NUMERICAL AND EXPERIMENTAL EVALUATION OF FRP REINFORCEMENT ON THE MECHANICAL BEHAVIOR OF TIMBER BEAMS

D. Bru[a*], F. J. Baeza[a], S. Ivorra[a], F.B. Varona[a]

[a]*University of Alicante/ Department of Civil Engineering, 03690 San Vicente del Raspeig-Alicante (Spain)*
**e-mail: david.bru@ua.es*

Keywords: Glass fibres, Carbon fibers, Wood, Damping ratio.

Abstract

A study on the static and dynamic properties of timber beams reinforced with FRP is reported in this paper. The main objective is to determine the best FRP reinforcement configuration when an architectonical retrofitting solution is designed. With this final purpose three different stages have been developed. First of all an analytical and experimental optimization of the laminates was made by combining different variables (glass or carbon fibers, fiber/resin dosage and number of layers). Afterwards, the orthotropic behavior of 3 timber beams (3 m long) was studied in a second phase. Mechanical parameters such elastic moduli and Poisson's coefficients were experimentally determined both using static and dynamic techniques. Finally, in order to study the behavior of different reinforcement schemes these parameters were formulated and implemented into FE model. Different simulations were analyzed to determine the reinforced beams strength, ductility, stiffness and dynamic behavior.

1. Introduction

Wood, and especially timber, is a widely used material for small houses, pedestrian footbridges with small span lengths and is present in most of historical buildings. The main reason was its high effectiveness as structural material, it is capable of supporting both compression and tension stresses especially related to its low specific gravity. However, some problems have resulted in the substitution or retrofitting of wood structures by concrete or steel elements, e.g. durability issues regarding biological agents [1] or service loading increases due to building reutilization. Among the reinforcement techniques usually employed the attachment of steel bars or aluminum or steel sheets can be quoted [2-3]. Even though these solutions were efficient, they highly increased the structure's weight. Nowadays, composite materials such as fiber reinforced polymers (FRP) come as an alternative to improve structural capacity and stiffness of timber structures [4-7].

From a dynamic analysis perspective, several authors have successfully achieved correlations between the static and dynamic elastic modulus of wooden elements [8]. However, there is a lack of information regarding the evaluation of the material's damping ratio and the dynamic behavior of timber beams reinforced with FRP, Zou [9] and Naghipour [10] analyzed the natural frequencies and damping ratios of reinforced laminated wood beams for different fiber orientation.

	Material			One layer weight (g/m²)	
Properties	**Epoxy Resin**	**Fiberglass**	**Carbon fiber**	**Fiberglass**	**Carbon fiber**
E (N/mm²)	2810	72400	230000	436(0º/90º)	230 (0º)
σ_{ult} (N/mm²)	555	3400	4300		

Table 1: Mechanical properties**.**

Finally, the main objective of this study was to evaluate the effect of different reinforcement schemes with glass fiber reinforced polymers (GFRP) and carbon fiber reinforced polymers (CFRP) in the mechanical parameters of the timber beams (natural frequencies, damping ratio, elastic modulus, and ductility).

2. Description of the analysis

2.1. Materials properties

The test material consisted of a set of three beams glulam Picea Abies species (GL24h Class, according to Spanish Technical Code for Building) and six prismatic timber specimens, Figure 1. The dimensions of the beams were 304x16x8 cm³ and the dimensions of the timber specimens were 48x16x8 cm³. As a reinforcing material was used Bidirectional (0º-90º) woven GF reinforcements, with 440 g/m² weight (213/217) and unidirectional (0ª) CF reinforcements with 230 g/m². An epoxy resin, type SR 5550 and SD 5503, was also used to fabricate the laminate. The mechanical properties of both materials (GF, CF and resin) are included in Table 1.

Figure 1. Left: Four-point bending tests. Right: Experimental setups for dynamic measures on small samples.

