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Timber in Bridge Structures

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The purpose of this final year project was to study the properties of timber as a structural material and the suitability of wood in load bearing members for bridge structures.

For a case study, an existing timber bridge was selected. Due to its condition the bridge should be replaced. The design of a new bridge with steel beams holding a glulam deck was made. During the case study the replacement of steel beams by glulam timber ones was discussed. Some calculations were made in order to estimate the amount of wood needed to replace steel beams and keep the same bearing capacity.

Advantages and disadvantages of timber used in load bearing structures of bridges were discussed in this thesis. This final year project shows the opportunities and attracts more interest to structures made of timber. This Bachelor's thesis shows that wood can compete in some cases with more common materials used for bridge structures. For cost estimation further study should be conducted.

Keywords	Timber, wood, bridge, glulam

Contents

1 Introduction

Wood was the first material bridges were made of long before steel or concrete. However, timber became less popular when those more homogeneous structural materials were introduced.

Timber is a building material with a lot of advantages. It is quite spread worldwide, multifunctional and easily obtained. Three fourth of the area of Finland is covered by forestland (Finnish Forest Association 2014). Timber is a renewable material. When older trees are harvested, they are immediately replaced by new ones. Nowadays, science can help to take care and manage forests that way, so the risk of fire, insects and different kind of deceases will be diminished.

In 2013 Finnish Transport Agency had 14 784 bridges. 637 which is 4,4% of those were timber bridges according to Finnish Transport Agency (figure 1).

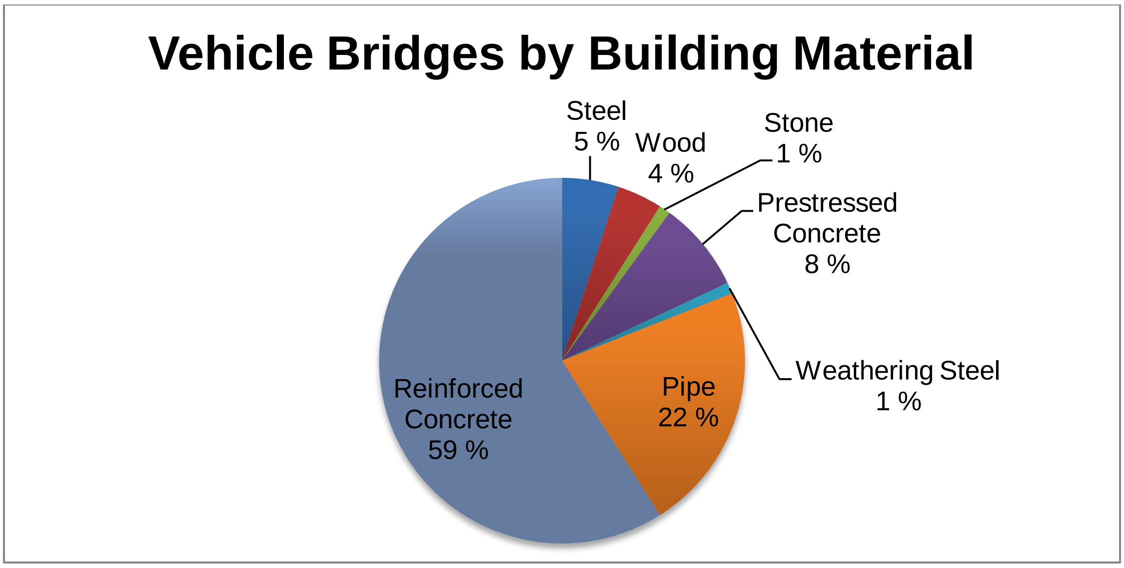


Figure 1. The amount of timber bridges is 4,4% out of all bridges in Finland (Finnish Transport Agency, 2014).

From figure 2 it can be seen that timber bridges are in quite good overall condition compered to all other bridges in Finland according to Finnish Transport Agency. Grade

0 means that the condition of a bridge is very good, the bridge is new or almost new. Grade 4 means that he bridge is in very bad condition and needs immediate action.

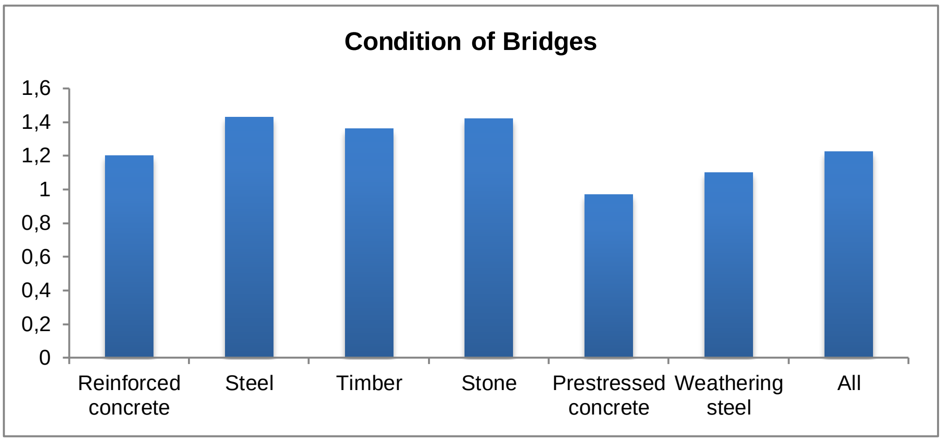


Figure 2. The condition of bridges in Finland (Finnish Transport Agency, 2014).

More and more clients are becoming interested in timber structures including bridges. About 200 bridges are built in Finland every year. However, only few of them are made of timber (Finnish Transport Agency 2015). In order to show to the potential clients the abilities of timber in bridge structures, the case study was conducted. The steel beams, holding the bridge deck, were replaced with the timber beams.

2 Background

In order to implement more timber in special structures such as bridges, it is important to study the material: Its properties, characteristics and special needs. In the background chapter the information about material is gathered and features are discussed.

2.1 Timber as a bridge material

Timber by itself is quite strong and at the same time lightweight material. Such features are desirable in bridge construction. Compared to other materials, wood can be more economical. Lower construction cost may be achieved with timber constructions.

In addition, weather does not affect the construction process so much, there is no danger of damaging the material. Freezing and thawing will not damage timber, neither will de-icing agents cause such deterioration in wood as in other bridge materials (Ritter 1990, 1-1). Moreover, the installation of a timber bridge normally does not require special additional equipment nor highly skilled labor.

Timber is often considered a short service life material. That misconception may be a result of wood being prone to decay or insect attacks. Fortunately, those problems may be avoided by protecting timber from moisture.

Modern techniques and preservative chemicals allow keeping timber bridges from deterioration for 50 years or even longer. Treated wood requires less maintenance and no painting needed. (Ritter 1990, 1-2)

Before glued-laminated timber (glulam), the size of sawn lumber was limited by the diameter of a tree. Glulam is manufactured by gluing sawn lumber laminations together. Structural adhesives are waterproof and the design strength of the material is higher than that of sawn lumber. The glulam members may have a wide variety of shapes, and are not limited by width, depth and length. As the process of manufacturing allows gluing smaller pieces into big members and elements, it provides better sustainability and utilization of the timber industry.

Timber is one of the oldest structural materials known in construction. If forest is managed properly, timber as a resource is highly sustainable and environmentally friendly. It has good strength compared to its own weight and is able to handle both tension and compression forces. Timber may be found in variety forms in construction: beams, trusses, columns, deck members, piles, concrete formwork, railway sleepers and etc.

However, it is important to understand the properties and characteristics of wood as a structural material as they differ according to the origin of the timber. The material itself is grown as a living tree, unlike the other raw materials used to produce structural parts and elements.

There are different species of trees. Hardwood and softwood are two general classes that trees and lumber are classified into. Despite the titles, hardwood does not necessarily have any grater hardness than softwood. Trees that belong to the hardwood class usually have broad leaves, which are shed yearly at the end of the growth season. The softwood group generally includes all year green conifer trees. The growth of hardwood is usually slower, and therefore, the lumber is often denser. It takes less time for softwood to grow. Thus, it is more commonly used for structural wood products. (Ritter 1990, 3-1)

Wood is an orthotropic material, which means that its properties vary on the axes. The structure of timber helps to understand why this happens. The smallest unit of timber is a tube resembling a cylindrical shaped cell. Closely packed together those cells create a strong composite system (figure 3). It is quite light but, if avoid lateral buckling, it can resist comparably big compression force to its longitudinal direction. However, it will yield under relatively small load to its perpendicular direction. (Ritter 1990, 3-2)

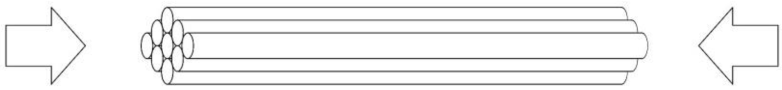


Figure 3. Wooden cells, often compared to a bundle of drinking straws

There are three axes in timber, as can be seen in figure 4. The longitudinal axis is parallel to the grain direction, the radial one is perpendicular to the grain and the tangential one is perpendicular to the longitudinal axis as well as tangent to growth rings. Radial and tangential axes directions do not have such a great properties differences as longitudinal does. Consequently, there are usually only two directions for which properties are given: parallel to the grain and perpendicular to the grain. (Ritter 1990, 3-2)

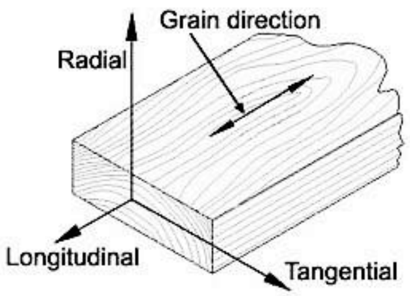


Figure 4. Axes of timber

During the design of a timber bridge the fact that wood may shrink or expand should be taken into account. This happens because wood is a hygroscopic material, which means that it easily absorbs moisture if the surrounding is moist and dries in a dry environment.

Water in wood fiber exists both as free water and bound water, on molecules of water bound by the walls of wood cells. When wood dries, free water is the first to dry out. When there is no free water left but cell walls are saturated it is called water saturation point. Shrinkage starts when the moisture content (1) of wood drops below the fiber saturation point, which may vary according to the tree species but has an average of 30% moisture content. (Ritter 1990, 3-6)

$$Moisture\ content\ (MC) = \frac{moist\ weight - dry\ weight}{dry\ weight} \times 100\% \qquad (1)$$

Because of the woods' property to shrink unevenly in different directions, elements made of wood may deform during drying. If the wood is constantly prone to shrinkage and expansion, during time, this will cause a separation along the annual rings, called checks. Most checks do not affect the strength much; however, larger cracks can be structurally significant. (Ritter 1990, 3-11)

The fire resistance or so-called pyrolytic properties of timber are ambiguous. Wood is considered an ignitable material. However, while being exposed to a fire an exterior surface will burn and form a char layer. Char itself will insulate the unburned wood from the flames of a fire. The thicker the char layer gets the slower the combustion rate gets. (Aseeva;Serkov ja Sivenkov 2013)

The advantage of wood as a material is that in case of fire that it does not distort under high temperatures as some other materials do. Its low thermal conductivity and insulation properties of char layer do not allow rapid heat transition to tunburned wood. (Aseeva;Serkov ja Sivenkov 2013)

Different wood species are more or less prone to decay and insect attacks. In order to protect wood from such harmful phenomenon, timber for bridge construction purposes is treated with wood preservatives.

Timber can be resistant to lots of chemicals. It is only vulnerable to strong acids and bases. After a strong base attack, wood is left bleached and white. After strong acid attack wood loses its strength and weight. (Ritter 1990, 3-16)

During the cold months in Finland, de-icing agents are used (Finnish Road Administration). For roads with little traffic, sand is allowed, but in major roads, NaCl is the main substance used for de-icing. Salty water may be very harmful to wood structure (Forest Product Labratory). Wood is absorbing salty water inside to keep a balance between the environment and itself.

