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Evaluating Fire-Damaged Components of Timber Bridges and Structures

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ABSTRACT

The goal of this research is to adapt a direct test to estimate the residual flexural properties of individual framing members for post-fire evaluations. The adaptation incorporates partial-composite action with an aluminum stock and a cycle of increasing load tests that are applied gradually. The evaluations of the methodology were based on eight, glued-laminated beams of which four were fire-damaged. The fire-damaged specimens were exposed to a time-temperature curve intended to produce a significant zone of damaged wood due to elevated temperatures within the residual wood section. Very good agreements were obtained between the estimated and actual apparent modulus of elasticity and modulus of rupture. The proposed test applies when flexural properties are to be refined beyond estimates that rely solely on reductions in cross section and tabulated values for fire damaged members and members that can otherwise be expected to remain in service.

INTRODUCTION

The goal of this research is to complement and enhance the Covered Bridge Manual's current coverage of post-fire evaluations, and to adapt a direct test to estimate the residual flexural properties of individual framing members. According to the Covered Bridge Manual (Pierce et al. 2005), site-specific post fire evaluations are necessary in a fire's aftermath. Often, decisions must be made about the rehabilitation, reconstruction, or replacement of individual wood components that comprise a timber bridge [or similar structure]. Additional information appertaining to post-fire evaluations has yet to be presented in this resource.

At present, there are a handful of methods used to determine decay in individual wood members. This line of testing is a promising field to obtain the in-service residual stiffness and related flexural properties of fire damaged members that exhibit varying degrees of degradation. Researchers have investigated wood decay using several techniques. Among these techniques are: forced vibration (Wang et al.

2005), drill resistance testing (Emerson et al. 1998). stress wave evaluation (Ross and Pellerin 1994), ultrasonic testing (Garab et al. 2010), and to a certain extent, radiography (Ross et al. 2005) and near infrared technologies (Nicholas and Crawford 2003). These methodologies may be classified as either semi-destructive (drill resistance testing), or non-destructive techniques. While these techniques show promise, employing any of these to definitively quantify the residual strength and stiffness directly, can prove to be a challenge.

Though destructive in nature, traditional laboratory tests such as those of ASTM D 198-09 (ASTM International 2009). can be used to definitively quantify the residual stiffness and strength directly. While destructive tests are quite accurate, they require the member to be taken out of service which is not practical in most cases. As an alternative to the above-mentioned approach, a new proposed field method was investigated in this study.

This research adapts a direct test for the engineer conducting the damage assessment to estimate the residual flexural properties for such a purpose. The adaptation incorporates partial-composite action with an aluminum stock. strain readings, and a cycle of increasing load tests that are applied gradually. The proposed test applies when flexural properties are to be refined beyond estimates that rely solely on reductions in cross section and tabulated values for fire damaged members and can otherwise be expected to remain in service.

This study is part of the Research, Technology and Education portion of the National Historic Covered Bridge Preservation (NHCBP) Program administered by the Federal Highway Administration. The NHCBP program includes preservation, rehabilitation and restoration of covered bridges that are listed or are eligible for listing on the National Register of Historic Places; research for better means of restoring, and protecting these bridges; development of educational aids; and technology transfer to disseminate information on covered bridges in order to preserve the Nation's cultural heritage. This study at Montana Tech of The University of Montana is conducted under a joint agreement between the Federal Highway Administration - Turner Fairbank Highway Research Center, and the Forest Service – Forest Products Laboratory.

PROPOSED FIELD TEST

The technique involved affixing a 6061-T651, type 200, aluminum block to the bottom of a beam with ¼-20X2 socket cap screws once 7/32 in (5.6 mm) pilot holes were drilled into the bottom of the beam at these locations. Each screw was inserted to a torque of 30 in-lbs (3.4 N-m) at an insertion depth of 0.75 in (19 mm). Next increasing loads were applied and deflections were recorded. Both the beam and the aluminum block were subject to bending, although at different rates; as such, measurable changes in average torque readings resulted from the interaction between the aluminum block and bottom of the beam after the load was removed for the partial-composite load tests.

