Master thesis in Civil Engineering

Compression perpendicular to grain in timber
– Bearing strength for a sill plate

Tryck vinkelrätt fibrerna hos trä
– Sylltryck
Abstract

Timber is widely used in the construction industry, because of its availability and good properties. The compressive strength perpendicular to grain (bearing strength) is one property of wood which is important for structural design. The bearing strength is important for the behavior of the structure in all contact points between wooden members. The calculations models for bearing strength have been a subject of discussion for many years and the different building codes in Europe has treated it differently during the years.

The aim of this thesis was to compare different calculations models for bearing strength with the results of an experimental study. In this study the bearing strength for a fully supported beam loaded with a point load was studied. Two different loading lengths were studied as well as loading in a point in the middle of the beam, at the edge of the beam and at a distance of 10 mm between the edge and the loading point. The loading was made with a steel stud. Calculations were also performed according to the following standards; Eurocode 5 (EN1995-1-1:2004) before and after amendment, the German Code (DIN 1052:2004), the Italian Code (CNR-DT 206:2006) and two versions of the Swedish Code (BKR).

The results showed that the results from the new version of Eurocode 5 agreed best with the experimental results. The tested results, however, were lower than the values calculated using Eurocode (and all the other codes); this might be explained by the hard loading conditions using a steel stud instead of a wood stud.
Acknowledgement

This master thesis was carried out at the School of Engineering at Linnaeus University in Växjö, Sweden as part of the master program in civil engineering. The work has been performed in the period 2011 to 2013. We would like to thank for the support, guidelines on this study and work provided by our supervisor and examiner Marie Johansson.

Secondly, we would like to say a big thank you to Bertil Enquist the research engineer, for help in our laboratory tests and analysis. In addition, we would like to thank those individuals that have helped including our friends and university staff for their support in project report writing.

Finally, we would like to express our gratitude for the support and encouragement by our families during the whole work.
Table of Contents

Abstract .............................................................................................................................................. I
Acknowledgement ................................................................................................................................ II
Table of Contents .......................................................................................................................... IV

1. Introduction ..................................................................................................................................... 1
   1.1. Background ............................................................................................................................ 1
   1.2. Objective ............................................................................................................................... 2
   1.3. Outline of the thesis ............................................................................................................... 2

2. Literature review .......................................................................................................................... 3
   2.1. Introduction about wood material and timber structures .................................................... 3
       2.1.1. Natural characteristics of wood ..................................................................................... 4
       2.1.2. Physical properties of wood .......................................................................................... 4
       2.1.3. Mechanical properties of timber ................................................................................... 5
       2.1.4. Strength grading ............................................................................................................. 6
   2.2. Compression strength perpendicular to grain ....................................................................... 6
       2.2.1. Load carrying capacity according to EN 408 ................................................................. 7
   2.3. Overview of methods and models to calculate design compression capacity .................... 8
       2.3.1. Eurocode 5 (EN1995-1-1:2004) before amendment ...................................................... 8
       2.3.2. Eurocode 5 (EN 1995-1-1:2004) after amendment ......................................................... 10
       2.3.3. Italian code (CNR-DT-206:2006) ................................................................................. 11
       2.3.4. German Code (DIN 1052:2004) ...................................................................................... 12
       2.3.5. Swedish new code (BKR: 2003) ...................................................................................... 13
       2.3.6. Swedish old code ............................................................................................................ 13

3. Description of material and methods ......................................................................................... 15
   3.1. Description of tests ................................................................................................................ 15
   3.2. Material .................................................................................................................................. 15
   3.3. Mechanical testing in the MTS machine .............................................................................. 17
   3.4. Strain field measurements ................................................................................................... 18

4. Results from the experiments .................................................................................................... 19
   4.1. Modulus of elasticity of the material .................................................................................... 19
   4.2. Compression force perpendicular to grain $F_{c,90,\text{max}}$ ................................................... 21
   4.3. General results from ARAMIS ............................................................................................. 22

5. Calculation according to different codes ................................................................................... 24
   5.1. Old version of Eurocode (EN 1995-1-1:2004) before amendment ...................................... 25
   5.3. Italian code (CNR-DT 206-2006) .......................................................................................... 28
   5.4. German code (DIN 1052:2004) ............................................................................................. 29
   5.5. Swedish new code (BKR: 2003) ............................................................................................ 31
   5.6. Swedish old code .................................................................................................................. 32

6. Analysis and discussion ............................................................................................................... 34
7. Conclusion ......................................................................................................................... 38
8. References .......................................................................................................................... 39
Appendix A: ARAMIS Images ................................................................................................. 41
Appendix B: Cross-sectional view of specimens ................................................................. 43
Appendix C: Force and deformation diagram ...................................................................... 51
Appendix D: Force-deformations graphs MTS 810 .............................................................. 57
1. Introduction

1.1. Background

Timber is a material that has many characteristics that make it a good material for construction of buildings. The material has a very high strength, especially when compared with its low weight. The material is, however, very anisotropic with different properties in different directions due to its make-up of oriented fibers. The strength parallel to the fiber direction is very good while the strength when loaded perpendicular to the fiber direction is very low. This low strength perpendicular to the fiber direction needs to be addressed when designing timber structures. In particular the compression strength perpendicular to the fiber direction needs to be taken into account at supports; see Figure 1.1.

![End support](image1.png)  ![Bottom and top Support](image2.png)

**a) End support**  **b) Bottom and top Support**

![Interior Support](image3.png)  ![Ledger](image4.png)

**c) Interior Support**  **d) Ledger**

Figure 1.1: Examples of supports where the timber is loaded in compression perpendicular to the fibers. [1]

When the wood material is subjected to a compression load perpendicular to the fibers the fibers react by collapsing causing large deformations, the fibers are crushed; see Figure 1.2. As can be seen in Figure 1.2(b) the material around the loaded area will help to minimize the deformation under the load. For this reason most models for calculating design capacity in these cases include not only the material strength and the loaded area but also a term that take the amount of unloaded area into account. Several different models for taking the unloaded area into account have been presented during the years. The total deformation will depend on the loaded area as well as how close to the end of a board the load is transferred.
Various design codes in Europe have used different models for calculating the design capacity. The value of the compression strength perpendicular to the grain varies greatly between different national codes as well as the models for taking the unloaded area into account. The common European code has also changed the model for calculating design capacity and several models have been presented at conferences during the last 10 years [1].

1.2. Objective

The aim of this thesis is to investigate the behavior of timber loaded perpendicular to the fiber direction. In the study different calculation models for bearing strength from the literature will be compared with the results from an experimental study.

The bearing strength will be studied experimentally and the deformations will be studied with both LVDT (Linear variable differential transformer) gauges and with the non-contact system ARAMIS which will give the total strain field under the load. Different loading lengths and different distances to the edge of the loaded member will be investigated. The results from the experimental study will be compared with results calculated using different models found in the literature. The study will show which of the models fits best with the experimental results.

The study will only investigate fully supported beams of Norway spruce with compression loads from a stud. Three different distances from the edge to the loaded point will be studied as well as two different loading areas.

1.3. Outline of the thesis

The work of the thesis consists of, in chapter one the background and the objectives. Chapter two gives a general introduction to timber and a literature review on compression perpendicular to the fiber direction including different design models described in the literature. Chapter three describes the testing including the material, the test-set-up and the procedures. Chapter four describes the results from the experiments and chapter five describes the design calculations for the same set-ups as in the experiments according to different models found in the literature. Chapter six includes an analysis of the results and compares the experimental results with the results from the design calculations. Chapter seven includes a summary and suggestions for further research.
2. Literature review

This section firstly addresses the wood material and timber structure and secondly a brief discussion of mechanical properties of timber; compression perpendicular to the fiber direction and models that have been proposed over the last decade.

2.1. Introduction about wood material and timber structures

Wood material is extracted from the main stem of a tree through various sawing processes. The tree stem is grown round which provides the rigidity, mechanical strength and height to maintain the crown, and to make the tree effective against gravity and wind loads. The stem wood also provides transportation of water and minerals from the root of the tree to the crown [2]. An image of a typical cross-section, as shown in Figure 2.1, illustrates the main features of a tree trunk, such as the outer bark layer which is dry and corky. The cambium is a layer of cells between the wood and the bark where new wood cells are formed on the inside and new bark cells formed the outside. A tree produces a new layer of thin walled cells in the cambium every year in the early growing season; mainly for transportation of water and nutrients, and later in the season it produces thick walled cells, mainly for structural purposes. This process makes a visible ring as shown in Figure 2.1 which is a so-called annual ring.

