent the roof elements form pressing the walls outward by simply keeping the walls together with a member in tension. The Polonceau truss utilises beams supported by posts in compression and rods in tension.[315] In the structural solution for the new equestrian hall the beams have been

[313] Johansson, L. 2005, p. 38
[314] Falk, A. 2002, pp. 71
[315] *In this way he obtained a clearer structural logic than seen before.*

replaced by plates and the posts by trestles. Similar structures have been built before e.g. in Krakau in Austria (*Fig. 7.5*), but with smaller spans.

Thus, from the very simple structures by Blom and others there is an obvious line of development in the solutions for increased structural capacity, following, however, the same structural principles of utilising different types of elements in tension and compression.

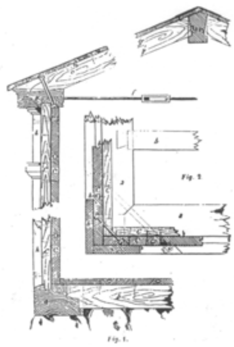

Fig. 7.4 Drawing of a prefabricated house design by Fredrik Blom.

Fig. 7.5 Turnsaal in Krakau, Austria.

7.1.2 Players

Client: Flyinge AB, Flyinge, Sweden

Architect: AIX Arkitekter AB, Stockholm, Sweden

Structural design of proposal: Tyréns, Stockholm, Sweden

Structural design for production: JR Consult, Graz, Austria

Production and construction: KLH Massivholz GmbH, Katsch a. d. Mur, Austria

7.1.3 The Structure

The plan of the equestrian hall measures 80.3 x 41.6 m^2 (*Fig. 7.6*) and is covered by a roof with rod stressed trestles (*Fig. 7.7*). The basic principle for the roof structure implies two plate elements jointed together forming a saddle roof mainly supported by two rows of columns. A lantern runs along the roof-ridge.

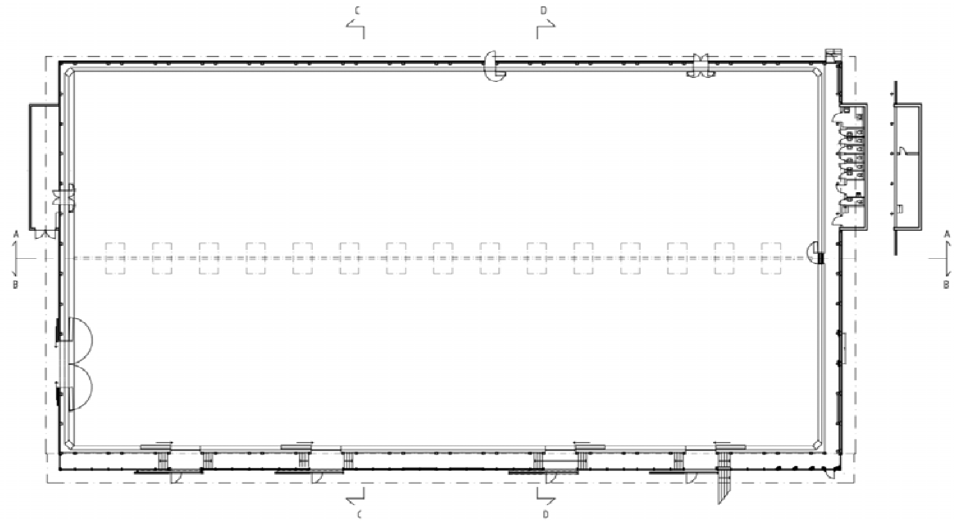

Fig. 7.6 Plan layout of the equestrian hall in Flyinge.

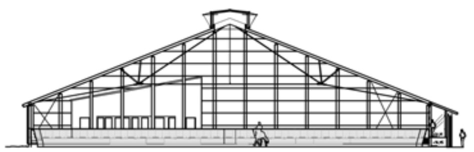

Fig. 7.7 Section viewing towards the north.

The roof

The plate elements for the roof measure 22.5 × 5.0 m^2. Two columns support each plate at the eaves and the plates meet in steel joints at the roof apex. The columns are erected two and two and are placed 575 mm in from each element edge.

The plate elements are built up by 225 mm thick cross-laminated timber plates with 7 layers (*Fig. 7.8*). Since the production line limits the original element size to 2.95 × 16.5 m^2 and considering the means of transport the roof elements were manufactured in four parts. Each element is composed of two plates measuring 14.2 × 2.5 m^2 and two plates measuring 8.2 × 2.5 m^2 (*Fig. 7.9*).

Fig. 7.8 The timber plate roof projection at the southern gable, during construction.

In the direction of the span the plates are jointed at the point with 0-moment, enabling connection with a simple butt joint (*Fig. 7.10*). Each element is tensioned with a trestle structure with steel tubes (88.9 mm in diameter) on the lower side with tension rods (50 mm in diameter) forming a diagonal cross across the plate surfaces (*Fig. 7.11*).

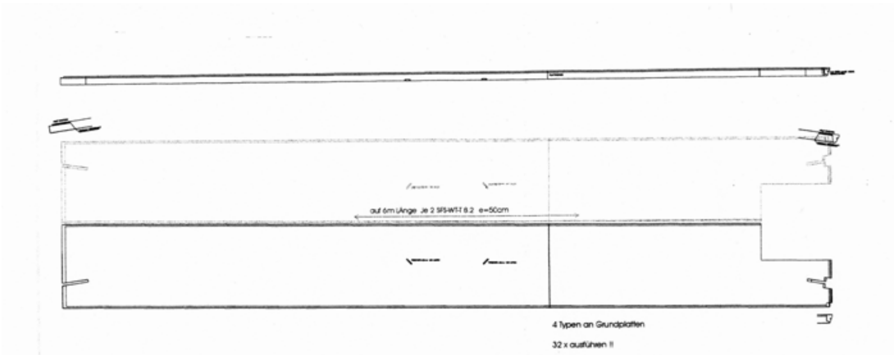

Fig. 7.9 Design of the four plates forming an element, with cuts for lantern and plate-rod connections.

Fig. 7.10 Butt joint in a roof element, supported during assembly.

Fig. 7.11 Trestle mounted on a plate element (left) and trestles when the elements have been put in place and connecting rods have been fixed (right).

During planning there were proposals for more supporting points along the span and to use trestles with a larger number of parts. This was not realised. The trestles are designed to carry the plate, metaphorically as a light tray. The trestles support the plates and act as a flat slab structure. A screwed connection to the plate was found sufficient (*Fig. 7.12*). Rods between the trestles connect the elements (*Fig. 7.11, right*). These trestles and the horizontal rods connecting them are the key elements for the structural principle.

Fig. 7.12 Screwed joint between trestle and plate.

The supporting walls

The design of the walls has been developed into four different types, one for each side. Along the long sides, towards east and west the roof structure is supported on timber columns arranged two and two, stabilised by cross bracing along the eastern side and by massive timber plates (108 mm massive timber plate with three layers) forming a continuous wall along the western side (*Fig. 7.13*). To the east the roof is elongated 3 m with timber plates (108 mm thick plate with tree layers) past the supporting columns to cover a lateral gallery for spectators (*Fig. 7.14, left*). At the gable towards the south evenly spaced timber columns support the outer roof element along its entire span stabilised by massive timber wall elements, closing the structure to the south. At the gable towards the north a row of steel columns supports the outer roof element and carries a glass façade (*Fig. 7.14, right*). An addition containing storage is made at the southern gable; another addition containing toilets is located at the northern gable (*see Fig. 7.6*).

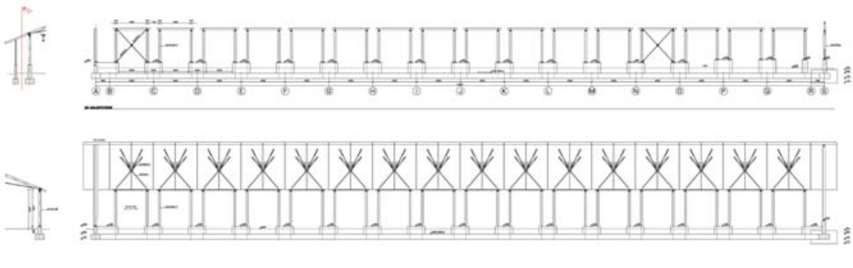

Fig. 7.13 Cross-braced columns supporting the eastern edge of the roof and plate stabilised columns of the western eves.

Fig. 7.14 The gallery along the eastern façade under an extended plate roof towards the north (left) and the northern glass façade (right)

Erection

The structure was erected with three cranes. The plates were delivered to the site where they were put together into lengths of 22.5 m. Each roof element was assembled on the ground, trestles were fixed on the lower side and tension rods were tightened from edge to edge under each trestle (*Fig. 7.15*). Then the elements were lifted in place in pairs with two cranes and a third crane lifted the connecting rod for the jointing of the two elements forming a roof section. When one such section had been secured in place, next section was assembled and erected (*Fig. 7.16 shows the structure when the last roof element, to be supported on the gable columns, was to be put in place*).

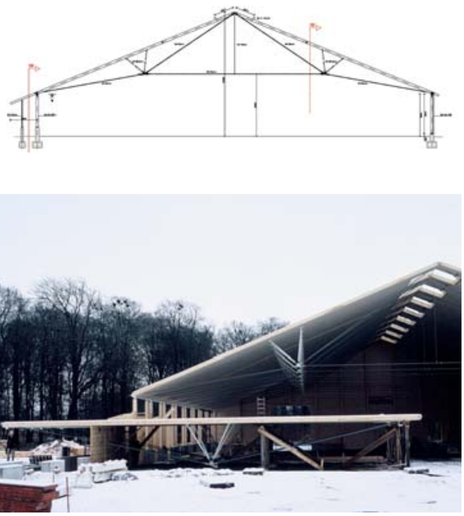

Fig. 7.15 Technical cross-section and a roof element after assembly, before erection.

Fig. 7.16 The last phase of the erection of the timber structure.

The concrete for the foundation was cast before the timber was delivered. The timber structure was then erected by workers sent out by the massive timber producer, who provided personnel with experience of massive timber construction. The roof was covered with asphalted paper during the erection. The lantern and the glazed northern gable were erected during the last phase of the construction.

During the erection it was shown to be difficult to obtain equal tension in the rods connecting the trestles. The roof ridge did not remain horizontal but varied slightly in height and finally dipped 70 mm at the last gable. Over its entire length of the ridge this is not much, but in the meeting with the glass façade of the northern gable it was problematic and adaptations had to be made. The precision in the meeting was not high enough. It is presumed that the required precision had been more easily obtained if the sections had been completely assembled on the ground and put in place after the tightening of the connecting rod. This would also have reduced the need for cranes to two.

Fig. 7.17 Lantern over the ridge with cuts made in the elements.

7.1.4 Detailing

The structure has been simplified where architectural design is concerned, i.e. it has been kept as simple as possible, and provided few additions. Storage and service buildings have been added as boxes at the gables, subordinate to the main hall. The lantern letting in daylight along the ridge has been obtained by making cuts in the elements where they meet in the roof apex (*Fig. 7.17, see also Fig. 7.9*). Artificial light is provided by strip-light fittings in widely spaced rows mounted directly on the plate elements, three rows on each side of the structure (*as can be seen in Fig. 7.34*). Power cords serving the electric fittings run in the joint zones between the timber elements. Water pipes for watering the floor in the hall are hung in the rod and trestle structure.

With a low number of utilised elements the detailing becomes more obvious and its importance for the overall experience increases. On the big, even surfaces the trestles and rods with their joints and connections are highlighted and the technical details are distinguishable in the structure. The joint solutions have been much studied and elaborated concerning their visual appearance but the design is mainly decided by the pure technical function and to express this in a clear way (*Fig. 7.24-25*). Efforts have been made to provide an experience of reliability for the structure, concerning joints and especially rod diameters. The wish has been structural elegance in combination with enough measures to give an impression of safety.

The coupled rhythm of the columns along the long sides is a result of the striving for a support of the plates that visually makes them stay safe in place. The plates manage to span over their entire surface with supports only at the edges. To avoid the impression of the plates risking to fall down from their supports, the number of columns was doubled providing each plate element with two separate columns supporting the plate at a distance from the edges.

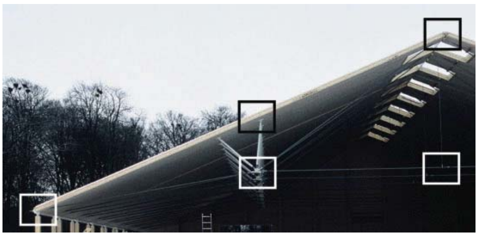

Fig. 7.18 Joint-zones between element types in the roof structure.

The joint zones can be divided into different types (*Fig. 7.18*): plate-plate (ridge), plate-column (eaves), plate-rod (ridge, eaves), plate-trestle (element centre), rod-trestle (trestle top) and rod-rod (connection centre). In *Fig. 7.18* the additional butt joint between the plates forming an element (*shown in Fig. 7.10*) is unmarked.

In the plate-plate joint the elements meet in the same zone as the upper plate-rod connections and the design is similar to the plate-rod/plate-column zone at the eaves. Cuts have been made at the edges where steel plates distribute the forces from the fixed tension rods tightened with nuts (*Fig. 7.19*). This means that much of the forces are loading the timber plates parallel to the grain.

Fig. 7.19 Plate-rod joint at the ridge end of a plate element.

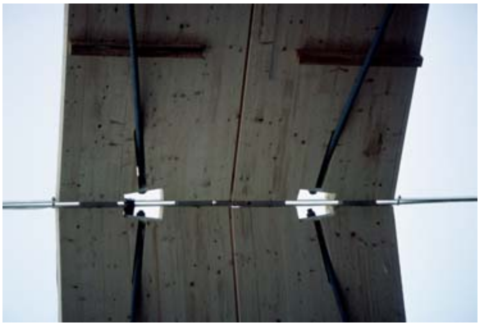

Fig. 7.20 Ridge connection between roof elements (plate-plate) after erection. The battens visible between plates and rods are temporary supports for the erection.

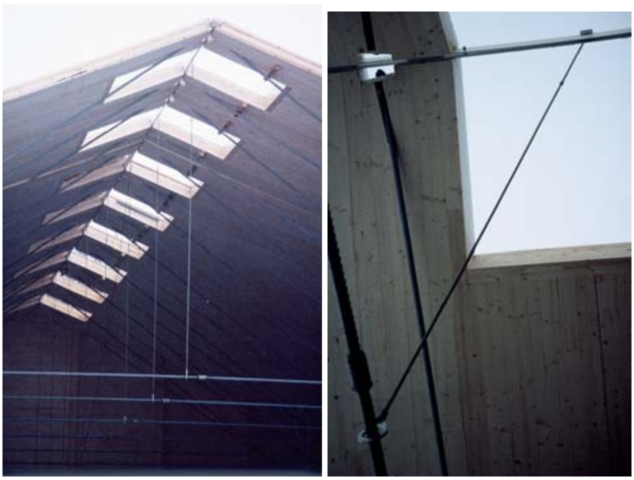

Fig. 7.21 Supporting rod between ridge and the rod connecting the trestles.

The end zones at the ridge end of the elements are provided continuous steel strips with mated joints, which meet and get fixed at the roof apex (*Fig. 7.20*). Vertical rods (16 mm in diameter) are fixed between the roof apex and the horizontal rods (50 mm in diameter) connecting the trestles (rod-rod connection). They keep the horizontal rods in place and prevent these from deflecting (*Fig. 7.21*).

At the eaves end of the elements the rods run through the plate and are fastened with nuts at steel fittings (*Fig. 7.22*), which are designed to rest on the columns thereby constituting both plate-rod and plate-column connections. Each steel fitting at the eaves is supported by two columns, which along the eastern wall between equestrian hall and gallery is stabilised by steel cross bracing (*Fig. 7.23-24*). The steel fittings are not covering the whole edge length and the rods are cut into the plates at a distance from the side, corresponding to the distance between the column couples supporting each element.

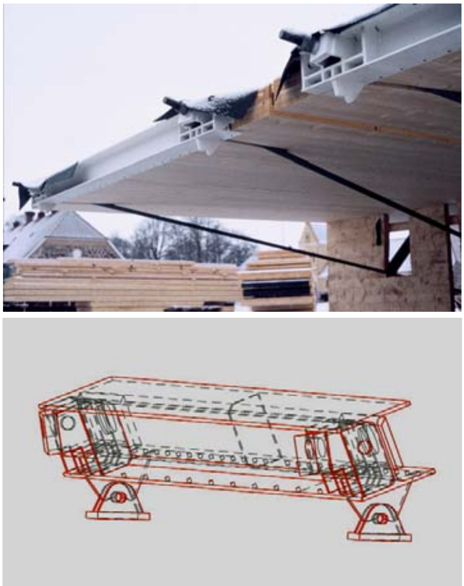

Fig. 7.22 Lower end of a roof element with plate-rod connection during assembly on the ground (above). Drawing of the same joint with steel fittings for placing on top of the columns (below).

Fig. 7.23 Plate-column connection at eastern wall eaves.

Fig. 7.24 The middle joint of the cross bracing (above) and cross bracing jointed to column base (below).

The columns are fastened to the foundation with slotted in steel joints, as can be seen in *Fig. 7.24*, where the joint is combined with the cross bracing.

