FLEXURAL STRENGTHENING OF TIMBER BEAMS USING GFRP

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ABSTRACT

The majority of timber bridges in the Province of Manitoba require flexural and/or shear strengthening to increase their load-carrying capacity in response to an increase in the allowable gross vehicle weight. The use of glass fibre-reinforced polymer (GFRP) has been investigated as an innovative approach for strengthening these bridges. This paper includes the results of an experimental program using half-scale and full-scale 200 by 600-mm, 10.4-m long beams. The half-scale beam specimens were tested to failure using different reinforcement ratios, including unstrengthened beams as control specimens. The cross section of these beams was 100 by 300 mm, and they were tested under four-point bending monotonic loading. The span of the beams was 4.0 m, with a shear span of 1.7 m. Twenty-two beam specimens, including seven plain timber and 15 timber beams reinforced with GFRP bars were tested. The GFRP bars were installed in grooves cut in the tension zone of the test beams. The grooves, 15 mm wide and 25 mm deep, were cut into the sides of the beams, with GFRP bars bonded to the timber using an epoxy resin. The three reinforcement ratios used were: 0.27, 0.41 and 0.82 percent.

Test results using the proposed technique indicate a possible increase in the flexural strength in the range of 25 to 50 percent. Ductility of the beams was also increased. The preliminary results indicate that GFRP is a feasible material for the strengthening of timber bridges. This paper describes the experimental program and the test results.
INTRODUCTION

Many historical buildings and bridges were built using timber. Currently, most of these structures are scheduled for reconstruction. With the recent use of composite materials in civil engineering, many new opportunities exist for the strengthening of timber structures. Composite materials can be used to increase the strength of existing structures or reduce the size of new beams, thereby creating a more efficient use of the timber supply.

Some of the early investigations of reinforcing timber considered available metals, such as aluminium and steel, as suitable reinforcement. The disadvantage of the use of metals is mainly in their weight and resistance to aggressive environment. These reinforcements were aluminium plates bonded to the top and bottom surface of wood cores, or between laminations of glulam (Mark, 1961). Steel plates and steel cables were used by Bohannan (1962) and Peterson (1965) to prestress laminated timber beams. Glulam beams were strengthened using steel rebars, as reported by Lantos (1970). In all of the studies, the variability in strength decreased for the reinforced beams compared to the unreinforced beams.

Recent work has examined the use of carbon and glass FRP sheets to reinforce sawn timber sections (Johns and Lacroix 1999). This work was conducted using small beams with a cross-section of 39-mm by 89-mm, tested on a simply-supported span of 1.4 m. The lack of literature describing the reinforcement of large sawn timbers has motivated the work reported in this paper. This paper describes an experimental program using half-scale and full-scale beam specimens to investigate the behaviour of timber beams reinforced with GFRP bars.

EXPERIMENTAL PROGRAM

The experimental program included testing of coupon specimens of timber and fibre reinforced polymers (FRP), to determine their fundamental characteristics. The material tests were conducted on large specimens of treated timber tested in tension, compression, flexure and shear. Tension tests and bond tests of a number of FRP materials were also conducted to determine the most suitable material for the application with timber. The determining factors were bond, durability, availability, ease of application, and cost. It was concluded from these preliminary tests that GFRP bars are the most suitable. The GFRP bars used in this investigation have a 5-mm diameter, a tensile strength 1800 MPa, and a modulus of elasticity 56 GPa. For brevity, only beam tests will be discussed in this paper.

Two sets of specimens were tested. The first set included 22 half scale beams cut from the larger timbers tested in three groups of varying reinforcement ratio, specifically 0.27, 0.41 and 0.82 percent, and the second set included three full-scale beams. The typical half-scale beam has a clear span of 4 m, with a shear span of 1.7 m, a cross-section of 100x300 mm, and is tested under four point bending. Load is applied at a stroke-controlled rate of 3 mm per minute to achieve failure in 10 to 20 minutes. Deflection is monitored at
five different locations using linear variable differential transducers (LVDT). Strain is monitored primarily in the constant moment region using pi-gauges. Details of the test set-up are shown in Fig. 1.

![Figure 1 Test set-up](image)

The full-scale specimens were 10.4 m long, 200-mm wide and 600-mm deep. The beams were tested in accordance to ASTM D198 (1992) with a simply-supported span of 10.0 m and a load span of 1.2 m. The GFRP used in the full-scale specimens had strength of 700 MPa and a Young’s modulus of 42 GPa. The bars were inserted in either bottom surface, or the side surface of the beams for comparison purposes.

**SPECIMEN PREPARATION**

The FRP bars are inserted on the side of the beams to ensure ease of field application. A groove is cut in the beam on both sides, 30-mm from the bottom fibres, to accommodate the FRP bars. The depth of the groove is a function of the number of bars used. The bars are bonded to the wood by epoxy and cured for five days before testing. All bars are instrumented by strain gauges to monitor the strain during testing.

For the full-scale specimens, the procedure was used to simulate real-life strengthening. The grooves were cut using a router from the bottom surface. The entire process was performed from underneath the beams. A bead of epoxy was injected in the groove and the FRP bar was put in place. Staples were used in 1-metre intervals to prevent the bar from slipping out. Fig. 2 shows the process of FRP application for the full-scale specimens. Smoothing the surface of the beam completed the process.
TEST RESULTS OF HALF-SCALE BEAMS

The strain was measured at four locations at mid-span throughout the depth of the timber beam and in the GFRP bars. The load-strain relationship was linear up to initiation of cracks in the tension zone and remained linear after cracking with a reduced slope, reflecting the effect of the reduced stiffness of the cracked section. The GFRP reinforcement caused an increase in the average extreme fibre tensile strain at failure from 0.0035 to 0.0058, which represents an increase of 62 percent. This supports the conclusions of Johns and Lacroix (1999) that the presence of FRP material arrests crack opening, confines local rupture, and bridges local defects in the timber. The result is that the timber can support higher nominal stresses and strains before failure.

