Timber bridges: General issues, with particular emphasis on Swedish typologies

Holzbrücken:
Allgemeine Themen, mit besonderem Schwerpunkt auf schwedische Typologien

Ponts de bois:
Questions générales, avec particularmente l'accent sur la typologie suédois

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1. Short historical overview of timber bridges

Until the first half of the nineteenth century, wood was one of the principal materials used in construction. Especially after the sixteenth century, bridges of considerable engineering interest were executed using wood. Wooden bridge were often used to overcome obstacles such as rivers, roads or valleys that sometimes also required considerable spans. Among the best known examples of this type of structures built between the sixteenth and nineteenth century, the following bridges can be mentioned:

- The bridges Andrea Palladio (XVI century), the great architect / engineer of the Italian Renaissance. Example: bridge of Bassano del Grappa, later renamed "Ponte degli Alpini", see Figure 1.

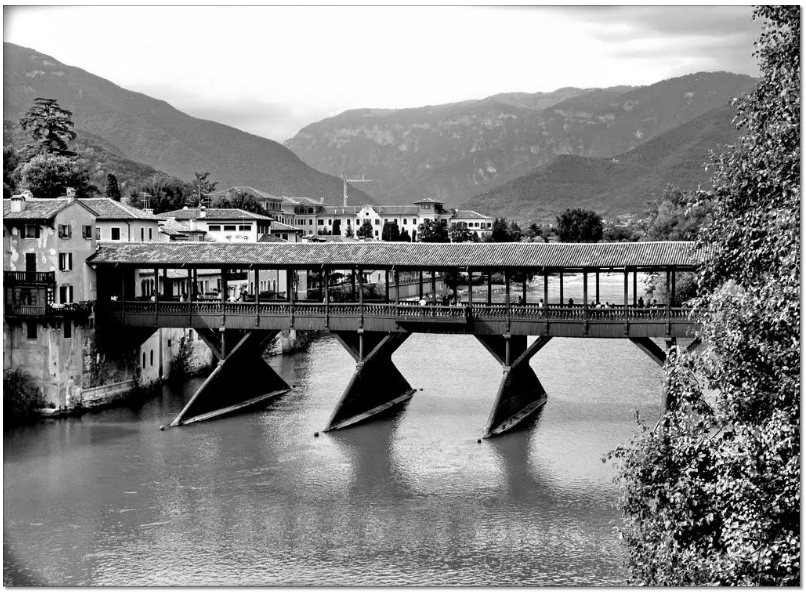


Figure 1: Ponte degli Alpini in Bassano del Grappa, IT.

- The works of two talented Swiss carpenters, the brothers Johannes and Hans-Ulrich Grubenmann (XVIII century), who built wooden bridges with spans never seen before. Example: Rheinbrücke in Schaffhausen built 1755 – 1758, Switzerland, Length: 120m, in two spans, see the model in see Figure 2.

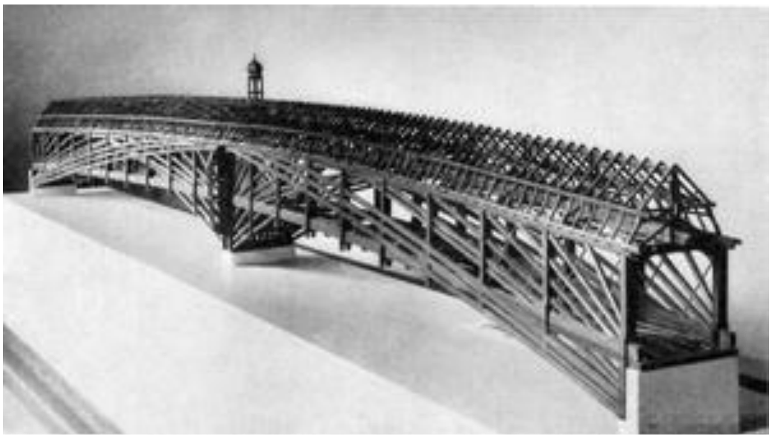


Figure 2: Model of the main structural members of the Rheinbrücke in Schaffhausen, CH.

