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Wood Research & Development

Viability of Modern Timber Highway Bridges

May 3, 2019

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Timber is among the oldest materials used in bridge construction, and is still widely used today, especially for short and medium span bridges. However, in the second half of the 20th century, the use of timber was largely displaced by steel and concrete, and there is a current perception among many bridge designers and highway officials that timber is no longer a viable option for large-scale highway bridge projects. This perception is largely based on concerns about life span, maintenance costs, load capacity with longer spans and susceptibility to decay (Smith, Bush, & Schmoldt, 1995). These concerns typically stem from past experience with bridges constructed in the mid twentieth century where design/construction techniques employed very poor details such as vertical fasteners that originated from the top surfaces of timber bridge elements. These vertical fasteners are responsible for the vast majority of the timber bridge degradation that is experienced today. Vertical fasteners allow moisture to gain access to bright center zones of the heavy dimension timbers where treatments aren't typically found. Moisture contents over 22% lead to decay from the inside out as the interior moisture can't evaporate quickly from the center zones of the heavy dimension timber generally utilized in the construction of timber highway bridges. Eighty-two percent of all timber bridge degradation is biotic and due primarily to fungal decay. Poor detailing in design and construction has caused this. During the last few decades advances have been made in preservative treatments, glulam technology, design methods and construction methods that have greatly improved the durability of timber structures (Flaga, 2000).

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ABSTRACT

Timber is among the oldest materials used in bridge construction, and is still widely used today, especially for short and medium span bridges. However, in the second half of the 20th century, the use of timber was largely displaced by steel and concrete, and there is a current perception among many bridge designers and highway officials that timber is no longer a viable option for large-scale highway bridge projects. This perception is largely based on concerns about life span, maintenance costs, load capacity with longer spans and susceptibility to decay (Smith, Bush, & Schmoldt, 1995). These concerns typically stem from past experience with bridges constructed in the mid twentieth century where design/construction techniques employed very poor details such as vertical fasteners that originated from the top surfaces of timber bridge elements. These vertical fasteners are responsible for the vast majority of the timber bridge degradation that is experienced today. Vertical fasteners allow moisture to gain access to bright center zones of the heavy dimension timbers where treatments aren't typically found. Moisture contents over 22% lead to decay from the inside out as the interior moisture can't evaporate quickly from the center zones of the heavy dimension timber generally utilized in the construction of timber highway bridges. Eighty-two percent of all timber bridge degradation is biotic and due primarily to fungal decay. Poor detailing in design and construction has caused this. During the last few decades advances have been made in preservative treatments, glulam technology, design methods and construction methods that have greatly improved the durability of timber structures (Flaga, 2000).

In the early twenty-first century there has been a resurgence in the use of timber for large structures. In recent years this is most notable in building construction, where new technologies, such as cross-laminated timber, and updates to building- and fire-codes have led to a major increase in mass-timber construction for mid-rise and high-rise commercial buildings. Designers, builders, and owners are finding advantages to timber construction that include aesthetics, rapid construction, low up-front costs, and significantly reduced carbon emissions. These same advantages apply to highway bridges.

Worldwide, there have been many prominent examples of new, large-scale, highway bridge projects over the last two decades. In the Nordic countries there have been several hundred new highway bridges built since the mid-1990s (Mohammad, Morris, Thivierge, de Jager, & Wang, 2014). In Norway approximately 10% of new bridges are constructed in timber, and in Sweden that number reaches 20% (Finnish Timber Council, 2019). A recent study commissioned by the Canadian Wood Council estimates that there are currently nearly 50,000 timber highway bridges in service in the United States and Canada, making up approximately 7% of all highway bridges. Further when considering all bridges in North America including railway bridges timber bridges make up approximately 289,000 of a total of nearly 900,000 total bridges in North America. The same study estimated with increased knowledge and acceptance of timber among bridge owners and designers, there could be demand for as many as 1300 new timber bridges each year (Tingley, Keller, Arthur, Hunter, & Legg, 2015).

The following paper will explore the current state of timber bridge design and construction and discuss the potential advantages and the current barriers to expanded use of timber in the construction of modern highway bridges.

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1.0 INTRODUCTION

Timber is among the oldest materials used in bridge construction, and is still widely used today, especially for short and medium span bridges. The high strength and light weight nature of timber make it a desirable material for bridge construction and it remains a cost competitive option when compared to other material choices. On a pound for pound basis cellulose is much stronger than steel. It has a higher Specific Tensile Capacity. However, in the 20th century, the use of timber has largely been displaced by steel and concrete, and there is a perception among many bridge designers and highway officials that timber is no longer a viable option for large-scale highway bridge projects. This perception is largely based on concerns about life span, maintenance costs, and susceptibility to decay (Smith, Bush, & Schmoldt, 1995). These concerns typically stem from past experience with bridges constructed in the mid twentieth century. Since then, advances have been made in preservative treatments, glulam technology, and construction methods that have greatly improved the durability of timber structures (Flaga, 2000).

In the early twenty-first century there is been a resurgence in the use of timber for large structures. This is, most notable in building construction, where new technologies, such as cross-laminated timber, and updates to building- and fire-codes have led to a major increase in mass-timber construction for mid-rise and high-rise commercial buildings. Designers, builders, and owners are finding advantages to timber construction that include aesthetics, rapid construction, low up-front costs, and significantly reduced carbon emissions. These same advantages apply to highway bridges.

Worldwide, there have been many prominent examples of new, large-scale, highway bridge projects over the last two decades. In the Nordic countries there have been several hundred new highway bridges built since the mid-1990s, thanks in part to the research efforts by the Nordic Timber Bridge Programme (Mohammad, Morris, Thivierge, de Jager, & Wang, 2014). In Norway approximately 10% of new bridges are constructed in timber, and in Sweden that number reaches 20% (Finnish Timber Council, 2019). A recent study commissioned by the Canadian Wood Council estimates that there are currently nearly 50,000 timber highway bridges in service in the United States and Canada, making up approximately 7% of all highway bridges. While that share has been decreasing, there was still an average of at least 100 new or reconstructed timber bridges per year between 2008 and 2012. The same study estimated with increased acceptance of timber among bridge owners and designers, there could be as many as 1300 new bridges to be erected each year that could benefit from the advantages of timber (Tingley, Keller, Arthur, Hunter, & Legg, 2015). When considering all bridges including railway bridges timber bridges comprise approximately 289,000 of the total of nearly 900,000 bridges in service in North American today.

This paper will explore the current state of timber bridge design construction and discuss the potential advantages and the current barriers to expanded use of timber in the construction of modern highway bridges.

2.0 Advantages of Timber

2.1 Low Self Weight

One of the biggest advantages of timber for large highway structures is its low self-weight. The dead-load of a timber bridge is generally much less than that of an equivalent steel or concrete bridge. Typically 1/8th the dead weight of concrete and 1/5th the dead weight of steel for a similar span/capacity. This is a big advantage, especially in long-span structures where self-weight of concrete often becomes the single biggest design criteria. The reduced dead-load allows for smaller foundations, which can account for a significant portion of the initial construction costs.

The reduced weight can also lead to cost savings related to transporting materials to the building site and can limit the amount of heavy equipment required for installation. (Moses, et al., 2017)

2.2 Rapid Installation

Thanks to its light weight and the ability to pre-fabricate components off-site where all the machining is completed before treatment, timber bridges can often be installed very rapidly, with much less time spent on-site. This means lower labor costs and fewer interruptions to traffic. This can be especially beneficial on railroad overpasses, where interrupting rail traffic is often quite costly.