2.2. Experimental test and numerical models

The experimental program of the research was divided into three phases. In the first phase, the laminates were characterized statically and optimal dosage was selected from the analysis of the elastic modulus, volume fraction of fibers, and ultimate stress of six different dosages (kilograms of resin/kilograms of fiber). Furthermore, dynamically and statically beams and timber specimens were tested in order to prove the viability of using smaller specimens to characterize the dynamic behavior of the whole structure, and to determine the orthotropic properties of wood. In the second phase, a numerical model of the whole beam was created. In order to calibrate this model, the mechanical properties used for timber and reinforcing materials were obtained from the experimental tests. The main objective of this phase was to determine the effect of different reinforcing schemes on ductility, stiffness, and vibration frequencies. Twenty seven models, Table 2, were analyzed according to the type of bottom reinforcement (length and material), and depending on the level of lateral section reinforcement (middle section, complete section or complete wrapping of the beam). In the third phase, the reinforcement effect with composite materials in relation to the failure mode was analyzed. Two different modes of failure were selected. The first one is due to shear stresses in support area, and the second one is due to shear stresses in hole area. The ultimate shear stress is 4 MPa. For shear failure criteria in support area, there have been 23 models varying the length of reinforcement, structural reinforcement scheme and the number of layers, Table 3. The objective of these models was to determine the reinforcement scheme that reduces shear stress value below the assumed boundary. The second one, failure for shear stresses in hole area, was analyzed by 18 numerical models, varying the longitudinal and transversal position of the hole, and the structural reinforcement scheme, Table 4.

Model	Zone	Type	Layers	Modelo	Zona	Type	Model	Model	Zone	Type	Layers
M1	L_C	I_C	1_C	M10	$1/2L_C$	I_C	1_C	M19	$2/3\ L_V$	C_V	3_V
M2	L_C	I_C	3_C	M11	$1/2L_C$	I_C	3_C	M20	$1/2\ L_V$	C_V	3_V
M3	L_C	I_C	6_C	M12	$1/2L_C$	I_C	6_C	M21	L_V	$H_{V/2}$	3_V
M4	L_V	I_V	1_V	M13	L_V	H_V	1_V	M22	$2/3\ L_V$	$H_{V/2}$	3_V
M5	L_V	I_V	2_V	M14	L_V	H_V	2_V	M23	$1/2\ L_V$	$H_{V/2}$	3_V
M6	L_V	I_V	3_V	M15	L_V	H_V	3_V	M24	$2/3L_C$+1/2 L_V	I_C+ H_V	3_V
M7	$2/3L_C$	I_C	1_C	M16	2/3 L_V	H_V	3_V	M25	$2/3L_C$+1/2 L_V	I_C+ C_V	3_V -6_C
M8	$2/3L_C$	I_C	3_C	M17	1/2 L_V	H_V	3_V	M26	$2/3L_C$+1/2 L_V	I_C+ $H_{V/2}$	3_V -6_C
M9	$2/3L_C$	I_C	6_C	M18	L_V	C_V	3_V	MC	-	-	-

Table 2: Numerical models for bending analysis. I_C= Lower reinforcement of CFRP . I_V= Lower reinforcement of GFRP o. H_V= Bottom and lateral continuous reinforcement section. C_V= Bottom, top and lateral continuous reinforcement section. $H_{V/2}$= Bottom and lateral continuous reinforcement of half section. L_V=Length L of fiberglass reinforcement. L_C= Length L of carbon fiber reinforcement. N_V= Number of layers of laminated glass. N_C= Number of laminated layers of carbon.

Model	Zone	Type	Layers	Modelo	Zona	Type	Model	Model	Zone	Type	Layers
C1	d/2	C_V	3v	C10	d/2	C_V	6v	C19	d/2	$H_{V/2}$	4v
C2	d/2	H_V	3v	C11	d/2	H_V	6v	C20	d/2	H_V	6v
C3	d/2	$H_{V/2}$	3v	C12	d/2	$H_{V/2}$	6v	C21	d/2	$H_{V/2}$	6v
C4	d	C_V	3v	C13	d/2	C_V	8v	C22	d/2	H_V	8v
C5	d	H_V	3v	C14	d/2	H_V	8v	C23	d/2	$H_{V/2}$	8v
C6	d	$H_{V/2}$	3v	C15	d/2	$H_{V/2}$	8v				
C7	d/2	C_V	4v	C16	d/2	H_V	3v				
C8	d/2	H_V	4v	C17	d/2	$H_{V/2}$	3v				
C9	d/2	$H_{V/2}$	4v	C18	d/2	H_V	4v				