Similarly, water evaporates when the environment becomes drier. Water gets more saturated with NaCl and, inevitably, crystals of salt are formed between the wooden fibers. The more crystals are formed inside the wooden element, the greater force is pushing the wooden fibers apart from each other. Luckily, right preservatives applied can form a barrier complicating the salt movement. Resistance to a huge number of chemicals is the marked advantage of timber over concrete or steel which are more vulnerable to external influences. (Forest Product Labratory)

The material deformation of which is immediately recovered after the stress below the elastic limit load is removed is called ideally elastic material. Wood does not recover immediately after the load is removed. Thus, it is not considered ideally elastic. The deformations are still recovered over time so wood is considered a viscoelastic material. However, in most of the cases, for calculation purposes, it is assumed that timber behaves as an elastic material. Creep, the time related deformation, is an exception, which is extremely important to take into account. (Ritter 1990, 3-17)

In order to describe the elastic properties and to make calculations involving elasticity of the wood, three constants are introduced: modulus of elasticity, shear modulus, Poisson’s ratio. As timber is an orthotropic material, those constants vary in different axis.

Untreated timber was successfully used in bridge construction for thousands of years. The secrete was to use heartwood of durable species – the species that are naturally resistant to decay and insect attack. Moreover, it was advisable to cover the structure in order to protect it from weathering. Through years the durable species of wood became unavailable in such quantities and shapes that were demanded. In addition, covering bridges with roof for weather protection became impractical economically as well as physically. (Ritter 1990, 4-1)

There are two types of agents attacking and degrading wooden structures (Ritter 1990, 4-1):

- **Physical agents**
  Physical agents are nonliving agents. There are heat, abrasion, sunlight, strong chemicals and etc. The physical agents decrease wood strength with time.

- **Biotic agents**
  The other agent type is living or biotic agents. Insects, fungi and bacteria are such an agents. Living agents are considered more dangerous as they may cause quite serious damage in rather a short period of time.

Nowadays, wood preservatives are used to protect wood from those agents. Keeping wood dry may also help the structure to last for centuries.

For most of biotic agents in order to attack a wood structure four basic factors are vital. To begin with, a moist environment is required. A moisture level above the wood saturation point is a favorable environment for harmful inhabitants. Secondly, biotic agents need free oxygen is needed for survival. The third factor is temperature. Most living agents require a temperature somewhere between 10°C and 30°C. Finally, the agents need food. Wood itself is the main food source of bacteria, fungi and other biotic agents. (Ritter 1990, 4-1)

Usually, in order to protect wood, one of the necessary factors is eliminated. When the food is removed, living agents cannot survive. Wood is made unsuitable as food with toxic preservatives. The other three factors mentioned above may also be controlled, also but it might be more challenging. The toxic preservatives are not the same as protective coating or stain. Toxic preservatives have to be forced inside the wood through a pressure treatment process. (Ritter 1990)

2.2 Types of timber bridge structure

There are different types of structure bridges can have. Timber bridges usually have beamed, arch, cable-stayed, truss or mixed structure. There are some recommendations concerning the relation between the dimensions of load bearing structure members (Figure 5). This table helps estimate the measurements for timber elements in bridge design.

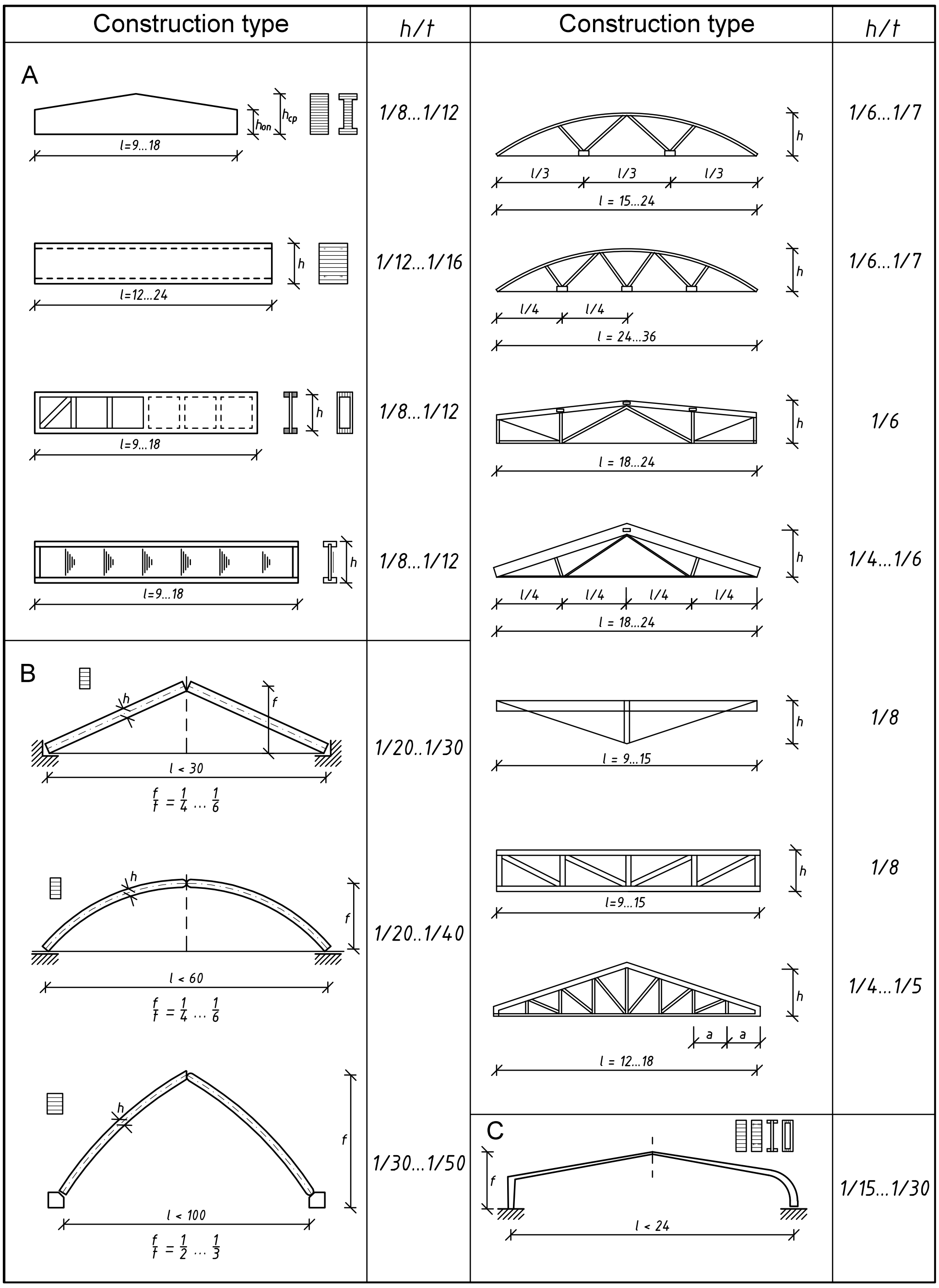


Figure 5. Structure types and primary measurements relations (Bergen, ym. 1989)

There are numerous examples of timber and composite timber contemporary bridges in Nordic countries. The table with examples and specifications can be found in Appendix 1.

Beam static system bridges are the oldest types of the bridges. Beam system simplicity is an advantage in design and construction (figure 6). However, it usually suits for spans of no more than 20-30 meters. Beam static system has different structural variations. The simplest beamed bridge structure is achieved with straight or slightly curved beams. Modern timber girders are usually made of glulam as the material allows a number of different shapes and dimensions. In some cases, composite girders are used.

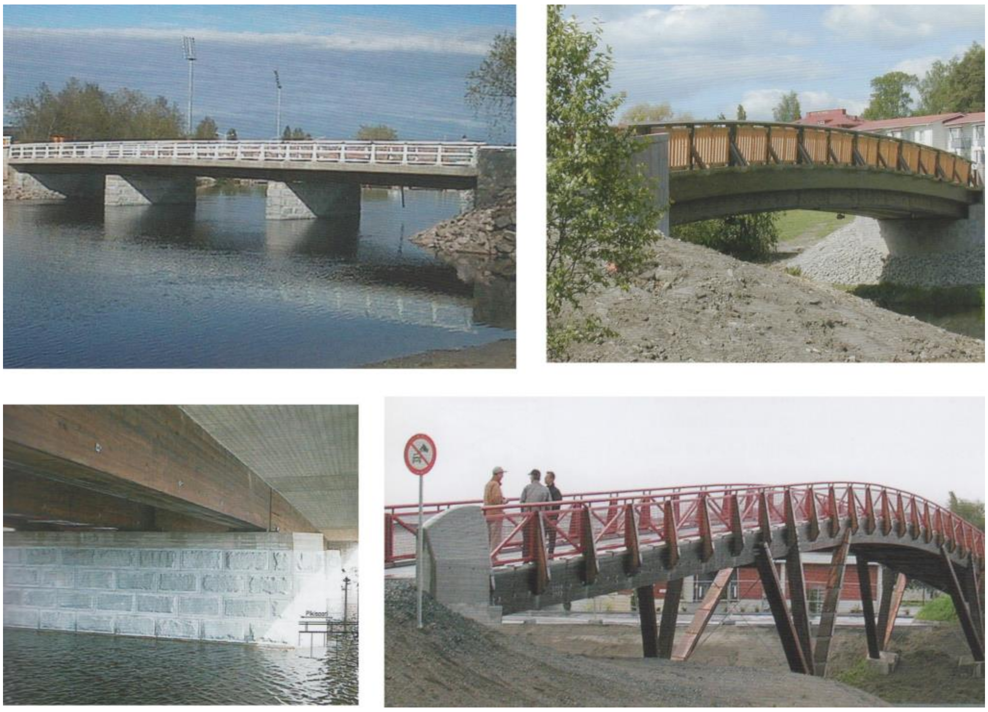


Figure 6. Examples of beam bridges (Nordic Industrial Fund 2002)

Plates working in one direction also belong to beamed bridges system. Glulam can be used to make loadbearing timber plates. This type of structure can be seen in Puokkasilta Ride Bridge (Nordic Industrial Fund 2002, 14). More information can be found in Appendix 1. Another, more common system is the stress-laminated timber plate (figure 8). In this case glulam beams are tightened up together with steel rods. This eases the transportation and allows in situ assembly. In some cases a stressed-box system is used (figure 8). It mimics the stress-laminated timber plate system but the plate is lighter thanks to empty spaces in the structure.

Figure 7. Mattisdammen Bridge (Nordic Industrial Fund 2002, 53).

Stressed-box system can be seen in Mattisdammen Bridge in figure 7. More information and specification can be found in Appendix 1.

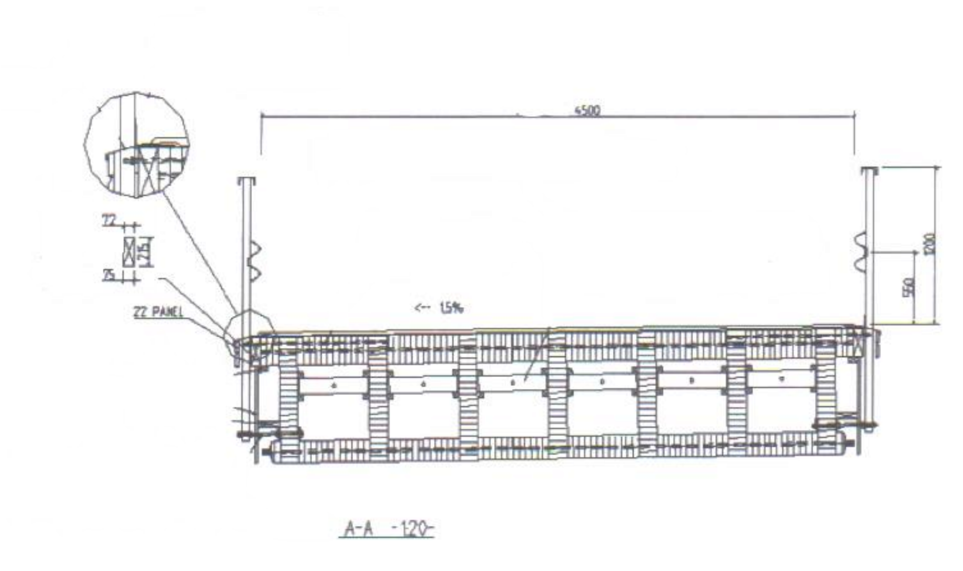


Figure 8. The stressed-box system the upper and bottom glulam plates are connected with glulam webs (Nordic Industrial Fund 2002).

