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AN EXPERIMENTAL INVESTIGATION OF FAILURE MODES IN SHORT SPAN FRP REINFORCED GLULAM BEAMS

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ABSTRACT: Although the Canadian bridge code has provisions for fibre-reinforced polymer (FRP) timber stringers, the lack of tools and limited understanding of the structural behaviour prevents widespread adoption, specifically for glulam beams. Thus, an experimental investigation examining the effects of FRP reinforcement configurations on short span glulam beams was undertaken. A total of fourteen glulam beams were tested to failure under four-point bending with five of them being unreinforced and the remaining nine reinforced with two or four layers of simple tension and U-shaped tension FRP reinforcement. In comparison to the unreinforced beams, FRP reinforced beams were observed to have an increase in maximum load with a lower maximum displacement. Although the addition of FRP reinforcement contributed to an increase in strength and stiffness, the primary failure mode changed from pure flexure, as found in the unreinforced beams, to longitudinal shear, tension perpendicular-to-grain or a combination of brittle failure modes. The brittle failure modes can be attributed to insufficient development lengths, the low shear span to depth ratio, and the inherent low shear strength of the tested glulam. These factors need to be considered in future models to accurately predict the structural behaviour of short span glulam beams in flexure.

KEYWORDS: fibre-reinforced polymers, glulam, timber, shear failure, flexural failure

1 INTRODUCTION

1.1 BACKGROUND

The resurgence of timber within the construction industry has been heavily influenced by the development and commercialization of mass timber products, such as glued-laminated timber (glulam) and cross-laminated timber (CLT). Significant research efforts have thus been undertaken in Canada and internationally to investigate the performance of different mass timber products. As a result, significant updates to the newest editions of the National Building Code of Canada [1] and International Building Code [2] have been implemented allowing for the construction of encapsulated mass timber buildings up to 12- and 18-storeys, respectively.

Despite the significant progress towards the development of design provisions and guides, one area that has not been fully investigated is the behaviour of glulam beams reinforced with fibre-reinforced polymers (FRPs). To this date, there are no design guidelines in the CSA O86 “Engineering Design in Wood” [3] nor the CSA S6 “Canadian Highway Bridge Design Code” [4] for glulam beams reinforced with FRPs. Although there are design provisions in the CSA S6 for timber stringers reinforced with FRP fabric and bars, the increased strength is tied to a minimum reinforcement ratio being met, thereby resulting in an increased strength of one grade category (e.g., from No.1/No.2 to Select Structural).

The overarching aim of the current research program at the University of Waterloo is to provide designers with guidance in the detailing of FRP-reinforced wood members in addition to providing tools to understand and predict their structural behaviour. Within the scope of the current paper, traditional FRP reinforcement methods on the performance of short span glulam beams are investigated and discussed.

1.2 PREVIOUS RESEARCH

Several types of FRPs exist and can be applied to wood (e.g., sawn timber, glulam) to strengthen deficient structural members, retrofit against extreme hazards (e.g., earthquakes, blast loading), or to use as a hybrid product in a new design. Common FRP types include glass FRP (GFRP), carbon FRP (CFRP), aramid FRP (AFRP), or basalt FRP (BFRP). These types can be installed through external bonding of FRP sheets [e.g., 5–7] or insertion of FRP bars or plates into the members [e.g., 8,9].

In general, whether in the form of sheets or bars, FRP generally contributes to an overall increase in stiffness

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and strength with an upper limit of 3% of reinforcement to wood area. Vetter et al. [10] conducted an analytical study on the effects of the material wood properties on the flexural behaviour of FRP-reinforced glulam. In the study, three different cross-section sizes, two reinforcement schemes (i.e., simple tension, and U-shaped up to mid-depth), six different number of FRP layers provided (i.e., 0, 1, 2, 3, 5, 7), and three different ratios of tension-to-compression moduli (i.e., 2:1, 1:1, 0.5:1) were investigated for a total of 99 simulations. The tensile-to-compressive wood strength ratio was observed to significantly affect the increases in moment resistance when the wood in tension is significantly weaker than in compression (i.e., 0.5:1), with increases in moment resistance of 1.95. In comparison, for the case where the wood in tension is significantly stronger than that in compression (i.e., 2:1), a maximum moment resistance increase of 1.19 was observed. This observation is in line with the literature that the contribution of the FRP is most evident for weaker specimens [6].