Additionally, installation can often be completed with less specialized labor and less heavy equipment compared to steel or concrete structures. (Moses, et al., 2017)

2.3 Low Initial Cost

Timber structures often have an advantage over steel and concrete structures based on initial construction costs. This is largely due to the lower self-weight and faster installation, as discussed above. Additionally, material costs for the timber superstructure is usually competitive with steel or concrete even before accounting for substructure and installation savings. The longer the span generally the bigger the cost advantage over other materials. This is particularly true when wood is compared to concrete. With clear spans over 30 meters the cost of wood construction is often ½ the cost of concrete. In cases where wood is compared to curved steel long span bridges when the span exceeds 40 meters wood will be less than steel by 30% or more.

These advantages can be improved when designers and builders are more familiar with timber. It has been shown that contractors who are unfamiliar with timber tend to giver higher bids for timber projects, compared to contractors that specialize in timber. (Moses, et al., 2017)

2.4 Reduced Carbon Emissions/Energy Consumption On a Load Capacity Basis.

Mass timber, when sourced from sustainable forests, has net negative carbon emissions. This means the use of timber as a primary structural material can offset the carbon emissions from the other portions of the project.

A recent example is the Mistissini Bridge in Quebec. The design team conducted a life cycle analysis for the both the timber design and an alternative design utilizing concrete and steel. The analysis found that the timber superstructure and deck had net negative emissions of -981 tonnes of CO_2. This more than offset the emissions from the concrete piers and other components, and the total project emissions came to -497 tonnes. By comparison the steel and concrete design would have generated 969 tonnes of CO_2 emissions, a total savings of 1466 tonnes (Lefebvre & Richard, 2014).

Typically timber bridges are 21 times more carbon friendly than steel and 16 times more carbon friendly than reinforced concrete. Further, similar values can be shown for energy consumption on a load capacity basis.

3.0 Perceived Barriers to Timber

Many bridge owners and designers do not see timber as a viable option for building new highway bridges. Timber is seen as short lived and prone to decay. It is often assumed that timber will require more maintenance than other materials. This perception is largely based on the past performance of bridges constructed in the mid twentieth century with many poor design methods. Since that time advances have been made in preservative treatments, glulam technology, and construction methods that have greatly improved the durability of timber structures (Flaga, 2000).

3.1 Timber Service Life

Timber is a naturally durable material in many respects: it can withstand short-term overloading, it is not damaged by repeated freeze-thaw cycles, it is not damaged by the deicing chemicals which cause corrosion in steel and reinforced concrete bridges, and large timber members can have fire-resistant properties equal to or better than that of other building materials (Ritter, 1990). In addition on long spans timber does not have the Coefficient of Thermal Expansion (CoT) problems that steel does (1/4th CoT of steel). There is a widespread perception that timber has a shorter service life than other bridge materials. However, a well-designed and properly maintained modern timber bridge can have a service life of well over 50 years (Ritter, 1990) and many examples exist of timber bridges that have been in service for 200 years or more (Gerold, 2006).

A study of bridge condition ratings in the US National Bridge Inventory has shown that the average age of bridges with satisfactory ratings is not dependent on the material type. Timber, steel, and reinforced concrete all showed average ages of 35 years, indicating that the life expectancy for all material types will be similar (Stanfill-McMillan & Hatfield, 1994). This study also showed that timber bridge performance has greatly improved for bridges built since the 1970s, when the use of modular glulam construction began to increase.

3.2 Susceptibility to Decay

The perception that timber has a shorter service life than other materials is primarily based on timbers' susceptibility to natural decay, but with proper design details the timber can be protected from moisture. When combined chemical preservatives, decay can easily be prevented, easily allowing for a service life comparable to other materials.

In Sweden for example, environmental regulations have prohibited the use of chemical preservatives containing arsenic, chrome, or creosote since the 1990s. Despite this, several hundred timber bridges have been built in Sweden since then. Designers implement details such as metal flashing and louvers to shelter the wood from rain and waterproof membranes below the wear surface to protect the deck. Using these details, bridges in Sweden are designed to have an 80 year service life (Troive, 2005). In New Brunswick, Canada where covered bridges are popular, it is common to have covered bridges reach one hundred years of service life because the roof and side walls keep moisture away from the connections and prevent accelerated decay from occurring.

3.3 Maintenance Costs

While it is easy to compare the initial construction cost of various material options, it is more difficult to predict the long term maintenance costs. Engineers and bridge owners will often assume that maintenance costs will be higher for timber, however a recent investigation found that the maintenance cost for properly protected timber bridges is substantially lower than typically estimated (Gerold, 2006).

The study evaluated over 50 modern timber vehicle, cycle, and pedestrian bridges in Germany and calculated the annual maintenance costs as a percentage of initial construction costs. Among the bridges tested, the annual maintenance costs varied from 0.1% to 2.5% of the initial construction costs. For road bridges with properly protected structures, the average was 0.7%. For the purposes of the study, a protected structure was defined as a bridge with the main beams being sheltered from weather on the top and sides; this shelter could be achieved with a closed deck with asphalt surface, sheet metal cladding with proper ventilation, or through the use of certain highly decay-resistant hardwoods. Gerold concludes that the service life and maintenance costs of timber bridges are comparable to those of steel and concrete structures. He suggests that an appropriately conservative estimate for road bridges would be 80 year service life and annual maintenance costs of 1.3% of construction costs.

3.4 Lack of Knowledge

The above misconceptions about timber largely stem from lack of knowledge and experience working with timber. Engineers and transportation officials are often less familiar with timber than with other materials, and there is a tendency to underestimate the lifespan and overestimate the maintenance costs for timber bridges. In a 1996 survey of bridge engineers and highway officials in the United States, only 46% had worked with timber in the last five years, compared with 79% who had worked with reinforced concrete; nearly 70% said their states had standard bridge designs, but only one third of those included timber in the standard designs (Smith & Stanfill-McMillan, 1996). This study also showed that in states with more experience and knowledge of timber, timber bridges generally performed better with longer life-spans and fewer deficiencies at a given age.

Initiatives such as the Nordic Timber Bridge Program, the USDA Forest Service’s Forest Products Laboratory, British Columbia’s Wood First program, and the recently published Ontario Wood Bridge Reference Guide have helped increased the knowledge with regard to timber bridge construction. This increase in knowledge is making designers and bridge managers feel more comfortable with timber, and is helping to dispel some of the popular misconceptions about timber bridges.

4.0 Examples of Timber Bridges

4.1 Historic Structures

4.1.1 Keystone Wye

The Keystone Wye is a pair of glulam timber bridges constructed in 1966 at the junction between U.S. Route 16 and U.S. Route 16A in the South Dakota. The upper bridge consists of a 14-span concrete deck totaling 88m (290 ft) in length, supported by glulam girders. The center eight spans are in turn supported by three glulam three-pinned arches, spanning 47m (155 ft). Passing under these arches, is a 3-span bridge consisting of a concrete deck supported on glulam girders. Each bridge carries two lanes of traffic, and a third two-lane roadway crosses under the lower bridge. The bridges have an HS-36 truck traffic rating as per ASHTO.

An in-depth inspection of the structures, including non-destructive testing, was conducted in 2018 by Wood Research and Development, after the bridges had been in service for over 50 years. The inspection was commissioned to confirm the need to spend over 20 million dollars which had been allocated to replace the bridges. The senior bridge officials had been told by their outside consultants that timber bridges didn’t last much longer than 50 years and they should be ready to replace these two bridges. The inspection found both structures to be in good condition, and recommended only routine maintenance to extend the life of the structures. The bridge has now been reinstated for another fifty years and will not be replaced. See Figures 4-1 to 4-4 below.