Arched bridges differ between each other with the position of the load bearing arcs. Arcs can support the deck either from underneath as in the Okb footbridge seen in figure 9, or from above it as in the Tynset Bridge in figure 10.

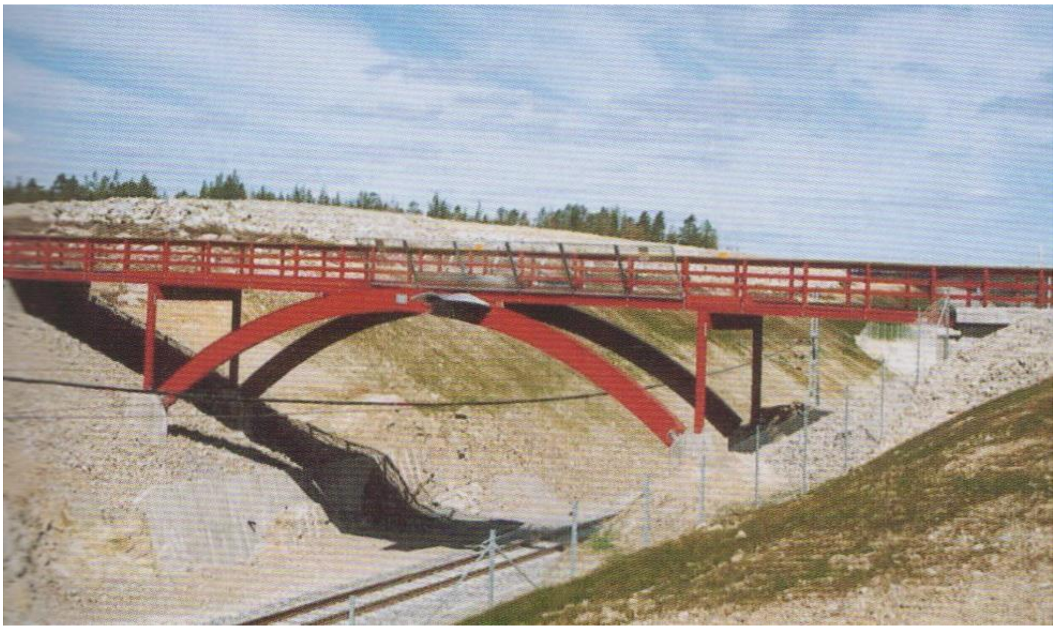


Figure 9. Okb Footbridge. Characteristics can be found in Appendix 1 (Nordic Industrial Fund 2002, 35).

The arc structure is highly efficient for covering long spans. Bracing is extremely important for this king of a bridge. Because of the high compressive stresses, buckling is one of the major concerns

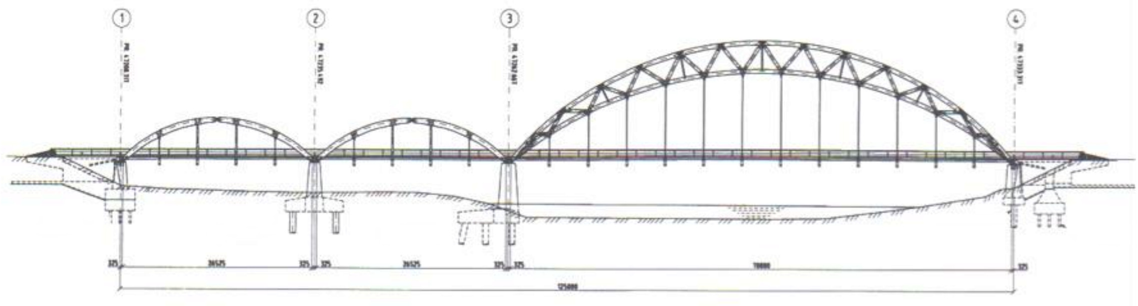


Figure 10. Tynset Bridge. More information can be found in Appendix 1 (Nordic Industrial Fund 2002, 58).

Hinges are placed in arches in order to release bending moment. A typical hinge for arc bridges is shown in figure 11. Hinges allow for small movements due to thermal expansion and other reasons without unnecessary bending stress. That hinges are usually placed on the top of the arch and supported ends. Depending on the structural model, an arch may require two or three hinges.

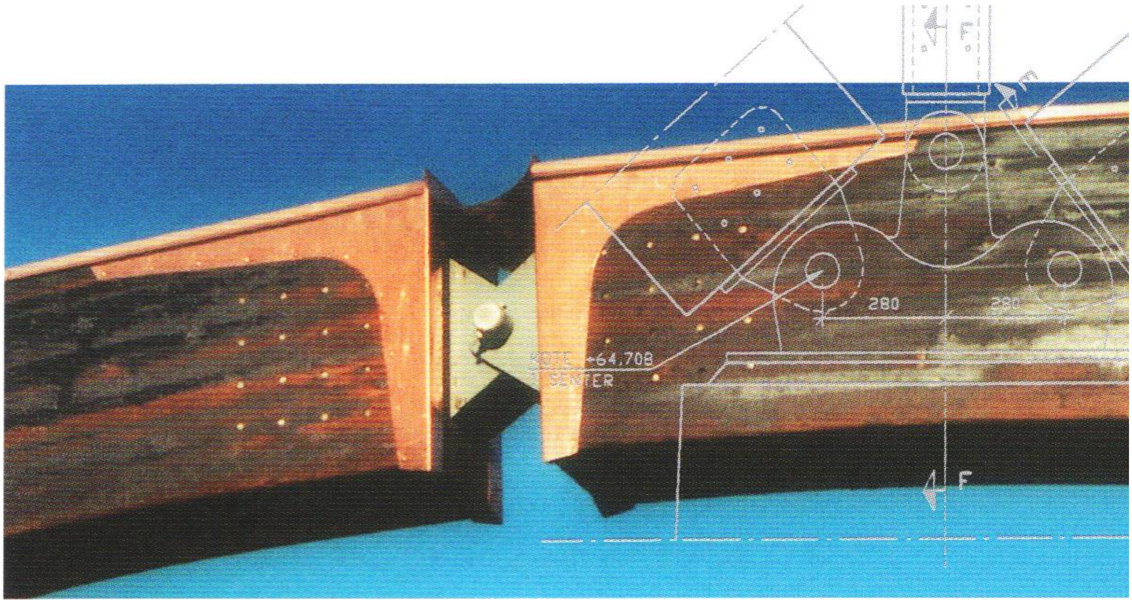


Figure 11. Hinged connection releases the moment stress in arches (Nordic Industrial Fund 2002, 47).

In truss bridges the shear and moment stresses are reduced. However, compressive and tension stresses are higher. Therefore, buckling should be considered. In the truss system stresses perpendicular to the grain are quite common. Thus, an extra attention should be paid to connections in timber truss bridges. Timber truss bridge systems can be divided into king post trusses and two Howe trusses.

Two Howe trusses are a pair of supporting crossbeams, which take the whole load and serve as railings for the bridge itself (Figure 12). The king post systems usually have bigger scale members, which bear the bridge deck with help of webs (Figure 12).

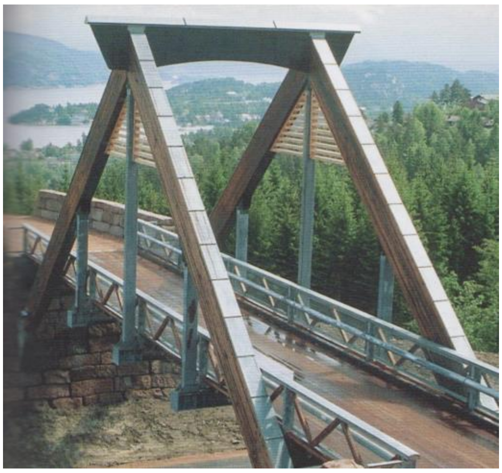


Figure 12. The two Howe and king post truss timber bridges (Nordic Industrial Fund 2002).

In most cases cable timber bridges are pedestrian bridges. It is very rear to see cable bridges designed for traffic. Cables support the deck and the need of intermediate supports is illuminated (Figure 13).

Usually the system consists of vertical pylons resting on the abutments, and of cables supporting the deck. This system partly bears a certain resemblance to the truss bridge system. However, the cable only functions on tension and cannot handle the compression force.

Figure 13. Cable timber bridge (Nordic Industrial Fund 2002).

2.3 Connections

It is important to conceder connections in timber bridges during the design phase. It is important to ensure the strength and stability of the timber structure by selecting proper connections. Connections weaken the strength of the cross-section and decrease the load-bearing capacity of the structural elements (American Society of Civil Engineers 1996). Because of holes and grooves they require. Failures of the timber structures begin in most cases in connections. Thus, the stability of the timber structure depends on the correct selection, design and assembly of the connection (Volik 2005).

The anisotropy, the small compression or tension strength perpendicular to the grain, causes great complexity and diversity. It makes the designing process more complicated. It is common to use steel as the main fastening material for timber structures. Steel is an excellent structural material for creating joints between timber members. Modern fasteners can provide reliable design criteria and a possibility to create high performance connections with supreme precision.

The two connection types commonly used in bridge construction are lateral (shear) connections and withdrawal (tension) connections (see figure 14).

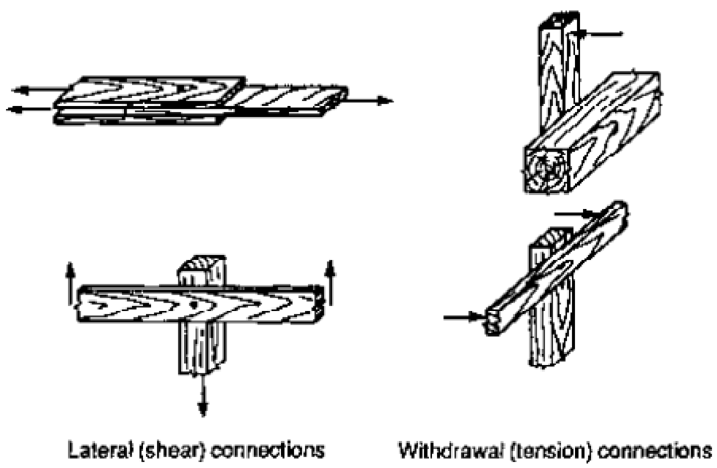


Figure 14. Most common types of connections used in bridge construction (Volik 2005)

All connections between timber elements can be divided into three groups: connections without any mechanical fasteners, known as contact connections, connections with mechanical fasteners, and glued connections.

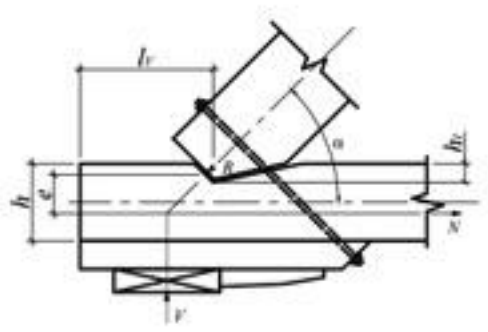


Figure 15. Contact connection holds everything on its place and is not involved in load transferring from one member to another (Volik 2005)

A contact connection, see in figure 15, works on compression only. Force is directly transferred through contact between two timber elements. Bolts are used in contact connections only as connectors, providing rigidity and stability of the structural system, as well as facilitating the distribution to loads acting on the system. (Volik 2005)

Mechanical connections are divided in dowel connections and bearing connections (can be found in figure 16). Dowel connection includes such fasteners as screws, nails, and bolts. These connections can transmit lateral or withdrawal loads.