Although the previous research provides a good insight on the behaviour of FRP-reinforced glulam beams, the material model used in Vetter et al. [10] assumed a flexural response and an infinitely rigid bond between the FRP and omitted FRP delamination and longitudinal shear failure in the wood.

1.3 OBJECTIVES

The primary aim of the research is to investigate the behaviour of both unreinforced and FRP reinforced glulam beams, in order to understand the limitations of reinforcement configurations on the flexural behaviour of glulam beams. This paper presents the findings of the research program, specifically the effects that FRP reinforcement has on the failure modes of short span glulam beams.

2 EXPERIMENTAL PROGRAM

2.1 DESCRIPTION OF SPECIMANS AND MATERIALS

The experimental program investigated the behaviour of fourteen unreinforced and FRP-reinforced 69 mm x 100 mm x 1355 mm 20f-EX glulam beams under four-point bending. Upon receipt of the glulam, it was observed that the specimens had minor deformities (e.g., uneven edges, inconsistent laminate widths, splits) which were removed by use of a planer and jointer to a final 69 mm x 100 mm cross-section. The specimen lengths, and clear span, were determined in accordance with ASTM D198 “Standard Test Methods of Static Tests of Lumber in Structural Sizes” [11]. According to the standard, a minimum shear span to depth ratio (a/d) of 4 allows for the evaluation of flexural properties. Therefore, shear and clear spans of 400 mm and 1,200 mm were chosen with beams having a total length of 1,355 mm. Prior to testing, the specimens were conditioned to an average moisture content of 11.4% (CoV 0.11). using a humidity chamber. The average density of the beams was determined to be 442 kg/m3 with a coefficient of variation of 0.06.

Of the fourteen specimens, five were unreinforced and nine were reinforced with glass FRP (GFRP). Five beams were reinforced with simple tension reinforcement and four with U-shaped reinforcement extending to mid-depth (Figure 1).

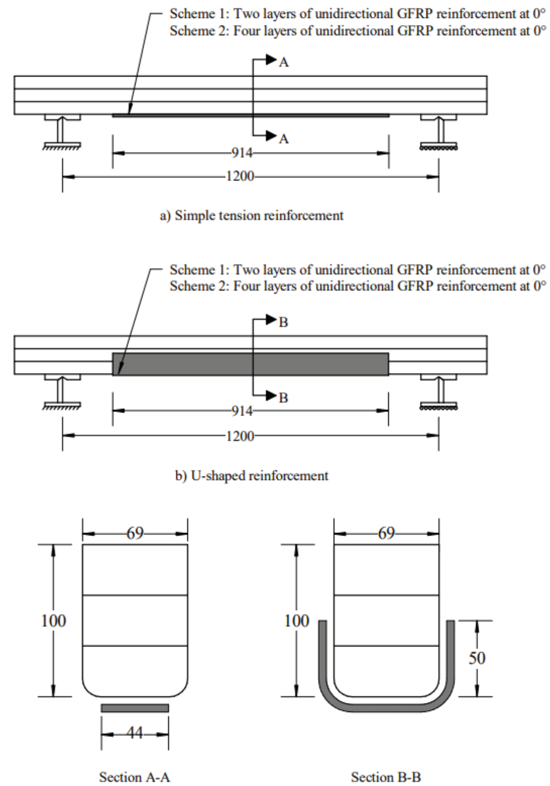

Figure 1: *Reinforcement Configurations*

All reinforced specimens were provided with either two or four layers of unidirectional GRFP reinforcement at 0°.The glulam tension laminate corners were routed using a corner round over bit (12.7 mm radius) prior to the application of the GFRP to prevent stress concentrations in the FRP extending beyond the bottom face. The application face(s) of the beams were wire brushed using a grinder to roughen the surface, providing an ideal interface for the bond between the FRP fabric and the glulam. The glulam FRP application face(s) were then coated with a layer of the epoxy resin mixture. The GFRP fabric was initially saturated with the epoxy resin followed by placing the FRP sheets onto the epoxy coated glulam beam surfaces. A summary of the test matrix is shown in Table 1.