The compression in each roof part is obtained with the trestles, which in compression between plate and rods prevent the plates from buckling. The joint solution for plate-trestle connection is shown in *Fig. 7.11-12*. The rod-trestle connection is the most conspicuous detail in the structure. It fixes the rods in tension over the trestles and is the fixing point for the horizontal connecting rod between the roof elements. The joint is designed as a steel plate with flanges to which rods are fixed with fork ends (*Fig. 7.25*).

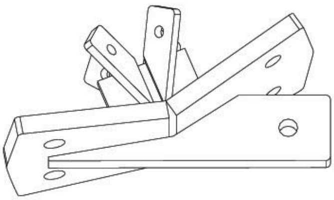

Fig. 7.25 Trestle-rod connection prior to application of paint.

7.2 Projects for Reference

For reference a number of structures can be briefly described. They are of different sizes and utilise other, though related structural solutions. The common principle is the use of cross-laminated timber-based plates. Exact measures and dimensions are not regarded here, nor are the descriptions intended to be complete. The following projects are just swiftly regarded for their structural principles/similarities and the structural and architectural impact of these.

7.2.1 Car-port in Katsch an der Mur (KAT)

Fig. 7.26 Sheltering structure at KLH factory in Katsch an der Mur, Austria.

Description

At the KLH factory in Katsch an der Mur, Austria, a plain plate structure has been provided timber based trestles and simple tension rods on the lower side to increase the span. In this way a slope of the roof surface is created (*Fig. 7.26*). The structure is very simple, almost as a shoebox but with a slightly altered upper element. It is a plain plate structure with the aim to be nothing more than a serving structure. The stressing rod in the roof structure, however, is an important development of the shoebox and allows with fairly small means a wide span with quite a thin plate.

The trestles are designed as triangular timber plates fixed along the centre line along the roof plate. Over each trestle a single rod is stressed with end joints over the supports at the walls on each side. The single row of two-dimensional trestles results in a roof shape more similar to a saddle roof than an even curve. In a case with a span of this length and a relatively small depth of the structure, i.e. small camber, this design is possible.

Planning and erection

Planning: KLH Massivholz GmbH

Erection: KLH Massivholz GmbH

7.2.2 Sports hall in Studenzen (STU)

Fig. 7.27 Sports hall in Studenzen, Styria, Austria

Description

The project is a sports hall in Studenzen, Austria, where cross-laminated plates have been assembled with a trestle structure in cross-laminated timber and tension rods (*Fig. 7.27*). The simple trestles are made of triangular perforated timber plates. The structure bears similarities with the first project, but is further refined, both structurally and architecturally. The spanning capacity of the plate structure has been increased with fairly small means. The span is supported along two rows of trestles, which have been painted to be distinguished from the ceiling surface.

More aesthetical care is taken than in the previous example, since this is a building for public use; the interior design is characterised by the trestles that signify and also express and emphasise the structural and aesthetical concept (which is not revealed in the exterior, however) (*Fig. 7.28*).

Planning and erection

Planning: Werner Trummer, Feldbach

Erection: Kulmer Holz – Leimbau

Fig. 7.28 Detail of the trestle structure.

7.2.3 Storage for Carpentry in Unzmarkt (UNZ)

Fig. 7.29 Roof structure over a storage hall at a carpentry in Unzmarkt, Austria.

Description

The project is a small storage building at a carpentry in Unzmarkt, Austria. The roof structure is built up with slightly curved cross-laminated timber plates spanning in the shorter direction over the building (*Fig. 7.29*). The curve is obtained and maintained with a stiff rod and trestle structure of steel of relatively simple design. The roof is supported on lintels that run along the short eaves all the way to take care of the loads from the projecting part of the roof. The lintels are fixed on short steel studs along the two long sides, lifting the roof over the wall structure, creating space for a ribbon-window along all walls. At each short side a pair of timber columns support the roof.

By the use of a steel structure of low complexity and with a single material type, a slight curve of the roof has been obtained, which enables simple plate elements to span the distance between the walls. The trestle structures are repeated along the building with the last one being outside at the front gable, where the roof protrudes over the entrance. This makes the structural principle more obvious. Inside the hall among installations running in the ceiling, the rod and trestle structure is less noticeable. The rods and the trestles are of the same diameter.

Planning and erection

Erection: Firma Ehrenreich

7.2.4 Building Laboratory in Graz (BTZ)

Fig. 7.30 BTZ - Bau Technik Zentrum at Graz University of Technology.

Description

The project, BTZ (Bau Technik Zentrum) is a building for laboratories and offices at Graz University of Technology. The building houses the Department of Timber Engineering at the Institute for Steel, Timber and Shell Structures. The main part is a laboratory hall whereas offices and workshops are located to building parts added along the main hall.

The roof over the laboratory (*Fig. 7.30*) covers about 19 × 53.5 m^2 and is supported by timber studs on top of the timber plate structure constituting the walls.[316]

The principle is the same as in the storage building mentioned above, but the span is wider and the technical detailing is more elaborated. The trusses are designed with larger diameter than in Studenzen. The tension rod structure consists of a single rod connecting the two trestles of each element, with two rods diverging from the trestles towards each side, fixing at two separate points at the edge of the plate for more even force distribution (*Fig. 7.31*). The rods run through the plates of each roof element at the supports and are fixed at fittings on the upper side of the plates.

The plate structure is composed of two elements jointed together along the longitudinal centre line of the roof. The plates were manufactured with a curve. The radius was then decreased at the fixing of the trestles. To utilise daylight the roof in provided a series of lantern-covered shafts cutting through the plates in their spanning direction. This makes the trestles more visible. In the exterior the last trestles are shown in the elevations gable walls, over which the roof plate projects.

Planning

Architects: W Kampits and W Nussmüller

[316] *The span between the supports is 19 m whereas the full length of the spanning roof elements is about 21.5 m. Each roof element is built up by two cross-laminated timber plates jointed along the centre line of the roof.*

7.31 Trestle structure and lantern opening, seen from inside the laboratory.

7.3 Flyinge in Short

The equestrian hall at Flyinge is a relatively rare structure utilising an advanced structural technique. Thorough calculations and detail design has been performed with close contacts between architect, engineer and producer. The structure was prefabricated at the Austrian factory to a level of plain elements, delivered to the site on trailers as plane elements that were assembled and put into place by workers with thorough experience of massive timber construction. The workers were provided by the producer.

The basic material and the applied structural principle were chosen to suit specific architectural ideas of a visually strong structural form, considering a modern appearance in a building-historical context. After casting the foundation the erection of the timber structure was fairly swift and caused little disturbance around the site.

The project is one of a kind but can be compared with other, earlier erected structures of simpler design. These can also be seen as partly experimental efforts, to try ideas under development, even if the structural purpose is not fully utilised in the four reference projects.

The projects of reference are more or less experimental structures, carried out with different degree of finish and detail design. The uses differ as well, but the aim to create a span in an unconventional way is common for the four reference projects. With relatively small means wider spans than what is possible with simple, plane plates have been obtained and the results show a range of uses, public as well as purely rational. The examples show how a structural element also can be utilised to enrich the architectural features of a structure. In STU the roof structure has been utilised as an important element in the interior design. In UNZ and BTZ the uses of the buildings are not public, but the structure has been used to advertise timber and structural innovation in the exterior.

7.4 Analysis

7.4.1 Roof Structure

The roof structure consists of three member types: plates, trestles and rods. The plates act in bending out of their plane, shear in the direction of the span and also perpendicular to this and by in-plane force distribution. The trestles act in compression stabilising the plates and preventing them from buckling and the rods act in tension.

The steel rods in FLY have much smaller dimensions than the posts and beams that would have built up a conventional truss. The force distribution in the plate element makes it possible to create a roof without beams, which reduces the number of elements. This structural reduction gives a more unbroken spatial expression and a freer view in the enclosed volume than with conventional roof trusses. This was a desired architectural effect in the winning proposal for the FLY project.

Fig. 7.32 Interior view towards the southeast, before application of the final paint.

The rods are of a rather small dimension, which makes them provide a very small disturbance to the view in the hall (*Fig. 7.32*). They visually stand back to the expressed wide timber surfaces. Rods and trestles are also painted in an even, pale grey colour which does not expresses the different structural function – tension and compression – of the two member types. The pale grey colour provides to the low visual effect of the steel parts, which is a completely different approach than in the reference project in STU.

The visual appearance of the plates in FLY is kept simple and the structural behaviour is shown to a practised eye (*Fig. 7.33*). The plate elements are jointed in plane and made to act as a uniform surface and coated a lightly pigmented paint treatment. The structure of the boards in the surface layers renders a texture visible when lit from the side. The element joints every 5 m are used for the location of electric cables and are visible as narrow grooves in the surface in the spanning direction.

Fig. 7.33 Interior view towards the west.

The plates form a continuous structural surface (*Fig. 7.34*). In the similar project in Krakau the plate elements do not cover the entire length of the building. There the elements have been spaced with infill parts of timber between them. This is another way to utilise the elements as load carrying structure for complementary elements.

Fig. 7.34 Interior view towards the south after treatment with paint.

The proposals with a larger number of supporting points may have lead to smaller thickness of the demanded cross-laminated plate. A solution with a large number of smaller plate elements instead of two big ones could have been used. This would have lead to more joint zones in the roof and maybe not as even or unbroken plate surfaces as in the realised case.[317] The total depth of the structure would perhaps had been bigger and the number of strut elements spread over the ceiling-surfaces and in the visual field would have been greater.

It is not certain, however, that such a solution would have been more catching to the eye, since a large number of elements tend to be easier to generalise and ignore than

[317] *This depends on if the joints would have been solved in plane or as externally applied fittings. The way to obtain co-action between the plate members and the trestles and/or struts would have had decisive effect as well.*

a small one, but the sight would not have been as clear and undisturbed. The visible effect of the structure is also depending on both colour and light conditions, against the light (*Fig. 7.35*) the arrangement of trestles and rods becomes much more obvious than during other conditions. Against the pale colours looses their effect and dimension and shape become the key factors for the experience.

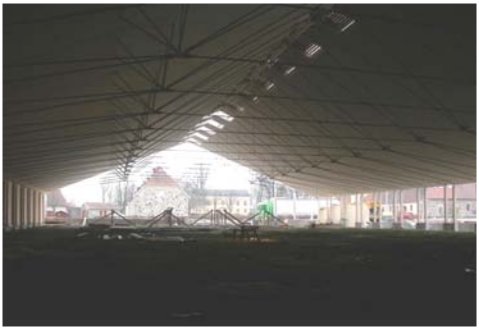

Fig. 7.35 Interior view during construction, towards the northern gable, which is now glazed.

With a thinner timber plate the appearance of the timber elements would also have been less massive (considering the visible thickness of the plates at the gables and eaves) and stiff and maybe also less reassuring. The weight of a timber structure is comparatively low and the large roof areas mean a vast exposure to wind loads. This can be a structural/stability problem and high demands are put on the joint solutions fixing the structure to the foundation, which may have to be increased to resist uplift forces.

7.4.2 Wall Structure

The characters of the wall types that have been used differ for reasons of utility. There are two types of structural, load bearing conditions: long sides and gables. For functional reasons the four walls have been designed with other differences: one long side and one gable are constructed with stabilising massive timber and are tight; the other long side and gable are constructed with cross bracing and are glazed.

The walls are designed with a clearly shown structural principle. The walls are subordinate to the roof, which is the main structural theme, but are not built in. The walls carry the roof and are provided with additions for the fulfilment of other tasks. The distances between the columns are along two sides covered with massive timber plates to obtain lateral stability and an enclosure that protects the interior; along two sides the walls consist of glass where the daylight conditions do not disturb the equestrian activities in the hall. Special care has been taken to prevent sun directly onto the floor, since horses are often easily frightened by sharp contrasts.

7.4.3 Comparisons

The load-bearing and load-distributing functions are developed step by step through the reference projects to the roof in FLY. The principle is developed and the complexity of the co-action grows. The utilisation of the structural principle for the architectural design differs as well, however, presumably partly caused by the projects having different uses, not all of them being public buildings.

The covering cross-laminated plate is the basic element in all examples and the wish to express the structural principle and to make also architectural use of it is rather obvious. The car-port in KAT is a plain service building constructed for practical needs, but with a structurally experimental aim concerning the solution for the roof. In the public sports hall in STU the trestles are emphasised by the use of paint and made to contrast to both plates and rods. Their form is also designed a step further from the project in KAT. The span is wider and in need of two rows of trestles supporting the plate.

In the carpentry in UNZ the structural expression is reduced to pure material character. It is still pronounced in the exterior design and efforts are made to utilise the structure for architectural effects. In BTZ in Graz the means to utilise the roof structure in the exterior composition are the same, with walls elongated past the gable wall and a projecting roof.

The solution in FLY with steel rods and pairs of steel trestles is comparable with BTZ. In BTZ the trestles fix a curved roof-structure composed of two jointed elements. The design of UNZ is simpler with one element managing the span of the building and with a rod and trestle structure in steel of one single dimension.

The span in FLY exceeds by far the other examples. Whereas the effects of the structural principle has been only partly utilised in the reference projects, the structural principle has been consistently utilised in FLY, for both exterior and interior architectural design. The scale of the project means a structure with a great number of elements but the visual effect of those has been greatly reduced. The visual impact of the structural elements has not been further marked but reduced by the use of paint, giving the entire interior an even shade of grey.[318] The function of the structure and the co-action between its parts are readable but not made over-explicit.

[318] *To minimise sharp contrasts is preferable in a building for horses, and has therefore been regarded in this case.*

8 THEORETICAL EXTENSION

The discussion initiated in *Chapter 6* can be extended further, to a thorough study of one possibility to utilise timber-based plates in advanced applications. The combinations of plates and tensile members, the concept of form finding, studies of literature, cases and other built structures have lead to a new structural element, described in the following theoretical extension.

8.1 Tensegrity

8.1.1 Tensegrity and Tensegric Characteristics

The works of Le Ricolais bear theoretical kinship with the works of the engineer Buckminster Fuller, who was engaged in searching the scientifically oriented structural expressions in architecture.[319] They both took part in a quest for static and geometrical optimisation. They also worked with room forming lattice structures like Konrad Wachsmann, the German architect (*referred to in Chapter 2*), who developed light building systems in timber in the US in the 1950's and 60's.[320]

Le Ricolais treated lattices following the principle that the way to optimal structures follows the principles of the forces, not only the geometry. In the following the model by Le Ricolais, shown to the right in *Fig. 6.4*, *Section 6.2.1,* is interesting to bear in mind.

The term *tensegrity* is an abbreviation of tensional integrity. It has three almost simultaneous origins, in the works of Buckminster Fuller, Kenneth Snelson and David Georges Emmerich[321], who discovered different aspects of tensegrity-like phenomena. Their descriptions show differences but they aimed, however, at the same functional properties.

Emmerich composed non-contiguous bar grids, whereas Fuller designed the first single-layer tensegrity dome. Snelson, being more of an artist, engaged in sculptural assemblies such as so-called needle towers.[322] The essential properties of all these creations are that loading under bending is avoided by transferring all forces to either compression or tension, and that the compressed parts are not in contact with each other (*Fig. 8.1*).

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[319] Vanggaard, O. 1998, p. 7
[320] Falk, A. 2002 pp. 75
[321] *Despite the fact that the Russian constructivist Karl Ioganson, cited in Chapter 6, had already patented similar structures, there has been a constant fight between those men about who was the real inventor.* International Journal of Space Structures Vol 11 Nos 1&2 1996.
[322] Hanaor, A. in Gabriel, J.F. 1997, p. 387; Motro, R. 2003, p. 2

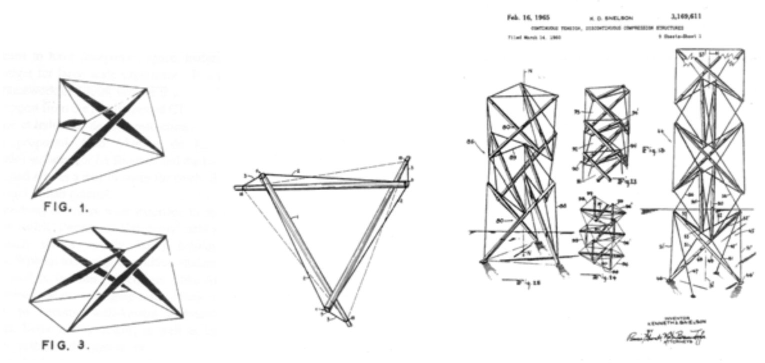

Fig. 8.1 Tensegrity, as sketched by Emmerich, Fuller and Snelson (from left to right).

8.1.2 Generating a Structural Unit

Three stiff bars of equal lengths and a number of connecting members in tension can produce a basic tensegric module, also called simplex. A simplified hypothetical transformation from an instable basic prism shape to a stabilised tensegric structure will work as an illustrative guide (*Fig. 8.2*).

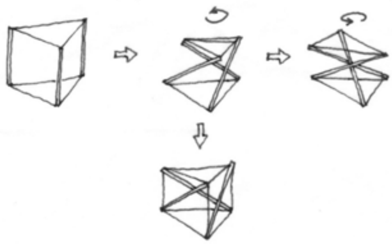

Fig. 8.2 Transformation of a basic prism.