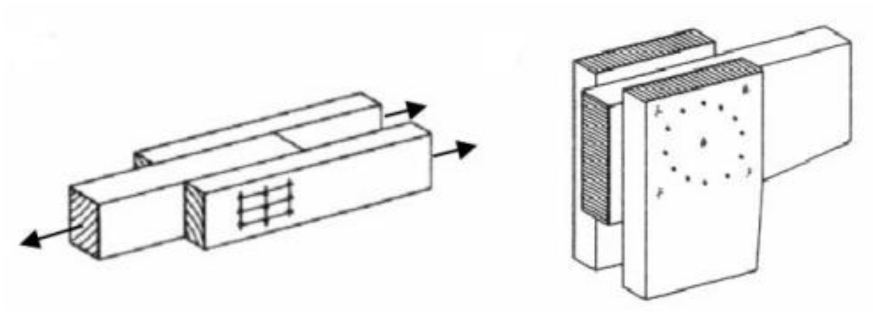


Figure 16. Dowel types of connections (Volik 2005)

A bearing connection, seen in figure 17, can only take lateral load. The most common bearing connections are shear plate and split ring connections.

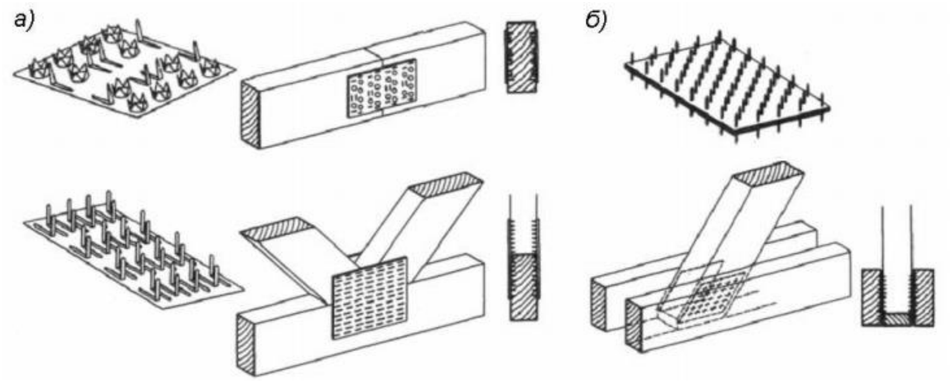


Figure 17. Bearing connections (Volik 2005)

Adhesively-bonded timber connections are widely used in prefabricated wooden structures. The adhesive in these types of connections is mainly synthetic glue. Glued connections, shown in figure 18, are characterized by a number of important advantages.

First of all, glued connection allows the fabricating of a wide variety of load-bearing structures in various sizes and shapes. Secondly, the adhesive helps the connection to avoid naturally accruing defects such as knots, shakes and etc. Moreover, glued connections are waterproof and have decay resistance even in chemically aggressive environments. These properties are very important for timber bridges in Finland where de-icing agents are heavily applied in wintertime. However, gluing is not possible in other than specially equipped workshops under strict laboratory control. Thus, the lack of possibility to make a glued connection on a site is a disadvantage. (American Society of Civil Engineers 1996).

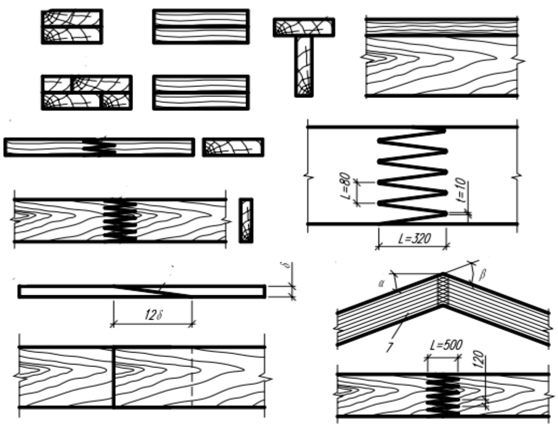


Figure 18. Glued connections (Ritter 1990)

3 Design

In order to make structural design it is important to study regulations and guides for the country the structure will be constructed. In this chapter the research of regulation for bridges in Finland is done as well as the case study.

3.1 Current Finnish regulations

For bridge design in Finland, certain regulations should be taken into account (Calgaro;Tschumi ja Gulvanessian 2010). As for other European countries the Eurocodes with together with national annexes are the most important design instructions.

Table 1 shows the list of Eurocodes that should be considered during the design phase of a bridge. Marked parts and sections of the Eurocodes were used for the new bridge design. The "*EN 1998: Eurocode 8 – "Design of structures for earthquake resistance*" is not relevant for bridges designed in Finland due to location.

In order to help designers to adopt a new design and calculation systems, most European countries have published so called NCCI documentation based on the Eurocodes and National annexes. NCCI stands for "Non-Contradictory Complementary Information".

For the case study bridge design several additional to Eurocodes standards and guidebooks were used. For the design of reinforcement TIEL 2170014-2000 guidebook was used. From NCCI the firs code containing loads acting on bridges and basics of design, the second code about the design of concrete structures, the fifth code explaining the design of timber structure and seventh code about geotechnical design were used.

Buildings in Finland as in many other countries need to have different kind of permits before being constructed. The structural design is one of the main checks to be done and approved in municipality.

However, there is no such system in bridge construction determined. For most of the cases Finnish Transport Agency is the client of a design company itself.

Table 1. The list of Eurocodes

Eurocode	**Part of Eurocode**	**Title and/or score**
EN 1990: Eurocode - Basics of structural design	Main text	Structural safety, serviceability and durability Principles of partial factor design
	Annex A2	Application for bridges (combinations and factors)
EN 1991: Eurocode I - Actions on structures	Part 1-1	Densities, self-weight and imposed loads
	Part 1-3	Snow loads
	Part 1-4	Wind actions
	Part 1-5	Thermal actions
	Part 1-6	Actions during executions
	Part 1-7	Accidental actions due to impact and explosions
	Part 2	Traffic loads on bridges (road bridges, foot bridges, railway bridges)
EN 1992: Eurocode 2 – Design of concrete structures	Part 1-1	General rules and rules for building
	Part 2	Reinforced and prestressed concrete bridges
EN 1993: Eurocode 3 – Design of steel structures	Part 1	General rules and rules for buildings, including: Part 1-1 – General rules and ruled for buildings Part 1-4 – Stainless steel Part 1-5 – Plated structural elements Part 1-7 – Strength and stability of planar plated structures transversely loaded Part 1-8 – Design of joints Part 1-9 – Fatigue strength of steel structures Part 1-10 – Selection of steel fracture toughness and through-thickness properties Part 1-11 – Design of structures with tension components made of steel Part 1-12 – Supplementary rules for high strength steel
	Part 2	Steel bridges
EN 1994: Eurocode 4 – Design of composite steel and concrete structures	Part 1-1	General rules and rules for buildings
	Part 2	Composite bridges
EN 1995: Eurocode 5 – Design of timber structures	Part 1-1	General rules and rules for buildings
	Part 2	Timber bridges
EN 1997: Eurocode 7 – Geotechnical design	Part 1	Geotechnical design
EN 1998: Eurocode 8 – Design of structures for earthquake resistance	*Part 1*	*General rules, seismic actions and rules for buildings*
	Part 2	*Bridges*

There are four design check before the final approval classes existing according to Finnish Transport Agency requirements. Class RS1 means that the designer himself checks the drawings and calculations. Class RS2 means that also only internal checks are required, but another designer is to do them. Class RS3 involves a second party company, not engaged in the design, into the verifying process. During class RS4 checks, a designer from the checking company has to do the calculations in order to compere the delivered drawings and calculations to his results.

If the amount of designed work is not too heavy, Finnish Transport Agency checks the drawings and calculations itself. If there is a huge workload Finnish Transport Agency may hire the other design company to make final checks instead.

In case of private bridges not owned by Centre for Economic Development, Transport and the Environment, the owner is responsible for the bridge, its design and maintenance.

3.2 Case study

The bridge studied in the last year project is the replacement of an old timber bridge owned by the Southwest Finland Centre for Economic Development, Transport and the Environment. The old bridge is to be replaced because it is no longer in a good condition. The structures that are looked into during the case study comparison are the deck holding structures of the newly designed bridge and an alternative bridge.

The case study bridge is not yet built, but it is designed and soon to replace the old timber bridge over the river in Satakunta region. During this case study the deck holding structures will be compered only.

3.2.1 Old bridge

The current timber structure bridge is located in Satakunta region. The bridge was designed in 1970. The drawings were approved in 1972 and the bridge itself was built in 1973. The bridge is supported by two end supports and two intermediate supports. Together with wooden piles they form a substructure of the bridge. Wooden logs rest on the supports and distribute forces between them while acting as a beam. The elevation drawing of an old bridge can be seen in figure 19.

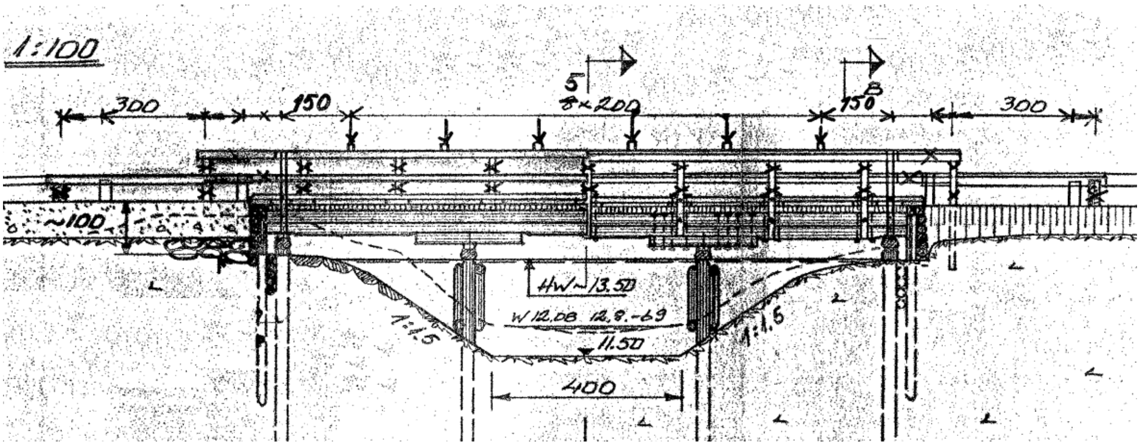


Figure 19. The elevation drawings of an old bridge from structural drawings form the 1970

According to old documents, the bridge has three openings, 4m, 5m and 4m wide. Wooden logs are connected to each other with steel rods and bolts, forming a deck. Beams are continued with overlapping of 700mm and with tying up using the same steel rods and bolds with the help of a washer for better friction. Figure 20 shows the detail drawing above the intermediate support.

