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Condition Assessment of a 55-year-old Glued-laminated Timber Arch: Nondestructive Evaluation and Toughness Test Results

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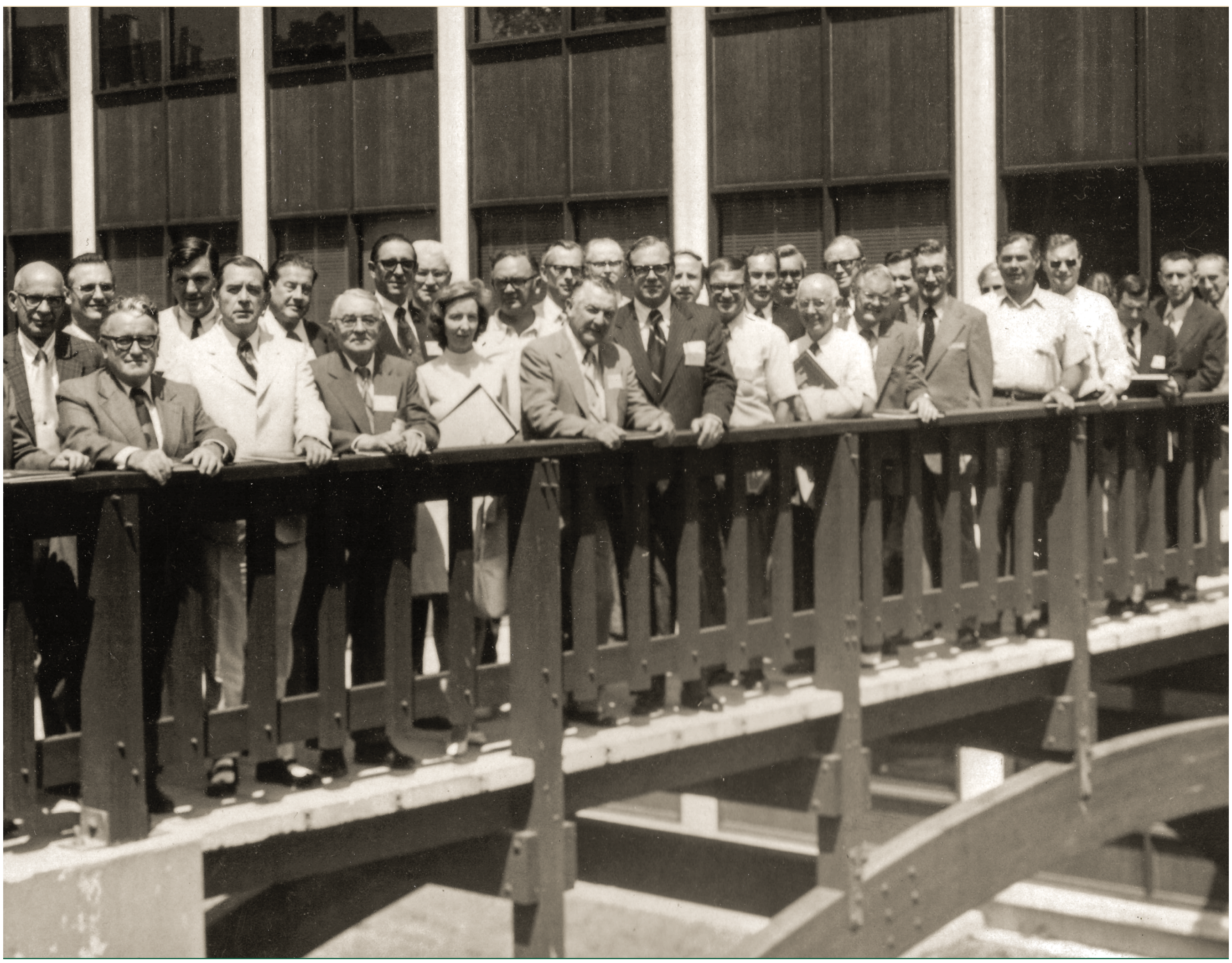

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Abstract

A condition assessment of several glued-laminated timbers recently removed from service was conducted on the ends of the timbers using stress wave nondestructive evaluation techniques. After the assessment, toughness tests were performed in the laboratory on specimens obtained from the timbers to determine residual strength. Several areas of deterioration from decay were found during the nondestructive assessment. Deterioration was verified during subsequent toughness testing. A statistical relationship was found to exist between nondestructive test measurements and toughness test results.