Figure 4-1: The Keystone Wye Bridges in South Dakota were recently inspected after more than 50 years in service, and were found to be in good condition; only minor repairs and routine maintenance were recommended to extend the longevity of the structures.

Figure 4-2: The wye includes an upper bridge supported on three-pinned glulam arches, and a lower three-span bridge supported by glulam girders.

Figure 4-3: The upper bridge is supported by glulam arches.

Figure 4-4: The substructure of the lower bridge consists of glulam timber frame bents.

4.1.2 Golden

Golden Bridge a 3-span forestry bridge in British Columbia. Each span is (90ft) long, and consists of two glulam I-beams supporting a solid-sawn primary transverse bearer and secondary longitudinal deck plank and running boards deck system. Constructed in the 1960s, the bridge was recently inspected and found to be in fair condition; it was found that in its current condition, the bridge can still support an L100 load rating as per S6-14 (Canadian Bridge Code). However, the inspection did reveal some deficiencies in the deck, primarily due to the use of vertical fasteners which have allowed moisture to penetrate into the timber elements. It was recommended that the deck be upgraded to a system that avoids the use of vertical fasteners. This bridge was slated for replacement because the engineers of record had determined that the bridge had reached the end of its life and that assessment was made based on the misconception that timber bridges only last for 40 years. This is a popular misconception based on assessments of timber bridges where poor design and construction detailing has been utilized. See Figure 4-5 to 4-7 below.

Figure 4-5: Golden Bridge, in British Columbia is a 3-span glulam timber bridge, totaling 82m (270 ft) in length.

Figure 4-6: Each 27m (90 ft) span consists of two glulam I-Beams which support transverse bearers. The deck and wear surface are made up of longitudinal planks.

Figure 4-7: A recent inspection of the bridge found it to be in fair condition overall. The only significant deficiencies found were in the deck system as a result of vertical fasteners allowing water to penetrate into the timber elements. Even with these deficiencies, the bridge can maintain an L100 load rating. Recommendations were given for repairs and maintenance that could extend the life of the bridge for as much as 80 more years.

4.1.3 Glulam Highway Bridges on Vancouver Island

Elk River Bridge, Cervus Creek Bridge, and Heber River Bridge are glulam girder bridges maintained by the British Columbia Ministry of Transportation and Infrastructure on Vancouver Island. The bridges are all approximately 60 years old and were recently inspected. They were found to be in fair condition overall. Some areas of moderate decay were noted, and recommendations were given for both short-term and long-term maintenance to extend the service life by 80 years or more.

All three bridges utilize connection details that avoid vertical fasteners the penetrated the top surface of the timber elements. Vertical fasteners allow moisture to penetrate into the center of the timber elements, beyond the treatment zone, and are a common cause of accelerated deterioration of timber bridges. Thanks to the forward thinking of the designers, the existing structures remain in fair condition following 60 years of service in harsh conditions. Analysis of the residual capacity of the structures found that all three remain capable of carrying CL-625 loading as per S6-14. Additionally, maintenance records from the government indicate that minimal work has been undertaken on this structure since construction, the most significant of which was re-paving of the road surface. See Figures 4-8 to 4-10 below.

Figure 4-8: Elk River Bridge consists of six glulam I-beams spanning 35m; at each end is an approach span of approximately 8m made up of solid sawn girders. The deck is transverse nail-laminated timber.

Figure 4-9: Cervus Creek Bridge is a 25m (82ft) single-span bridge consisting of four glulam I-beams with a transverse nail-laminated deck.

Figure 4-10: Heber River Bridge is a single-span, 34.5m (113ft) long consisting of four glulam I-beams and a transverse nail-laminated deck.

4.1.4 Kindee

The Kindee bridge is the oldest longest suspension bridge in New South Wales, Australia with a length of nearly 90 meters. It is rated for vehicle traffic and continues on in service today (2019) as per AS5100 the Australian Bridge Code. See Figure 4-11 below.

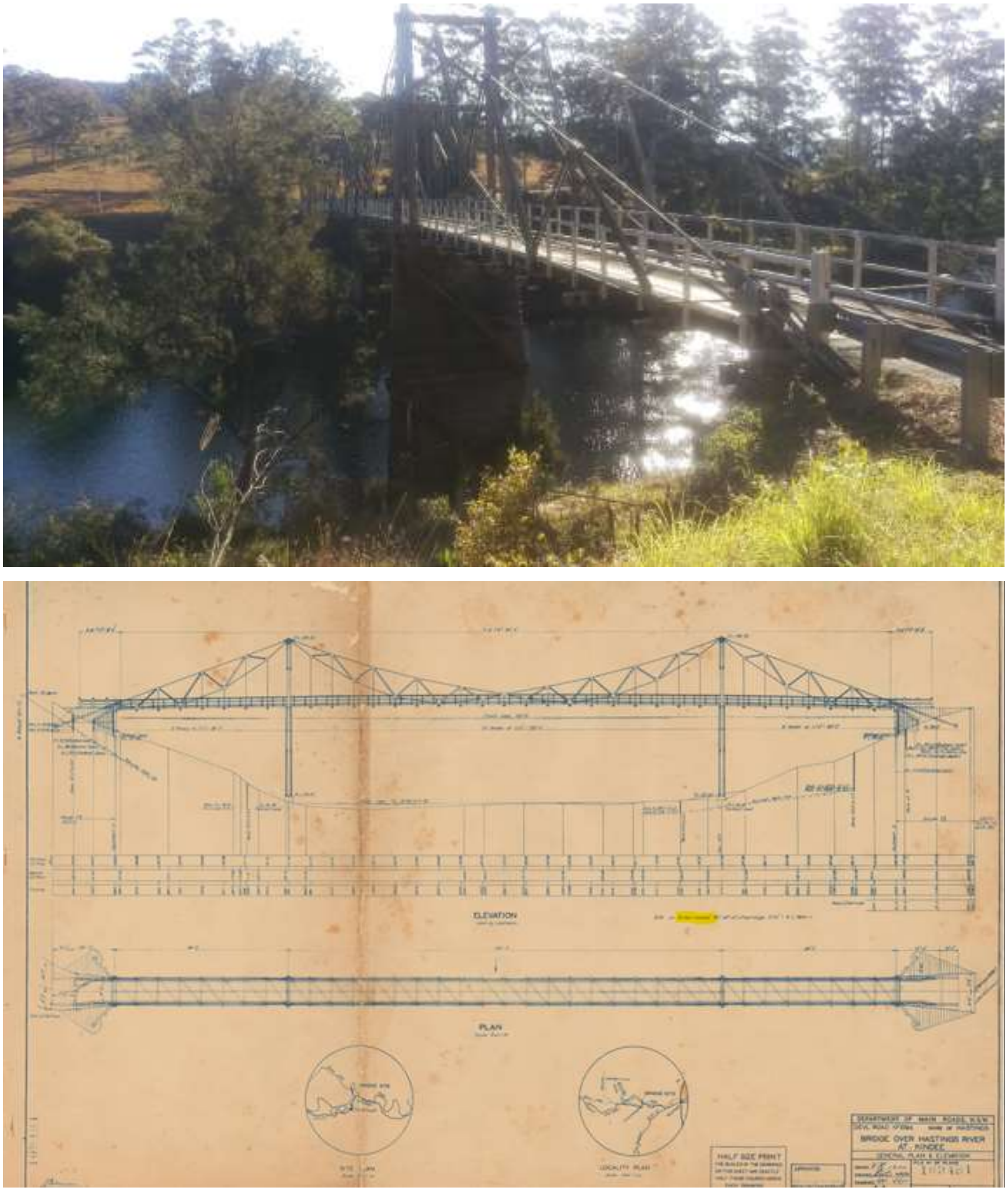


Figure 4-11: Kindee Suspension Bridge.