The basic prism of three vertical bars and six jointing tension rods has five facets, five faces, two triangular of horizontal orientation, and three rectangular of vertical orientation. The prism-form is not stable and if it collapses regularly, with all rods in equal tension, the bars will tend to lean to the side and the horizontal facets will rotate around the mid-axis of the assembly, perpendicular to their plane. The rotation will go on until the bars touch each other at the centre of the former prism. Before this happens the structure can be stabilised with additional tensional members and a tensegric structure has been created. Such so-called anti-prisms were drawn by Emmerich.[323]

[323] Robbin, T. 1996, p. 27

One can build up the basic types of tensegric structures by stiff compression bars, nearing a 1-dimensional nature, and tension rods. In different types of developed spatial structures, membranes are used to take up tension forces, thereby exchanging the 1D rods to 2D and 3D surfaces[324].

Fuller regarded tensegrity as a revolution for structure and construction, but saw no realistic applications in large-scale permanent structures. It was not until 1981, five years after Fuller's death, when the engineer D. Geiger presented the "cable-dome" (*Fig. 8.3*), a developed version of a project by Fuller from 1964.[325] The idea is to hang a hoop from an outer wall structure and to erect posts on the hoop. From the posts a new inner hoop is hang to support new posts, and so on.

The visions about utilisation of tensegrity in full-scale have been many, e.g. large open spaces with light or translucent coverings, temporary dismountable structures such as exhibition halls, deployable structures etc. Geiger viewed tensegrity as a way to support fabric roofs without the expense of mechanically inflating pneumatic supporting structures.[326]

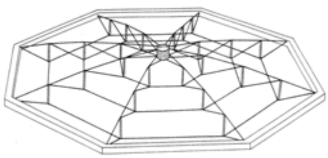

Fig. 8.3 A so called cable dome as presented by Geiger.

Tony Robbin has noted that the patent of Fuller actually contains an idea about using "sheets, plates of panels" in the place of hoops and posts, which has not been tried (*Fig. 8.4*).[327]

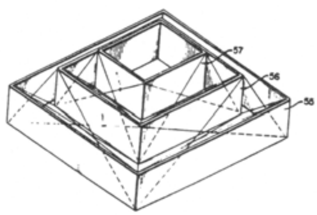

Fig. 8.4 A plate based tensegric structure, as sketched by Fuller.

[324] *Membranes can take plane as well as single-curved and double-curved shapes, its all a matter of the art of the tensional conditions.*
[325] Saitoh, M. 2001, p. 2, Schlaich, J. 2004, p. 168
[326] Robbin, T. 1996, pp. 32
[327] Robbin, T. 1996, p. 32

8.2 Plate Tensegrity

Structures of tensegric character utilise balance between compressed members and members in tension, thereby gaining from effective utilisation of material properties. Proposed advances of such structures are "simplification of joints, control of structural behaviour due to pre-stressing, easiness of production and transparency of structural appearance"[328]. They are pre-stressed cable networks and as such in most cases deformable; negative features such as large deflections, geometric and conceptual complexity, long buckling-prone bars and incomplete understanding of behaviour easily occur.[329] Tensegrity has been described as "small islands of compression in a sea of tension", by B. Fuller in the late 1920's; those islands are of course more than necessary and their properties and behaviour crucial. However, as long as they exist and take up compression forces their design can differ and the overall system can vary.

8.2.1 A Tensegric Perspective

The possibilities to vary the properties and geometric features of the islands of compression in a tensegric structure provide an interesting potential. In most models of tensegric structures the compressed parts are in the shape of straight beams, more or less 1D-elements. Plates on the other hand provide a surface, i.e. a second dimension. If 2D-elements, plates, are chosen for those parts more potential possibilities appear: the plates create surfaces and provide 3D by the use of tension rods.

The shear capacity of a cross-laminated timber-plate makes forces fairly easily transferred to edges and supports, even in case of cantilevering structures. The relative thickness of a timber-plate is another important characteristic, since joints and shear-action along the edges can obtain the transfer of forces in plane. Glass sheets can be utilised for stabilising plates in a structure, but are not capable of the transference in plane from one sheet to another, depending on relatively thin and brittle edges. Plate-based elements in compression have as described above potential use in roof structures for example, where each element spans the entire distance to be covered. But there should also be potential in structures with tensegric function and shear-based transference of forces in combined action.

In the search for possible practical uses in the characteristics of tensegrity have been regarded and evaluated. Those characteristics are in the writings of Fuller, Snelson and Emmerich strict and excluding, rather than including. They are defining arrangements that are both structurally and visually fascinating. A structure with a conventional structural principle as origin usually does not show the same thrilling appearance, and to make deviations from the characteristics of tensegrity easily reduces the experience of breathtaking and elegant solutions.

Would it thus be impossible to make exceptions from the stated rules with the fantastic and gainful properties of tensegrity generally remaining? How can a structure be changed, altered, still showing interesting tensegric features? Examples of the theoretical foundation for tensegrity are that: two types of structural members occur – rods/cables and bars/struts – active in tension and compression respectively; the inscribing structure must not contain any compressed members; the compressed members must not be in contact with each other.

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[328] Saitoh, M. 2001, p. 2
[329] Hanaor, A. in Gabriel, J.F. 1997, p. 406

A group of researchers at Delft University of Technology has regarded the strict characteristics trying to find applications for glass structures. Their main contribution to the discussion in this context is the inclusion of a surrounding structure, which is not part of the structural system. This makes the system open for static co-action, primarily for providing horizontal and vertical support reactions.[330]

To use plates in a tensegric basic unit would mean to introduce a completely different member. The use of a plate in a tensegric structure, as tensed or compressed member, would imply addition of a surface in the basic structure, making sheeting/membranes for covering purposes redundant.

The properties of a cross-laminated timber plate allow it, however, to take up both tension and compression effectively. When seeking applications for such plates in tensegrity structures, one can therefore theoretically put the plates in either of the two positions, either in tension or in compression. There is a problem though with the dual capacity, since a member in tension, which also can take up compression, will offer an alternate route for forces through the structure. A rod in tension will slack if the tension decreases too much and if exposed to compression it will not take loads. A timber member in tension will offer the structure to rearrange the forces and turn the tensioned member into a compressed one. This does not have to be a structural disadvantage, but it introduces an impurity in the structure, and makes its action more difficult to analyse visually.

Exchanging rods (the tensed enclosing structure) with plates would then result in a much less tensegric structure than the original one. The new tensed members would easily create a static redundancy in the structure, since forces are very likely to take a path when provided one. A plate as a compressed member, replacing one or some of the bars (the compressed core structure) would then be more interesting, since both the bar and the plate can take both tension and compression, but will not be exposed to tension since that would imply the rods acting in compression, which they are incapable of. To use plates in tensegric structures, a need appears for exceptions from the above stated rules, and for the stating of a set of new prerequisites.

8.2.2 A Plate-Structure with Tensegric Properties

Prerequisites

There are three types of structural members – rods, bars and plates – active in respectively tension (rods) and compression (bars and plates), or respectively tension (rods), compression (bars) and shear (plates); The inscribing structure does not contain any compressed members; The compressed members are in contact with each other for optimal structural function and architectural (utility) result.

Transformation and its effects

Regarding a single basic tensegric unit with three bars one can note in some arrangements that two of the bars are close to forming a plane. The third bar can then be viewed as perpendicular to this plane, penetrating it. A hypothetical new structure is created by exchanging the plane-forming bars with a plate, penetrated by the remaining third bar (*Fig. 8.5*).

[330] Eekhout, M. 2004

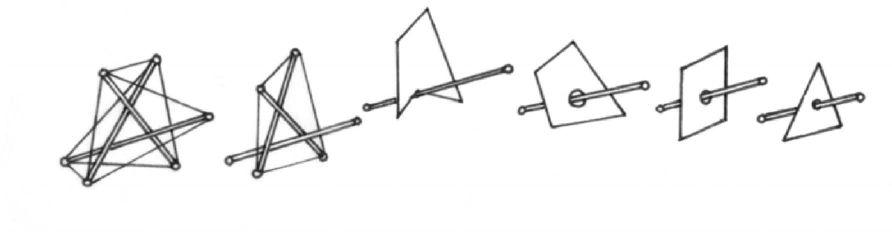

Fig.8.5 Transformation, made by the author, from tensegrity unit (far left) to plate tensegrity module (far right). (For graphic reasons cables are left out in the transformation.)

The result is a triangular plate-element stabilised by a bar and three rods. The new basic module consists of a triangular surface element, which can be repeated resulting in e.g. a roof structure, covered by the plates and stabilised and fixed by the rod and bar structure (*Fig. 8.6*).

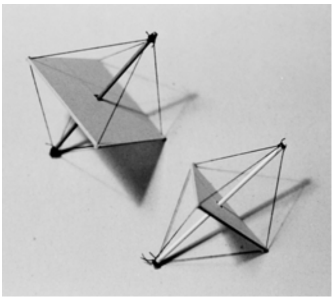

Fig. 8.6 Plate-structures with tensegric character.

One basic criterion for tensegric structures is that the envelope, i.e. the enclosing members of the structure must contain no compressed parts. ”[...] the ends of the compressed parts belong to the continuum of tension, whether one of them is, or is not, on the boundary.”[331] The structure fulfils this criterion, since all inscribing elements (rods) consist of tension lines only. Another criterion is that the compressed parts must not be in contact with each other. “A Tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components.”[332]

Fixing the bar at the penetration point creates a hybrid, a semi-tensegric structure. This introduces moment in the structure and breaks the second criterion, but still fulfils the first. The plate and the bar is then to be viewed as one 3D-element inscribed by rods. The bar could also be divided in two, with each half being fixed with non-stiff joints on each side of the plate centre. However, considering the

[331] Motro, R. 2003, p. 22
[332] Motro, R. 2003, p. 19

original criteria the structural behaviours in these cases are not regarded as interesting as the case with the penetrated plate and moment free bar.

Making a hole in the plate, letting the remaining bar go through the plate without touching it and be held in position by the rods only, validates the structure for this criterion as well. In this situation both the compressed members will be moment free. To secure the moment free state, in case of displacements, it should however be advisable to fix the bars with torus-shaped fittings, which keep them in place but allow movements in all directions around the penetration. The fittings also provide the advantage of reducing the buckling-length of the bars and sealing the roof structure.

To replace some of the bars with a plate changes the force situation since bars and plates transfer forces in different ways. Bars concentrate the forces and plates distribute them. A rod and bar structure is totally open whereas a plate structure is closed. A rod and bar structure with plates is thus a combination of those principles of appearance. In the same way as with polyhedra[333], elaboration with nodes and planes is allowed. "For lattice[334] structures the point (node) is the basic element and two linked points define a bar, whereas three points define a plane, which is a non-active open mesh. For plate structures the plane (plate) is the basic element, two linked planes define a line (shear-line) and three planes define a vertex."[335]

To replace some of the bars with a plate is a method of reducing the number of members with remaining spatial extension. In a single plate module, regarding the plate as one element and the remaining bar as one, the basic description of tensegrity still fits, concerning the structural action – they are free to move in all directions in relation to each other, around their common centre; the core is compressed and the enclosure is in tension.

This method of reduction has been applied on bars, connected through the application of internal joints[336], varying the tensegric unit to obtain a better function concerning structural capacity and material optimisation. The plate in the plate tensegrity module is in its singular state active only in compression. In an arrangement with repeated modules it can be active in shear as well, depending on the type of jointing.

Structural behaviour

A condition for original tensegric units is the pure action of its members – rods active only in tension and bars active only in compression. To follow this principle the plate could be regarded and utilised primarily for its own featuring characteristic, the shear-capacity. The aim should then be to purify the structural interrelations.

In a single unit, the plate takes up compression forces transferred by the rods in tension, like the bar. In relation to neighbouring plates in a constellation it has potential to be more active in shear and the overall structure should be designed to support this relation. The plates in the units will then have to be in contact with each other, with neighbouring plates to create a continuous plane, in this case providing the main path of transference of lateral loads.

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[333] *A* polyhedron *is a 3-dimensional geometric form or solid body with an enclosing surface built up by a number of* facets. *The lines formed by the interfaces between neighbouring facets are called* edges *and the points where three or more plates/edges meet are called* vertices*.*

[334] *A polyhedron can be turned into a* lattice structure*, by replacing the edges with* bars*, the vertices with* nodes *and by taking away the facets.*

[335] Wester, T., in Gabriel, J.F. 1997, p. 317

[336] Wang, B.B. and Li, Y.Y. 2003, pp. 97

Seen in this repeated arrangement, the series of plates can be regarded as one internally flexible plane enclosed and kept in place by rods acting as continuous tension at a distance decided and kept by the bars (*Fig. 8.7*).

Fig. 8.7 Side view of a modelled plate tensegrity assembly.

8.2.3 Member Types

The design of elements in a structure depends on the needed function. In masts and deployable tensegric structures both joints and elements may be movable, and elements extendable. The most common deployable structures are composed of bars. Antennas and similar structures, which need to be stowed in small volumes tend to be composed by primarily tensile members.

In the plate tensegrity module there are three element types: four cables, one bar and one plate. They all have fixed dimensions. Their performance may be modified to better performance and a higher over all behaviour. Tensioning of the cables decrease the risk of slackening through compression. For increased efficiency in any load bearing structure as much of the loads as possible should be transferred to tension forces. If e.g. a structure is stabilised by cross-bracing cables, deformation of the structure tends to put one of the cables in tension and the other in compression and thus slacken the latter. If the cables are pre-stressed, the same deformation may lead to increased tension in the first cable but the compression of the other cable will only result in decreased tension.[337]

It is important to choose the type of tension members. In structures like the equestrian hall in Flyinge it is accurate to speak of and use rods, which are stiff members, commonly of steel showing little strain under tension load, with primary capacity to take up tension forces. The behaviour in compression is not as obvious, however, though they actually do slacken. The stiffness of the steel makes the rods less flexible so the behaviour in compression is not easily observed. In the current context, where the theoretical starting point is refined structural behaviour and the visual expression is important for the structural experience rods are not optimal elements. Cables can be manufactured in steel-wire or carbon-fibre and show more obvious slackening behaviour in compression. Therefore cables should be preferable to use as structural element in the plate tensegrity unit.

[337] Schlaich, J. 2004, p. 163

8.2.4 Joint Types

In an ideal, hypothetic situation the elements are dealing with one single type of force each. Optional joint types to be applied are nodal hinges at the plate-corners, or continuous hinged joints along the edge-lines. Bending moments must not be transferred between the members. The nodes distribute axial forces – tension and compression – between elements. The linear hinges distribute shear between the elements – tension and compression are transformed into shear between the elements. With nodal joints the plates act horizontally as beams, spanning between the nodes, concentrating the forces. With continuous hinges the plates transfer forces from plate to edge to plate by spreading the forces.

For proper action the joints between the plate modules in the system must be hinged, to avoid moment between the modules. This assembly of plates is in some aspects similar to a polyhedral structure, composed of plates that are rigid in plane and hinged together along shear lines. A line-hinged plate continuum is based on active shear lines between the plate modules. The optimal action is obtained with an unbroken series of plates.

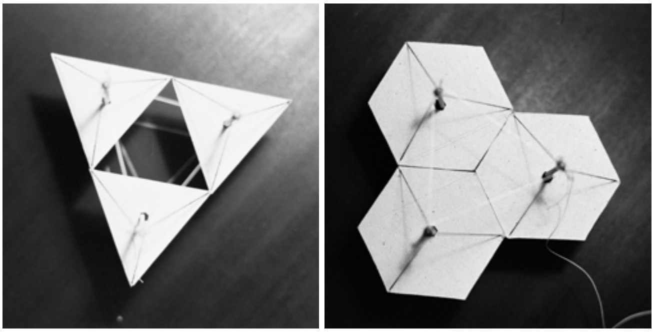

Fig. 8.8 Basic triangular plate modules (left) and cantilevering ones (right).

A node-hinged plate-structure allows for breaking up the structure, creating openings, as long as the forces are transferred between the nodes. To reduce the complexity of the cable-arrangement every second plate module can be excluded and the remaining structure is a visually broken one letting the light through. The openings can be covered with a transparent membrane or be left uncovered. To cover the openings structurally the remaining plate modules can cantilever, partly or totally covering the openings (*Fig. 8.8*).

The plates are still fixed with three rods but the plate shape is a hexagon instead of a triangular plane. If fully cantilevered the plates meet again, along new shear lines and in vertexes. Between the triangular-based and the hexagonal-based patterns there can be many varieties (*Fig. 8.9*), similar to descriptions of framing of plate polyhedra[338] and also form experiments by the Dutch artist M.C. Escher[339], whose work has inspired to studies of shell-patterns[340].

[338] Wester. T 1984, p. 43
[339] Schattschneider, D. 1990
[340] Huybers, P. and van der Ende, G. 2001

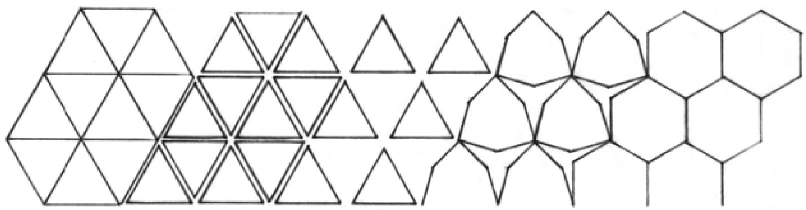

Fig. 8.9 A variety of plate-combinations: From plate modules with linear hinges (to the left) to nodal hinges (in the middle) to linear hinges (to the right).

The outcome of this theoretical/hypothetical section can be summarised in two points:

- Identified problems with practical uses of tensegrity.
- Potential increase of load-bearing capacity and performance of timber-plates.

which are to be dealt with from an application point of view below.

