In: Proceedings of the 18th International Nondestructive Testing and Evaluation of Wood Symposium held on Sept. 24-27, 2013, in Madison, WI.

Nondestructive Evaluation of a 75-Year Old Glulam Arch

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Abstract

The purpose of this study was to explore the possibilities of using existing nondestructive evaluation (NDE) methods to assess delamination and decay of glulam structures. A glulam arch removed from a research building after more than 75-year service was used as a test specimen. The glulam arch section was tested using stress wave timing, ultrasonic wave propagation, and resistance micro-drilling methods at a series of locations. The arch was subsequently cut open for visual inspection and small compression and shear samples were obtained for strength testing. It was found that wave propagation times or wave velocities measured across the laminations were good indicators of internal decay. Stress wave timing and ultrasonic propagation methods were able to detect moderate to large delamination, but not micro-delamination. Resistance micro-drilling was found not effective in detecting delamination. Further research is planned to evaluate the possibility of using pulse-echo method to detect internal delamination of glulam members.

Key words: glued laminated timber (glulam), stress wave, ultrasonic wave, resistance micro-drilling, strength, modulus of elasticity.

Introduction

The use of glued laminated timber (glulam) has become widespread all over the world extending the modern wooden building capabilities. Solid wood members are increasingly being replaced by modern engineered timber laminates glued and stacked together, enabling timber structures to carry more loads (for instance in large-span roofs). As innovative construction techniques for timber buildings are continuously being developed, the need for modern assessment methods are increasing to assure or extend the service life of the glulam structures, especially due to the problems related to the adhesive bonding causing delamination in glulam elements. Delamination usually results from manufacturing failures, improper bonding, overloading during the service life of a structure, or by moisture changes causing stresses. Since the visual assessment is typically confined to the surface conditions and provides only limited information on internal wood condition and the bond lines between laminates in glulam timber, more advanced methods need to be explored and developed for field inspection of glulam timber components in modern buildings.

In the fall of 2010, a glulam arch structure at the USDA Forest Products Laboratory (FPL) was deconstructed after more than 75 years of use. Since these arches represent the first generation of both construction adhesives and glued-laminated development, the glulam arches were preserved as research specimens for various groups at FPL to evaluate the durability and residual strength of these aged arch members. The objective of the study reported herein was to assess the physical conditions of the arch members and evaluate the effectiveness of several nondestructive testing methods, including stress wave timing, ultrasonic wave propagation, and resistance micro-drilling, for detecting delamination and decay in wooden glulam beams.

Materials and Methodology

Old Glulam Arch Structure

A research building incorporating glued laminated wooden arches was erected on the USDA Forest Products Laboratory's campus in 1934 (Figure 1). As one of the first examples of glulam structures in the United States, this building represented FPL's early efforts on developing arches from thin, individual wood laminations that could be bent into flowing shapes. In addition to its primary service function, this building was also intended to demonstrate the adaptability of wood to modernism in both design and construction. The construction embodied special features developed or adopted through research at the FPL. One special feature was to create unobstructed floor space and ample overhead clearance for sawmill and other industrial projects. For this reason, arched supports were chosen in preference to column-and-girder or standard truss construction (Wilson 1939).

Three types of arch supports were used in the building—one solid glulam, one of double I-beam section, and one of trussed arch held together at the joints with split-ring and hinge-and-plate connectors. Five solid arches and two each of the composite types were built and symmetrically disposed in the building, solid arches at the middle bays, double I-beam arches next, and trussed arches at the ends. The halves of the large glued arches were bent at the knee but were straight below and above the knee, and were held together at the apex with bolted plates. Flanged plate bearings for all arches were provided at the foundations.

Throughout the years the building was used for various research applications and the interior was configured to meet those needs. In 1993, while drying fiber an intense fire was started on the west end of the building. During this event, several of the arch members were exposed to elevated temperature and fire conditions. Those affected members were repaired/strengthened by retrofitting one or two sister members following the fire event. The repaired arch members have performed well since the fire event.

