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Changes on dynamic properties of retrofitted timber beams using GFRP

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Corresponding Author:	Salvador Ivorra, PhD. Eng. University of Alicante Alicante, Alicante SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Alicante
Corresponding Author's Secondary Institution:	
First Author:	David Bru, MsC Eng.
First Author Secondary Information:	
Order of Authors:	David Bru, MsC Eng.
	Francisco Javier Baeza, PhD
	Francisco Borja Varona, MsC Eng.
	Javier Garcia-Barba, PhD
	Salvador Ivorra, PhD. Eng.
Order of Authors Secondary Information:	
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Changes on dynamic properties of retrofitted timber beams using GFRP

D. Bru; F.J. Baeza; F.B. Varona; J. García-Barba; S. Ivorra.

Civil Engineering Department, University of Alicante, 03690, San Vicente del Raspeig, Spain.

Telephone number: +34 965 90 3707

Fax number: +34 965 90 3678

e-mail: sivorra@ua.es

url: blogs.ua.es/gresmes/

Abstract: A study on the static and dynamic properties of sawn timber beams reinforced with glass fiber-reinforced polymer (GFRP) is reported in this paper. The experimental program is focused on the behavior of unidirectional wooden slabs, and the main objective is to fulfill the service state limit upon vibrations using GFRP when an architectural retrofitting project is necessary. Two different typologies of reinforcement were evaluated on pine wood beams: one applied the composite only on the lower side of the beams, while the other also covered half of the beams depth. For the dynamic characterization, the natural frequency, damping ratio, and dynamic elastic modulus were measured using two different techniques: experimental modal analysis upon the whole beams; and bandwidth method using smaller samples of the same material. The static characterization consisted on four point bending tests, where elastic modulus, bending strength and ductility were assessed. The lower composite had better ductility and bending strength. On the other hand, the U-shaped laminate showed higher stiffness but also at a higher material cost. However, it allowed some ductility, i.e. compressive plasticity, even in the presence of hidden knots. Both dynamic techniques gave similar results and were capable of measuring the structure stiffness, even if short samples were used. Finally, the changes on dynamic properties because of the GFRP did not jeopardize the dynamic performance of the reinforced timber beams.

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1. Introduction

Wood, and especially timber, is a construction material widely used 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 relatively to its low specific gravity. However, some problems led to the substitution or retrofitting of timber elements, e.g. durability issues regarding biological agents (Vignote and Martínez 2005) 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 ([Bulleit et al. 1989](#); [Arriaga et al. 2002](#)). Even though these solutions were efficient, they highly increased the structure's weight. Nowadays, composite materials such as fiber reinforced polymers (FRP) come as a new option in order to improve structural capacity and stiffness of timber structures ([Triantafillou 1998](#); [Johns and Lacroix 2000](#); [Lopez-Anido and Xu 2002](#); [Radford et al. 2002](#); [Borri et al. 2005](#); [Buell and Saadatmanesh 2005](#); [Yail and Kent 2010](#)).

From a dynamic analysis point of view, several authors have successfully achieved correlations between the static and dynamic elastic modulus of wooden elements ([Perstorper 1994](#); [Ilic 2001](#); [Divos and Tanaka 2005](#)). 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 et al. \(2003\)](#) and [Naghypour et al. \(2005\)](#) analyzed the natural frequencies and damping ratios of reinforced laminated wood beams for different fiber orientation.