The purpose of this was to establish a definitive, target deflection that the beam could be re-loaded to that was within the linear elastic range. In so doing, the corresponding load, otherwise identified as the “40% estimate of maximum” load

(hereafter referred to as the 40% load) is achieved once mean torque readings correspond to values in this range. (Here, deflections were recorded along with values for the increasing, applied loads using a data acquisition system.) The estimated maximum load is simply a multiplier of the 40% load. With this value, both the residual stiffness (apparent modulus of elasticity. E_f) and the residual strength (modulus of rupture, $\mathbf{S_R}$) can be accurately estimated, using conventional equations found in the appendix of D 198-09 (ASTM International 2009). The difference is that the flexural property approximations now stem from a definitive load estimate in the linear elastic range. The tests performed on two expendable beams eliminated a considerable amount of trial and error that would have otherwise accompanied the load tests. The field equipment items illustrated in Figure 1 include: a digital level, a calibrated toque wrench, a pair of calipers and a pre-drilled aluminum bar (attached to the bottom of a fire damaged beam, far right).

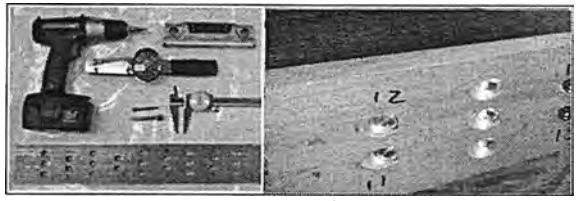

Figure 1. Aluminum block and field equipment items.

EVALUATION OF METHOD

The evaluations are based tests of eight 24F-V8 DF/DF5-1/8 in x 12 in x 10 ft (130 mm x 305 mm x 3 m) glued-laminated beams. All beams were ordered from the same supplier and were used as the test specimens for this project. Upon arrival, each of the glued laminated beams were conditioned until equilibrium moisture content was reached; thereby, limiting the variability amongst the beams due to moisture content. The beams were conditioned using the heated room dry method at a temperature of 83°F (28.5°C) with a 14.7 percent ± 1.0 percent relative humidity. Both the moisture content and relative humidity were tracked on a regular basis using a Delmhorst Moisture Check Meter and a Delmhorst Thermo-Hygrometer. All of the beams were then wrapped in Visqueen, polyethylene sheeting to avoid reconditioning. Four of these beams served as the control group. These beams were not fire-damaged. The other four beams were fire-damaged in a furnace at the U.S. Forest Service Forest Products Laboratory (FPL).

Fire Damage. These four beams were exposed to a time-temperature curve intended to produce a significant zone of damaged wood due to elevated temperatures within the residual wood section. The 4 ft by 7 ft (1.2 m x 2.1 m) horizontal furnace has a series of eight diffusion-flame natural gas burners on the floor of the furnace. Each of the four 5 1/8 in x 12 in x 10 ft (130 mm x 305 mm x 3 m) test beams was inserted in openings on the ends of the furnace and exposed to a relative low fire exposure for