8.3 Applications of Tensegric Plate Structures

8.3.1 Problems to Solve; Advantages to be Found.

The structural potential of tensegrity has been treated many times[341], and some authors have addressed the architectural potential as well[342]. The reason for this may be the viewpoint that architecture = sculpture, which in this thesis is not the case. Sculptures seldom fill other functions than pure aesthetical ones whereas architecture concerns structural, functional and aesthetical properties at the same time.

Regarding what has been built with tensegrity so far, doubts about the architectural use are reasonable since rather few functional applications, except for masts, have crossed the border between computer modelling and physical world in full scale. Tensegrity in its original design bears merely too rigid, fantastic characteristics to be turned into usable reality. If the definitions are somewhat modified, however, the possibilities seem to unfold.

The application of plates in cable-stayed structural elements casts a new light on tensegrity structures and the principles and definitions concerning them. Pure tensegrity structures consist of continuous cables and discontinuous struts. These structures possess several interesting features, from both technical and architectural points of view. In terms of utility, however, there are a number of problems associated with tensegrity.

The attachment of covering surfaces, stabilisation of members, connection design and deployment technology have been regarded as unresolved questions.[343] Masts and irregular space frames for exhibition purposes have been constructed, but tensegrity-like structures for more common applications are still few.[344]

[341] By e.g. Fuller, Motro, Hanaor, and Wang
[342] Wang, B.-B. 2003, p. 109
[343] Hanaor, A. in Gabriel, J.F. 1997, p. 406
[344] *E.g. so called cable domes by Geiger and deployable masts as treated by Tibert (2001)*

One reason for the problem of using the tensegrity concept for covering spaces might be the absence of a surface element in the original definition. For example, adding a pre-stressed membrane on top of a space tensegrity structure introduces disturbing forces in the initial tensegrity configuration and makes erection and pre-stressing difficult and structural behaviour, in terms of load sharing between various elements, difficult to analyse to a certain degree of reliability.

By introducing a surface element in a cable-stayed structure such as a basic tensegrity unit a tight surface for e.g. rain protection or sun shield is achieved, and the joint zones can be sealed with gaskets, sealing fabric or rubber sheets.

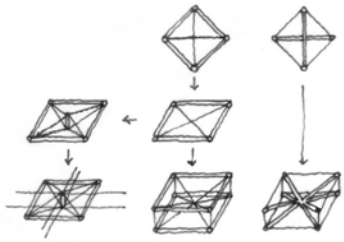

Fig. 8.10 Three types of the tensegric truss/unit system described by Saitoh, M. et al.

Different types of similar truss structures have been described before by e.g. Saitoh et al.[345], Hangai et al.[346] and Wang[347] (*Fig. 8.10*), where bars in the units are connected to each other to form a continuous framework. The main difference to the one currently described is the use of a plate, instead of bars in the middle layer. The plate provides shear stiffness to the middle layer without significantly altering the load paths in the structure. As mentioned above, the plate also functions as roof covering integrated in the main load bearing system, whereas in systems like those previously described, it has to be attached afterwards.

8.3.2 Applications

The first studies of physical models resulted in triangular and hexagonal plates with a 3-node restraint. With these basic modules, or plate simplexes, different covering surfaces can be created. Plane assemblies with horizontal or inclined orientation can form e.g. sheltering structures of varying designs. The applications can, for example, be long-span roofs over arenas, exhibition halls, flight terminals and industrial units.

In plane assemblies there are tension forces in the cables in the upper and lower plane nets. The plates take up compression forces in the direction of the span and stabilise the assembly through shear action i.e. against lateral forces.

Tensegrity structures are flexible due to internal mechanisms and for certain load-cases significant displacements are inevitable. A definition of tensegric structures has e.g. been formulated by Motro [348] as ”a system in a stable self-equilibrated state […]”. This is a problem when leaving the field of sculptural art where Snelson is so

[345] Saitoh, M. et al. 2001
[346] Hangai, Y. et al. 2001
[347] Wang, B.B. 1996
[348] Motro, R. 2003, p. 19

creatively active.[349] This also alters the prerequisites of the ideal, hypothetic state described above and introduces impurity in the force distribution.

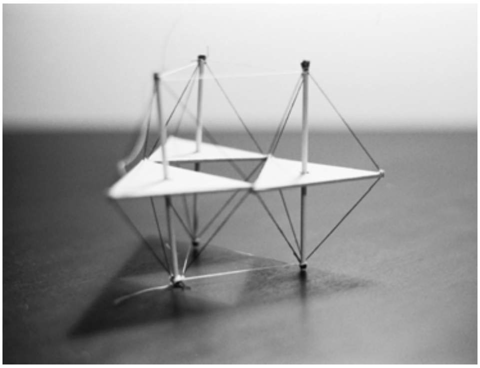

Fig. 8.11 Plate tensegrity assembly model with internal cables (black) and external cables (white).

The cables only connect to the peripheries of the strut and the plate and circumscribe in this way compressed members with tension, as in the original simplex (*Fig. 8.11*). In an assembled state the strut end joints are further interconnected with cables to neighbouring plate modules. On both sides of the plates cables form cable nets active in tension. As plate in the tensegrity module, a cross-laminated timber plate is chosen with a timber post as strut. The strut length can be adjusted for sufficient tension in the cables by a turnbuckle at the lower strut end. The turnbuckle enables both pre- and post-stressing of each module.

By fixing the plate tensegrity modules at an angle to each other, curved shapes and other 3-dimensional surfaces can be obtained (*Fig. 8.12)*. The load transfer may in this way be more easily handled and deformations and deflections decrease.

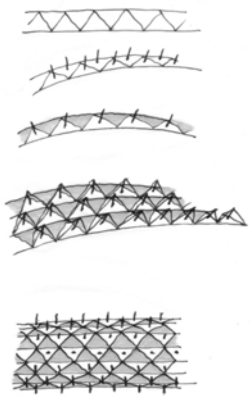

Fig. 8.12 Repetition of triangular plate tensegrity units in curved assemblies.

[349] *For structural uses deformations and deflections had better be decreased to a minimum.*

In curved assemblies the tension and compression forces in the plate elements increase; in a convex arch shape the compression increases and in a concave shape they start to act in tension as a hanging roof. Double curved, hyperbolic structures are possible to create, but demand different shapes of the plates and more intricate work with methods for assembling and erection. A single curved structure is feasible with a uniform design of the modules, i.e. a single plate-element type.

In a square plate unit the tensile state of the cables is not guaranteed. The four cables easily counteract each other and moment appears. A triangular plate with a three-node restraint moment is efficiently avoided and is thus more statically suitable.

However, for reasons of modular simplicity suiting rational and economic, repetitive production a square plate element has been proposed for the aim of creating a circular curved structure.[350] The modelling that has been performed so far (described below) concerns straight assemblies of square plate units.

8.3.3 Calculations

The nature of the tensegrity structures as they were originally defined makes them difficult to calculate. In perspectives of mathematics and static analysis their behaviour is termed static indeterminacy. An important part of the almost magical appearance is a result of the redundancy of a statically indeterminate system. Tools and methods for treating these complex reticulated structures were not available at the time of the invention of tensegrity. The development of numerical analysis methods of form finding have however provided an excellent tool and in theory made the architectural applications more reachable.

The structural behaviour of the plate tensegrity module and assemblies has been modelled and analysed by turning the plate into an equivalent framework.[351] The assemblies considered in these analyses are shown in *Fig. 8.13-14*. Results from the structural analysis and computer modelling, performed by PhD Gunnar Tibert at KTH Mechanics, show an increased stiffness with increased strut length (*see Appendix IV, Fig. 6*).

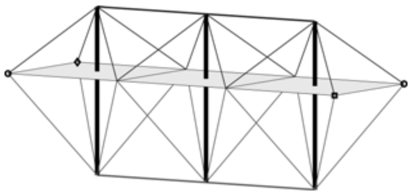

Fig. 8.13 A plane three-plate system with the shorter part of the strut above and the longer part under the plate.

An assembly with five units shows, as can be expected, higher stiffness than an assembly with ten units. The behaviour is linear in both cases. The units in the modelling measure 1 × 1 m^2 and the strut length is 1 m. Modifications of the strut length show an increased stiffness with increased strut length, as a result of lever action. The struts acting as levers increase the stiffness around the plane of the plate, where the compression is transferred.

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[350] Falk, A. and Tibert, G.A. 2005
[351] Falk. A. and Tibert, G.A. 2005

In the modelled structure the upper cable is allowed to slack. The criterion for failure is that the structure fails when the second cable slackens. Thus, the model shows a beam with the plate as upper flange and the lower horizontal cable as lower flange.

The modelled loading show a reliable behaviour for loads by far exceeding the variable loads from snow and wind during normal conditions in Sweden.

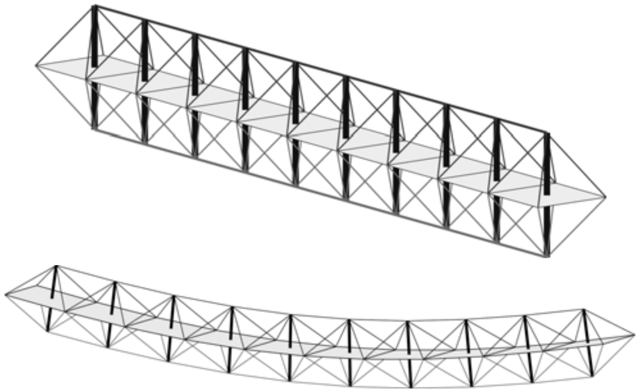

Fig. 8.14 A straight plate tensegrity assembly in an unloaded and a deformed shape of a straight ten-plate system (displacement scale factor = 10).

8.3.4 Solutions for Joint Zones and Connections

In the basic module there are only pure tension and pure compression forces. In the assembly however shear appears as a third force. With the originally discussed configurations two different joint scenarios are possible: either triangular modules are connected to each other with nodal joints, or hexagonal modules are connected edgewise along their sides.

In the first case the plates will distribute the compression forces in the elements between the nodes by shear but there will not be any shear in the joints. In the second case with contact along the edges the joints will be active in shear as well, thus the assembly will act with continuous shear-plate action.

There is a dual nature of this basic module, since either the plate or the strut can be chosen as its centre. The plate should be able to have different angles both to the strut and to other plates. The plate can be viewed as a cable-stayed surface, with the strut ensuring that the cables remain in tension and the plate remains in compression. The strut can be viewed as a cable-stayed column, with the plate securing that the cables remain in tension and that the strut remains in compression.

There are two levels of joints. One level is the internal joints in each 3-dimensional module. Another level is the external joints fixing the modules to each other, keeping the shape of the assembly. The joint types that are needed to study are of four kinds: cable-strut, cable-plate, plate-strut and plate-plate as shown in *Fig. 8.15*, with numbers referring to the numbered sections below.

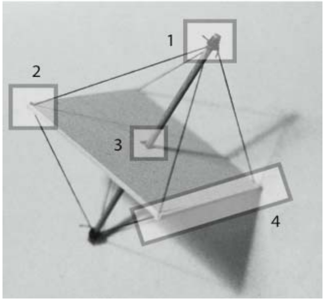

Fig. 8.15 Joint zones in the plate tensegrity module.

Internal joints/Level I

1. Cable-strut connections fix the cables to the strut, thereby restraining the strut at both ends. The cable-strut connections secure tension in the cables at opposing sides of the module/assembly. These end details can be seen in *Fig. 8.16*. At the lower side of the element the strut end joint is provided with a turnbuckle to allow tightening of the module.

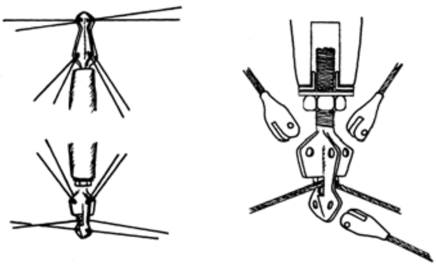

Fig. 8.16 Cable-strut connections and lower strut end joint with turnbuckle.

2. Cable-plate connections are used to keep the cables in place at the plate corners, to make the cables fix and stabilise the plate in its plane. The plate secures the tension in the cables and the compression in the strut by keeping the distance between cables and strut centres. These joints can be designed as wheels or pulleys fixed on the plates. The joints should be possible to fix once the assembly is erected, before loading. Detail is shown in *Fig. 8.17*.

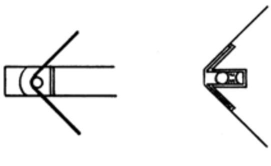

Fig. 8.17 Cable-plate connection, section and plan.

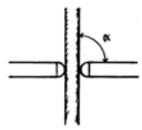

Fig. 8.18 Plate-strut connection.

3. Plate-strut connections centre the strut in the perforation of the plate.[352] The orientation of the covering surface can be designed independently from the orientation of the stabilising strut and net structure as in *Fig. 8.19* but depends on the designed cable lengths.[353] The joint should be moment free. This could be achieved with the strut running through a simple hole in the plate without contact, only kept in place by the cables. For sheltering, however, the joint should be possible to seal, not allowing water to come through the hole (*Fig. 8.18*). This is achieved with a torus-shaped rubber socket in the perforation. Such a joint also reduces the buckling length of the strut.

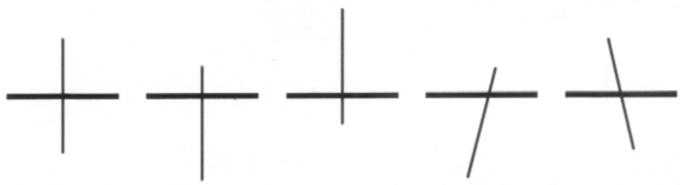

Fig. 8.19 Different strut positions in relation to plate.

External joints/assembly/Level II

1. Cable-strut connections stabilise and secure shape and co-action of the overall structure. The cables that stabilise the overall assembly by linking the modules to each other are fixed to the strut ends and form two cable nets, parallel to the plates on each side. The cables on the upper side are discontinuous, connecting the struts in pairs along the span.

Perpendicular to the span discontinuous cables link between each spanning section. The joints are designed to take up forces mostly perpendicular to the struts. The cables on the lower side are continuous in the spanning direction and discontinuous perpendicular to the span.

The continuous cables are used for tensioning of the span and are tensioned momentarily during the erection until the final radius/shape is obtained. The discontinuous cables are used merely to fix the modules laterally and to transfer forces in this direction. The cable-strut joint is designed as a pulley over which the continuous cables can run and which can lock when the tightening is achieved. In the lateral direction end details as in *Fig. 8.16* serve as suitable joints.

[352] *The strut could also have been divided into two parts, fixed with hinged joints on each side of a plate without penetration. This, however, would further modify the original criteria for tensegrity and has therefore been chosen not to deal with here.*
[353] *Different angles between strut and plate require different lengths of the inscribing cables.*

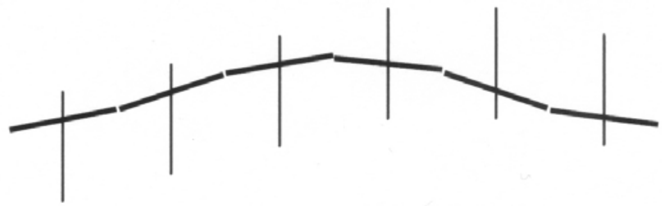

Fig. 8.20 Varying plate orientation in an assembled state.

4. Plate-plate connections stabilise the assembly and are to transfer forces between the plates. They should act as hinges to allow the plates to shift angle in relation to each other e.g. as in *Fig. 8.20*. One solution is to use thin metal plates bent over rubber battens. This joint is fastened between the plates as a pre-fabricated package.

Another solution is to fix steel hinges on each plate pre-assembly. The joints transfer shear forces in the structure, between the individual plate modules. The same type of joints, shown in *Fig. 8.21*, can be used perpendicular to the span, linking the curved plate sections to each other.

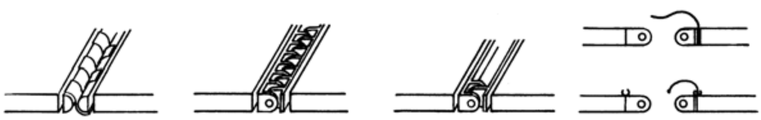

Fig. 8.21 Plate-plate connections; possible designs and sealing.

The joint design should match the erection method. Across the structure in the direction of the span the plate-plate connections are to be fixed one at the time and precision is fairly easy. In the perpendicular direction, the plate-plate connections are to be fixed section-by-section, which makes precision more difficult, since the curves must match for fixation.

a) plate-plate connections meet half-in-half and are fixed with bolts

b) plate-plate connections are designed as linking steel joints mounted after the plate sections have been erected

8.3.5 Assembling Techniques and Erection Methods

A common structural application for tensegrity designs is deployable structures such as masts and retractable membrane roofs. The element designs for such structures are often utilising scissor or pneumatic telescoping methods for unfolding and folding.[354] Both joints and elements can be utilised for the flexibility; joints are movable during the change of shape and must then be fixed; the elements can be adjustable in length extending into their final position tensioning the cables.

The demands of non-foldable structures may be less complex, the joints less intricate, but the assembling and erection of the structure may as well put equal or similar demands on the joints. Most tensegrity structures rely on self-stress in a stable

[354] Wang, B.B. 2003

equilibrium, which is not obtained until the final position is reached by each of its members. Until then the structure is on the verge of collapse.