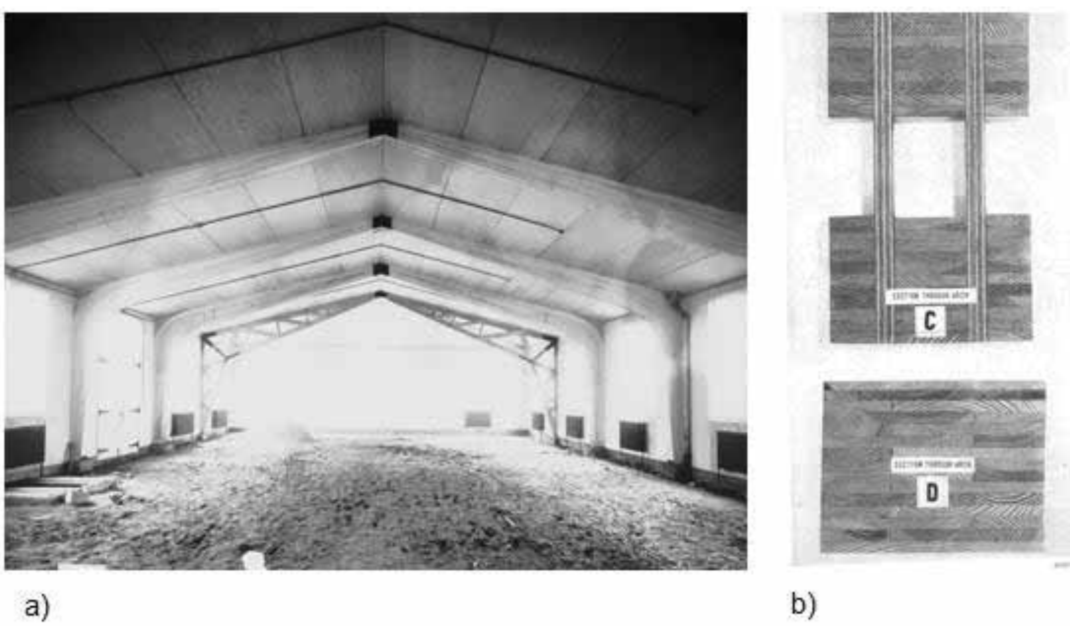

Figure 1—a) Inside view of the USDA Forest Products Laboratory service building, b) Cross-section views of C-type and D-type glulam used as the bearing structural components in the building.

Experimental Procedure

The solid glulam arches were glued up of laminations of 1.4-cm (9/16-in.) material to a width of 29.2-cm (11 ½ -in.) and a thickness of 30.5-cm (12-in.) at the base, 61.0-cm (24-in.) at the knee, and 20.3-cm (8-in.) at the apex. Each layer was made of 10.2 cm (4-in.) and 20.3-cm (8-in.) pieces, with the edge joints staggered in alternate laminations. Through a preliminary stress wave and ultrasonic timing inspection, we were able to determine the general physical conditions of all the solid glulam arch sections removed from the building. Glulam arch section No. 5 was found to contain a wide range of decay and delamination due to moisture intrusion and exposure to the elevated temperatures in fire. We selected this section as a specimen for an in-depth study.

Extensive non-destructive testing was performed on the selected glulam arch section using several different types of NDE techniques, including stress wave timing, ultrasonic transmission, pulse-echo, and resistance micro-drilling. Figure 2 shows the glulam specimen under testing and locations that NDE measurements were conducted. The physical condition of the section changed through the length, thus we began the measurements at the cross-section 50 mm from the decayed end (lower end), followed by 200 mm and then by 300 mm increments (Figure 2b). At each of these locations, measurements were taken at three levels which were designated as A, B and C for upper, middle, and lower levels respectively. The experiments were carried out in a laboratory at 21 °C and 50% relative humidity.

Upon completion of nondestructive measurements, the glulam section was cut open at each tested cross-section, resulting 13 glulam blocks B, C, D, …, and N (block A was severely decayed, delaminated, and fall into pieces after cutting). Visual inspection was conducted at each opened cross-section to identify decay, cracks and any delamination that can be visually seen. A high-resolution digital image of each cross-section was subsequently obtained to document the internal conditions of the glulam section. Following visual inspection of the cross-sections, shear and compression samples were cut from the blocks to obtain the residual mechanical properties of the glulam arch section through destructive testing.