a period of three hours. The top of the beams was covered with gypsum board so three surfaces were exposed to the fire. Approximately 6 ft (1.8 m) of the middle of each beam was subjected to fire exposure. Exposure to the standard fire exposure of fire resistance tests would have resulted in a fairly steep temperature gradient within the wood beam. Since the intent was to evaluate the ability to determine loss in strength of the residual section, a longer and lower temperature fire exposure was used in hope of a more gradual temperature gradient within the charred member. A modification of a curve previously used to represent the plenum exposure in a protected wood truss assembly was employed (White et al. 1993). This idealized time-temperature curve was 149°F, 199°F, 370°F. 500°F. 621°F, 662°F and 707°F (65°C, 93°C, 188°C; 260°C, 327°C, 350°C and 375°C) at 10, 20, 30, 45, 60, 120 and 180 minutes, respectively. At the end of the approximately 3 hours of fire exposure, the beams were quickly removed from the furnace and sprayed with water. A series of thermocouples were inserted 4 in (102 mm) down from the top surface of the specimen at various distances of 0.25 to 2.5 in. (6 to 64 mm) from the surfaces of the sides of the beam. The temperature data were used to plot a temperature profile at the time of test termination. Analysis of the combined temperature data for all four tests indicated that the char depth (572°F (300°C)) was at approximately 0.3 in (8 mm) and the center temperature was approximately 212°F (100°C). In contrast with temperatures of 356°F (180°C) and 68°F (20°C) at 0.25 in. (6 mm) and 1.3 in (33 mm), respectively, inward from the base of the char layer for semi-infinite slab subjected to standard fire resistance test conditions, the temperatures at 0.25 in (6.3 mm) and 1.3 in (33 mm) inward were approximately 491°F (255°C) and 252°F (122°C), respectively. There was more charring along the bottom of the beams than along the sides. Each fire damaged beam was cooled to room temperature prior to being packaged and shipped back to Montana Tech of The University of Montana for further evaluation and testing.

Laboratory Tests. After removing the char layer from each of the fire damaged beams the section properties for all beams were measured and recorded. The beams were then instrumented with epoxied (Vishay foil strain gage) and removable (Bridge Diagnostics, Inc., Transducer Model BDI ST350) uniaxial strain gages. The two types of strain gages were affixed at comparable locations, above, below, and near the depth-wise center of each beam (Figure 2).

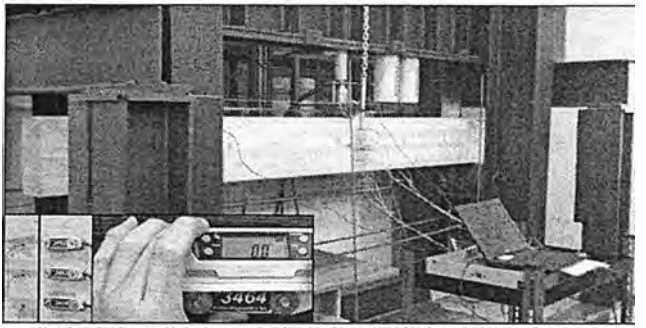

Figure 2. Measuring the neutral axis for a typical, non-composite beam.

Values collected from the gages were used to verify the amount of composite action that was achieved. All beams were load-tested at Montana Tech of The University of Montana using a steel load frame (Figure 2). The load frame consists of four HP Shapes, a reaction beam, and various support beams. Hydraulic loads were applied with a 10,000 psi (69 MPa) capacity hydraulic hand pump and cylinder equipped with a tilt-saddle. The values associated with the applied loads and corresponding deflections were recorded using load cells and displacement transducers during the appropriate stages of testing (Figure 2).

RESULTS AND DISCUSSION

Partial Composite Action. The results from the load-test data indicate that a modest, neutral axis shift of 2.5% or less was achieved. Further evaluation of these results indicated that the partial composite action between the aluminum stock and a glued laminated beam was appropriate at this level. This is because the measurable changes in the mean, machine screw torques were also germane to the proposed field test. The shift in the neutral axis of each beam was identified and the amount of partial-composite action was assessed from the strain measurements at three different locations. To measure this, values for strain were plotted at three distinct locations for three distinct linear-elastic loads. The intersection of the resulting lines that were fit to the data denotes the measured neutral axis. The neutral axes were measured with the aluminum stock affixed to the tension face of the beam (partial-composite action) and without the aluminum stock affixed to the tension face (non-composite action). Figure 3 depicts such a plot for a typical non-composite beam test.