The erection may thus be a delicate task and the adjustments of the final structure a time consuming iterative process of tightening cable-by-cable, joint-by-joint. The structures must be designed to manage two different loading-conditions, one during erection and one during its service life. Both joints and elements must be designed for this two-step nature of the static context. For swift assembly simple joints and stable modules are prerequisites.

Freivorbau erection of the plate tensegrity single curved roof:

Freivorbau is a method where a structure is assembled element-by-element and momentarily erected in the aimed shape, without temporary supports. A spanning structure like a bridge, or in this case a section of a roof, is constructed from either one or two sides until the span is complete. Cranes will be needed to lift the modules and keep them in place until they are fixed. During the erection the elements and joints are supported from one side only. When the structure is fixed to its other support the flow of forces is balanced.

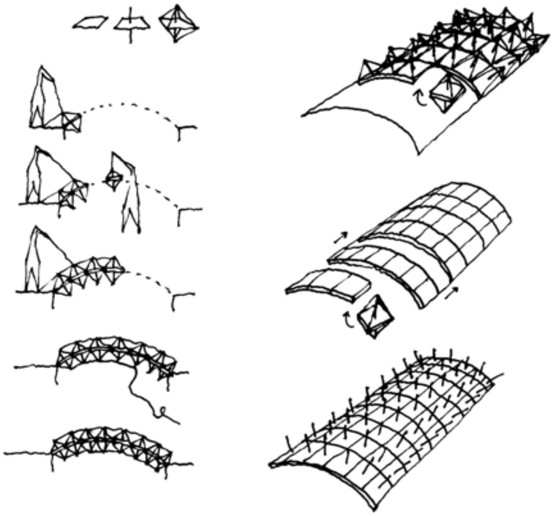

Fig. 8.22 Plate tensegrity version of Freivorbau.

In case of a plate tensegrity structure the plates of the first plate modules are fixed to the abutments at opposite sides of the planned span in the desired starting angle. The first cables are fixed to the upper end of the strut. The second plate is fixed to the first with plate-plate connections at a new angle – to describe the facetted outline of the desired curve – and upper side cables are fixed to the strut of the second module. And so on along the span.

In this way the span is hanging, supported by the cables on the upper side during the erection, cantilevering until the spans reach and meet at the apex. The cables on the lower side can be put in place and momentarily tensioned along the span during the erection, or they can be placed and stressed when the section is finished. When one section is finished the next neighbouring section is erected (*Fig. 8.22*).

Jacking method for erection of the plate tensegrity single curved roof:

The method regarded here is to assemble a complete section or the entire structure flat on the ground (*Fig. 8.23*). Jacks can be used instead of cranes to push the structure up from the ground into its final shape and place. In a curved structure the joints have to allow continuously changing angles between the elements during the erection.

The elements of the plate tensegrity structure are assembled into tensile modules, cables tightened by the strut end turnbuckles and the modules are fixed with plate-plate connections on the ground. The upper strut ends are connected with slack cables to allow the desired curvature. The length of the connecting discontinuous cables on the upper side decides the radius and shape of the curvature.

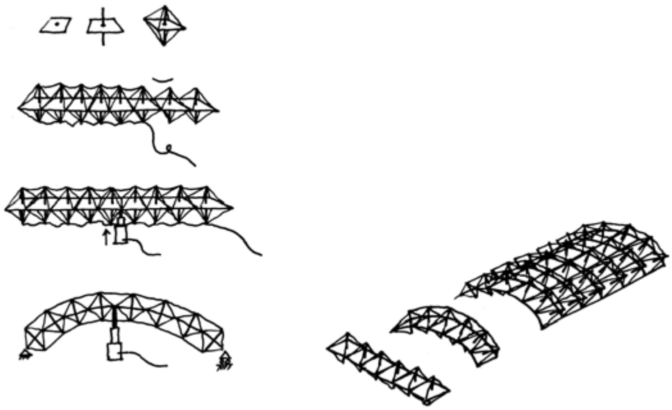

Fig. 8.23 Jacking method for erection of the plate-structure.

The curvature is obtained when the structure is jacked in place; the shape is then fixed by tensioning the continuous cable on the lower side. The structure is erected section-by-section, fixing the lateral plate-plate connections between every section. The sections can be erected over the abutments and directly jacked in place. Otherwise they can be erected, tightened and fixed, and then lifted in place and fixed to the other sections.

When all sections have been erected the joints of the continuous lower side cables can be tightened and fixed at each strut end and the cables in the lateral direction can be fixed connecting the strut ends creating the cable nets. With the turnbuckles the final adjustments of the cables of each module can be made.

8.4 Plate Tensegrity in Short

This theoretical study has described the results from a first evaluation of plate tensegrity as modules and assemblies. Substitution of the plate by a deformation equivalent framework, enables the use of robust, numerical methods for the analysis of statically indeterminate bar frameworks. A suitable analytic tool is thereby available. The stiffness of a plane assembly under normal loading is mainly governed by the axial stiffness of the bottom cable. The geometry of individual modules affects the displacement and cable force magnitude but not the load level at which the cables become slack.

Also described are the desired behaviour of the modules in assemblies, erection methods and possible designs for joints and joint zones. The joints should fulfil three criteria: simplicity for swift assembly and erection, adequate movement and orientation flexibility between the parts and water tightness. Suitable joint details which fulfil these criteria have been proposed, matching a reasonable method for erection. With this type of structure a large number of vault applications are feasible. It is e.g. hypothetically realistic to replace the roof of the recently erected equestrian hall in case #7: FLY in the case study on advanced structures (*Fig. 8.24*).

Fig. 8.24 Comparison between the principles of an ordinary frame, a roof truss, the rod and trestle structure in Flyinge and a solution with plate tensegrity.

Either the entire length of the structure is composed of sections of plate tensegrity modules. Or the plate tensegrity modules are spaced and their intermediate spaces covered with simple plane plate elements, supported by plate tensegrity arches (*Fig. 8.27*). Symmetrically curved structures need further modelling and analyses of behaviour under load and in buckling and so do asymmetrically curved structures.

8.5 Analysis

8.5.1 Architectural Variety

The range of possible forms and properties is wide. The technical possibilities pointed at here cover both tight roof structures and partially open ones. The architectural aspects can vary between the need for a continuous surface for a tight roof and the gains for architectural treatment of light through the structure (*Fig. 8.25*). There can be a play between parts and modules with variable cantilevers and in pattern-changes.

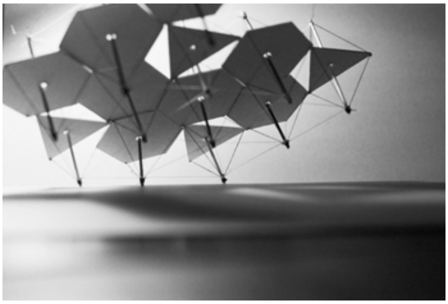

Fig. 8.25 A combination of hexagonal and triangular plate modules.

In a shear-line based structure with hexagonal plates some modules can be left out or be replaced by plain plates, which can be designed with cut-outs. The plates are then used as frames, as studied in FEM-models by Lee et al.[355] The capacity of force distribution in the plates allows for variable design and treatment of the plane area between the plate-edges.

A structure with line-hinged hexagonal plates could also change locally into being node-hinged, creating a variety of the resulting surface design as in the model photo in *Fig. 8.26*. Depending on the needs one can pick and combine modules of different design properties. Though the rules of tensegrity have been somewhat changed, the possibilities of structural elegance, repetition of well elaborated detailing, and an expression the visual complexity being higher than the actual structural one, still are notable.

[355] Lee, H.P. et al. 2003

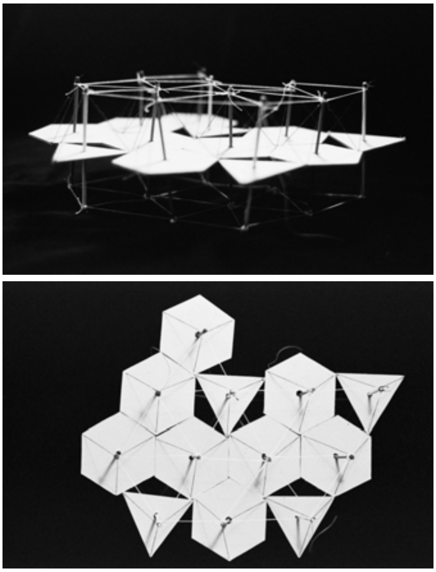

Fig. 8.26 A varied plate tensegrity assembly, view from the side and from above.

8.5.2 Theoretical Tensegric Potential

With different degrees of structural complexity, possible applications are e.g. roof structures composed of a small number of big-sized plates, reaching quite large spans in a few steps. Examples of this are as mentioned conventional pitched roof structures for halls of different scales, but also small-scale objects like single-family houses. Tensegric units can form different types of vaulted structures, with a continuous tensegric structure or with plane elements or boarding between curved (or straight, inclined) tensegric trusses (*Fig. 8.27*). This principle was used in the saddle roof of the project in Krakau, seen in *Fig. 7.1* (*Section 7.1.1*)

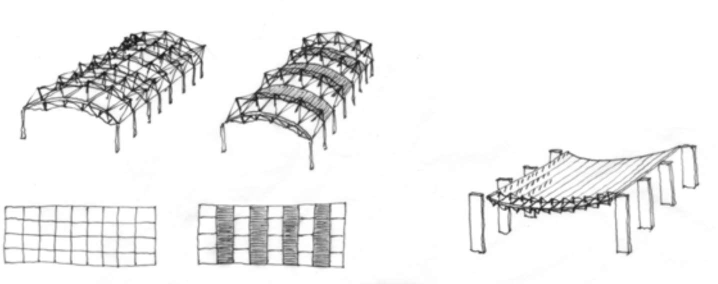

Fig. 8.27 Vaulted plate structures in perspective and plan and a hanging roof.

The computer model of the straight assembly showed that the bottom cable was of primary importance for the overall stiffness, since the top cable was slackened almost immediately. Under load the active depth of the structure was reduced to the distance between the plate elements and the bottom cable. Hypothetically, this means that the top cable could be omitted, not only in the computer model, as done by Wang[356], but also in the full-scaled structure. However, the straight assembly must stand and be stabilised against uplift forces as well, which result in a tendency towards a vault shape. In this case the upper cable is necessary. In a vaulted assembly the upper cable is necessary to fix the structural form during erection and to stabilise it in its finished state.

Models of plate based tensegric structures tend to be stable when the inscribing tension is completely obtained fixing all members, and act with overall stiffness. More and deeper studies are however needed, as well as calculations and computer-modelling, and full-scale physical models. It can however be stated already at this stage, that the combination of plates and tensegric-based systems show a thrilling and promising potential, both structurally and architecturally (*Fig. 8.28*).

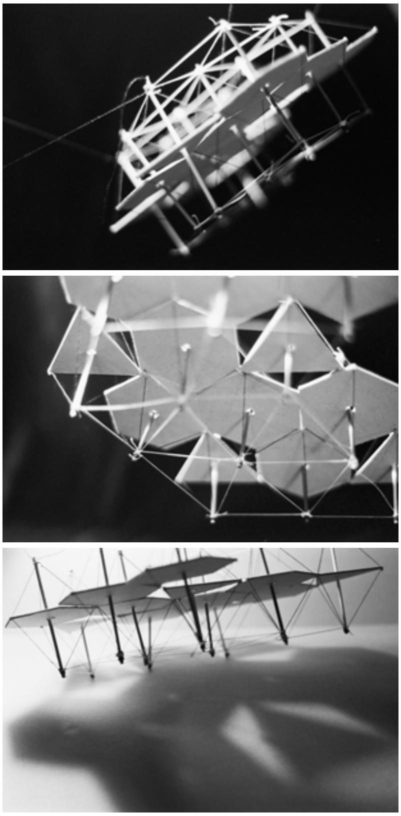

Fig. 8.28 Model photos of plate tensegrity spatial structures.

[356] Wang, B.B. 1996

9 CLOSING

9.1 Discussion

9.1.1 Method

In this work case studies and sketching have been used as tools for the study of massive timber architecture, construction and development. The case study methodology provides a form for collecting and analysing information. It is not the nature of case studies to support generalisation in a wide meaning. It is however possible to do analytical generalisation, where "the investigator is striving to generalise a particular set of results to some broader theory"[357], as has been discussed in *Section 1.2.2.* This has suited the work in this thesis and has lead to useful findings.

The research questions were rather widely formulated. They could have been more specific and less inclusive. They have, however, served as efficient searchlights and matched the holistic approach of the work and provided to the forming of a contextual understanding. Matters to be focused on in further studies have also been revealed and opened up.

The findings have been analysed and used as a foundation for further discussions on the central topic. The disparate types of the cases in the two different case studies have provided the desired overview of possibilities, potentials and problems of the structural applications of massive timber realised so far.

The case study on building systems has provided a relatively brief overview of different approaches to system applications, where several aspects have not been covered. The case study on building systems could have been performed as a single-case study like the one on advanced structures. This would have enabled the study of more aspects of a single case and a more thorough and complex illustration of that structure. The depth would, however, not have been fruitful in the context of this work, where the wide range has been more useful in order to reach the desired overview of the structural potential.

The sketching has been used as an efficient tool for initial analyses of hypothetical steps of structural development. Available knowledge and experience decide the reliability of sketching as an initial method of form finding. By the use of literature and studies of projects on site it has been possible to iterate the structural principles and solutions.

Analytic generalisation and comparisons between different sources, both case-specific and general technical reports, have enabled validation of the findings.

9.1.2 Case-studies, Analyses and Theoretical Extensions

This thesis contains two parts: one part on building systems and one part on advanced structures. Construction at large can also be divided into two approaches: production en masse and production for special, more or less unique projects. The two approaches to construction can be applied on both building systems and advanced structures.

[357] Yin, R.K. 2003, p. 37

A case study has been performed on building systems. On advanced structures a case study and a theoretical study have been performed. The two case studies have treated different aspects of massive timber products in construction, i.e. two different approaches to utilisation of building products on the market.

In the study on building systems the structural spans are relatively small, technical solutions are to suit rational assembly and the aimed production volume is large and repetitive. The planning has concerned structural systems and rational production and utilisation of those. In the projects, much work has been put in system development, which together with the function of the production chain is decisive for the competitiveness of the utilised system. For these structures aspects such as production, acoustics and detail design are of great importance, which generates a high degree of co-ordination complexity. The study has come to focus on architectural and structural effects of the *material in the process*.

In the study on advanced structures the structural span is wide and the project has been aimed at the production of separate objects. The planning has concerned development of static co-action and the architectural expression of this. The utilisation of material and element properties are decisive for the production and function of the utilised system. Load-bearing, stability and sustainability are of main importance and the structural relationships has to be refined. The study has come to focus on the architectural and structural *performance of the material*.

The theoretical study on advanced structures has utilised the findings from the case study and from literature studies for the design of a new structural element and possible applications for this. The study has tried to capture the essence of form finding and structural morphology in the case of large span applications of timber-based plates.

Building systems

Thus there are two ways to optimise building systems: one rationality for more complex forms (i.e. surface-elements) suited for optimised utilisation of plate-specific structural form and one rationality for repeated simplicity (i.e. volume-elements) suited for optimised production. The plates are robust and stiff and stand long transports. As volume-elements they can protect a high interior finish even with fragile interior additions. Massive timber elements allow wide freedom of adjusting and perforating both in advance and on site, which enables the choice to place installations when it is considered most efficient, either early or late in the building process.

For field factory production plane timber-elements can be completed to a relatively high degree, still being 2D, with surface layers and preparations for installations. They are easy to load for transport and to deliver to the site in an economic way as compact packages. The different tasks are carried out at the stage where they are dealt with most efficiently.

Experience from the projects presented in this thesis points at reasons for restricting the number of storeys to three or four. One reason is the increased demands concerning fire-safety from four to five storeys. Another reason is the magnitude of forces that must be handled, e.g. hold-down forces and wind loads. Five storeys have also been regarded as unnecessary in Sweden where there are many areas where the city plans allow three to four storeys.

Experience also shows that a project may very well fail from a mismatch between architecture and structural engineering. In the case with Sundsvall I the utilised building system was neither complete nor tested at the start of the project and much effort had to be put into tests and development during the construction phase. The workers on site were not used to working with timber in construction, which in this case lead to problems during erection. This situation can, however, be compared with a) the case Spöttlgasse, where the workers were not used to massive timber construction either, but where this was not regarded as problematic and b) the case Flyinge where the structure was erected by highly experienced workers sent out by the element supplier.

The experience of the workers is thus not the most crucial factor, but rather whether the project has been designed for the current system. In other countries massive timber elements have been produced for a number of different building systems, like e.g. systems from Klimaplan, Merk GmbH, KLH Massivholz GmbH, Lignotrend, Santner Holz Bau Element and STEKO.[358]

The building should be architecturally and structurally designed for the chosen structural system and the system should be developed to a functional degree. When a timber building is desired the importance lies in drawing and planning for timber. That is when competition tends to become realistic. The cases in Sundsvall show lack of competence caused by a mismatch of architecture, structural design and system-based demands.

The architectural result in massive timber depends on the chosen prefabrication/modularisation and how closely this is followed. To use massive timber as an anonymous covered structural servant risks limiting the competitiveness. It is important to define which features to compete with and why.

