ARCHITECTURAL AND STRUCTURAL DEVELOPMENT
OF PLATE TENSEGRITY

Andreas FALK
Researcher, SP Trätek, Swedish Inst. for Wood Technology Research, Box 5609, S-114 86 Stockholm, Sweden
E-mail: ateljefalken@yahoo.se

ABSTRACT

Plate tensegrity is a structural principle combining the approach to the play of forces seen in tensegrity with plate and shear-plate action of surface elements and faceted shells. The origin of the concept and the potential development as a structural element system describes a step-by-step modification of the original definitions of tensegrity towards a hybrid structure with cable-stayed plates [1, 2]. The work deals with development of the combination of structural elegance and efficiency and architectural utility and quality. The structural principle has not yet been applied in practice, but the performance of different assemblies are being further analysed from structural and architectural points of view.

There are a number of features of plate tensegrity that can be utilised both structurally and architecturally. Stability of plate shells has been treated by e.g. Almegaard and Vanggaard [3]. Pure shells tend to be sensitive to cuts in their edge zones and lose in stability and there are polyhedral types showing the same behaviour if certain facets are removed, as described by e.g. Wester [4]. The cable network in plate tensegrity may be utilised to allow removal of elements inside as well as at the edge of an assembly. The cables also make possible different geometries of the assemblies, by variations in lengths i.e. intermediate distances between the strut ends in the structure. The first modelling of plate tensegrity [5] was focused on straight assemblies of a single unit type with a square plate shape, considering production rationality and economy. Analyses of curved assemblies are now in progress, however, and triangular plate shapes to open up for other geometries are aimed at and planned.

The geometrical relations in the structure are of importance for both structural performance and architectural usability. Comparisons with an existing equestrian hall have been initiated and are to be continued, eventually aiming for a stock example of a hall of medium size. In the case of the structural performance, geometries, shapes, cuts and edge stabilisation are of interest. In case of the architectural usability the utilisation of the structural potential as well as relations between the structural principle, its supporting structure and the created space need to be worked through.

The paper describes further development of structural principles and architectural use.

INTRODUCTION

High-tech use of engineered timber-products offers structural and architectural possibilities such as structures with tensegric function, and plate- and shear-based transfer of forces in combined action imply a potential step of development. In this article the utilisation of plate tensegrity in practice is focused through a study of a cable-stayed plate-based structural element and its hypothetical application in a roof structure for an equestrian hall. An existing riding hall is used as reference object regarding means of production, structural function and architectural impact.

TENSEGRITY AND ARCHITECTURE

The structural potential of tensegrity has been treated many times (by e.g. Fuller, Motro, Hanaor, and Wang), and some authors have addressed the architectural potential as well [7]. Such an addressing tend in several cases to reflect the viewpoint that architecture equals sculpture, which is not the perspective in this paper. Sculptures seldom fill other functions than pure aesthetical ones whereas architecture concerns structural, functional and aesthetical properties at the same time. This definition was given in the first century B.C. by the Roman architect Vitruvius, who viewed stability, utility and aesthetics as three equally important properties. Considering this, regarding what has been actually built with tensegrity so far, doubts about the architectural utility are reasonable
since rather few functional applications, except for cable domes and masts, have crossed the border between computer modelling and the physical world in full scale. The original definitions of tensegrity are merely too restrictive and fantastic to be turned into an architecturally usable reality. The attachment of covering surfaces, stabilisation of members, connection design and deployment technology have been regarded as unresolved questions [8].

Motro and Raducanu have defined “a tensegrity state” [9], thereby referring to tensegrity as a system to distinguish characteristic components, relationships, overall structure and 3D form. The system approach is of crucial importance for both structural elements and overall form and the definitions of tensegrity can be followed to different extents on different system levels e.g. fulfilling the original tensegrity definitions in the single unit while allowing deviations from them when assembling the units in the system. The system should comprise not only the tensegric components but also the supporting structure, which may be decisive for the functional use. The distinction of a system should thereby lead to the issue of the aimed at practical function.

To let the structural unit comprise a surface in its original design means one way to deal with the demands of a functional result already at the stage of the basic principles of the structural system. This implies extending the utilisation of the materials and elements by developing their structural and functional tasks in the light of the finished building.

**PLATE TENSEGRITY**

By introducing a surface element in a cable-stayed structure such as a basic tensegrity unit a tight surface for e.g. rain protection and sun shield is achieved, and the joint zones can be sealed with gaskets, sealing fabric or rubber sheets. The plate module consists of a plate, a strut and interconnecting cables fixing the strut in an axis through the plate. The cables only connect to the peripheries of strut and plate and circumscribe in this way compressed members with tension, as in the original simplex. 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. In the middle layer the plates are jointed to form a continuous surface.