![Figure 2.1: Cross-section of tree trunk [1].](image)

Wood, in general, is composed of mainly three elements; 50% carbon, 6% hydrogen and 44% oxygen in the form of cellulose, hemicelluloses and lignin [4]. Cellulose is a long chain molecule; the cellulose chain are bound together to form crystalline strands called fibrils. These fibrils are bound together with lignin and makes up the cell wall. Up to 80 to 95% of the wood cells are oriented parallel to the longitudinal axis of the tree. The most common type of cell in softwood is the so-called tracheid; a tube-shaped cell with a size of approximately 2-4 mm in length and 0.1 mm in width. This tracheid makes up the main part of the wood tissue; they are often called grain or fiber [4].
2.1.1. Natural characteristics of wood

Wood has a number of natural characteristic which can be seen as defects, some of them described below. Often such characteristics can cause a reduction of the wood strength. For example; knots, slope of grain, juvenile wood, reaction wood [2].

Knots in wood structures are common. The knots are the part of the branch wood that can be seen inside the tree trunk, see Figure 2.2. The knot influences the strength of the timber by the discontinuity of fibers. The size, shape and location of the knots affect the strength of timber. Hence for a better strength timber should have few and smaller knots.

![Knots](image)

*Figure 2.2: Knots in wood section, [3]*

2.1.2. Physical properties of wood

Furthermore, some of the physical properties of wood have a large influence on the behavior of wood and timber. These properties are density, wood and moisture, seasoning defects, shrinkage and swelling, etc. [2]. Density is one important physical characteristic of timber, which affects the timber strength properties. High density is often associated with high strength of the wood material. The density is defined as follows:

\[
\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{M}{V} \tag{2.1}
\]

Where \( M \) is the mass in [kg] and \( V \) is the volume in [m³].

The density for wood has to be defined also in terms of moisture content; since the mass and volume are both dependent on water content. Water content in timber is one of the external factors that have a large influence on wood properties. Moisture content is usually defined as follows:

\[
\text{Moisture content (M.C)} = \frac{W_w - W_d}{W_w} \cdot 100 \tag{2.2}
\]

Where, \( W_w \) is wet weight of the sample, and \( W_d \) is weight of the sample after drying in 104°C for 24 hours [2].
2.1.3. Mechanical properties of timber

The wood material strength refers to the ability to resist the applied force until the material fails, and the amount of the deformation determines the elasticity of material [1]. The structure of wood material is an example of an orthotropic material because it has different properties in different directions. Thus for structural purposes wood material is assumed to be anisotropic. Figure 2.3(a-b) shows the definition of the direction of the stresses in wood. The property, which is along the X-axis; aligned with the grain direction (L) is referred to as stress parallel to the grain. Stresses across the grain direction in the tangential (T) or radial (R) direction are referred to as stresses perpendicular to the grain. For structural purposes the strength perpendicular to the grain is assumed to be the same in both tangential and radial directions. The symbols used for these stresses according to EC 5 are: [1]

\[ \sigma_{c,90,d} \] is the design compression stress parallel to grain, where \( c,0,d \) refers to compression at zero degree angle and ‘d’ is for design.

\[ \sigma_{c,90,d} \] is the design compression stress perpendicular to the grain, where \( c,90,d \) refers to compression at 90° angle and ‘d’ is for design.

![Figure 2.3 (a): The principle direction of wood grain and stresses. (b): Direction of load with respect to direction of annual growth rings: ‘90°or perpendicular (R), [1]
2.1.4. Strength grading

Wood is a natural material, and due to its very varying properties, it is necessary to sort, or grade, the sawn material into different strength classes to have better control of the strength properties. The strength of the sawn timber is dependent on several parameters such as: species, size, density and the size and dimension of knots. The sawn timber is therefore graded into different strength classes with given values for modulus of elasticity, bending and shear strength parallel to grain, compression and tension strengths parallel and perpendicular to grain and density.

There are many techniques used to grade the sawn material into strength classes, most of them are based on the relationship between the modulus of elasticity and the bending strength. There are different ways to measure the modulus of elasticity; static bending machines or machines based on measuring resonance frequency [2]. Determination of modulus of elasticity (MOE) from resonance frequency is one of the most commonly used techniques. A board’s MOE can be determined by introducing vibration into it and evaluate its resonance frequency. The equation for determining the longitudinal modulus of elasticity $E_{0,\text{mean}}$ from resonance frequency can be expressed as following [5]:

$$E_{0,\text{mean}} = 4 \cdot \rho \cdot (f \cdot l)^2$$

(2.3)

Where $\rho$ is density [kg/m$^3$], $f$ is first resonance frequency in the longitudinal direction [Hz], $l$ is length of material (beam) [m].

2.2. Compression strength perpendicular to grain

In structural design the compression strength perpendicular to grain is an important property, as it determines the bearing strength. The bearing strength depends on loading conditions and specimen type as discussed in the background. Timber is composed of thin tubular cells, and these cells are bound together by a substance, called lignin as explained in Chapter 2.1. In principle, these cells looks like a bundle of narrow thin-walled tubes as shown in Figure 2.4.

![Figure 2.4: Microscopic view of wood cell in structure of timber, [1].](image)
When a load applied perpendicular to the cells (grains), the thin walled tubes are affected laterally and will be squeezed together with the increase of compression stresses and start to collapse. This behavior continues until all the fibers are fully crushed. When all fibers are crushed together it is possible to once again increase the loads and it is difficult to define a failure level. As read in [1] “The strain in the wood can exceed 30% and failure may still not arise”. The deformation will at this stage, however, be very large and in most structures too large for a rational use in the structure. To determine a strength value for compression perpendicular to grain a maximum strain value is normally used.

Normal stress in a structural member is defined by dividing the resultant force \( F \) by the cross-sectional area \( A \). The mathematical expression as follows: [5]

\[
\sigma = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}
\]  

(2.4)

Similarly, in timber with a design load applied perpendicular to the grains, the design stress perpendicular to grain \( \sigma_{c,90,d} \) can be obtained by dividing the design load \( F_{c,90,d} \) by the (contact area) effective area \( A_{ef} \).

\[
\sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}}
\]  

(2.5)

Where, the effective area is obtained from multiplying the contact width, \( b \), with the effective contact length, \( l_{ef} \). This effective length can be the actual length or it may be derived from different models which will be discussed further in the next section. Thelandersson and Martensson, [6], Blass and Görlacher [7], Van der put [8] and several other researchers have proposed many models to calculate the effective length.

The capacity of the material \( f_{c,90,d} \) can also be increased by a factor \( k \) that takes the effect of the surrounding material into account (unloaded length).

2.2.1. Load carrying capacity according to EN 408

The compression force perpendicular to grain \( F_{c,90} \) can be estimate from the tests performed according to EN 408:2010.

To calculate the compressive force perpendicular to grain the following process will have to be used. Firstly the load-deformation curve will have to be drawn, see Figure 2.6. From this curve an estimated value for the \( F_{c,90,\text{max,est}} \) is decided. Secondly that the value of \( 0.1F_{c,90,\text{max,est}} \) and the value of \( 0.4F_{c,90,\text{max,est}} \) is calculated and their value levels drawn into the curve. Then a straight line 1 is drawn through these two points as shown in Figure 2.6. Another line 2 is then drawn parallel to line 1, with the deformation at the origin load \( F=0 \) equal to 0.01h as shown in Figure 2.6, where the h is total depth of specimen.

The value of the compressive strength \( F_{c,90,\text{max}} \) then corresponds to the load value that corresponds to the intersection of line 2 and the load-deformation curve of test results. If the value of \( F_{c,90,\text{max}} \) determined is within 5% of the estimated \( F_{c,90,\text{max,est}} \), then that value may be used to determine the compressive strength; otherwise, repeat the procedure until a value of within the tolerance is obtained [9].
2.3. Overview of methods and models to calculate design compression capacity

Most codes in Europe have had different methods to calculate the design capacity for compression perpendicular to the grain, for example the German Code, the Italian Code, the Swedish Code. Since 2012 Eurocode 5 is used all over Europe. For Eurocode there has been a discussion about which model to use for calculating the design capacity which has led to changes in the code. The codes all have different methods for taking the unloaded length into account. In this study only the case with a concentrated load applied to a fully supported beam (sill) is included. Only models regarding this load case is therefore presented.

