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Three-dimensional Visualization and Connection Assessment of Roofed Lumber Footbridges

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Abstract: An installation of a covering, such as a roof or shell, can help a bridge become more durable and last longer. In Sweden, there is now just one historic covered bridge, the Vaholms bridge, despite the fact that other timber bridges have been constructed recently. Since the design ofthe connections has a significant impact on the structure's performance, wood can be considered a more competitive structural material for bridges than steel or concrete. Although connections are typically described as either pinned or fixed, their degree of fixation is really intermediate. Over dimensioning of the structural parts or the connections themselves results from failing to take the degree of fixation into account during the design process. The degree of attachment might be taken into consideration to minimise needless over-dimensioning. A 30-meter-long covered timber bridge for bicyclists and pedestrians is the focus of this master's thesis project. Flårback (2015) was responsible for the architectural and conceptualdesign of this bridge. The purpose of this thesis was to propose a bridge roof connector design of one kind. The experiment also sought to determine how the semi-rigid connection's rotational stiffness affected the bridge's structural behaviour. In order to accomplish the goals, the bridge was 3D-modeled using the Dassault Systèmes finite element modelling (FEM) programme Abaqus, and its performance was structurally analysed in both the ultimate limit state (ULS) and the serviceability limit state (SLS).

***Keywords**: experiment, serviceability, architectural, bicyclists*

1. Introduction

Human history is replete with instances of bridging hurdles. The ability to span rivers or ravines may have originated from naturally falling trees. In time, a more methodical approach to navigating the terrain's challenges involved the usage of logs. Bridges' original purpose as utilitarian objects evolved into an object of construction as bridge building techniques advanced. Bridge construction currently takes into account a variety of factors, including technical, artistic, and craftsmanship considerations. Due to its versatility and widespread availability, wood became an increasingly essential building element.

Many timber bridges were constructed between the middle ages and the 1800s, which led to the creation of various arch and truss forms. Covered timber bridges date back to the 1700s and were constructed in Nepal and India by the 1800s, a huge number of wooden bridges with large truss constructions were constructed and eventually became commonplace. Withthe rapid advancement of transportation and technology in the late 1800s and early 1900s, steel and concrete soon supplanted lumber as the primary building material for bridges. Nonetheless, some nations continue to build bridges using wood as the building material. More than 200 timber bridges can be found in Nepal and India, with a large number dating from the Middle Ages, particularly in Switzerland. The fact that historic timber bridges are covered is the reason so many of them still stand today. years has led to a greater understanding of their benefits as compared to alternative bridge kinds. In terms of pedestrian and bicycle bridges as well as overpasses designed to handle high traffic, timber bridges perform and last technically equal to bridges composed of steel and concrete. The advancement of wood materials and construction techniques has allowed timber bridges to fulfil the specifications of contemporary bridges. The 1990s saw the development of glulam, which allowed for the production of larger beams and longer spans for girder bridges. In addition, compared to other types of bridges, the time required to assemble a timber bridge is typically lot shorter, and the material is highly

2. Methodology

In order to ensure the structural integrity of wooden constructions, timber connectors are anessential component of construction. To firmly link wood members, they use a variety of techniques include mechanical fasteners, adhesive bonding, conventional joinery, and metal connectors. These connections allow for mobility and environmental conditions while efficiently distributing loads. In buildings and other wooden structures, long-term stability and safety depend heavily on well-planned and implemented timber connections. It takes routine maintenance and inspections to find and fix any problems that can develop over time.

Upper row from left: *half lap joint, regular scarf joint, dovetailed scarf joint.*
Middle row from left: *table scarf joint, double lap joint, half lap joint with tapered shoulders.*
Lower row from left: *scarfed finger joint with dovetail fingers (fingers along width), Scarfed*

2.1 Framing connections

Framing is the process of joining pieces at an angle to one another, such as at intersections or corners. There are several techniques to do this forms like the letters T, L, and X or other forms can be created by connecting elements end-to-end, end-to-face or face-to-face, perpendicularly or obliquely (Woodworker Series, 2003). Figure provides descriptions of several connection kinds.