Keywords

structural condition assessment, toughness, visual inspection, decay, moisture, glued-laminated timber, glulam

Contents

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Cover photo: The executive committee of the National Forest Products Association on the Forest Products Laboratory footbridge, July 17, 1973. Forest Service photo.

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Introduction

Glued-laminated timbers (glulam) are an engineered wood product widely used in timber structures today. The U.S. Department of Agriculture, Forest Service, Forest Products Laboratory (FPL) has provided scientific and technical information used by manufacturers and users of glulam since its first use in the United States. Early research at FPL is summarized in Wilson (1939) and included the development of fundamental information on material preparation (e.g., lumber properties and appropriate adhesive specifications), laboratory testing procedures and results, and design considerations. The laboratory also demonstrated the use of glulam, constructing one of the first structures built with glulam timbers in the United States on its campus in 1935.

The subject of this report is a timber footbridge constructed during the 1960s to connect two buildings on the FPL campus. The main supporting members were glulam arches manufactured by Sentinel Structures (Peshtigo, WI, USA) from southern pine dimension lumber (Fig. 1). A structural condition assessment of the arches was performed in 1997. After deconstruction of the bridge in 2024, the ends of the arches were retained for study. A condition assessment of the retained ends was performed, and the ends were tested in the laboratory to determine their residual strength (toughness). This report summarizes results from the structural condition assessments and the laboratory tests.

Background

Public safety is a primary concern for structural use of wood. In many regions of the United States, fungal decay is a serious and common cause of deterioration of wood structures. The decay of a wood load-bearing member in service can be caused by several types of fungi that derive their nourishment from the components of the walls of the cells in which they live. The hyphae of these fungi secrete enzymes that depolymerize the wood and lower its density, strength, and toughness, resulting in a significant reduction in the load-carrying capacity of the member that may lead to structural failure.

Early research on the effect of decay on various strength properties of wood is summarized in Table 1 (Wilcox 1978) and on the page that follows.