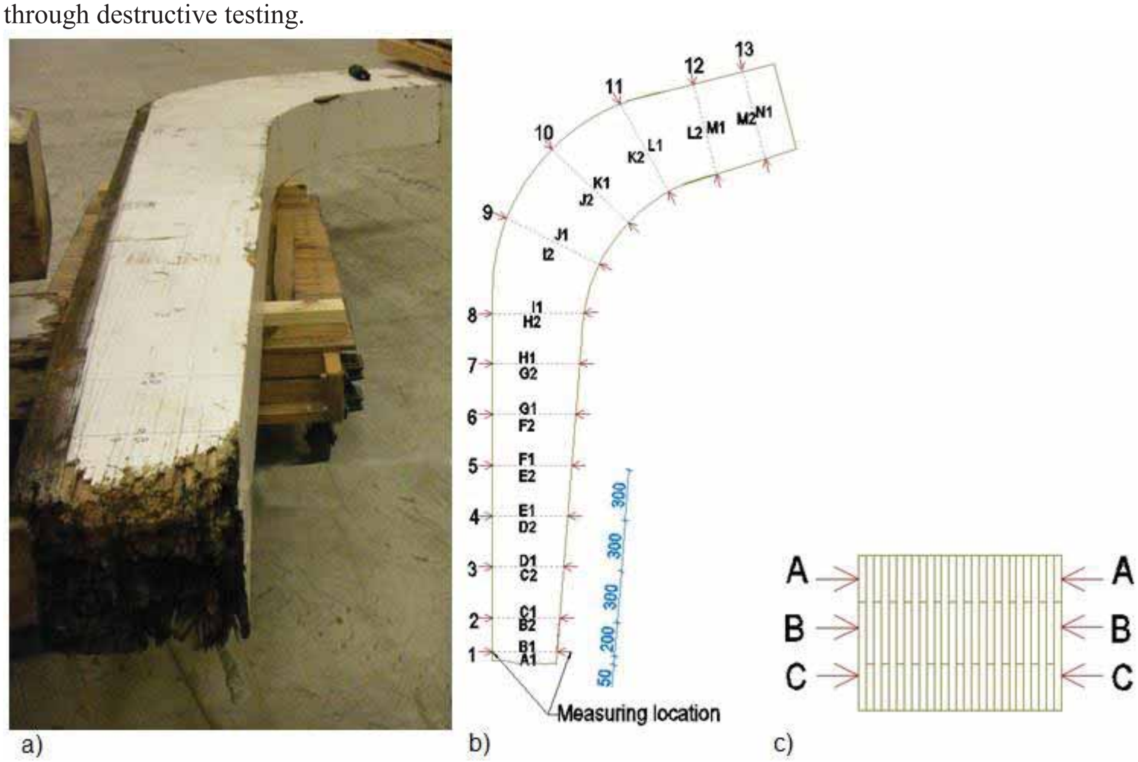

Figure 2—a) Glulam arch under testing; b) Plan view showing measurement locations; c) Cross-section view showing measurement locations (A, B, and C were 45, 135 and 225 mm from the edge of the cross-section respectively).

Testing of glulam arch section

Stress wave timing

Stress wave timing (SWT) measurement for decay detection is based on the concept that stress wave propagation is sensitive to the presence of deterioration of wood members (Pellerin and Ross 2002). Stress waves travel faster through sound wood than they travel through decayed and delaminated wood. Conducting stress wave timing measurement on a glulam member requires access to two opposite sides of the member for attaching sensor probes. The glulam arch section was tested through the thickness (perpendicular to the laminations) using a Fakopp stress wave timer. The sensor probes were inserted into opposing faces of the glulam at the same cross-section and same level. Stress waves were generated through a hammer impact.