Frame connections can be made using simple lap joints of various forms, such as notched joints and single, double, or dovetailed half laps, in a manner similar to the extending connections previously discussed. As with a table top junction, the bearing faces, also known as shoulders, can be angled, as in dovetail connections, or straight. Beyond the directions secured by the straight shoulders (the transverse direction of the protruding element), the inclination of the shoulders in the dovetail connection generates an interlocking, locking yetanother direction of motion (the axial direction of the protruding element). It is possible to secure elements without axial interlocking using adhesives, transverse fasteners, or extra wedges.

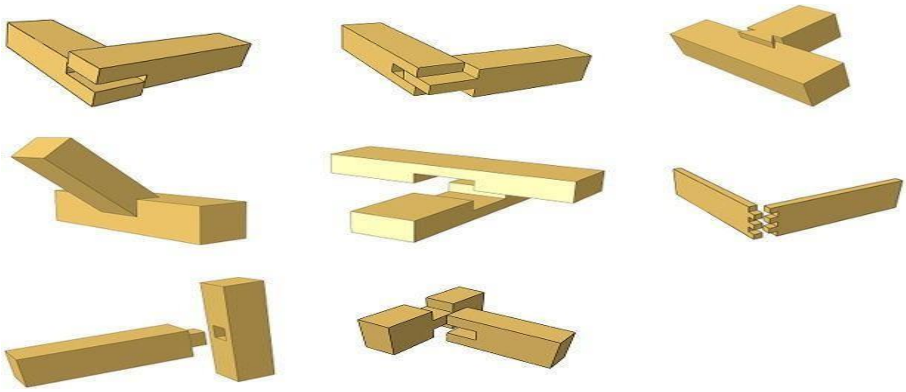

Figure 2.1 Framing connections

2.2 Modelling connections

Due to the non-linear load-deformation behaviour in connections caused by factors like plasticity and gaps in predrilled holes, as well as the heterogeneous characteristics of timber,performing very precise structural studies of a jointed timber structure can be challenging (Engström, 1994). Typically, the joints are represented as fully pinned or perfectly fastenedin order to simplify the process. Assuming that all connections are precisely hinged, rotations are permitted but moments are not transmitted, leading to an effective use of material because the elements work solely in tension or compression rather than bending, although their moment peaks are substantial. Assuming complete fixity, connections permit no
rotations and moments to be communicated via them. This results in elements acting inbending, which is

less effective than acting in pure tension and compression but produces amore uniform distribution of moments (see Figure).

