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SERVICE LIFE ASSESSMENT OF TIMBER HIGHWAY BRIDGES IN USA CLIMATE ZONES

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ABSTRACT: As engineers begin to estimate life-cycle costs and sustainable design approaches for timber bridges, there is a need for more reliable data about their durability and expected service life. This paper summarizes a comprehensive effort to assess the current condition of more than one hundred timber highway bridge superstructures throughout the United States. This national study was jointly administered by the Forest Products Laboratory and the Federal Highway Administration. In depth inspections were conducted using visual and non-destructive evaluation techniques to characterize the condition of the primary bridge components and detect any structural deficiencies. The most popular superstructure system studied in this project was the multiple sawn stringer and plank deck system. This system was evaluated in a number of wood hazard (climate) zones with numerous examples of 60 or 70 year service records. These inspection results will be eventually incorporated into an ongoing national program effort aimed at monitoring the long-term performance of various types of highway bridges in the USA.

KEYWORDS: Life-cycle cost, inspection, durability, wood, timber, bridge, performance, superstructure, service life

1 INTRODUCTION

Timber is the oldest bridge building material and with proper design, construction, and maintenance practices, it can offer good durability comparable with, or exceeding that, of other bridge materials. A combination of chemical preservatives by pressure treatment methods and proper drainage detailing is the best practice for protection of the primary structural bridge components. When these strategies are employed during the design and construction phases, deterioration due to decay can be prevented or delayed indefinitely, resulting in a good service life expectancy. Surprisingly, little information exists to reliably estimate the service life of timber highway bridges in the United States even though it has been used since colonial times. Many state transportation agencies have developed timber bridge service life estimates based on personal experiences, which tend to be rather subjective and conservative.

Literature reviews did not reveal much published information about the expected service life of timber bridges in the United States. However, a noted timber bridge guidance manual [1] claims "*using modern application techniques and preservative chemicals, bridge components can now be effectively protected from deterioration for periods of 50 years or longer*". With such wide disparity in service life prediction, there is clearly a need for more reliable data about timber bridge durability to support bridge material decisions during the preliminary phase. It has become an increasingly important consideration as design engineers began to consider bridge costs over the entire (service) life-cycle to select the most economical bridge alternative. In order to start building a reliable database about timber bridge durability, a rigorous timber bridge inspection study of national scope was established through a joint agreement between the Federal Highway Administration (FHWA) and the U.S. Forest Service, Forest Products Laboratory (FPL).

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Table 1: *Superstructure type and state locations for all 132 bridges inspected during this study.*

Bridge type	Material	Deck type	Total	Number of bridges inspected by state													
				AL	CA	GA	IA	LA	MD	MN	MS	NC	NY	OR	TN	WA	WI
Girders	Sawn	Timber plank	53	5	2	6	10	9		1	8	3		2	3		4
		Nail-laminated	19		1					3				5		10	
		Concrete	15	4		1		2				3			4	1	
	Glulam	Nail-laminated	6		1					5							
		Concrete	3		3												
		Glulam panel	4										4				
	Steel	Timber plank	2			2											
		Nail-laminated	5							5							
Slab	Sawn	Spike-laminated	17				5		5	4				3			
	Glulam	Glulam panel	8										6	2			

2 OBJECTIVE AND SCOPE

The primary goal of the study was to assess the condition of timber highway bridges located throughout the United States under various service conditions. In-depth inspections were conducted at more than one hundred timber bridge field sites using a specific protocol which included the use of nondestructive evaluation tools. The main focus of these bridge inspections was limited to the superstructures elements, even though many of them were supported by timber substructures. The study results will help provide a better understanding of the design, performance, and durability characteristics of timber bridge structures within the USA, which can potentially help to extend the service life of existing structures.

2.1 BRIDGE LOCATIONS AND TYPES

A total of 132 timber bridges had field assessments performed during the two year period ending in the fall of 2013. Bridges were located in several different climate regions of the United States (Figure 1), with a large majority located in the eastern portion of the country. Several different superstructure types were evaluated; including those constructed of sawn lumber and glued laminated timber (glulam) materials (Table 1). Girder systems and slab-deck systems were investigated with the most common type being the sawn girder system supporting either a timber or concrete deck system. A significant number of bridges were also located in the southern and south-eastern coast regions, which represents "severe" conditions for timber structures, as defined by the American Wood Protection Association [2].