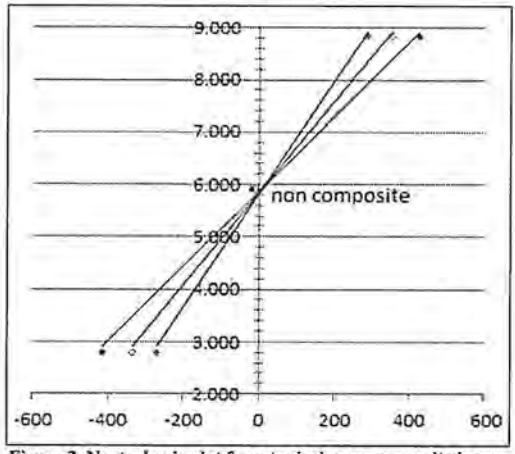

Figure 3. Neutral axis plot for a typical, non-composite beam.

The neutral axis shifts 2% on average when the partial-composite tests are compared to the non-composite tests using epoxied stain gages. This shift is 2.5% on average when removable strain gages are used. The results indicate that both the removable strain gages and epoxied strain gages are comparable. However, field applications may make one type of gage preferable to the other.

Torque Readings. Torque readings as they relate to four different insertion depths were explored in this study: 0.75 in, 0.5 in, 0.25 in and 0.125 in (19 mm, 13 mm, 6.3 mm, and 3.2 mm). The results from laboratory experiments and statistical analyses indicate that, for both the control and fire damaged group, the variability at an insertion depth of 0.25 in (6.3 mm) was greater than the variability at insertion depths of 0.5 in (13 mm) and 0.75 in (19 mm). These results are based on the Brown-Forsythe test with an initial p-value < 0.0001 when testing the equality of all variances for both groups. Note, at an insertion depth of 0.125 in (3.2 mm), the variability of the machine screw torque values were unreliable due to missing values which occurred because the machine screws stripped out upon contact.

The mean torque readings were compared using the 2-way ANOVA F-tests as well as the Tukey HSD multiple comparison procedure. Plots of the mean torque readings, along with individual 95% confidence intervals collected at these depths are depicted in Figure 4.

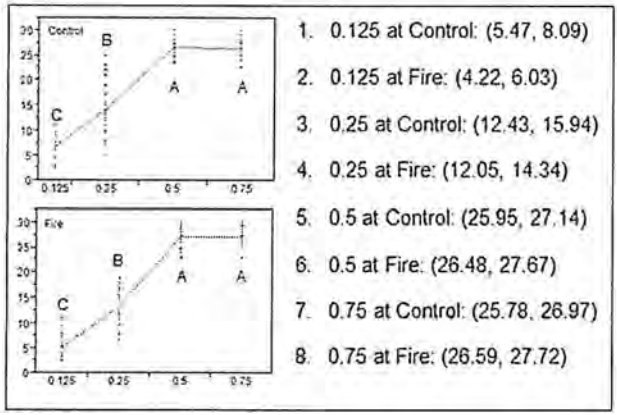

Figure 4. Summary of statistics for the control and fire damaged groups.

When comparing across the control and fire damaged groups, as well as across insertion depths, the Tukey HSD multiple comparison procedure, calculated at the 95% experiment-wise error rate, are significantly different where the levels are not connected by the same letter (Figure 4).

Note that at the conclusion of the partial-composite load tests, residual machine screw depths of 0.25 in (6.3 mm) or less are to be avoided; due to increased potential for variability in torque readings and (or) the inability to obtain them. We recommend that the average values for torque be used on a given beam and that the test is performed on a number of beams as a way of controlling for naturally occurring variability inherent to these measurements.

