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FIRE PERFORMANCE OF FRP REINFORCED GLULAM

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Abstract

One of the emerging advanced engineered wood technologies in the United States and other countries is the use of high strength fiber-reinforced polymers (FRP) to reinforce the tension zone of structural glued laminated timber (glulam). Glulam is used in numerous long-span commercial building applications where the glulam is exposed for architectural reasons. For some occupancy use classifications, the U.S. building code mandates that these exposed glulam members be rated for one-hour fire construction. The most structurally efficient use of FRP reinforcement is to place the FRP on the outermost face of the glulam member. However, there is no published information on how a glulam beam reinforced in this manner will perform when directly exposed to fire.

In order to address this concern, representatives of APA - The Engineered Wood Association (APA), the Market Development Alliance (MDA) Engineered Wood Team, and the University of Maine Advanced Engineered Wood Composites Center (AEWCC) sponsored a fire test program of FRP reinforced glulam beams at Omega Point Laboratories in San Antonio, Texas. The purpose of the testing was to gain an understanding of the performance of FRP composites exposed to fire when used as a structural reinforcement for glulam beams.

This paper describes the results of two test programs conducted in accordance with ISO Standard 834. The first test program was a pilot study involving relatively small FRP reinforced glulam beams. Based on the results of this pilot study, a second test program was then undertaken to evaluate the fire performance of FRP reinforced glulam beams designed to achieve a one-hour fire rating. The results of these tests led to the development of a design methodology to permit establishing fire ratings for FRP reinforced glulam.

1. Introduction

Structural glued laminated timber (glulam) is used in numerous commercial building applications where the glulam is exposed for architectural reasons such as in the roof framing of a school gymnasium, the sanctuary of a religious facility or many other similar situations. In some instances the applicable building code, such as 2006 International Building Code (IBC) in the United States [1], requires that these exposed glulam members be rated for one-hour or greater fire resistive construction.

The determination of fire ratings for glulam is described in Chapter 16 of the National Design Specification (NDS) for Wood Construction [2] promulgated by the American Forest and Paper Association (AF&PA) and published as an American National Standard Institute (ANSI) standard, which is referenced by the 2006 IBC. The methodology is based on the approach of determining an effective char rate based on published nominal one-hour char rate data. Fire endurance times of 1 hour, 1-1/2 hours and 2-hours may be calculated using this methodology. Further details are provided in American Wood

Council (AWC) Technical Report 10, *Calculating the Fire Performance of Exposed Wood Members* [3].

To achieve these fire ratings, it is required that the glulam members be manufactured using an additional outer tension lamination per each one hour of fire rating to be achieved. It is assumed that this outermost tension lamination will serve as a sacrificial lamination to protect the next innermost tension lamination form exposure to the fire and thus maintain the structural integrity of the beam.

One accepted way in the U.S. to achieve a one-hour fire rating for an FRP reinforced glulam is to use a similar approach of positioning a so-called “bumper lamination” (sacrificial lamination) on the exposed face of the beam to protect the FRP layer from direct exposure to the fire. However, the use of a bumper lamination introduces other design considerations that must be addressed, such as defining ultimate failure of the beams. In addition, the most structurally efficient use of FRP reinforcement is to place the FRP on the outermost face of the glulam member. However, there is little published information on how a glulam beam reinforced with FRP in this manner will perform when directly exposed to fire.

In order to address this concern, representatives of APA - The Engineered Wood Association (APA), the Market Development Alliance (MDA) Engineered Wood Team, and the University of Maine Advanced Engineered Wood Composites Center (AEWCC) sponsored a fire test program of FRP reinforced glulam beams at Omega Point Laboratories in San Antonio, Texas. The purpose of the testing was to gain an understanding of the performance of FRP composites exposed to fire when used as a structural reinforcement for glulam beams.

The tests were conducted in accordance with ASTM E 119 [4], which is the prescribed U.S. standard for evaluating products exposed to a fire of controlled extent and severity. It is noted that the *International Standard for Fire Resistant Test – Elements of Building Components*, ISO 834 [5], is very similar to ASTM E 119. Both of these test methods are intended to evaluate the duration for which assemblies will contain a fire, retain their structural integrity, or exhibit both properties.