Ultrasonic transmission

Sylvatest Duo device equipped with two 22 kHz transducers was used to measure the ultrasonic velocity across the thickness of the glulam (perpendicular to the laminations). The transmitter probe and the receiver probe were positioned at the opposite faces of the glulam with a relatively constant handheld pressure applied to the probes to improve the coupling between the probes and wood. For each measurement, the transmitter probe emitted five consecutive pulses through the glulam. An average ultrasound propagation time (UPT) and peak energy of the receiving signal were recorded after each measurement. The ultrasonic velocity (*V*) of the specimen across laminations was calculated based on the average UPT value and the thickness of the glulam at the cross-section (distance between two probes):

$$V = \frac{L}{UPT} \text{ (m/s)}$$

Resistance micro-drilling

Resistance micro-drilling tests were conducted after the acoustic measurements. Resistance micro-drilling enables detection of internal deterioration in a timber through measuring the relative resistance in the drilling path. The output of a micro-drilling test is a resistance profile showing density changes along the drilling path. The high output characterizes high resistance or high density and the low output characterizes low resistance or low density. Internal decay or cavities in a timber is typically characterized as extremely low resistance or zero resistance in the resistance charts (Kotlinova et al. 2008). An IML PD-400 Resistograph unit was used to obtain resistance profiles at the same locations where stress wave timing and ultrasonic measurements were conducted.

Testing of small lamination samples

To evaluate the compression strength of the glulam arch and the shear strength of the bond lines after 75 years of service, we cut small samples from the glulam blocks according to the specifications of the ASTM D905-08 and D143-09 standards. Twenty five 50 by 50 by 200 mm compression samples were obtained from blocks C, D, E, F, and G, five from each block (Figure 3a). Fifty 38 by 50 by 50 mm shear samples were cur from blocks B, C, D, E, F, G, and N (Figure 3b), five from each block for blocks C, D, E, F, and G, ten from block N and fifteen from block B. But thirty five samples were good enough for successful testing. Both compression and shear samples included 3 bond lines. Special care was taken to ensure that the bond line being tested for shear was located in the center line and the loading surfaces were smooth, parallel to each other, and perpendicular to the height (Figure 3b).

Ultrasonic measurements

The compression and shear samples were first acoustically evaluated using a Sylvatest Duo device before destructive testing. For compression samples, ultrasonic measurements were conducted in both radial (3 points) and longitudinal directions. For shear samples, ultrasonic measurements were conducted in radial directions (2 points). The transmitter probe and the receiver probe were positioned at the opposite faces of a sample with a constant pressure (196 kPa) applied to the probes to improve coupling between the probes and wood.

Mechanical testing

Compression-parallel-to-grain test was conducted on each compression sample using an Instron machine in accordance with ASTM D143-09 standard. Modulus of elasticity (MOE) and compression strength (CS) parallel to grain were subsequently determined for each compression sample.

Shear samples were tested using the same Instron machine by compression loading in accordance with ASTM D905-08 standard. The shear strength of the bond line was determined based on the maximum compression load and the bond line area between the two laminations.

All the experimental data was processed and analyzed using MS Excel and STATISTICA 12.

