

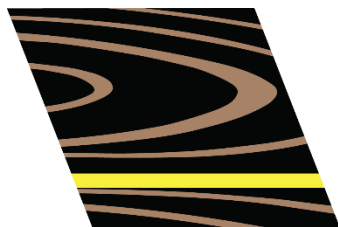
December 15, 2020

Timber Bridge Best Practices and the State of the Industry in Atlantic Canada

PREPARED AND PRESENTED BY:

Christopher Legg, Timber Structures Designer, Senior CAD Technician

Dan Tingley, Senior Timber Structures Engineer / Wood Technologist
PhD | PEng (CA) | MIEAust | CPEng | RPEQ (AU)



Wood Research and Development

4288 Route 114
Lower Cape, NB E4H 3P4
506-734-3074
woodrandd.com

ABSTRACT

Wood – including heavy timber, dimensional lumber and engineered wood products – has been used in bridge building for centuries. It is cost competitive and environmentally friendly with a much smaller carbon footprint than other bridge construction materials. However in the twentieth century, the use of timber in new construction was largely displaced, first by steel and later by reinforced concrete. 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).

Existing timber bridges are generally only maintained with short term fixes, with the expectation of replacement with steel or concrete in the near future. Modern inspection and restoration methods can be utilized to identify problem areas, repair, and strengthen timber bridges, greatly extending their life-spans and achieving significant cost savings compared to replacement.

In the early twenty-first century there was 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 can apply to highway bridges. Worldwide, there have been many prominent examples of new, large-scale, highway bridge projects over the last two decades, and there is potential for significant growth in the timber bridge industry.

This paper will investigate the causes for the decline in the use of timber. It will address some misconceptions about timber and discuss some advantages of wood as a building material with the goal of demonstrating that wood is still a viable solution for bridge construction.

TABLE OF CONTENTS

ABSTRACT.....	2	2.5.1 Utilize Non-Destructive Testing.....	23
TABLE OF CONTENTS	3	2.5.2 Eliminate Vertical Fasteners	25
INTRODUCTION.....	5	2.5.3 Eliminate Waterproof Membranes.....	27
1.0 INTRODUCTION TO TIMBER	6	2.5.4 Avoid High-Solids Paints	28
1.1 PROPERTIES OF WOOD	6	2.6 SPAN CAPABILITIES	29
1.1.1 Variability	6	2.7 FIRE RESISTANCE.....	31
1.1.1.1 Anisotropic Nature of Wood.....	6	2.7.2 Fire rating of heavy timber	32
1.1.1.2 Hygroscopic	7	2.7.3 Improving Fire Resistance	32
1.1.1.3 Variability by Species	8	2.7.3.1 Utilize larger members.....	32
1.1.1.3.1 Hardwoods vs Softwoods	8	2.7.3.2 Fire Protective Coverings	32
1.1.1.3.2 Species Groups.....	9	2.7.3.3 Chemical Fire Protection	33
1.1.1.4 Variability within a Species / Grade Classifications	9	3.0 ADVANTAGES OF TIMBER.....	33
1.1.2 Specific Gravity	10	3.1 LOW SELF WEIGHT	33
1.2 WOOD DETERIORATION	11	3.2 RAPID INSTALLATION	34
1.2.1 Fungal Decay	11	3.3 LOW INITIAL COST.....	34
1.2.1.1 Preventing Decay	12	3.4 REDUCED CARBON EMISSIONS	36
1.2.1.1.1 Decay Prevention through Design .	12	3.5 CHEMICAL RESISTANCE.....	39
1.2.1.1.2 Decay Resistant Species	12	3.6 FATIGUE RESISTANCE	39
1.2.1.1.3 Chemical Preservatives	13	3.7 REINFORCED GLULAM	39
1.2.1.1.3.1 Oil Based vs. Water Based.....	13	3.7.1 Moment Reinforcement	40
1.2.1.1.3.2 Pentachlorophenol.....	14	3.7.2 Shear Reinforcement.....	41
1.2.1.1.3.3 Copper Naphthenate.....	14	3.7.3 Pile Wraps.....	42
1.2.1.1.3.4 Creosote	15	3.7.4 Retrofits.....	43
1.2.1.1.3.5 DCOI.....	15	4.0 SCOPE OF TIMBER BRIDGE MARKET.....	44
1.2.1.2 Field Treatments	15	4.1 CURRENT SIZE OF NORTH AMERICAN TIMBER BRIDGE INDUSTRY	44
1.2.1.3 Effects of Fungal Decay on the Properties of Wood	17	4.1.1 National Bridge Inventory	44
2.0 PERCEIVED BARRIERS TO TIMBER	17	4.1.2 Atlantic Canada.....	46
2.1 TIMBER SERVICE LIFE.....	18	4.2 NEW TRENDS IN TIMBER BRIDGE INDUSTRY	46
2.2 SUSCEPTIBILITY TO DECAY.....	19	4.2.1 Recent Use in Atlantic Canada	46
2.3 MAINTENANCE COSTS	19	4.2.1.1 Use of Local Resources	47
2.4 LACK OF KNOWLEDGE	20	4.2.2 Recent Trends in Europe.....	48
2.4.1 No Specs in State and Provincial Codes.....	20	5.0 EXAMPLES OF TIMBER BRIDGES.....	48
2.4.2 Limited Coverage in Engineering Schools.....	21	5.1 HISTORIC STRUCTURES	48
2.4.3 Limited Experience among Contractors.....	22	5.1.1 Keystone Wye.....	48
2.5 INEFFECTIVE INSPECTION AND MAINTENANCE STRATEGIES.....	22	5.1.2 Golden.....	50
		5.1.3 Glulam Bridges on Vancouver Island .	53
		5.1.4 Kindee	56
		5.1.5 Kintai Bridge.....	58

5.2	NORTH AMERICA	60	5.3.1.5	Kjøllsæter	84
5.2.1	Roger Bacon Bridge.....	60	5.3.1.6	Asta	85
5.2.2	McGillivray Bridge K162	67	5.3.1.7	Flisa.....	86
5.2.3	Meadow Lake Bridge 61.4.....	70	5.3.2	Krastalbrücke	87
5.2.4	Canadian Pacific Railroad Overpasses	72	5.3.3	Nissan River Bridge.....	88
5.2.5	Overpeck Park Bridges	75	5.4	AUSTRALIA	89
5.2.6	Mistissini Bridge	76	5.4.1	Cowley Creek Bridge.....	89
5.2.7	Tamiscame River Bridge	78	5.4.2	Queensland Rail Overpasses.....	90
5.2.8	Lighthouse Bridge.....	79	5.4.3	Newry Island	92
5.3	EUROPE.....	80	6.0	CONCLUSION	94
5.3.1	Norway.....	80	REFERENCES.....		95
5.3.1.1	Sletta	80			
5.3.1.2	Skogsrud	81			
5.3.1.3	Tretten	82			
5.3.1.4	Evenstad.....	83			

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 of timber make it a desirable material for bridge construction and it remains a cost competitive option when compared to other material choices. 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. There are over 100,000 timber railway bridges in North America. In addition there are over 50,000 timber forestry road bridges in North America. While the share of timber highway bridges in terms of the total of nearly 950,000 highway bridges in North America 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).

1.0 Introduction to Timber

1.1 Properties of Wood

1.1.1 Variability

One of the most important factors to understand, when considering wood as a building material, is the wide range of variability. All of the physical properties of wood, including strength, stiffness, weight, and dimensions, can vary according to a number of factors. These factors can include the species of tree, growth conditions, and moisture content. Furthermore, wood is anisotropic, meaning the mechanical properties vary depending on what direction forces are applied.

1.1.1.1 Anisotropic Nature of Wood

Wood is an anisotropic material, meaning its properties vary depending on orientation. On a cellular level, trees are made up of long, vertical fibres that carry water and nutrients from the roots up to the branches and leaves. As a tree grows, new fibres are added to the outside of the trunk in concentric rings. This structure gives the wood varying properties along three different axes: longitudinal (also known as parallel-to-grain), tangential, and radial. For structural design purposes, tangential and radial properties are often considered together and referred to as perpendicular-to-grain; however, in some cases, especially when considering potential shrinkage and warping it may be important to consider radial and tangential properties separately.

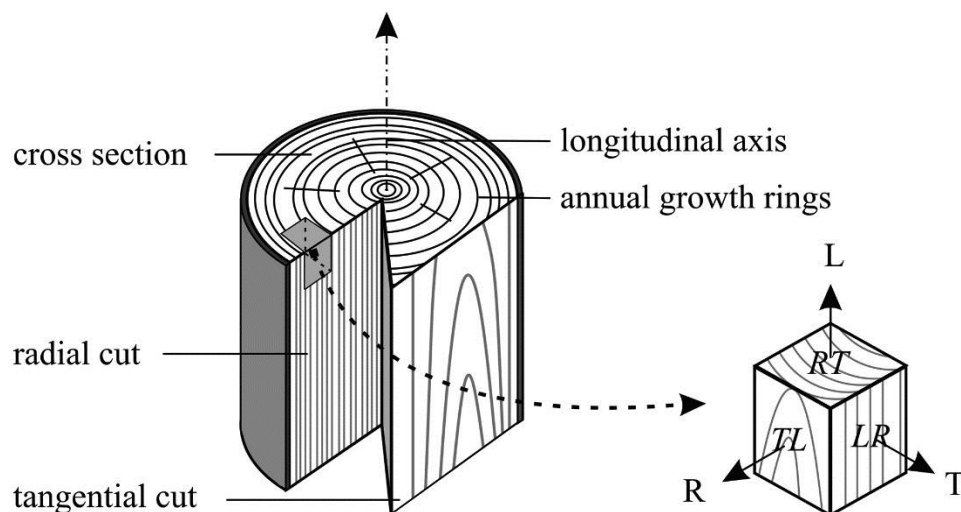


Figure 1-1: Grain structure of showing longitudinal (L), radial (R), and tangential (T) axes.

In general, wood is strongest when resisting compression forces applied parallel-to-grain, followed by tension parallel to grain. As such, lumber is typically cut with the long axis parallel to the grain, so that

applied axial and bending loads generated parallel-to-grain stresses. When loaded in compression perpendicular-to-grain, wood is significantly weaker and becomes susceptible to crushing; this must be considered, for example at the bearing points of a horizontal spanning girder. Wood is weakest by far when loaded in tension perpendicular to grain. Care should be taken when designing a structure to avoid arrangements that may result in tension perpendicular to grain.

1.1.1.2 Hygroscopic

Wood is hygroscopic, meaning that it can absorb moisture from its surroundings. Changes in moisture content will affect other physical properties, such as dimensions and strength. Controlling moisture content is also important preventing decay. Moisture content (MC) is referred to as a percentage representing the weight of water in a sample, relative to the dry weight of the wood (e.g. a sample at 20% MC is 20% heavier than the same sample at 0% MC). This means that wood can have a moisture content of greater than 100%. This simply means that the weight of water in the sample is greater than the weight of wood; this is often the case with green (freshly cut) lumber.

Water can be stored in wood either in the cell cavities (free water) or in cell walls (bound water). As wood dries, the free water is lost first. The point at which all of the free water is gone (i.e. the cell cavities are empty) but the bound water remains is known as the fibre saturation point (FSP). The fibre saturation point varies according to species and other factors, but a typical value is approximately 26-30% MC. As the wood continues to dry below the FSP, and the bound water leaves, the wood properties begin to change. Most notably, the wood will shrink as it dries.

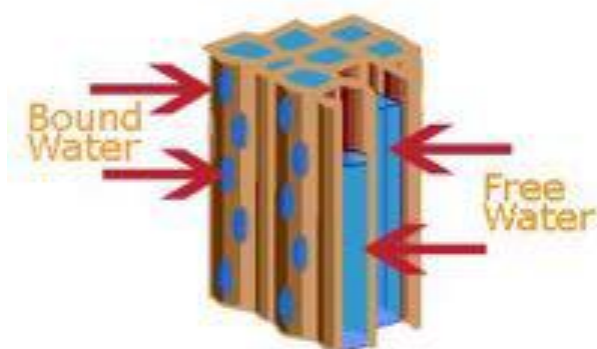


Figure 1-2: Cell structure of wood, showing free water (in the cell cavities) and bound water (in the cell walls).

Shrinkage is typically greatest in the tangential direction and slightly less in the radial direction. Typical North American species range from 2-7% radial shrinkage and 5-13% tangential shrinkage when drying from FSP to oven-dry. Often the precise grain orientation is not known, and it is sufficient to use

an average of radial and tangential values to estimate shrinkage; in some special cases it may be important for the designer to specify the grain orientation so shrinkage can be more precisely accounted for. When the growth rings are not orthogonally aligned to the faces of a piece, the combined radial and tangential shrinkage may cause distortions to the cross-sectional shape, such as cupping, twisting, or diamonding. Some species, such as ipe, have similar radial and tangential shrinkage, minimizing these distortions; thus, they are often used to make wood dowels so that they stay round during MC change. Shrinkage in the longitudinal direction is much smaller and is generally considered negligible in structural design.

Shrinkage must be accounted for in connection design – especially where large members are connected using steel brackets and multiple bolts. If the steel connectors restrict the relative positions of the bolts, then when the wood shrinks between the bolts, tension stresses will be generated perpendicular to the grain; these stresses can be enough to crack the wood member.

1.1.1.3 Variability by Species

The properties of wood can vary widely according to species. For design purposes, species are often grouped into various categories with other species that share similar characteristics.

1.1.1.3.1 Hardwoods vs Softwoods

The broadest categories used to classify species of wood are hardwoods and softwoods. As the name implies, hardwoods are often denser and harder than softwood. However, this is not always the case; some hardwoods (such as basswood or balsa) are very light and soft, while some softwoods may be much harder.