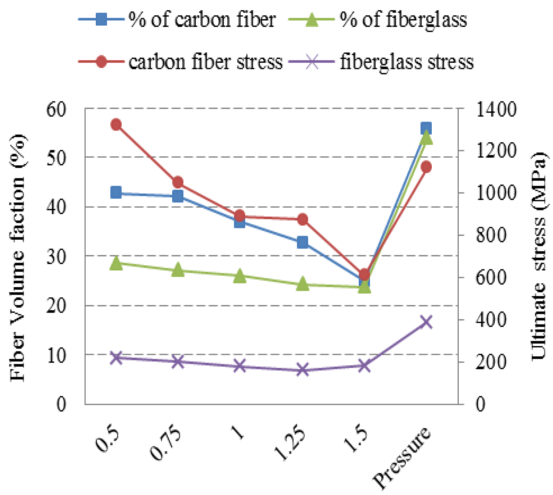
Table 3 Numerical models for shear analysis.d= Reinforcement length equal to the height of the section. d/2= Reinforcement length equal to the height of half section. H_V= Bottom and lateral continuous reinforcement section. C_V= Bottom, top and lateral continuous reinforcement section. $H_{V/2}$= Bottom and lateral continuous reinforcement of half section. L_V=Length L of fiberglass reinforcement. N_V= Number of layers of laminated glass.

Model	Type	Hole position	Model	Type	Hole position	Model	Type	Hole position
M1	-	1	M10	H_V	1	M19	$H_{v/2}$	1
M2	-	2	M11	H_V	2	M20	$H_{v/2}$	2
M3	-	3	M12	H_V	3	M21	$H_{v/2}$	4
M4	-	4	M13	H_V	4	M22	$H_{v/2}$	5
M5	-	5	M14	H_V	5			
M6	-	6	M15	H_V	6			

Table 4 Numerical models for timber with holes. 1= middle of the beam, lower edge. 2= middle of the beam, bottom section. 3= middle of the beam, upper section. 4 = maximum shear zone, lower edge. 5= maximum shear zone, bottom section. 6= maximum shear zone, top of section. $H_{V/2}$= Bottom and lateral continuous reinforcement of half section. H_V= Bottom and lateral continuous reinforcement section.

During de experimental test, bending modulus: four point bending tests were measured according to UNE-EN 408, for the whole timber beams, Figure 1. Dynamic mechanical parameters, natural frequencies, elasticity modulus and damping ratio for axial mode were measured according to ASTM E1876 and bending mode according to ASTM D6874. GFRP and CFRP laminate tension strength and elastic modulus was measured according to ASTM D3039/D3039M. Finally, in order to know the dynamic and static orthotropic properties of the timber beams, small samples were tested according to ASTM C215, Figure 1, and UNE-EN 408. The results of tests are summarized in Figure 2 and Table 5 and 6.

In relation to the finite element model, a shape factor of the mesh was equal to 1 with rectangular elements of size 10x10 mm². The contact between the wood and FRP material elements was done by node-to-node contact, assuming a perfect contact between them. Non-linear analysis case by means of the control of the deformation was established. Furthermore, mechanical properties of finite element models were taken from the experimental results. Regarding the behavior of the wood material, elasto-plastic curve was assumed for compressive stress, and elastic curve for tensile stress. The values of ultimate strain for compression and tensile stress were assumed to -7.413 mm/m and 6.91 mm/m, respectively. Moreover, ultimate shear stress was 4 MPa, only in supports areas and hole areas. FRP was modeled as elastic material, and its mechanical properties were taken from the experimental results. For the glass fiber and carbon fiber reinforcement, dosage 1/1 and 0.5/1 were used respectively.



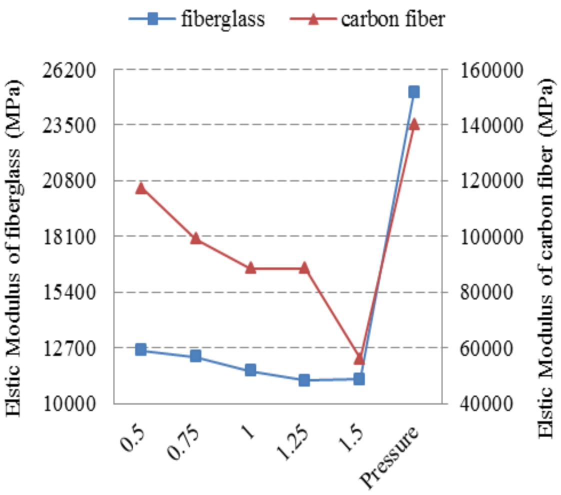


Figure 2. Left: Laminate tension strength, Fiber Volume fraction and Elastic modulus results.