- The spectacular railway bridges by Isambard Kingdom Brunel (XIX century), one of the greatest British engineers of all times. Example: railway bridge at Moorswater, Great Britain, total length 290 m, height: 45 m, see Figure 3.

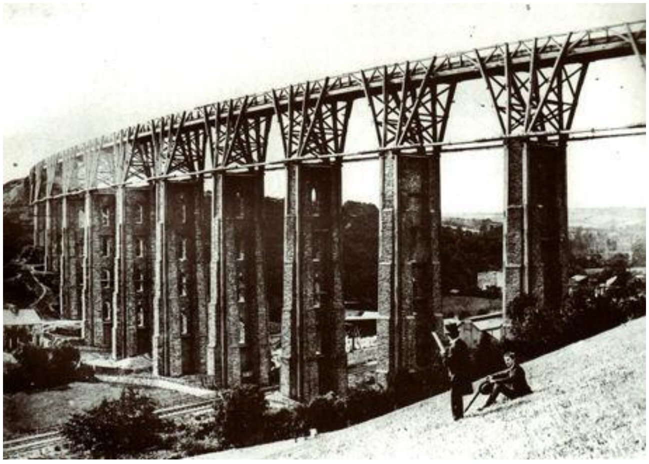


Figure 3: Railway bridge at Moorswater, UK.

From the second half of the nineteenth century onwards, with the advent of steel and reinforced concrete, wood began to be removed from the knowledge of the builders and designers.
However, since a couple of decades, in many European countries there has been a "renaissance" of wood as a building material for bridges. The reasons for this renaissance are probably to be sought in the development (and sometimes in the rediscovery) of:

- New wood-based materials such as Glulam, LVL (Laminated Veneer Lumber), CLT (Cross Laminate Timber), etc.
- New types of connectors and connections, for example self-tapping screws, connections made by means of slotted-in plates and dowels, etc.
- New methods of wood protection, both chemical and structural-constructive

Timber bridges with large very large spans were constructed over the past 10-15 years. Two representative examples of large-span timber bridges recently built in Scandinavia are:

- the two-hinged trussed arch bridge for road traffic at Tynset, Norway, with a central span of 70 m
- the cable-stayed structure for pedestrian traffic in Skellefteå, Sweden with span of 130 m

Figure 4: Left: two-hinged trussed arch bridge at Tynset, NO. Right: cable-stayed bridge over the river Älvsbacka in Skellefteå, SE.

2. The Nordic Timber Bridge Project

The revival of the timber bridge in the Nordic countries is a result of the Nordic Timber Bridge Project which was carried out in three phases from 1994 to 2001. The main objective of the program was simply to increase the competitiveness of timber as a bridge material compared with concrete and steel. The program was a joint effort by Finland,

Norway and Sweden. Denmark did also participate in the two first phases of the project, and Estonia was an observer throughout the project period.
The project was financed by timber industry and road/bridge authorities(50%), Nordic Industrial Fund and Nordic Wood (30%) and National research funds (20%). The total project was divided into about 20 sub-projects covering the whole area, from market research and economy to structural design and durability. Each sub-project produced its own report. Three Nordic Timber Bridge Conferences were organized as well as a number of national workshops and seminars. A number of papers and articles were published at conferences, magazines, periodicals and newspapers. An important outcome of the project was the emergence of a limited number of dedicated enthusiasts who managed to overcome some deeply rooted scepticism and were able to complete a couple of successful pilot projects [1].