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Table 1: *Test Matrix Summary*

Specimen Number	Specimen Type	Reinforcement Configuration
G-1 - G-5	Unreinforced	-
GS_2-1 – GS_2-3	Reinforced	Simple Tension, 2 Layers
GS_4-1 – GS_4-2	Reinforced	Simple Tension, 4 Layers
GU_2-1 – GU_2 -2	Reinforced	U-Shaped, 2 Layers
GU_4-1 – GU_4 -2	Reinforced	U-Shaped, 4 Layers

2.2 DESCRIPTION OF TEST SETUP

A total of fourteen glulam beams were tested under static four-point bending, in accordance with ASTM D198-21a "Standard Test Methods of Static Tests of Lumber in Structural Sizes" [11]. Simply supported boundary conditions were provided through the use of an anchored pin and roller system.

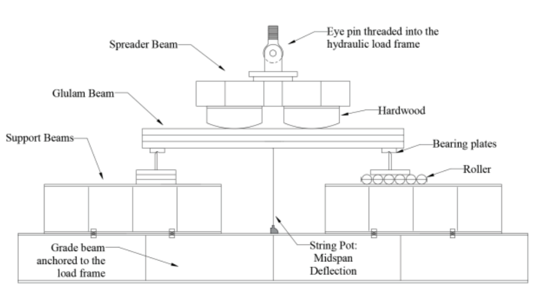


Figure 2: *Flexural Test Set Up*

A 500 kN hydraulic load frame with a load cell connected to the actuator was used to load all bending tests. The unreinforced and reinforced beams were loaded in displacement control until failure, with loading protocols ranging from 3.5 mm/min to 10 mm/min to ensure ultimate failure within five to ten minutes [11]. During the tests, a data acquisition system recorded the data. The applied load and midspan deflection were measured using the load cell in the test frame and a wire (i.e., string pot) respectively. Furthermore, the strains of the wood and FRP were recorded at midspan using strain gauges. Before testing the weights, moisture readings and visual observation of the specimens were recorded.

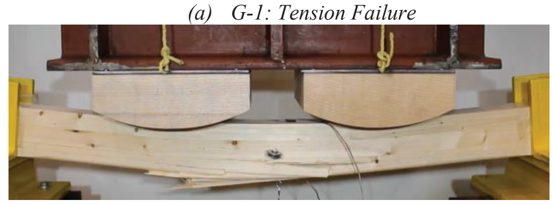
3 EXPERIMENTAL RESULTS

3.1 FAILURE MODES

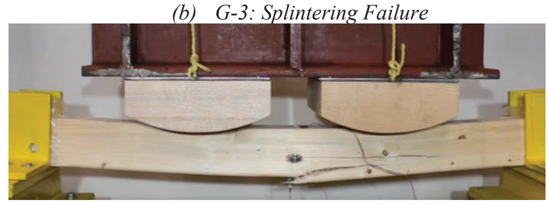
A total of five unreinforced and nine FRP-reinforced glulam beams were tested to failure. The observed failure modes in the unreinforced glulam beams consisted of simple tension and splintering (Figures 3a and 3b), as well as cross-grain tension in one specimen (Figure 3c).

For the simple tension reinforcement configuration with two layers and four layers, the failure mode changed from a flexure failure to one that is dominated by longitudinal shear and stress concentrations. Figure 4 shows a representative failure progression where a longitudinal shear failure first occurred followed by a failure of the wood where the simple tension reinforcement ended (GS_2-2, GS_2-3, GS_4-1). For all three beams, FRP debonding on the tension face or tensile failure of the FRP were not observed. This observation conflicts with other studies that reported debonding of the FRP caused by a flexural failure of the wood material on the tension side pushing on the FRP laminations [12–15].