We recommend that torque readings collected after a load is removed should conclude when torque readings fall between a range of 20 and 25 in-lbs (2.3 and 2.8 N-m) based on the results from the laboratory experiments. This recommendation is also supported through the results of the statistical analyses; wherein, the variability in torque readings is reduced as the insertion depth passes 0.25 in (6.3 mm) and levels off at 0.5 in (13 mm). Torque readings within this range can be achieved by incrementally loading each of the beams in the laboratory and collecting torque readings once the load is removed. This range falls below the 95% confidence intervals for the average screw torque readings at insertion depths of 0.75 in (19 mm) and 0.5 in (13 mm). As supported by the Tukey HSD procedure, any measurable changes in average torque readings at these levels is non-significant Moreover, any measurable changes in average torque are attributed to the resulting interaction between the aluminum stock and bottom of the beam. It should also be noted that this range is above the 95% confidence intervals for mean screw torque readings at insertion depths of 0.25 in (6.3 mm) and 0.125 in (3.2 mm). These values are also presented in Figure 4.

Flexural Properties. The estimated values for flexural properties were obtained by using the methodology established through the proposed field test. Table 1 presents the results for the torque tests, the corresponding target values for deflection, along with the actual and estimated flexural properties for all of the beams evaluated herein.

Table 1. Summary of Results.

Beam ID	Avg. Torque Reading in-lbf (N-m)	Target Deflection in (mm)	Apparent E_f, x10^3 lbf/in^2 (MPa)		S_R, lbf/in^2 (MPa)	
Control			Actual	Estimate	Actual	Estimate
Beam 3	24 (2.7)	0.327 (8.3)	749 (5170)	793 (5470)	5060 (34.9)	4640 (32.0)
Beam 7	24 (2.7)	0.339 (8.6)	736 (5070)	729 (5030)	6740 (46.5)	5530 (38.1)
Beam 8	20 (2.3)	0.218 (5.5)	1109 (7650)	1106 (7630)	5000 (34.5)	4900 (33.8)
Bean L	22 (2.5)	0.192 (4.9)	1075 (7410)	1090 (7520)	7440 (51.3)	4150 (28.6)
Average	-	-	**917** (6320)	**930** (6410)	**6060** (41.8)	**4810** (33.1)
Fire Damaged			Actual	Estimate	Actual	Estimate
Beam 2	24 (2.7)	0.247 (6.3)	810 (5590)	818 (5640)	3620 (25.0)	3600 (24.8)
Beam 4	22 (2.5)	0.306 (7.8)	645 (4450)	652 (4500)	3890 (26.8)	3750 (25.9)
Beam 5	25 (2.8)	0.145 (3.7)	887 (6120)	891 (6150)	2560 (17.6)	2440 (16.8)
Beam 6	23 (2.6)	0.277 (7.0)	570 (3930)	567 (3910)	3060 (21.1)	2990 (20.6)
Average	-	-	**728** (5020)	**732** (5050)	**3280** (22.6)	**3190** (22.0)

The determination of the actual values for the beams tested destructively without the aluminum bar was made using the methodologies described in ASTM D198 for each beam with solid rectangular homogeneous cross-section and center point loading. The modulus of rupture, S_R. was calculated using the maximum bending moment at the maximum load borne by the beam. The apparent modulus of elasticity, E_f, was calculated using the equation in the appendix of D198 with the load-deflection slope determined for the range of 20 to 40% of the maximum load.

The data collected from the laboratory tests indicate that the averages for the estimated and actual E_f differed by less than 2% for the control group and less than 1% for the fire damaged group. Should beam L be omitted, the averages for the S_R for

the control group differ by approximately 10% where that actual values and estimated values are compared to one another. Including Beam L this average becomes larger. A comparison of averages made within the fire damaged group shows that the S_R differs by less than 3% for the actual and estimated values. These results are depicted in Figure 5.