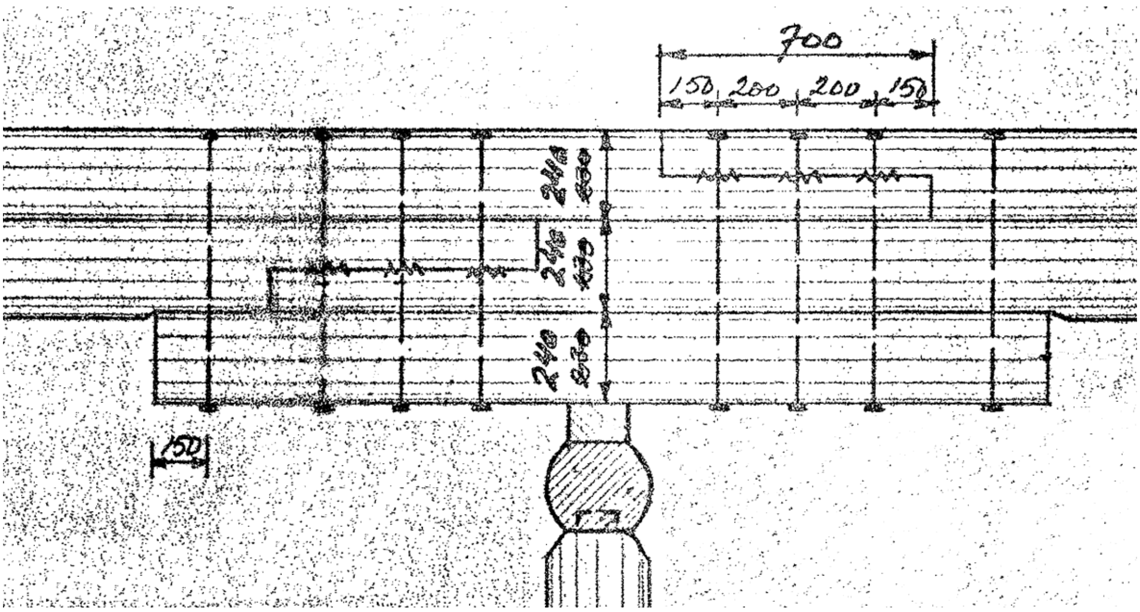
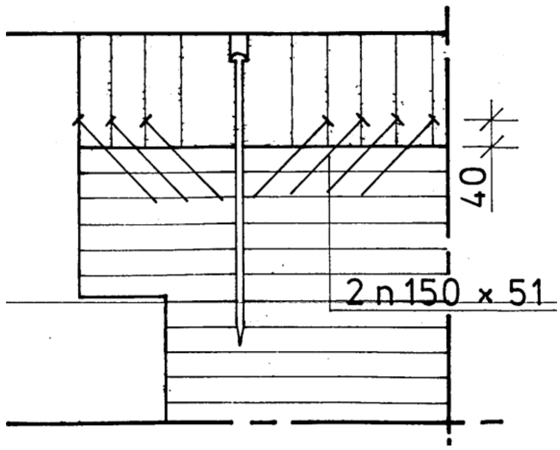


Figure 20. The connection drawings ant the middle supports from structural drawings from the year 1970



In the main drawing from the year 1970 the driveway surface is laid with 2'' x 5'' (50mm x 120mm) sawn timber planks laid vertically. The planks are connected to each other and to the main beams with nails (figure 21). Most nails are hammered down by hand and with an angle to the surface. Because, typically, nails for a nail gun have a smoother surface which causes less friction and looser connection.

Figure 21. Planks are fastened with nails to the deck (Finnish Road Administration)

Taking into account the age of the bridge it is in a fairly good condition. It has been checked in 1995, 1998, 2003, 2008 and 2011. Some parts of it were changed such as the deck and railings. According to the latest check the bridge had some issues to be dealt with. Table 2 shows the problems of the old bridge detected during the last check in the year 2011. It also shows the time during which such problems should be fixed.

Table 2. Existing bridge problems detected in the year 2011 inspection

Problem	**Reason**	**Years to fix**
Scratches on the deck surface	improper maintenance	>4
Rusting of steel bolts connecting wooden parts	aging	>4
Loosened up bolts	aging	>4
Railings are too short (before and after the bridge as well as on the bridge itself) and low according to updated legislation		2-4
Cracking of the asphalt on the ends of the bridge	construction mistake	2-4
Deflection of the road next to the bridge edges	traffic loading	2-4

3.2.2 New Bridge

Classification

In order to start the design process core information should be determined. In classification the basic knowledge is defined.

- Consequences class: CC2
- Tolerance class
    - Superstructure: 2
    - Substructure: 2
- Load models:
    - LM1
    - LM2
- Fatigue design:
    - Fatigue Load Model FLM3
    - Traffic category: Road bridge
- Bridge placement class IV
- Speed limitation 50km/h
- The bridge design checks class RS2

The Eurocode defines the Consequences class 2 as "Medium consequence for loss of human life, economic, social or environmental consequences considerable" [Eurocodes]. Thus, the general rules of Eurocodes should be used without additional severe requirements when designing the bridge.

Tolerance class stands for the rate of deviation that may be acceptable during construction such as dimensions of the elements, the reinforcement position etc. If the builder fails the realization of the bridge in the acceptable frames, consequences will follow.

In order to verify limit state loads other than fatigue four load models are used. Type of traffic on specific bridge defines combination of which load models should be used. LM1 is a tandem system (which is concentrated load representing two axles vehicles) and distributed load combined. LM1 is applied to all bridges. LM2 is added to LM1 as it represents one-axle vehicles with two wheels. LM3 taking into account special vehicles. LM4 Uniformly distributed load representing crowd.

The traffic category is important for fatigue design. Possible traffic categories are: road bridge, footbridge and railway bridge. (Calgaro, Tschumi, Gulvanessian 2010)

The bridge placement class describes how strict the visual picture of the bridge should be. "Class I" means that the bridge is located in a city and the municipality specifies what the bridge should look like. “Class IV” means that the bridge is located in a less crowded area and the designer may decide most of the visual details guided by regulations.

New bridge basic information

The new bridge was designed by Pöyry Finland. The new bridge is typical glulam deck and steel beamed bridge. Figure 22 shows the elevation of the new bridge. The old structure is possible to see in dotted lines. The superstructure of the bridge consists of an I-beam (HEB500) as a deck structure and glulam driveway surface elements. Figure 23 shows the cross-section of the new bridge. The piled concrete foundation and concrete end supports form the bridge substructure.

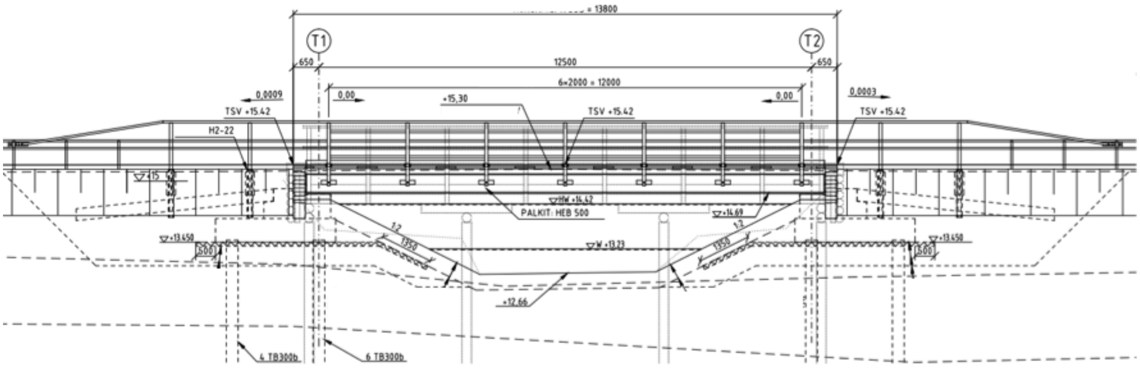


Figure 22. Designed bridge elevation. The old structure is shown by dotted lines

The steel beams rests on concrete end supports. Usually a road has a tendency to settle down, and the driveway surface lowers due to traffic loads. Whereas, the supports do not deviate much. In order to make the level difference less distinctive and avoid future problems with asphalt pavement, transition slabs are placed underneath the ground on both sides of the bridge. The slabs prevent the rapid ground settlement at the end of the abutment. In the old bridge, there were no transition slabs and this caused asphalt cracking.

From the end supports, the loads are transferred through the concrete piles to the ground. In order to handle the loads, ten piles are designed on both sides (figure 24). The piles have 300 x 300 mm sides and the length varies from 5.7m to 8.3m. The length difference is caused by the bedrock level fluctuation underneath the structure, since the piles start from the bedrock.

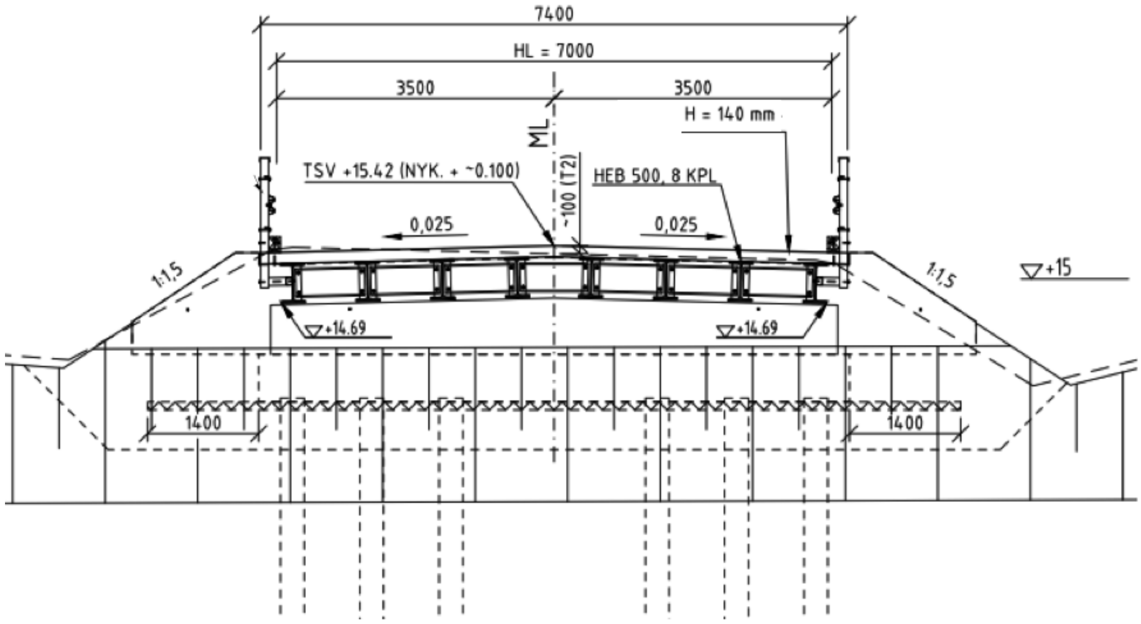


Figure 23. Cross-section of the bridge.

It is important to take into consideration that the substructure does not only transfer vertical but also horizontal loads. Horizontal loads are induced in any kind of vehicle acceleration or breaking on the deck surface of a bridge. Load models are used in order to estimate the maximum stresses on bridge structure members.

The new bridge has only one opening of 12.5m with no intermediate supports. This is possible because the steel beams can bear more loads than logs could.

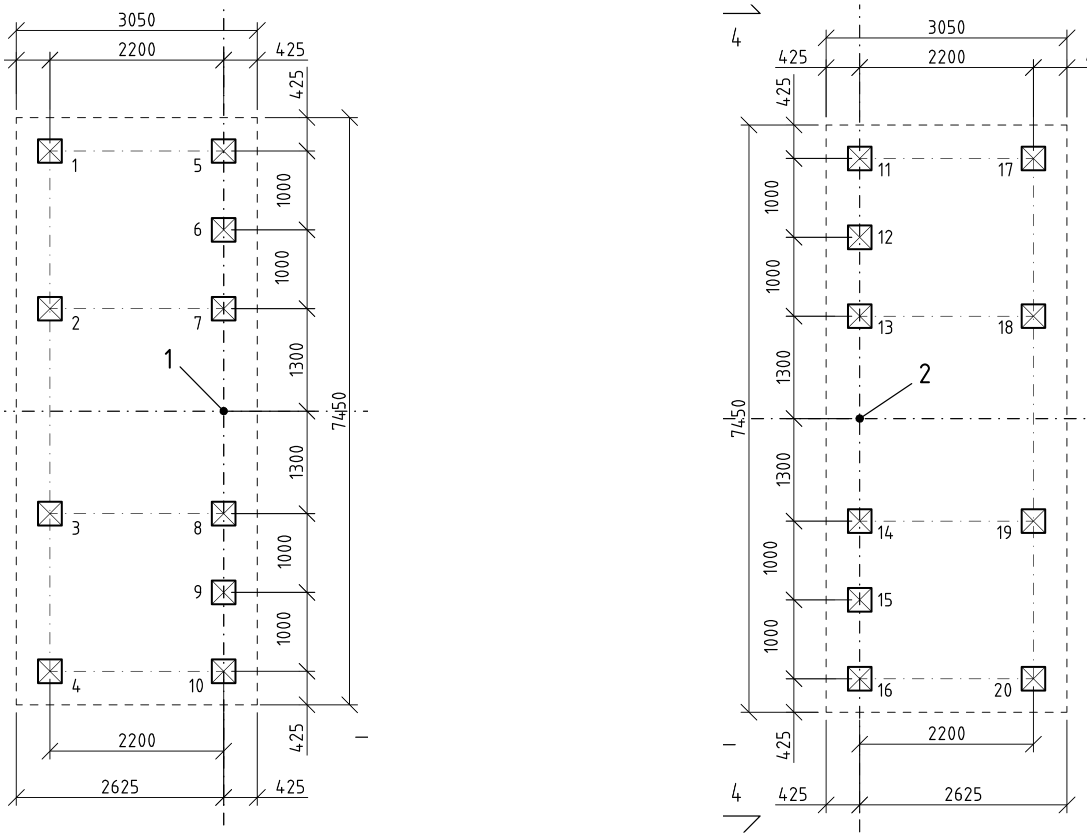


Figure 24. The plan of the piles for bridge structure

As shown in the drawing, the glulam deck rests on eight HEB 500 steel profiles. The length of each beam is 13,14m. The spacing between them is 943-944 mm. For the stability of the system, U-profiles connect the main beams in a perpendicular direction.