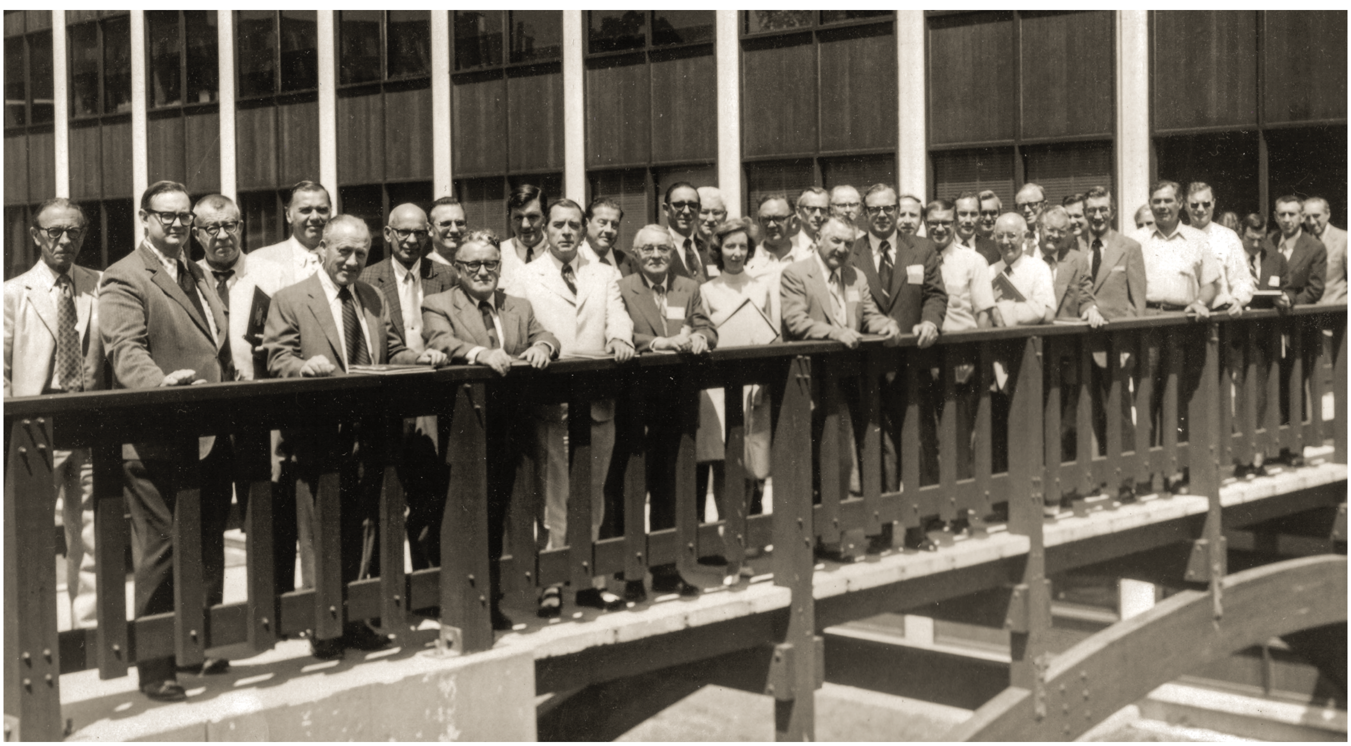

Figure 1.—The executive committee of the National Forest Products Association on the Forest Products Laboratory footbridge, July 17, 1973. Forest Service photo.

Table 1.—Estimated values for strength property losses in softwoods and hardwoods at early stages of decay (indicated by weight loss) by brownrot and white-rot fungi as a percentage of the value for nondecayed samples[a]

			Static bending								
Approximate weight loss (%)	Toughness	Impact bending	General bending strength	Work to maximum load	MOR[b]	MOE[c]	Compression perpendicular (radial)	Compression parallel	Tension parallel	Shear parallel	Hardness
Brownrot fungi											
Softwoods											
1	57	20–38	—	—	—	—	—	—	—	2	—
2	—	20–50	5	27	13–50	4–55	18–24	10	23–40	—	—
4	75	25–55	—	—	—	—	25–35	—	—	6	7
6	—	62–72	16	—	61	66	48	25	60	—	—
8	—	78	—	—	—	—	48–60	—	50	15	21
10	—	85	36	—	70	—	66	45	—	20	—
Hardwoods											
1	—	6–27	—	—	—	—	—	—	—	—	—
2	36	31–50	—	54	32	—	6–10	—	56	—	—
4	—	60–70	—	69	49	—	—	—	—	—	—
6	—	80	—	75	61	—	16–25	—	—	—	—
8	—	9–89	13–34	—	—	—	19	—	82	—	—
10	60	70–92	—	—	—	—	—	—	—	—	—
White-rot fungi											
Softwoods											
1	55	—	—	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	10–20	—	4–38	—	—
4	—	—	—	—	—	—	—	—	8–43	—	—
6	75	—	—	—	—	—	32–61	—	10–49	—	—
8	—	—	—	—	—	—	—	—	14–58	—	—
10	85	—	—	—	—	—	—	—	20–63	—	—
Hardwoods											
1	—	21	—	—	—	—	4	—	—	—	—
2	—	26	—	28–35	13–14	4	5	—	22–42	—	—
4	70	44	—	38	20	—	—	—	17–44	—	—
6	75	50	—	45–53	20–27	10	12–27	14	12–58	—	18
8	—	—	—	—	—	—	—	—	14–49	—	
10	85	60		58	24	14	35	20	20–50		25

[a] Source: Wilcox (1978). Values obtained from published experimental results and adjusted to equivalent weight loss levels.
[b] Modulus of rupture.
[c] Modulus of elasticity.

Toughness (Impact Bending)

Toughness (the ability of a wood member to withstand shock loading) is generally considered to be the strength property most affected in early stages of decay. Research dating to 1954 has indicated that a loss of only 1 percent in weight corresponds to a toughness loss of up to 50 percent (Table 1).

Static Bending

Research dating to the 1930s has been conducted on modulus of elasticity, modulus of rupture, and work-to-maximum-load in bending mode. Reported results have indicated a significant loss in modulus of rupture (strength) after wood has decayed (Table 1).

