

복합재료로 보강된 집성보의 휨 실험에 대한 연구

Study on the Bending Test of Glulam Beam Reinforced with GFRP Strips

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Abstract

A recent application of advanced composite materials, primarily fiber-reinforced plastic (FRP) composites, in structures is the reinforcement of conventional structural materials, such as concrete and glued-laminated timber (glulam), to increase their performance. In particular, the construction of large-scale glulam structures usually requires members with large depths and to significantly increase the stiffness and strength of glulam, the members can be reinforced with FRP at top and bottom surfaces. In this paper, glulam beams reinforced with GFRP strip are tested under 2-point bending and results are compared with numerical solution using layer-wise beam theory.

요 약

최근에 복합재료는 콘크리트, 집성보와 같은 기존의 구조재를 보강하여 성능을 향상시킬 목적으로 적용되고 있다. 특히, 대규모의 집성보 구조물은 춤이 큰 부재를 필요로 하는데 섬유보강판을 이용하여 보의 상하부를 보강하면 춤을 크게 하지 않고도 보의 강도와 강성을 증가시킬 수 있다. 본 연구에서는 집성보에 유리섬유 보강 플라스틱판(GFRP)을 붙여 스패 중앙에 집중하중을 가한 휨실험을 수행하였고 실험결과를 층간이론을 이용한 수치해석법과 비교하였다.

Key words : Composite material, glulam beam, reinforcing method, bending test of beam.

핵심용어 : 복합재료, 집성보, 보강공법, 보의 휨실험

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1. Introduction

The reinforcement of concrete and glulam beams has been explored either as a rehabilitation technique or as a means of reducing the depth of a member, which in turn can reduce the weight and the bracing requirements to prevent lateral buckling. Because of corrosion problems and as an alternative to the use of steel plates for strengthening purposes, glass fiber-reinforced plastic (GFRP) plates were bonded to the tension face of reinforced concrete beams. Similarly, wood beams were reinforced with non-prestressed or prestressed epoxy-bonded carbon fiber-reinforced plastic (CFRP) sheets. Glued-laminated timber beams (Glulam) are used extensively for long-span bridges and roof structures, such as frames, arches, and reticulated domes (Davalos et al. 1992). The advantages of glulam are light weight, economical production of tapered and curved members, excellent energy absorption characteristics, high chemical and corrosion resistance, and with proper surface treatment better fire resistance than steel. However, due to the relatively low bending stiffness and strength of glulam, the construction of large structures usually requires glulam members of large depths, which in turn require bracing to prevent lateral-torsional buckling. To significantly

increase the stiffness and strength of glulam, while reducing the depth, a glulam beam can be reinforced with fiber-reinforced plastic (FRP) composites at bottom and/or top surfaces.

One of the first model of glulam beam strength is called the I_k/I_g method, where I_k is the moment of inertia for the knot area within a prescribed beam length of the critical cross section and I_g is the gross moment of inertia; this method reduces the flexural strength of clear wood section using the I_k/I_g factor, and it is the basis of strength prediction specified in ASTM D3737 (1992). However, this model does not include the influence of finger joints on the failure response. A transformed section method is a common engineering approach to simulate a composite cross section by an equivalent homogeneous cross section, which permits the use of isotropic elastic formulas for the computation of bending moments and deflections.

In this paper, linear and failure responses of glulam beam reinforced with GFRP are presented. A layer-wise beam theory (Kim et al. 1994) is adopted for the numerical prediction of linear response. The accuracy of the model is evaluated with experimental results.

Table 1. Specimen Specification

		Layer	
		Wood	GFRP
Layer thickness(in)		1.3	0.1875
No. of layer - location in beam	bottom reinforced beam	4-core(No. 2 grade)	2-bottom surface
	top-bottom reinforced beam	2-next to core(Select Structural grade)	1-top, 1-bottom surface
Volumetric ratio in beam(%)		97.2	2.8

2. Experimentation

Eleven glulam-GFRP beams were tested to failure under four-point bending (Fig. 1). Five beams are reinforced at the bottom and six beams at the top and bottom. Specification and arrangement of layers are given in Table 1.

The beams designed following ASTM D3737 (1992) were manufactured in a commercial glulam plant. Following guidelines of ASTM D198 (1992), the beams were subjected to four-point bending, with a support-span of 19 ft. and a load-span of 6 ft. Displacements and strains at midspan were recorded with a data acquisition system.