3. Pros and cons of timber bridges

It should be remembered that - depending on the circumstances – all types structural materials, e.g. steel, concrete or timber, may be more or less appropriate for the construction of a bridge. In general, factors such as the geometry of the deck, the geomorphologic land geological characteristics of the ground, achievability of material, etc, determine what type of material is more appropriate for the construction of a bridge.
There are, however, some unique aspects that sometimes make a timber bridge more suitable than for example bridges made of steel or reinforced concrete. They are:

- Quick and easy assembly
- Ease of manufacturing/production
- Exceptional strength in relation to its mass density
- Aesthetic
- Ecological aspects
- Simplicity of realization of the expansion joints
- Cost of material (generally lower than the cost of other construction materials, especially in case of curved geometries)
- Excellent resistance to salt used to melt ice and snow
- Etc.

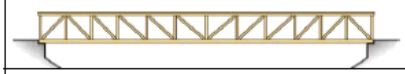
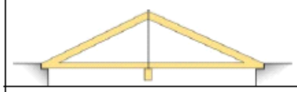
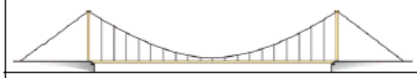
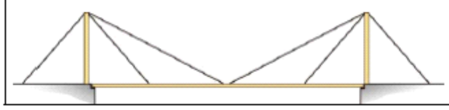
There are, obviously, also a number possible "cons" concerning the use of timber as a building material for bridges, e.g:

- Low durability, if the wood is not properly protected from the weather and possible insects. (Protection of timber should primarily be performed e.g. by fixing protective wooden boards or metal sheets around the load bearing parts especially at the end-grain zones and on horizontal surfaces of beams)
- Risk of fire (wood is a combustible material)
- Poor shock resistance, for example due to a possible vehicle collision
- etc.

4. Structural types

The structural type most suitable for a wooden bridge designed to overcome a specific obstacle (such as a road or a waterway) often depends on factors such as: the span length, the type of obstacle to be overcome, possibility of access crane or other lifting machines, free height, type of traffic expected, etc.
The aesthetic aspect should not be overlook neither: the structural typology should respect the fact specific architectural style of the area and, above all, to be in harmony with the surrounding landscape.
The bridge deck typically consists of beams or a deck plate. For longer spans the bridge deck can be complemented by other structural parts. Different bridge types such as trusses, arches, cable stayed bridges and suspension bridges can be used for both road and bridges and pedestrian bridges. Some structural types of wooden bridges are shown in Table 1.

Table 1: Some typical structural types for timber bridges (adapted after [3]).

Bridge type	Structure	Typical span (m)
	SLTD (*)	0-25
	Beams	0-30
	Truss	15-70
	King Post	10-50
	Strut Frame	20-40
	Beam on V-supports	20-75
	Arch	30-70
	Suspension (**)	50-200
	Cable-stayed	40-100

(*): Stress Laminated Timber Deck
(**): For longer spans a heavy deck or prestressing of the main cables by means of a secondary cable system is normally required in order to limit displacements and vibrations

5. Typical superstructures for timber bridges used in Sweden

5.1. Beam bridges

In beam bridges the beams are the main structure. For other bridge types beams can be combined with additional structures such as arches or struts, see Table 1. The beam bridges are often constructed with glued laminated beams located below the bridge deck and with transverse or longitudinal plank decks. The traditional beam bridge typically consists of the main beams, cross beams, transversal bracing, transverse floor beams and a plank deck. This type of bridge is suitable for pedestrian bridges, but also small road bridges. The glued laminated beams are usually manufactured with a pre-camber so that the bridge is slightly curved. Beam bridges have a simple static system and they are easy to manufacture and build. The beams must be transversely braced to provide lateral strength and rigidity [3]. Normally, bracing is achieved by means of a horizontal truss between the main beams, placed in the upper part of the beams. The truss takes the wind loads across the bridge and it also restrains the beams against lateral buckling. The bridge decks are normally open plank decks, but also glued laminated panels or other wood panels can be used together with a waterproofing layer under the wearing surface.