Different types of similar truss structures showing deviations from the tensegrity definitions have been described before by e.g. Saitoh et al. [6], Hangai et al. [10] and Wang [11], where bars in the units are connected to each other to form a continuous framework as a rigid layer in the structural unit. Wang has treated a number of varieties of contiguous and non-contiguous strut assemblies and analysed deviating units, patterns and grids, modelling and comparing them with conventional space truss design, thereby defining non-contiguous structures to be less efficient than contiguous ones [12]. The main types of tensegric structures dealt with by Wang are plane assemblies, which are compared with conventional space trusses with orthogonal grids.

**Structural Assemblies**

In a single plate tensegrity unit, the plate and the bar take up compression forces transferred by the rods in tension. In an assembly the struts transfer forces to the cable nets and the plates transfer forces in the middle layer. The plates in the units will be in contact with neighbouring plates to create a continuous plane, providing a path of transference of lateral loads. 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.

In a straight assembly this means that a single large plate could constitute the plane of the span (massive timber can be manufactured in lengths of 24 m and widths up to 2.95 m and can be finger jointed into even larger elements). This solution results in a less flexible structure, which in a plane assembly could add to its structural, static performance and increase the stability of each element/span. At construction a span or an entire structure could be obtained with a reduced number of elements. It would on the other hand result in less freedom in the shape of the structure (circular or parabolic curves and asymmetric cross-sections) and reduce the tensegric character. At the construction site a small element size means a large number of joints but also units with lower weight to lift in place.

This difference is important to consider in relation to conventional space trusses, which are easily and rationally produced and assembled. To work with product specific properties and to extend the utilisation of these is in the project regarded gainful not only for the structural efficiency but also for the competitiveness on the market. The reason to deal with and develop tensegry should be a combination of structural and productional efficiency/rationality and an adaptive, variable structural/architectural capacity e.g. to span and cover. The
continuous cable nets provide possibilities to vary the design and composition of an assembly – issues treated by e.g. Almegaard and Vanggaard [3] and Wester [4]. As long as the cable nets remain, cuts will be allowed along the edges, where cable nets and bars stabilise the remaining plates. Depending on the needs, stipulated and calculated loads, layout is variable by exchanging cable-stayed plates for simple plate elements, elements of other materials, transparent elements or by leaving elements out, resulting in an open grid pattern. Inside an assembly cable nets, bars and remaining plates form a stable structure surrounding eventually left out elements (both linear and nodal joints may be utilised).

Plate tensegrity can form straight assemblies and upper and lower cables can be provided extra tension through pre-stressing to increase the load capacity and decrease deflection. There are two different cable-cases for pre-stressing: cables in the units and cables in the nets. Depending on the geometry of the basic unit the pre-stressing directions of the cable nets will be oriented differently – orthogonally with square elements and diagonally with triangular elements. Under load, disturbing deformation will, however, risk to appear both inwards/downwards and outwards/upwards. Wang has proposed a method where the ratio between those forces decides the dimensions and structural design of the elements and the relation between outer and inner structural layers [12].

Another structural situation is created in the design of a curved assembly, which may lead to higher efficiency than a plane assembly by taking advantage of the vault/shell/shear capacity of the plates. Curved assemblies can be applied either as hanging roofs or vaulted structures, where the tension cables will fix and maintain the initial shape. Deformations may in this case be smaller and/or less disturbing than in plane assemblies. With concave curves (hanging roofs) the need for statically fixed supports increase. A plausible solution is to use timber plates as columns, oriented in the direction of the span, which provides rigidity in this direction.

**Element Design**

The surface design and thereby the assembly patterns are variable. The basic plate geometries are those of quadratic and triangular shaped plates (see Figure 1). The basic patterns are generated through repetition of the basic elements and the most simple structural shapes are obtained with only one element type. This answers to needs of rationality in series-production and construction. The strut runs through a hole in the plate. Important to note is that the joint decreases the buckling length of the strut but is moment free. As has been briefly discussed in [5] the strut may be given different positions and angles in relation to the plate to stabilise non-circular and asymmetrical cross-sections, i.e. the part of the strut above may be bigger or smaller than the part below the plate. This possibility could lead to structural gains similar to those seen in the Berlin Railway Station (by J. Schlaich 2002) [13].