Material		Elastic modulus (MPa)			Damping ratio (%)		
		Axil	Bending	Torsion	Axil	Bending	Torsion
Beam	A	11937.6	10183.71	967.28	2.13	2.08	1.15
	B	15180.39	12439.39	1082.05	2.22	1.47	1.22
	C	11948.20	11067.33	1036.22	2.13	1.82	1.38
Small specimen	A	12598.24	10611.86	741.43	0.95	1.83	2.63
	B	12859.40	9938.91	739.81	1.36	1.35	2.20
	C	13080.11	9629.14	697.07	1.43	1.87	2.02

Table 5. Dynamic mechanical properties: Whole beams and small specimens (MPa)

Material	Elastic modulus (MPa)				Poisson ratio					
	E_{11}	E_{22}	Bending whole beam	Torsion whole beam	υ_{12}	υ_{13}	υ_{21}	υ_{23}	υ_{31}	υ_{32}
A	12258	537	11746	990	0.36	0.41	0.017	0.34	0.022	0.34
B	17094	625	13525	1009	0.45	0.41	0.017	0.34	0.022	0.34
C	12152	777	12450	994	0.34	0.40	0.022	0.34	0.026	0.34

Table 6. Static mechanical properties: Whole beams and small specimens (MPa)

3. Results

3.1. Experimental results

The study of the static and dynamic parameters for whole beams has determined a good correlation between both methods in both flexural and torsional mode. The coefficients obtained were lower than 10%, 6% and 8% for beams A, B and C, respectively. Similar results were obtained for static elastic moduli when small specimens and whole beams were compared (3%, 16.5%, and 1.7%). Finally, if we compare the results on small specimens between static and dynamic tests, acceptable coefficients of variation were obtained, too (1.9%, 20% and 5.2%). These results show a good correlation between the static and dynamic methods, for determining the mechanical properties of timber beams. Furthermore, these results show the possibility of analyzing small samples instead of whole beams. The damping results between beams and small samples showed a coefficient of variation for the bending mode, less than 10% in all cases. However, axial and torsional vibration modes showed a coefficient of variation between 30% and 50%. These results show the feasibility of using small samples for determining the flexural mode, instead of using whole beams. For axial and torsional mode, it has not been able to demonstrate its feasibility.

3.2. Numerical results

Figure 4 summarizes the results of the numerical analysis. Dynamic results, showed that the effect of reinforcing with glass fiber, decreased the natural frequencies, both axial and flexural mode. These results were obtained for all combinations of reinforcement. Therefore, the effect of use GFRP as reinforcement material resulted in a further increase in the mass ratio, and a negligible increase in stiffness properties. However, the effect of reinforcing with carbon fiber showed an increase in the natural frequencies both axial and flexural mode. Moreover, these results were better with the increase of the reinforcement level. However, from a length of the reinforcement level equal or higher than 2L/3, the ratio between stiffness and mass ratio decreased, and therefore, the natural frequencies decreased too. This can be seen by comparing M3, M9 and M12 models. For this reason, it can be concluded that in case of an intervention on a floor by interaction problems of vibrations, may be desirable to apply a lower reinforcement by carbon fiber to increase these frequencies, or applying a laminated glass fiber to decrease the natural frequencies.

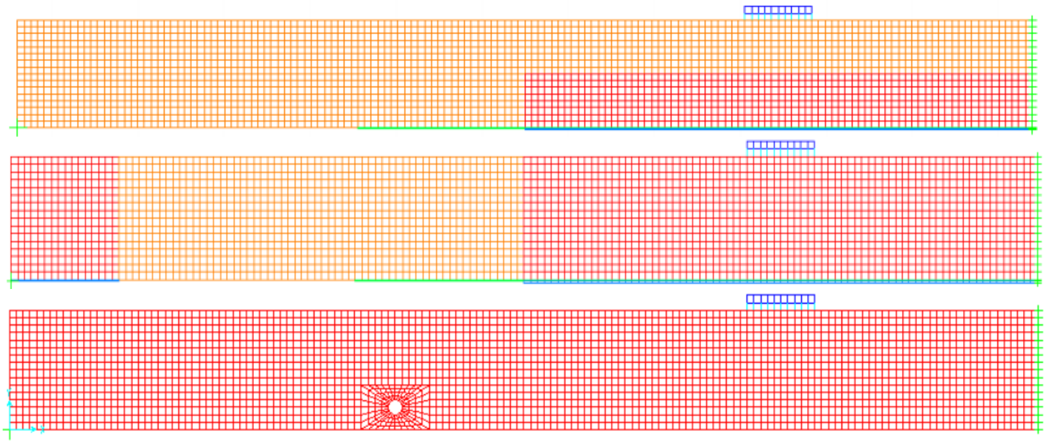


Figure 3. Different configurations for numerical models.