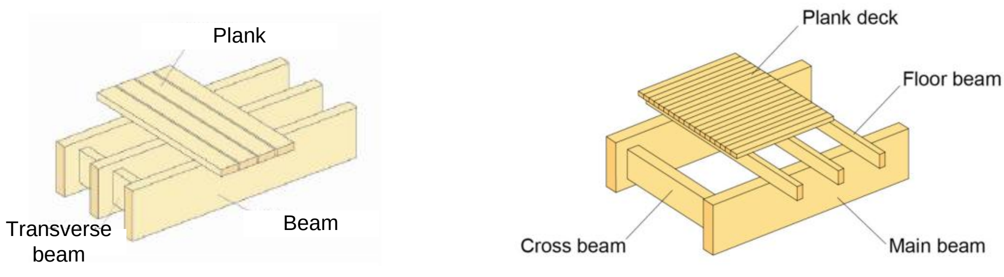


Figure 5: Typical deck types for timber bridges [3]

The depth and the number of beams depend mainly on the span of the bridge and the width of the deck. For pedestrian bridges with width up to 2.5 m, two longitudinal beams are normally sufficient to support the deck, respectively. For greater widths, up to 4 m three or more longitudinal beams will normally be necessary. As regards the depth of the beams, indicatively, for simply supported bridges for pedestrian traffic, it should be in the following ranges:

- approximately 600-800 mm for span of ~10 m
- approximately 1200-1400 mm for span of ~20 m

5.2. Deck superstructures

Stress Laminated Timber Deck, or simply "SLTD" are among the most widespread deck superstructures for timber bridges in Sweden.

The basic idea is shown schematically in Figure 6. Timber laminations (planks of structural timber or glulambeams) are stacked, side by side, in the full width of the deck, and pre-stressing rods, through pre-drilled holes at regular intervals, will, when stressed, make the assembly of laminations behave like an orthotropic plate.
Laminations are of limited length (generally less than 30 m), and they therefore need to be joined, butt to butt, see Figure 6. According to [8], not more than one butt joint shall occur in any four adjacent laminations within a length l_1 defined as the minimum value of2*d*, 30*t* and 1.2 m (where *d* is diameter of the pre-stressing bar and *t* is the width of the laminations)

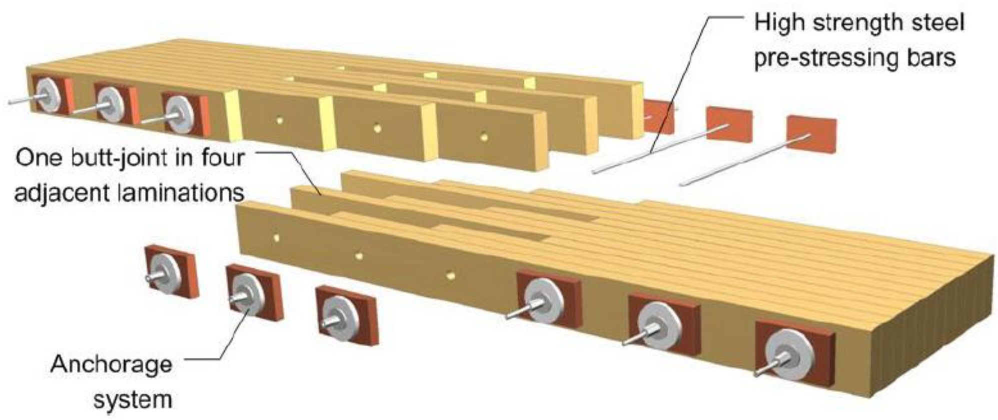


Figure 6: Components of a Stress Laminated Timber Deck (SLTD)