![Figure 2 Strengthening of full-scale beams](image)

The load-deflection curves reflect the linear behaviour of timber before initiation of first cracks. Test results show a large variation in the measured stiffness and strength for both the plain and reinforced specimens. Fig. 3 shows the low and high bound load-deflection behaviour for typical plain and GFRP-reinforced timber specimens.

Failure of the plain timber specimens usually occurred at Point A for both weak and strong timber, shortly after initiation of cracks in the tension zone. For the stiffest and strongest plain timber specimens, some non-linearity of the load-deflection behaviour was observed, however, failure was always governed by the bending strength of the timber.
For the reinforced specimens, the initial load-deflection 0-A was linear until the timber cracked in the tension zone at Point A. The stiffness then gradually decreased until maximum load was reached at Point B and crushing started in the compression zone. Deflection continued to increase with a minor decrease in load up to Point C, at which point a significant crack occurred in the tension zone, causing a rapid drop in load to Point D. The beam was capable of additional deflection and load-carrying capacity up to Point E, where the testing was terminated due to limitations of the testing equipment.

![Figure 3 Typical load-deflection curves](image)

**Failure Mode**

All beams were loaded monotonically up to failure. Fig. 4 shows a typical beam during loading. The majority of the beams failed in flexure (19 beams out of 22 tested), while three beams failed in a combination of flexure and shear. This paper focuses on flexural strengthening and, therefore, the flexural-shear failures will not be discussed.

Two flexural failure modes were observed: compression and tension failure. If the beam exhibited crushing in the compression zone at maximum load, the failure was classified as a compression failure. If crushing did not occur at the maximum measured load, the failure was classified as a tension failure.

For the compression failure, cracking is also present in the tension zone. All of the beams initially cracked in the tension zone, but for the compression failures, crushing in the compression zone controlled the ultimate load. All plain timber specimens failed in tension with no sign of crushing in the compression zone. For the reinforced specimens that failed in flexure, 60 percent of the specimens failed in compression failure mode. The addition of
the GFRP bars caused a change in the failure mode from brittle tension in the plain timber specimens to a more ductile compression-initiated failure. Table 1 summarizes the failure modes observed for the beams based on their reinforcement ratios, $\rho_{GF}$.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
$\rho_{GF}$ & Beams & Failure Modes & & \\
& (%) & in Total & Tension & Compression & Flexure-Shear \\
\hline
0 & 7 & 7 & N/A & N/A \\
0.27 & 3 & 1 & 2 & N/A \\
0.41 & 6 & 2 & 2 & 2 \\
0.82 & 6 & 2 & 3 & 1 \\
\hline
\end{tabular}
\caption{Typical failure modes of half-scale beams}
\end{table}

Due to the high strength of the GFRP reinforcement, the GFRP bars did not rupture in any of the specimens. There was some localized debonding of the bars adjacent to tension cracks in the timber, but the bond between the bars, epoxy and timber remained intact outside the failure region. None of the failures were due to debonding or delamination of the reinforcement, as has been observed in applications using FRP strips or sheets for external reinforcement (Hernandez et al. 1997).

\section*{TEST RESULTS OF FULL-SCALE BEAMS}

Three reinforced beams were tested with reinforcement ratios 0.26 percent (one beam) and 0.42 percent (two beams), and one plain timber beam as control specimen. The
beam with the highest stiffness was strengthened with the lowest reinforcement ratio, and the two beams with the lowest stiffness were strengthened with the highest reinforcement ratio of 0.42 percent. Note that all reinforced beams behaved linearly up to 95 percent of the ultimate load. One of the beams was linear-elastic up to failure and failed due to propagation of tension cracks along a large defect in the timber before crushing in the compression zone.

The non-linear behaviour of two full-scale beams tested was similar to the behaviour of the reinforced specimens in the half-scale experimental program. One of the beams was strengthened with a reinforcement ratio of 0.26 percent, but achieved a higher strength than that strengthened by 70 percent more reinforcement. The full-scale tests confirmed that beams from the high end of the strength distribution required less reinforcement than beams from the low end of the strength distribution. The load deflection behaviour can be found in Fig. 5.

![Graph showing load deflection behaviour of full-scale beams](image)

**Figure 5 Load deflection behaviour of full-scale beams**

**Failure Mode**

Two modes of failure were observed in this experimental program. The plain timber specimen failed in tension at a deflection of 94-mm. One of the beams failed in tension due to a weak plain in the timber, and two beams failed in compression and underwent substantial deflection before failure. The failure modes observed for the full-scale beams were the same as those observed for the half-scale specimens.
CONCLUSIONS

The behaviour of sawn timber beams reinforced with GFRP bars has been investigated. The failure mode changed from brittle tensile-flexural failure in the plain timber specimens to more ductile compression-flexural failure in the reinforced specimens. A strength increase of 25 to 50 percent was obtained, depending on the reinforcement ratio and strength of the original timber. Results from the half-scale experimental study were reproduced in the tests of full-scale specimens. GFRP bars can be used as a feasible method for the flexural strengthening of sawn timber beams. Further research is needed to determine the long-term performance of the proposed strengthening technique.

ACKNOWLEDGEMENTS

Chris Gentile wishes to acknowledge the funds received from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada). Financial support and materials provided by the Manitoba Department of Highways and Transportation and Concrete Restoration Services Ltd. is greatly appreciated.

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