2.3.1. Eurocode 5 (EN1995-1-1:2004) before amendment

In Eurocode 5 the design rules for the compression perpendicular to the grains were as follows before the last amendment [2]. According to Eurocode 5 the following expression shall be satisfied for the beam in compression: [2]

\[ \sigma_{c,90,d} \leq k_{c,90} f_{c,90,d} \]  \hspace{1cm} (2.6)

\[ \sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}} \]  \hspace{1cm} (2.7)

And the design compression force perpendicular to grain is

\[ F_{c,90,d} = k_{c,90} f_{c,90,d} A_{ef} \]  \hspace{1cm} (2.8)
Where,

- $k_{c,90}$ - is a factor taking into account the load configuration, possibility of splitting and degree of compressive deformation.
- $\sigma_{c,90,d}$ - is the design compressive stress in the contact area perpendicular to the grain.
- $f_{c,90,d}$ - is the design compressive strength perpendicular to grain.
- $A_{ef}$ - is the effective area

The design compression strength perpendicular to grain $f_{c,90,d}$ value is 2.5 N/mm$^2$. And the value of $k_{c,90}$ should be calculated for the case with a concentrated load as follows. For a member with a depth $h \leq 2.5b$ where a concentrated force with contact over the full width, $b$ of the member is applied to one face directly over a continuous or discrete support on the opposite face, the factor $k_{c,90}$ is given by:

$$k_{c,90} = \left(2.38 - \frac{l}{250}\right)\left(\frac{l_{ef}}{l}\right)^{0.5}$$  \hspace{1cm} (2.9)

Where:

- $l_{ef}$ - is the effective length of bearing stresses,
- $l$ is the contact length,
- $h$ is the total depth of specimen and $b$ is the width of specimen.

![Figure 2.6: Determination of effective lengths for a member with $h/b \leq 2.5$, (a) and (b) are continuous support, [1]](image)

The effective length for a load perpendicular to the grain shall be determined by a line with the vertical inclination of 1:3.

The effective length of the load adjacent to the end of the member which is shown in Figure 2.6 (a) is.
\[ l_{ef} = l + \frac{h}{3} \]  
(2.10)

Where \( h \) is depth of member.

Where the distance \( a \geq 2/3 \, h \), from the edge of applied load to the end of member, Figure 2.6(b).

\[ l_{ef} = l + \frac{2h}{3} \]  
(2.11)

Where the \( h \) is depth of member, 40 mm or whichever is largest.

2.3.2. Eurocode 5 (EN 1995-1-1:2004) after amendment

Eurocode 5 was updated with an amendment for the calculation of compression strength perpendicular to grain which was published 2009-05-20. In the new version of the standard when a member is loaded perpendicular to the grain by a design load \( f_{c,90,d} \) the expression for compression stress \( \sigma_{c,90,d} \) will be derived at the plane of contact between the load and the member [2][1].

\[ \sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}} \]  
(2.12)

Where:

- \( A_{ef} \) is the effective contact area perpendicular to the grain. “The effective area is obtained by multiplying the contact zone width by an ‘effective contact length’. The effective contact length can be the actual contact length, \( l \), as indicated in Figure 2.6, or may be derived by adding 30 mm to each end of the actual contact length but not more than “a” or “F”,[10] as shown in Figure 2.6.

The validation requirement will be:

\[ \sigma_{c,90,d} \leq k_{c,90} \cdot f_{c,90,d} \]  
(2.13)

And the design compression force perpendicular to grain is

\[ F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} \]  
(2.14)

The value of \( k_{c,90} \) should be taken to be 1, however for the bearing conditions which is shown in Figure2.6, when \( l_f \geq 2h \), where \( h \) is the depth of the member, a higher value can be used for solid softwood and glued laminated timber as given in Table 2.1. The design compression strength perpendicular to grain \( f_{c,90,d} \) value is 2.5 N/mm².
Table 2.1: Value of $k_{c,90}$ for solid timber and glued laminated timber members subjected to compression perpendicular to the grain [10]

<table>
<thead>
<tr>
<th>Member support condition</th>
<th>Solid softwood timber member</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous support</td>
<td>$k_{c,90} = 1.25$</td>
</tr>
<tr>
<td>Discrete support</td>
<td>$k_{c,90} = 1.5$</td>
</tr>
</tbody>
</table>

2.3.3. Italian code (CNR-DT-206:2006)

In the Italian code the unloaded length deals with in this certain way [2] [11].

Figure 2.7: Effective length, [2]

Where the expression shall be satisfied:

$$\sigma_{c,90,d} \leq f_{c,90,d}$$  \hspace{1cm} (2.15)

$$\sigma_{c,90,d} = \frac{F_{90,d}}{b \cdot l_{ef}}$$  \hspace{1cm} (2.16)

$$F_{c,90,d} = f_{c,90,d} \cdot b \cdot l_{ef}$$  \hspace{1cm} (2.17)

$l_{ef}$ - is effective length given by considering the stress field distribution parallel to the grain with an inclination of 1/3 and the limits shall be following:

$$l_{ef} \leq l + \frac{1}{3}h$$  \hspace{1cm} (2.18)

$$l_{ef} \leq 2l$$  \hspace{1cm} (2.19)

The design compression strength perpendicular to grain $f_{c,90,d}$ value is 5 N/mm². However, when it is allowed for the point of a maximum deformation perpendicular to grain it is possible to use a value of 1.5 times the strength.
2.3.4. German Code (DIN 1052:2004)

In the German code the unloaded length is dealt with in the following way [2]:

Where the following expression shall be satisfied

$$\frac{\sigma_{c,90,d}}{k_{c,90} \cdot f_{c,90,d}} \leq 1$$  \hspace{1cm} (2.20)

And the compressive design stress is

$$\sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}}$$  \hspace{1cm} (2.21)

And the design compression force perpendicular to grain is

$$F_{c,90,d} = k_{c,90,d} f_{c,90,d} A_{ef}$$  \hspace{1cm} (2.22)

The symbols which are used:

- $A_{ef}$ - is the effective area under the load perpendicular to the grain.
- $k_{c,90}$ - is the factor taking into account for unloaded length.

To calculate the effective area, $A_{ef}$, of the applied load in compression perpendicular to the grain; it is possible to increase the length of the surface of the applied load along the direction of grain up to 30 mm on both sides.[2]

The design compression strength perpendicular to grain $f_{c,90,d}$ value is 4.8 N/mm². Principally the German code is same as the new version of Euro-code and some of the values for $k_{c,90}$ are also equal. The value of $k_{c,90}$ is possible to assume from 1 to 1.75 for distances according to Figure 2.8 can be found in Table 2.2.

![Effective length determination](image)

**Figure 2.8:** Effective length determination (a): continuous support (b): member with discrete support, [2]
Table 2.2: The value of the factor according to the germen code

<table>
<thead>
<tr>
<th>Material</th>
<th>$k_{c,90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glue-Laminated plain timber, $I_i \geq 2h$</td>
<td>1.0</td>
</tr>
<tr>
<td>Plain timber with compressed tie, $I_i \geq 2h$</td>
<td>1.25</td>
</tr>
<tr>
<td>Glue-Laminated timber with compressed tie and $I_i \geq 2h$, $l \leq 400, \text{mm}$</td>
<td>1.5</td>
</tr>
<tr>
<td>Glue-Laminated timber and $I_i \geq 2h$, $l \leq 400, \text{mm}$</td>
<td>1.75</td>
</tr>
</tbody>
</table>

2.3.5. Swedish new code (BKR: 2003)

According to the Swedish code the bearing strength can be calculated as follows [2] [12], the resistance of timber member in compression perpendicular to grain is:

$$R_{c,90,d} = \kappa_{c,90} \cdot f_{c,90,d} \cdot A$$

(2.23)

Where:

- $R_{c,90,d}$ is the design value for compression perpendicular to the grain
- $f_{c,90,d}$ is the design compressive strength of member
- $A$ is the cross-sectional area of member
- $\kappa_{c,90}$ is the factor taking into account for the effected length according to Eurocode 5. In practice normally $k_{c,90}$ is not used and is therefore set to 1.0.