Other Strength Properties

Research has shown that compression perpendicular to the grain, compression parallel to the grain, tension parallel to the grain, shear parallel to the grain, and tangential hardness are also impacted by deterioration caused by decay.

Materials and Methods

Nondestructive Test Procedures

Stress wave (stress wave/sound transmission) nondestructive testing techniques have been successfully used in decay detection in a variety of wood structures. The concept of detecting decay using this method is that stress wave propagation is sensitive to the presence of degradation in wood. The underlying premise is that stress waves travel faster through sound and high-quality wood than through deteriorated or low-quality wood. The time of flight (or transmission time) of the stress wave is typically used as a predictor of the physical condition of the wood. By measuring the time of flight of a stress wave travelling through a wood member (perpendicular to grain), the internal condition of the member can be determined. Detailed information on the principles of this technique, guidelines for use and interpretation, commercially available equipment, and examples of its use are given in White and Ross (2014). Supporting research is summarized in Senalik et al. (2022).

1997 Inspection—On July 3 and July 18, 1997, inspections of the glulam arches in the footbridge were conducted using visual and stress wave nondestructive testing techniques. The inspections focused on the ends of the arches because end areas are generally most susceptible to degradation. Special note was taken of any deep checks within the members of any sections containing visibly evident deterioration, such as crumbly wood.

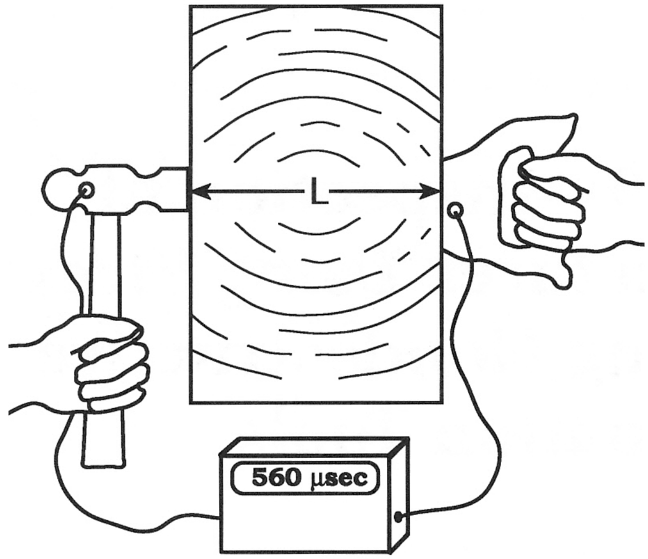

Figure 2.—Schematic diagram of test setup used to inspect glulam arch ends in the footbridge at the Forest Products Laboratory in 1997. Source: White and Ross (2014).

A stress wave inspection of the ends was conducted following the approach used by Hoyle and Pellerin (1978). A schematic diagram of this test setup in shown in Figure 2. Several readings were taken at various positions in the arch ends.

2024 Inspection—The footbridge was deconstructed in 2024. During deconstruction, the ends of each arch were cut and placed in a conditioned space at FPL. In June of that year, specimens were transported from FPL to Mississippi State University for testing on the same arch ends that were tested in 1997 (Fig. 3). Each end was nondestructively tested using the 1997 inspection method. The 1997 and 2024 inspections yielded comparable results.

Toughness Test Specimen Preparation and Procedures

The following steps were used to prepare specimens for toughness testing. First, the steel anchorage shoes were removed from the glulam stubs, which were approximately 5.5 in. wide, 14 in. deep, and 12 to 24 in. long (Table 2). Next, the tops and bottoms of the stubs were marked, and the ends were painted blue, red, green, and

Table 2.—Color scheme and minimum stub length after shoe removal

Source location	Color	Minimum stub length (in.)
Northeast	Blue	16
Northwest	Red	17
Southeast	Green	24
Southwest	Black	12

Figure 3.—Nondestructive testing of arch end sections (stubs). Courtesy photo by Laurice M. Spinelli Correa.

Figure 4.—Glulam stubs after steel anchorage shoe removal and color coding. Courtesy photo by Laurice M. Spinelli Correa.

black to correspond to the original location of arch ends and preserve identification throughout processing (Table 2). Figure 4 shows the stubs after steel anchorage shoe removal and color coding. Stubs were stored in an outdoor protected shed, where the approximate equilibrium moisture content was 12 to 16 percent.