The approximate elastic moduli, E , of the lumber components were 2.0×10^6 psi for Select Structural and 1.6×10^6 psi for No. 2 grade, and the approximate shear moduli were $E/14$. The material properties of the GFRP obtained from tension and torsion tests were $E_1 = 6.03 \times 10^6$ psi, $G_{12} = G_{13} = 6.8 \times 10^5$ psi. First, the linear response of the beams is discussed briefly, and then, the failure evaluation of the beams is examined.

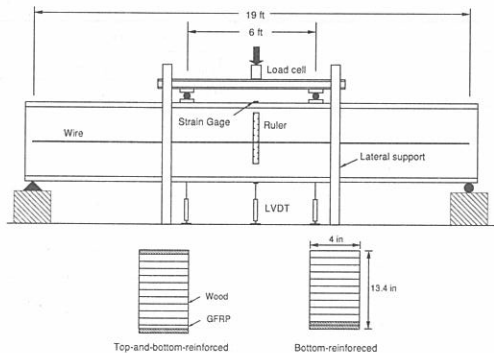


Fig. 1 Test setup and cross-section of beams

3. Experimental and numerical correlations

3.1 Numerical Prediction

To predict the linear response of the laminated beam lamination beam theory and a layer-wise beam theory are employed and their formulations are presented here briefly. In lamination beam theory, the laminate constitutive equations are derived by integrating stresses through a section (Fig. 2) as follow:

$$N_x = b \int_{-h/2}^{h/2} \sigma_x dz,$$

$$Q_x = b \int_{-h/2}^{h/2} \sigma_{xz} dz,$$

$$M_x = \int_{-h/2}^{h/2} z \sigma_x dz$$

From the classical lamination theory (Jones, 1974), the resultant forces can be expressed as

$$N_x = A \epsilon_x + B \kappa_x$$

$$M_x = B \epsilon_x + D \kappa_x$$

$$Q_x = F \gamma_{xz}$$

where ϵ , κ are in-plane strain and curvature, respectively, and A is the extensional stiffness, B is the bending-extension coupling term, D is the bending stiffness, and F is the shear stiffness. The bending stiffness which can be used in the flexural formula to compute deflection and stress is

$$D = b \sum_{i=1}^N E_x^i \left[t_i (\bar{z}_i - z_o)^2 + \frac{t_i^3}{12} \right]$$

where t_i is the thickness of the i -th layer and the neutral axis z_0 is

$$z_0 = \frac{\sum E_x^i t_i \bar{z}_i}{\sum E_x^i t_i}$$

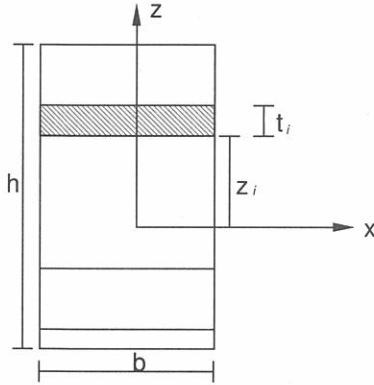


Fig. 2 Laminated beam section

In the layer - wise beam theory(Kim et al. 1994), in-plane displacements are selected as degrees of freedom(dof) per each layer instead of rotational dof for the cross section while the transverse displacement is equal through-the-thickness. This kinematical assumption is equal to applying the Timoshenko beam theory to each layer, plane section is no longer plane after deformation. In the finite

element formulation of the Beam element with Layer-wise Constant Shear(BLCS), 3-node isoparametric element is used with reduced integration. For accurate shear stress computation, constant shear stress on each layer is converted into parabolic distribution.

3.2 Comparison of results

In the test, the load-displacement and load-strain curves showed linear relation up to near ultimate failure. For experimental and analytical comparisons, we assume linear response of the specimens only up to one half of their ultimate loads, and therefore, linear regressions of the experimental data are performed for up to one half of the ultimate loads. The visual displacement reading with the wire are used to verify the reliability of the electronic data recorded with LVDTs. Lamination Beam Theory(LBT) underpredicted displacement for most of the specimens, with a maximum difference of 14% for Beam 4(Table 2). In contrast, the BLCS displacement were more accurate, with a maximum difference of about 10 %.