2.3.6. Swedish old code

According to the Swedish old code the compression force perpendicular to the grain can be calculated as follows [13], the resistance of timber member in compression perpendicular to grain is:

$$\sigma_{c,90} \leq \kappa_{c,90} \cdot f_{c,90}$$

(2.24)

$$\sigma_{c,90} = \frac{F}{b \cdot l}$$

(2.25)

$$F_{c,90,d} = b \cdot l \cdot \kappa_{c,90} f_{c,90}$$

(2.26)

Where:

- $F_{c,90,d}$ is the design value for compression perpendicular to the grain
- $f_{c,90,d}$ is the design capacity for compression perpendicular to the grain
- $b$ is the loaded area width
- $l$ is the loaded area length
- $\kappa_{c,90}$ is an increase factor which accounts for the unloaded length
\( \kappa_{c,90} = 1 \) for cases A2, A3 and B2, B3

For cases A1 and B1 the value for \( \kappa_{c,90} \) will calculate according to the following equation:

\[
\kappa_{c,90} = \begin{cases} 
1,8 & \text{for } l \leq 15 \text{mm} \\
\frac{4}{l} \sqrt[4]{\frac{150}{l}} & \text{for } 15 < l < 150 \text{mm} \\
1,0 & \text{for } 150 \leq l 
\end{cases}
\]

\[
\kappa_{c} = \frac{4}{l} \sqrt[4]{\frac{150}{l}} \quad \text{for } 15 < l < 150 \text{mm} \quad (l=90)
\]
3. Description of material and methods

3.1. Description of tests

A series of tests was performed at Linnaeus University, Växjö laboratory on behalf of the University in order to verify the compression strength perpendicular to grain of timber. The experiments were divided into six different set-ups with two different loading areas and three distances from the edge. The first series named A1, A2, A3 and the second named B1, B2, B3 as shown in Figure 3.1. All specimens have a dimension of (45 x 95 x500) mm. And the compression tests were performed by applying a load on the specimens by using two steel plates having contact area (45x95) mm or (90x95) mm, see Figure 3.1.

![Figure 3.1: Schematic diagram for the series A1-A3 and B1-B3](image)

3.2. Material

The material was 15 Norway spruce boards of strength class C24 with dimension (45 x95 x 4500) mm. The boards were all sawn with the annual rings more or less parallel with the face side of the board. The boards were conditioned at a temperature of 21°C and a relative humidity of 65% before the experiments. The dynamic modulus of elasticity of the boards was measured using an MTG-grader before the tests. The boards were marked with a number from 1 to 15 on one edge. Six 500 mm long sections were selected from each of the boards, one for each loading case according to Figure 3.1. The selection were made so that the specimens in the series A1 and B1 were without knots in the central 300 mm and the specimens in series A2, A3, B2 and B3 were without knots in 200 mm in one end. Of the 15 boards 11 boards were selected as giving specimens without knots in the right area, and these selected boards were cut into six specimens. These six set-ups marked with board number and specimen number, e.g. (1:A1 – 1:A3) and (1:B1 – 1:B3), see Figure 3.2.
Figure 3.2: Specimen numbers marked on the board. Note: There should not be large knots on the specimen’s compression area

A piece of wood was taken in the middle of the board for evaluation of density and moisture content of the board. The cross-sections of each 500 mm long specimen were placed on a flat-bed scanner for recording of the annual ring orientation, for an example see Figure 3.3.

All cross-sections can be seen in Appendix B.

Figure 3.3: Scanned image of the cross-sections for each for each of the six specimens from board no 1.

The density of the material was evaluated from the weight and dimensions of the small piece of wood taken from each board. The moisture content was calculated by equation (2.2) based on the weight of the pieces directly after sawing and the weight of the pieces after being dried in 104°C for 24 hours, see Table 3.1.
Table 3.1 Values of density and moisture content for boards.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Board No.</th>
<th>Density (kg/m$^3$)</th>
<th>Moisture content (MC in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>395</td>
<td>11.96</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>490</td>
<td>12.40</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>428</td>
<td>11.67</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>366</td>
<td>10.78</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>503</td>
<td>12.09</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>436</td>
<td>10.91</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>402</td>
<td>12.78</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>377</td>
<td>11.52</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>405</td>
<td>11.81</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>482</td>
<td>15.87</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>415</td>
<td>11.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean Density=412</td>
<td>Avg. MC= 12.1</td>
</tr>
</tbody>
</table>

3.3. Mechanical testing in the MTS machine

The mechanical tests were performed in an MTS 810 machine, which is a hydraulic one axial loading machine with a capacity of 100 kN. The test specimens were mounted with the flat side down on a steel beam, see Figure 3.4. The free end or both free ends were clamped to the steel beam to avoid bending of the specimens. The load was applied with a steel stud with the dimensions of (45 x 95) mm or (90 x 95) mm. The specimens were all placed with the pith side down.

Figure 3.4: Material testing machine 810(MTS-810) with a specimen loaded in the center mounted on a steel beam and clamped down in the ends.
The specimens were compressed with the steel studs at load rate of 1 mm/minute until the deformation reached 3 mm; the loading rate was thereafter increased to 3 mm/minute. The loading was stopped when the total deformation was 10 mm. The load was registered by a load cell placed between the machine and the steel stud and the deformation registered was the movement of the steel stud (the piston in the machine). The load and deformation was registered in a computer and later stored as excel files.

3.4. Strain field measurements

The ARAMIS (Optical 3D Deformation Analysis) was used to record the deformation during the test. This system is based on two 4-mega pixel digital cameras, which take stereoscopic images during the test. The specimen is sprayed with a speckle pattern that the ARAMIS system is able to recognise between the images. By the speckle recognition system it is possible to calculate the deformations and strains on a complete surface during loading. In this case one set of specimens were recorded in all six load cases. The ARAMIS recorded the deformations at each load step of 200 N. The data was used to calculate the strain field in x and y direction. The ARAMIS system can be seen in Figure 3.5.

![Figure 3.5.](image-url)

*Figure 3.5.: ARAMIS setup with the speckle pattern painted on the specimen loaded close to the end with the large steel stud. In the foreground the two cameras used for taking stereoscopic images of the specimen during loading can be seen.*
4. Results from the experiments

The compression perpendicular to grain test were performed as described in Chapter 2.2.1 and evaluated according to EN 408:2010. [14] The experimental results are summarized in the following three sub chapters.

4.1. Modulus of elasticity of the material

The longitudinal modulus of elasticity $E_{0,\text{mean}}$ can be calculated by the Equation 2.3, explained in Chapter 2.1. [14]

$$E_{0,\text{mean}} = 4 \cdot \rho \cdot (f l)^2$$  \hspace{1cm} (4.1)

Where $\rho$ is density [kg/m$^3$], $f$ is frequency [Hz], $l$ is length of the beam [m].

The modulus of elasticity perpendicular to grain $E_{c,90}$ can be calculated using the following equation

$$E_{c,90} = \frac{(F_2 - F_1) \cdot h}{(w_2 - w_1) \cdot b \cdot l}$$  \hspace{1cm} (4.2)

Where:

$F_2 - F_1$ - is the increment of load on the linear portion of load deformation curve, in N.

$w_2 - w_1$ - is the increment of deformation corresponding to $F_2 - F_1$, in mm.

Figure 4.1 shows one of the curves from the experiments where the linear part of the curve, the two points on line 1, is used to determine the $E_{c,90}$ and the line 2 used to determine the $E_{c,90,\text{max}}$ value.
The modulus of elasticity in the longitudinal direction and perpendicular to the grain direction of the boards obtained from experimental investigation is presented in Table 4.1. This table shows the average modulus of elasticity perpendicular to the grain for the six specimens from each board. These six cases are from A1 to A3 and B1 to B3.

Table 4.1: Modulus of elasticity of boards

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Board No.</th>
<th>Average $E_{c,90}$[MPa]</th>
<th>$E_{0,\text{mean}}$[MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>348</td>
<td>10092</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>436</td>
<td>13841</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>387</td>
<td>11926</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>377</td>
<td>9347</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>383</td>
<td>16401</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>346</td>
<td>12154</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>347</td>
<td>10833</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>335</td>
<td>11372</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>311</td>
<td>9987</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>369</td>
<td>15276</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>356</td>
<td>8817</td>
</tr>
</tbody>
</table>

Mean $E_{c,90} = 363$  \[\text{MPa}\]  \[\text{Mean } E_{0,\text{mean}} = 11822\]
4.2. Compression force perpendicular to grain $F_{c,90,max}$

The second part of the result includes the calculation of the values of maximum compression force $F_{c,90,max}$ shown in Table 4.2. The maximum compression force perpendicular to grain $F_{c,90,max}$ can be determined by using the definition according to EN 408 for block compression as explained in the Chapter 2.2 by using the Figure 2.5.

Table 4.2: Compression force perpendicular to grain for each board and loading case

<table>
<thead>
<tr>
<th>Board No.</th>
<th>Compression force perpendicular to grain $F_{c,90,max}$[kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>1</td>
<td>23.80</td>
</tr>
<tr>
<td>2</td>
<td>30.67</td>
</tr>
<tr>
<td>3</td>
<td>23.66</td>
</tr>
<tr>
<td>4</td>
<td>24.66</td>
</tr>
<tr>
<td>5</td>
<td>22.70</td>
</tr>
<tr>
<td>6</td>
<td>25.70</td>
</tr>
<tr>
<td>9</td>
<td>21.66</td>
</tr>
<tr>
<td>10</td>
<td>22.03</td>
</tr>
<tr>
<td>11</td>
<td>22.32</td>
</tr>
<tr>
<td>14</td>
<td>26.16</td>
</tr>
<tr>
<td>15</td>
<td>24.66</td>
</tr>
</tbody>
</table>

The mean of the results for the compression force perpendicular to grain for each loading configuration is presented in Table 4.3.