A visual inspection showed that the southwest stub had heavy deterioration and delamination; however, the constituent pieces were maintained in order throughout, so the original shape of the stub was preserved. The northeast stub had significant deterioration in two laminae that were otherwise covered by the steel anchorage shoe. The stubs had dot markings that indicated the locations of the time of flight measurements. In each stub, five laminae had time of flight measurements. The time of flight measurement scheme is shown in Figure 5. Note that due to the length of the specimen stub, no evaluation was conducted at 12 in. for the southwest stub.

Sawmilling was required to reduce the stubs to their five constituent laminae of interest. The goal of the sawmilling process was to remove these five laminae from each of the stubs in order to produce toughness specimens from the same five laminae on which time of flight measurements had been made. Stubs were band sawn on July 2, 2024. For specimen preparation, stubs were placed on a portable bandsaw mill. Layer by layer, the time of flight laminae were removed and reserved. Figure 6 illustrates one stub on the bandsaw mill. Figure 7 illustrates the laminae of interest recovered after bandsaw milling.

Next, toughness specimens were machined from the laminae of interest. Figure 8 illustrates the ripping process by which cross section toughness specimens measuring approximately 0.79 by 0.79 in. were recovered from the laminae. Many of the laminae were split at mid width, and many had previous inspection or fumigation holes at mid width. Effort was made to recover one specimen from each edge of each lamina, which yielded two toughness specimens per lamina (most laminae yielded two clear specimens). A total of 40 toughness specimens were produced (four stubs, each with five laminae of interest and two toughness specimen laminae). While the arches were subjected to compression forces in-service, toughness was chosen to evaluate degree of deterioration because it has been shown to be the most sensitive to deterioration from decay (Table 1).

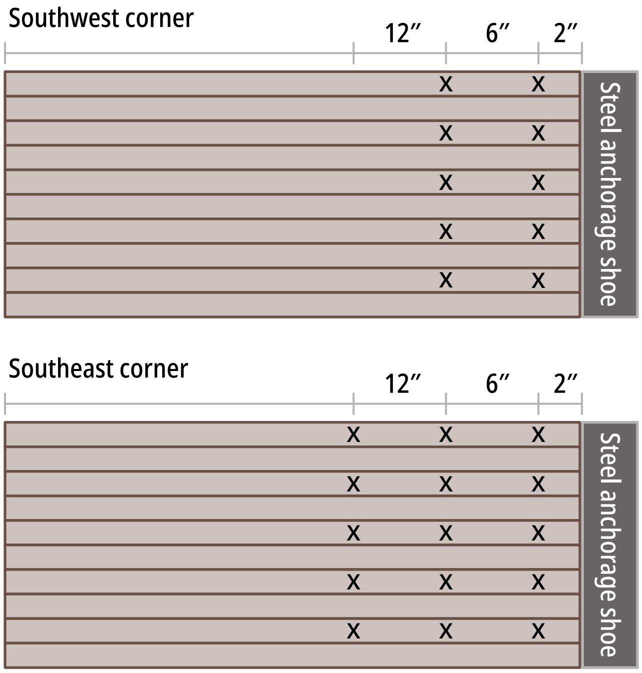

Figure 5.—Schematic depicting the locations of the time of flight measurements on the glulam stub specimens.

Figure 6.—Glulam stub on the bandsaw mill during lamina-of-interest recovery. Courtesy photo by Laurice M. Spinelli Correa.

Figure 7.—Laminae of interest during recovery and sorting while bandsaw milling. Courtesy photo by Laurice M. Spinelli Correa.

Figure 8.—Ripping operation by which 0.79 by 0.79 in. cross sectional toughness specimen blanks were recovered from each lamina of interest. Courtesy photo by Laurice M. Spinelli Correa.

Figure 9.—Toughness specimens after processing, prior to moisture conditioning at 12 percent equilibrium moisture content. Courtesy photo by Laurice M. Spinelli Correa.

A small number of specimens would not yield clear specimens. These nonclear specimens contained a knot, a finger joint, decay, or other characteristic. The laminae were numbered 1 to 5, top to bottom, with 5 denoting the bottommost layer from which time of flight measurements had been taken. It was anticipated that average toughness values could be directly compared to the average time of flight measurements from each lamina.