The true distinction between hardwoods and softwoods are biological differences between the trees they come from. Hardwoods come from angiosperms (flowering plants); these are most often broadleaf, deciduous trees. Softwoods, on the other hand, come from gymnosperms, meaning “naked seed”; these are usually evergreen, coniferous trees. Hardwoods have a more complex cellular structure than softwoods with the distinctive feature being the presence of vessels within hardwood. In hardwoods there are two types of cells that make up the water transport system; vessels and tracheids. When viewing the end-grain of a piece of hardwood, the vessels can be seen as relatively large pores between the smaller tracheid cells; depending on the species, magnification may or may not be required to see the pores. Softwoods do not contain vessels; with only tracheids present, the end grain will have a more uniform appearance.

1.1.1.3.2 Species Groups

For design and marketing purposes, it is often not practical to differentiate between every possible species. Design standards and lumber grading agencies typically designate species combinations made up of species that share similar properties. These species combinations are assigned design values (such as strength and modulus of elasticity) that are used for all of the species within the group.

Examples of species groups designated in CSA O86 are Douglas Fir-Larch (Douglas fir and western larch), Hem-Fir (Pacific Coast hemlock and Amabilis fir), Spruce-Pine-Fir (spruce, jack pine, lodgepole pine, balsam fir, and alpine fir), and Northern Species (any Canadian species allowed by the National Lumber Grades Authority).

If the designer simply specifies the species combination, the builder can use any of the individual species interchangeably. Alternatively, the designer may require a specific species. For example, Coastal Douglas fir is often specified for its superior treatability compared to the other species in the Douglas Fir-Larch combination. This treatability is due to the absence of aspirated pits. When the pits are not aspirated they allow the passage of treatment liquid perpendicular to the grain for deeper more effective preservation of the wood for bridge manufacture.

1.1.1.4 Variability within a Species / Grade Classifications

Within a given species or species combination, properties can vary according to growing conditions, the age of the tree when it was harvested, and many other factors; these can effect properties such strength, density, and hardness. Local defects such as knots, splits, checks, and sloping grain can weaken a member.

To account for this variation, lumber can be assigned to a structural grade. Lumber grades are determined according to rules published by various grading agencies. In Canada, these rules are written by the National Lumber Grading Agency (NLGA); the rules have been standardized throughout North America such that the NLGA grades are consistent with the grade defined by the US agencies. These rules may be based on visual grading or mechanical grading. For visual grading, trained inspectors check characteristics like tightness of grain, size and number of knots, and presence of splits or checks; they then assign a grade according to the established rules. For mechanical grading, properties such as density and Modulus of Elasticity are directly measured, and formulas are applied to assign the grade.

Within a given grade of lumber, variation will be much lower than within the species as a whole. Design values for structural properties such as strength and stiffness are assigned to each grade and published in the applicable building code or design manual.

1.1.2 Specific Gravity

Compared to other building materials, wood has a relatively low density. Density is the mass of a material per unit of volume (e.g. pounds per cubic foot or kilograms per cubic meter). When discussing the density of wood is typically expressed as specific gravity (SG); this a unitless ratio of the density of the wood sample to the density of water. This allows the use of SG values to describe wood characteristics in a way that is independent of type of units used.

Since wood is hygroscopic and its dimensions change with moisture content, both the measured weight and volume will vary according to the moisture content at the time of measurement. Thus, it is important to know the conditions under which the measurements are taken. The weight and volume may not always be taken under the same conditions.

When comparing the material properties of various species of wood, it is common to use the oven-dry specific gravity; this means both weight and volume are measured in the oven-dry condition (0% MC). This condition can be easily reproduced in a laboratory setting when conducting tests, but it does not represent a real world use-case. When calculating the self-weight of a structure, it is best to use conditions that will approximate the in-service moisture content. For an interior structure, this is often approximated as 12% MC; this may be referred to as the air-dry specific gravity. Additionally engineering wood such as glulam beams are manufactured at 12-15% MC as this is midway between FSP and oven dry such that the wood is the most dimensionally stable in various environments. In addition this moisture is ideal for wood glue use that requires dehydration of the glue to cure. Other values that may be used include 19% MC (the maximum allowable moisture content for dry-service conditions, this is the typical MC value targeted for solid sawn lumber such that it will not support fungal activity) or the fibre-saturation point, usually estimated at 26-30% MC.

Oven-dry specific gravity for commercially available North American species range from 0.30 to 0.75. The most commonly used softwoods falling near the middle of that range, from 0.40 to 0.50; these correspond to air-dry (12% MC) densities of 350 to 500 kg/m³. By comparison, reinforced concrete has a density of 2400 kg/m³, and steel has a density of 7850 kg/m³. This allows wood structures to be much

lighter than their steel or concrete counterparts for a given load capacity, which in turn allows for smaller members and reduced foundation sizes, potentially leading to significant cost savings.

1.2 Wood Deterioration

Wood deteriorates for a number of reasons which adversely affects the wood properties. The two primary causes of deterioration in wood are biotic (living) agents and physical (nonliving) agents. The physical agents that may deteriorate wood include chemical agents (e.g. ferric degradation), ultraviolet light, erosion or abrasion (e.g. wind, water, tire wear), and impact damage. Biotic agents include fungi, bacteria, insects, marine borers, and birds. Often, these agents compound on each other, with one form of deterioration creating conditions that allow another form of deterioration to occur. For example, insects may attract woodpeckers, or tire wear may break through the preservative layer, allowing decay to proceed.

1.2.1 Fungal Decay

Biotic agents that attack wood including bacteria, fungi, insects, and marine borers are living organisms. Like all living organisms, they require certain conditions for survival. These conditions include appropriate levels of moisture, oxygen, and temperature, as well as a source of food; the food is typically the wood itself. When these basic living conditions are provided, biotic agents of wood deterioration will freely proliferate. But if any one of those conditions is removed, the wood is safe from further biotic attack.

Fungal decay is the most common form of wood deterioration. When exposed to favorable levels of moisture, oxygen, and temperature, most types of wood become an attractive food source for a variety of decay-producing fungi. The precise conditions vary according to the species of wood and the species of fungi, but some general rules apply. The fungi require moderate temperatures. Growth progresses most rapidly between 10°C and 35°C. Outside of this range, growth significantly slows; below 2°C or above 38°C, growth will cease. Moisture content (measured as a percentage of the dry-weight of the wood) typically needs to be above 22% for fungal growth. Lastly, there must be sufficient oxygen; if the wood is fully saturated with water, the oxygen supply (>21%) will be cut off, and fungal growth will stop. If any of these conditions is not met, fungal decay will cease. However, it is important to note that this typically does not kill the fungus. The fungus goes dormant, but remains in the wood; as soon as the favorable conditions, fungal growth and decay will resume.

1.2.1.1 Preventing Decay

Preventing decay in timber structures begins by identifying which of the four conditions for fungal growth (moisture, oxygen, temperature, and food) can be controlled. Removing one or more of the conditions stops the decay from occurring. Temperature and oxygen levels are factors of the surrounding environment, and under real-world conditions, the designer will have little or no control over them. Decay prevention typically focuses on controlling moisture through design details and/or the use of chemical preservatives or decay resistant species which make the wood a less desirable food source.

1.2.1.1.1 Decay Prevention through Design

Moisture can often be controlled through simple design interventions. Careful consideration of geometry, drainage, and connection details can keep moisture content low enough to prevent decay, but poor details can greatly accelerate decay. Connections with exposed vertical fasteners create a path for moisture to reach the center of the wood members; this is especially problematic where preservative treated wood is used, and the fasteners allow water past the treated surface layer. Poorly placed deck drains may direct water onto structural elements below; improper use of flashings or waterproof membranes may trap moisture and prevent air-flow; exposed horizontal surfaces may allow water to pond. These conditions can all cause elevated moisture content and accelerated decay. Whenever possible, a bridge should be designed to shed water away from the structure, while allowing maximum air flow to keep the elements dry. Throughout Atlantic Canada there are numerous examples of timber covered bridges that have lasted well over 100 years with minimal repairs and without the use of chemical preservatives; this is achieved simply by keeping moisture away from the main structural elements. In these bridges it is most often the metal components that are corroded that need to be replaced. The wood outlasts the steel!

1.2.1.1.2 Decay Resistant Species

When a structure will have moderate exposure to moisture and weather, longevity can be improved by selecting a decay resistant species. Certain species of wood are more decay resistant than others, and for most species, the heartwood is more decay resistant than the sapwood. This is often a desirable alternative to chemical preservatives for elements, such as handrails, that will have direct human contact. Common decay resistant species in North America include Alaskan Yellow Cedar and Redwood. Many tropical hardwoods are also highly decay resistant.

1.2.1.1.3 Chemical Preservatives

When it cannot be ensured that moisture will remain low enough to prevent decay, chemical agents can be used to make the wood an inhospitable environment for fungal growth.

There are a variety of chemical preservatives used to prevent fungal decay in wood. These are pesticides which are toxic to the fungi that cause wood decay. They are typically applied to the wood through the process of pressure-treating. The wood is placed in a high-pressure cylinder and undergoes various cycles of vacuum, high-pressure, submersion in the preservative chemical, and sometimes heat. This processes allows deeper penetration and higher, more uniform levels of preservative retention than can be achieved with other application methods, such as brushing or dipping.

Ideally, all machining (cutting, drilling, etc.) of the timber components should be completed before they are pressure treated. This ensures that no bright-wood (the untreated wood at the center of a member) is exposed in the finished structure. If field modifications cannot be avoided, any new holes or cut surfaces should be field-treated with a preservative. The typical preservative for field treatment is Copper Naphthenate; it is a non-restricted pesticide which is available for purchase in hardware stores. Incising of the wood to be treated is the process of installing slots in the surface of the wood typically 5/8" deep, 1/8" thick, and 1/2" long parallel to the grain. There is a pattern used for maximum effectiveness but typically the slots can be no more than 2" apart transverse to the grain and 6" apart parallel to the grain. Incising doesn't affect the strength of the wood element and provide for better depth of penetration and uptake of the preservative. The uptake and depth of penetration are improved by the exposure of end grain where moisture flow is 100 times faster than perpendicular to grain.

1.2.1.1.3.1 Oil Based vs. Water Based

Preservative pressure-treatments are broadly categorized as either water-borne or oil-borne, depending on the type of solvent used to carry the pesticide chemical.

As the name implies, water-borne preservative are dissolved in water. They typically leave the wood with a dry, paintable surface and have little odor. These are seen as advantages in light-frame construction and consumer products. Most pressure treated wood sold at lumber yards and hardware stores is treated with water-borne preservatives. Water based-preservatives include Copper Chromium Arsenate (CCA), Copper Azole (CA), Alkaline Copper Quaternary (ACQ), and Ammoniacal Copper Zinc Arsenate (ACZA), among others.

However, the water-based carrier causes swelling during treatment, which is problematic when components are to be machined prior to treatment. The rapid swelling that occurs during pressure treatment can also damage the glue joints in glulam timbers. Water-based preservatives are also more susceptible to leaching when exposed to rain or standing water, which can cause environmental contamination.

Oil-borne preservatives are dissolved in petroleum based solvents; these are further classified as either heavy-oil (diesel) or light-oil (mineral spirits). Heavy-oil treatments tend to leave a residue on the wood surface and can have a significant odor; therefore oil-based preservatives are typically limited to outdoor and industrial applications, where human contact is limited. The oil residue does provide some water resistance to the wood, which helps improve dimensional stability and minimize cracking. Oil-borne preservatives generally provide greater durability where ground- and water-contact are expected, so they are typically preferred over water-borne preservatives for industrial uses such as bridge timbers and utility poles.

1.2.1.1.3.2 Pentachlorophenol

Pentachlorophenol is a crystalline solid first produced in the 1930s and widely used as a wood preservative since the 1940s. Historically, it has been used as a pesticide for many purposes and may have been applied by sprayer, brush, or dipping, but its use is now limited to industrial wood preservation through the pressure-treating process. For pressure treating, it may be dissolved in either heavy-oil or light-oil solvents; heavy-oil is generally preferred, as it is more durable where ground- or water-contact is likely.

1.2.1.1.3.3 Copper Naphthenate

Copper Naphthenate is a salt derived from copper and naphthenic acid. It has been widely used as a preservative since the 1940s. It can be dissolved in either heavy- or light-oil, and a water-based formula is also available. The heavy-oil formula provided the most durability and the most commonly used formula.

Unlike most other preservatives, copper naphthenate is listed as an unrestricted pesticide by the EPA, meaning no special certification is required to purchase or apply the chemical. Copper naphthenate is available for purchase in liquid form at many hardware stores, and it is commonly used as a field treatment to protect cut ends or holes that are made after the piece has been pressure treated.

1.2.1.1.3.4 Creosote

Creosote is the oldest available wood preservative and is still in use for bridges, railroad construction, and utility poles. Creosote is distilled from coal-tar and is a thick, dark, oily liquid. Creosote may be diluted in oil-based solvents or may be used undiluted.

Creosote is the only oil-borne treatment standardized for use in seawater environments where wood will be susceptible to attack by marine borers. Creosote is different from Penta or Cu Nap treatments in that it is a cell lumen treatment not a cell wall treatment.

1.2.1.1.3.5 DCOI

DCOI is a preservative ingredient available in either oil-borne or water-borne formulations. The oil-borne formula has recently been approved for treatment of utility poles, cross-arms, and bridge timbers. DCOI is nearly colorless and imparts very little color change to the treated wood. DCOI is being marketed as a more environmentally friendly alternative to Creosote or Pentachlorophenol, with lower ecotoxicity and less risk of soil and water contamination.

1.2.1.2 Field Treatments

The pressure treating chemicals discussed above are typically applied in specialised facilities at the time of manufacture. Other treatment options are available for treating timber elements that are already in service.

Copper naphthenate, discussed above, is the only pressure chemical that is also available for purchase by consumers. It can be purchased as brush-on liquid and is frequently used for field-treat timber elements. The most common application is treating cut surfaces or drilled holes when pressure-treated elements are field modified.

Fumigants were developed to provide in-situ chemical treatment of timber elements. The initial use of the technology was for utility poles, it has since expanded to timber bridge columns and beams. Fumigants are applied by drilling holes in the timber and installing the chemicals in either liquid, solid rod, or powdered form. Over time, the chemicals vaporise and travel through the wood. These chemicals are toxic and kill the decay causing fungi.