Moment

$$M_d := 1054kN \cdot m$$

$$W_{eL.y} := 4287cm^3 = 4.287 \times 10^6 \cdot mm^3$$

$$f_y := 355 \frac{N}{mm^2}$$

$$\sigma_{m.d} := \frac{M_d}{W_{eL.y}} = 245.86 \cdot \frac{N}{mm^2}$$

$$\frac{\sigma_{m.d}}{f_y} = 0.693$$

Shear

$$Q_d := 437kN$$

$$S_y := 2339.709cm^3 = 2.34 \times 10^6 mm^3$$

$$I_y := 107176cm^4 = 1.072 \times 10^9 \cdot mm^4$$

$$t_w := 14.5mm$$

$$\tau_{v.d} := \frac{Q_d \cdot S_y \sqrt{3}}{I_y \cdot t_w} = 113.956 \cdot \frac{N}{mm^2}$$

$$\frac{\tau_{v.d}}{f_y} = 0.321 \qquad (2)$$

The maximum moment according to load models is 1054 kNm at the middle of the beam. The maximum shear is 437 kN at the supports. With the help of basic calculations (2) it is possible to say that the stresses are smaller than the strengths of the chosen beam.

3.2.3 An alternative bridge design

In an alternative bridge design, glulam timber beams are examined to replace steel beams. For the alternative design, a rectangular cross-section is chosen. The standard sized glulam beams are not suitable for the bridge as their cross-sections are not big enough to have the strength required by the maximum bending moment and shear, which are calculated on the basis of the load models. That is why beam would have to be custom made.

In order to establish the thickness of the beam to its height dependency calculations have to be done (3).

Moment

$$M_{s.d} := 1054\text{kN}\cdot\text{m}$$

$$p_s := m_s \cdot g = 1.935 \cdot \frac{\text{N}}{\text{mm}}$$

$$\frac{\sigma_{m.d}}{f_{m.d}} < 1$$

$$f_{m.d} := k_{mod} \cdot \frac{f_{m.k}}{\varphi_m}$$

$$\sigma_{m.d} := \frac{M_{w.d} \cdot 6}{b \cdot h^2}$$

$$M_{w.d} := M_{s.d} + \frac{l_b^2}{8} \cdot (p_w - p_s)$$

$$p_w := m_w \cdot g$$

$$m_w := \rho_{w.m} \cdot h \cdot b$$

$$b_{min.moment} := \frac{6 \cdot \varphi_m \cdot \left(M_{s.d} - p_s \cdot \frac{l_b^2}{8}\right)}{k_{mod} \cdot f_{m.k} \cdot h^2 - 6 \cdot \varphi_m \cdot h \cdot g \cdot \rho_{w.m} \cdot \frac{l_b^2}{8}}$$

Information

$$\rho_{w.m} := 470 \frac{\text{kg}}{\text{m}^3}$$

$$f_{m.k} := 32 \frac{\text{N}}{\text{mm}^2}$$

$$f_{v.k} := 3.2 \frac{\text{N}}{\text{mm}^2}$$

$$k_{mod} := 0.9$$

$$\varphi_m := 1.2$$

$$l_b := 13140\text{mm}$$

$$m_s := 197.3 \frac{\text{kg}}{\text{m}}$$

Shear

$$Q_{s.d} := 437\text{kN}$$

$$\frac{\sigma_{v.d}}{f_{v.d}} < 1$$

$$\sigma_{v.d} := 1.5 \cdot \frac{Q_{w.d}}{b_{es} \cdot h}$$

$$b_{es} := 1 \cdot b$$

$$Q_{w.d} := Q_{s.d} + \frac{l_b}{2} \cdot (p_w - p_s)$$

$$f_{v.d} := k_{mod} \cdot \frac{f_{v.k}}{\varphi_m}$$

$$b_{min.shear} := \frac{1.5 \cdot \varphi_m \cdot \left(Q_{s.d} - \frac{l_b}{2} \cdot p_s\right)}{h \cdot \left(k_{mod} \cdot f_{v.k} - 1.5 \cdot \varphi_m \cdot \frac{l_b}{2} \cdot \rho_{w.m} \cdot g\right)}$$

(3)

In calculation (3) maximum bending moment and maximum shear was used to determine the dimensions of the beam cross section. If the h is considered a variable, the minimum thicknesses of the beam are the functions given by the formula. Thus, a graph of the functions can be drawn, as shown in figure 25.

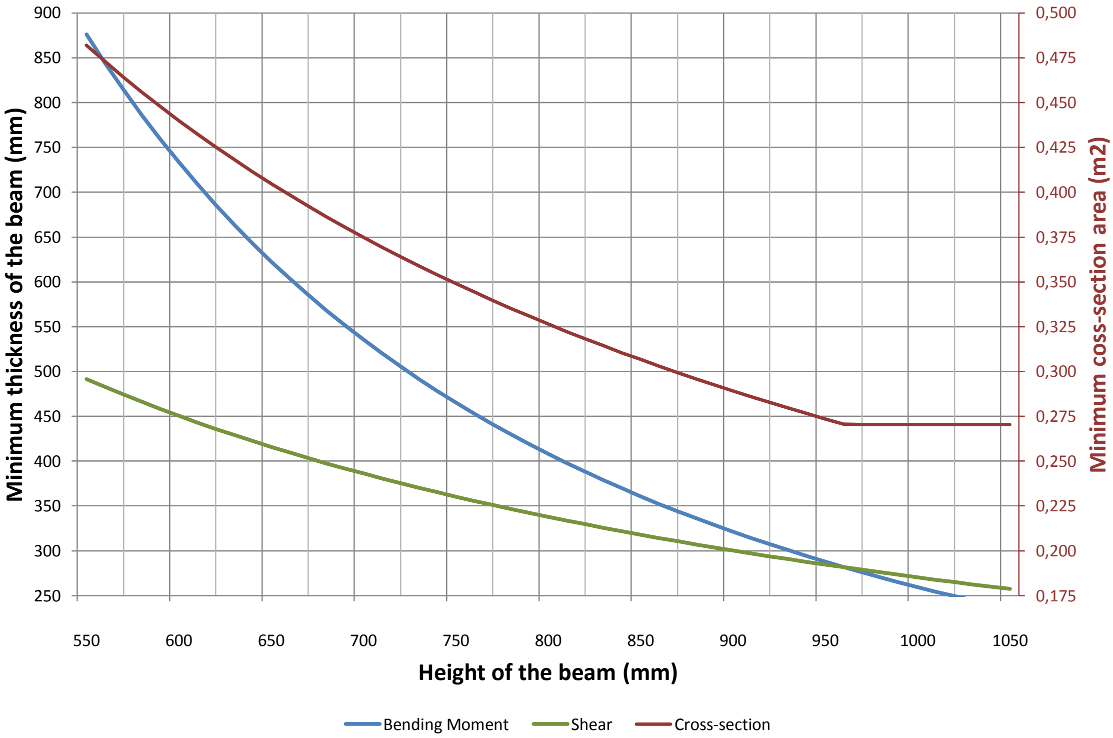


Figure 25. Minimum thickness of the beam according to its height

Figure 25 shows the graph for easier dimension recognition. ***Blue M(h)*** and ***green Q(h)*** lines show the minimum thicknesses of the beam according to the height of it, given on the horizontal axis, in order to have strength of the profile higher that the stresses from maximum ***bending moment*** and ***shear force*** respectively. The higher value should be considered as an actual minimum in order to $\begin{cases} bmin > bmin.moment \\ bmin > bmin.shear \end{cases}$ be satisfied. ***Red A(h)*** line represents the minimum cross-section area of the beam on the beam height dependency. GL32c is used.

According to functions and their graphics in figure 25 ***M(h)*** intersects with ***Q(h)*** when the height of the beam reaches 960 mm (both functions have the same value for the thickness of about 283 mm). Before this point the ***M(h)*** gives the true value of minimum thickness, after the beam with height above 960mm, the shear stress becomes the major concern. It is also easy to notice that when the ***A(h)*** function reaches the same point, the change in cross-section area becomes less rapid. Because the cross-section area stops decreasing so rapidly, after the beam height reaching the 960mm, it is not practical to use beams with bigger height.

Depending on the bridge placement, the requirements of shape may differ. In this case study the bridge provides a passage over a river. It does not require any clearance underneath in order to provide passage for boats. However, the water level might limit the height of the beams. In the case study, the normal water level is quite low which allows glulam beams to be bigger in its height than the steel beams.

Information

$$\rho_{w.m} := 470\frac{kg}{m^3}$$

$$h := 800mm$$

$$b := 450mm$$

$$m_w := \rho_{w.m}\cdot h\cdot b = 169.2\frac{kg}{m}$$

$$f_{m.k} := 32\frac{N}{mm^2}$$

$$f_{v.k} := 3.2\frac{N}{mm^2}$$

$$f_{c.90.k} := 2.9\frac{N}{mm^2}$$

$$k_{c.90} := 1.75$$

$$k_{mod} := 0.9$$

$$\varphi_m := 1.2$$

Moment

$$M_{s.d} := 1054kN\cdot m = 1.054\times 10^9\cdot N\cdot mm$$

$$m_s := 197.3\frac{kg}{m}$$

$$l_b := 13140mm = 13.14\,m$$

$$W_d := \frac{b\cdot h^2}{6} = 0.048\cdot m^3$$

$$p_s := m_s\cdot g = 1.935\cdot\frac{N}{mm}$$

$$p_w := m_w\cdot g = 1.659\cdot\frac{N}{mm}$$

$$M_{w.d} := M_{s.d} + \frac{l_b^2}{8}\cdot(p_w - p_s) = 1.048\times 10^3\cdot kN\cdot m$$

$$\sigma_{m.d} := \frac{M_{w.d}}{W_d} = 21.8\cdot\frac{N}{mm^2}$$

$$f_{m.d} := k_{mod}\cdot\frac{f_{m.k}}{\varphi_m} = 24\cdot\frac{N}{mm^2}$$

$$\frac{\sigma_{m.d}}{f_{m.d}} = 0.91 \quad (4)$$

The width of the beam may be a concern. The load on a beam causes compression at the supports. This compression is perpendicular to the grain. Because of the wood structure itself, the compressive strength of the timber perpendicular to the grain direction is about nine times lower than the compressive strength to parallel direction.

The rectangular cross-section with a height of 800 mm and width of 450 was chosen for the case study bridge. The calculations proving the suitability of GL32c 800x450mm L13140mm c/c 943mm can be seen in (4) and (5) calculations.