Table 4.3: Mean values of max bearing force

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Test Name</th>
<th>No. Of Test</th>
<th>Loaded Length(mm)</th>
<th>Mean value of Max-Compression Force $F_{c,90,max}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$A_1$</td>
<td>11</td>
<td>45</td>
<td>24.36</td>
</tr>
<tr>
<td>2</td>
<td>$A_2$</td>
<td>11</td>
<td>45</td>
<td>21.58</td>
</tr>
<tr>
<td>3</td>
<td>$A_3$</td>
<td>11</td>
<td>45</td>
<td>19.48</td>
</tr>
<tr>
<td>4</td>
<td>$B_1$</td>
<td>11</td>
<td>90</td>
<td>40.45</td>
</tr>
<tr>
<td>5</td>
<td>$B_2$</td>
<td>11</td>
<td>90</td>
<td>36.99</td>
</tr>
<tr>
<td>6</td>
<td>$B_3$</td>
<td>11</td>
<td>90</td>
<td>32.13</td>
</tr>
</tbody>
</table>
4.3. General results from ARAMIS

The results from the ARAMIS-3D optical measurement system are presented for one board loaded with a loading plate with the length $l = 90 \text{ mm}$. The result presented shows the strain field in the $y$-direction (vertical) at two loading stages, approximately 20 kN and 40 kN. The lower load is taken in the linear part of the load-deformation curve and the higher load is the maximum compression force.

(a): specimen loaded at center

(b): specimen loaded at distance 10 mm from the edge.
Figure 4.2(a-c): Effect of load on the specimen where the load at center, at distance 10 mm and at the end of the member (specimen 12B1, 12B2 and 12B3 respectively)

Generally, from these images, it is observed that the stresses are concentrated in the region below the loading contact area, see Figure 4.2. The maximum strain was in the range of -2 to 2%. As shown in Figure 4.2 the tested set of specimen's series (load in the center of specimen, specimen loaded at distance 10 mm and series loaded at the end) with constant specimens size ($l \times b \times h$). However, within the subject boundaries, this visualization study is not a complete study of strain and distribution of the bearing stresses of the specimens, but it gives an impression of strain field and stress dispersion. All pictures are presented in Appendix A.

(c): specimen loaded at the end
5. Calculation according to different codes

In this chapter, the calculations of the maximum compression force perpendicular to grain \(F_{c,90,d}\) according to the standards Euro-code 5 (EN1995-1-1:2004), old Euro-code, German Code (DIN 1052:2004), Italian Code (CNR-DT 206:2006), Swedish Code (BKR: 2003) and old Swedish code are presented. All codes were explained in chapter 2.3. And the design compressive strength, \(f_{c,90d}\) for all these codes are given in Table 5.1.

Table 5.1: Value of \(f_{c,90d}\) for different codes

<table>
<thead>
<tr>
<th>Strength value (f_{c,90d} (N/mm^2))</th>
<th>EU-5 before amendment</th>
<th>EU-5 after amendment</th>
<th>Italian code</th>
<th>German code</th>
<th>Swedish new code 'BKR 2003'</th>
<th>Swedish code 'old'</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2.5</td>
<td>5</td>
<td>4.8</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 5.1: Schematic diagram for test series

The calculation for compression force perpendicular to the grain according to different codes as follows
5.1. Old version of Eurocode (EN 1995-1-1:2004) before amendment

The calculation of compression force perpendicular to the grain is: [2]

\[ F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} \]  

(5.1.1)

Where the factor \( k_{c,90} \), effective length \( l_{ef} \), design compression strength perpendicular to grain \( f_{c,90,d} \) and the effective area \( A_{ef} \). The geometry of the specimen is described earlier and it can be seen in Figure 3.1. However, the calculation of the setups will yield the following result.

**Calculation for setup A1**

With dimension \( b = 95\text{mm}, h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) as follows:

\[ l_{ef} = l + \frac{2h}{3} = 45 + \frac{2 \cdot 45}{3} = 75\text{mm} \]  

(5.1.3)

\[ k_{c,90} = \left(2.38 - \frac{l}{250}\right) \cdot \left(\frac{l_{ef}}{l}\right)^{0.5} = \left(2.38 - \frac{45}{250}\right) \cdot \left(\frac{75}{45}\right)^{0.5} = 2.84 \]  

(5.1.4)

\[ A_{ef} = l_{ef} \cdot b \]

\[ F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 2.84 \cdot 2.5 \cdot 95 \cdot 45 = 30.35\text{kN} \]

**Calculation for setup B1**

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 90\text{mm} \) will be as follows:

\[ l_{ef} = l + \frac{2h}{3} = 90 + \frac{2 \cdot 45}{3} = 120\text{mm} \]

\[ k_{c,90} = \left(2.38 - \frac{l}{250}\right) \cdot \left(\frac{l_{ef}}{l}\right)^{0.5} = \left(2.38 - \frac{90}{250}\right) \cdot \left(\frac{120}{90}\right)^{0.5} = 2.333 \]

\[ A_{ef} = l_{ef} \cdot b \]

\[ F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 2.333 \cdot 2.5 \cdot 95 \cdot 90 = 49.87\text{kN} \]

**Calculation for setup A2**

With dimension \( b = 95\text{mm}, h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) are as follows:

\[ l_{ef} = l + \frac{h}{3} = 45 + \frac{45}{3} = 60\text{mm} \]

\[ k_{c,90} = \left(2.38 - \frac{l}{250}\right) \cdot \left(\frac{l_{ef}}{l}\right)^{0.5} = \left(2.38 - \frac{45}{250}\right) \cdot \left(\frac{60}{45}\right)^{0.5} = 2.54 \]

\[ A_{ef} = l_{ef} \cdot b \]

\[ F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 2.54 \cdot 2.5 \cdot 95 \cdot 45 = 27.15\text{kN} \]
Calculation for setup B2

With dimension $b = 95\text{mm}$, $h = 45\text{mm}$ and the contact length $l = 90\text{mm}$ is as follows:

\[
k_{c,90} = \left(2.38 - \frac{l}{250}\left(\frac{l_{ef}}{l}\right)^{0.5}\right) = \left(2.38 - \frac{90}{250}\left(\frac{105}{90}\right)^{0.5}\right) = 2.18
\]

\[
l_{ef} = l + \frac{h}{3} = 90 + \frac{45}{3} = 105\text{mm}
\]

\[
A_{ef} = l_{ef} \cdot b
\]

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 2.18 \cdot 2.5 \cdot 95 \cdot 90 = 46.64kN
\]

For setup A3 and B3 the calculation will be same as setup A2 and B2 respectively because of the amplification factor $k_{c,90}$ is the same.


The calculation of compression force perpendicular to the grain according to the new version of Eurocode 5 as follows: [2]

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 2.5 \text{N/mm}^2
\]

Where the factor $k_{c,90} = x_c$, effective length $l_{ef}$, design compression strength perpendicular to grain $f_{c,90,d}$ and the effective area $A_{ef}$.

The geometry of the specimen is described earlier and it can be seen in Figure 3.1.