Figure 1: *US Map with locations of all timber bridges inspected during this study. (Google Maps)*

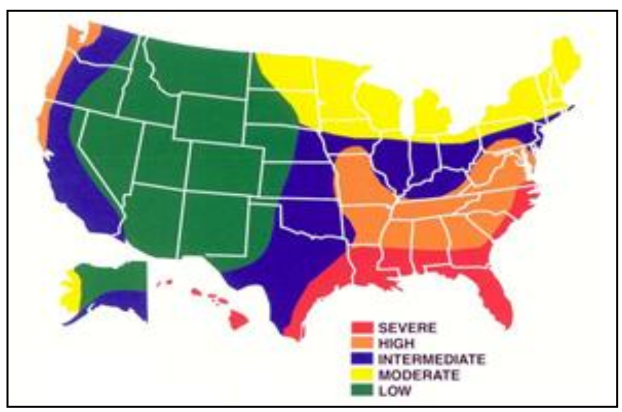

Figure 2: *Wood hazard (climate) zones for timber structures as defined by the American Wood Protection Association. (AWPA)*

Table 2: *Rating scale required for bridge inspections.*

Code	NBI[a] Rating	Description
9	Excellent	New condition
8	Very good	No problems detected
7	Good	Minor problems, but no structural defects
6	Satisfactory	Some minor defects, with no measurable section loss at critical locations
5	Fair	Primary structural elements show moderate to serious defects or deterioration with measurable section loss at critical locations and no significant loss of load capacity
4	Poor	Primary structural members show moderate to serious defects with advanced section loss at critical sections and diminished load capacity is evident
3	Serious	Widespread defects that have substantially reduced the load carrying capacity and local failures may be evident
2	Critical	Advanced deterioration resulting in significant number of local failures with close monitoring deemed necessary and/or closure
1	Imminent failure	Major deterioration or section loss in critical members affecting the structural capacity and the bridge should be closed immediately

[a]- *National Bridge Inventory (NBI) by Federal Highway Administration;*

3 SELECTION OF BRIDGES

3.1 KEY CRITERIA

There are estimated to be more than 50,000 timber highway bridges in-service throughout the United States according to the National Bridge Inventory database [3]. A sampling approach identifying clusters of timber bridges was the preferred approach for identifying bridges within the project constraints. The timber bridges selected for this study were from states that have significant timber bridge inventories (i.e., greater than 500). Many of them were located in the eastern half of the country. In conducting field inspections, safe and economical access to the bridge underside was a top priority. Selected timber bridges for inspection were required to be located along a public roadway and been in-service for at least 16 years in order to be considered for inclusion in this study. Lastly, bridge inspection, maintenance, and repair records had to be made available for review by the inspection teams, in order to identify previous bridge component upgrades or replacement activities. In some cases, these constraints made it difficult to locate clusters of timber bridges.

4 INSPECTION METHODOLOGY

4.1 PROJECT TEAMS

A team approach was utilized to complete the large scope of field inspection work within the project timeframe. Organizations participating in the study included the U.S. Forest Service, Louisiana Department of Transportation, University of Minnesota-Duluth, Iowa State University, Mississippi State University, The University of New Orleans, Laminated Concepts Inc., T.Williamson-Timber Engineering LLC, FPL, and the FHWA Turner-Fairbank Highway Research Center.

4.2 INSPECTION PROCEDURES

All project teams followed the same field protocol to ensure consistency within the overall bridge inspection results. In-depth inspections were completed using visual, moisture content, probing, resistance micro-drilling, and stress wave acoustic techniques. Visual techniques were employed to detect external indicators of deterioration or distress in bridge components. A moisture meter was used to identify areas of the superstructure with sufficient moisture to support decay activity. Hammer sounding, along with probing and picking, was used to initially scan each superstructure element. Areas with potential internal deterioration were further investigated with a stress wave timer when both sides of the member were accessible [4,5], and with a resistance micro-drilling tool (Figure 3) especially when access was limited to only one member side [6]. Detailed field notes and sketches were completed on site for each bridge inspected and they were later archived as AutoCAD images. High resolution digital photographs and video were recorded of the bridge with special emphasis on deteriorated or damaged areas. Raw data from stress wave timer and resistance micro-drill were processed and recorded. Lastly, the inspection team rated the primary structural components according to condition ratings system provided in the FHWA National Bridge Inspection Standards (Table 2). More detailed inspection procedures are also available [7].