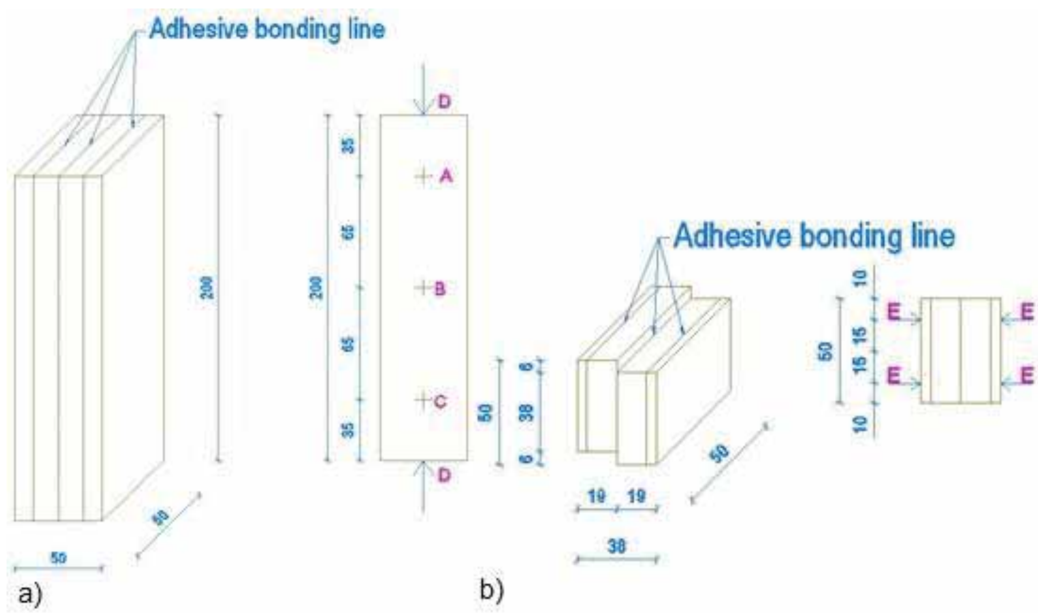

Figure 3—Small samples cut from the glulam blocks for mechanical testing. a) Compression test sample with ultrasonic measurements at point A, B, C and D; b) Shear test sample with ultrasonic measurement at point E.

Results and Discussion

NDT assessment of the glulam arch section

The results of ultrasonic and stress wave timing measurements from the glulam section are illustrated in Figure 4 and Figure 5 in the form of time/velocity distribution along the length. Two methods produced similar mappings of the condition in terms of acoustic measures. Ultrasonic measurement results indicated potential structural defects at location 1 for entire cross-section, at location 2 for upper (A) and middle (B) areas, and at location 10 for lower (C) area. Similarly, stress wave measurement results identified structural problems for the entire cross-sections of location 1 and 2, and the lower area (C) of location 10.

After the glulam arch was cut open along the measurement lines, moderate to severe delamination and decay were found at locations 1 and 2, which confirmed the evaluation results of acoustic measurements. Delamination was observed in few outer laminations at location 10, which caused abnormal ultrasonic and stress wave readings as illustrated in Figure 4 and 5. The delamination in this arch section was likely caused by the exposure to high temperature during the fire event occurred in 1993.

Figures 6 and 7 show the images of the glulam cross-sections at locations 1 and 2 superimposed with the resistance profiles of three drilling paths A, B, and C. It is clear that high relative resistance in the profiles corresponded to the solid laminations and low relative resistance corresponded to the deteriorated or decayed laminations in the glulam arch. Despite of being able to detect degraded areas of glulam, our results indicated the otherwise for using resistance micro-drilling to detect internal delamination. By comparing the visually identified delamination and internal checks with the relative resistance measured, we found that most delamination was not observable in the resistance profiles. Even though some of the low valleys in the resistance profiles clearly corresponded to the big delamination per visual assessment, the relatively high resistance at the low valley would make it difficult to judge whether it is delamination or early wood.

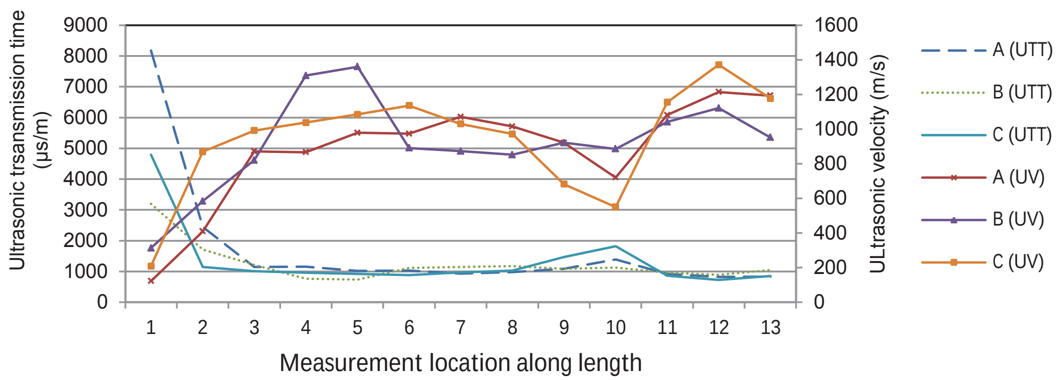

Figure 4—Ultrasonic transmission time and ultrasonic velocity measured across laminations of the glulam arch section (Notes: UTT – ultrasonic transmission time, UV – ultrasonic velocity).