(a) G-1: Tension Failure



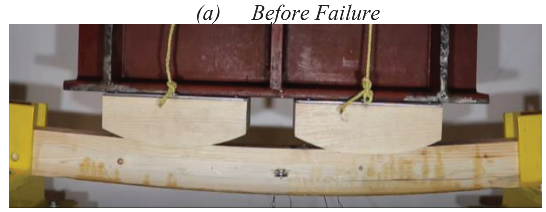
(b) G-3: Splintering Failure



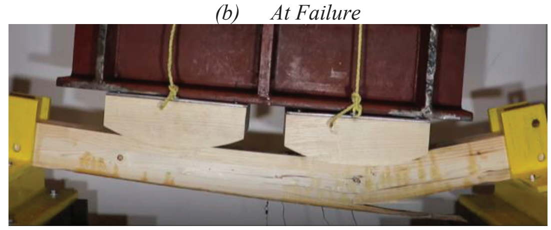
(c) G-4: Cross-grain Failure

Figure 3: *Failure Modes of Unreinforced Specimens*

(a) Before Failure



(b) At Failure



(c) After Failure

Figure 4: *Representative failure of longitudinal shear dominated failure modes in simple tension reinforcement (GS_2-2)*

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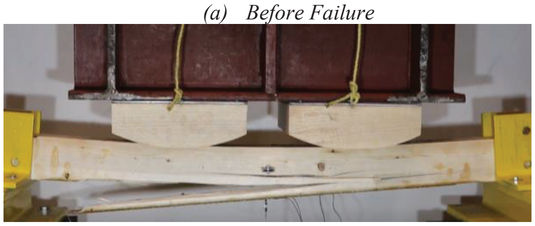
A second failure mode was observed for specimens reinforced with simple tension reinforcement where failure was observed to occur at the ends of the simple tension GFRP strips causing horizontal shear and tension perpendicular to grain stresses (GS_2-1, GS_4-2). The bond between the reinforcement and the wood remained intact, followed by the propagation of the failure throughout the wood.

(a) Before Failure



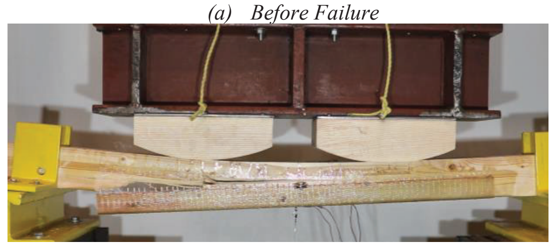
(b) After Failure

Figure 5: *Representative Failure of Tension Perpendicular-To-Grain Dominated Failure for Specimens with Simple Tension Reinforcement (GS_4-2)*

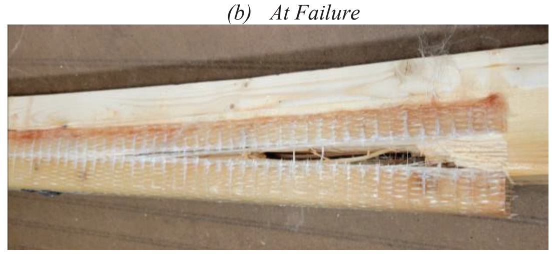
The conflicting failures modes observed for the configuration of simple tension reinforcement glulam beams can be attributed to a combination of factors including: 1. Insufficient development length of the reinforcement, 2. Lower bound shear span to depth ratio (a/d), and 3. Shear strength of glulam. The simple tension reinforcement configuration appears to have provided insufficient development length causing stress concentrations between the supports and end of FRP reinforcement, ultimately leading to an initial failure mode dominated by tension perpendicular-to-grain. In comparison to Lacroix and Doudak [12] for which the FRP reinforcement ended 82.5mm from the centre of the supports, the FRP reinforcement in the current study was terminated 143mm from the centre of supports. Furthermore, while the shear span to depth ratio (a/d) was within the recommended range in the standard [11] with a value of 4:1, it was at the lower end, thus even providing minimum reinforcement shifted the failure mode from flexure to one that is predominantly dominated by longitudinal shear. This can also be attributed to the fact that the glulam in the current study had a lower shear strength, thus only minimal reinforcement was required to alter the primary failure mechanism as Lacroix and Doudak had an a/d ratio of 3.85:1 [12], but did not observe the failure modes reported herein.