Diffusers are similar to fumigants, except they do not begin to vaporise until the moisture content of the wood rises above approximately 20%. This allows the diffusers be utilised more efficiently, as they will remain intact until conditions reach the point where decay may begin. Diffusers are solid rods which

typically consist of borate salts. In contrast to fumigants, these salts have low toxicity. Rather than killing the fungi directly, they function by neutralizing the PH wave that is created by fungi hyphae secreting acidic enzymes that break down the wood. This makes the wood no longer a suitable food source for the fungi, preventing continued decay.



Figure 1-3: Diffuser Rods



Figure 1-4: Diffuser rod installation in bridge piles (left) and girders (right). The yellow plastic bungs are the locations of diffuser rods.

1.2.1.3 Effects of Fungal Decay on the Properties of Wood

The primary effects of fungi attack on wood can be characterized by the following points (Bodig & Jayne, 1993):

1. Change of color
2. Change of odor
3. Decreased weight
4. Decreased strength
5. Decreased stiffness
6. Increased hygroscopicity (easier absorption of water)
7. Increased combustibility
8. Increased susceptibility to insect attack

The incipient stages of fungi attack are characterized by a change of color and perhaps a change in the odor and may not be detected by changes in hardness or by surface tests. This stage may be very difficult to detect visually. Decay may reduce the mechanical properties by 10 percent before any significant weight reduction is noticed. When weight loss is between 5 and 10 percent, the reduction in mechanical properties may be reduced 20 to 80 percent (Clausen, 2010). Advanced stages of fungi attack reduce the specific gravity (weight) which decreases nearly every other mechanical property, including strength and is indicated by soft, punky, or crumbly wood. Usually when decay is discovered by visual inspection, the damage has already been done.

2.0 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. 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).

2.1 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, it is resistant to fatigue damage from repeated loading, and large timber members can have fire-resistant properties equal to or better than other building materials (Ritter, 1990). 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).

In European countries, timber bridges are often designed for a service life of 80 to 100 years. In Sweden, for example, there were over 800 timber bridges built between 1994 and 2013, including over 300 highway bridges (Gustafsson, et al., 2014). Swedish bridge design codes include prescriptive design requirements to achieve either 40 or 80 year design service life. Sweden prohibits the use of chemical preservatives, including creosote, chromium, and arsenic, so the design requirements generally depend on sheltering the structural elements from exposure to moisture (Troive, 2005).

A study of bridge condition ratings in the US National Bridge Inventory in 1994 showed 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. Furthermore the study showed that bridges on federal Interstate and numbered highways had better performance while county highways and city streets had lower performance. The federal highway system tends to be built to higher design standards and have greater access to maintenance funding than county and city roads. This indicates bridge longevity is effected more by design standards and maintenance practices than by material selection.

A more recent study involved in-depth inspections of 132 timber bridges throughout the United States; most of these bridges were constructed from either Douglas fir or Southern Yellow Pine and were treated with either pentachlorophenol or creosote. The study found examples of both solid sawn and glulam bridges that have been in service for 70 to 75 years and remain in satisfactory condition (Wacker & Brashaw, 2017).

2.2 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 decay. The conditions that allow for decay are well understood; decay causing fungi require adequate oxygen, moderate temperatures (2 to 38 °C), sufficient water (moisture content above 19%), and access to a food source (the wood itself). If any of these conditions is removed, decay will not proceed. The easiest of these conditions to control is moisture content. Careful design details that shed water away from the structure and allow air flow for quick drying can keep moisture content low enough to prevent decay.

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). See Section 1.2.1.1.1 for additional discussion on designing protected structures to prevent decay.

When these design details are combined with chemical preservatives such as creosote, pentachlorophenol, and copper naphthenate, decay can easily be prevented, allowing for a service life comparable to other materials. Chemical preservatives are discussed in more detail in Section 1.2.1.1.3. While preservative treatments are an effective way of limiting decay, designers should not become overly dependent on them. Preservatives should be used in conjunction with careful design details to minimize the risk of decay.

2.3 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 often assume that maintenance costs will be higher for timber than for other materials; however, a recent investigation found that the maintenance costs for properly protected timber bridges are 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.

2.4 Lack of Knowledge

The above misconceptions about timber largely stem from lack of knowledge and experience with 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. One of the key reasons that timber maintenance costs have been considered higher than steel and concrete is that the current maintenance and design methods are archaic and not effective. They actually reduce the timber bridge life not extend it. Proper design and maintenance details are required for bridge owners to see the proper value in their inventory and for extension of life. 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 around timber. This increased knowledge will make designers and bridge managers more comfortable with timber, and help dispel some of the misconceptions.

2.4.1 No Specs in State and Provincial Codes

In Canada and the United States, bridge design is regulated in a multi-tiered system. The national bridge design codes (CSA S6 - Canadian Highway Bridge Design Code in Canada and AASHTO LRFD Bridge Design Specifications in the United States) regulate all bridges within each country. These codes both permit timber as a bridge material and contain sections detailing its use. Each code references a separate document, which defines the material properties to be used when engineering with timber.

AASHTO references the National Design Specification for Wood Construction (ANSI/AWC NDS), and the Canadian code references CSA O86, Engineering Design in Wood.

In addition to the bridge codes, the Federal Highway Administration (FHWA) publishes design guidelines and specification to be used on all federal highway projects. These documents go beyond the requirements in the bridge codes, by specifying the policies of the FHWA. Whereas the bridge codes are primarily concerned with structural integrity of the bridge, these specifications and guidelines are also intended to create cost-savings, simplified maintenance, and consistency throughout the federal highway system. These documents only briefly address timber bridges, with much more focus on steel and concrete structures.

State and Provincial transportation departments typically have a set specifications and design manuals that govern projects that are managed by the state. Additionally they serve as guidelines for counties and municipalities to use on local projects.

In general, most states and provinces allow the use of timber, but the information and guidance they provide is very limited compared with what they provide for steel and concrete construction. In some cases, timber is allowed, but clearly discouraged. In many cases, the recommendations in these documents are outdated and do not reflect modern technologies or current best-practices. For example, most of the specifications require that deck planks be secured with vertical spikes into the tops of timber stringers; this is still a common practice, but it will greatly increase the rate of decay in both the deck and the stringers. While most states provide standard drawings for simple concrete bridges, few states have standard drawings for timber structures. In our literature review, no standard drawings for timber structures were found for Canadian provinces.

2.4.2 Limited Coverage in Engineering Schools

Over the last several decades, there has been a significant decline in wood design being taught in North American engineering schools. A 2016 survey showed that only 55% of structural engineering programs offer a dedicated timber design course. By contrast 100% of the surveyed programs offered at least one steel design and at least one concrete design course. 58% of programs offer two steel design courses and 63% offer two concrete design courses (Perkins, 2016).

Among the programs that offer timber design courses, it is typically offered as an elective, rather than a core required course. In many cases, the timber design it is not offered every year, and it may be combined with a masonry design course (Lawson, Kam-Biron, & Perkins, 2019). From 1978 to 1994, the

portion of civil engineering students who were required to take a wood design course dropped from 14% to 9%. This rate has almost certainly continued to decline (Gupta & Gopu, 2005).

As a result of this lack of focus on timber design in engineering schools, students are graduating with little or no exposure to the use of wood as a structural material. As these students enter the workforce, they are likely to avoid the use of timber in their professional careers (Lawson, Kam-Biron, & Perkins, 2019). With recent interest in mass-timber construction and tall wood buildings, there is increasing demand for timber designers in the industry. Students also show significant interest in learning more about timber design. Current engineering curriculums in the United States and Canada are not meeting these demands. Schools are beginning to explore ways of introducing additional timber education to their curriculums; this could include adding new timber design courses or integrating timber design into existing courses. Evidence has shown that even a small increase in timber coursework significantly increases students' confidence in contributing to the design of a timber structure (Chorlton, Mazur, & Gales, 2019).

2.4.3 Limited Experience among Contractors

There are relatively few contractors who have experience with heavy timber construction. The vast majority of wood used in the building industry goes into light wood framed residential structures; this requires a different skillset and knowledge base from heavy timber construction. Larger structures, such as high-rise buildings or bridges, are most often built from steel or concrete. As a result, there is a lack of builders with knowledge of heavy timber construction. A recent study conducted at the University of Toronto (Syed, 2020) found that the two biggest challenges to mass timber construction in Canada are “inadequate skilled workforce” and “inadequate specialized subcontractors”.

2.5 Ineffective inspection and maintenance strategies

Over the last several decades, advances have been made in preservative treatments, glulam technology, and construction methods that have greatly improved the durability of timber structures. Unfortunately, these improvements have not always been adopted by bridge owners maintaining existing timber bridges. The lack of experience among engineers and builders, discussed above, means that many bridge owners are still utilizing outdated inspection and maintenance strategies which are adversely affecting the lifespans of timber bridges.

The items below are some basic improvements to maintenance practices that can help prevent the premature decay of timber structures. Utilizing these methods will significantly increase the lifespan of a structure and encourage the bridge owners to utilize timber more often in their networks.

2.5.1 Utilize Non-Destructive Testing

The traditional method for identifying and assessing internal decay in timber bridges has been bore-sounding, in which a small hole is drilled into a member, and a probe is inserted to measure the cavity size. This testing method is damaging to the timber, and it creates a path for water to enter the member. When this test is repeated in subsequent inspections, the damage can be substantial as shown in Figure 2-1. Furthermore, because of the destructive nature of this test its use must be limited to relatively few locations on the bridge and significant areas of decay can easily be missed.



Figure 2-1: Repeated bore sounding on this road-over-rail bridge in Queensland has created a path for water and insects to enter the timber elements, and eventually destroyed the elements' integrity.



Figure 2-2: This photo demonstrates the danger of using bore sounding to locate decay. The pile was tested with a sounding hole from the wrong side of the pile and the cavity, caused by the track spike visible at the top left, was not detected.

Advanced non-destructive testing methods exist that can be more effective in locating decay without damaging the timber. One of these test methods is Stress Wave Timing (SWT). Degraded wood or cavities caused by decay can be found by measuring the velocity of a sound wave traveling through the timber. The sound wave is introduced by striking the member with a hammer which contains one half of a transducer pair, which also starts a timer. When the wave reaches a receiver containing the other half of a transducer pair held on the opposite side of the member, the timer is stopped. See Figure 2-3. The velocity of this wave is related to the Modulus of Elasticity and the density of the timber, and can be used to identify where the timber has been degraded by decay. Because this test is non-destructive, it can be used in more locations throughout the bridge as shown in Figure 2-4. This method also has the advantage that it can detect decay before a cavity has formed. As little as 10% reduction in density due to decay can cause as much as a 75% loss of strength, so detecting decay before a cavity has formed is clearly important.



Figure 2-3: Taking readings with the stress wave timer



Figure 2-4: A crew inspects a railroad bridge. Yellow chalk marks indicate where SWT readings will be taken. This frequency of testing would be impractical with destructive methods such as bore sounding.

Compared to bore-sounding, stress wave analysis shows much more about the condition of the bridge, thereby allowing maintenance programs to be targeted more efficiently. This can both reduce maintenance costs and increase the life of the bridge.

2.5.2 Eliminate Vertical Fasteners

Traditional timber bridge construction frequently uses vertical through-bolts, spikes, and drift-pin connections that have their origins on the top surfaces that are exposed to ambient water. These fasteners provide a path for water to enter the interior of the timber elements, where it cannot readily evaporate. This elevates the moisture content of the wood and promotes decay as shown in Figures 2-5 and 2-6 below.

In spite of the clear evidence for the detrimental effects of vertical fasteners, many state departments of transportation still require these connections in their timber bridge specifications, see more discussion of this in Section 5. Redesigning these connections to use horizontal fasteners is one of the most effective ways to extend the life of a timber bridge. Figure 2-7 below shows examples of connection designs that avoid vertical fasteners.



Figure 2-5: Highly decayed posts in a bridge in Ontario. In both of these posts, a vertical drift-pin is visible in the center of the cavity.



Figure 2-6: Deck and stringers being removed from a bridge in Ontario. There is clear decay at the top of each stringer, originating around the vertical deck spikes.



Figure 2-7: In this replacement bridge in Ontario, the deck is secured using z-clips which fit into pre-cut horizontal slots in the girders and lag screws that do not penetrate the top of the deck. The posts are fastened to the caps and sills using steel face plates and horizontal bolts.

2.5.3 Eliminate Waterproof Membranes

Waterproof barriers such as roofing felt and tin flashing are often used in timber construction in an attempt to protect timber elements from exposure to moisture. Unfortunately, these barriers often have the opposite effect. If space is not provided for sufficient air flow between the barrier and the wood elements, as shown in Figure 2-8, moisture will become trapped and be unable to evaporate. This elevates the moisture content and accelerates decay. In many cases the barriers should simply be eliminated from the design. In cases where protection is necessary, a better solution would be sheet-metal flashing; however, care must be taken to ensure that enough air space is provided between the metal and the timber to allow sufficient air flow and drying of the timber.



Figure 2-8: Waterproof coverings such as these are ineffective at keeping the timber dry, especially where they are penetrated by fasteners or subjected to flooding. Instead they limit air flow and cause the moisture content to remain elevated.

2.5.4 Avoid High-Solids Paints

Another common mistake when attempting to protect timber from moisture, is painting large timber members as shown in Figure 2-9. Much like the use of waterproof membranes, high-solids paint prevents proper drying of the timber. Over time, small cracks and pores develop in the paint allowing water to enter the timber. The paint then traps this water, keeping the moisture content elevated.

Timber elements with a minimum dimension of 50mm or greater should not be coated with paints containing more than 29% solids. Alternatives include preservative treatments and low-solids wood-stains. Paraffin-based sealants designed for use on end grain help reduce the speed of moisture travel through the end grain; this allow more uniform drying throughout the piece, and thus reduces end checking and feathering. These products do not pose the same problems and should be used instead of paint on large timbers.



Figure 2-9: Examples of painted curbs on two bridges in Australia. Water will inevitably enter these members – through cracks and chips in the paint, as well as through fastener holes – and the paint will slow the drying process.