5 SUMMARY OF FINDINGS

Preliminary findings are included for only the sawn lumber and glulam girder system bridges based upon a preliminary analysis of the completed bridge inspections. Condition ratings for these bridges are tabulated to shown the effects of wood hazard (climate) zone on bridge performance and longevity. Also included are some pertinent findings from the inspection teams on key details that can affect the overall bridge durability. Reporting of more regional bridge inspection results are also available [8, 9, 10, 11]. Several interesting aspects were revealed about timber bridge durability characteristics within the United States. Nearly three-fourths of the bridges evaluated were girder style bridges supporting a lumber, glulam, or a concrete deck.

Table 3: *Total number, deck type, and wood hazard (climate) zone for the 87 sawn girder bridges inspected.*

State (alphabetical)	Total number of sawn girder bridges by wood hazard (climate) zone				
	Low (1)	Moderate (2)	Intermediate (3)	High (4)	Severe (5)
AL				5[a] 4[c]	
CA			2[a] 1[b]		
GA				1[a]1[c]	5[a]
IA		10[a]			
LA					9[a] 2[c]
MN		1[a] 3[b]			
MS				8[a]	
NC				3[a] 2[c]	1[c]
OR			2[a]	5[b]	
TN				3[a] 4[c]	
WA			7[b]	3[b] 1[c]	
WI		4[a]			
Total	0	18	12	40	17

[a]-lumber plank deck; [b]-nail-laminated deck; [c]-concrete;
State abbreviations are defined in Table 5 footnotes;

5.1 SAWN LUMBER GIRDER BRIDGES

The sawn girder superstructure type represented 66 percent of the 132 bridges evaluated (Table1). 61 percent of the sawn girder bridges supported a lumber plank deck system, with 24 percent supporting a nail-laminated lumber deck and 15 percent supporting a concrete deck. The sawn girder bridge clusters were located in four of five wood hazard zones as defined by the American Wood Protection Association (AWPA) (Table 3). No bridges were located in the low (1) hazard zone which represents the arid west region of the country. A total of 18 sawn girder bridges were inspected in the moderate wood hazard zone; 12 in the intermediate wood hazard zone; 40 in the high wood hazard zone; and 17 in the severe wood hazard zone. Nearly three-quarters of these sawn girder bridges were located in the high-to-severe wood hazard zones. The high-to-severe localized bridge conditions are some the most challenging environments for timber bridges within the continental United States.

Several examples of outstanding sawn girder bridge durability were discovered; one from Yakima County, Washington is shown in Figure 4. This bridge has no record of repair or rehabilitation, with the exception of one sister beam added near the deck edge. It has been in-service for approximately 75 years and still maintains an average daily traffic of 1,600 vehicles and trucks. The bridge remains in satisfactory condition (NBI condition rating of 6) with no measurable section loss or deterioration at critical locations.

5.2 GLULAM GIRDER BRIDGES

The glulam girder superstructure type represented only 10 percent of the 132 bridges evaluated (Table 1). The glulam girder bridge clusters were located in 4 of 5 wood hazard zones (Table 4), with 9 within the moderate wood

***Figure 3**: The resistance micro-drill, a minimally-invasive NDE tool, being used to inspect a sawn lumber girder.*

***Figure 4**: 75-year old sawn girder bridge located in Yakima County, Washington remains in satisfactory condition.*

Table 4: *Total number, deck type, and wood hazard (climate) zone for glulam girder bridges inspected.*

State (alphabetical)	Total number of glulam girder bridges by wood hazard (climate) zone				
	Low (1)	Moderate (2)	Intermediate (3)	High (4)	Severe (5)
CA			1[c]	1[a] 2[c]	
MN		5[a]			
NY		4[b]			
Total	0	9	1	3	0

[a]-nail-laminated deck; [b]-transverse glulam panels; [c]-concrete;

Table 5: *Condition rating percentages of sawn girder bridges inspected by wood hazard (climate) zone.*

Wood Hazard (climate) zone[a]	State[c]	Number of bridges	Percentage of sawn girder bridges by NBI[b] condition rating					
			Deck			Superstructure		
			Poor and worse (1-4)	Fair (5)	Satisfactory and better (6-9)	Poor and worse (1-4)	Fair (5)	Satisfactory and better (6-9)
Moderate (2)	IA	10			100.0			100.0
	MN	4		25.0	75.0		25.0	75.0
	WI	4	25.0	50.0	25.0			100.0
	All	18	5.6	16.7	77.7		5.5	94.5
Intermediate (3)	CA	3		33.3	66.7			100.0
	OR	2			100.0			100.0
	WA	7	28.6		71.4		42.9	57.1
	All	12	16.7	8.3	75.0		25.0	75.0
High (4)	AL	9		22.2	77.8		11.1	88.9
	GA	2	50.0		50.0	50.0		50.0
	MS	8		12.5	87.5		12.5	87.5
	NC	5	20.0	20.0	60.0		20.0	80.0
	OR	5			100.0	20.0		80.0
	TN	7		14.3	85.7		14.3	85.7
	WA	4			100.0			100.0
	All	40	5.0	12.5	82.5	5.0	10.0	85.0
Severe (5)	GA	5	20.0	80.0		20.0	80.0	
	LA	11		36.7	63.4	18.2	36.4	45.4
	NC	1		100.0			100.0	
	All	17	5.9	52.9	41.2	17.7	52.9	29.4