For all but one specimen, the U-shaped tension reinforcement eliminated the horizontal longitudinal shear failure as shown in Figure 6. All three specimens (GU_2-1, GU_2-2, GU_4-2) failed due to stress concentration at the end of the FRP reinforcement resulting in debonding of the FRP. Nonetheless, shear stresses are clearly evident as indicated by the splitting of the FRP. This failure mode in the FRP is to be expected due to the use of unidirectional FRP, thus there are no FRP fibres aligned with the depth of the beam. The addition of the reinforcement resulted in a primary failure mode of sudden brash failure at the end of the FRP reinforcement combined with horizontal shear failure of both the wood and FRP reinforcement on the side faces, rather than flexural failure as observed in the unreinforced specimens (Figure 6c). The change in failure mode was expected since the additional reinforcement provided some shear reinforcement.

(a) Before Failure



(b) At Failure



(c) Close Up of Back-Side Failure

Figure 6: *Representative Failure of Tension Perpendicular-To-Grain Dominated Failure for Specimens with U-Shaped Tension Reinforcement (GU_2-1)*

The second failure mode observed for the specimens reinforced with U-shaped tension reinforcement is one that is dominated by a longitudinal shear failure as shown in Figure 7. GU_4-1 failed in horizontal shear at the support with the failure propagating throughout the beam, accompanied with splitting of the FRP reinforcement. Debonding of the FRP was not observed even at large displacement (Fig. 7c).

In general, the failure modes of the unreinforced and reinforced specimens were observed to be different. For all unreinforced specimens, wood tension-dominated failures were observed. This failure mode was not the primary failure mode observed in reinforced specimens as the increase in the woods tensile strength provided by a minimum 2% reinforcement ratio proved to be significant enough to cause the failure mode to change from flexure

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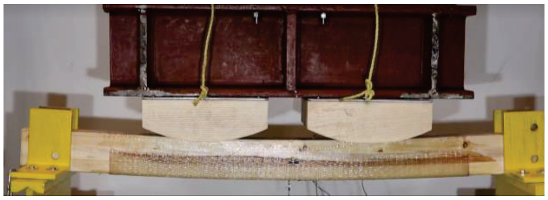
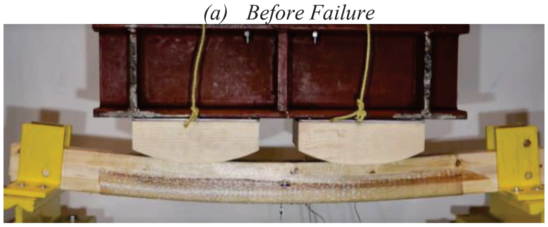
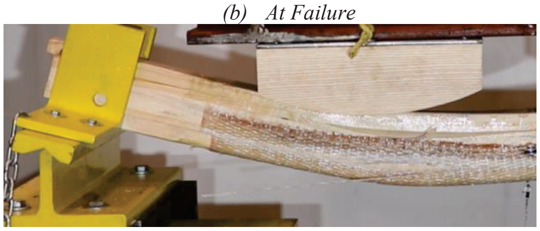
to shear for simple tension and U-shaped reinforced specimens.



(a) Before Failure



(b) At Failure



(c) Close Up of Failure

Figure 7: *Representative Failure of Longitudinal Shear Dominated Failure Mode for U-Shaped Tension Reinforcement (GU_4-1)*

3.2 ANALYSIS OF EXPERIMENTAL RESULTS

In this section, key parameters describing the behaviour of the unreinforced and FRP-reinforced specimens are presented, including: the maximum applied load (P_{max}), displacement at the maximum applied load (Δ_{Pmax}), and the initial stiffness defined as the slope from 10 to 40% of load-displacement curve. The results are summarized in Table 2-3 and Figures 8-10. The flexural response of the unreinforced beams is summarized in Table 2 whereas the individual load-displacement curves as well as the average curve are presented in Figure 8.

Table 2: *Unreinforced Beam Flexural Test Results*

Specimen Number	P_{max} (kN)	Δ_{Pmax} (mm)	K (N/mm)
G-1	27.9	26.4	1620
G-2	30.8	29.3	1541
G-3	36.8	24.3	1731
G-4	36.8	23.3	2107
G-5	31.9	29.8	1510
Average	32.8	26.6	1702
Std. Dev.	3.5	2.6	216
CoV	0.11	0.10	0.13

The load-displacement curve of the unreinforced beams is observed to behave in a linear fashion with some level of softening caused by compression yielding prior to the wood tensile failure. Since glulam beams consist of different laminates glue-pressed together, the variability and location of naturally occurring defects often leads to wood tensile failures occurring prior to reaching the maximum compression resistance of the laminates.