The cases in this thesis show different applications of massive timber and also different ways to utilise the properties of the products. Features of potential utility are for example uncovered timber surfaces providing to an even indoor climate, elements of large sizes for shear-plate action, beam action, frame action around openings and combinations for the build up of floors with hollow box-sections. The utilisation of the potential benefits from the plate elements and structures depend on the type, size and aim of each project and how it is planned.

The choice of a modular solution thus depends on the desired result, whether there is a demand for optimised rationality during construction with a simple, pragmatic result, or a demand for a more laborious, complex and time-consuming production and a richer, more varied result. If the project is strictly planned for the system and all players are aware of their responsibilities, soft values like indoor climate or wood feeling can be enough to compete, even with a covered or partly covered structure. An obvious, revealed visual wooden appearance and a salient structural form, generated by the used products may, however, add to this.

Advanced systems

In advanced systems the low stiffness-to-weight ratio can be utilised for relatively light, high performance structures. The composition of the cross-section can improve the behaviour of the plate in itself to manage more load and different uses. With rods, cables and trestles the capacity of timber-plate structures can be further increased and elaborated to an emphasised structural form in interplay with the created space. The lightness is at the same time a potential problem for stability, which places demands on an otherwise presumably simple solution for the foundation. Thorough planning for the intended structural system is as important as in the case with a residential block.

With a wider open space, often inherent in the large span, it can be easier to motivate an increased level of elaboration concerning the structural design and joint detailing.

[358] Limberg, T. and Willemsen, T. pp. 30 – 47

There are more possibilities to make architectural use of a structural identity and its characteristics since the structure and its impact on the created space grows in scale and magnitude. It becomes a more evident tool for advertising the client, the achievements of man or just a thought-provoking/exciting structural experience. Plate-based advanced structures do not suit every structural context and not every built environment, but they provide a structural alternative in projects where the form of the structural elements is of importance for the intended use and for the client and/or intended public status.

The complexity and developed structural performance of elements and parts in the advanced systems dealt with in this work tend to turn their applications into more or less unique projects, like the case on advanced structures. There are different deciding factors, for example the technology being new and the type/scale of the project. The concept of utilising plate action in large elements is rather efficient and by refining the assembly of the elements the production competitiveness will increase.

So far, curved timber-plates are quite labour-intensive and costly. This is also the case for tensegric structures today. There are advantages in the lightness and in the refined efficiency, however, which very well motivates an increased use and further developed they should be possible to manage within smaller budgets.

Theoretical extension

The theoretically extended search for material- and product-based structural form has entered the area of not yet seen structural types. Seen in the light of the advanced applications dealt with in the case study on advanced structures the step is not unrealistic and the first analytical tests have shown a structural efficiency that make further analyses and also tests in a physical reality in larger scale than small cardboard models reasonable.

Plate tensegrity is the result of a form finding process in search of an architectural-structural utilisation of material-characteristics. The result mirrors the theme of the entire work and should be referred to as an example of material- and product-based design with both architectural and structural benefits.

9.1.3 A Characteristic Timber Architecture?

"One cannot doubt that Finnebyen is a group of timber buildings, when one sees the clad houses painted in many different colours."[359]

Historically, timber houses have most often been clad with timber. But, as has been noted, timber houses have also been treated to look like something else. Today almost any load-bearing structure can be (and indeed often is) clad with any type of façade product. The stud and beam system of the light timber-frame is also always clad on the inside, for obvious reasons.

What is it then, that characterises a timber house and is that reasoning applicable on all types of buildings? For reasons of city planning, rationality and competing capacity it is a relevant question, above all for residential blocks. The level of prefabrication basically determines the relation between prefabrication and modular aesthetics, concerning features of the layout and the expression of the exterior, but how much of the structural method should be expressed by the exterior design?

In two of the cases (Vetenskapsstaden I and Spöttlgasse) the timber-structure has been clad with plaster, which speaks of a structural system possible to use for any appearance. For reasons of restrictive city plans and fire-regulations the timber may have to be clad. For reasons of competitiveness in other projects it may, however, be gainful to choose a structure for other benefits than pure rationality at production and to utilise material characteristic and/or structural specific form features in the design.

To utilise the structural system for material- or element-specific structural form is one way. Each structural system has properties, which make them differ from other systems. To utilise these hypothetically unique features, it can be possible to create system-specific structural solutions and architectural expressions, which may render more arguments and better competitiveness for that specific system. On the market the visual appearance is important and *What you see is what you get* plays a decisive role in the initial evaluation of a product, to be dealt with by the architect. To advertise a timber building system with system-specific features should therefore be gainful.

[359] *Remark concerning Finnebyen in Denmark, an area with element construction of Finnish design erected 1948. (Translation by the author.)* Træ er miljø

9.1.4 A Characteristic Massive Timber Architecture?

"One cannot say that a wooden house should appear this way or that way. If […] it has been well built and if it has a clear and coherent design the goal has been achieved. […] Each new task presents its own demand and will, therefore, always require new solutions. These, as long as they remain faithful to the materials themselves, will always have their unique attributes."[360]

Plate-structures are not new in buildings and we have seen them cast in concrete for a long time. In timber-buildings, however, it is so far the principle of the log-house or the light timber-frame that has determined the building design, its structure as well as its utility.

Design today tends to be of a global kind. Projects that are being built follow the trends on the international arena and the differences between them are less dependent on context or material than on the status of the project. The situation on the market turns more and more towards the exploitation of trademarks, simple and obvious messages to reach out to the buyers of products, whatever the products are. A new building-system with a traditional or old-fashioned design risk to be judged as traditional or old-fashioned.

The possibility to utilise massive timber for designs based on characteristic properties should therefore be of interest in architectural work. Deliberate over-sizing of timber-structures may for example increase their optional capacity to architectural impact and can e.g. lead to better fire-performance and thereby safer timber-structures. If this principle is applied at an early stage it will become a part of the building system and the increased mass of the structure can be utilised as an architectural means.

This can be interpreted differently, especially the essential term *coherent design*. In the context of this thesis the coherent design denotes a structurally logical architectural form. Combinations of structural systems may among other features provide architectural surprises of materiality, such as a massive timber mezzanine floor in the core of a concrete building, or as a balcony in a chapel constructed from rammed earth. If the combined solution is chosen for an efficient and suitable architectural and structural function, then it is an example of coherent design.

[360] Wachsmann K. 1930, p. 42

9.2 Conclusions

In this thesis the use of massive timber products in construction has been studied both in practice and theoretically. The product type has been shown to provide structural, architectural and environmental possibilities that potentially enrich the structural, architectural and environmental function, but also that these possibilities so far have been utilised to different extents. The differences depend in the studied cases on variations in experience, know-how and degrees of co-ordination.

Experience from the cases shows three different approaches to development of massive timber in structural applications; depending on the project/case/task/context, the material will have to be utilised to different extents:

- *Form follows manufacturing.* Massive timber systems for fully prefabricated apartment blocks should aim at pure, complete volume-elements delivered to the site for incorporation in the building and let the form be restricted.
- *Form follows production.* Massive timber systems for apartment blocks with wider freedom in designing the layout and form should utilise different types of semi-prefabricated surface-elements, and locate the finishing to field factories on site.
- *Form follows material.* Massive timber systems for advanced structures should utilise material properties and tailored build-ups for structurally optimised forms, which more or less directly generates the architecture.

Developing the features of timber building does not have to be a matter of creating a new architectural style, but should be a search for rational realisation of useful forms. In this way the material technology and the structural system become competitive. The structural forms of the most advanced created structures are directly dependent on what is actually possible with the chosen material and within this, one finds the heart of the matter, the utilisation of the characteristic properties.

This approach to design is fully applicable on building systems, where industrialisation has already brought up the term lean construction, which basically deals with cutting away unnecessary parts and decreasing waste in production. To utilise the types of products that fulfil the demands in the best way, and to develop the architectural and structural design and performance of the structure according to the materials and elements in use, should therefore be advantageous.

As can be learned from the cases it is important to plan a project for the intended structural system and that both production and result benefit from co-ordinated structural and architectural planning and an accurate choice of structural material.

The consequence of this points at the advanced structures with combinations of massive timber and e.g. tension members of steel. The advanced structures dealt with in this work show a useful efficient potential through their utilisation of different materials, i.e. timber and steel, and elements in structurally optimised locations. They provide a salient material-characteristic and architecturally enriching structural form. As has been shown in the theoretical extension, this aspect can be taken further with developed principles and even result in new structural elements.

The scientific contribution of the thesis is primarily that

The work provides knowledge necessary to utilise the advantages of and gains from a joint architectural and structural engineering approach to the planning process and an architectural-technical perspective on construction.

Practical benefits from the thesis/contribution to society is primarily that

The work provides a broadened perspective on and deepened understanding of timber-based plate-products and their applications.

9.3 Future Work

9.3.1 Material and Elements

The potential increase of the material and element related capacity through tailoring of the cross-lamination design/build up should be studied further, regarding both load-bearing, failure and behaviour under fire-load. The produced elements should be further tested and put in full-scale applications to study their structural and architectural behaviour and possible benefits. Production of curved elements and pure, three-dimensional shells should be taken further in practice.

9.3.2 Building Systems

In this thesis building systems have been studied on site and this experience has been combined with theories on form finding[361]. Lines of development, as dealt with below, stem from this combined approach.

Architectural design in industrialised building production is in need of further studies. A close relationship between architecture and structural engineering is one of the keystones, which should be encouraged and thoroughly documented and analysed in full-scale projects. A suitable form for this would be a number of pilot projects on massive timber construction for medium-rise apartment blocks, possibly preceded or aligned by a number of small-scaled projects for structural and architectural part-studies of structural principles and detailing. These projects should be prepared through thorough research phases dealing with the architectural-structural interaction.

Plate and shear-plate action in prefabricated concrete structures could eventually be analysed more regarding the effects of decreased density and other prerequisites for jointing in the case of replacing concrete with timber. Apartment blocks with concrete cores and timber additions have been mentioned as a possible solution for rational structures. Such structures have been erected with the concrete cores oriented both vertically (e.g. the SH-Holz school building in Biel, Switzerland with structural design by the Swiss engineer Jürg Conzett) and horizontally (e.g. case #6: SPG), but the structural effects and architectural possible benefits should be researched further.

Other types of composite structures should be tested systematically as well. Timber plate elements in combination with structural elements in other materials should be developed, for example timber floor decks combined with steel stud walls. The load-transference, acoustic behaviour, joint solutions and co-action need to be studied in

[361] *also most relevant for advanced structures*

other cases than pure timber-structures and so do the architectural utilisation of thereby created structural forms.

9.3.3 Advanced Structures

This section is based on the experience from advanced structures and a theoretical extension. To a large extent, lines of development dealt with in this section stem from theoretical studies on advanced structures, but have been regarded in the light of the studies on building systems, where the form finding process is as relevant, but steered by partly other factors.

Plate tensegrity has so far been analysed in plane assemblies of square units, but should be further analysed in symmetrical and asymmetrical curved assemblies and in 2D- and 3D-assemblies with triangular and hexagonal units. Plate tensegrity should also be tested in a full-scaled structure.

The plate tensegrity structures are theoretically closely related to polyhedral structures. Plate structures like those investigated by professor Ture Wester[362] in Copenhagen would be suitable applications for cross-laminated timber plates. More intricate structures are possible with plate tensegrity units of other geometries than the orthogonal quadratic.[363] The quadratic form is not optimal for transference of plate action, but by designing with trivalent vertices, i.e. utilising e.g. triangular or hexagonal units lattice action can be avoided and the forces are more easily distributed. In polyhedral structures designed in this way stability is more easily obtained through shear forces along shear lines.

Polyhedral structures with plate tensegrity units mean a combined structure with potential gains from both types: pure plate assemblies and plate tensegrity. A critical issue for polyhedral structures is stabilising of the edges. In a complete polyhedron the stability is intact, but if the polyhedral structure is opened up the edge stability has to be gained in other ways, e.g. reinforcement of the edge zones. Tensegrity is a stable phenomenon inside its envelope of pure tension. The tensegric function may therefore stabilise opened polyhedrons.

Inspiration has in recent research come in very different ways. Buckling patterns in structural elements under load have reached stable states and such patterns can be used in structural design for better performance.

Corrugated steel or fibre reinforced plastic are examples of products gaining strength and stiffness from folding, but these are thin products folded during production. Folding of structural elements is not obtainable in all materials. But by stiff joints plate elements can form big assemblies with folded character, providing increased overall stiffness and stability.

[362] Wester, T. 1984
[363] Wester, T. 1984; Huybers, P. and van der Ende, G. 2001

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Appendix I

Questionnaires

Questions concerning building systems and installation systems for residential building construction in massive timber

Structure:

- What degree of prefabrication is used?
- Why was this chosen?
- Can it be further optimised?
- How much was prefabricated?/How much was prepared on site?
- How was the on site work managed?
- How are the joints designed? (Timber/timber: in plane, perpendicular to surface, timber/other materials: structure-foundation, plate-post/beam, massive element/light element)
- Are the joints fully prepared in factory, or are some parts left to treat on site?
- Could the joints and/or the elements be designed differently for better performance at the assembling?

Installation system:

- How have the installations been solved?
- Where and how are they located?
- What has directed the choice of location?
- Have installations been integrated in the structure/in the structural elements?
- How much of the installations have been put in place in factory; how much on site? An optimal level?
- Is there an overall main principle for locating the installations?
- Are different installation types treated/located differently?
- Have the elements been modified to suit the installations?
- Is the installation system influencing the architectural solutions?
- How have connections been treated concerning installations?
- How to connect in factory, at delivery and on site?
- What has directed the chosen prefabrication level?

Questions concerning cross-laminated timber plates in tensile structures in connection to the riding hall in Flyinge

Design:

- What factors were deciding the design of the original structure?
- What became the crucial points in calculating the structure?
- How is it most likely that the structure will perform in the usage phase? (Will there be deformations, needs for post stressing of cables?)
- What kind of steel is used in cables and trestles?
- How are timber plates and rods designed for close structural and behavioural fit?
- What characteristics guided the choice of steel?
- Can deformations be predicted and/or avoided?

Production/erection:

- Are there swift methods for post stressing?
- To what extent were the plate elements prepared in the factory?
- Was the pre-fabrication optimised?
- Was everything concerning the design finished before delivery, or has there been adaptations made on site?
- What have been the most difficult things on site?
- Is the method for assembling and putting the roof structure in place optimal?
- Have new structural principles/productional methods been developed in/for this project? (Are they usable in other projects to come?)

Appendix II

Sundsvall: Documentation and Development

Results from the development project on the apartment blocks in the Inner harbour in Sundsvall, Sweden.

One issue that was dealt with in the joint venture between NCC Construction Sverige AB and Luleå University of Technology was the mismatch between the structural demands and the architecture. The demands were discussed and the layouts for other medium- and high-rise buildings constructed in timber during recent years were studied. The effects of alternate layout forms on foundation work and resistance to uplift forces in the walls were studied and discussed.

Three meetings were held where the author, a structural engineer and a market analyst discussed prerequisites and possible steps for improving the structural behaviour of the apartment blocks. *Fig. A.1* and *A.2* show the original layouts for SVA1 and SVA2 respectively. *Fig. A.3* and *A.4* show different alternatives for apartments obtained with as little changes of the original layout as possible. In *Fig. A.5* more free layouts for the apartments have been allowed. *Fig. A.6* shows the layout that was finally proposed.

The walls in massive timber construction are marked grey in the layouts. The letters in the layouts represent the type of rooms.

K: Kitchen

M: Dining area

S: Bedroom

V: Living room

W: Bathroom

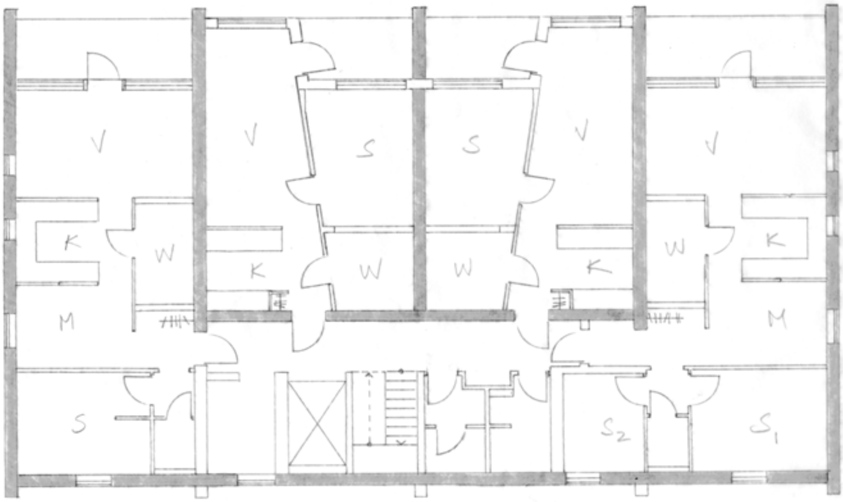

Fig. A.1 Layout for Sundsvall I, apartment block 1-3.