Typically, spacing between pre-stressing bars is between600 to 900 mm. Generally, if the deck thickness exceed 500m, two or more pre-stressing bars are placed in column (one on the top of the other) to distribute the compressive stress in a uniform manner. The common practice is to use high strength steel bars($f_y \geq$ 1000 MPa) of diameter *d*=20 mm.
In Sweden, most of the timber road bridges built during the last decade have stress laminated timber decks, in which the laminations are untreated glulam beams with dimensions 90 mm (or at times 115 mm) by (at least) 315 mm. The relatively large minimum thickness (315 mm) is required in order to achieve an adequately stiff connection of the railing posts.
From the static point of view the pre-stress is particularly effective in the case of presence of concentrated loads orthogonal to the plane of the deck, such as loads due to vehicles tyres. In this case, in fact, besides bending moments and shear forces typical of beam structures, transverse shear and moments (and to a lesser extent also torques) typical of the plate structures also are generated in the timber deck. The transversal compression generated by the pre-stressing bars in the deck has two fundamental effects: *i*) to take the transverse shear stress through the friction that occurs between the laminations, *ii)* to take the tensile stress generated by the transverse moments [9], see Figure 7.

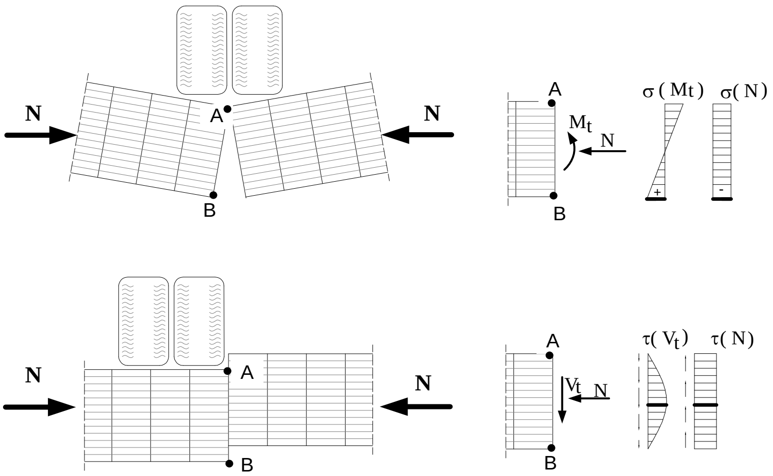


Figure 7: Possible failure modes and correspondent resistance mechanisms of SLTD

The initial pre-stress results in a normal stress between the laminations of approximately 1MPa. The pre-stressing needs normally to be performed 3-4 times before the level of tension in the bars has stabilised. It has been shown by laboratory testing that as long as tensile stress in the bars does not drop below 40 % of its initial pre-stress, the SLTD will performs satisfactorily. Most of the SLTD built in Sweden after year 2000 have not shown significant loss of pre-stress, therefore there has been no need of re-stressing the bars.

The design of SLTD can be performed using the theory of orthotropic plates, and then solving the system of differential equations by numerical methods, for example using the finite element method or, more simply, by the use of simple calculation models.
Among the simplified models there is that of the EN 1995-2 (2004); the dimensioning of the deck in this case is reduced to the calculation of a beam having the depth equal to the thickness of the deck and an "effective width", generally less than the actual width of the deck.
One might be drawn to think that SLTDare not very optimal from the point of view of a rational use of wood. However, there are a number of important advantages with this kind of bridge deck, among which are: a) simplicity and speed of manufacturing, b)ease of transport and assembly, c) adaptability to complicated geometries, even with the horizontal curvature of the roadway, see Figure 8, d) durability, especially due to the ease with which the deck can be protected[9].

Figure 8: Arch Bridge with deck type "SLTD" at Tomasjord, near Tromsø, Norway. Note the horizontal curvature of the deck.

Moreover, it should not be neglect the fact that, thanks to the excellent dimensional stability of the SLTD, there is normally no significant moisture induced expansion or contraction of the deck. Thus, the risk for possible cracking of the waterproofing membrane and consequently problems related to water infiltration are minimised.