4.1.5 Kintai Bridge

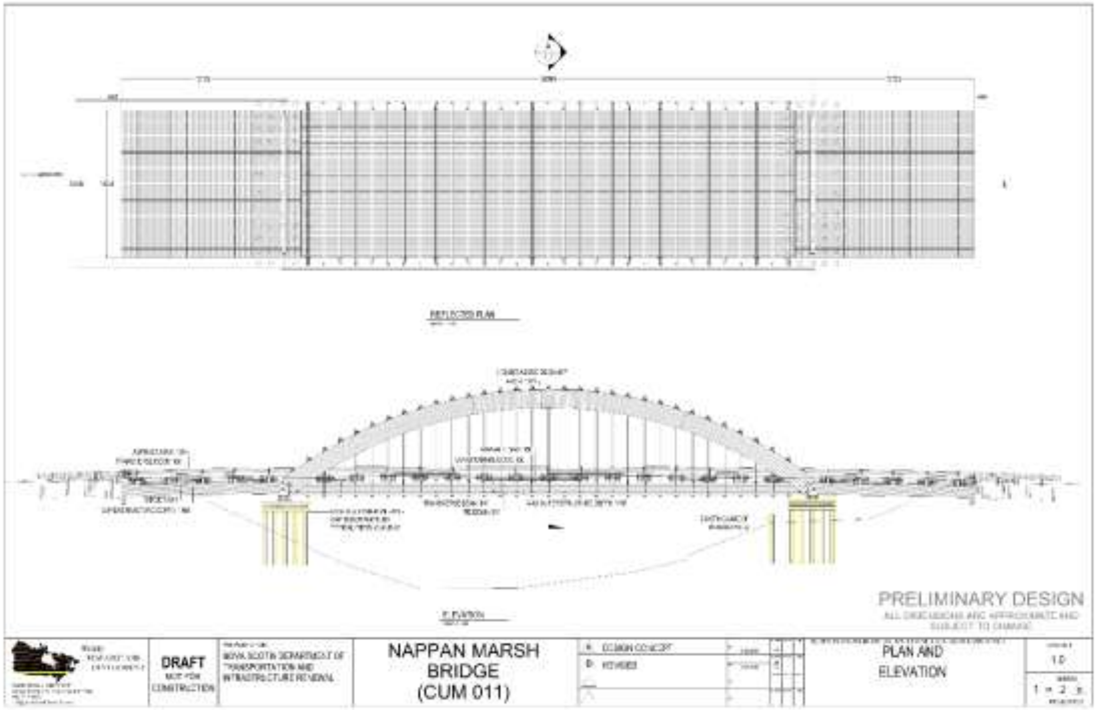
The Kintai Bridge was originally constructed in 1673 spanning the Nishiki River in Japan, and has be restored and rebuilt a number of times since then. The bridge is made up of five wooden arches, each spanning approximately 35m (115ft). The arches consist of a unique leaf-spring style design, with multiple layers of timber joined together with iron straps. See Figure 4-12 below.

Figure 4-12: Kintai Bridge, spanning the Nishiki River in Japan, was originally constructed in 1673

4.2 North America

4.2.1 Nappan

Nappan Marsh Bridge is currently in the design phases for Nova Scotia Transportation and Infrastructure Renewal. The bridge, a replacement of an existing steel arch bridge, will be a glulam side-arch structure with a main span of 39.5m (130ft) and two approach spans of 12m (39ft) each. The new glulam timber bridge superstructure and deck will utilize the existing timber piles from the original bridge. The light weight nature of the new timber bridge being 1/8th the dead weight of concrete and 1/5th the dead weight of steel makes this possible. This bridge was tendered at a cost to province that was nearly a million dollars less or nearly 30% less than the curved steel alternative specified in the tender documents. See Figure 4-13 below. Current trends are revealing that long span curved steel pricing is significantly higher than timber for a similar span and load rating. Further the curved steel bridge being replaced is less than 50 years old and was rusted completely out in the tension cord. The replacement timber bridge has further advantages over the steel bridge alternative in that it has built in redundancy with multiple tension and compression element cords. This provides for servicing should elements drop out of service for some reason. See Figures 4-13 and 14 below.



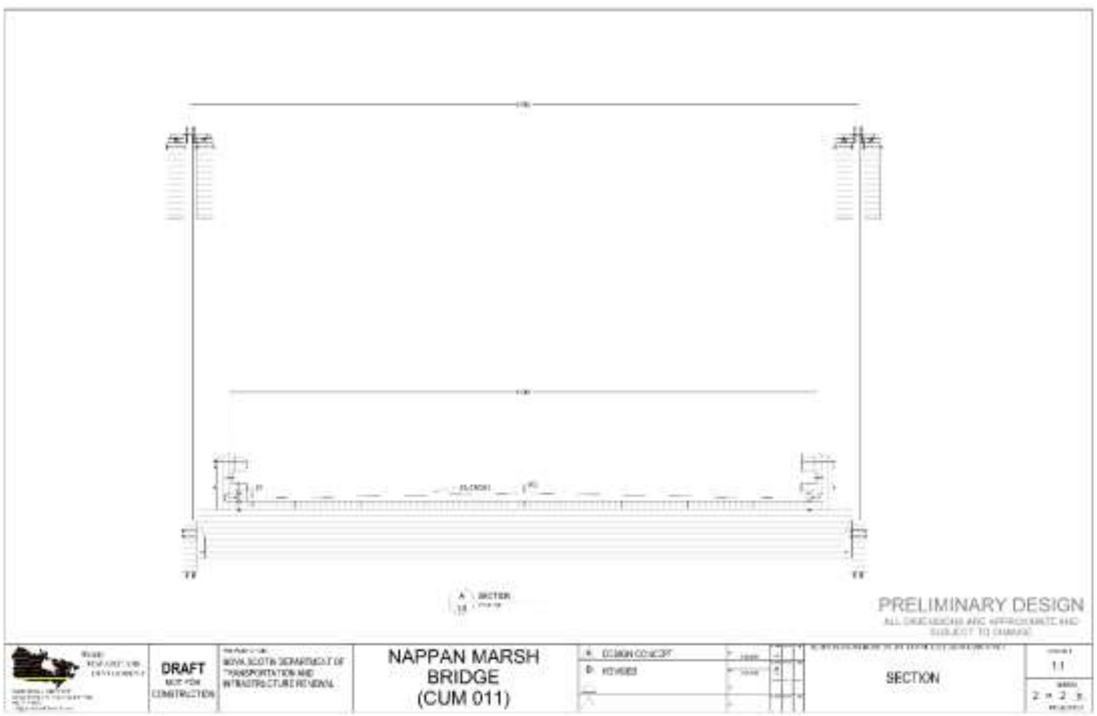


Figure 4-13: Preliminary design documents for the Nappan Marsh Bridge

Figure 4-14: Photograph of the existing steel arch span that will be replaced by the new timber structure shown in Figure 4-13. Middle photograph shows the rusted through tension cords (out of service) in the old bridge that was less than 50 years old. Steel has not yet solved its rust problems with rust resistant steel particularly in marine environments where a patina of moisture that stays in place over prolonged periods. In such cases rusting of less than 25 year old elements like the bottom photo reveals have been found to occur. Bottom photograph of rust resistant steel in a railway bridge in Georgia near the coast. Wood doesn't rust!