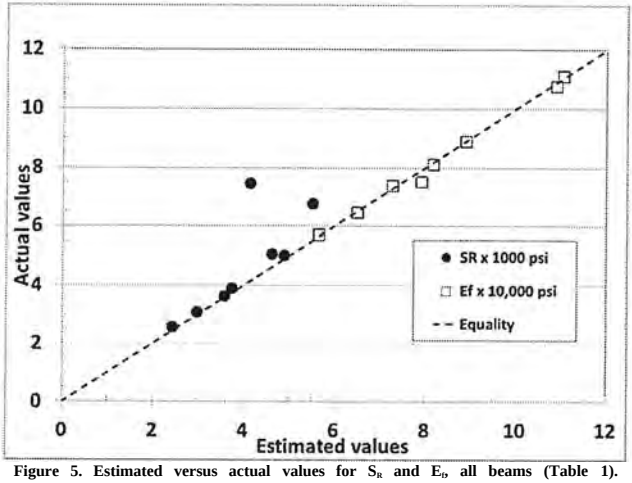

Figure 5. Estimated versus actual values for S_R and E_f, all beams (Table 1).

CONCLUSIONS

This research presents a proposed field technique that can be used to determine the residual flexural properties in glued-laminated beams that have been fire damaged. Two treatment groups were established herein. Namely, a control group and a fire damaged group. The non-destructive values, arrived at through the proposed field test, were compared to the destructive values for the beams from both groups. The following conclusions are based on these results.

- The results show that relative changes in the apparent modulus of elasticity and the modulus of rupture changed by 20% and 46% on average after the beams had been fire damaged. This marked decrease in flexural properties goes beyond simply reducing cross section once the char layer has been removed.
- The results of this research indicate that torque readings collected after a load is removed should conclude when torque readings fall between a range that is inclusive of 20 and 25 in-lbs (2.3 and 2.8 N-m). The same finite range was applicable to beams in either group. This approach has been validated in the laboratory and is specific to the beams tested herein.

- The results corroborate the proposed field technique when direct determinations of estimates of the residual flexural properties are sought. This is important where like members that exhibit varying degrees of degradation are tested in the field and are otherwise expected to remain in service; because, the flexural property approximations now stem from a definitive load estimate in the linear elastic range.

REFERENCES

ASTM International. (2009). "Standard test methods of static tests of lumber in structural sizes." *D 198 - 09.* West Conshohocken, Pennsylvania.

Pierce, Phillip C., R.L. Brungraber, A. Lichtenstein, and S. Sabol, (2005). "Covered bridge manual." *FHWA-HRT-04-098,* Federal Highway Administrdtion, McLean, Virginia.

Emerson, R. N., Pollock, D. G., Kainz, J. A., Fridley, K. J., McLean, D. L., and Ross, R. J. (1998). ''Nondestructive evaluation techniques for timber bridges." in: *Proc. 5th World conference on timber engineering,* Swiss Federal Institute of Technology, Lausanne, Switzerland, pp. 670-677

Garab, J., Toth, A., Szalai, J., Bejo, L, and Divos, F. (2010). "Evaluating glued laminated beams using a nondestructive testing technique." *Transactions of FAMENA,* 34(4), 33-33-46.

Nicholas, D. D., and Crawford, D. (2003). "Concepts in the development of new accelerated test methods for wood decay." in *ACS SYMPOSIUM SERIES* (Vol. 845, pp. 288-312). American Chemical Society, Washington, DC.

Ross, R. J., and Pellerin, R. F. (1994). "Nondestructive testing for assessing wood members in structures : A review." *FPL-GTR-70,* USDA, Forest Service, Forest Products Laboratory, Madison, WI.

Ross, R. J., Brashaw, B. K., Wang, X., White, R. H., and Pellerin, R. E (2005). "Chapter 4: Post-fire assessment of structural wood members." in *Wood and timber condition assessment manual,* Forest Products Society, Madison, WI.

Wang. X., Wacker, J. P., Ross, R. J., and Brashaw, B. K. (2005). "Nondestructive assessment of timber bridges using a vibration-based method." in *Proceedings of the 2005 structures congress,* The Structural Engineering Institute of the American Society of Civil Engineers, New York, NY.

Winandy, J. E., Lebow, P. K., and Nelson, W. (1998). "Predicting bending strength of fire-retardant-treated plywood from screw-withdrawal tests." *FPL-RP–568,* USDA, Forest Service, Forest Products Laboratory, Madison, WI.