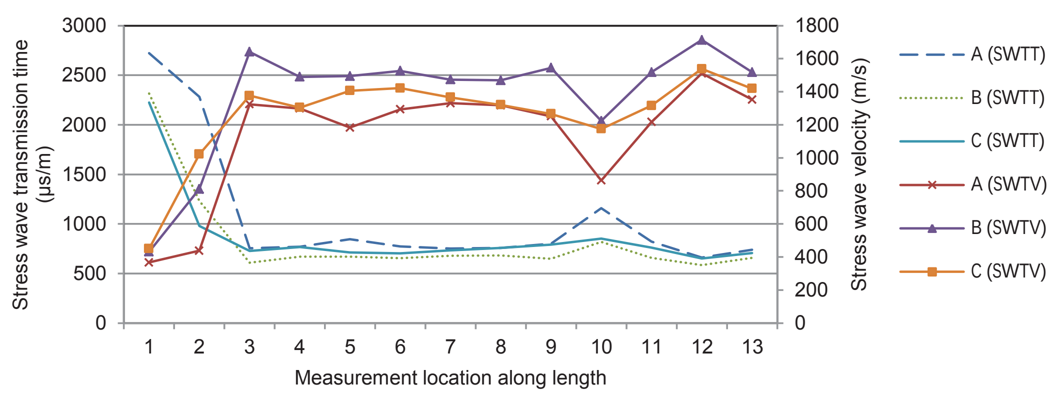

Figure 5—Stress wave transmission time and stress wave velocity measured across laminations of the glulam arch section (Notes: SWTT – stress wave transmission time, SWTV – stress wave transmission velocity).

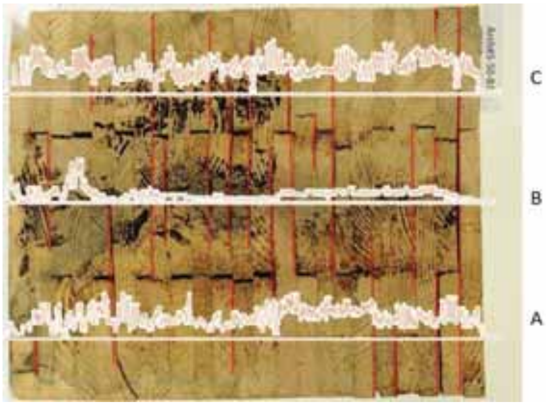

Figure 6— Image of the glulam cross-section at location 1 superimposed with the resistance profile of three drilling paths (Red lines indicate delamination by visual inspection).

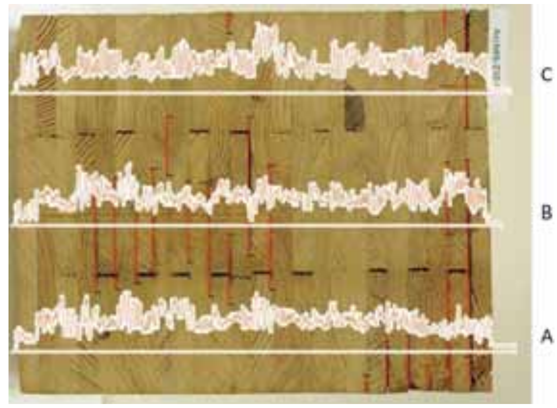

Figure 7— Image of the glulam cross-section at location 2 superimposed with the resistance profile of three drilling paths (Red lines indicate delamination by visual inspection).

Residual strength of the glulam arch

Figure 8 shows the compression strength (CS) of the compression samples at different locations (along length) and positions (through thickness) in the glulam arch. At each location (from C to G), the first 5 bars show the distribution of CS in thickness direction, with the very first bar represents the CS value of the wood close to the outer layers. The sixth bar (shaded) is the average CS at each location. The testing results indicated that the outer laminations (first bar) of the arch consistently had low compression strength, especially at C, D, and E areas. Given the history of fire event in the building and the visual signs of fire exposure (dark color), it is clear that the part of the glulam arch (outer laminations) has been deteriorated due to exposure to the elevated temperature. Assume that the laminations with relatively higher CS were intact (for example, 2^{nd}, 3^{rd}, fourth and fifth bars at location C1-C2), then the strength reduction of the outer laminations is estimated to be from 12.1% to 36.4%. Excluding the deteriorated portion, the average CS of the glulam arch was in the range of 71.7 to 75 MPa, which was significantly higher than the values given in the Wood Handbook for some pine species. This suggests that the intact glulam arch was still in a good quality condition after 75-years of service.