Since fire testing can be complicated and expensive and virtually no fire test data was available for this type of FRP reinforced member, the research team decided to start with a small-scale pilot study involving relatively small FRP reinforced glulam beams. Based on the results of this pilot study, a second test program was then undertaken to evaluate the fire performance of larger FRP reinforced glulam beams designed to achieve a one-hour fire rating.

2. Phase I Testing

Lacking published data, the research team initially evaluated a set of relatively small size FRP reinforced glulam beams to develop benchmark data. Several MDA companies expressed interest in supplying FRP reinforcement for this test phase. Based on their experience working with this type of reinforcement technology, the AEWCC staff required that any products offered for testing had to pass two screening tests: The FRP products bonded to wood had to pass ASTM D 2559 [6] for adhesive durability and ASTM D 905 [7] for shear compression loading. The first test was to determine the resistance to delamination during accelerated exposure of FRP/wood laminations based on a modified ASTM D 2559. The second test was to determine the resistance to shear by compression loading. Two companies, Creative Pultrusions and Gordon Composites, submitted products and passed the screening tests established by the University of Maine.

Creative Pultrusions and Gordon Composites fabricated two samples each that were 2.5 mm x 127 mm x 3.94 m and 6.4 mm x 127 mm x 4.3 m. A manufacturer certified to produce glulam in accordance with the *American National Standard for Wood Products - Structural Glued Laminated Timber*, ANSI A190.1 [8], which is the U.S. manufacturing standard applicable to glulam, produced glulam beams made of Douglas Fir that were 127 mm x 229 mm x 4.3 m in length. The beams were manufactured in accordance with industry lay-up provisions for a beam having an allowable bending strength of 16.5 MPa and a modulus of elasticity of 12,410 MPa with no additional special tension lamination. These non-reinforced beams were then shipped to the AEWCC where the FRP layer was applied. A total of 9 beams (8 with FRP reinforcement and one control) were fabricated. Four FRP reinforced beams were destructively tested in the as-received conditions at the University of Maine prior to fire testing to determine the design loads to be applied during the fire test.

As noted, it was decided to test the glulam beams without the bumper lam to evaluate the effect of the FRP directly exposed to fire. These beams were tested in accordance with ISO 834/ASTM E 119 at the Omega Point Laboratories in San Antonio, Texas. Table 1 summarizes the results of these Phase I tests.

Table 1. Summary of Fire Test Measurements and Observations for Phase I Tests

	Test #1	Test # 2	Test # 3	Test # 4	Test # 5
Beam Reinforcement	2.50%	Control	2.50%	1.20%	1.20%
Laminate Construction	Roving/CSM	None	Roving	Roving	Roving/CSM
FRP Materials	E-glass/urethane	None	E-glass/epoxy	E-glass/epoxy	E-glass/urethane
Manufacturing Process	Pultrusion	None	Continuous lamination	Continuous lamination	Pultrusion
Center-point Load	29.3 kN	18.7 kN	29.3 kN	24.5 kN	24.5 kN
Time to break (min:sec)	27:47	36:37	21:42	24:26	20:44
Deflection (mm) @ min:sec	60.3 @ 27:30	77.8 @ 36:00	61.9 @ 21:00	52.4 @ 24:00	38.1 @ 20:00
Type of failure	Tension	Tension	Delamination	Tension	Delamination

Figure 1 shows one of the FRP beams positioned in the test element prior to placing it in the furnace. Figure 2 shows one of the FRP layers was delaminated and fell onto the bottom of the furnace after the completion of the test. Figure 3 shows the resulting cross-sections after the fire. Specimen A shown in Figure 3 was a reinforced beam and Specimen B was the control beam showing the greater charring of the control beam.