Shear

$$Q_{s.d} := 437kN$$

$$Q_{w.d} := Q_{s.d} + \frac{l_b}{2} \cdot (p_w - p_s) = 435.19 \cdot kN$$

$$b_{es} := 1 \cdot b$$

$$I_d := \frac{b \cdot h^3}{12} = 0.019\,m^4$$

$$S_d := \frac{b \cdot h^2}{8} = 0.036 \cdot m^3$$

$$\tau_{v.d} := \frac{Q_{w.d} \cdot S_d}{I_d \cdot b_{es}} = 1.813 \cdot \frac{N}{mm^2}$$

$$f_{v.d} := k_{mod} \cdot \frac{f_{v.k}}{\varphi_m} = 2.4 \cdot \frac{N}{mm^2}$$

$$\frac{\tau_{v.d}}{f_{v.d}} = 0.756$$

Compression permendicular to the grain

$$l_{sup} := \frac{l_b - 12.5m}{2} = 0.32\,m$$

$$A_{ef} := b \cdot (l_{sup} + 30mm) = 0.158 \cdot m^2$$

$$\sigma_{c.90.d} := \frac{Q_{w.d}}{A_{ef}} = 2.763 \cdot \frac{N}{mm^2}$$

$$f_{c.90.d} := k_{mod} \cdot \frac{f_{c.90.k}}{\varphi_m} = 2.175 \cdot \frac{N}{mm^2}$$

$$\frac{\sigma_{c.90.d}}{k_{c.90} \cdot f_{c.90.d}} = 0.726$$

(5)

It is interesting to notice that the maximum moment obtained from the load model for steel profile and maximum moment caused by the load model for the timber profile have almost the same values. First of all, the weight of the beams per meter is not very different. In order to bear the same load as steel, glulam beams were supposed to have larger dimensions. Secondly, the self-weights of the beams are not large compared to other loads in the load models.

A typical solution for the alternative bridge design connections can be found in Appendix 2.

3.2.4 Cost estimation

Table 3. Cost of the bridge

Part		Price
1000	Ground, earth and rock structures	€50 704
1100	Existing structures	€16 587
1300	Foundation structures	€5 606
1400	Ground structures	€13 486
1600	Excavation works	€3 969
1800	Embankments and fills	€11 056
2000	Substructure and surface	€20 659
3000	Trafic orgenization	€6 110
4000	Civil structures	€135 398
4200	*Bridges*	*€135 398*
4207	Foundation slab	€8 490
4211	End supports	€11 838
4223	Steel in supestructure	€83 931
4233	Deck toping/pavement	€19 066
4242	Bearings and joints	€558
4244	Transition slabs	€3 924
4245	Grotection layers	€7 533
4249	Other bridge equipment	€58
5000	Construction works	€44 703
	Delivery	€18 030
Total (Alv. 0%)		*€275 604*
Total (Alv. 24%)		**€341 749**

The cost estimation was done with Fore. Fore is a system that contains the prices for different materials, components, elements and works. The system also takes into account the inflation rate. The cost index was introduced for cost conversion.

The cost of a new bridge was calculated on the basis of a cost index of 112.80 (2010=100), which means that the prices are 112.80% of the 2010 prices taken as 100%. In order to estimate the costs of the bridge in the future, the current index will have to be used.

The cost of the bridge with the cost index of 112.80 is €342 000. The table 3 contains the structural parts and construction elements, the construction work itself, as well as the delivery of everything on site.

In order to figure out the difference in the price for the construction between the steel beams and glulam beams, the costs of the beams should be compared.

Table 4. Beam price comparison. Steel & glulam

	Part	Units	Ammount	Price per unit	Total price
4223	Steel in supestructure				€83 931
	Main beams	kg	19 900	3,89 €	€77 333
	Secondary beams	kg	2 100	3,14 €	€6 598
4224	Glulam beams				€70 595
	Main beams	m^3	38	1 687,39 €	€63 856
	Secondary beams	m^3	4	1 687,39 €	€6 739

As can be seen in table 4, the costs of load bearing beams are not radically different. The cost of beams does not influence the total construction cost so much. Moreover, the lifetime of steel and glulam parts may be different. That is why it is hard to distinguish which option is actually economically beneficial.

4 Maintenance

Finland is divided into 15 Centres for Economic Development, Transport and the Environment. The centres are responsible for the infrastructure and roads. Therefore they own most public bridges in Finland. In order to be sure that all the bridges are maintained and checked well, the centres hire companies which maintain bridges and roads.

There are guides issued by the Finnish Transport Agency (Liikennevirasto 2014) with information about what service bridges and roads should get and how often. According to the guides the maintenance companies should check the bridge, clean up, fix the roads, make sure that the plants growing near a bridge are trimmed and do not disturb the traffic or block any part of the traffic organization system.

There are special service requirements for bridges both in wintertime, and for the summer. In addition, bridges should be checked annually. A form gather and store the information about bridge condition is filled.

The maintenance guidebooks do not separate bridges according to the material they are built of. The guidebooks give an overall picture of the services to provide to keep bridges in good condition.

5 Advantages and Disadvantages

Timber as construction material has a number of advantages. First of all, wood is a renewable source. For countries rich in forests, like Finland, that makes perfect opportunities for using timber in construction. They have a big amount of raw material, as well as a developed forestry and wood industry. Moreover, the production of structural elements in timber has lower impact on the environment due to a smaller carbon footprint from the cradle to grave life cycle. This is obtained not only through the manufacturing process, but also with transportation and recycling.

As established in the case study, steel may be replaced by wood as a construction material for load bearing elements. The development of glued laminated timber has given desirable physical properties to the material. For example, glulam is more homogenous than sawn timber and has more consistent load bearing abilities along the structural member. Wood, naturally, has different kinds of defects, and gluing smaller pieces together into a bigger element helps to eliminate the defects consistently rather than leave them concentrated in one place.

Glulam also allows the making of different shapes, and does not limit the size of the element much. That makes it a much more flexible material than centuries ago. The members can have arched shapes without the strength being compromised.

However, the maintenance of timber bridges might be tricky. While, wood is more resistant to some chemical compounds, it still is quite prone to deterioration and insects attacks. Modern timber treatment methods protect wood to a degree. But it is extremely important to conduct the examination and recognize the issues at early stages.

The cost estimation is not straightforward and requires more research in the field. Structural wood itself is less expensive than concrete or steel. It is also lightweight which makes the transportation and assembly processes easier and less expensive. The less the self-weight of a bridge structure is, the less load is transferred to the ground. Therefore, the foundation may be lighter compared to steel bridges, which also affects the cost. However, the lifetime of timber elements might be shorter due to the properties of wood being more exposed to harmful environment.

6 Conclusion

Timber becomes more and more popular structural material for bridges in Nordic countries. That is due to its environmental advantages compared to other materials used in construction. However, the lifespan of timber is shorter than of e.g. steel. Also the maintenance needs and exploitation concerns are grater. Wooden bridges can be great for many small scale spans and perfect for private roads. Such bridges might be a disadvantage for those who do not pay attention to the bridge conditions and maintenance needs.

Glulam members can replace steel or concrete members with the loadbearing capacity with some limitations. The case study of this thesis is an example of this. Nevertheless, the dimensions of the timber beam had to be changed in order to handle the load; the weight of the glulam beam did not exceed the weight of a steel profile.

A timber bridge can be more environmentally friendly or suit better in some aesthetical reasons. Maybe today the emissions are not the main concern during the design and construction of a bridge or any other structure. However, in the future, the environmental impact might play a significant role in the material choosing process. With its load bearing capacity and mechanical properties, timber has a potential to become a great solution for bridge structures.

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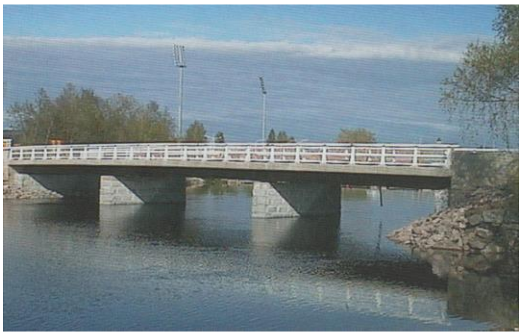
Examples of timber bridges from Finland, Sweden, Norway and Estonia

Name:	Byholmen Footbridge
Location:	Dragsfjärd, Finland
Year of Completion:	1997
Structural system:	Glulam timber girders
Bridge deck:	Sawn timber
Total length:	24,0 m
Span:	23,0 m
Width:	4,0 m
Wood quantity:	55 m^3
Total price:	118 000 euro

Name:	Lehmilahti Bridge
Location:	Sonkajärvi, Finland
Year of Completion:	2000
Structural system:	King-post truss
Bridge deck:	Sawn timber
Total length:	20,8 m
Span:	19,0 m
Width:	5,0 m
Wood quantity:	26 m^3
Total price:	50 000 euro

Name:	Maarinkunnas Footbridge
Location:	Vantaa, Finland
Year of Completion:	2001
Structural system:	Glulam timber girders
Bridge deck:	Sawn timber
Total length:	39,8 m
Span:	28,5 m
Width:	4,0 m
Wood quantity:	93,5 m^3
Total price:	64 000 euro

Name:	Pikisilta Bridge
Location:	Oulu, Finland
Year of Completion:	2001
Structural system:	Wood-concrete composite bridge
Bridge deck:	Concrete
Total length:	50,5 m
Span:	13,0 + 16,0 + 13,0 m
Width:	9,5 m
Wood quantity:	90 m^3
Total price:	420.000 euro



Name:	Poukkasilta Ride Bridge
Location:	Ypäjä, Finland
Year of Completion:	2001
Structural system:	Truss bridge
Bridge deck:	Glulam timber slab
Total length:	33,8 m
Span:	32,0 m
Width:	3,5 m
Wood quantity:	49 m^3
Total price:	114 000 euro

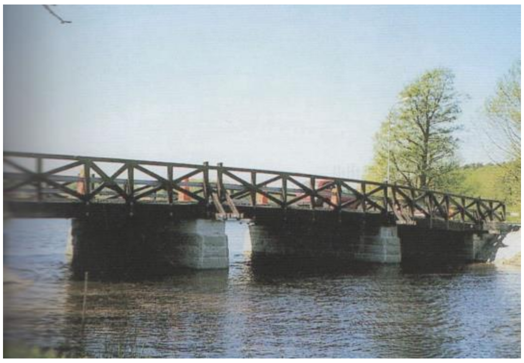
Name:	Talvitie Bridge
Location:	Isojoki, Finland
Year of Completion:	2001
Structural system:	Wood-concrete-wood composite bridge
Bridge deck:	Wood and concrete
Total length:	31,6 m
Span:	11,6 + 10,8 m
Width:	4,5 m
Wood quantity:	25 m^3
Total price:	64 000 euro

Name:	Vihantasalmi Bridge
Location:	Mäntyharju, Finland
Year of Completion:	1999
Structural system:	glulam king-post truss in three middle span, concrete-glulam timber composite girders in two side spans
Bridge deck:	concrete-steel-glulam timber composite structure
Total length:	182 m
Span:	21,0 + 42,0 + 42,0 + 42,0 + 21,0 m
Width:	11,0 +3,0 m
Wood quantity:	985 m^3
Total price:	3 900 000 euro

Name:	Avesta Footbridge
Location:	Avesta, Sweden
Year of Completion:	2000
Structural system:	two Howe trusses supporting crossbeam and serving as railings
Bridge deck:	140 mm glulam with 60 mm asphalt pavement on a welded bitumen mat
Total length:	61 m
Span:	26,2 + 26,2 m
Width:	3,0 m
Wood quantity:	82 m^3

Name:	Dabbsjö Bridge
Location:	Dabbsjö, Sweden
Year of Completion:	1998
Structural system:	stress-laminated plate on two supports
Bridge deck:	stress-laminated deck of untreated glulam of European whitewood
Total length:	15,3 m
Span:	15 m
Wood quantity:	44 m^3

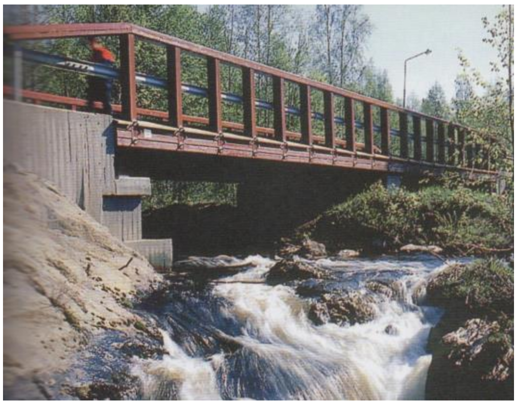
Name:	Gunnebo Bridge
Location:	Gunnebo, Sweden
Year of Completion:	1998
Structural system:	stress-laminated plates on four supports
Bridge deck:	stress-laminated deck
Total length:	25 m
Span:	7,5 + 10,0 + 7,5 m
Clearance:	8,6 m
Wood quantity:	24 m^3