2.6 Span Capabilities

There is a common perception that timber is a weak material and is not suitable for long-span structures. In fact, timber has a higher strength-to-weight ratio than steel or concrete. This can result in a much lower self-weight for a timber bridge than an equivalent steel or concrete structure. This low weight can be an even bigger advantage on longer span structures, where self-weight becomes a much more important design factor.

While it is true that the majority of the currently existing timber bridges are under 10 meter spans, there are many prominent examples of longer span timber bridges. In 2019, the National Bridge Inventory lists 450 timber bridges with spans of 20 meters or longer in the United States. Section 5 of this report includes several examples of long-span timber bridges throughout North America and Europe.

Superstructure Type	Typical Span	Maximum Span	Notes
Log Beam	6-18m (20-60 ft.)	30m (100 ft.)	Span limited by available trees.
Sawn Timber Beam	5-8m (15-25 ft.)	9m (30 ft.)	Limited by size of available timbers, glulam has become more practical for long spans.
Glulam Beam	6-24m (20-80 ft.)	43m (140 ft.)	Beam size and span limited by fabrication, treatment, and transportation facilities. Fixed End Moment resisting splices can be used to allow longer spans.
Longitudinal Deck		11m (36 ft.)	Includes glulam, nail laminated, and stress laminated decks.
Pony Truss		30m (100 ft.)	
Through Truss	Over 30m (Over 100 ft.)	76m (250 ft.)	
Deck Truss	Over 30m (Over 100 ft.)	76m (250 ft.)	
Glulam 2-Pin Arch		24m (80 ft.)	
Glulam 3-Pin Arch	Over 24m (Over 80ft)	60m 200 ft.	
Suspension Bridge		150m 500 ft.	

Figure 2-10: Span lengths for various timber superstructure types. Typical spans are the lengths that are usually most economical for the given structure type. Maximum spans listed are the longest practical spans under normal conditions. Longer spans may be possible and practical under certain unique circumstances. (Ritter, 1990)

2.7 Fire Resistance

Wood is a combustible material, meaning it burns when exposed to high temperatures. Therefore, it is intuitively assumed that timber structures do not perform well in fires. In fact, large timber members, like those typically used in bridges, have fire resistance comparable to or greater than other building materials.

When wood is exposed to high temperatures (typically around 250° C), the outer surface will ignite. As the outer surface burns, it forms a layer of char. This charred wood loses its structural capacity, but it serves as an insulator, keeping the interior temperature of the wood much lower. The uncharred interior wood maintains its strength, and, thus, the member maintains the capacity of the uncharred section, even when surface temperatures exceed 800° C. Additionally, wood has a relatively low coefficient of thermal expansion; even when exposed to extreme heat, a wood structure can maintain its shape with very little geometric distortion.

By contrast, steel loses strength rapidly when exposed to high temperature. Steel has higher thermal conductivity, so when the surface is exposed to high surface temperatures, that heat quickly spreads through the whole member. As temperature rises, the strength of steel decreases; at a temperature of 800° C, the yield strength of steel can be as little as 20% of the room temperature strength. This can lead to rapid collapse of a structure when unprotected steel members are exposed to fire.

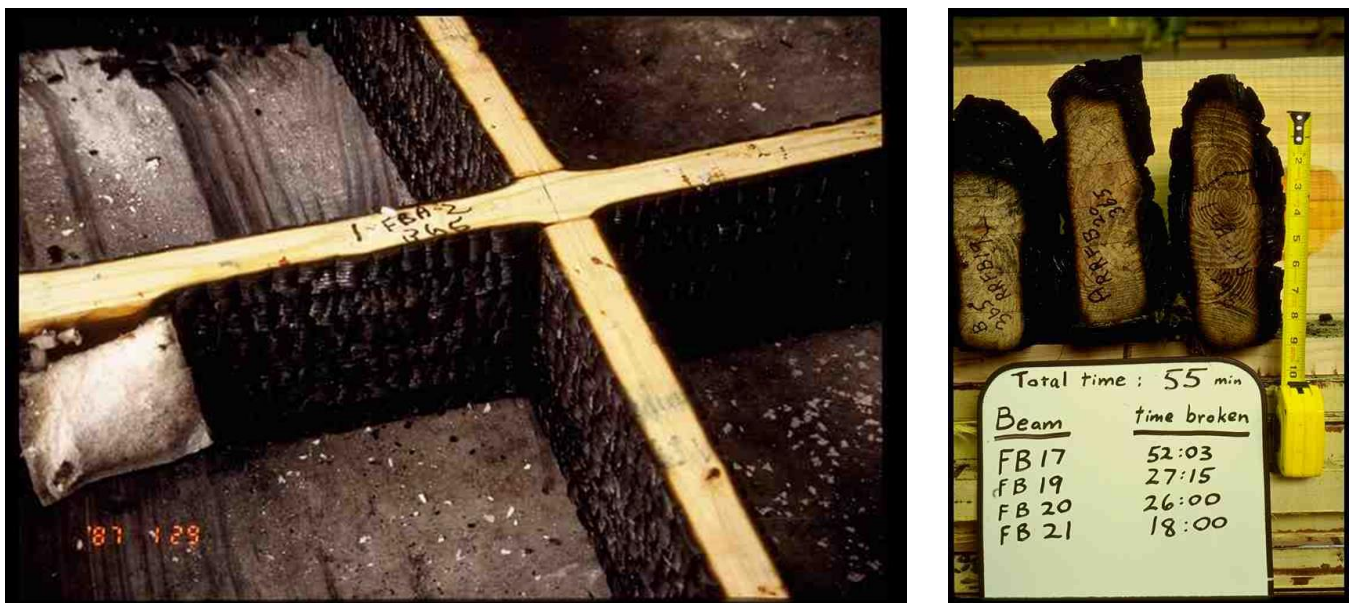


Figure 2-11: Timber beams following fire resistance testing. The charred layers progress from the surfaces that are exposed to fire, while the interiors of the members remain sound.

2.7.2 Fire rating of heavy timber

As wood burns, the outer surface chars, while the interior of the member remains undamaged. The charred layer progresses at a predictable rate; for Douglas fir, it is approximately 38mm per hour. This allows a designer to estimate how much residual capacity a member will have after being exposed to fire for a given period of time. Typically heavy dimension timber with a minimum dimension over 150 mm will have a minimum of 1 hour fire resistance rating.

2.7.3 Improving Fire Resistance

As discussed above, wood can have fire performance equal or greater than that of other building materials. But with any building material, certain strategies must be employed to ensure adequate fire performance. With timber, these strategies may be different than with other materials. With timber bridges the decayed wood in old timber bridges has a lower fire ignition temperature. These decayed areas are also associated with vertical fasteners that originate from the top faces of the timber elements. The steel serves as a thermal conductor during fires and allows heat energy to gain access to the decayed wood thus meaning lower fire resistance ratings for heavily decayed timber bridges. If there weren't these poor connector details the timber bridges would have greater fire resistance. More decay means lower fire resistance rating. Some railway companies now rate their timber bridges in terms of fire and these ratings are directly related to decay in the timber.

2.7.3.1 Utilize larger members

As wood burns, it deteriorate from the outer surface, while the interior maintains its strength. Thus, one strategy for improving fire performance is to reduce the surface area that will potentially be exposed to fire. This means that structures that utilize a small number of large members will perform better than structure that utilize many small members. Building codes define this as *heavy-timber (typically accepted as timber elements with a minimum dimension greater than 6" nominal)* or *mass-timber* construction and allow these structures to be used in larger and higher risk buildings than would be permitted with traditional light-wood framing.

2.7.3.2 Fire Protective Coverings

An alternative to larger members is to use insulating materials to protect the wood members from high temperatures. Typical protective materials include gypsum board, fiberglass, or rock-wool insulation.

This strategy is less applicable to bridge construction, but it is commonly used in architectural construction. This is essentially the same strategy that is used for protecting steel and concrete structures.

2.7.3.3 Chemical Fire Protection

Chemical fire protection systems can be used to improve the fire resistance of timber. A variety of systems are available for different applications.

Fire-retardant-treated (FRT) wood is pressure-impregnated with fire-retardant chemicals to reduce the flame-spread properties. When exposed to heat, the treatments create a chemical reaction which inhibits the spread of flame. These pressure-impregnated systems are recognized by building codes and permitted for use in certain applications where combustible materials would otherwise not be permitted. However, these treatments typically reduced the strength of the wood and increase the rate of char formation. Fire-retardant treatments are typically not recommended for use on glulam timbers or in outdoor applications. Similar treatments are also available in brush-on or spray-on versions; however, these tend to be less effective and would not be classified as fire-retardant-treated wood by the building codes.

An alternative type of treatment is an intumescent coating. These are brush-on or spray-on coatings which expand when exposed to high temperatures. This forms an insulating layer, which protects the wood from the heat and prevents combustion. A variety of these systems are commercially available, often marketed for protection of utility poles. It is important to use a system that has been designed and tested for use on outdoor timber structures. The intumescent are typically silica based, and will tend to trap moisture in the timber elements. When using them, it is important to protect the wood from decay with diffusers or other chemical treatments.

3.0 Advantages of Timber

3.1 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. 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)

3.2 Rapid Installation

Thanks to its light weight and the ability to pre-fabricate components off-site, 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)



Figure 3-1: Installation of a railroad overpass in Queensland. The center span, over the railroad tracks, was pre-assembled alongside the approach road and installed by crane. The light weight of the timber structure allowed this installation to be completed quickly, without interrupting rail traffic.

3.3 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 (resulting in smaller foundations and reduced installation costs) and faster installation, as discussed above. 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 give higher bids for timber projects, compared to contractors that specialize in timber. (Moses, et al., 2017)

Additionally, material costs for the timber superstructure is usually competitive with steel or concrete even before accounting for substructure and installation savings. An extensive survey conducted by the Forest Products Laboratory compared the initial superstructure costs for timber bridges constructed in the 1980s and 90s against those for steel, concrete, and prestressed concrete bridges (Forest Products Laboratory and Federal Highway Administration, 2001). Each timber bridge in the study was matched with one or more steel, concrete, or prestressed bridge located in the same state with similar characteristics including structure length ($\pm 15\%$), number of lanes, load rating, age (± 15 years), and maximum span length ($\pm 15\%$). The results showed that the mean cost per square foot of timber bridges was 2.9% lower than steel and 13.1% lower than concrete; the timber bridges were 28.3% more costly than the matched prestressed concrete bridges. The findings showed that the timber bridge was cheaper than the matched steel bridges in 50% of cases and cheaper than the matched concrete bridge in 53% of cases. The timber bridge was cheaper than prestressed concrete in only 24% of cases. When the matching criteria did not include maximum span length, the results were slightly less favorable to timber.

	No. of Bridges	Cost of Timber Bridge (\$/ft ²)	Cost of Non-Timber Bridge (\$/ft ²)	Cost Difference (\$/ft ²)
Timber vs. Steel	16	\$32.81	\$33.78	-\$0.96 (-2.9%)
Timber vs. Concrete	15	\$27.48	\$31.62	-\$4.13 (-13.1%)
Timber vs. Prestressed	45	\$27.37	\$21.34	\$6.03 (28.3%)

Figure 3-2: Comparison of average superstructure costs for timber bridges and matched non-timber bridges. Note that this comparison does not include substructure and foundation costs; these costs are likely to be lower for timber bridges due to the lower self-weight of timber structures. (Forest Products Laboratory and Federal Highway Administration, 2001)

The results showed a wide range of variations for each material. Costs varied according to a number of factors including structure length, construction type, geographic region, and load rating. For timber bridges, the cost per square foot was lowest for mid-range of structure length (50-100ft) and was higher for both the shortest and longest structures. Costs were lowest in the Midwest region of the United States, which also had the largest number of bridges, representing over half of the timber bridges in the data set. It was noted that there was less cost variation for prestressed concrete bridges; this is likely due to the larger data set for prestressed bridges and the relatively high level of standardization in the prestressed concrete industry.

It was observed that prestressed concrete bridge superstructures tend to be less costly than equivalent timber superstructures, with the prestressed option being less expensive in 66% of cases. This is likely due to the high level of standardization for prestressed bridges. Prestressed concrete bridges tend to be highly standardized, off-the-shelf structures. This allows costs to be minimized through prefabrication and economies of scale. Conversely, timber bridges are more likely to be custom site-specific designs, which may require more on-site labor. Increased standardization in timber bridges may help reduce variation and lower the average costs by eliminating some of the outliers at the high end of the spectrum. Furthermore, underutilization of timber bridges may contribute to the higher cost of timber bridges through lack of knowledge and lack of competition in the timber bridge industry. Increased use of timber bridges should help reduce the average costs.

This study only considered the costs of the superstructure, not the substructure and foundations. As noted above, the low self-weight of timber can result in significant savings on substructure and foundation costs for timber bridges. A typical concrete bridge may weigh more than eight times as much as an equivalent timber bridge. This drastic difference in self-weight allows timber structures to have much smaller substructures and foundations. This will result in reduced material costs as well as reduced labor and site-work costs related to the substructure and foundations. These savings on the substructure will offset the extra superstructure costs when compared to a prestressed bridge.

3.4 Reduced Carbon Emissions

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, a 160 meter glulam girder bridge in Quebec. The design team, at Stantec in Quebec, conducted a life cycle carbon analysis for the timber design along with an alternative design utilizing steel girders and a concrete deck. The analysis found that the timber superstructure and deck had net negative emissions of -981 tonnes of CO₂. This more than offset the emissions from the concrete, steel, and asphalt used in the substructure and elsewhere in the bridge. The total project emissions came to -497 tonnes. By comparison the steel and concrete design would have generated 969 tonnes of CO₂ emissions. Thus, the timber design resulted in a total carbon emission reduction of 1466 tonnes compared to the steel and concrete alternative (Lefebvre & Richard, 2014).



Figure 3-3: Mistissini Bridge, a 160 metre glulam bridge in Quebec, designed by Stantec. A carbon footprint analysis conducted by Stantec found that this bridge sequestered 497 tonnes of carbon (Lefebvre & Richard, 2014).