![Figure 1. Assembling of square and triangular plate tensegrity units.](image)

The system geometry is basically generated by the utilised elements. The first models were for practical reasons designed with square plate elements. The computer models are so far based solely on rectangular elements whereas physical cardboard models have been produced with triangular ones. In a square/rectangular plate unit the moment free state is not guaranteed and the four cables easily counteract each other. In a triangular plate with a three-node restraint moment is avoided. It also provides another variability of structural shapes than rectangular elements. Construction of vaulted assemblies is possible by adding elements row-by-row or bow-by-bow, as seen in Figure 2. Depending on the overall shape and the conditions on the building site the construction method may be altered and adapted to what is most suitable. Available crane capacity will also be decisive for the relation of rationality between element size/weight and construction method.
Depending on the structural and functional needs the elements may form either a load-carrying grid structure (a 2D space truss) or spanning bows (straight or curved truss beams) with infill non-load carrying elements in between (see Figure 3, left). Triangular elements can be assembled through Freivorbau row-by-row (see Figure 3, right), resulting in a faceted vault section similar to the shape obtained with rectangular elements. The basic assembly is constructed with elements, which all contain cable-stayed plates. To simplify the structure and to reduce the number of cables every second unit may be replaced by a simple plate element without cables and strut. Earlier models of plane assemblies were composed of three-node restrained hexagonal plates cantilevering to cover the gaps where triangular elements had been left out [1]. This approach saves cables and reduces the structural complexity as well, but does not allow curved assemblies with repetition of one single plane element.

The angle between the facets of the curved shell will under normal design load cause forces out of the plane. These will be taken up by the inclined cables on the lower side, which transfer the forces to the struts and into the cable nets. The forces are in this way kept inside the overall structure. For short spans the cable nets will be capable of controlling the lateral forces in the system like in plane assemblies. Some increase of the loads can be taken care of by increasing the pre-stressing of the cable nets. To control the lateral forces at the abutments at large spans and to decrease the demands on the supporting structure, the tensioning of the lower cable net can be complemented with a horizontal tensioned member – cable or rod – on the lower side of the assembly e.g. between the lower strut end nodes of the outer elements at the base edges of the roof, if the height of the supports and the need for free spatial volume inside allow it.

A STRUCTURAL COMPARISON

The initial computer modelling was performed based on a plane assembly of ten plate tensegrity units. This modeling showed an interesting static capacity and a well-working behaviour [5]. The aim has been set at curved assemblies, why the modelling methods have been further developed, also suiting calculations of the behaviour of similar structures, for structural comparisons. To compare the function, structural properties and element design an existing advanced structure with a cross-laminated plate roof is currently being regarded. The construction of this roof has been documented and analysed in a recently finished project on architectural utilisation of structural principles and systems [2]. The roof structure is described below.

Flyinge Equestrian Hall
Close to the city of Lund, Sweden, an equestrian hall was constructed 2004-2005 (see Figure 4). The project was designed by a Swedish architect and an Austrian engineer to make a new, modern building suit a historical site. The principle of the Poloncéau truss was transformed into a rod-stayed cross-laminated timber plate supported by a steel trestle structure. The structural principle reminds of the historical buildings in the area and provides at the same time a modernised design. The roof structure measures 41.6 × 80.3 m². The span is covered by a saddle
roof constructed with two roof elements connected by a hinged joint at the apex and a horizontal steel rod in the direction of the span connecting the trestles of the elements two and two. The structural depth is 8.6 m. The interior appearance is visually much lighter than what had been the result with a conventional timber beam or steel truss roof, which was an important reason for choosing this solution.

The elements were prefabricated as plane elements of 225 mm thickness with the dimensions 14.2 × 2.5 m² and 8.2 × 2.5 m². These were transported to the site where they were assembled four and four into elements measuring 22.5 × 5.0 m² on which trestles were fixed with screws and rods. The elements were then lifted into place with two cranes and a third crane provided the horizontal rod. The elements are mainly jointed half-in-half or butt-jointed and fixed with skewed screws. At the apex steel plates are fixed at each timber edge and connected by steel strips with mated joints. At the base the saddle roof rests on simple cross-braced columns along two sides and on columns stabilised with plates along the other two. The technology required rather heavy lifts and laborious work keeping the overall shape while mounting and fixing the elements along the hall. Well in place the structure shows good structural behaviour and an architectural effect of experienced lightness and low visual disturbance, as desired.

The main roof structure is symmetrical (see Figure 5). To the west an elongation of the roof has been added outside the row of supporting columns, to cover an aisle for spectators. This addition does not co-act statically with the main structure. It is connected with reinforced butt-joints to the main roof elements and simply supported by a latera row of columns. The architectural effect of the Flyinge structure is rather neutral regarding materiality, though visually very massive. The elements are big sized and the supports are relatively widely spaced [2]. Seen from one of the gables, however, the building shows high visual complexity.