4.2.2 McGillivray Bridge K162

McGillivray Bridge was developed for the BC Ministry of Forests Lands and Natural Resource Operations as a proof of concept demonstrating the use of timber structures on forestry roads. The 21m (70ft), single-span bridge, consists of five fiber-reinforced glulam girders and a transverse glulam deck and is supported by glulam frame bents. This bridge utilizes an all wood sub and superstructure as well as deck. The bridge was completely assembled and then taken apart prior to pressure treating such that all the machining was completed prior to treatment. The bridge is designed to support L100 loading – a BC standard design load representing off-highway logging equipment as per S6-14. See Figures 4-15 to 17 below.

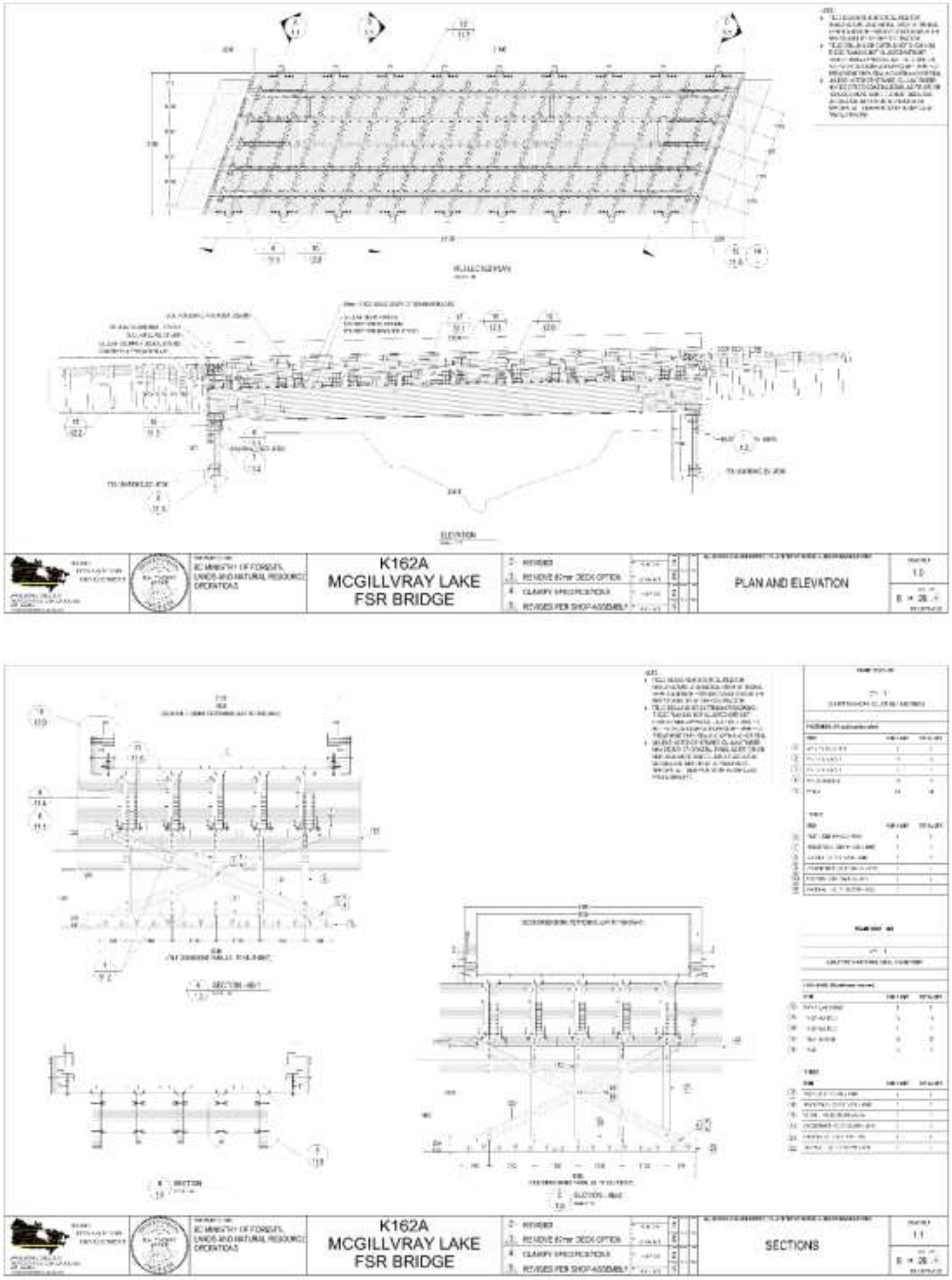


Figure 4-15: Construction documents for McGillivray Bridge.

Figure 4-16: The glulam girders are reinforced with high-strength fiber on the tension face. This fiber-reinforcing is installed in the shop prior to assembling the structure.