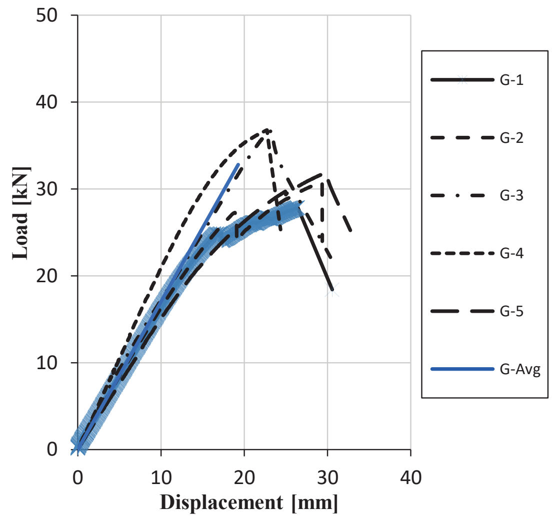


Figure 8: *Load – Displacement Curves of G-Specimens*

The flexural performance of the reinforced beams is summarized in Table 3. The majority of the reinforced specimens showed an increase in the maximum load (P_{max}) and stiffness (K). The provided FRP reinforcement contributed to stiffening of the beams, allowing for greater loads to be sustained. Therefore, leading to a combination of horizontal shear failures and tension perpendicular-to-grain as opposed to that of flexure for the unreinforced beams. As all reinforced beams failed in either shear, delamination, or a combination of alternative failure modes, rather than tensile flexural (e.g., splintering, cross-grain) this is an indication that an increase in tensile strength from the FRP reinforcement schemes can lead to an alternate failure mode. The reinforcement prevented failure of wood tensile fibres observed during the unreinforced beam tests, ultimately increasing the shear stresses in the specimens. This resulted in alterative brittle failures beyond tensile flexural failures observed in the unreinforced beams.

Table 3: *Reinforced Beam Flexural Test Results*

Specimen Number	P max (kN)	Δ_{Pmax} (mm)	K (N/mm)
GS_2-1	32.1	12.8	2544
GS_2-2	35.2	24.1	1783
GS_2-3	36.8	19.5	2082
Average	34.7	18.8	2137
GS_4-1	44.4	27.4	2459
GS_4-2	50.0	25.8	2499
Average	47.2	26.6	2479
GU_2-1	42.9	21.5	2277
GU_2-2	39.6	29.1	1976
Average	41.2	25.3	2126
GU_4-1	46.8	35.1	2259
GU_4-2	46.9	19.5	2844
Average	46.8	27.3	2552

3.2.1 GS Specimens

The addition of two unidirectional GFRP sheets applied longitudinally (GS) increased the capacity and stiffness of the beams on average by a factor of 1.06 and 1.26, respectively. With four unidirectional GFRP sheets, the capacity and stiffness increased by an average factor of 1.44 and 1.46, respectively. However, on average the GS_2 beams failed at a maximum displacement of 0.72 times less than that achieved in the unreinforced beam tests, whereas the GS_4 beams showed an increase of 1.02 times the displacement of unreinforced beams. Relative to the unreinforced beams, the displacement at maximum loads did not increase proportionally (Figure 9).