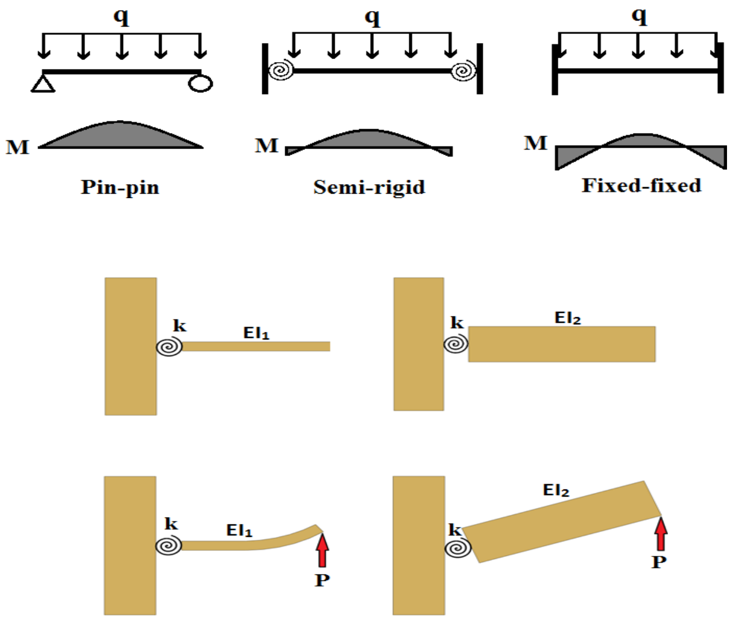

Figure 2.2 Moment distribution for a beam with different support connections

2.3 Structural behaviour

Below is a presentation of the bridge's structural performance under simply vertical loads. The major arches and the truss system are the two competing load-bearing mechanisms of the bridge. Figures 4.3 and 4.4, respectively, depict the force pattern of the axial sectional forces of the deck and the roof, respectively. With the exception of the cables, Figure 4.5 depicts the overall bridge's axial sectional force distribution. Since the cables' axial sectional force could not be shown in Abaqus, the figures are obtained from the Abaqus model. It wasnecessary to plot the axial stress (S11) in order to see the forces in the cables.

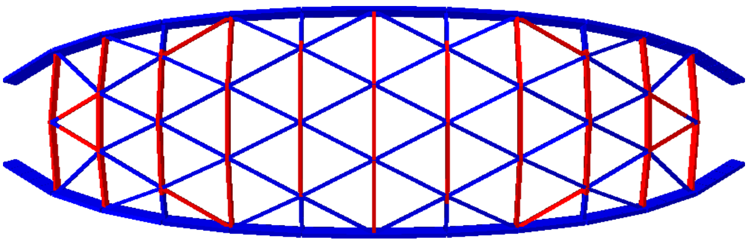

Figure 2.3 Force pattern in the roof structure. Blue = compression, red = tension.

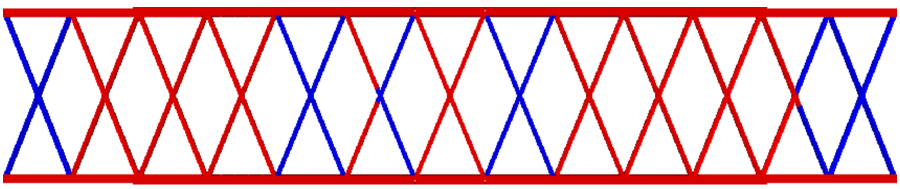

Figure 2.4 Force pattern in the floor structure. Blue = compression, red = tension.

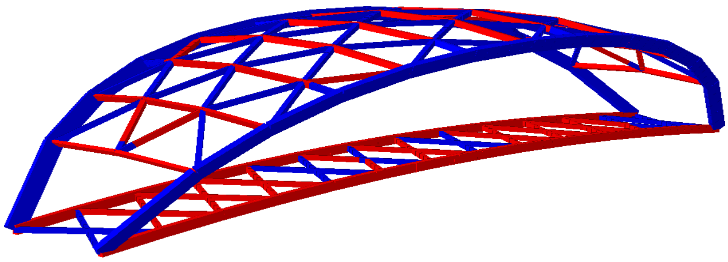

Figure 2.5 Force pattern in the entire bridge. Blue = compression, red = tension.

3. Analysis of Bridge

3.1 Numerical Analysis of the *Leaf Bridge*

With the aid of the finite element programme Abaqus/CAE (Dassault Systèmes), numerical linear studies were carried out to look into the performance differences of the bridge between perfectly and partly fastened connections. If the strain is kept below 5%, a linear analysis may be assumed. Given that lumber has a far smaller capacity than its Young's modulus, a linear analysis is the likely outcome.

When the bridge construction was first modelled, its connections were precisely pinned and fastened. The objective of the numerical analysis was to extract stresses from the elements and verify utilisation ratios after performing an SLS analysis to check maximum deflections and adjust element dimensions if the SLS limits of deflections were not met. There was no attempt to further enhance the structure in order to meet the ULS limitations. The connections were then built to meet ULS criteria using the element stresses from the ULS analysis as input values. Following the design of the connections, the rotational stiffness of the connections was computed, added to the Abaqus SLS model, and fresh studies were conducted. The elements' stresses and deflections from the updated analysis were verified and contrasted with those from the original analyses. Furthermore, the effect of the degree of fixation, ranging from 0% to 100%, on deflection was examined.

Three bars make form the truss, and they are fastened to the supports and to one another. The place where the components converge is subjected to an 80 kN point load. Every element has a 200 GPa Young's modulus. Table 4.1 displays the respective element's lengths and cross sectional areas. Figure 4.2 depicts the structure's deflected form as a result of the load.