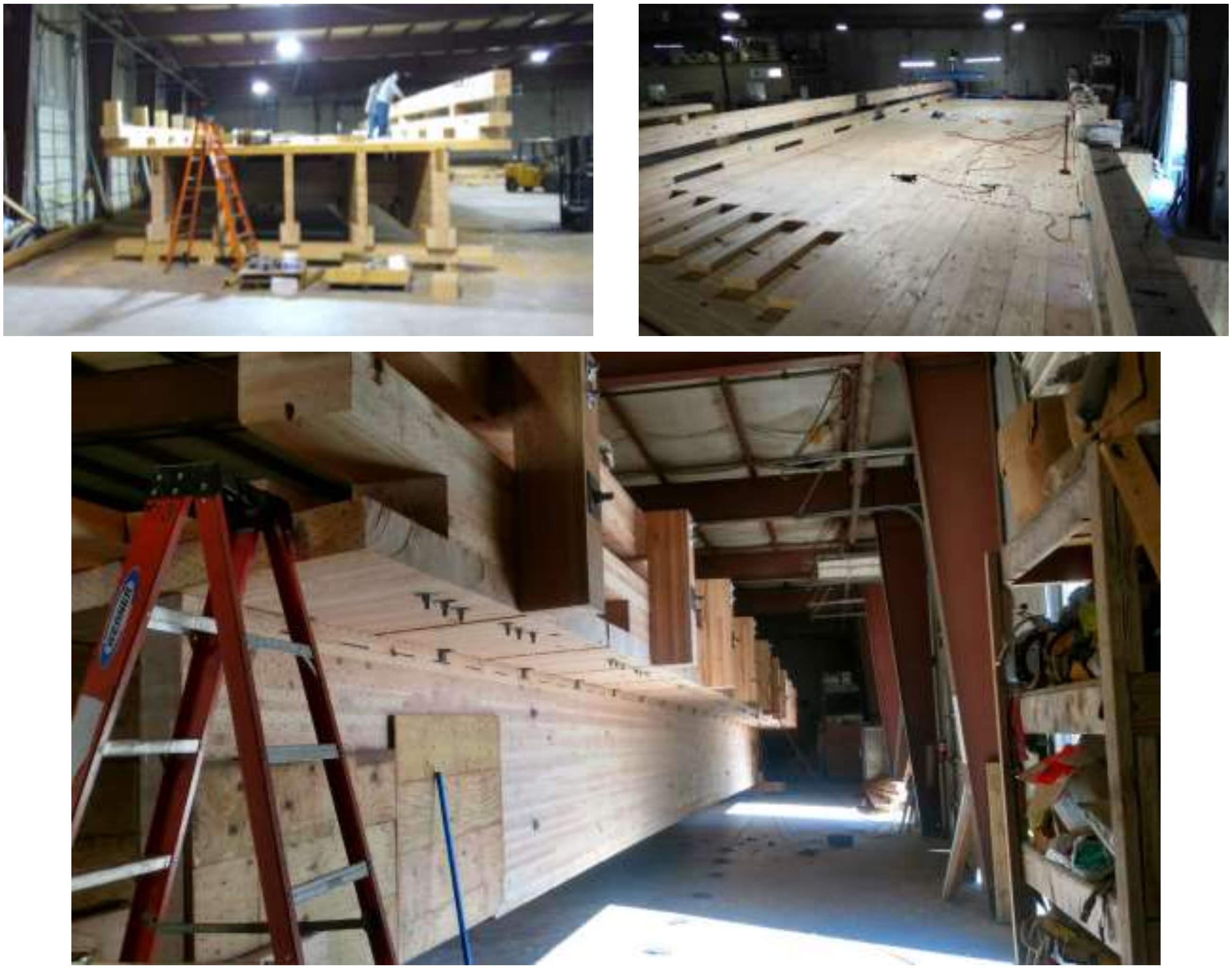


Figure 4-17: All timber components are fabricated and pre-assembled in the shop prior to preservative treatment. This dry-fit process helps avoid any field modifications that might compromise the preservative treatment layer. The bridge is then disassembled and the components are pressure-treated. They will later be shipped to the site for final assembly. The bridge incorporates an all timber TL4 truck crash proof rail system. The abutments are totally constructed of wood as well. The use of timber abutments versus concrete allows a much shorter construction period as there are no cure time issues relating to placement of the superstructure.

4.2.3 Meadow Lake Bridge 61.4

Meadow Lake Bridge 61.4 is a conversion of an old rail-trestle over 60 years old for use as a forestry bridge (L100 as per S6-14) on a Tolko Mill property outside of Meadow Lake, Saskatchewan. The rail lines had been decommissioned ten years earlier, and Tolko purchased the old right-of-way to provide access to their timber lands. Several bridges along the route had to be restored to carry the new logging traffic.

The restoration consisted of high-strength fiber-reinforcement of the existing stringers and substructure. Additionally, the existing railroad ties were replaced with a new transverse glulam deck and curb. See Figures 4-18 and 19 below.

Figure 4-18: Meadow Lake Bridge is a conversion of a decommissioned railroad trestle to be used as a forestry bridge.

Figure 4-19: The Existing piles, caps, and chords were reinforced with high-strength fiber to restore capacity that had been lost due to decay. The old deck was removed and replaced with a new transverse glulam timber deck and curb.

4.2.4 Canadian Pacific Railroad Overpasses

Providence Road Bridge, Snake Road Bridge, and Dickinson Road Bridge are overpasses crossing Canadian Pacific Railroad tracks in southern Ontario. They were replacement of existing timber overpasses which had become deteriorated over time and were no longer sufficient to carry modern traffic loads. All three bridges consist of new glulam girder superstructures with transverse glulam decks. All three include timber guard rails based on a design that has been crash-tested according to TL-4 criteria in NHCRP 350. Further all bridges has substructures that were comprised mostly of timber.

All three bridges are built on timber substructures. Providence Road and Snake Road both utilized significant portions of the existing substructure, while Dickinson had a full new substructure installed. The bridges all meet the loading requirements of Ontario CL625 loading (S6-14). See Figures 4-20 to 22.

Figure 4-20: Providence Road Bridge in Clarington, Ontario consists of five lines of glulam girders supporting a transverse timber deck. The existing solid sawn frame bents were restored, including the addition of high-strength fiber reinforcing in some locations to restore capacity that had been lost due to decay. An asphalt wear surface was installed on top of the transverse timber deck. The timber guard rail is crash-tested to TL-4 specifications.

Figure 4-21: Snake Road Bridge, on the border between Hamilton and Burlington, Ontario, consists of six glulam girder lines. The substructure was completely rebuilt; however, much of the material from the original structure was salvaged for use in the new bridge. The substructure was completely timber and the highway was designed for two lane heavy truck use beyond a conventional CL625 rating. It also incorporated an all timber TL4 truck crash proof rail system.

Figure 4-22: Dickinson Road Bridge, in Port Hope, Ontario consists of six glulam girder lines. The substructure was completely rebuilt; however, much of the material from the original structure was salvaged for use in the new bridge.

4.2.5 Overpeck Park Bridges

The Overpeck Park Bridges, designed and built by Western Wood Structures, in Teaneck, New Jersey is a pair of glulam through-arch bridges, each with a span of 43m (140ft) and a roadway width of 9m (30ft) plus a walkway of 3m (10ft) on one side (Gilham, 2013). HS20 loading as per ASHTO. See Figure 4-23 below.

Figure 4-23: Overpeck Park Bridges, by Western Wood Structures, are a pair of two identical through-arch bridges. Each bridge spans 43m (140ft) and carries two lanes of traffic and a pedestrian walkway. The arches are three-pin arches, with a hinge at mid-span; to reduce the size of the individual members, each arch segment is broken into two pieces with a moment splice at its midpoint.

4.2.6 Mistissini Bridge

Designed by Stantec and built by Nordic Structures in 2014, Mistissini Bridge spans Uupaachikus Pass in Mistissini, Quebec. The 4-span bridge has a total length of 160m (525ft) made up of two 37m

(121ft) spans and two 43m (141ft) spans. The bridge employs a unique structure consisting of half-arch knee-braces attached to the face of the concrete piers, which spliced to the straight girders above with moment resisting connections. This forms a continuous structure without deck joints over the piers. These structures were designed for L100 heavy truck traffic as per S6-14.

The engineering team developed the timber design in parallel with a conventional steel and concrete design. It was found that the timber option was slightly less expensive than the concrete and steel option, largely due to the reduced transportation costs. A carbon study was also conducted to compare the greenhouse gas emissions from each of the design options. It was found that the timber option had net-negative carbon footprint equivalent to -497 tonnes of CO_2 emissions. By comparison, the steel and concrete option would have generated 969 tonnes of CO_2 emissions (Lefebvre & Richard, 2014). See Figure 4-24 and 25 below.

Figure 4-24: Mistissini Bridge is a 4-span bridge totaling 160m (525ft) long. The bridge is 9.25m (30ft) carrying two lanes of traffic, plus a pedestrian walkway on one side. It consists of glulam girders and arched knee-braces supporting a glulam deck with an asphalt wear-surface. (Forestrie Nordic, 2015)

Figure 4-25: The arched braces are connected to the piers with pinned connections. The connection between the arches and the girders serves to both support the girder ends and to create a moment-resisting splice in the girders. This forms a continuous structure with no deck joints, which will help avoid cracking of the asphalt and maintain a waterproof surface. (Forestrie Nordic, 2015)

4.2.7 Tamiscame River Bridge

Built in 2009 by Nordic Structures, Tamiscame River Bridge is a forestry bridge (L100 as per S6-14) in Quebec supported by a glulam arch-under system. The arches span 30m (98ft) and the total deck length is 34m (112ft). (Forestrie Nordic, 2015). See Figure 4-26 below.