Figure 1. An FRP beam positioned in the test element

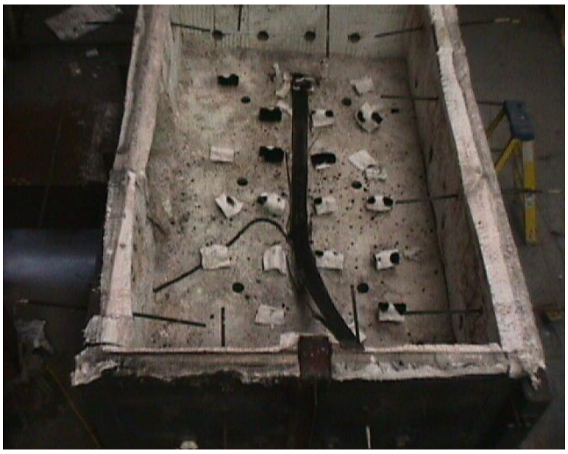

Figure 2. A delaminated FRP layer fell onto the bottom of the furnace

Figure 3. The resulting cross-sections after the fire

One observation to note from the test results is the load difference of the control beam (18.7 kN) compared to the FRP reinforced beams (24.5 kN or 29.7 kN). Based on an analysis by the AEWCC, the FRP reinforced beams had higher allowable bending stresses, 19.3 MPa for the 1.2% reinforced beams and 22.7 MPa for the 2.5% reinforced beams, as compared to 16.5 MPa for non-reinforced beams, resulting in the higher allowable design loads for beams of the same size. To test the control beam at the same load as the FRP reinforced glulam, it would have been necessary to use a larger cross-section for the control beam and it was decided this could significantly bias the results by testing the larger cross-section.

Visual observations by the research team of this testing indicated that the FRP materials began to burn at approximately 2 minutes after the ignition of the furnace and that the FRP layers began to delaminate from the beams at approximately 15 and 20 minutes.

The four FRP reinforced beams lasted from 21 to 28 minutes in comparison to the 36.5 minutes for the control beam. Neither the reinforcements nor the bond was designed to specifically resist exposure to fire since the focus of these tests was primarily on meeting the requirements of ASTM D 2559 and D 905. Given the low Tg values (150^{o}C to 200^{o}C) for the matrix and adhesive used in the reinforcements, it was concluded that the beams performed well. As expected, while the fire endurance of the FRP reinforced glulam beams was less than that for the control beam, the results were encouraging and provided insights for the next testing phase involving larger beams.

An analysis of the char rates indicated an average rate of 37.3 minutes per 25mm of char. This equates to 40mm/hr. A nominal char rate of 38mm/hr is normally assumed for glulam manufactured using softwoods. For a one-hour rated beam this results in an effective char rate of 46mm/hr per the NDS.

3. Phase II Testing

In order to achieve a one-hour fire rating according to the NDS methodology, typically a 170 mm wide x 343 mm deep glulam is required. The goal was thus to design a similar size beam reinforced with FRP composites that would meet the one-hour test criteria to satisfy the building code requirements. APA staff conducted some preliminary analyses based on the results of the Phase I pilot study and the accepted methodology of rating glulam beams using the char rate as published in the NDS. The analysis hypothesized that an FRP reinforced beam with a depth of 10% greater than that required for full design load plus one additional tension lamination could achieve a one-hour rating.

For example, if the non-reinforced design depth is 343 mm, then the FRP reinforced beam would need to be 343 mm x 1.1 plus one additional tension lamination. Based on a lamination thickness of 38 mm, the required size for a one-hour rating would be 377 mm + 38 mm or 415 mm. Thus, it was determined that a beam having a cross-section of 165 mm x 420 mm should meet the one hour criteria. However, due to the uncertainty of the analysis and the fact that the width was only 165 mm vs. the standard minimum width of 170 mm for a non-reinforced beam, it was decided to also test beams having a cross sectional dimension of 165 mm x 455 mm. The reason for the slightly narrower width was to accommodate the manufacturing process for the FRP materials. Also the depths used represented standard multiples of the 38 mm lamination thickness.