[a]-Wood hazard (climate) *zones for exterior/exposed wood as defined by the American Wood Protection Association;*
[b]-*National Bridge Inventory as maintained at the Federal Highway Administration;*
[c]-*IA-Iowa; MN-Minnesota; WI-Wisconsin; CA-California; OR-Oregon; WA-Washington; AL-Alabama; GA-Georgia; MS-Mississippi; NC-North Carolina; TN-Tennessee; LA-Louisiana; NY-New York;*

Table 6: *Condition rating percentages of glulam girder bridges inspected by wood hazard (climate) zone.*

Wood hazard (climate) zone[a]	State	Number of bridges	Percentage of glulam bridges by NBI[b] condition rating					
			Deck			Superstructure		
			Poor and worse (1-4)	Fair (5)	Satisfactory and better (6-9)	Poor and worse (1-4)	Fair (5)	Satisfactory and better (6-9)
Moderate (2)	MN	5			100.0			100.0
	NY	4			100.0			100.0
	All	9			100.0			100.0
Intermediate (3)	CA	1			100.0			100.0
	All	1			100.0			100.0
High (4)	CA	3			100.0			100.0
	All	3			100.0			100.0

[a]- *Wood hazard (climate) zones for exterior/exposed wood as defined by the American Wood Protection Association;*
[b]-*National Bridge Inventory as maintained at the Federal Highway Administration;*

hazard zone, 1 in the intermediate wood hazard zone, and 3 in the high wood hazard zone. The deck type varied for the glulam bridge superstructure system with the older bridges typically using a nail-laminated or a concrete deck, and the newer bridges typically using a transverse glulam panel system. Nail-laminated deck bridges were inspected in southern Minnesota and northern California; A single cluster of concrete deck bridges were inspected in northern California; a single cluster of transverse glulam panel bridges were inspected in western New York. Good examples of glulam girder bridge durability were also discovered as a few bridges have been in-service for over 70 years. This group of older glulam bridges includes many built prior to more stringent lumber quality requirements for tension-side laminations being adopted by the industry (AITC) standards. Despite their deficient tension-side laminations, these pre-1970 glulam girder bridges are still in satisfactory or better condition and without significant structural issues.

5.3 CLIMATE INFLUENCE

The influence of wood hazard (climate) zone on the durability of those bridges inspected is presented for the sawn girder bridge inspections (Table 5) and for the glulam girder bridge inspections (Table 6). In general, the percent of condition ratings that were satisfactory and better were lower as the climate zone became more hazardous for exposed wood, with a few exceptions.

For sawn girder decks, lower percentages of the total bridges inspected fell in the poor and worse (1-4 rating) condition category They ranged from 5.6 percent in the moderate zone, 16.7 percent in the intermediate zone, 5.0 percent in the high zone, and 5.9 percent in the severe wood hazard (climate) zone. Medium percentages of the total bridges inspected fell in the fair (5) condition category. They ranged from 16.7 percent in the moderate zone, 8.3 percent in the intermediate zone, 12.5 percent in the high zone, and 52.9 percent in the severe wood hazard (climate) zone. High percentages were found in the satisfactory and better (6-9) condition category with 77.7 percent in the moderate zone, 75.0 percent in the intermediate zone, 82.5 percent in the high zone, and 41.2 percent in the severe wood hazard (climate) zone.

For sawn lumber superstructures, low percentages fell within the poor and worse (1-4) category, ranging from 5.0 percent in the high zone and up to 17.7 percent in the severe wood hazard (climate) zone. Increasing percentages were found in the fair (5) condition category with 5.5 percent in the moderate zone, 25.0 percent in the intermediate zone, 10 percent in the high zone, and 52.9 percent in the severe wood hazard (climate) zone. High percentages were found in the satisfactory and better (6-9) condition category with 94.5 percent in the moderate zone, 75.0 percent in the intermediate zone, 85.0 percent in the high zone, and 29.4 percent in the sever wood hazard (climate) zone. The general trend in this condition category clearly shows the effect of climate with decreasing percentages of bridges meeting the satisfactory and better condition criteria as the wood hazard (climate) zone went from moderate towards severe. An exception to this general trend was that 85 percent of the bridges inspected in the high wood hazard climate zone were rated at satisfactory and better condition..