Another interesting bridge deck used in some Swedish pedestrian bridge consists of a plate made of cross Laminated Timber Veneers (LVL) glued on the top of two or more longitudinal glulam beams. Typically, the deck thickness is 126 mm. Due to the composite action of the deck with the underlying glulam beams, the system has a significant stiffness. One drawback for this type of deck is the limited resistance to "rolling shear," which could cause failure of the LVL in case of high concentrated loads [5], see Figure 9.

Figure 9: typical failure due to "rolling shear" in a cross laminated veneer lumber plate.

6. Structural details

6.1. Connectors and joints

The correct conception of the connections in a bridge is essential both to ensure sufficient load-bearing capacity and to ensure adequate durability.
Nails, bolts, dowels and screws are connectors typically used in most joints for timber structures. In the design, in addition to the ultimate resistance, stiffness of the connections is an important issue. A low stiffness of the connections, for example, could result in excessive deformation of the bridge and, in the case of compressed elements, even in a possible reduction of the bearing capacity due to second-order effects. In the case of road bridges the strength of the connection to cyclic loading (possible fatigue failure of the steel parts) need also to be checked.

When it comes to transmission of high forces between elements, the connections that are commonly used are:

- Connections with bonded-in rods, typically used for the transmission of axial forces
- Connections with inclined screws, typically used for the transmission of shear forces
- Connections with slotted-in plates and dowels, typically used for the transmission of both shear and axial forces.

The connections with slotted-in plates and dowels are particularly used in structures subjected to very large forces, for example in truss nodes (Figure 10). These connections also have satisfactory fatigue resistance.

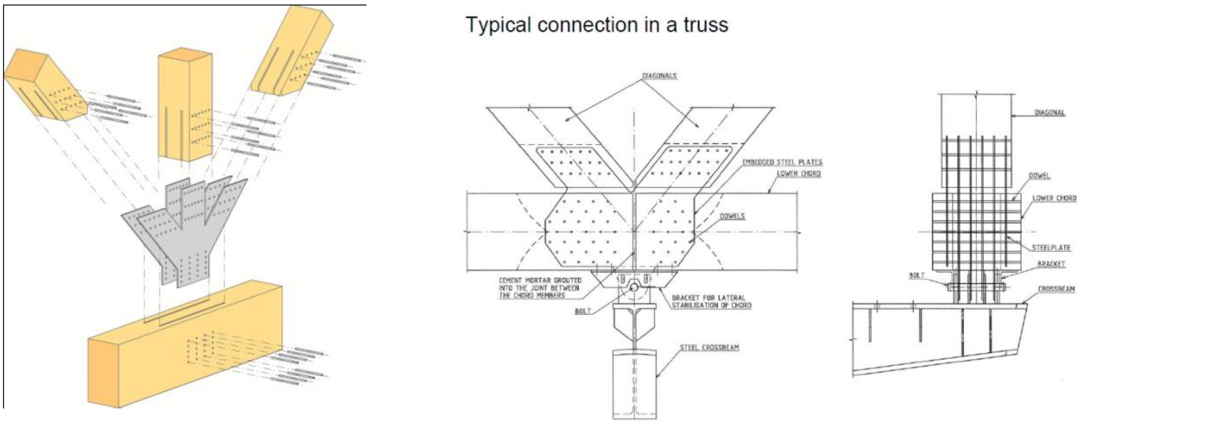


Figure 10: Connection with slotted-in plates and dowels. Left: Exploded view of a typical connection. Centre: Elevation of a truss node (timber lower chord, timber diagonals and steel hanger). Right: Cross section of another truss node(timber lower chord, timber diagonal and cross beam of steel).