Calculation for setup A1

With dimension $b = 95\text{mm}$, $h = 45\text{mm}$ and the contact length $l = 45\text{mm}$ are as follows

\[
f_{c,90,d} = 2.5 \text{N/mm}^2
\]

\[
A_{ef} = b \cdot (l + 2 \cdot 30 \text{mm}) = 95 \cdot (45 + 2 \cdot 30) = 9975\text{mm}^2
\]

\[
x_c = k_{c,90,d} = 1.25
\]

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A_{ef} = 1.25 \cdot 2.5 \cdot 9975 = 31.17kN
\]

Calculation for setup B1

With dimension $b = 95\text{mm}$ and the contact length $l = 45\text{mm}$ are as follows

\[
f_{c,90,d} = 2.5 \text{N/mm}^2
\]

\[
A_{ef} = b \cdot (l + 2 \cdot 30 \text{mm}) = 95 \cdot (90 + 2 \cdot 30) = 14250\text{mm}^2
\]

\[
x_c = 1.25
\]
Calculations for setup A2

With dimension $b = 95\text{mm}$, and the contact length $l = 45\text{mm}$ are as follows

$f_{c,90,d} = 2.5 \text{ N/mm}^2$

$A_{ef} = b \cdot (l + 30\text{mm} + 10\text{mm}) = 95 \cdot (45 + 30 + 10) = 8075\text{mm}^2$

$x_c = 1.25$

$F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} A_{ef} = 1.25 \cdot 2.5 \cdot 8075 = 25.23\text{kN}$

Calculations for setup B2

With dimension $b = 95\text{mm}$ and the contact length $l = 45\text{mm}$ are as follows

$f_{c,90,d} = 2.5 \text{ N/mm}^2$

$A_{ef} = b \cdot (l + 30\text{mm} + 10\text{mm}) = 95 \cdot (90 + 30 + 10) = 12350\text{mm}^2$

$x_c = 1.25$

$F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} A_{ef} = 1.25 \cdot 2.5 \cdot 12350 = 38.60\text{kN}$

Calculations for setup A3

With dimension $b = 95\text{mm}$ and the contact length $l = 45\text{mm}$ are as follows

$f_{c,90,d} = 2.5 \text{ N/mm}^2$

$A_{ef} = b \cdot (l + 30\text{mm}) = 95 \cdot (45 + 30) = 7125\text{mm}^2$

$x_c = 1.25$

$F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} A_{ef} = 1.25 \cdot 2.5 \cdot 7125 = 22.27\text{kN}$

Calculations for setup B3

With dimension $b = 95\text{mm}$ and the contact length $l = 90\text{mm}$ are as follows

$f_{c,90,d} = 2.5 \text{ N/mm}^2$

$A_{ef} = b \cdot (l + 30\text{mm}) = 95 \cdot (90 + 30) = 11400\text{mm}^2$

$x_c = 1.25$

$F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} A_{ef} = 1.25 \cdot 2.5 \cdot 11400 = 35.63\text{kN}$
5.3. Italian code (CNR-DT 206-2006)

The calculation of compression force perpendicular to the grain according to Italian code as follows: [2]

\[
F_{c,90,d} = f_{c,90,d}A_{ef}
\]

\[
f_{c,90,d} = 5 \text{ N/ } \text{mm}^2
\]

Where the factor \( k_{c,90,d} \), effective length \( l_{ef} \), design compression strength perpendicular to grain \( f_{c,90,d} \) and the effective area \( A_{ef} \).

The geometry of the specimen is described earlier and it can be seen in Figure 3.1.

Calculations for setup A1

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) will be as follows:

\[
f_{c,90,d} = 5 \text{ N/ } \text{mm}^2
\]

\[
l_{ef} = \min\left\{2 \cdot l : l + \left( 2 \times h \right) + 3 \right\} = \min\{90,75\} = 75\text{mm}
\]

\[
F_{c,90,d} = f_{c,90,d}b \cdot l_{ef} = 5 \cdot 95 \cdot 75 = 35.63\text{kN}
\]

Calculations for setup A2

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) will be as follows:

\[
f_{c,90,d} = 5 \text{ N/ } \text{mm}^2
\]

\[
l_{ef} = \min\left\{2 \cdot l : l + \frac{1}{3} \cdot h + 10 \right\} = \min\{90,70\} = 70\text{mm}
\]

\[
F_{c,90,d} = f_{c,90,d}b \cdot l_{ef} = 5 \cdot 95 \cdot 70 = 33.25\text{kN}
\]

Calculations for setup A3

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) will be as follows:

\[
f_{c,90,d} = 5 \text{ N/ } \text{mm}^2
\]

\[
l_{ef} = \min\left\{2 \cdot l : l + \frac{1}{3} \cdot h \right\} = \min\{90,60\} = 60\text{mm}
\]

\[
F_{c,90,d} = f_{c,90,d}b \cdot l_{ef} = 5 \cdot 95 \cdot 60 = 28.50\text{kN}
\]

Calculations for setup B1

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 90\text{mm} \) will be as follows:

\[
f_{c,90,d} = 5 \text{ N/ } \text{mm}^2
\]
\[ l_{ef} = \min \{ 2 \cdot l \cdot l + \left( 2 \times h \right) \div 3 \} = \min \{ 180 \times 150 \} = 150 \text{mm} \]
\[ F_{c,90,d} = f_{c,90,d} \cdot l_{ef} = 5 \cdot 95 \cdot 150 = 71.25 \text{kN} \]

**Calculations for setup B2**

With dimension \( b = 95 \text{mm} \) and \( h = 45 \text{mm} \) and the contact length \( l = 90 \text{mm} \) will be as follows:

\[ f_{c,90,d} = 5 \text{ N/ mm}^2 \]
\[ l_{ef} = \min \left\{ 2 \cdot l \cdot l + \frac{1}{3} \cdot h + 10 \right\} = \min \{ 180 \times 140 \} = 140 \text{mm} \]
\[ F_{c,90,d} = f_{c,90,d} \cdot l_{ef} = 5 \cdot 95 \cdot 140 = 66.50 \text{kN} \]

**Calculations for setup B3**

With dimension \( b = 95 \text{mm} \) and \( h = 45 \text{mm} \) and the contact length \( l = 90 \text{mm} \) will be as follows:

\[ f_{c,90,d} = 5 \text{ N/ mm}^2 \]
\[ l_{ef} = \min \left\{ 2 \cdot l \cdot l + \frac{1}{3} \cdot h \right\} = \min \{ 180 \times 120 \} = 120 \text{mm} \]
\[ F_{c,90,d} = f_{c,90,d} \cdot l_{ef} = 5 \cdot 95 \cdot 120 = 57.00 \text{kN} \]

**5.4. German code (DIN 1052:2004)**

The calculation of compression force perpendicular to the grain according to German code as follows: [2]

\[ f_{c,90,d} = 4.8 \text{ N/ mm}^2 \]

\[ \frac{\sigma_{c,90,d}}{k_{c,90,d} f_{c,90,d}} \leq 1 \]
\[ \sigma_{c,90,d} = \frac{F_{c,90,d}}{A_{ef}} \]

And,
\[ F_{c,90,d} = k_{c,90,d} f_{c,90,d} A_{ef} \]
\[ k_{c,90} = 1.25 \]

Where the factor \( k_{c,90,d} \), effective length \( l_{ef} \), design compression strength perpendicular to grain \( f_{c,90,d} \) and the effective area \( A_{ef} \).

The geometry of the specimen is described earlier and it can be seen in Figure 3.1
Calculations for setup A1

With dimension $b = 95\text{mm}$ and $h = 45\text{mm}$ and the contact length $l = 45\text{mm}$ will be as follows:

\[ l_{ef} = \min\{2 \cdot l; 1 + \left( 2 \times h \right) / 3 \} = \min\{90, 75\} = 75\text{mm} \]

\[ F_{c,90} = k_{c,90} f_{c,90} b \cdot l_{ef} \]

\[ F_{c,90} = 1.25 \cdot 4.8 \cdot 95 \cdot 75 = 42.75\text{kN} \]

Calculations for setup A2

With dimension $b = 95\text{mm}$ and $h = 45\text{mm}$ and the contact length $l = 90\text{mm}$ will be as follows:

\[ l_{ef} = \min\{2 \cdot l; 1 + \frac{1}{3} \cdot h + 10 \} = \min\{90, 70\} = 70\text{mm} \]

\[ F_{c,90} = k_{c,90} f_{c,90} b \cdot l_{ef} \]

\[ F_{c,90} = 1.25 \cdot 4.8 \cdot 95 \cdot 70 = 39.9\text{kN} \]

Calculations for setup A3

With dimension $b = 95\text{mm}$ and $h = 45\text{mm}$ and the contact length $l = 90\text{mm}$ will be as follows:

\[ l_{ef} = \min\{2 \cdot l; 1 + \frac{1}{3} \cdot h \} = \min\{90, 60\} = 60\text{mm} \]

\[ F_{c,90} = k_{c,90} f_{c,90} b \cdot l_{ef} \]

\[ F_{c,90} = 1.25 \cdot 4.8 \cdot 95 \cdot 60 = 34.2\text{kN} \]

Calculations for setup B1

With dimension $b = 95\text{mm}$ and $h = 45\text{mm}$ and the contact length $l = 90\text{mm}$ will be as follows:

\[ l_{ef} = \min\{2 \cdot l; 1 + \left( 2 \times h \right) / 3 \} = \min\{180, 150\} = 150\text{mm} \]

\[ F_{c,90} = k_{c,90} f_{c,90} b \cdot l_{ef} \]

\[ F_{c,90} = 1.25 \cdot 4.8 \cdot 95 \cdot 150 = 85.5\text{kN} \]