Ductility and stiffness results are shown in Figure 4. In the same way as in dynamic analysis, the reinforcing effect with GFRP produced a low increase in stiffness in any of the configurations analyzed. Moreover, the higher reinforcement level with carbon fiber, the higher increase in stiffness properties. However, for the same number of layers of carbon fiber, it can be seen that longitudinal reinforced length higher than 2L/3 produces similar results to reinforced length equal to whole beam. The difference between them is less than 5%. Results related with ductility of the structure showed an opposite behavior regarding the results obtained in the previous case. In this case, glass fiber reinforcement improves the ductility more than the bottom reinforcement with carbon fibers. Specifically, the best ductility results were obtained for full beam wrap models (M18, M19, M20). One of the outstanding results is the low efficiency of the midsection reinforcement with GFRP (M18, M19, M20). In these cases, the increase of the ductility was only 14%. The improve of the ductility in models M18, M19, M20 is due to the elastic deformability of GFRP. Thus during the plasticizing section, the stiffness of the timber decreases, but a pair of elastic forces is maintained due to the composite reinforcement with 176 MPa ultimate stress. This allows increasing the ultimate load until the time when the last timber tensile deformation is reached, and the collapse of the beam occurs.

Regarding the numerical analysis of the local reinforcement in support zone, it showed that all the numerical models without local reinforcement (M1/M26), exceeded the maximum shear stresses of 4MPa. These results indicate that all these models collapse before reaching the maximum flexural deformation. Figure 4 shows the distribution of the shear stresses in the support zone for each of the models. Only models C10 to C15 and models C22 and C23 allow reducing tensions below the ultimate shear stress. These results show a local reinforce scheme with d/2 length and only mid-section without lower reinforcement is enough to avoid the failure of the structure. Finally, numerical models referred to the analysis of beams with defects show an improvement of 20% for the area of maximum deflection and 30% for the area of maximum shear stress using GFRP, Table 7.

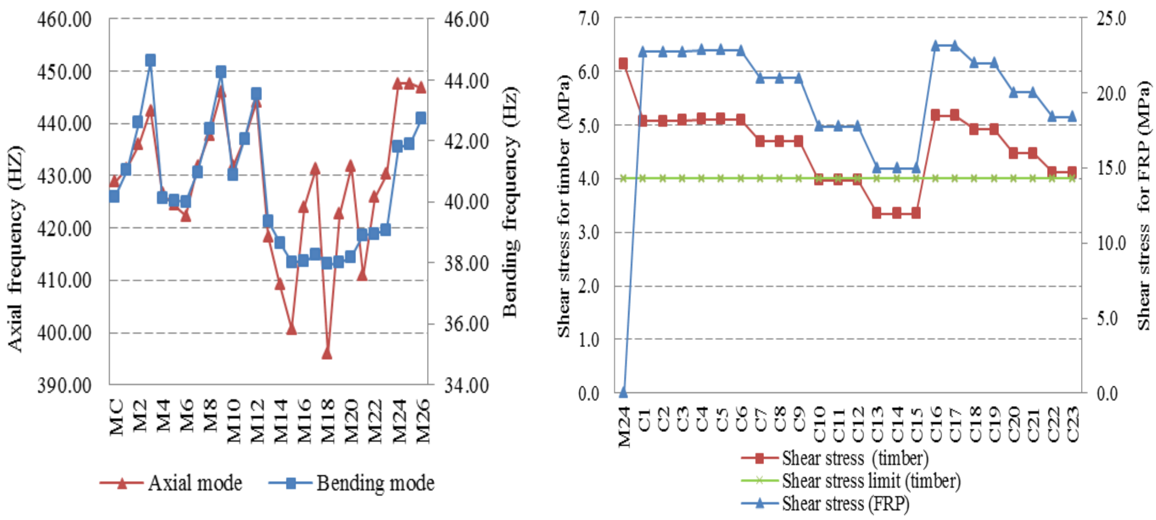


Figure 4. Left: Dynamic numerical results. Right: Shear stresses distribution of the numerical results.