	Girders and Deck	Miscellaneous Steel and Hardware	Foundation Concrete and Reinforcing Steel	Asphalt Concrete Paving	Total
Timber Design	-981	49	418	16	-497
Steel and Concrete Design	519	22	418	11	969
Total Carbon Emission Savings:					1466

Figure 3-4: Global warming impact in Tonnes CO₂ Equivalent emissions for timber vs steel and concrete designs for Mistissini Bridge (Lefebvre & Richard, 2014).

The life-cycle global warming impacts for various building materials are presented in Figure 3-5. These values are taken from the Athena Impact Estimator for Buildings (version 5.4.0103) software produced by the Athena Sustainable Materials Institute. The carbon sequestration credited to timber are dependent on certain conditions being met; the timber must be harvested from a sustainable source (i.e. the forest is replanted following harvest), and certain assumptions must be made regarding how the timber will be disposed of at the end of its service life. Athena bases their disposal assumption on current disposal practices. In particular, the majority of timber will be disposed of in a landfill with the remainder combusted or recycled, and the majority of landfills attempt to capture landfill gas emissions. If, for example, the wood were incinerated or if landfill gas is not captured, this would result in greater CO₂

emissions to the atmosphere. These impacts are credited to wood in the beyond structure life phase of the life-cycle assessment. Similarly, structural steel is often produced from recycled material and/or recycled at the end of its life. If the steel is produced from recycled material, this is reflected as reduced impacts in the production phase, but increased impacts in the beyond structure life phase. If the steel is recycled after use, this is reflected as negative impacts in the beyond structure life phase. Where the beyond structure life impact is negative, this indicates that more scrap is recycled at end-of-life than was consumed during production. (Athena Sustainable Materials Institute, 2019). A three pinned glulam arch recently built near Amherst Nova Scotia, featured on the cover of this report, had a projected carbon dioxide savings over steel for the same bridge of 3395 metric tonnes.

Material	Production	Construction	End of Life	Beyond Structure Life	Total
Wood					
Glulam	140.61	9.48	17.12	-449.12	-281.90
Small Dimension Softwood Lumber	33.16	23.95	15.51	-350.06	-277.45
Large Dimension Softwood Timber	37.12	62.94	15.51	-365.30	-249.73
Steel					
Steel Plate	9881.66	397.71	286.03	-1810.74	8754.67
Galvanized Sheet	17019.20	495.72	286.03	-6454.02	11346.93
Bolts Fasteners Clips	10024.29	619.13	271.06	5348.23	16262.72
Rebar	7072.77	396.10	161.35	3847.46	11477.68
Concrete					
Concrete 35MPa	369.49	50.71	25.35	0.00	445.55
Concrete 45MPa	376.97	52.20	26.29	0.00	455.46
Concrete Precast	458.27	32.02	26.76	0.00	517.04

Figure 3-5: Life cycle global warming potential, in Tonnes CO₂ equivalent emissions per Cubic Metre of material, from Athena Impact Estimator for Buildings (version 5.4.0103), assuming a project location of Halifax, NS. Life cycle stages include Production (harvest or mining of raw material and manufacturing of the product); Construction (installation on site); End-of-Life (demolition and disposal of the structure); Beyond Structure Life (benefits and loads outside the system boundary). All of these phases include associated transportation. For timber, the beyond structure life impacts include carbon sequestration (negative emissions) and off gassing of carbon dioxide and methane during decay (positive emissions). For steel, beyond structure life impacts include recycling (negative emissions) and consumption of scrap metal (positive emissions); negative values indicate that more scrap is recycled at the end of life than was consumed in the original production (Athena Sustainable Materials Institute, 2019).

3.5 Chemical Resistance

Wood is naturally resistant to many chemicals that are harmful to other building materials. This has made wood a preferred building material for harsh environments such as chemical storage or processing facilities.

This is an advantage for bridges, especially in cold climates. Wood is not adversely effected by the salts and deicing chemicals used by many highway departments. These chemicals accelerate corrosion of steel and reinforced concrete structures, leading to premature deterioration. Wood is not harmed by these chemicals; in fact, the salts can help reduce fungal decay, increasing the service life of the structure. Furthermore, wood is not damaged by freezing temperatures; this is in contrast to concrete which often suffers from spalling and delamination when it is subjected to repeated freeze-thaw cycles. The combination of chemical resistance and durability under freeze-thaw conditions makes wood an ideal structural material for bridges in cold climates.

Similarly, timber can be an ideal material for structures in marine and coastal environments where they may be exposed to saltwater. Seawater can accelerate the corrosion of steel, leading to premature failure of reinforced concrete and steel structures; timber is not harmed by salt water.

3.6 Fatigue Resistance

Compared to other building materials, wood performs well under cyclic loading conditions. Where steel and concrete are subject to fatigue failures due to repetitive loads, this is typically not a concern for wood structures. This can be advantageous in high-volume, short-span bridges, where each vehicle or axle will load and unload the span. Atlantic Canada also has

3.7 Reinforced Glulam

Modern technologies, such as fibre-reinforced plastic (FRP) can be utilized to increase the capabilities of timber construction. Fibre reinforcing can be applied in the high-tension or high-shear zones of timber elements to allow more efficient use of the timber. Fibre reinforcing is most often used with large glulam beams, but can also be used with other engineered wood products or solid timber elements. Retrofit products can be applied in the field to upgrade or repair existing structures. Most fibre reinforcing strategies utilize proprietary systems which must be designed by a qualified engineer and installed by trained technicians.

Fibre reinforcing can allow more efficient use of the timber, by only providing reinforcing where the extra capacity is needed. When sizing a girder, multiple stresses, such as moment, shear, and compression, must be accounted for; the girder must be sized to account for the worst case scenario. In the case of medium- and long-span timber bridge girders, the controlling factor is usually moment-stress, which reaches its maximum at mid-span. If the girder is sized with a constant section to resist the mid-span moment, there will be excess moment and shear capacity at the ends; this excess capacity is effectively wasted material. Providing tension reinforcing only in the high-tension zones, allows the use of smaller timber elements, avoiding the wasted material.

3.7.1 Moment Reinforcement

A common application of FRP reinforcing is on the tension face of girders to resist bending stresses. Tension reinforcing panels consists of longitudinal glass, aramid, and/or carbon fibres. These panels are bonded to the tension face of the beam, or sandwiched between the bottom laminations of a glulam beam. In addition to providing its own tensile capacity, the FRP transitions tension and other applied stresses across localized defects, such as knots and splits, in the timber. This gives the composite section significantly increased bending capacity. On a long span structure, use of FRP reinforced timber can significantly reduce the overall depth of the structure. This can be an important advantage, for example where flood clearances over a river are an important requirement.

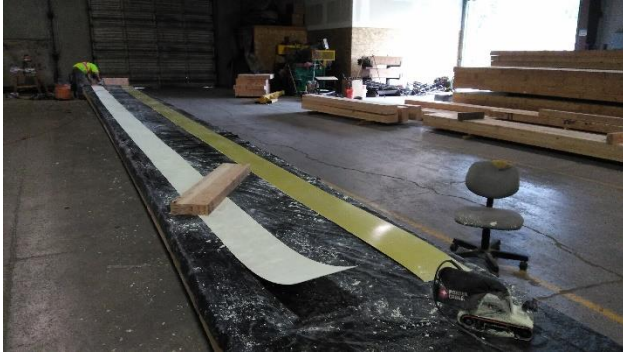


Figure 3-6: Moment reinforcing being installed on a bridge girder. The fibre-reinforce polymer (FRP) panels are glued to the tension face of the glulam beam, and a final lumber lamination is installed to protect the FRP from impact.

3.7.2 Shear Reinforcement

Short-span elements are more likely to be controlled by shear capacity. Examples of shear-controlled elements might include stringers in a railroad trestle or caps in a pile bent. FRP reinforcing can provide extra shear capacity without requiring larger timber elements. Shear reinforcement might consist of FRP panels or fabrics bonded to the vertical faces of the beam or FRP rods embedded inside the beam.



Figure 3-7: Fiber-reinforced shear panels on a forestry bridge in British Columbia.

3.7.3 Pile Wraps

High-strength fibre wraps can be applied to round timber piles or poles to increase axial and bending capacity. One strategy consists of wet-applied fibreglass fabric wrapped around (but not directly bonded to) the pile; it is important to allow some slip between the fibre wrap and the timber, so that expansion of the timber driven by changes in moisture content does not damage the wrap. Similar fibre wraps have been developed for the strengthening of utility poles in the high-moment zone near the ground line.

Due to the difficulty of replacing a deteriorated pile, FRP wraps can be a very advantageous strategy for repairing an existing structure. In the case of an existing, cavitated pile, these wraps would be paired with epoxy injection to fill the cavities; this is important to prevent inward buckling of the pile annulus.



Figure 3-8: High-strength fibre pile wraps on a railroad trestle in British Columbia. Traditional repair methods would have been impractical on this structure. Driving new piles would have been cost prohibitive and would have required extended bridge closures, and posting multiple piles within a single bent is not recommended, as lateral resistances is significantly reduced.

3.7.4 Retrofits

Some FRP reinforcing products can be field-installed to upgrade or repair existing structures. This may be used to upgrade a structure beyond its original design capacity, for example bringing a historic bridge up to modern highway load requirements.

Alternatively, FRP reinforcing may be used to make targeted, in-situ repairs of elements that have become degraded by decay or other damage. Often, these FRP retrofits can be installed while the bridge remains in service. This can provide significant cost savings compared to kind-for-kind replacement strategies by avoiding costly demolition work, temporary structures, and detours. When combined with advanced inspection and preservation strategies, FRP retrofits can significantly extend the useful life of a structure that might otherwise be slated for replacement.



Figure 3-9: High-strength fibre retrofits on a railroad bridge, including tension reinforcement and pile wraps. These targeted retrofits were designed to reinforce deteriorated elements to restore the capacity of the structure. The retrofits could be installed while the bridge remained in service without interrupting rail traffic.

4.0 Scope of Timber Bridge Market

4.1 Current Size of North American Timber Bridge Industry

4.1.1 National Bridge Inventory

A 2015 report compiled by Wood Research and Development estimated that, as of 2013, there were approximately 48,000 timber highway bridges in North America; this represents approximately 7% of the total number of highway bridges of all materials.

Based on analysis of the National Bridge Inventory, from 1992 to 2019, the number of highway bridges with timber superstructures in the United States declined from 44,673 to 18,153 – an average of 3.3% decline each year. Over this same period, the total number of bridges increased from 572,629 to 617,084, a 0.3% increase per year. Bridges with timber superstructures have declined from 7.8% of the total highway bridge inventory in 1992 to only 2.9% in 2019.

These trends indicate that a large number of timber bridges are being decommissioned and replaced by steel or concrete structures. Bridge engineers and owners are often less familiar with timber than with other materials and unfairly assume timber structures will have a life span of only 20-30 years. Additionally, bridge inspectors who are unfamiliar with timber are likely to unnecessarily downgrade their condition ratings. As a result, many timber bridges are assigned poor load ratings or deemed in need of replacement when, in fact, they could have many years of satisfactory service life remaining (Brashaw, Wacker, & Jalinoos, 2013). There are over 900,000 bridges including railway bridges in North America. Of these bridges over 250,000 of these bridges are timber. There are many more railway timber bridges

than highway timber bridges in North America. Railway companies like Union Pacific have close to 40,000 timber bridges still in service today.

Year	Bridges With Timber Superstructure						Total Bridges					
	Count	Change		SD	FO	Total Deficient	Count	Change		SD	FO	Total Deficient
1992	44,673			24,911	5,547	30,458 68%	572,629			124,072	92,229	216,301 38%
1993	42,919	-1,754	-3.9%	22,474	5,772	28,246 66%	574,115	1,486	0.3%	116,400	92,214	208,614 36%
1994	41,702	-1,217	-2.8%	20,967	5,863	26,830 64%	576,396	2,281	0.4%	111,533	92,571	204,104 35%
1995	41,434	-268	-0.6%	19,546	5,871	25,417 61%	583,089	6,693	1.2%	107,909	93,538	201,447 35%
1996	40,040	-1,394	-3.4%	18,410	5,672	24,082 60%	582,037	-1,052	-0.2%	105,462	93,415	198,877 34%
1997	38,299	-1,741	-4.3%	17,118	5,514	22,632 59%	583,203	1,166	0.2%	102,129	88,724	190,853 33%
1998	36,841	-1,458	-3.8%	15,782	5,542	21,324 58%	583,408	205	0.0%	96,319	90,506	186,825 32%
1999	35,744	-1,097	-3.0%	14,976	5,380	20,356 57%	585,936	2,528	0.4%	91,087	92,625	183,712 31%
2000	34,496	-1,248	-3.5%	14,267	5,143	19,410 56%	587,735	1,799	0.3%	89,460	91,182	180,642 31%
2001	33,690	-806	-2.3%	13,529	4,997	18,526 55%	590,153	2,418	0.4%	86,144	91,357	177,501 30%
2002	32,362	-1,328	-3.9%	12,698	4,901	17,599 54%	591,243	1,090	0.2%	84,031	90,823	174,854 30%
2003	30,915	-1,447	-4.5%	12,153	4,611	16,764 54%	592,337	1,094	0.2%	82,283	90,346	172,629 29%
2004	29,660	-1,255	-4.1%	11,441	4,427	15,868 53%	594,100	1,763	0.3%	79,971	90,076	170,047 29%
2005	28,497	-1,163	-3.9%	10,944	4,212	15,156 53%	595,668	1,568	0.3%	77,863	90,010	167,873 28%
2006	27,610	-887	-3.1%	10,422	4,065	14,487 52%	597,561	1,893	0.3%	75,422	89,591	165,013 28%
2007	26,682	-928	-3.4%	10,077	3,808	13,885 52%	599,880	2,319	0.4%	74,066	89,080	163,146 27%
2008	25,876	-806	-3.0%	9,714	3,666	13,380 52%	601,506	1,626	0.3%	72,883	89,189	162,072 27%
2009	25,106	-770	-3.0%	9,801	3,477	13,278 53%	603,310	1,804	0.3%	72,402	87,460	159,862 26%
2010	24,267	-839	-3.3%	9,479	3,228	12,707 52%	604,493	1,183	0.2%	70,431	85,858	156,289 26%
2011	23,461	-806	-3.3%	9,018	3,125	12,143 52%	605,103	610	0.1%	68,759	84,832	153,591 25%
2012	22,724	-737	-3.1%	8,715	2,997	11,712 52%	607,380	2,277	0.4%	66,749	84,748	151,497 25%
2013	21,469	-1,255	-5.5%	7,820	2,889	10,709 50%	607,751	371	0.1%	63,522	84,348	147,870 24%
2014	21,406	-63	-0.3%	7,489	2,927	10,416 49%	610,729	2,978	0.5%	61,365	84,510	145,875 24%
2015	20,459	-947	-4.4%	6,958	2,886	9,844 48%	611,845	1,116	0.2%	58,791	84,124	142,915 23%
2016	19,944	-515	-2.5%	6,643	2801	9,444 47%	614,387	2,542	0.4%	56,008	83,756	139,764 23%
2017	19,464	-480	-2.4%	6,545	2,702	9,247 48%	615,002	615	0.1%	54,561	83,665	138,226 22%
2018	18,813	-651	-3.3%	6,172	2,678	8,850 47%	616,096	1,094	0.2%	53,588	83,345	136,933 22%
2019	18,153	-660	-3.5%	5,820	2,575	8,395 46%	617,084	988	0.2%	52,223	83,538	135,761 22%
Total		-26,520	-59.4%					44,455	7.8%			
Average		-1,105	-3.3%					1,646	0.3%			