In some cases, additional processing was required to remove warp, cross grain, or other potentially strength-reducing characteristics. Once the specimen blanks were ripped, each specimen was crosscut to the requisite 11-in. length and the ends repainted. Figure 9 shows the specimens after machining and repainting. Specimens were then placed in an environmental chamber for moisture conditioning at approximately 70 °F (21.11 °C) and 12 percent equilibrium moisture content for approximately 30 days.

Toughness was tested per ASTM D143. Test machine settings were as follows: pendulum length was 13.875 in., weight was 50 lb, and initial angle was 45 degrees. Post testing, the final angle was read and recorded, and a moisture content/specific gravity specimen was cut from one end of each test specimen. Actual toughness values were calculated and recorded in pound-force per inch (lbf-in.).

Results and Discussion

Nondestructive Test Results from Inspections

1997 Inspection—Visual inspection revealed no evidence of gross deterioration. There was no observation of fruiting bodies, brown crumbly wood, or signs of mechanical damage. Several deep checks, surface checking, and signs of weathering were noted. Results from the stress wave analysis indicated that several areas were deteriorated. The areas were localized and were not indicative of severe deterioration.[1]

2024 Inspection—Results from the stress wave testing of the stubs are presented in Figure 10. Note that the numbers reported are simply the time, in microseconds (10^{-6} seconds), that it took the wave to travel through the member. Multiple studies (Senalik et al. 2022) have shown that the extent of degradation of a wood member is closely related to the time it takes a wave

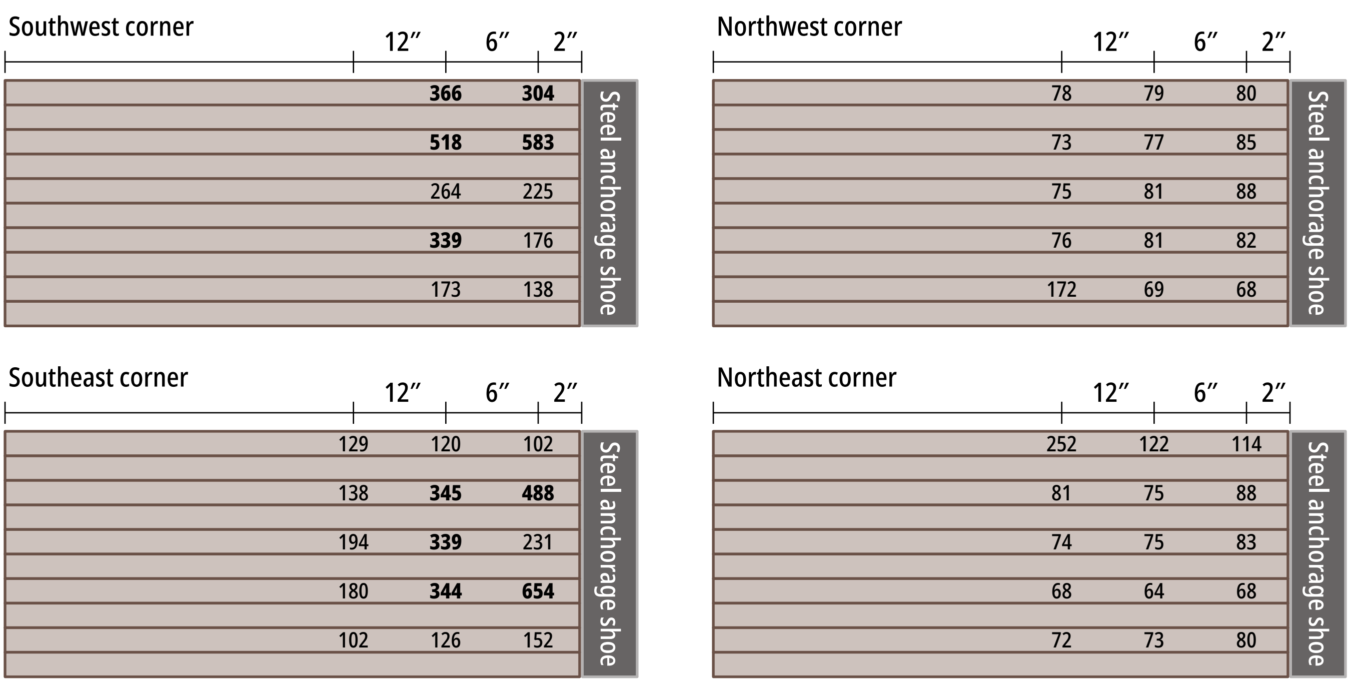

Figure 10.—Results from the 2024 stress wave testing on the glulam stub specimens.