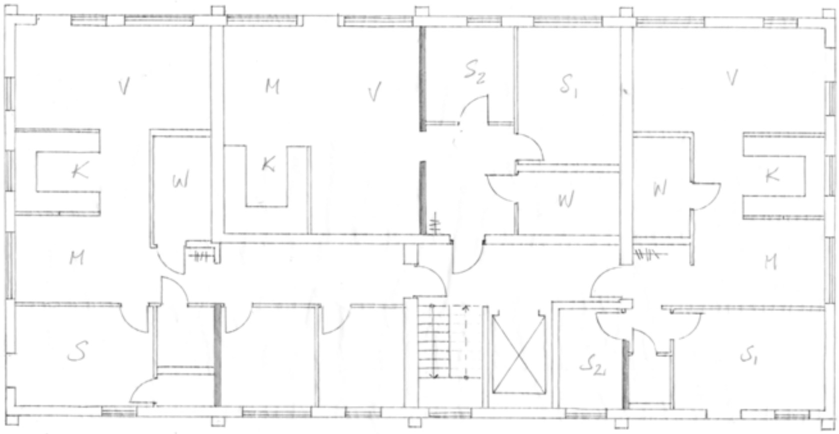

Fig. A.2 Layout for Sundsvall II, apartment block 4-5.

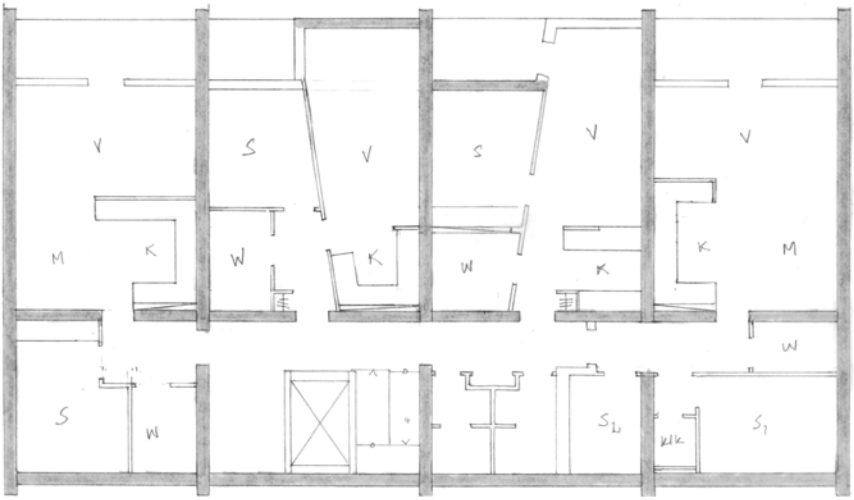

Fig. A.3 The first sketch for different possible changes of the layout. Different alternatives in the same drawing.

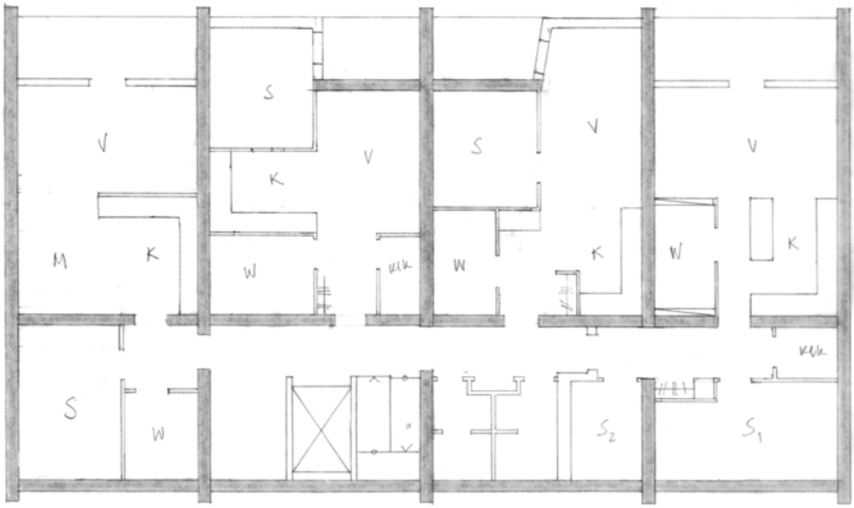

Fig. A.4 The second sketch for a new layout. Different alternatives in the same drawing.

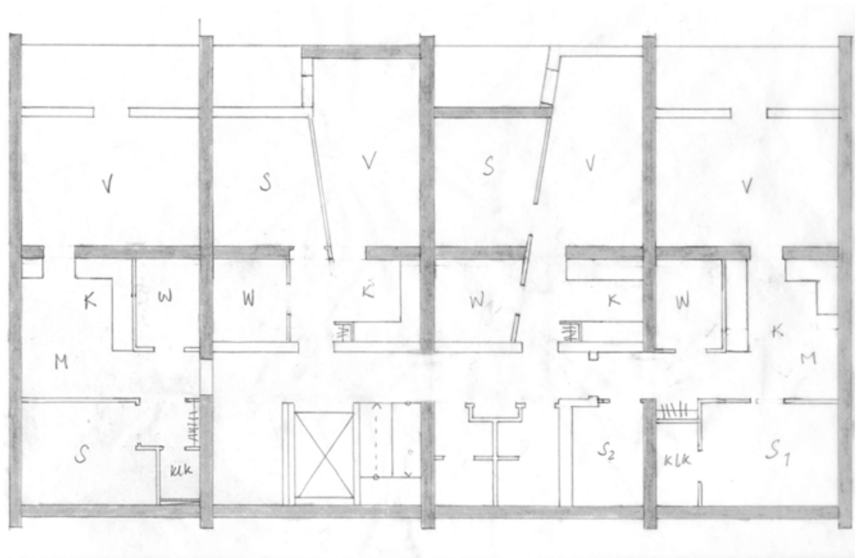

Fig. A.5 The third sketch for a new layout. Different alternatives in the same drawing.

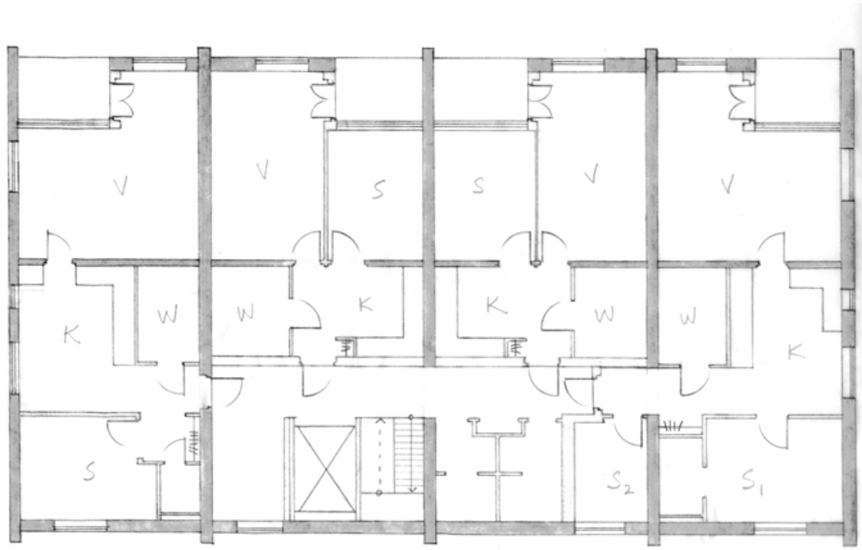

Fig. A.6 The final proposal for a new layout.

Appendix III

Paper Presented at WCTE 2004 in Lahtis, Finland, July 2004

Relations Within a System - Installing a Prefabricated House

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Summary

Building construction is a highly organisational as well as a technical design- and system-issue. New trends in building construction turning towards increased industrialisation, together with growing needs for various installations, put higher demands on technical solutions for assembling and connecting prefabricated parts, modules and systems on the building site. With increased degree of prefabrication demands rise on installation systems being developed together with structural systems for proper function. When e.g. prefabricated-elements arrive to a building site they are to be assembled into a working building in as short time as possible, following the ideas about the gains from prefabrication. Localisation and connections of installations decide the planning of module units and their geometric and structural interrelations as well as the rationality at on-site construction. This paper deals with possibilities of system-interfaces and production development.

Keywords

Prefabrication, massive timber building systems, elements, installations

Introduction

Today the building-industry is capable of delivering more and more complete products to the building sites. The wish for good working-conditions, rational use of tools, machines and manpower, production control as well as shelter for materials and building-parts results in increased degrees of prefabrication. Modules for multi-storey residential buildings are e.g. provided with interior detailing, surface finishing, wallpaper and complete bathroom installations already in the factory. The work on site is then largely reduced to joining of the different modules why these must provide swift completion to a working entity.

The number of different required installations is with changing needs constantly increasing. Installation systems can however be chosen and developed to suit the structural system in question. If integrated properly they can both take advantage of and support the main system by effective and safe location, serviceability, preserving of structural advances and freedom of choice concerning design of structural and aesthetical detailing. Several light timber-systems are available on the market with conventional installations produced relatively separately. Structures with massive timber-plates are so far less used but show promising properties concerning prefabrication. This leads to the interesting task to investigate the possibilities with massive timber-frames and system-principles for current and future installations.

Conditions for Different Degrees of Prefabrication

Industrialised building construction implies transportation, which means that the produced elements must stand handling in several steps before being put into place, assembled and taken into final use. The elements can be plane (2D) or volumes (3D). For dry working conditions volume modules with close to finished interiors are optimal, also saving time on the building site. Light timber-frame systems are today produced in this way on regular basis. But volume elements put high demands on joints during handling/transport and cause easily complicated and expensive transport conditions. Massive timber is heavier than light timber systems, which makes it difficult to compete with such, concerning handling of volume elements, whereas it is far lighter than concrete elements systems, which are mainly transported to the site as surface elements. Massive timber elements furthermore allow wide freedom of adjusting and perforating both in advance and on site, which enables placing of installations late in the building process. Plane timber-elements can be completed to a relatively high degree, still being 2D, with surface layers and preparations for installations. They are easy to load for transport and to deliver in an economic way as compact packages. They can then rather swiftly be finished and assembled into complete volumes in a field factory on site. A very plausible proposal would therefore be production of semi-manufactured articles, thus, a production in two steps – production in a factory; transport; assembly and finishing in a field-factory. The different tasks are carried out at the stage where they are dealt with most efficiently.

Installations and Structural Systems

Installations imply technical systems used for the maintaining of a healthy, comfortable and – for our life and work – practical environment, mainly inside our buildings. Construction must support a rational application of installation equipment, tubing and cable-location. Regarding the global need of lowered energy consumption it is also important to seek to develop new combinations of building technique and installations with a possible result in decreased needs of heating and ventilation. [2] Such combinations require a mutual adaptation of structure and installations. New ways for building production must therefore be carefully studied in the complete context of the finished structure. Location of installations has large effects on the rationality and logistics of production, on the manufacturing of elements in the factory and on the assembling of elements on site through the design of their connections.

Several wall systems of massive timber utilise air, partially hollow cores, inside their structures. These air gaps provide with increased sound and heat insulation but can also be utilised for electric, water and heating installations. Other element types are designed with air spaces at even distances for installations only. Installations can thereby be kept invisible, but two aspects are most important to regard. I) Installations must be accessible for service, maintenance and even exchange. This can be achieved by placing hatches at even distances. Electric installations such as cables are mainly easy to handle, since they are dry and easily lead through a structure through e.g. plastic pipes placed in advance or in prepared channels in the structure. II) Installations for water and heating are delicate to place, since pipes are time consuming to install and exchange, and since such systems may leak. If a leakage appears inside the structure, it must be detected and fixed – systems for detecting are crucial. Wet installations inside the elements are not advisable. Built into the massive plate/shear plate they can cause large damage in case of leakage. If placed on the lower side (the neighbour's side) of a floor element, in a suspended ceiling, problems with sound insulation easily occur. Sewage pipes should, for optimal function as far as possible, be vertically oriented and the horizontal parts from floor drains and toilet seats should be as short as possible.

Location of Installed Systems

Thorough planning for installations is important for the aspects of visibility/non visibility and access. The installations are not often wished to be seen, but they must despite this be located in a way making access easy, for service and over time presumed necessary replacements of parts of or whole systems. Installations can be placed in different ways, in different areas of the vertical section of the structure. [4] The two main groups of installations are a), primary, vertically oriented ones, i.e. sewage systems, main water and sprinkler pipes, main cables for electricity and telecommunication, and b), secondary, horizontally oriented ones, i.e. electrical installations, pipes for heating, and sprinkler pipes. The primary ones had better be concentrated to a few centralised shafts, i.e. mainly 1-dimensional like the stem of a tree, serving as many units/rooms/areas in the building floor plan as possible. The secondary ones are of a lighter kind, preferably concentrated to the floor elements, horizontally 2-dimensional like tree branches, more easily installed, and not as geometrically restricted in plan as the before mentioned type. The vertical system is then to serve the horizontal system. The ideal is to purify the verticality of the former type and the horizontality of the latter.

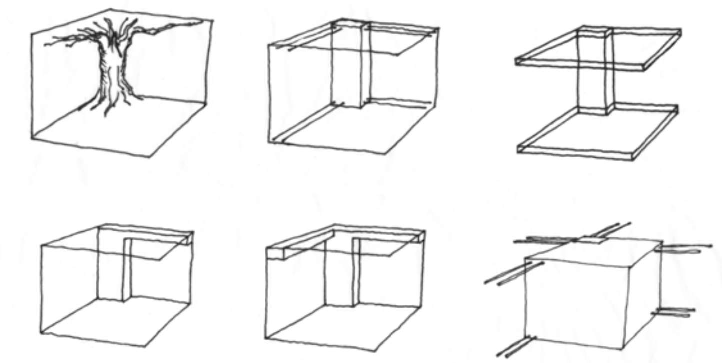

Fig. 1 Simplified principles for location of installations and installation zones.

Sewage Systems and Water Pipes (a)

The main location and orientation of sewage pipes, main water and sprinkler pipes as well as main serving electric cables are vertical. In buildings with one or two floors only, the location in plan is neither crucial for the rationality/economy of the construction nor for the plan layout. With increasing number of floors the number of pipes increase and it gets important to place the pipes in positions equal on all floor plans. Concentration of several pipes to a few shafts is a common way to handle the problem. Prefabricated, moisture insulated shaft modules to be built into volume elements could be a simple solution, providing when necessary a module with a serving core, to which the horizontal installation parts can be connected. It should be designed to provide with easy access and to enable easy connection conditions for on-site assembly.

Sprinkling Systems, Heat and Electricity (b)

There are two main types of sprinkling systems: systems with separate water supply and systems connected to the tap water system. Both types are mainly of horizontal orientation, with connections to vertical providing pipes in central shafts, placed together with tap water, sewage and main cables. Sprinkling systems are acoustically non-disturbing wet installations belonging to the apartment they serve and can are easily placed in suspended ceilings, on the served apartment's side of the floor construction.

Floor-heating systems are frequently installed in floors of any kind and material. Regarding the movements in timber caused by shifting temperature, and regarding the risk of leakage in the floor and the damages that presumably cause, it is not an advisable solution to install such a system in a timber floor. The increased heat close to the timber furthermore lead to increased cracking from drying and also an unnecessary exaggerated heating of material. To avoid cracking a well-insulated heating-system may be contained in a built up floor but the risk of leakage and problems with detection is still to regard. Another possibility is provided by cutting grooves in the floor slab. Heat and eventual necessary water pipes can run in a cut groove in the upper surface of the floor plate in the served apartment, not in the entire floor but as a frame along the walls. This restricts the installations to well defined zones and the groove can easily be securely moisture insulated with sheet metal or plastic, preventing leakage to damage the floor timber and even provided with heat insulation protecting the timber floor from extreme temperatures. It can be covered with a perforated steel plate or wooden/plywood frieze.

Vertical main electrical cables are placed in central shafts. Secondary horizontal cables connected to these are, as frequently seen today, placed in suspended ceilings, which are commonly used to handle demands on sound insulation between storeys. These ceilings are easily made to allow partial removal for access for maintenance. Lamps can today be remote controlled, but they still need the power cords for energy and so do our electric household, working and leisure devices. For the supply of power points along walls cables can run in internal channels in the wall elements, behind an internal board cladding fixed with distance to the wall element, or be placed in cut grooves in the lower part of the wall elements, covered with e.g. a batten, sheet metal or plywood. If no suspended ceiling is available a cut groove can run along the upper part of the wall as well, to give more freedom with elevated power points.

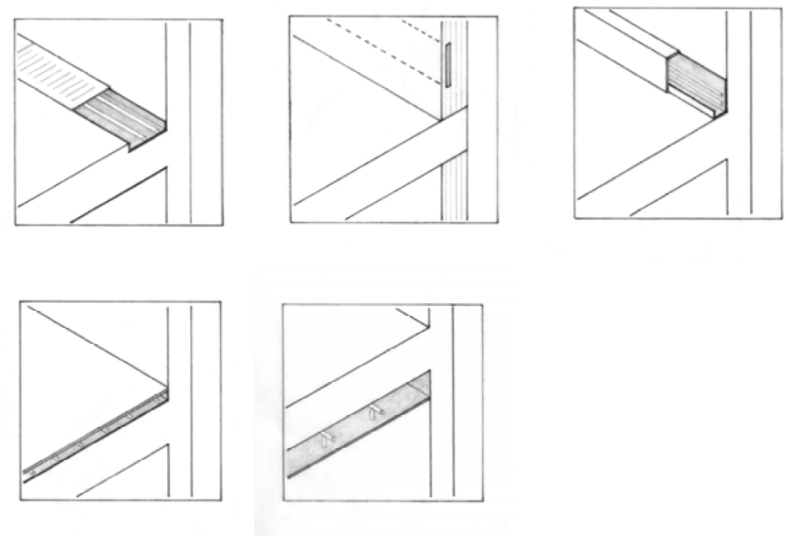

Fig. 2 Location of different types of installations.