It should be noted that the 10% depth increase plus one additional tension lamination for the FRP reinforced beam is intended to compensate for the reduction in the beam strength by the increase in the section modulus when the FRP layer fails during the one-hour fire exposure. Therefore the percentage of depth increase required for a one-hour fire rating is dependent on the bending strength ratio between the reinforced and non-reinforced beams. For the beams tested in Phase II, the strength ratio between the reinforced and non-reinforced beams was determined to be 1.25. Therefore, the depth ratio could be calculated as $\sqrt{1.25}$ or 1.12. From the example given above, the 420 mm deep beam provides a depth ratio of 1.22 over the 343 mm deep beam.

The FRP used was again supplied by the same manufacturers involved in Phase I and consisted of 0.6 mm x 165 mm x 4.3 m samples using a pultruded E-glass/urethane and a continuous E-glass/epoxy lamination.

The non-reinforced Douglas fir glulam beams were manufactured by an ANSI-certified manufacturer using a 24F-V4 lay-up (F_b = 16.5 MPa and MOE =12,410 MPa) combination with a second tension lamination added per the requirements for a one-hour rated beam. An approved phenol-resorcinol adhesive typical of those used by the glued laminated timber manufacturing industry in the U.S. was used. APA staff witnessed the grading of the lumber, the lay-up of the test beams and the manufacturing of the beams. Two of the beams were 165 mm x 420 mm x 4.3 m and the other two beams were 165 mm x 455 mm x 4.3 m.

After manufacturing, the non-reinforced beams were shipped to the AEWCC at the University of Maine where the FRP was installed on the bottom face of the test beams. Based on an analysis by the AEWCC staff, it was determined that the allowable bending stress for these FRP reinforced glulam was equivalent to 20.7 MPa and this was used to establish the design loads applied during the fire test. The beams were then shipped to the Omega Point Laboratory in San Antonio, Texas and tested using the ISO 834 test protocol.

Figure 4 shows one of the test beams being installed in the furnace and Figure 5 shows the application of the design load. The design load for the 420 mm deep beams was 69.4 kN and the design load for the 455 mm deep beams was 85.4 kN.

Figure 4. A test beam being installed in the furnace

Figure 5. Application of the design load

Results of these tests supported the proposed design hypothesis of adding 10% plus one lamination to the beam depth to achieve a one-hour fire rating. Three of the test beams reached 60 minutes with the beams still maintaining full design loads. The fourth beam, one of the 420 mm deep beams, achieved 56 minutes, but it was felt that this result was within the variability associated with glulam beam fabrication and fire testing. Following the extinguishment of the fire, the three test beams that had achieved the one-hour rating were loaded to failure and all three had at least 15% additional reserve capacity after the one-hour fire exposure.

Figure 6 shows the residual cross sections of test beams after the one-hour test visually demonstrating the charring effect. The two beams on the left are the 420 mm deep beams and the two beams on the right are the 455 mm deep beams. There was no noticeable difference in the performance of the two sets of beams with the approximate percentage of wood remaining ranging between 47% and 49% indicating that both FRPs used performed similarly. In fact, the ultimate failure load for the two 455 mm deep beams was identical.

Figure 6. Residual cross sections of tested beams

4. Conclusions

Based on these tests, it was clearly demonstrated that a glulam beam with an FRP applied to the bottom face of the beam and directly exposed to a fire (no bumper lamination) can be designed to achieve a one-hour fire rating when evaluated in accordance with the ASTM E 119 or ISO 834 fire test protocol. It was also shown that for the two different FRP reinforcement layers used in this study there were no discernible differences in overall fire and structural performance. These results should open up new market opportunities for FRP reinforced glulam when a one-hour fire rating is required with the FRP applied to the outermost tension face.

Results of these tests suggested that the FRP reinforced glulam could be designed for fire rating in a similar manner as the conventional non-reinforced glulam. Test data from these studies supported the proposed mechanics-based methodology by increasing the depth of the FRP reinforced beam to achieve a one-hour fire rating. As manufacturers in the U.S. seek building code acceptance of proprietary FRP reinforcement systems, this testing will provide the basis for justifying one-hour rated assemblies using FRP reinforced glulam beams.

5. References

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