[1] Ross, R.J.; Kainz, J. 1997. Inspection of members of bridge connecting buildings 01 and 33 of the Forest Products Laboratory, Madison, WI. Unpublished report.

to travel through it (i.e., a longer travel time corresponds to lower quality of wood). Baseline travel times for a section of sound wood of the size of the arches should be approximately 100 microseconds (White and Ross 2014). Similarly, laboratory studies (Ross et al. 1999) have shown that members having travel times greater than 300 microseconds are deteriorated. In the 2024 inspection, areas that had travel times greater than 300 microseconds were found in the southwest and southeast stubs (bold numbers in Fig. 10). This result was expected because the members in the southeast and southwest locations were highly exposed to moisture and, during the winter months, snowfall and snow piles created by the plowing of adjacent parking lots.

Laboratory Test Results

Moisture Content (MC)—Test results are summarized in Table 3. Note that all MC values were significantly lower than the commonly used value for fiber saturation point (approximately 30 percent). The MC of the south end specimens was higher than that of the north end specimens. It is surmised that the higher MC was due to the presence of decay, bacteria, or both in the south end specimens, which were either slower to release the MC during environmental conditioning or ultimately equilibrated at a higher MC value.

Specific Gravity—Table 4 provides a summary of the specific gravity (SG) values found for the test specimens. All are comparable to SG values reported by Senalik and Farber (2021) for several species in the southern pine lumber grouping. Note that the southwest corner specific gravity had significantly higher variability due to deterioration from decay.

Toughness Test Results—Table 5 provides a summary of toughness test results. The specimens from the stubs from the northeast and northwest had toughness results similar to those reported by Senalik and Farber (2021) for several species of southern pine. The results for the southeast and southwest stubs were significantly lower. Note that the in-service stubs from the southeast and southwest ends of the bridge were subjected to longer periods of moisture from melting snow every year because the south ends of the arches were near one of Forest Products Laboratory's main parking lots. As such, south end specimens were wetter after moisture equilibration, seemingly contained more deterioration, and resulted in toughness values that were both lower and more variable than those from the north end.

Table 3.—Percent moisture content of stubs, 10 stubs per corner

	Northeast	Northwest	Southeast	Southwest
Mean	13.6	12.7	15.9	15.1
Median	13.2	12.6	16.7	14.1
Maximum	16.5	13.7	18.3	19.0
Minimum	12.1	12.0	11.2	11.7
Standard deviation	1.4	0.6	2.3	2.5
Coefficient of variance	10.1	4.5	14.2	16.9

Table 4.—Specific gravity of stubs, 10 stubs per corner

	Northeast	Northwest	Southeast	Southwest
Mean	0.44	0.51	0.43	0.47
Median	0.43	0.50	0.41	0.41
Maximum	0.49	0.59	0.57	0.68
Minimum	0.40	0.44	0.36	0.39
Standard deviation	0.03	0.06	0.06	0.10
Coefficient of variance	7%	12%	15%	22%

Table 5.—Toughness test results of stubs, in pound-force per inch (lbf-in.), 10 stubs per corner

	Northeast	Northwest	Southeast	Southwest
Mean	104.6	142.1	77.9	87.6
Median	100.6	144.6	73.5	89.6
Maximum	170.0	197.3	190.0	192.7
Minimum	46.3	80.5	12.7	8.5
Standard deviation	32.5	47.8	49.2	51.5
Coefficient of variance	31%	34%	63%	59%

Relationship Between Nondestructive and Toughness Test Results

The average stress wave transmission times (in microseconds) for each stub were compared with corresponding average toughness values. Figure 11 illustrates the comparison. Note that a relationship exists: stubs with longer stress wave transmission times had lower toughness values.