Calculations for setup B2

With dimension $b = 95\text{mm}$ and $h = 45\text{mm}$ and the contact length $l = 90\text{mm}$ will be as follows:

\[ l_{ef} = \min\{2 \cdot l; 1 + \frac{1}{3} \cdot h + 10 \} = \min\{180, 140\} = 140\text{mm} \]

\[ F_{c,90} = k_{c,90} f_{c,90} b \cdot l_{ef} \]

\[ F_{c,90} = 1.25 \cdot 4.8 \cdot 95 \cdot 140 = 79.8\text{kN} \]
Calculations for setup B3

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 90\text{mm} \) will be as follows:

\[
l_{ef} = \min \left\{ 2 \cdot l \cdot l + \frac{1}{3} \cdot h \right\} = \min \{ 180, 120 \} = 120\text{mm}
\]

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot b \cdot l_{ef}
\]

\[
F_{c,90,d} = 1.25 \cdot 4.8 \cdot 95 \cdot 1.20 = 68.4\text{kN}
\]

5.5. Swedish new code (BKR: 2003)

The calculation of compression force perpendicular to the grain according to the new Swedish code as follows: [2]

\[
R_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A
\]

\[
R_{c,90,d} = \frac{F_{c,90,d}}{A}
\]

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A
\]

\[
f_{c,90,d} = 7\text{N/mm}^2
\]

Where the factor, \( k_{c,90} \), effective length, \( l_{ef} \), design compression strength perpendicular to grain \( f_{c,90,d} \) and the effective area \( A_{ef} \).

The geometry of the specimen is described earlier and it can be seen in Figure 3.1.

Calculations for setup A1

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) will be as follows:

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A = 1.7 \cdot 95 \cdot 45 = 29.92\text{kn}
\]

Calculations for setup B1

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 90\text{mm} \) will be as follows:

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A = 1.7 \cdot 95 \cdot 90 = 59.85\text{kn}
\]

Calculations for setups A2 and A3.

With dimension \( b = 95\text{mm} \) and \( h = 45\text{mm} \) and the contact length \( l = 45\text{mm} \) will be as follows:

\[
F_{c,90,d} = k_{c,90} \cdot f_{c,90,d} \cdot A = 1.7 \cdot 95 \cdot 45 = 29.92\text{kn}
\]
Calculations for setups B2 and B3

With dimension \( b = 95 \text{mm} \) and \( h = 45 \text{mm} \) and the contact length \( l = 90 \text{mm} \) will be as follows:

\[
F_{c.90.d} = k_{c.90} \cdot f_{c.90.d} \cdot A = 1.7 \cdot 95 \cdot 90 = 59.85 \text{kN}
\]

5.6. Swedish old code

The calculation of compression force perpendicular to the grain according to the Swedish old code as follows: [13]

\[
\sigma_{c.90} \leq \kappa \cdot f_{c.90}
\]

\[
\sigma_{c.90} = \frac{F}{b \cdot h}
\]

\[
F_{c.90.d} = b \cdot h \cdot \kappa \cdot f_{c.90}
\]

\[
f_{c.90} = 7 \text{N/mm}^2
\]

Where the factor is \( \kappa \), design compression strength perpendicular to grain \( f_{c.90} \), width of specimen \( b \), contact length, \( h \).

The geometry of the specimen is described earlier and it can be seen in Figure 3.1.

Calculation for setup A1

With dimension \( b = 95 \text{mm} \) and \( h = 45 \text{mm} \) \( l = 90 \text{ mm} \) will be as follows:

\[
\kappa_{c.90} = \begin{cases} 
1.8 & \text{for } l \leq 15 \text{mm} \\
\frac{150}{l} & \text{for } 15 < l < 150 \text{mm} \\
4 & \text{for } 150 \leq l 
\end{cases}
\]

\[
\kappa = \frac{4 \cdot 150}{l} \text{ for } 15 < l < 150 \text{mm \ (l=90)}
\]

\[
\kappa = \frac{4 \cdot 150}{90} = 1.136
\]

\[
F_{c.90.d} = b \cdot h \cdot \kappa \cdot f_{c.90} = 95 \cdot 45 \cdot 1.136 \cdot 7 = 34.00 \text{kN}
\]

Calculations for setup A2 and A3

With dimension \( b = 95 \text{mm} \) and \( h = 45 \text{mm} \) will be as follows:
\( \kappa_c = 1 \)

\[
F_{c,90,d} = b \cdot h \cdot \kappa_c \cdot f_c = 95 \cdot 45 \cdot 1.7 = 29.93 \text{kN}
\]

**Calculation for setup B1**

With dimension \( b = 95 \text{mm} \) and \( h = 90 \text{mm} \) \( l = 90 \text{ mm} \) will be as follows:

\[
\kappa_c,90 = \begin{cases} 
1.8 & \text{for } l \leq 15 \text{mm} \\
\frac{\sqrt{150}}{l} & \text{for } 15 < l < 150 \text{mm} \\
1.0 & \text{for } 150 \leq l 
\end{cases}
\]

\[
k_c = \sqrt[4]{\frac{150}{90}} = 1.136
\]

\[
F_{c,90,d} = b \cdot h \cdot \kappa_c \cdot f_c = 95 \cdot 90 \cdot 1.136 \cdot 7 = 68.00 \text{kN}
\]

**Calculations for setup B2 and B3**

With dimension \( b = 95 \text{mm} \) and \( h = 90 \text{mm} \) will be as follows:

\[
\kappa_c = 1
\]

\[
F_{c,90,d} = b \cdot h \cdot \kappa_c \cdot f_c = 95 \cdot 90 \cdot 1.7 = 59.85 \text{kN}
\]

All calculated values for the maximum compression force perpendicular to grain (\( F_{c,90,d} \)) according to the different codes which are present in Table 5.3.

**Table 5.3: Compression force (\( F_{c,90,d} \)) according to different codes**

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>EU5 Old (kN)</th>
<th>EU5 New (kN)</th>
<th>Italian (kN)</th>
<th>German (kN)</th>
<th>Swedish New (kN)</th>
<th>Swedish Old (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>30.35</td>
<td>31.17</td>
<td>35.62</td>
<td>42.75</td>
<td>29.92</td>
<td>34.00</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>27.15</td>
<td>25.23</td>
<td>33.25</td>
<td>39.90</td>
<td>29.92</td>
<td>29.93</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>27.15</td>
<td>22.27</td>
<td>28.50</td>
<td>34.20</td>
<td>29.92</td>
<td>29.93</td>
</tr>
<tr>
<td>( B_1 )</td>
<td>49.87</td>
<td>44.53</td>
<td>71.25</td>
<td>85.51</td>
<td>59.85</td>
<td>68.00</td>
</tr>
<tr>
<td>( B_2 )</td>
<td>46.64</td>
<td>38.60</td>
<td>66.50</td>
<td>79.82</td>
<td>59.85</td>
<td>59.85</td>
</tr>
<tr>
<td>( B_3 )</td>
<td>46.64</td>
<td>35.63</td>
<td>57.00</td>
<td>68.40</td>
<td>59.85</td>
<td>59.85</td>
</tr>
</tbody>
</table>

(*) The codes or models are explained in chapter 2.3. And all calculations are presented in appendix A.
6. Analysis and discussion

Compression tests perpendicular to grain were made according to EN408 in an MTS-810 testing machine. The tests were performed as loading from a stud on a continuously supported rail. The load was in this case transferred through a steel stud. Two loading areas were tested (45 x 95) mm and (90 x 95) mm as well as three distances from the edge of the specimen 0 mm, 10 mm and in the middle of the specimen. The first series named A1, A2, A3 (loading length 45 mm) and the second named B1, B2, B3 (loading length 90 mm) are shown in Figure 6.1. The results from the test are summarized in Table 6.1.

![Tested load cases](image1)

*Figure 6.1: Tested load cases*

The results obtained from the test can be summarized in force-deformation curves of the different configuration setups, e.g. for the force-deformation curve of case B1 for specimen 2, as shown in Figure 6.2.

![Example of force-deformation calculation curve for the case B1 for specimen 2](image2)

*Figure 6.2: Example of force-deformation calculation curve for the case B1 for specimen 2*
Figure 6.3 shows the resulting force-deformation curve for all six types (A1-3 and B1-3) for specimen number 1. The curves show that for setup B with a longer loading length the maximum capacity is larger than for setup A with a smaller loading length.