Table 3.1 List of length and cross sectional area of the elements.

	Element 1	Element 2	Element 3
Length [m]	1,6	1,2	2,0
Cross sectional area [m2]	$6{,}0 \cdot 10^{-4}$	$3{,}0 \cdot 10^{-4}$	$10{,}0 \cdot 10^{-4}$

Table 3.2 List of all cases and their model type, element type and connection type. OP = one part, MP = multiple parts.

Case	Model	Element type	Connection type
1	Task in book	Unknown	Pinned
2	OP	Truss	Pinned
3	OP	Beam	Fixed
4	MP	Truss	Pinned
5	MP	Truss	Fixed
6	MP	Beam	Pinned
7	MP	Beam	Fixed

Additionally, a type MPC beam connection was tested, although in this model, the element also broke. This suggests that it is not possible to repair truss members. Tied connections will act like pinned connections even if they are applied to the structure.
Another finding is that the system's balance is confirmed by adding the reaction forces RF1, which equals zero, and RF2, which equals the entire load applied.
Furthermore, it is evident that the deflections derived from the MP-truss-pinned and OP- truss-pinned models are identical. Additionally, there is no difference in the deflections derived from the MP-beam-fixed model and the OP-beam-fixed model. This finding confirms that there is no difference in performance between utilising a single-part model anda multi-part model that requires human connection.

4. Result & Discussion

The next sections provide the final element dimensions, the findings from the SLS and ULS studies, and an assessment of how applied rotational spring stiffness affected the deflections.

Table 4.1 Old dimensions and new dimensions, altered to satisfy SLS limit.

Component	Old dimensions	New dimensions
Arches	405 x 215 mm	630 x 215 mm
Roof curved beams	245 x 140 mm	270 x 140 mm
Roof truss beams	225 x 140 mm	225 x 170 mm
Edge beams	180 x 90 mm	405 x 215 mm
Deck truss beams	180 x 90 mm	225 x 140 mm
Cables	Ø 19mm	Ø 30 mm

4.1 Influence of rotational stiffness

The figures below show the resulting deflections in the deck for different rotating spring stiffness for all load scenarios. Depending on the direction the wind force is acting, the load instances are grouped. Figure 2.1 displays the findings for the load situations with vertical windload, whereas Figure 2.2. The findings for the load instances with horizontal wind loads in thelongitudinal and transverse directions, respectively, are displayed in 2.3. For load scenarios including the presence of the service vehicle's vertical load, there is an additional group. The deflections arising from the rotating spring stiffness computed from the connection design are indicated by the diamond marks. Asobserved in the images, because these joints are located on the inclination of the curves, they may be classified as semi-rigid due to their rotational stiffness.

4.2 Connections in timber structures

Because wood is not as strong as other materials like steel and concrete, connecting pieces in wooden constructions can be difficult to design, particularly for those that are subjected to heavy loads. Since wood is brittle, the goal is to establish a connection with a ductile behaviourin which the failure happens in the fasteners rather than the wood itself. The fasteners must beweak enough to break before the timber in order to do this. A connection must be robust enoughto support the loads it is subjected to at the same time. The strength of the entire connection will rise with more fasteners, but this will also result in an increase in size, which is not always ideal. The dimensions of the components are often determined by the size of the connections. Over-dimensioning of the elements is caused by the necessity to increase their size in order to fit the connections. More effective connections can be used to lessen over-dimensioning.

5. Conclusion

- To help and expedite the 3D modelling process, more resources and lessons about intricate 3D modelling in Abaqus are required.
- The dimensions of the components may be determined by the size of the connection.
- The stiffness of the connecting parts affects the joint stiffness even with a constant rotational spring

stiffness.

- More effective connections that lessen element over-dimensioning and so save material, money, and environmental effects are required to boost the competitiveness of lumber as a structural material for bridges.

The following should be investigated further:

- Analysis and proposal of alternative connection design types.
- Bridge dynamics including semi-rigid connections.

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