Summary

- A condition assessment of glued-laminated timbers that had recently been removed from service in a footbridge was conducted on the ends of the timbers using common stress wave nondestructive evaluation techniques. Several areas of deterioration from decay were found. Those areas, in the southeast and southwest corners of the footbridge, had been subjected to extended moisture exposure during 55 years of service.
- Toughness tests were also performed in the laboratory on specimens obtained from the timbers. Deterioration was verified. Toughness test results from undeteriorated sections had values that essentially matched published values, indicating minimal deterioration after 55 years of service.
- A statistical relationship was found to exist between nondestructive test measurements on the timbers and toughness test results. To examine the relationship more fully, it would be beneficial to design and conduct a follow-up study that includes more specimens. In addition, ongoing toughness testing in and among wider applications would be beneficial because toughness is one of the earliest reliable indicators of deterioration. Toughness testing, and variants thereof, would advance protective design of wood structures because energy absorption and performance in building materials are critical for blast resistant design and for mitigating progressive building collapse.

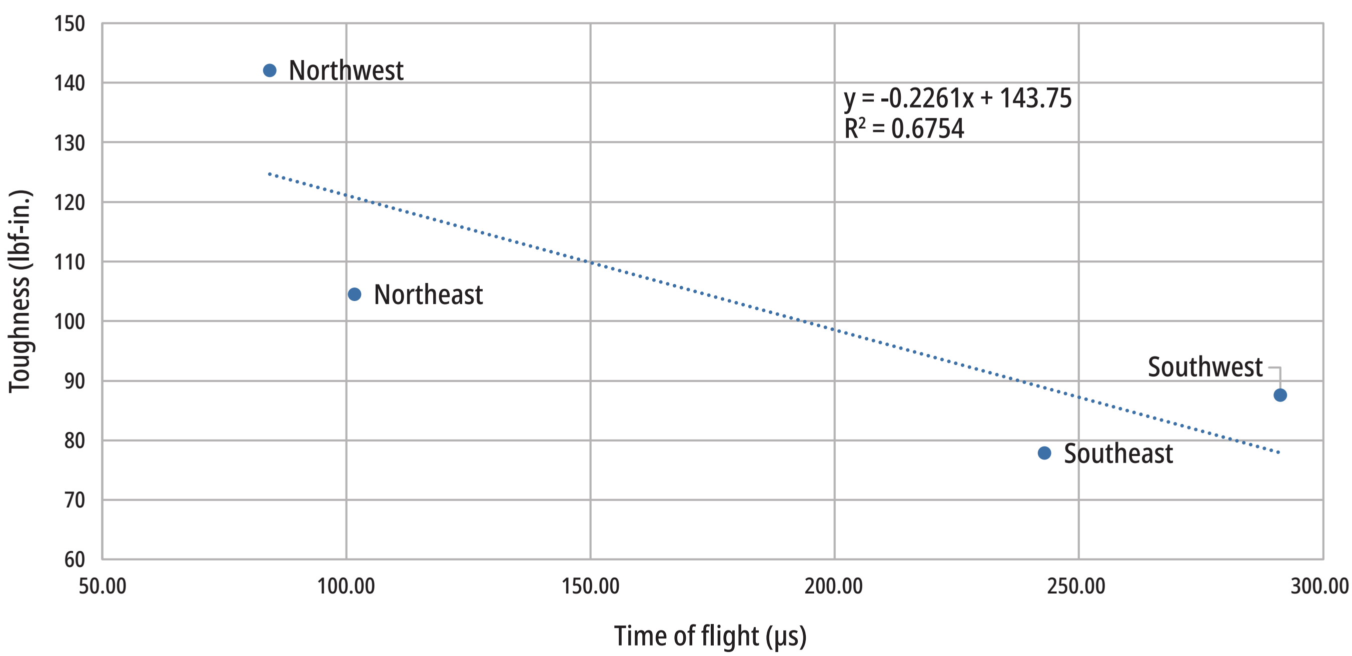

Figure 11.—Average time of flight versus average toughness for each of the stubs.

Conversions

When you know	Multiply by	To convert to
in. (inches)	2.54	cm (centimeters)
lb (pounds)	0.453592	kg (kilograms)
lbf-in. (pound-force per inch)	0.1129848	N-m (Newtons per meter)

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