Moreover the results obtained from the test have shown that the compression perpendicular to grain strength of the beam when loaded is dependent on the loading situation and the loading area. The compression capacity is about 65-70% higher for the case with a doubled loading area. There is also an effect of the distance from the end of the rail. Loading in the middle of the long specimen increased the capacity with approximately 25%. Moving the loading point only 10 mm from the edge increased the capacity by 10% compared to loading at the edge, see Table 6.1.

Several researchers, e.g. Van der put et al. [7], Madsen [8], Blass and Görlacher[9], as well as several codes have proposed that the design should be based on an assumption of an effective length \( l_e \) due to the load spread in the material. For example see Eurocode (Chapter 2.3.1) where the load spread is assumed to be 1:3. The ARAMIS-3D optical measurement images as shown in Figure 6.4, (compression at center, at distance 10 mm and at the edge) with constant specimens’ size (90x 95), it is observed that the stresses are concentrated in the region below the loading contact area. The load spread in these images seems to be steeper than 1:3. This might be due to the sharp edges of the steel stud used to transfer the load. Especially the load close to the edge seems to have a load spread that is very small and a very limited area outside the directly loaded area is affected by strains.
The capacity of the compression force was calculated according to six different codes. The codes were two versions of Eurocode 5, the Italian code (CNR-DT 206-2006), the German code (DIN 1052:2004) and two versions of the Swedish code. As shown in Table 6.1 below it is easy to see that the different codes will lead to different maximum compression force even when the test material was the same. In general the highest compression stress value was the B1 case which has the biggest loading area (90x95) and the largest effective length. The effective length will be increase in both directions of the loaded area for this case. The opposite case was A3 which has the smallest loading area (45x95) and the smallest effective length, because of the edge load position, where the effective length can be included in one direction only. The effect of increasing the effective length in only one direction compared to the two other cases (load in the middle and load from 10 mm from the edge) will lead to a lower maximum compression force.
Table 6.1: Comparison of test results of Max Compression Force with different codes

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Test Data</th>
<th>EU5 Old (kN)</th>
<th>EU5 New (kN)</th>
<th>Italian (kN)</th>
<th>German (kN)</th>
<th>Swedish New (kN)</th>
<th>Swedish Old (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>24.36</td>
<td>30.35</td>
<td>31.17</td>
<td>35.62</td>
<td>42.75</td>
<td>29.92</td>
<td>34.00</td>
</tr>
<tr>
<td>A₂</td>
<td>21.58</td>
<td>27.15</td>
<td>25.23</td>
<td>33.25</td>
<td>39.9</td>
<td>29.92</td>
<td>29.93</td>
</tr>
<tr>
<td>A₃</td>
<td>19.49</td>
<td>27.15</td>
<td>22.27</td>
<td>28.50</td>
<td>34.2</td>
<td>29.92</td>
<td>29.93</td>
</tr>
<tr>
<td>B₁</td>
<td>40.45</td>
<td>49.87</td>
<td>44.53</td>
<td>71.25</td>
<td>85.5</td>
<td>59.85</td>
<td>68.00</td>
</tr>
<tr>
<td>B₂</td>
<td>36.99</td>
<td>46.64</td>
<td>38.60</td>
<td>66.50</td>
<td>79.8</td>
<td>59.85</td>
<td>59.85</td>
</tr>
<tr>
<td>B₃</td>
<td>32.13</td>
<td>46.64</td>
<td>35.63</td>
<td>57.00</td>
<td>68.4</td>
<td>59.85</td>
<td>59.85</td>
</tr>
</tbody>
</table>

Comparing the results from the different calculations according to the codes it is possible to see that calculations according to the new Eurocode 5 resulted in the lowest maximum compression force. The results also showed that the effect of load area is taken into account in all the codes. For the Eurocode the compression force is approximately 1.5 times higher for the bigger load area while for many of the older national codes the maximum is almost doubled for the bigger load area. Several of the codes also show an effect of load spread. The value for loading in the middle of the specimen, with the load spreading in two directions, is higher than loading at the edge.

The results also showed that in all cases the experimental results were lower than the capacity calculated according to the codes. Moreover the code that gave results closest to the experimental results was the new version of Eurocode 5. The results from the code showed results that were 10-25% higher than the results from the experiments.

The results also show that Eurocode is farther from the experimental results for the 45 mm wide specimens than for the 90 mm wide specimens. But the results from Eurocode show a result that is approximately 25% higher for loading in the middle of the specimen than at the edge, which agrees well with the experimental results. The effect of loading 10 mm from the edge is also approximately 10% higher than loading at the edge which also agrees well with the code. This shows that Eurocode at least takes the loading area and distance from the edge into account in a reasonable way at least when compared with these tests.

However, the compression stress perpendicular to grain in new Eurocode 5 are higher than the test data and that happen because of some reasons such as

1) Using a steel stud with sharp edges. Steel stud is a much harsher condition than using a wood stud.

2) The specimens were not knot free 100% and that will surely affect the test results.
7. Conclusion

Based on a literature review and from the specimens tested in this study, it can be concluded that the compression perpendicular to the grain in timber is an important property for structural design. It is dependent on the loading situation, the loading area and the type of specimen. The case studied in this case is the loading from a stud on a continuously supported rail. In this thesis especially the effect of loading area and loading position was investigated. Two loading areas were tested (45 x 95) mm and (90 x 95) mm as well as three distances from the end of the specimen 0 mm, 10 mm and in the middle of a long specimen.

The results show that there is a great influence of loading area. The compression capacity is about 65-70% higher for the case with a doubled loading area. There is also an effect of the distance from the end of the rail. Loading in the middle of the long specimen increased the capacity with approximately 25%. Moving the loading point only 10 mm from the edge increased the capacity by 10% compared to loading at the edge.

The capacity of the compression force was calculated according to six different codes. The codes were two versions of Eurocode 5, the Italian code (CNR-DT 206-2006), the German code (DIN 1052:2004) and two versions of the Swedish code (BKR). The results showed that in all cases the experimental results were lower than the capacity calculated according to the code. The main explanation to this is probably that the loading was done with a steel stud with relatively sharp edges. Compared to a timber stud this loading is much harder.

The code that gave results closest to the experimental results was the new version of Eurocode 5. The results from the code showed results that were 10-25% higher than the results from the experiments. The results also show that Eurocode is farther from the experimental results for the 45 mm wide specimens than for the 90 mm wide specimens.

The results from Eurocode show a result that is approximately 25% higher for loading in the middle of the specimen than at the edge, which agrees well with the experimental results. The effect of loading 10 mm from the edge is also approximately 10% higher than loading at the edge which also agrees well with the code. This shows that Eurocode at least takes the loading area and distance from the edge into account in a reasonable way at least when compared with these tests.

The experimental results still show to low strength compared to the codes. A further study using another material in the loading stud should be done. This could show how much of the low strength is due to the rather hard loading conditions in this study.
8. References


Appendix A: ARAMIS Images

The following images which were taken by ARAMIS are general view of the effect on wood structures at the maximum force.

Figure 9.1- ARAMIS test result A1

Figure 9.2 - ARAMIS test result A2

Figure 9.3 - ARAMIS test result A3
Figure 9.4 - ARAMIS test result B2

Figure 9.5 - ARAMIS test result B3
Appendix B: Cross-sectional view of specimens

Following pictures below are tested board’s specimens’ cross-sectional area which shows the grains direction.

Figure 10.1 - Specimen no 1

Figure 10.2 - Specimen no 2
Figure 10.3 - Specimen no 3

Figure 10.4 - Specimen no 4
Figure 10.5 - Specimen no 5

Figure 10.6 - Specimen no 6
Figure 10.7 - Specimen no 7

Figure 10.8 - Specimen no 8
Figure 10.13 - Specimen no 13

Figure 10.14 - Specimen no 14
Appendix C: Force and deformation diagram

The following figures below are general expression for each board’s combine graph for different series.

Figure 11.1a - Specimen no 1A

Figure 11.1B - Specimen no 1B
Figure 11.3A - Specimen no 3A

Figure 11.3B - Specimen no 3B
Figure 11.5A - Specimen no 5A

Figure 11.5B - Specimen no 5B
Figure 11.9A - Specimen no 9A

Figure 11.9B - Specimen no 9B
Figure 11.15A - Specimen no 15A

Figure 11.15B - Specimen no 15B
Appendix D: Force-deformations graphs MTS 810

The following figures below are general expression for each board’s single graph for different series in MTS 810.

*Figure 12.1 Force-deformation for different loading situations 2A1, 2A2 and 2A3*
Figure 12.2 Force-deformation for different loading situations 2B1, 2B2 and 2B3
Lnu.se

Institutionen för teknik
351 95 Växjö
tel 0772-28 80 00, fax 0470-76 85 40