Model	Δ Ultimate load (%)	Model	Δ Ultimate load (%)
M10	19.38	M15	8.55
M11	14.92	M19	19.09
M12	10.50	M20	13.43
M13	20.10	M21	29.31
M14	16.95	M22	16.01

Table 7. Ultimate load improvement for reinforced knot models.

4. Conclusions

After analyzing the different techniques used in static and dynamic characterization of timber structures, it can be concluded that there is a good correlation between the two methods, with good results between small specimens and beams. Moreover, good results were obtained when comparing specimens and beams results. From the dynamic point of view, a good correlation to the bending vibration modes is obtained. Furthermore, it has been observed the viability of using lower reinforcements carbon fiber for increasing frequencies both axial, and bending, and the use of schedules of reinforcement by wrapping section with fiberglass for decreasing bending and axial frequencies.

In relation to the contribution of stiffness to the structure, it was observed that the most efficient reinforcement system corresponds to the M25 model; however, it seems more appropriate to select a pattern corresponding to the model M24 due to the constructional arrangement and the low difference in the contribution of stiffness between the two models. For analyzing the increased ductility in the structure, it was observed that complete wrap reinforcements beam through glass fiber showed the best results. Furthermore, it should be noted that both the lower reinforcement and “Hv/2” reinforcement scheme, produce negligible improvement in ductility. Moreover, a local reinforce scheme with d/2 length and only mid-section without lower reinforcement is enough to avoid the failure of the structure on the support zone. Finally, using GFRP to reinforce the areas with holes, it has improved tensile strength by 20% for maximum tensile area and at 30% for maximum shear area.

Acknowledgements

The authors express deep gratitude to the GRESMES Research Group at Alicante University for their useful assistance. This work was partially financed by the University of Alicante by means of the GRE12-04 Research Project and by means of the scholarship research project VIGROB-212.

References

[1] S. Vignote, I. Martínez, *Tecnología de la Madera*. Ediciones Mundi-Prensa, Madrid (2005). [In Spanish]

[2] W M. Bulleit, LB Sandberg, GJ Woods, *Steel-reinforced glued laminated timber*, Journal Structure Engineering, Vol. 115, No. 2, American Society of Civil Engineers, pp. 433-444, 1989.

[3] F. Arriaga, F. Peraza, M. Esteban, I. Bobadilla, F. García, *Intervención en estructuras de madera*. Editorial AITIM, Madrid (2002). [In Spanish]

[4] A. Borri, M. Corradi, A. Grazini, *A method for flexural reinforcement of old Wood beams with CFRP materials*, Composites Part B: Engineering, Vol. 36, No. 2, pp. 143-153, 2005.

[5] J. K. Yail, A. H. Kent, *Modeling of timber beams strengthened with various CFRP composites*, Engineering Structures, Vol. 32, No. 10, pp. 3225-3234, 2010.

[6] R. Lopez-Anido, M. ASCE, Han Xu, *Structural Characterization of Hybrid Fiber-Reinforced Polymer-Glulam Panels for Bridge Decks*, Journal of Composites for Construction, Vol. 6, No. 3, pp. 194-203, 2002.

[7] T. C. Triantafillou, *Composites: a new possibility for the shear strengthening of concrete, masonry and wood*, Composites Science and Technology, Vol. 58, No. 8, pp. 1285-1295, 1998.

[8] J. Ilic, *Relationship among the dynamic and static elastic properties of air-dry Eucalyptus delegatensis* R. Baker, European Journal of Wood and Wood products, Vol. 59, No. 3, pp. 169-175, 2001.

[9] G. P. Zou, M. Naghipour, F. Taheri, *A nondestructive method for evaluating natural frequency of glued-laminated beams reinforced with GRP*, Nondestructive Testing and Evaluation, Vol. 19, No. 1-2, pp. 53-65, 2003.

M. Naghipour, F. Taheri, G. P. Zou, *Evaluation of Vibration Damping of Glass-Reinforced-Polymer-Reinforced Glulam Composite Beams*, Journal of Structural Engineering, Vol. 131, No. 7, pp. 1044-1050, 2005.