6.2. Railings

Railings are usually made of wood or steel, see Figures 11.Besides load and safety requirements, railings must also comply with requirements regarding e.g. minimum height and spacing of the various components. Especially for pedestrian bridges there are recommendations for clearance between the posts and clear distance between parts. This means that if the dimensional requirements are met, the railing is designed so that it cannot be climbed. In addition, the aesthetic design is of great importance for railings, especially for pedestrian bridges [3].

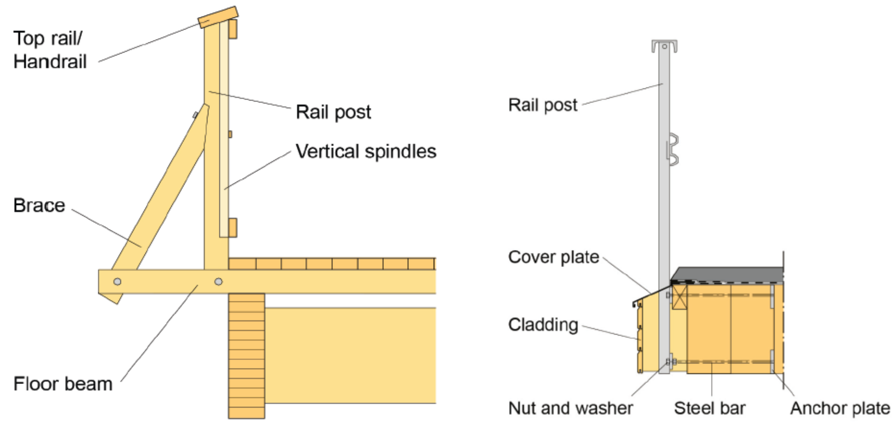
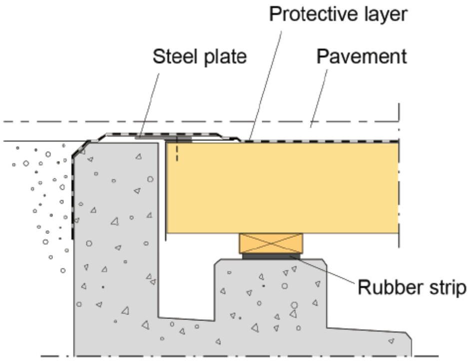


Figure 11: Cross section of two bridge types. Left: Wooden railing on pedestrian bridge. Right: Steel railing on road bridge.

To carry all forces from the superstructure into the substructure and to allow necessary superstructure motions to take place bearings are typically utilized in bridge structures. They must be designed to withstand both i) downwards and upwards forces (due to gravity loads and uplift, respectively), ii) longitudinal forces (e.g. the force caused by the braking of a vehicle) and transverse forces (e.g. the action of the wind). Normally, at least one support will be immovable (i.e. a fixed bearing, which prevents longitudinal movements) and the other of movable (i.e. a sliding bearing, which allows for longitudinal movements). In timber bridges, the he sliding bearing is normally achieved by introducing horizontal oval holes in the metal plates used as a connection between wood and concrete. On the other hand, the holes at the fixed bearings are circular with hole diameter approximately 2 mm greater than the diameter of the connectors.

In general, for the transmission of vertical forces in bridges, suitable bearing devices, often rather complicated and expensive (e.g. pot bearings or similar devices)are adopted. In the specific case of timber bridges, however, the bearings are, in general, much simpler. It is often sufficient to interpose a simple rubber mat between the beam (or the deck) and the top of thee abutment or pier, see Figure 12, left.

The movements in the longitudinal direction of timber bridges are usually very small. Therefore, for these bridges also the expansion joints are in most cases much simpler and therefore much less onerous of the joints used in bridges of steel or concrete, see Figure 12.