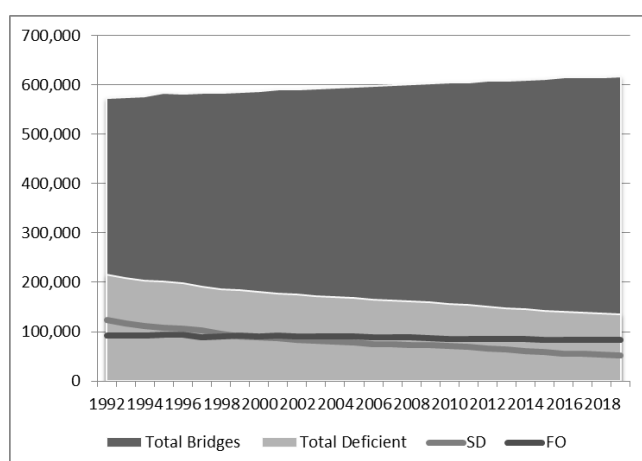
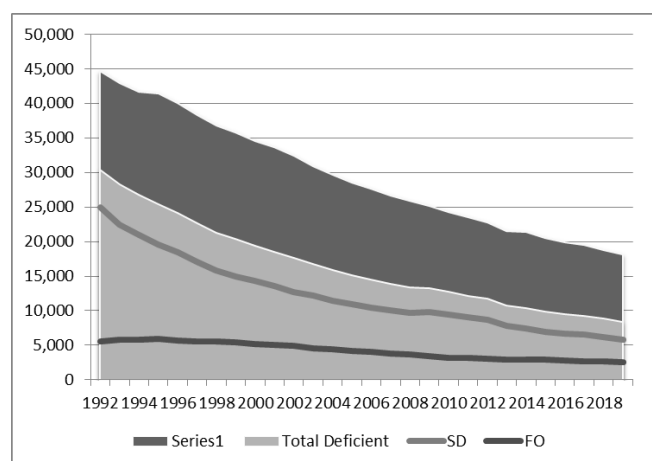


Figure 4-1: The number of highway bridges in the National Bridge Inventory since 1992, for bridges with timber superstructures (left) and bridges of all materials (right). The number of timber bridges has been decreasing by approximately 3.3% per year, while the total number of bridges has increased by 0.3% per year.

4.1.2 Atlantic Canada

Based on industry experience and knowledge of the Atlantic Canada region, it is believed that a larger share of bridges in Atlantic Canada are built from timber, compared with the United States. However, detailed statistics are not readily available. The rural nature of the Atlantic Provinces means that the highway system is largely made up of relatively low-volume roads. Timber bridges are generally seen as more viable on these low-volume roads.

There are a total of 8,300 provincially managed bridges in Atlantic Canada (New Brunswick Department of Transportation, 2008). According to a 2007 report on Canadian bridge management systems, 60% of the bridges in Nova Scotia and 50% of the bridges in Prince Edward Island are built from timber (Hammad, Yan, & Mostofi, 2007). If these percentages hold true for all four provinces, there would be 4000-5000 timber bridges in Atlantic Canada. As of 2020, the province of New Brunswick reports that they have over 2800 timber or partial timber bridges including 54 operating covered timber bridges. Nova Scotia reports over 1800 timber bridges including partial or total timber bridges. While it is likely that these numbers have been decreasing in recent years, it is clear that timber bridges represent a significantly higher share of the bridge inventory in Atlantic Canada than in the United States.

4.2 New Trends in Timber Bridge Industry

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.

4.2.1 Recent Use in Atlantic Canada

There has recently been some increased interest in the use of new timber highway bridges in Nova Scotia and New Brunswick. One prominent example is the Roger Bacon Bridge in Nappan, Nova Scotia. This is a 65 metre bridge, including a 40 metre timber arch span, which replaced a failed steel arch bridge. The tender for this bridge was issued by the province with a specific option for a timber design; the winning bid was 25% lower than the leading steel or concrete option (Maritime Lumber Bureau, 2020). More detail on the Roger Bacon Bridge is included in Section 5.2.1.

Following the completion of the Roger Bacon Bridge, Nova Scotia issued a tender for the replacement of Dillman's Bridge, a two lane, 35 meter clear span bridge in Halifax County. This tender was issued specifically for a timber bridge, without the option of a steel or concrete structure.

4.2.1.1 Use of Local Resources

The wood products industry has a long history in Atlantic Canada. The industry has always been largely driven by exports. Beginning in the early 19th century, demand was largely driven by the British Navy; as of 2014, approximately 70% of lumber produced in Atlantic Canada was exported to the United States, primarily for use in residential construction. Atlantic Canada also has a large history of timber bridge construction. In New Brunswick, there are currently 54 timber covered bridges in service; this is down from as many as 400 in the past. It is estimated that there are at least 5000 timber bridges currently in service throughout Atlantic Canada.

Historically, these bridges would have been built from locally sourced wood. Typical species would have been softwoods including spruce, pine, fir, and hemlock. Modern timber bridges are more likely to be Douglas fir (sourced from the west coast) or southern yellow pine (sourced from the southeast United States). These species are widely available as glulam and large dimension sawn products, and they readily accept preservative treatment, providing excellent durability.

Local species in Atlantic Canada that would be suitable for modern bridge construction include red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), and balsam fir (*Abies balsamea*). These species are considered relatively easy to treat, and can achieve a life span of 80-100 years. In particular, red pine and jack pine are standardized in the CSA-O80 series of codes for use categories UC4.1, UC4.2, and UC5A, the high-hazard conditions applicable to bridge construction. Note that eastern white pine and balsam fir are not standardized for use in marine exposures (UC5A), and eastern hemlock is not standardized for use in ground or water contact (UC4.1), but in the right use conditions these species can all be adequately treated to achieve a life span of 80-100 years. Other species found in Atlantic Canada, such as spruce, are structurally sufficient, but do not accept preservative treatment; thus, they would have a much lower durability in bridge applications.

These species are currently not widely available as glue-laminated beams, which limits their application in the current market. Red pine is currently an underutilized species in Atlantic Canada. Production of glue-laminated beams from red pine or other local species is a potential growth market for

the Atlantic Canada timber industry and would allow for construction of timber bridges utilizing entirely local resources.

4.2.2 Recent Trends in Europe

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).

5.0 Examples of Timber Bridges

5.1 Historic Structures

5.1.1 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.

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 report found both structures to be in good condition, and recommended only routine maintenance to extend the life of the structures.



Figure 5-1: 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 5-2: The wye includes an upper bridge supported on three-pinned glulam arches, and a lower three-span bridge supported by glulam girders.



Figure 5-3: The upper bridge is supported by glulam arches.



Figure 5-4: The substructure of the lower bridge consists of glulam timber frame bents.

5.1.2 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 transverse bearers and longitudinal deck planks and running boards. 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.

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. The Department of Forestry in British Columbia reports over 2,800 timber bridges in inventory. The Ministry of Transport reports a similar number in operation for a total approaching 5,700 timber bridges in British Columbia.



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

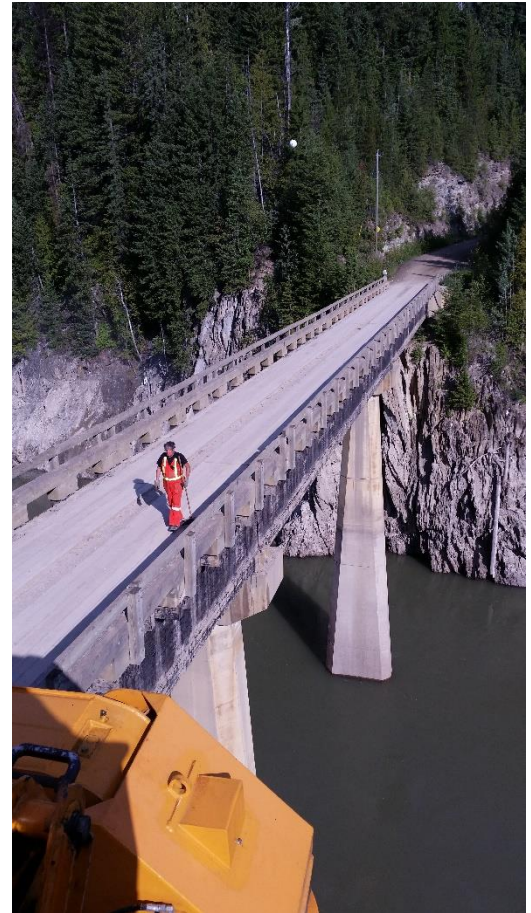
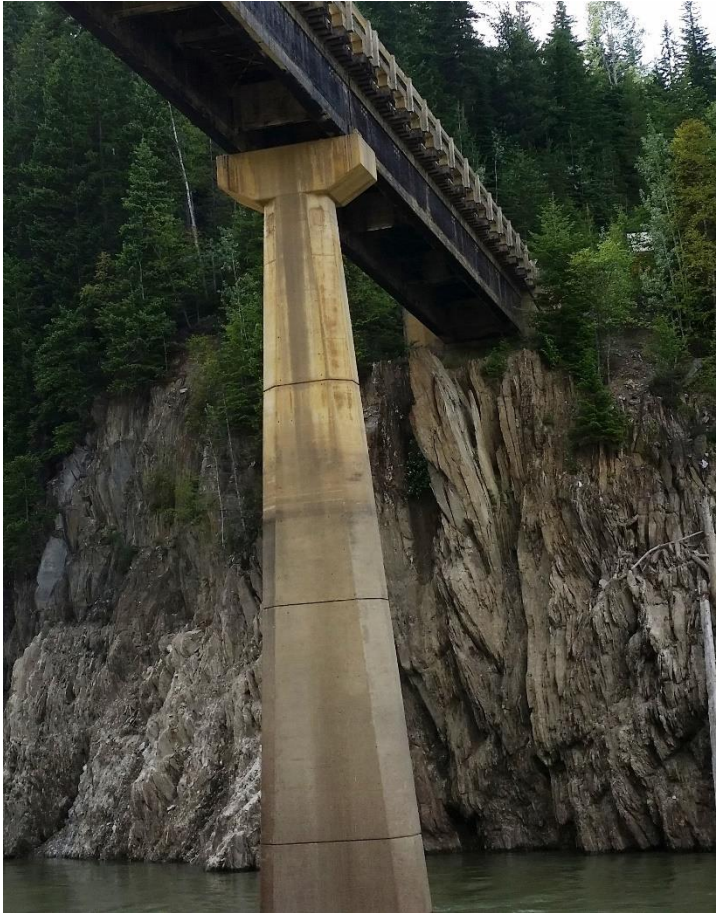


Figure 5-6: Each 27m (90 ft.) span consists of two glulam I-Beams which support transverse bearers. The deck and wear surface are made up of longitudinal planks.



Figure 5-7: 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.

5.1.3 Glulam 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 that 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.



Figure 5-8: 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 5-9: Cervus Creek Bridge is a 25m (82ft) single-span bridge consisting of four glulam I-beams with a transverse nail-laminated deck.



Figure 5-10: Heber River Bridge is a single-span, 34.5m (113ft) long consisting of four glulam I-beams and a transverse nail-laminated deck.

5.1.4 Kindee

The longest timber suspension bridge in Australia still in service is the Kindee Bridge. See Figures below. Kindee Suspension Bridge over the Hastings River at Kindee comprises of three spans; 26.8m, 67.1m and 26.8m respectively. The timber deck is supported from the trussed cables with a panel length (longitudinally along the bridge) of 3.35m. The bridge has a camber of 0.915m and the clearance height above the highest known flood is 1.830 m at the center of the bridge. The center span truss is an inverted three hinged arch with the side spans acting as a simply supported truss to carry loads on the span itself whilst also acting as a back stay to support the horizontal tension in the center spans truss when loaded. The bridge is over 84 years old.