Communication and Development of Living
The most fast-growing technical area is currently of course computers and communication. Cables are still needed, and opto-fibres are still physical items. Airborne transference of information and communication show, however, a strongly growing technical development, which can make the physical connections surplus and remote controlling of technical equipment a reality. More and more functions are possible to handle, steer and control without physical contact. This will for certain effect our indoor environments, and in laboratory homes and piloting projects it already has.
The term “smart homes” have been used for residential units with highly developed systems for IT, information technology. A description of smart homes can be a living environment where a number of installations and technical devices can communicate with each other via a local network, as well as with the external surroundings. The idea with the fully developed smart home is that the inhabitant can remote control all installations in the apartment, check and program room temperatures, check energy consumption and alarm functions, program lamps, write and transfer shopping lists to cellular phones etc. In a piloting project in Stockholm, built during 2000-01, the aim was to provide the inhabitants with rational living, safety and comfort regardless of age, i.e. apartments where the inhabitants can remain while aging and even if a situation with a handicap occurs. [3] The aim has been non-visible installations. Several different scenarios or levels of control are possible.

Prefabrication: Assembly and Connections
A rational method for wet installations would be using precast completed boxes, wet units in plastic or composite materials, with wet installations for toilets and bathrooms. Such small volume modules are light, they can be provided with simple and swiftly locked connections and be put into raw timber-framed spaces in the structure of each storey on site, before elements of the next storey are put into place. There should also be a vertical shaft cast together with the wet unit, a spine to be connected to the horizontal nerve net of wet and dry installations in the horizontal elements.

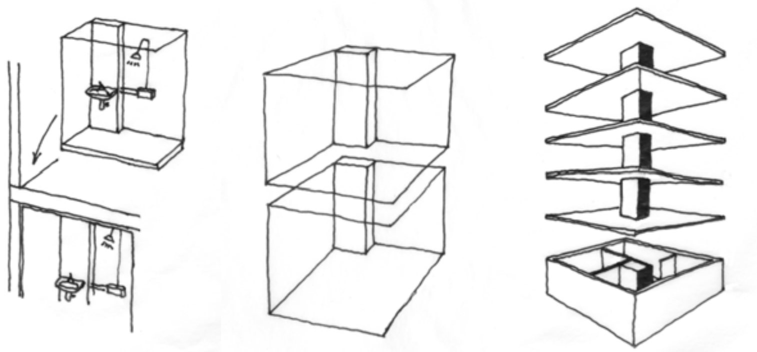

Fig. 3 Incorporation of a prefabricated wet unit and a serving vertical spine.

Massive timber building can be discussed in terms of constructing with geometrically simple, sustainable surface elements. The plane massive elements can be prepared with dry installations and cuts for wet ones and then delivered to a site factory where they are used as walls, floor and ceiling/roof in modular box structures. The finish of the interior and additions of wet installations can then be carried out safely on site. The structural jointing, the integration of different types of installation systems and methods for connection of installations for sewage and electricity become the keys to the finishing of the construction.

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Appendix IV

Excerpt from the paper on plate tensegrity by Falk and Tibert (2005) submitted to and presented at IASS 2005 in Bucharest, Romania, September 2005. Analysis performed by Tibert.

STRUCTURAL ANALYSIS

Structurally, the plate-tensegrity module bear strong similarities with the *triple layer tensegric truss module* by Saitoh et al. [2], the *truss structure stabilized by cable tension* by Hangai et al. [3] and the *cable-strut system* by Wang [4]. The main difference is the use of a plate, instead of a four-bar linkage, for the middle layer. The plate provides shear stiffness to the middle layer without significantly altering the load paths in the structures. As mentioned above, the plate also functions as roof covering, whereas in the previous systems it has to be attached afterwards. Wang discusses that the cables connecting the end points of the struts above the roof can be used as ridge cables for a lightweight membrane cover, but has not shown how this could be done. Thus, the main advantage with the present system in comparison with the cable-strut systems is the incorporation of the roof covering as a part of the main load bearing system.

Analysis by the Force Method

The most efficient approach to find the characteristics of the plate-tensegrity structure and analyse its behaviour under external loads is by the Force Method outlined by Pellegrino [5]. This method is linear and requires that all cables are under tension. For structural uses, linear behaviour and small displacements are often desirable, so the assumption that all cables must remain in tension under all loads is valid also in practice.

Converting the Plate Into an Equivalent Framework

In order to use the Force Method as presented in [5], the plate element must be converted into an equivalent framework. Hrennikoff [6] replaces a plane-stress continuum with a framework of bars arranged according to a certain pattern. The bars are endowed with elastic properties, which render equal deformations for the continuum and the equivalent framework in the infinitesimal case. The equivalent square and rectangular frameworks are shown in Fig. 1.

	Square	Rectangle	
$A_1 =$	$\frac{3}{4}$	$\frac{3(3k^2-1)}{8k}$	$\times Lt$
$A_2 =$	$\frac{3}{4}$	$\frac{3(3-k^2)}{8}$	$\times Lt$
$A_3 =$	$\frac{3}{4\sqrt{2}}$	$\frac{3(1+k^2)^{3/2}}{16k}$	$\times Lt$

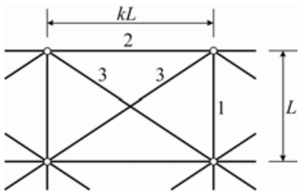
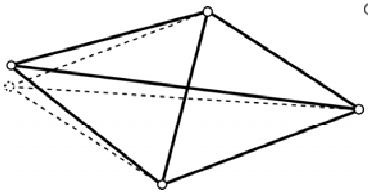


Fig. 3: Cross-sectional areas of bars that make the framework deformation equivalent to a plane stress continuum.

In three dimensions, Hrennikoff's module has seven mechanisms, of which six are rigid-body mechanisms. The single, remaining internal mechanism is shown in Fig. 2. By itself, the two-dimensional model by Hrennikoff cannot be readily used in three dimensions. However, when considering a complete plate-tensegrity module, the internal mechanism is eliminated by the cables connecting the strut to the plate. As each plate-tensegrity module thus forms a stable unit, the equivalent framework model by Hrennikoff may be used to model the in-plane plate behaviour. Note that the bending deformations of each plate are neglected, as this analysis focuses on the global behaviour of a plate-tensegrity system.



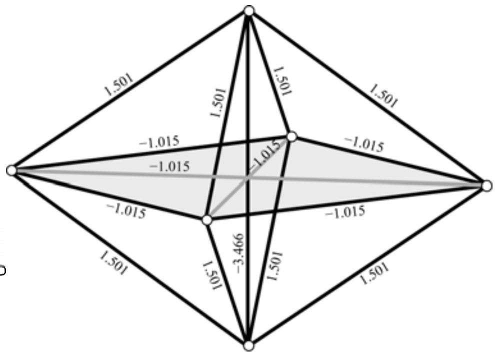


Fig. 4 (left): Out-of-plane mechanism for the plate equivalent framework.

Fig. 5 (right): Prestress distribution in plate-tensegrity framework module.

The solution by Hrennikoff is valid only for $\nu = 1/3$, which somewhat restricts its applicability. As a possible remedy, Hrennikoff presents a framework, which can accept arbitrary values for ν, but that framework may contain bars with negative areas, which is obviously not desirable.

Structural Characteristics of a Single Plate Tensegrity Module

Treated as an equivalent bar framework, the plate-tensegrity module has 6 joints and 15 bars, which, when inserted into the generalised Maxwell's rule [5], yields $m - s = -3$. A singular value decomposition of the equilibrium matrix produces $m = 0$ and $s = 3$. In the absence of external loads, the element forces may be written [7]:

$$\mathbf{t}_{\mathbf{e}_0} = -[\mathbf{S}(\mathbf{S}^{\mathrm{T}}\mathbf{\Phi}\mathbf{S})^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{\Phi}]\mathbf{\Psi}\mathbf{e}_0 \tag{1}$$

where $\mathbf{e_0}$ is the vector of initial elongations, $\mathbf{S}$ contains the bases for the states of self-stress, $\mathbf{\Phi}$ and $\mathbf{\Psi}$ are diagonal matrices containing the element flexibilities, L/AE, and axial stiffnesses, AE/L, respectively. Assuming equal axial stiffness for all elements, AE = 1000 N, an initial elongation of 0.01 m for the strut yield the symmetric prestress distribution shown in Fig. 3. While there are many ways a single module can be prestressed, the most practical way is presumably to lengthen the strut by a turnbuckle. Thus, assigning an initial elongation only to the strut mimics the practial prestressing procedure.

Structural Behaviour of a Plane Plate Tensegrity System

First, the geometrical effects on the load-bearing capacity of a plane assembly of plate-tensegrity modules will be studied. For square plates, the geometrical properties of interest are [4]:

1. the ratio of the parts of the strut length above and below the plate, h/H,
2. the length of the strut in relation to the size of the plate.

In the case of downward acting loads, the tension in the cables connecting the struts over the plate will decrease and eventually become slack. Wang [4] takes the slackness in those cables into account by simply omitting them. Further cable slackening during loading was analysed by a non-linear finite element program [4]. Saitoh *et al.* [2] also takes cable slackening into consideration. In the present analysis, the top and bottom cables are not prestressed, so the top cables will become slack when the loading is applied. To remove these cables from the analysis, they are assigned with a very small modulus. The chosen failure criterion is when any additional cable, apart from the top ones, becomes slack. Prestressing also the top and bottom cables, will only increase the load for which the top cables will become slack. Thus, the efficiency of the system is determined by the magnitude of the uniform load it can sustain before any additional cables become slack.

The optimum value for h/H is tested for plane systems with 5 or 10 square panels (1×1 m^2) in one direction and one panel in the other direction. The systems are supported at the shorter sides as shown for the three-plate system in Fig. 4. Each system is subjected to a uniform load, which is converted to equivalent nodal loads. Note that the bending deformations of each plate are not taken into account in this analysis. For all systems, the initial compression in the struts is set to -100 kN. Initially it is assumed that all cables have AE = 20 MN with a breaking load of 160 kN. The tubular steel struts chosen for the analysis (D = 82.5 mm and t = 4.5 mm) have AE = 231 MN and EI = 177 kNm^2. If the maximum length of the strut is set to 2 m, this gives an Euler buckling load of 436 kN. The timber plate is 94 mm thick with E = 5 GPa.

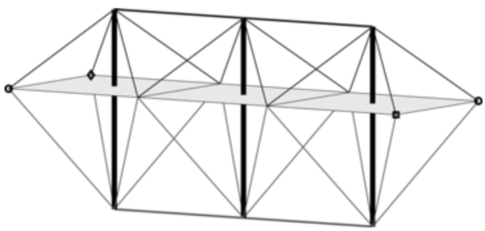


Fig. 6: A plane three-plate system with the shorter part of the strut above and the longer part under the plate.

Preliminary studies show that the stiffness of the bars comprising the plate has little influence on the deflection, whereas higher stiffnesses of the bottom cables significantly decrease the deflection. Although the displacements decrease when the stiffness of the bottom cables is increased, the cable forces stay constant. This is partly because the present analysis is linear. Also notable is that the force in a strut stays almost constant during loading, meaning that each module basically undergoes a rigid-body motion during loading, Fig. 5. Based on the preliminary studies, the axial stiffness of the bottom cables is increased ten-fold to AE = 200 MN. With the bar properties set, the optimum ratio h/H and the length of the struts are sought.

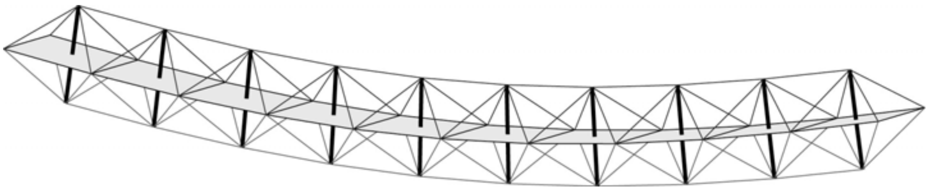


Fig. 7: Deformed shape of a ten-plate system (displacement scale factor = 10).

The results are presented in Fig. 6. Decreasing the ratio h/H, i.e. making the part of the strut under the plates longer than that above the plates, yields smaller deflections and lower forces in the bottom cables. This is fully expected since the lever arm for the tensile forces in the bottom cables increase. Increasing the length of the struts has the same effect, as shown in Fig. 6 for h/H = 1.0. However, the magnitude of the uniform load for which additional cable slackening occurs does not increase, e.g. for the ten-plate system the slackening load is 11.023 kN/ m^2 for h/H = 1.0 whereas it is 11.057 kN/ m^2 for h/H = 0.4. Increasing the strut length does not make much difference as the slackening loads are 11.061 and 11.083 kN/ m^2 for 1.5 and 2.0 m long struts (h/H = 1.0), respectively. The reasons for the almost constant value for the slackening load are due to the end constraints and the asymmetry of the plate-tensegrity modules at the ends. Intermediate modules undergo mainly rigid-body motions, as discussed above, and also have two cables attached to each strut end, which almost equilibrate. The end modules are constrained along one side and have only a single cable attached to the strut ends, which disturbs the equilibrium in the plate-tensegrity module.

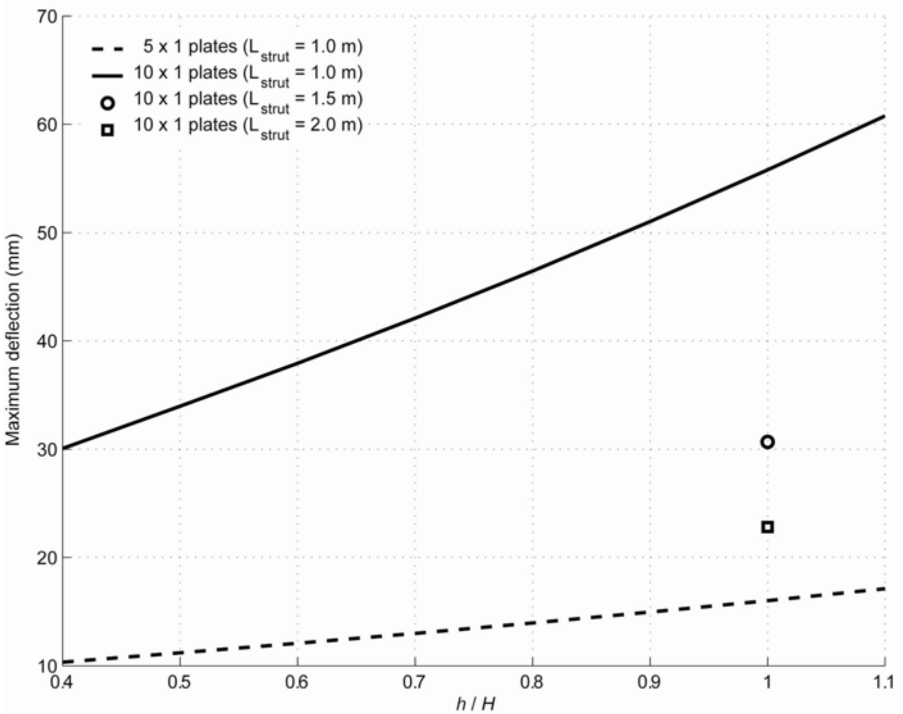


Fig. 8: Maximum deflection of 5- and 10-plate systems at cable slackening load as a function of the ratio of the strut lengths above and under the plates for a constant strut length.

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Quaerendo Invenietis

("Search and You will find")

Johann Sebastian Bach
Musikalisches Opfer, BWV 1079
Canon for clavecin

"Out! Out! into the Buddah*f*ields,
among stars to wander forever,
weightless witho*u*t a headline,
without thought,
without newspapers to read
by the light of the Galaxies"

Allen Ginsberg (1926-1997)
from "Ayers Rock/Uluru Song" and "Throw out the Yellow Journalists…"

Människan upptäckte mer och mer
och Jorden blev större och större
Och människan upptäckte ändå mer
och Jorden blev bara en pric*k*
En liten leksaksballong
i oändligheten
.

Nils Ferlin (1898-1961)
"Större och mindre" from "Från mitt ekorrhjul" 1957

Long long I lay in the sands Sound of trains in the surf in subwa*y*s of the sea And an even greater unders*o*und of a vast confusion in the universe a rumbling and a roaring as of some enormous creature turning under sea & earth a billion sotto voices murmuring a vast muttering a swelling st*u*ttering in ocean's speakers world's voice-box heard with ear to sand a shocked echoing a shocking shouting of all life's voices lost in night And the tape of it somehow running *b*ackwards now throu*g*h the Moog Syntheziser of time Chaos unscrambled back to the first harmonies And the first lig*h*t

Lawrence Ferlinghetti (∗ 1919)
*"A vast conf*u*sion" from Who are we now? 1976*

Silence in the woods
Into the roc*k*'s heart seeps just
A cicada's voice

Basho Matsuo (1644-1694)
Interpretation by Andreas Falk.

Laurie Anderson (∗ 1947)
"Same time tomorrow" from "Bright Red Tight Rope" 1994:

…So here are the questions: is time long or is it wide?
– And the answers?
– Some*t*imes the answers
just come with the mail. And one day you get that letter
you've been waiting for forever.
And every*th*ing it says is true.
And then in the last line it says:
Burn this

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