Figure 4-26: Tamiscame River Bridge, by Nordic Structures, consists of 12 glulam arches spanning 30m (98ft) which support 10 glulam girders and a transvers glulam deck. (Forestrie Nordic, 2015)

4.2.8 Lighthouse Bridge

The Lighthouse Bridge near Clallam Bay, Washington is a 2-span, 50m (160ft) bridge consisting of fiber-reinforced glulam girders and a transverse glulam deck. Constructed in 1995, the Lighthouse Bridge was the first vehicular bridge designed for heavy loading (HS25-44) to utilize FiRP® Reinforcing in the United States (Tingley & Gai, 1998). Figures 4-27 and 28 below.

Figure 4-27: The Lighthouse Bridge, under construction in Clallam Bay, Washington. The bridge consists of six fiber-reinforced glulam girders in each span.

Figure 4-28: The glulam girders are reinforced with a layer of fiber-reinforced polymer (FiRP®) which permitted a significant reduction in the volume of wood required compared to an unreinforced bridge. This bridge has been in service since the early 1990's.

4.3 Europe

4.3.1 Norway

Along with Sweden, Denmark, and Finland, Norway participated in the Nordic Timber Bridge Program between 1994 and 2002. Since that time, several hundred timber highway bridges have been constructed in Norway, many of them featuring glulam arches or trusses carrying longitudinal stress-laminated timber decks (Mohammad, Morris, Thivierge, de Jager, & Wang, 2014).

4.3.1.1 *Sletta*

Sletta Bridge, in Eidsvoll, is a 2-span, 47.7m (157ft) bridge featuring unique, asymmetrical glulam trusses. These trusses carry steel crossbeams supporting a longitudinal stress laminated deck. The glulam timbers were dual-treated – first the individual lamina were treated with a copper based preservative, then, after fabrication, the finished components were treated with creosote. See Figure 4-29 below.

Figure 4-29: Sletta Bridge in Eidsvol, Norway. The structure consists of asymmetrical glulam trusses which carry steel crossbeams and a stress laminated deck. In addition to being dual preservative treated (with a copper-based preservative and creosote) the main elements are sheltered from moisture using metal flashing.

4.3.1.2 *Skogsrud*

Skogsrud Bridge, in Tangen, is an overpass crossing a 4-lane highway, with a main span of 37m (122ft) and a total length of 49m (160ft). The structure consists of glulam, three-pinned arches supporting steel crossbeams and a stress-laminated deck. The arches are sheltered from rain by metal flashing on top and wood louvers on the vertical faces. See Figure 4-30 below.

Figure 4-30: Skogsrud Bridge in Tangen, Norway consists of two glulam arches and a stress-laminated deck. The arches are protected with metal flashing on top and wood louvers on the vertical faces. This shelters the elements from rain while still allowing sufficient air flow to keep the moisture content of the wood low.

4.3.1.3 *Tretten*

Tretten Bridge is a two-lane three-span bridge with a total length of 148m (485ft) and a longest span of 70.2m (230ft). The bridge replaced an existing steel bridge, and utilized the original concrete abutments and piers. See Figure 4-31 below.

Figure 4-31: Tretten Bridge is a continuous truss across three spans. The truss is a hybrid truss made primarily from glulam timbers with steel vertical web members and steel shoes at the nodes. Corten weathering steel was used for the steel elements.

4.3.1.4 *Evenstad*

Evanstad Bridge is a five-span, 180m (590ft) bridge. Each 36m (118ft) span consists of a pair of arched glulam trusses. These trusses carry steel crossbeams and a longitudinal stress-laminated deck.

See Figure 4-32 below.

Figure 4-32: Evenstad Bridge is made up of five glulam truss spans, each 36m (118ft) long. The trusses support steel cross beams and a stress-laminated deck.

4.3.1.5 *Kjøllsæter*

Kjøllsæter Bridge, in Rena, is five-span, 145m (476ft) bridge with a maximum span of 45m (148ft). The structure consists of a continuous glulam truss carrying a concrete slab deck. The bridge is designed for heavy military loading of over 100 tons, making it the strongest timber bridge in Norway. See Figure 4-33 below.

Figure 4-33: Kjøllsæter Bridge consists of a continuous glulam truss with a total length of 145m (476ft) and a maximum span of 36m (118ft). The glulam truss supports a concrete slab deck.

4.3.1.6 *Asta*

Asta Bridge, in Rena, is a longitudinal stress laminated deck supported on steel crossbeams. The deck totals 96.6m (317ft). The central span of 38.5m (126ft) is supported by glulam arches. See Figure 4-34 below.

Figure 4-34: Asta Bridge is a stress laminated deck supported by glulam arches. The deck totals 96.6m (317ft), and the arches span 38.5m (126ft).

4.3.1.7 *Flisa*

Flisa Bridge is a three-span glulam truss bridge totaling 196m (643ft) with a maximum span of 70m (230ft). The trusses carry steel cross beams and a stress laminated deck. See Figure 4-35 below.

Figure 4-35: Flisa Bridge is a three-span glulam truss bridge totaling 196m (643ft) with a maximum span of 70m (230ft).

4.3.2 Krastalbrücke

Krastalbrücke is a tied-arch glulam bridge in Treffen, Austria. The arches carry transverse glulam beams which, in turn, support a cross-laminated timber deck. The bridge carries two lanes of traffic and a sidewalk and is designed for 60 ton vehicle loads. See Figure 4-36 below.

Figure 4-36: Krastalbrücke consists of two glulam tied-arches. These support steel hangers which carry the transverse glulam beams which, in turn, carry the deck. This bridge has been in service since 1995.

4.3.3 Nissan River Bridge

At 47.4m (155ft) Nissan River Bridge is the longest single-span timber highway bridge in Sweden. It consists of two three-pinned arches which carry steel cross beams and a longitudinal stress-laminated deck. Lateral stability of the arches was achieved by using stiff steel hangers and moment resisting connections from the arch to the hangers and from the hangers to the crossbeams (Ekholm, Nilson, & Johansson, 2013). See Figure 4-37 below.

Figure 4-37: Nissan River Bridge spans 47.4m (155ft) and consists of two three-pinned arches. The arches carry steel hangers and crossbeams which in turn carry a stress-laminated deck. The glulam arches are sheltered by steel flashing on top and vented would panels on the vertical faces.

4.4 Australia

4.4.1 Cowley Creek Bridge

Cowley Creek Bridge is a 16.5m (54ft) two-lane bridge made up of glulam girders, transverse glulam deck, and a timber guard rail rated to TL-4 crash test standards. The bridge is a preplacement for an existing structure. The superstructure and deck were fully assembly adjacent to the roadway. After the foundation upgrades have been completed, the bridge will be lifted into place by crane, to limit the necessary road closures. See Figure 4-38 below.

Figure 4-38: Cowley Creek Bridge, fully assembled and ready to be installed as soon as the foundation upgrades are completed.

4.4.2 Queensland Rail Overpasses

Boundary Road Bridge and Alderley Avenue Bridge are overpass bridges crossing Queensland Rail tracks near Brisbane. Both bridges consist of glulam girders supporting transverse glulam deck panels. The bridges were replacements for existing overpasses, and the existing timber substructures were restored using high-strength fiber to carry the new bridges. The lightweight timber superstructures allowed rapid installation that minimized interruptions to rail traffic below. Both bridges were designed to 44T loading as per AS5100. See Figure 4-39 and 40 below.