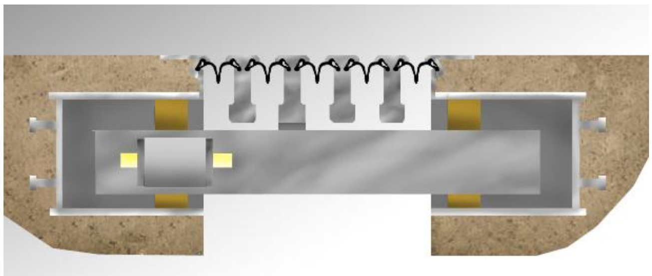


Figure 12: Left: Detail of the support of a timber bridge (note the simplicity of both bearing and expansion joint). Right: typical expansion joints for large movements suitable for steel bridges and concrete bridges.

7. Durability

Several timber bridges made hundreds of years ago and survived to the present day show that, if used in a correct manner, wood has a very good durability.
The durability of a timber bridge depends on the type and quality of the timber. Structural timber in the Nordic countries is, almost exclusively, limited to spruce and pine. Larch, which is believed to be more durable species, is used, but not nearly as much as e.g. in Germany, Austria and Switzerland. Tests carried out in Sweden and in Norway seem to indicate that heartwood of larch is rather durable, but not significantly more durable than heartwood of e.g. pine. Sapwood of larch, on the other hand has low durability. The main difference between larch and pine is that the heartwood part in the former is normally larger than in the latter.

It should not be forgotten, however, that all wood species, as organic products, are subject to the destructive action of time. Therefore, timber load-bearing members of a bridge should always be equipped with adequate protection. In general, there are two methods to protect a timber bridge, namely:

- Chemical protection
- “Mechanical” protection

As a general rule, it should first be remembered that it is always necessary – when possible – to take all measures to protect the timber by means of “mechanical” protection. Complementary to such a protection, chemicals may also be used to further enhance the durability of the timber bridge.

The chemical protection is obtained by use of suitable preservatives. The chemical treatment makes the wood unsuitable for the settlement and growth of destroying organisms: for example, preventing the fungal spores, which are always present in the air, to develop when they come in contact with the wood. The effectiveness of treatment, besides the nature of the active ingredient of the preservative, depends on the amount of substance absorbed by the wood and also on the penetration depth of the preservative. The absorption and penetration are dependent on the wood species, the type of preservative and by the methods of application (i.e. with or without pressure). Normally, the treatments are performed in vacuum pressure impregnation autoclave and ensure good penetration of the preservative on wood species easily impregnable, e.g. pine. Recently, under the new laws related to the prohibition of the use of preservatives based on salts of arsenic and chromium, the treatments are normally carried out using a pressure organ metallic compounds with the copper.
However, the best method, and the method which is always recommend to protect load bearing members of a timber bridge, is the “mechanical” protection together with an

accurate design of structural details and connections. This is demonstrated by a number of timber bridges built hundreds of years ago and still in service with wood species with low natural durability (e.g. spruce or pine), see Figure 13.

Figure 13: Ponte Timber bridge over the river Finn at Loom, Norway. Note the meticulous protection of the building structural load-bearing parts. The bridge is more than 100 years old.

The "mechanical" protection essentially consists in covering all the load bearing members of the bridge (and possibly its connections) with secondary wearing elements, for example, boarding and/or sheet metal. The purpose is to preserve the structure of the bridge from the direct action of sunlight and water, as well as to ensure an adequate ventilation.

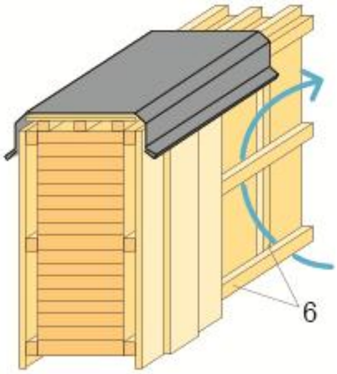


Figure 14: Left: principle of "mechanical" protection of a timber load bearing member by means of wearing planks at sides and metal sheet on top. Right: example of a timber bridge near Stockholm, Sweden; note the mechanical protection of the arches and of the deck.

8. References

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