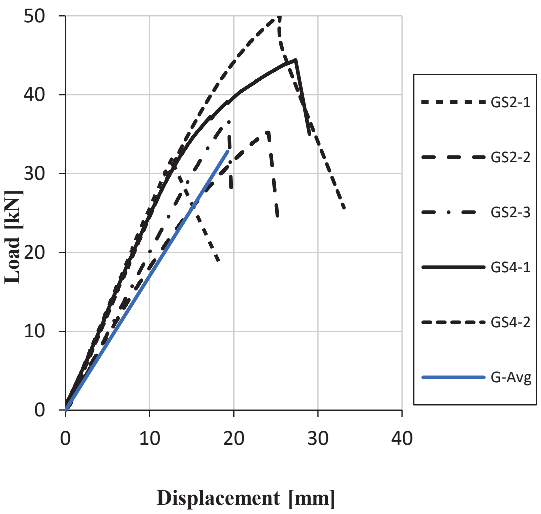


Figure 9: *Load – Displacement Curves GS Specimens*

The significant difference in the change of resistance versus the change of maximum displacement observed in GS can be attributed to a change in failure mode. The addition of simple tension reinforcement altered the failure mode from a wood tension failure in flexure to a horizontal shear failure or stress concentration failure located where the simple tension FRP reinforcement sheets were terminated. The FRP was shown to effectively increase the bending stiffness and reinforced the wood fibres, allowing for the specimens to support greater loads at smaller displacements. The reinforcement provided did not allow for further increase in the beams' bending performance by causing it to fail in a brittle manner (i.e., shear, tension perpendicular-to-grain).

3.2.2 GU Specimens

For beams reinforced with two layers of U-shaped reinforcement (GU), the average resistance and stiffness increased by 1.26 and 1.25 respectively, when compared to the unreinforced beams. For four layers, the average resistance and stiffness increased by 1.43 and 1.50, respectively. Similar to the GS beams, the increases in maximum load and maximum displacement were not proportional. When compared to the unreinforced beams, a decrease of 0.03 times the displacement was observed for the GU_2 beams, whereas a slight increase of 1.05 was observed for the GU_4 beams.

When comparing the effect of U-shaped reinforcement (GU) to the simple tension configuration (GS), the overall flexural behaviour of the specimens is similar. The specimens reinforced with 2 and 4 layers of U-shaped reinforcement (GU) were observed to have an increase in maximum resistance by an average of 1.26 and 1.43, respectively relative to the unreinforced beams.

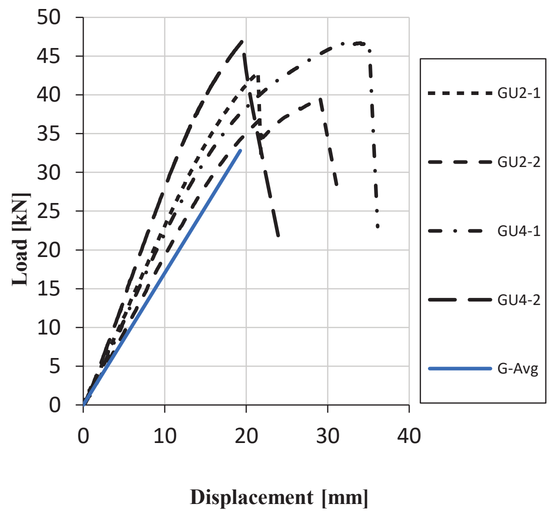


Figure 10: *Load – Displacement Curves GU Specimens*

4 CONCLUSIONS

The current research program investigated the effects of simple tension and U-shaped tension FRP reinforcement on the performance of short span glulam beams. It was observed that while the addition of FRP reinforcement to glulam beams contributed to an increased strength and stiffness when compared to the unreinforced glulam beams; that alternate failure modes consisting of longitudinal shear, tension perpendicular to grain, or a combination of rather than flexure were observed. The alternate brittle failure modes can be attributed to insufficient development lengths, the low shear span to depth ratio, and the inherent low shear strength of the tested glulam. The conflicting failure modes reported herein when compared with the literature [12] indicate that further investigation into the development length of the FRP reinforcement and the corresponding shear concentration at the start and end of FRP reinforcement should be undertaken for the development of future models.

Overall, specimens with two layers of FRP reinforcement increased in capacity by 1.06 to 1.26 for simple and U-shaped configurations respectively. For specimens with four layers of reinforcement, the capacity increased by 1.26 to 1.43, respectively. Similarly, the beams had an observed stiffness increase of 1.25 to 1.26 for two layered configurations, and 1.46 to 1.50 for four layered

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configurations. Additionally, the increase in the resistance at a lower maximum displacement of the GS and GU specimens relative to the unreinforced beams indicate benefits attributed to specific FRP reinforcement schemes. While the main objective of the reinforcement is to increase the ultimate capacity of the beam at locations of large bending stresses, to remain effective, the reinforcement is required to be adequately anchored or bonded, to allow the transfer of stresses.

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