Figure 9 shows the modulus of elasticity (MOE) of the compression samples at different locations (along the length) and positions (through thickness) in the glulam arch. The testing results indicated that the fire event had very little impact on MOE of the outer laminations for most locations, except E1-E2, where MOE reduction was 16.7% (1^{st} bar) and 6.5% (2^{nd} bar). Excluding the deteriorated portion (outer laminations), the average MOE of the glulam arch was in the range of 7.67 to 8.08 GPa.

Similarly, Figure 10 shows the shear strength of the shear samples at different locations (along the length) and positions (through thickness) in the glulam arch. The testing results indicated that the shear strength of the bond lines varied greatly, indicating a significant delamination issues existed in the glulam arch, particularly in sections from B to E. Some shear samples cut at B, C, and D sections were separated after cutting and some were tested as almost zero strength.

Table 1 summarizes the results of linear correlations between ultrasonic propagation time (UPT) and compression and shear strength of the glulam samples. Ultrasonic propagation time measured in longitudinal direction of the glulam had no correlation with compression strength. UPT measured in radial direction (perpendicular to grain) had a moderate correlation with both compression strength (R^2=0.419) and shear strength (R^2 = 0.433). The results from small glulam samples indicated that ultrasonic measurements on glulam beams are not effective in predicting the compression and shear strength of the glulam beams.

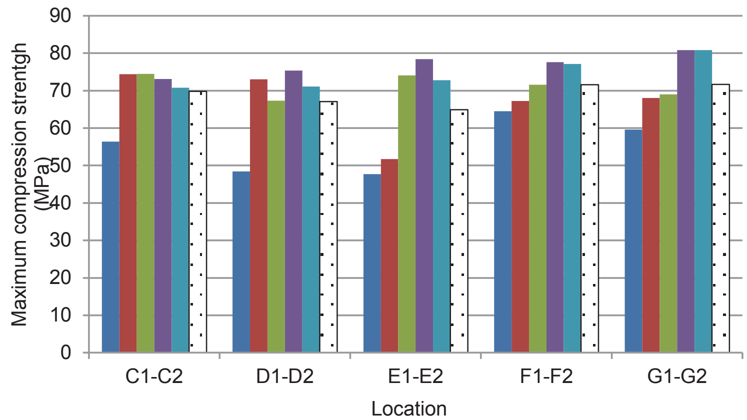

Figure 8—Maximum compression strength (parallel to grain) of small samples obtained from the glulam arch (Note: Shaded colums represent mean values).

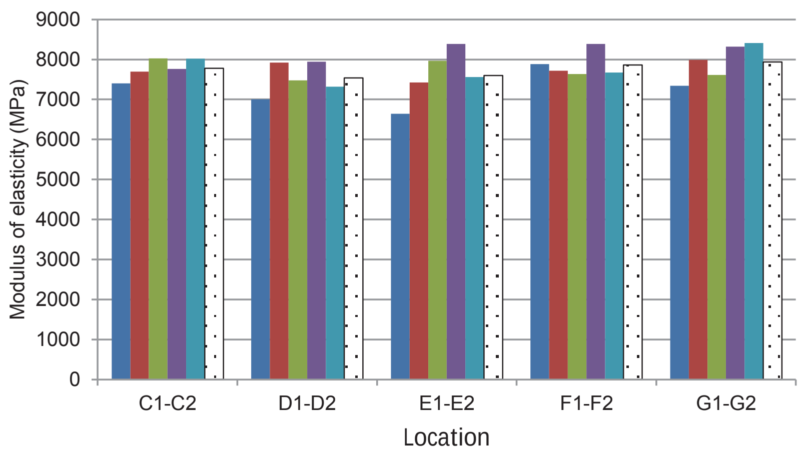

Figure 9—Modulus of elasticity (in compression) of small samples obtained from the glulam arch (Note: shaded colums represent mean values).