Exchange of Structural Solutions
The span of Flyinge equestrian hall is hypothetically manageable with a curved assembly of cable-stayed plates. The hereby-proposed assembly is a plate tensegrity vault of the same structural depth as the existing saddle roof. The change of systems means a change of numbers and sizes of the utilised elements as well as the overall form. A vault replaces the saddle roof and both the distance between and the design of the joints are changed. The supporting structure is taken as support condition for the new structure and the substitution concerns the roof structure only, to enable comparison and structural analysis.
The cross-section can be given different designs. As a first step a circular curve is chosen; a parabolic section could be more efficient but will be dealt with at a later stage. Proposed measures for the cable-stayed plates are rectangular elements of 2.0 – 2.95 m in length and 2.0 – 2.5 m in width and triangular elements with 2.0 – 2.95 m side (see Figure 6). The thickness of the plates should suit the rigidity and deformations of the overall system. With a flexible system like the proposed one, with cable-nets, hinged joints between the plates and 0-moment connection between plate and strut, there is no need to use plates with very high stiffness since their deflections then may be much smaller than the deflections of the enclosing system.

![Figure 6. Cardboard model of a roof section with plate tensegrity based on triangular elements.](image)

**Production and Construction**

During the design work and production of the Flyinge project several potential customers made contact and showed their interest. The main demands can be summed up in a number of needs: a cheap timber-based system, efficient construction and simple solutions for everyday use. This puts rationality in focus and comprises production, construction and use, methods, detailing and overall design.

The element structure may be constructed using either of the methods of jacking or Freivorbau, as described in [5]. In both cases the supporting columns are erected in place and used as abutments for the construction of the span. For the fixing at the supports steel fittings of the same design as in the existing structure may be utilised (see Figure 7). Instead of discontinuous fittings as in Flyinge a continuous fitting can be used at the base along each long side, or discontinuous fittings with shifted joints to connect the plate elements. At Freivorbau temporary supports may be needed during the stepwise addition of element units/rows/strips.

![Figure 7. Steel fittings at the roof edge in Flyinge; joint between plate elements and columns.](image)

Single plate geometry means a precise structural restriction. Exchange of plate elements means variability with rather small means. In a grid structure where cable-stayed elements carry intermediate plane elements the number of cables is reduced and thereby the number of connections, which simplifies the structural system and the construction.

**Architectural Impact**

Compared to both visual appearance and structural build-up of the existing roof, the plate tensegrity structure will be of higher complexity (see Figure 8). The increased complexity is due to smaller elements and a larger number of rods. The number of struts will also be larger than in the case with the existing trestle supports. The structural depth is equal to the one of the existing structure. The experienced space of a vault is another than the one of a saddle roof (see Figure 9). The created physical volume is somewhat bigger but the visual impact of the structural elements may reduce the experienced volume.
A plate tensegrity structure obtained with triangular elements will, as already noted, form a different overall geometry than with rectangular elements, if only one element shape is utilised. To construct an orthogonal roof, a small number of infill elements with other shapes will be needed along the vault gables. The cable nets fix the struts of the cable-stayed elements along the edge. In between those, plane infill elements are connected with linear joints to cantilever along the eaves.

Figure 8. Interior view of a cardboard model of a plate tensegrity roof.

Figure 9. Comparison of different roof structures. Sketched principles.

The upper side of the roof will show the most apparent difference, since the structural design of the plate tensegrity unit is principally symmetrical in the vertical direction. This means that the upper side of the roof will show the same amount of cables and struts as the lower side except for the jointing horizontal cables. The exterior will thus show a significantly more complex structural and thereby a more complex architectural appearance (see Figure 10). As with e.g. the Olympic arenas in Munich from 1972 the cables will have to withstand weathering induced ageing. The upper element surface will need cladding to protect the timber. Asphalted paper, steel sheets or rubber sheets are plausible products, which are preferably applied before assembly. Only the edge zones on the elements should be left unclad, to be covered/coated/sealed on the assembled structure.

Figure 10. Exterior effects of struts and cables as seen in a model study.
CONCLUSIONS

In the development work with plate tensegrity from a combined architectural and structural perspective, several properties of interest have been noted, along with several so far unsolved issues. The overall design will show the structural principle very clearly, even on the outside. The architectural concept of form is derived from the structural solution, which in turn is being developed regarding its architectural and purely functional effects. By utilising the cable nets the variability of the composition of assemblies increase and with rather small means big effects can be obtained within a fairly restrictive system. Simple elements can replace cable-stayed units in a tensegric grid, which gains rationality with remaining experienced complexity.

The triangular basic plate is as expected found to be structurally more efficient than rectangular ones but it also shows good variability of design possibilities concerning structural geometries on the system level. Triangular elements should, however, be further modeled and analysed in computer simulations. The relation between deflections of the units and deflections of the system remain to be studied when deciding the final dimensions of the elements and in this context prototypes for joints need to be designed more in detail.

REFERENCES