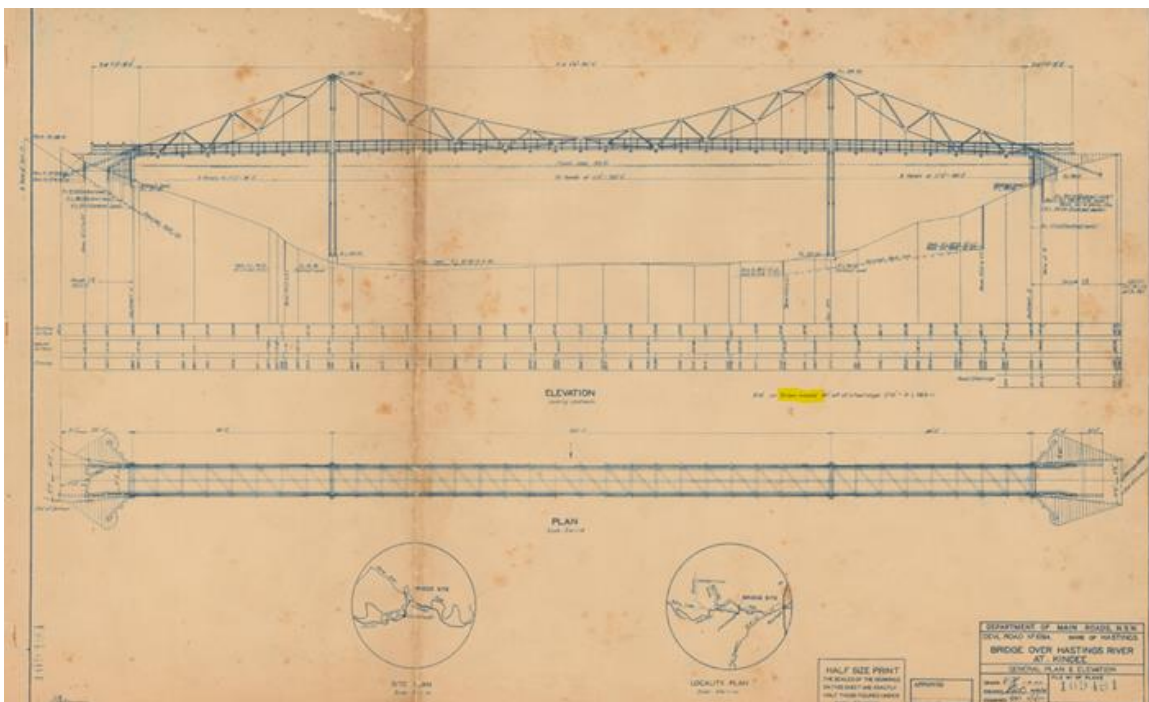


Figure 5-11: Kindee Suspension Bridge.

5.1.5 Kintai Bridge

The Kintai Bridge was originally constructed in 1673 spanning the Nishiki River in Japan, and has been 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.

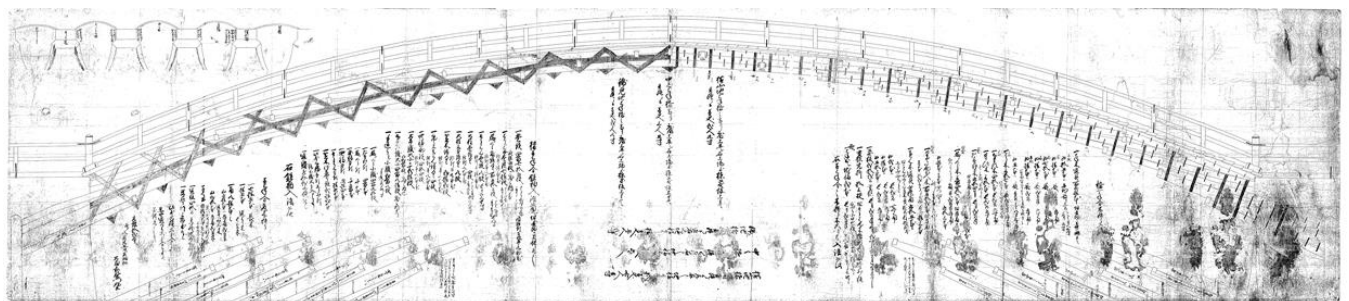


Figure 5-12: Kintai Bridge, spanning the Nishiki River in Japan, was originally constructed in 1673

5.2 North America

5.2.1 Roger Bacon Bridge

The Roger Bacon Bridge, designed by Wood Research and Development and constructed by Timber Restoration Services, was installed in late 2019. The bridge features a glulam through-arch structure with a main span of 39.5m (130ft) and two approach spans of 12m (39ft) each.

Located in Nappan, Nova Scotia, the bridge replaced an existing steel arch bridge which had failed and was taken out of service. The existing timber piles remained in good condition, and the new bridge was built on these piles with only minor repairs needed.



Figure 5-13: Roger Bacon Bridge in Nappan, N.S. consists of glulam arches spanning 39.5m and girder-under approach spans spanning 12m at each end.

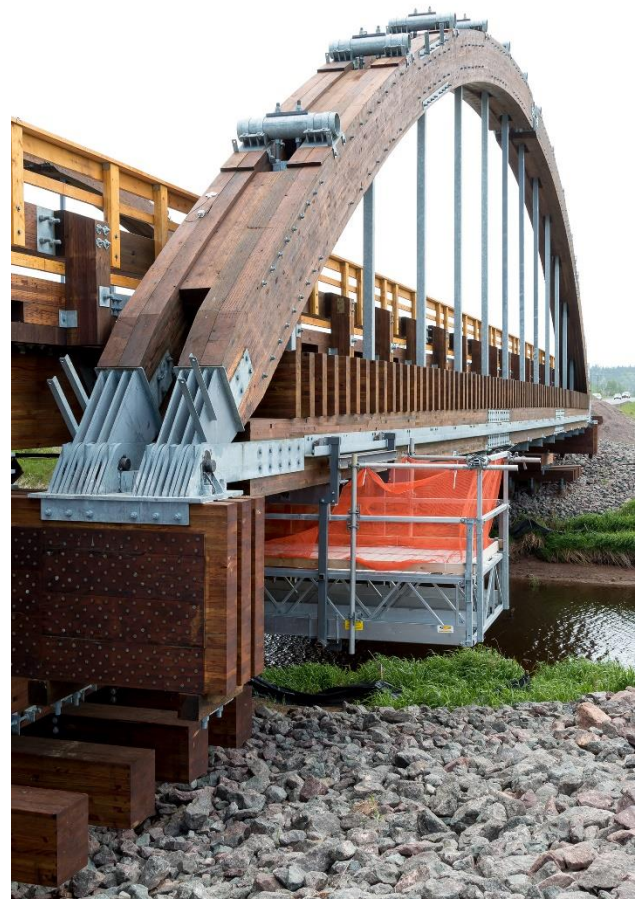


Figure 5-14: The main arches are made up of four layers of glulam beams with spacer blocks between. These arches support steel hangers, which carry the transverse glulam deck system.



Figure 5-15: The bridge carries a two-lane highway with wide shoulders; the design allows the bridge to safely carry up to three lanes of traffic.

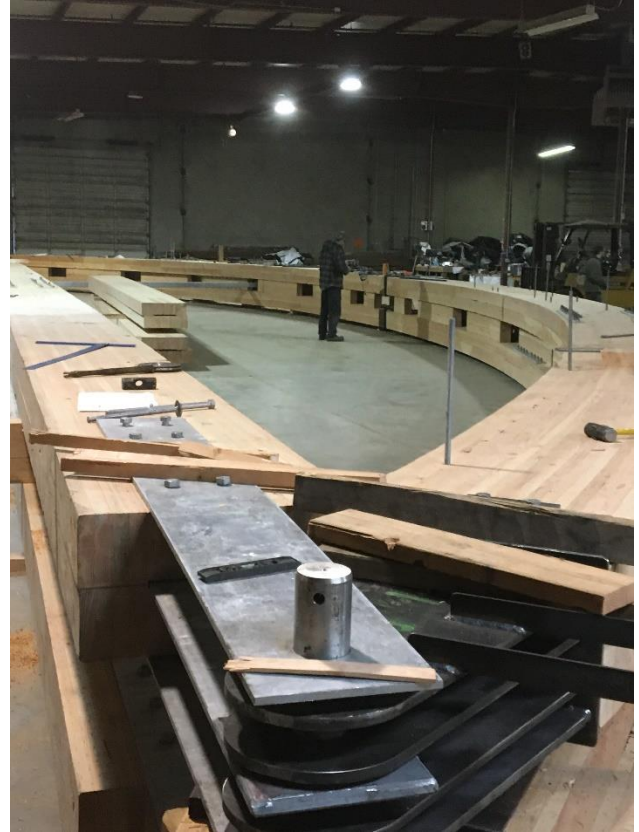


Figure 5-16: The timber components were preassembled prior to preservative treatment to ensure a proper fit and minimize on-site modifications.

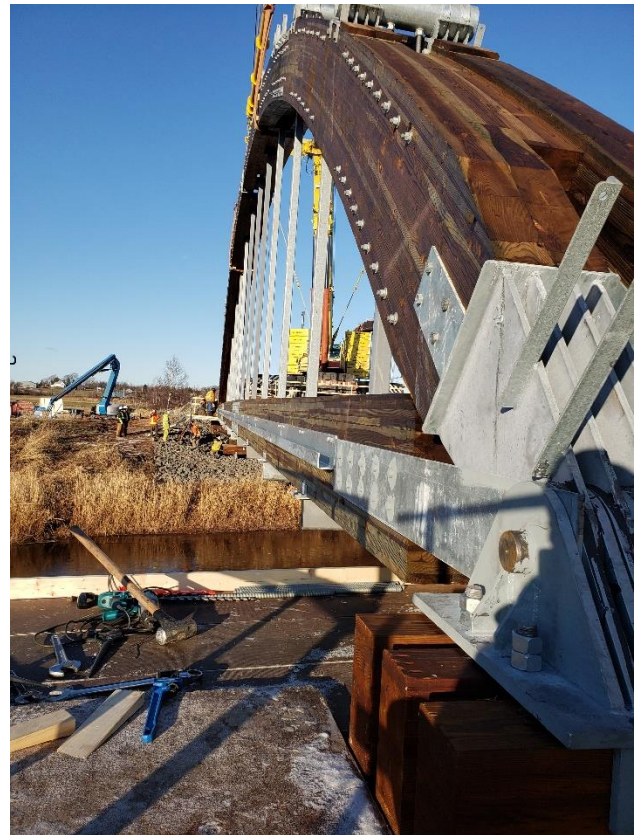


Figure 5-17: The arches were assembled alongside the road, on shore, and then flown into position by crane.

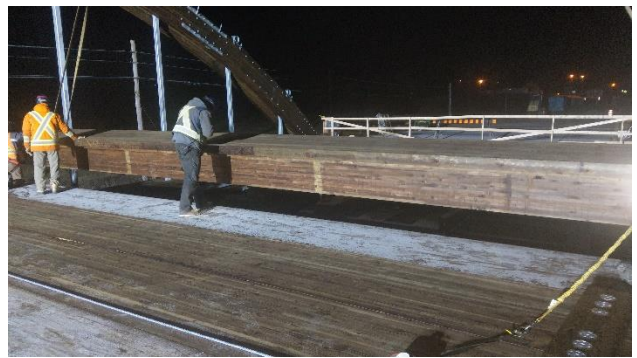
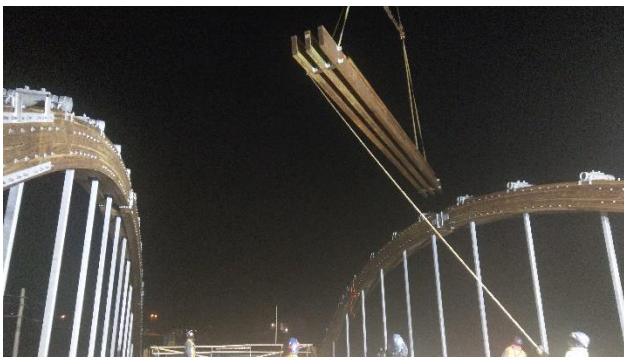


Figure 5-18: The deck in the main arch span consists of transverse “Triple-T” panels. These panels are made up from glulam three transverse floor beams with a glulam deck panel glued to the top. The beams and panels are bonded with structural epoxy adhesive to act as a composite section. Each panel laps over the previous beam and is field glued, so that the entire deck acts as a continuous diaphragm.



Figure 5-19: The existing steel arch span that was replaced by the new timber structure. Note in the lower photo the failed tension cord having rusted through and failed. The bridge is located in the highest embedded and exposed corrosion zone in Canada. Wood is the best option. The bridge was first built in wood on wood piles 100 years ago. The steel bridge was built on the old piles with more piles added to accommodate the dead weight less than 50 years ago. Now after a short life (less than 50 years) the steel bridge is replaced with wood, the best option in this case!! Lower cost and better design life.

5.2.2 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 (70 ft.), single-span bridge consists of five fibre-reinforced glulam girders and a transverse glulam deck and is supported by glulam frame bents. The bridge is designed to support L100 loading – a BC standard design load representing off-highway logging equipment.



Figure 5-20: McGillivray Bridge is a 21m fibre-reinforced glulam bridge on a forestry road in British Columbia.



Figure 5-21: The glulam girders are reinforced with high-strength fibre on the tension face. This fibre-reinforcing is installed in the shop prior to assembling the structure.



Figure 5-22: 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 before being shipped to the site for assembly.

5.2.3 Meadow Lake Bridge 61.4

Meadow Lake Bridge 61.4 is a conversion of an old rail-trestle for use as a forestry bridge on a Tolko Mill property outside of Meadow Lake, Saskatchewan. The rail lines had been decommissioned ten years earlier and it was 52 years old when it was decommissioned, 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 fibre-reinforcement of the existing stringers and substructure. Additionally, the existing railroad ties were replaced with a new transverse glulam deck and curb.



Figure 5-23: Meadow Lake Bridge is a conversion of a decommissioned railroad trestle to be used as a forestry bridge.



Figure 5-24: The Existing piles, caps, and chords were reinforced with high-strength fibre 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.

5.2.4 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 NHCPR 350.

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.



Figure 5-25: Providence Road Bridge in Clarington, ON 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 fibre 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 5-26: 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.



Figure 5-27: 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.

5.2.5 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).



Figure 5-28: 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.

5.2.6 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.

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 CO₂ emissions. By comparison, the steel and concrete option would have generated 969 tonnes of CO₂ emissions (Lefebvre & Richard, 2014).