Table 2. Displacement and strain ratios

Location of GFRP strip in Beam	Beam No.	Displacement Ratio			Strain Ratio	
		LBT/LVDT	BLCS/LVDT	Wire/LVDT	Tensile	Compressive
Bottom	1	0.905	0.942	0.983	1.029	0.904
	2	0.962	1.010	1.041	0.961	1.124
	5	0.887	0.941	0.999	1.007	- a)
	6	0.914	0.935	0.985	1.034	1.000
	9	0.928	0.965	0.987	1.036	1.019
Top & Bottom	4	0.879	0.911	0.961	1.011	0.796
	7	0.956	0.998	0.998	0.980	0.967
	8	0.908	0.943	0.984	1.018	0.959
	10	0.891	0.926	0.957	0.879	0.959
	11	1.021	1.060	1.079	1.038	1.025
	12	0.945	0.979	1.001	0.964	0.986

a) Gage malfunction

Table 3. Comparison of Stiffness

Location of GFRP strip in Beam	Beam No.	MOE(10 ⁶ psi)			
		Exp (a)	LBT (w/o GFRP)(b)	LBT (w/GFRP)	Ratio(a)/(b)
Bottom	1	1.95	1.70	2.15	1.15
	2	2.05	1.68	2.12	1.22
	5	1.89	1.67	2.13	1.13
	6	2.00	1.74	2.19	1.15
	9	1.95	1.66	2.11	1.17
Top & Bottom	4	1.94	1.75	2.20	1.11
	7	2.10	1.71	2.19	1.23
	8	2.06	1.79	2.23	1.15
	10	1.90	1.65	2.14	1.15
	11	2.22	1.70	2.18	1.30
	12	2.09	1.73	2.21	1.21

Table 4. Comparison of failure load

Reinforcement Type	Beam No.	MOE(10 ⁶ psi)		
		Experiment	BLCS	Exp/BLCS
BR Beam	1	27.64	26.70	1.04
	2	28.17	27.33	1.03
	5	24.22	26.85	0.90
	6	28.37	25.78	1.10
	9	28.37	23.84	1.19
Mean		27.35	26.10	1.05
TBR Beam	4	22.76	28.27	0.81
	7	26.51	28.71	0.92
	8	23.24	25.60	0.91
	10	22.76	28.17	0.81
	11	25.93	27.80	0.93
Mean		23.91	27.28	0.88

Strain predictions with BLCS were very close to the experimental values, and in general, the prediction for tensile strain was more reliable than that for compressive strain, which is partially due to the possibility of delamination or wrinkling of the material on compression face. In the Table 3, effective or equivalent moduli of elasticity(MOE) of the beams are compared using LBT. With respect to the wood core alone, the average increase of stiffness of the bottom-reinforced(BR) beams is about 16% and that of the top-and-bottom-reinforced (TBR) beams is approximately

19%. Considering only linear response, the TBR beams had a higher bending stiffness than the bottom-reinforced beams. In the test, most beams failed catastrophically without significant visible failures before reaching ultimate load. Compression wrinkling was observed in three of the BR beams. Also, delamination buckling of the top GFRP layer was evident in three of the six TBR beams. A post-failure examination of the beams suggested that the failure generally initiated at a finger joint in the outermost tension layers within the midspan of the beams.

The failure loads summarized in Table 4 are obtained using the Tsai-Wu criterion and displacement-controlled scheme. For the BR beams, the failure loads is in close agreement, except for BR beam-9, where the discrepancy is about 19%. However, the predicted values are within 5% of the experimental mean values for BR beams. For the TBR beams, in relation to the experimental value, the predicted mean ultimate loads are approximately 12% higher. This difference is primarily due to the delamination buckling of the top GFRP layer. If this delamination buckling was precluded, the expected ultimate load-carrying capacity of both sets of beams should be approximately the same, as predicted by the analysis.

4. Conclusion

Full-scale tests of glulam-GFRP beams were conducted under four-point bending. In the linear response, the top-and-bottom-reinforced (TBR) beams showed higher stiffness than the bottom-reinforced (BR) beams, but, in the failure response, BR beams had higher ultimate loads than TBR beams. This difference in load capacity was partially due to the premature separation of the GFRP layers from the wood laminates; the delamination buckling of the compression GFRP layer was a contributing factor to the lower ultimate load capacity of TBR beams.

Therefore, in the future studies of glulam reinforcement with composite materials, the quality of bonding between the wood and GFRP layers in the compression zone must be improved. From the test, it was observed that the ultimate strength of TBR beams may be significantly lower than that of BR beams, unless a good bonding between GFRP and wood layers is provided.

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