For glulam girder bridges, one hundred percent of those inspected fell in the category of satisfactory and better, both for the deck and the superstructure condition ratings. Most of these glulam bridge structures were inspected at approximately 30 years in-service, but there were a few structures built over 50 years ago. With a relatively low number of glulam girder bridges (13 total) inspected within this study, it will prove difficult to draw any definitive conclusions about their durability performance in the various wood hazard (climate) zones, or any potential role that the deck type may contribute to bridge longevity. Additional inspection work on glulam girder type bridges is needed in the future to statistically support more reliable conclusions about bridge performance data.

Many complexities are involved in the maintenance and replacement decision process undertaken by individual state or local governments. This factor likely plays a role in the longevity of a specific bridge, and may have contributed to the exceptions to the general trends noted above.

5.4 ISSUES AFFECTING DURABILITY

Several inadequate deck drainage deficiencies were noted by bridge inspectors. Bridge durability could be further enhanced by solutions that protect the deck and superstructure from moisture intrusion.

For the multiple span bridge structures that were supported by intermediate timber pile supports, the susceptibility of the cap beams to moisture accumulation and decay activity is fairly common. Typically, the asphalt has transversely oriented “reflective” cracking directly over the cap member and provides the avenue for moisture intrusion. Also, many bridges do not include the recommended waterproof geotextile membrane beneath the asphalt wearing surface. Solid sawn cap timbers often exhibit drying checks on their top surface that provides an avenue for moisture intrusion to the interior which promotes potential decay activity. Effective flashing placed over the cap member is one proposed solution for solving this drainage deficiency.

For plank deck bridges, there is typically no asphalt wearing surface present. When the roadway approaches are gravel, large amounts of sand and silt accumulates in the vicinity of the abutments and traps moisture leading to conditions that promote decay. Paving the approaches is one solution that can effectively eliminate this activity.

For all timber bridges, effective deck drainage is typically hampered as soon as surface runoff hits the curb and scuppers along the deck edges. It is not uncommon for ponding and silt accumulation to occur in these shoulder zones that promotes early decay and deterioration. Routine cleaning of the deck roadway and including clearing of the supper openings will help alleviate the problem. Design details are currently available that outline how to install effective flashing and drip edges in conjunction with repaving operations to protect the bridge deck against moisture degradation.

6 SUMMARY

A total of 132 timber highway bridges were inspected recently by a diverse team of bridge inspectors as part of a national program aimed at determining their durability characteristics. Nearly all of these bridges were built with either Douglas fir or southern yellow pine wood species, and were pressure-treated with creosote or pentachlorophenol oil-type preservatives. The following conclusions are based upon the findings:

- Timber is a durable option for primary structural members in highway bridges and can perform satisfactorily for up to 75 years when properly pressure-treated with preservatives. Its durability can be enhanced by effective deck drainage detailing and preventative maintenance practices focused on eliminating moisture traps.
- Each superstructure type is represented by a limited number of in-depth bridge inspections. Future additional inspection work is warranted in order to support more reliable service life estimates.
- The sawn girder superstructure type represented 66 percent of the 132 bridges evaluated. The sawn girder bridge clusters were located in 4 of 5 wood hazard zones as defined by the AWPA. 61 percent of the sawn girder bridges supported a plank deck system. This system proved to have a good record on longevity in many wood hazard (climate) zones. About 75 percent of the bridges in the moderate and intermediate wood hazard zones were rated at satisfactory & better condition. Nearly 83 percent of the bridges inspected in the high wood hazard zone were rated at satisfactory and better condition. Only 41 percent of the bridges in the severe wood hazard zone were rated satisfactory and better. The advantage of this system may lie in its member redundancy (i.e., closely spaced girders) which enhances the overall resiliency of the bridge.
- The glulam girder superstructure type represented 10 percent of the 132 bridges evaluated. With a relatively low number of glulam girder bridges (13 total) inspected within this study, it will prove difficult to draw substantive conclusions about their durability performance in the various wood hazard (climate) zones, or any potential role that the deck type may contribute to bridge longevity.
- Several inadequate deck drainage issues were noted by bridge inspectors. These poor design details promote moisture accumulation and accelerated deterioration of bridge components. Remedial actions to alleviate these deck drainage issues will undoubtedly help to further extend bridge service life.

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