Figure 4-39: Alderley Avenue Bridge crosses a pair of Queensland Rail tracks. The new glulam superstructure and deck were installed on the existing substructure. Localized decay in the substructure was repaired using high-strength fiber wraps on the piles and tension reinforcement on the headstocks. This bridge was installed in 39.5 hours. From the start of design phase to the completion of works was 65 days.

Figure 4-40: Boundary Road Bridge is a four-span overpass crossing a pair of Queensland Rail tracks. The light weight of the timber superstructure allowed each span to be preassembled alongside the road and lifted into place by crane. This limited the interruptions to rail traffic on the tracks below. This bridge was installed in 41 hours.

4.4.3 Newry Island

Newry Island Bridge is a six-span timber bridge totaling 62m (203ft). The glulam girder and transverse deck replaced an older timber bridge, and used the existing substructure. The bridge is the only access to the neighborhood on Newry Island, so it was important to limit the time that the bridge was closed. Removal of the existing structure occurred in tandem with installation of the new bridge. Total closure time was limited to only eight days. During this time the municipality offered ferry service to provide access to residents. See Figure 4-41 below.

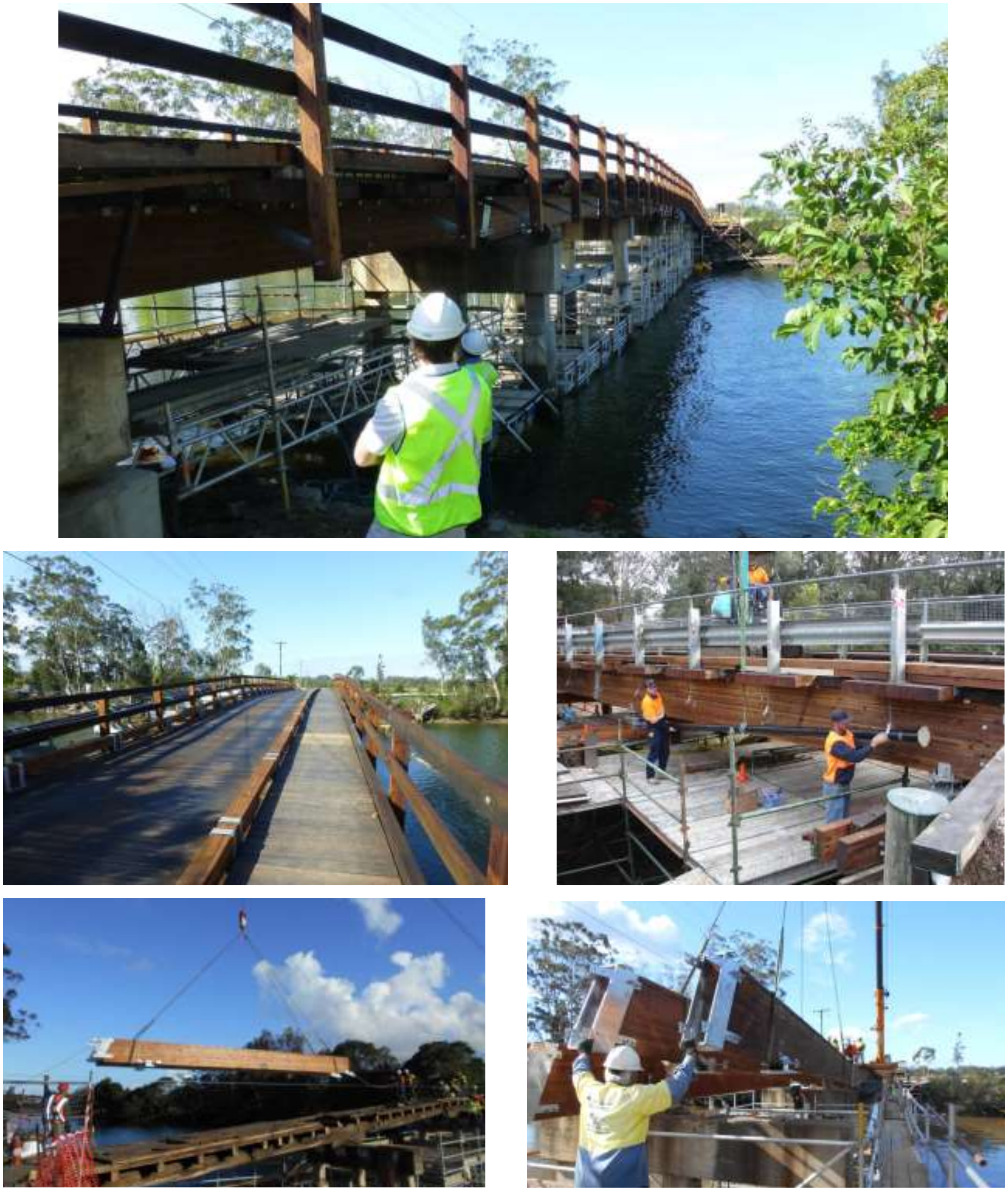


Figure 4-41: The new glulam superstructure and deck were installed on the existing substructure at Newry Island Bridge. Removal of the existing structure and installation of the new occurred in tandem to limit the road closure time.

4.5 Japan

4.5.1 Hokkaido Bridge - Bridge of a Thousand Trees

Hokkaido FiRP® Reinforced Glulam Bridge is a 40 m clear span (131ft) two-lane bridge HS-25 highway bridge. The bridge was a greenfield structure. The bridge had a requirement that the height of the girders be 1 meter or less. High Strength Fiber reinforced glulam beams was the only economical option. This bridge has been in service since 1995. The superstructure was assembled near one of the abutments by using Fixed End Moment connectors and 12 meter long girder sections. Each girder was then lifted into place with a light weight crane as the girders weighed 1/8th the dead weight of an equivalent capacity concrete girder and 1/5th the dead weight of a steel girder. See Figure 4-42 below.

Figure 4-42: The new glulam superstructure was preassembled using 12 meter long sections of high strength fiber reinforced glulam beams. The bridge had a 1 meter depth girder limitation and high strength fiber reinforced glulam beams were the only economical option. This structure has been in place close to twenty-five years.

5.0 Conclusion

Timber bridges that are properly designed and constructed can last hundreds of years. Their longevity is equal to or greater than steel and concrete in a wide range of environments under a wide range of loading requirements. The maintenance cost for a properly designed and constructed timber bridge is equal to or less than steel and concrete bridges. Timber bridges are particularly suited to high levels of chemical exposure such as salted road conditions. Further, they are particularly suited for high embedded and exposed corrosion zones found near marine environments.

The cost of timber bridge construction has been shown to less than concrete and steel construction and in cases where spans are long and loading is high timber bridges will be much less than steel and concrete such as clear spans over 30 meter and CL625 loading. Timber bridges are gaining in popularity in recent times because of their carbon advantage and reduced energy consumption for a given load and span. Timber bridges have been shown to be 21 times more carbon friendly than steel and 16 times more carbon friendly than reinforced concrete. In situations where speed of installation is important timber bridges can be constructed much more quickly due to the elimination of the need for cure time associated with concrete construction. In situations where soils bearing capacity is low timber bridge offer a light weight solution that reduces the cost of foundations and substructure. Timber bridges are 1/8th the dead weight for an equivalent load capacity. They often provide an opportunity to overcome load rating issues when substructures are down rated due to soil condition and limited bearing considerations as timber bridges are much lighter in weight for a given load capacity.

In summary there are plenty of great reasons why the current global movement to Mass Timber buildings and bridges is occurring. Timber is the right choice for bridge construction as compared to steel and concrete.

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