Name:	Husån Bridge
Location:	Husån, Sweden
Year of Completion:	2000
Structural system:	stressed-box
Bridge deck:	215 mm upper plate of the box protected by 30 mm asphalt pavement on a welded bitumen mat
Total length:	17,2 m
Span:	14,1 m
Clearance:	4,5 m
Wood quantity:	50 m^3

Name:	Kallinge Footbridge
Location:	Kallinge, Sweeden
Year of Completion:	2000
Structural system:	Two Howe truss supporting crossbeam and serving as railings
Bridge deck:	Open plank deck on longitudinal beams
Total length:	29 m
Span:	28 m
Clearance:	2,5 m
Wood quantity:	30 m^3

Name:	Klintforsån Bridge
Location:	Klintfors, Sweden
Year of Completion:	2000
Structural system:	stress-laminated plate on three supports
Bridge deck:	stress-laminated deck and asphalt pavement wearing surface
Total length:	19,1 m
Span:	9,33 + 9,33 m
Cleaance:	5 m
Wood quantity:	36 m^3



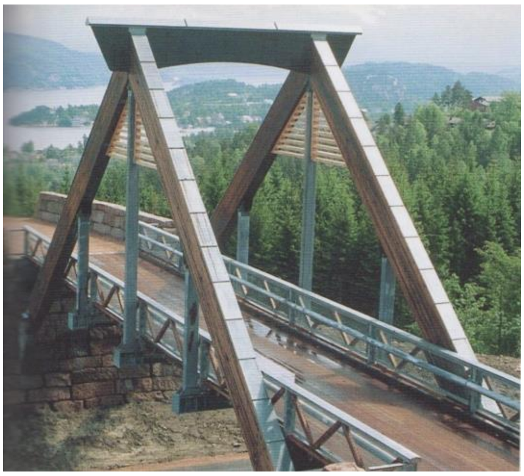
Name:	Munkedal Footbridge
Location:	Munkedal, Sweden
Year of Completion:	1999
Structural system:	Pylons and bars system. Horizontal truss caries the deck
Bridge deck:	Open plank deck on longi-tudinal timber beams
Total length:	60 m
Span:	60 m
Clearance:	3,5 m
Wood quantity:	57 m^3

Name:	Okb Footbridge
Location:	Söderhamn, Sweden
Year of Completion:	1998
Structural system:	Two two-hinged arches
Bridge deck:	Stress-laminated plate
Total length:	39,4 m
Span:	19 m
Clearance:	4 m
Wood quantity:	60 m^3

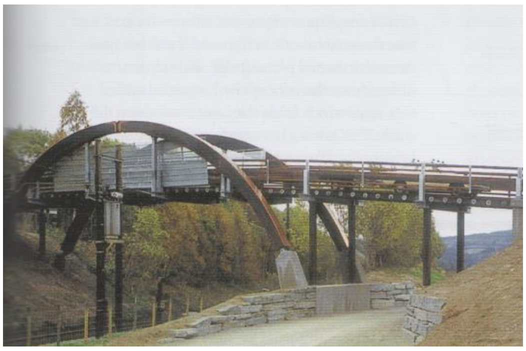
Name:	Spångerum Footbridge
Location:	Spångerum, Sweeden
Year of Completion:	2000
Structural system:	Pylons and bars system. Horizontal truss caries the deck
Bridge deck:	
Total length:	Open plank deck on longi-tudinal timber beams
Span:	95,5 m
Clearance:	20,0 + 54,0 + 20,0 m
Wood quantity:	3,5 m
Total price:	124 m^3

Name:	Svanstein Footbridge
Location:	Svanstein, Sweeden
Year of Completion:	1995
Structural system:	Stress-laminated plate supported by the abut-ments and two V-shaped bents
Bridge deck:	Continuous stress-laminated deck and asphalt pavement as wearing sur-face
Total length:	24,5 m
Span:	6,0 + 12,0 + 6,0 m
Clearance:	3m
Wood quantity:	22,5 m^3

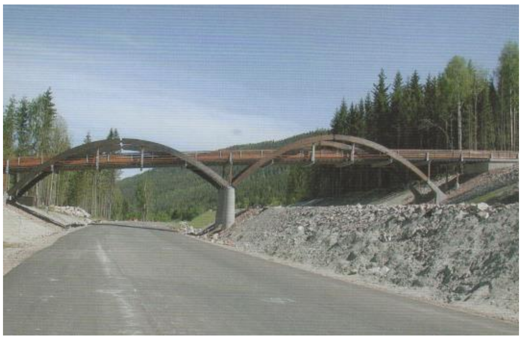
Name:	Beston Bridge
Location:	Beston, Norway
Year of Completion:	1999
Structural system:	King post bridge with glu-lam struts
Bridge deck:	Partly elevated, stress-laminated timber plate, supported by steel cross beams and suspended by the king post and two verti-cal steel hangers
Total length:	24,0 m
Span:	24,0 m
Clearance:	4,0 m
Wood quantity:	40 m^3



Name:	Bordal Bridge
Location:	Sokndal, Norway
Year of Completion:	2000
Structural system:	Three-hinged, glulam arch-es with a suspended, partly elevated bridge deck
Bridge deck:	Stress-laminated timber deck, supported by steel crossbeams and vertical steel suspension ties
Total length:	34,2 m
Span:	3,5 + 19,4 + 5,5 + 4,0 m
Clearance:	4,0 m
Wood quantity:	68,0 m^3



Name:	Daleråsen Bridge
Location:	Mjøndalen, Norway
Year of Completion:	2001
Structural system:	Two glulam arches with a suspended partly elevated bridge deck
Bridge deck:	Stress-laminated timber deck
Total length:	68,9 m
Span:	32,6 + 27,4 m
Clearance:	5,0 m
Wood quantity:	150 m^3



Name:	Hanskemaker (Tinder) Footbridge
Location:	Verdal, Norway
Year of Completion:	2000
Structural system:	Two continuous beams in three spans
Bridge deck:	Transverse timber beams with plank pavement in the middle and steel grating in the driving tracks
Total length:	51,6 m
Span:	21,5 m
Clearance:	3,0 m
Wood quantity:	30 m^3
Total price:	1,78 mill. Nok

Name:	Kjørem Bridge
Location:	Kvam, Norway
Year of Completion:	2000
Structural system:	Three-span plate
Bridge deck:	Stress-laminated timber deck with an asphalt wear-ing surface
Total length:	26,0 m
Span:	8,0 + 10,0 + 8,0 m
Clearance:	4,0 m
Wood quantity:	50,0 m^3
Total price:	2,0 mill. Nok

Name:	Mattisdammen Bridge
Location:	Nord-Odal, Norway
Year of Completion:	2000
Structural system:	Simply supported plate
Bridge deck:	Stress-laminated timber deck
Total length:	7,2 m
Span:	7,2 m
Clearance:	8,1 m
Wood quantity:	27,0 m^3
Total price:	1,0 mill. Nok

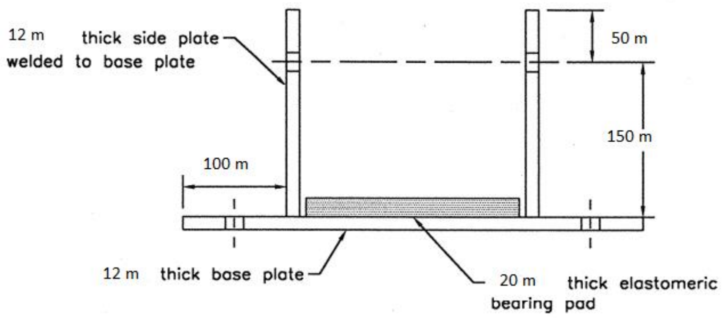
Name:	Nesoddveien Footbridge
Location:	Nesodden, Norway
Year of Completion:	1999
Structural system:	Glulam truss bridge with parallel chords
Bridge deck:	Partly elevated stress laminated timber plate, supported by steel cross beams and vertical steel suspension ties fixed to the upper chord.
Total length:	24 m
Span:	24 m
Clearance:	3,0 m
Wood quantity:	40,0 m^3
Total price:	2,7 mill. Nok

Name:	Tynset Bridge
Location:	Tynset, Norway
Year of Completion:	2001
Structural system:	Three-hinged arches supporting small spans. Two-hinged truss arches – long span. Both systems with a suspended deck.
Bridge deck:	Stress-laminated timber deck
Total length:	124 m
Span:	27,0 + 27,0 + 70,0 m
Clearance:	10 m
Wood quantity:	600 m^3
Total price:	25 mill. Nok

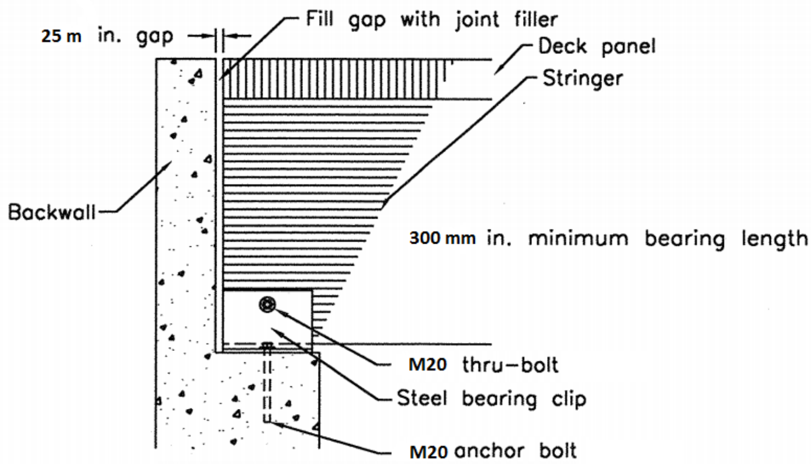
Name:	Merirahu Bridge
Location:	Tallinn, Estonia
Year of Completion:	2000
Structural system:	Two three-hinged arches tilting towards each other with partly suspended deck
Bridge deck:	Longitudinal glulam beams and transversal solid wood planks
Total length:	35,6 m
Span:	24,0 m
Clearance:	6,3 m
Wood quantity:	27,2 + 23,3 m^3
Total price:	172 600 euro

Solution of the connection used in case study

All steel parts of the connection shall be galvanized. Glulam beams shall be preserved by Pentachlorophenol or Copper Naphthenate.

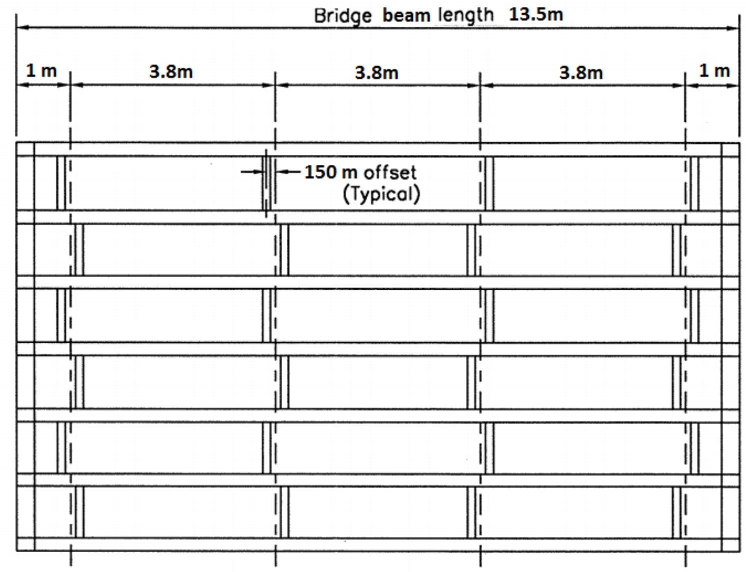


Steel Plate Bearing Shoe
End view



Concrete Substructure Connection
Side view

Glulam Diaphragm Layout



Plan view

Diaphragm-to-Stringer Connection