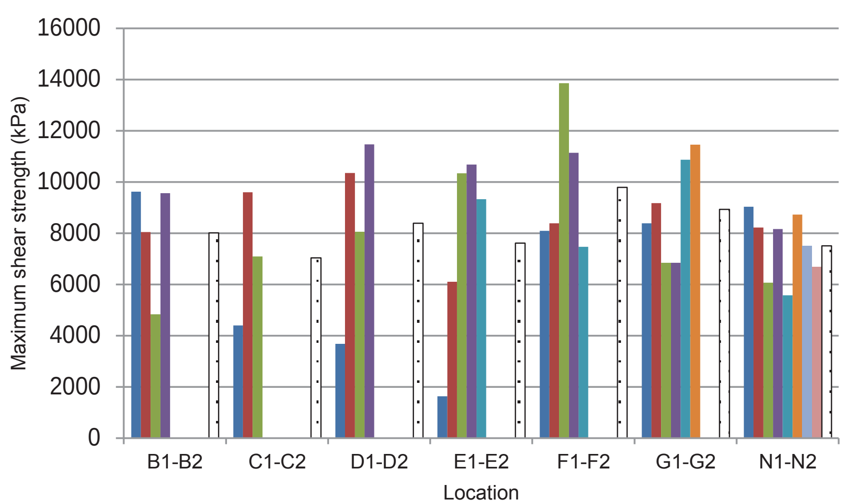

Figure 10—Maximum shear strength of small samples obtained from the glulam arch (Note: shaded colums indicate mean values).

Table 1—Results of the linear correlations between ultrasonic propagation time (UPT) and the compression and shear strength of the glulam samples (linear regressioon model: $y = ax + b$) [a]

Specimen	*Y*	*X*	*a*	*b*	R^2	p-value
Compression samples	CS	UPT_R	-21.60	83452	0.419	<0,001
	CS	UPT_L	-136.7	153473	0.277	0,0069
Shear samples	SS	UTT_R	-7.318	13327	0.433	<0,001

[a] UPT_R—ultasonic propagation time perpendicular to grain; UPT_L—ultrasonic propagation time along the grain (longitudinal); CS—compression strength; SS—shear strength.

Conclusions

Stress wave timing, ultrasonic wave propagation, and resistance micro-drilling methods were used to evaluate the physical conditions of a glulam arch removed from the USDA Forest Products Laboratory research building, after more than 75 years of use. The purpose of this laboratory study was to explore the possibilities of assessing glulam structural condition in situ with some existing NDE methods. Based on the results from this investigation, we concluded the following:

1. Both stress wave timing and ultrasonic propagation methods are effective in detecting internal deterioration of glulam components in building. Wave propagation times or wave velocities measured across the laminations in a glulam member are good indicators of internal decay.
2. Stress wave timing and ultrasonic propagation methods were able to detect moderate to large delamination in glulam, but not micro-delamination.
3. Resistance micro-drilling is effective in detecting decay, but not successful in detecting delamination in glulam.
4. Exposure to elevated temperature during the past fire event had a significant impact on the compression and shear strength of the glulam arch evaluated, but not on the modulus of elasticity. The intact portion of the glulam arch remained having high strength.
5. Further research is needed to look into the possibility of using pulse-echo method to detect internal delamination of glulam members.

Acknowledgments

The authors would like to thank Steve Schmieding, technician and photographer of the USDA Forest Products Laboratory (FPL), Dr. Junguo Zhang, visiting professor from Beijing Forestry UNiversity, and Jim Gilbertson, technician of the USDA Forest Products Laboratory (FPL) for providing assistance. Marko Teder's stipend for studies and research at FPL was provided by Foundation Archimedes European Social Fund's DoRa programme.

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General Technical Report

FPL–GTR–226

Proceedings

18th International Nondestructive Testing and Evaluation of Wood Symposium

Madison, Wisconsin, USA
2013

Abstract

The 18th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service's Forest Products Laboratory (FPL) in Madison, Wisconsin, on September 24–27, 2013. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 18th Symposium is captured in this proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

September 2013 (Corrected October 2013, pages 716–722)

Ross, Robert J.; Wang, Xiping, eds. 2013. Proceedings: 18th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-226. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 808 p.

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