Figure 5-29: 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. (Forestry Nordic, 2015)

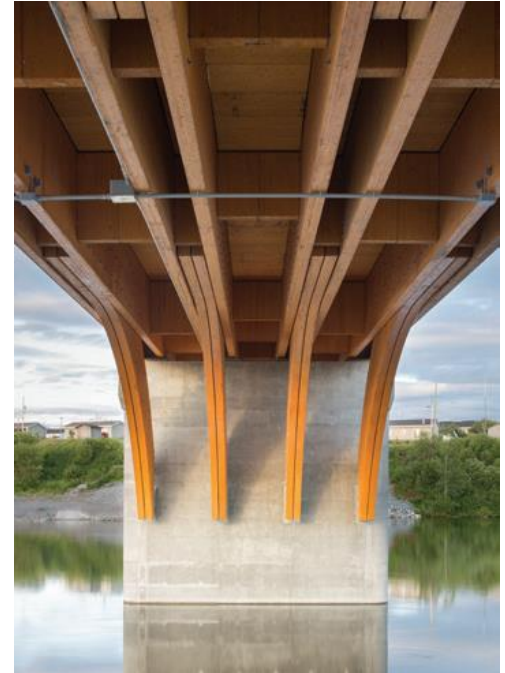


Figure 5-30: The arched braces are connected to the piers with pinned connections. The connection between the arches and the girders serves to both support the girder ends and to create a moment-resisting splice in the girders. This forms a continuous structure with no deck joints, which will help avoid cracking of the asphalt and maintain a waterproof surface. (Forestrie Nordic, 2015)

5.2.7 Tamiscame River Bridge

Built in 2009 by Nordic Structures, Tamiscame River Bridge is a forestry bridge 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)



Figure 5-31: 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)

5.2.8 Lighthouse Bridge

The Lighthouse Bridge near Clallam Bay, Washington is a 2-span, 50m (160ft) bridge consisting of fibre-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 FRP reinforcing in the United States (Tingley & Gai, 1998).



Figure 5-32: The Lighthouse Bridge, under construction in Clallam Bay, Washington. The bridge consists of six fibre-reinforced glulam girders in each span.



Figure 5-33: The glulam girders are reinforced with a layer of fibre-reinforced plastic (FRP) which permitted a significant reduction in the volume of wood required compared to an unreinforced bridge.

5.3 Europe

5.3.1 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 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).

5.3.1.1 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.

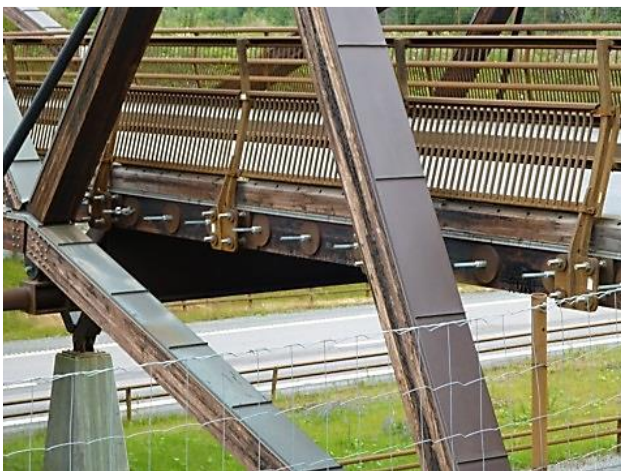


Figure 5-34: Sletta Bridge in Eidsvoll, Norway. The structure consists of asymmetrical glulam trusses which carry steel crossbeams and a stress laminated deck. In addition to being dual preservative treated (with a copper-based preservative and creosote) the main elements are sheltered from moisture using metal flashing.

5.3.1.2 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.



Figure 5-35: 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.

5.3.1.3 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.



Figure 5-36: 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.

5.3.1.4 Evenstad

Evenstad 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.



Figure 5-37: 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.

5.3.1.5 Kjølssæter

Kjølssæter 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.



Figure 5-38: Kjølssæter 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.

5.3.1.6 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.



Figure 5-39: Asta Bridge is a stress laminated deck supported by glulam arches. The deck totals 96.6m (317ft), and the arches span 38.5m (126ft).

5.3.1.7 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.

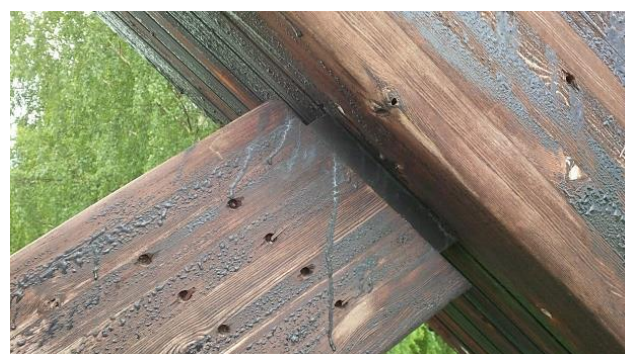


Figure 5-40: Flisa Bridge is a three-span glulam truss bridge totaling 196m (643ft) with a maximum span of 70m (230ft).

5.3.2 Krastalbrücke

Krastalbrücke is a tied-arch glulam bridge in Treffen, Austria. The arches carry transvers 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.



Figure 5-41: Krastalbrücke consists of two glulam tied-arches. These support steel hangers which carry the transverse glulam beams which, in turn, carry the deck.

5.3.3 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).



Figure 5-42: 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 wood panels on the vertical faces.

5.4 Australia

5.4.1 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.



Figure 5-43: Cowley Creek Bridge, fully assembled and ready to be installed with one crane one lift. A concrete bridge of the same length and width could not have been lifted into place totally assembled.

5.4.2 Queensland Rail Overpasses

Boundary Road Bridge and Alderly Avenue Bridge are overpass bridges crossing Queensland Rail tracks near Brisbane. Both bridges consist of glulam girders supporting transvers glulam deck panels. The bridges were replacements for existing overpasses, and the existing timber substructures were restored using high-strength fibre to carry the new bridges. The lightweight timber superstructures allowed rapid installation that minimized interruptions to rail traffic below.



Figure 5-44: 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 fibre wraps on the piles and tension reinforcement on the headstocks.



Figure 5-45: 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.

5.4.3 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, using 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.

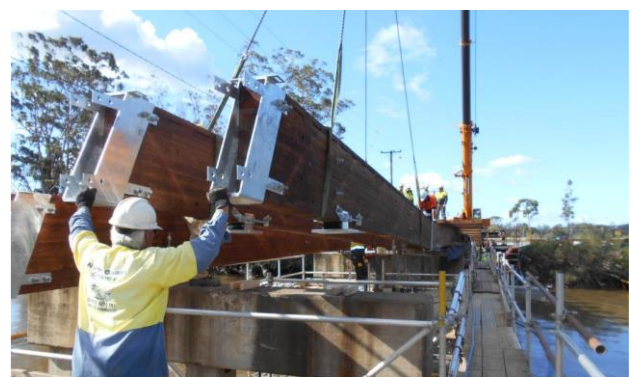


Figure 5-46: The new glulam superstructure and deck were installed on the existing substructure at Newry Island Bridge. Removal of the existing structure and installation of the new occurred in tandem to limit the road closure time.

6.0 Conclusion

The growth potential for timber bridges in today's carbon conscious market place is significant. Timber bridges are clearly more carbon friendly than steel and concrete; in fact, timber structures can have net-negative carbon emissions. Further, the use of advanced technologies like high strength fiber reinforced polymer reinforcements for wood elements has allowed much longer spans and more effective designs to be developed allowing timber options to be more cost competitive. These advanced systems have developed to a point such that today timber bridge options are lower cost than concrete and steel. There are important areas that have to be considered and developed with bridge owners. These are; better maintenance and greenfield design details, more effective maintenance techniques, training of advanced and conventional methods of timber bridge design at the university level for engineers at the undergraduate level, advancements in code language to provide engineers with references to these advanced methods of designing timber bridges. Training programs to educate and train timber bridge carpentry and construction workers. Awareness campaigns by quasi and local government bodies to make the public and bridge owners aware that timber bridges are a true and effective option to the conventional steel and concrete bridge strategies. Create awareness that timber bridges last as long if not much longer than steel and concrete and cost less to maintain when properly designed and constructed.

REFERENCES

- Athena Sustainable Materials Institute. (2019). Athena Impact Estimator for Buildings. v5.4.0103. Retrieved from <http://www.athenasmi.org/our-software-data/impact-estimator/>
- Athena Sustainable Materials Institute. (2019). *User Manual and Transparency Document - Impact Estimator for Buildings v.5*. Ottawa, ON.
- Bodig, J., & Jayne, B. A. (1993). *Mechanics of Wood and Wood Composites*. Malabar, FL: Krieger Publishing Co.
- Brashaw, B. K., Wacker, J., & Jalinoos, F. (2013). Field Performance of Timber Bridges: A National Study. *International Conference on Timber Bridges*. Las Vegas, NV.
- Chorlton, B., Mazur, N., & Gales, J. (2019). Incorporating Timber Education Into Existing Accredited Engineering Programs. *Canadian Engineering Education Association Conference*. Ottawa, ON.
- Clausen, C. A. (2010). Biodeterioration of Wood. In *Wood Handbook, Wood as an Engineering Material*. Madison, WI: Forest Products Laboratory.
- Ekholm, K., Nilson, P., & Johansson, E. (2013). Case Study of the Longest Single Span Timber Bridge for Highway Loads in Sweden. In J. Wacker, & J. Krohn (Ed.), *Proceedings, 2nd International Conference on Timber Bridges*. Washington, DC: WoodWorks –Wood Products Council.
- Finnish Timber Council. (2019, April 30). *Wooden Bridges*. Retrieved from Wood Products Fi: <https://www.woodproducts.fi/content/wooden-bridges>
- Flaga, K. (2000). Advances in Materials Applied in Civil Engineering. *Journal of Materials Processing Technology*, 106(1), 173-183.
- Forest Products Laboratory and Federal Highway Administration. (2001). *Timber Bridge Economics*. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Foretrie Nordic. (2015). *Bridge Portfolio*. Chibougama, QC.
- Gerold, M. (2006). Economic Viability of Modern Timber Bridges - Lifespan and Costs of Maintenance. *IABSE Reports*, 92, p. 384. Budapest, HUN.
- Gilham, P. C. (2013). Stretching the Limits - Modern Timber Bridge Case Studies. In J. Wacker, & J. Krohn (Ed.), *Proceedings, 2nd International Conference on Timber Bridges*. Washington, DC: WoodWorks –Wood Products Council.
- Gupta, R., & Gopu, V. (2005). *Wood Engineering Education – Trends and Challenges*.
- Gustafsson, A., Parikka, H., Ekevad, M., Hagman, O., Hourunranta, J., Saukko, O., & Pahkasalo, M. (2014). Cluster Wooden Bridges.
- Hammad, A., Yan, J., & Mostofi, B. (2007). Recent Development of Bridge Management Systems in Canada. *2007 Annual Conference of the Transportation Association of Canada*. Saskatoon, SK.
- Lawson, J., Kam-Biron, M., & Perkins, B. (2019, August). Used the Most, Taught the Least: An Analysis of Current Wood Engineering Education in U.S. Universities. *Structure Magazine*, pp. 32-34.
- Lefebvre, D., & Richard, G. (2014). Design and construction of a 160-Metre-Long Wood Bridge in Mistissini, Québec. *Internationales Holzbau-Forum*.
- Maritime Lumber Bureau. (2020). *The Roger Bacon Bridge, Nappan, Nova Scotia*.
- Mohammad, M., Morris, P., Thivierge, C., de Jager, C., & Wang, J. (2014). *Innovative Timber Bridges: Technical Tour of Norwegian Timber Bridges*. Pointe-Claire, QC: FP Invoations.
- Moses, D., Alexander, M., McAlister, K., Mesa, K., Lehan, A., Brown, S., & Dulay, G. (2017). *Ontario Wood Bridge Reference Guide*. North Bay, ON: Ontario Wood WORKS.
- New Brunswick Department of Transportation. (2008). *Charting the Course: The Atlantic Canad Transportation Strategy 2008-2018*. Fredricton, NB: Province of New Brunswick.

- Perkins, B. (2016, September). 2016 NCSEA Structure Engineering Curriculum Survey. *Structure Magazine*, pp. 10-19.
- Ritter, M. A. (1990). *Timber Bridges: Design, Construction, Inspection, and Maintenance*. Washington, DC: USDA Forest Service.
- Smith, R. L., & Stanfill-McMillan, K. (1996). Perception versus Reality: An Analysis of Timber Bridge Performance in the United States. *National Conference on Wood Transportation Structures* (pp. 467-475). Madison, WI: Forest Products Laboratory.
- Smith, R. L., Bush, R. J., & Schmoldt, D. L. (1995). A hierarchical model and analysis of factors affecting the adoption of timber as a bridge material. *Wood and Fiber Science*, 27(3), 225-238.
- Stanfill-McMillan, K., & Hatfield, C. A. (1994). Performance of Steel, Concrete, Prestressed Concrete, and Timber Bridges. *Developments in short and medium span bridge engineering '94: Proceedings of 4th International conference on short and medium span bridges* (pp. 341-354). Halifax, NS: The Canadian Society for Civil Engineering.
- Syed, T. (2020). *Identifying Mass Timber Research Priorities, Barriers to Adoption and Engineering, Procurement and Construction Challenges In Canada*.
- Tingley, D., & Gai, C. (1998). FRP Reinforced Glulam Performance: A Case Study of the Lighthouse Bridge. In J. Natterer, & J.-L. Sandox (Ed.), *Proceedings: 5th World Conference on Timber Engineering, Montreaux, Switzerland*. Lausanne, CHE: EPFL.
- Tingley, D., Keller, R., Arthur, R., Hunter, M., & Legg, C. (2015). *Developing the Market for Solid Sawn and Engineered Wood Products in North American Bridges*. Jefferson, OR: Candian Wood Council.
- Troive, S. (2005). Environment and maintenance requirements on Swedish timber bridges. *NVF Conference on Timber Bridges: Proceedings and Abstracts* (pp. 44-48). Hamar, NOR: Nordic Roads Association.
- Wacker, J. P., & Brashaw, B. K. (2017). Comparative Durability of Timber Bridges in the USA. *IRG48 Scientific Conference on Wood Protection*. Gehnt, Belgium: The International Research Group on Wood Protection.