The material behavior under dynamic actions is determined by its dynamic properties (such as dynamic modulus of elasticity or Poisson's ratio), which present different values compared with their static counterparts. These changes are usually expressed as a function of the strain or stress rates ([Ross et al. 1995](#); [Bachmann 1997](#)). Besides, there are several studies reporting the relationship between the static and dynamic parameters of different civil engineering materials ([Sandoz 1989](#); [Pellerin et al. 2002](#); [Ilic 2003](#); [Bui et al. 2009](#); [Giner et al 2011 and 2012](#); [Brotóns et al. 2013 and 2014](#); [Kranitz et al. 2014](#)). The characterization of these dynamic properties can be experimentally achieved according to the standard test method ASTM C 215, for concrete specimens. Furthermore, the dynamic performance of a structure is also highly conditioned by its damping ability. In a vibrating structure, damping is understood as the dissipation of the mechanical energy, generally by converting it into thermal energy ([Bachmann 1997](#)). In order to describe the damping ability of a structure or material, the more often used parameter is the damping ratio ξ . This non-dimensional parameter can be defined as follows ([Bachmann 1997](#); [Paz and Leigh 2004](#)):

$$\xi = \frac{c}{c_{cr}} = \frac{c}{2 \cdot m \cdot \omega} = \frac{c}{2\sqrt{k \cdot m}} \quad (1)$$

where c is the damping coefficient that represents viscous or linear damping; c_{cr} is the critical damping coefficient; m is the mass of the system; ξ is the natural frequency of the undamped system; and k is the stiffness of the system. The main role that the damping ratio plays on the dynamic behavior of a structure can be clearly noticed in Fig. 1, in which the Dynamic Magnification Factor (DMF) is represented for different values of the damping ratio. This non-dimensional constant describes the ratio between the displacement under a dynamic (harmonic) load and the displacement under a static load of the same magnitude (amplitude). Its value is given by the following expression (Bachmann 1997; Paz and Leigh 2004):

$$DMF = \frac{1}{\sqrt{(1-r^2)^2 + (2 \cdot r \cdot \xi)^2}} \quad (2)$$

where $r = \frac{\bar{\omega}}{\omega}$ is the frequency ratio (between the frequency of the excitation and the natural frequency of the undamped system).

As can be observed in Fig. 1, for small values of the damping ratio an important value of DMF is detected in the [0.8,1.2] interval of the frequency ratio; that is, the damping ratio specially affects the vibration behavior significantly near to the resonance interval ($r = 1$). Theoretically, the DMF reaches its maximum value at the resonance situation, and then it is inversely proportional to the damping ratio (Bachmann 1997; Paz and Leigh 2004):

$$DMF(r = 1) = \frac{1}{2 \cdot \xi} \quad (3)$$

However, the total overall damping of a structure is a complex concept that depends on several different factors, and it is considered a sum of the contributions of the damping of the bare structure, the damping by the non-structural elements and the damping by the energy radiation to the soil. The damping of the bare structure contributes to the energy dissipation by the material damping and the damping at the bearings and joints. In most cases, the material damping is predominant (Bachmann 1997).

The measurement of the damping properties of structures can be mainly achieved by two methods, which are the decay curve method and the bandwidth method. In most practical cases with real structures, the most recommended and used method is the first one. This is because non-linear behavior of structures makes it very difficult to evaluate the resonance curve. Hence, by the bandwidth method, any

measuring error will severely affect the damping evaluation (Katzensteiner 1994; [Bachmann 1997](#)). Nevertheless, at a material design level where the structural complexity is reduced to a simple specimen, there are standard test methods to determine the resonance curve in an accurate way. Thus, it is possible to use the resonance curve of small specimens, obtained according to these standard test methods, to evaluate the material damping by the bandwidth method with an adequate precision, as reported in previous work on concretes with silica fume and fibers admixtures ([Giner et al. 2011 and 2012](#)).

The main objective of this paper was the study of timber beams retrofitting using GFRP, from a static and dynamic point of view, and to assess the viability of using small samples to characterize the wood dynamic behavior. Therefore the dynamic properties (natural frequencies, stiffness and damping ratio) measured under different circumstances could be compared with two different techniques, bandwidth method and logarithmic decrement technique. Finally, the influence of GFRP performance on the ductility of each beam was also determined.

2. Materials and methods

2.1. Materials properties and fabrication of samples

Three different timber beams (*Pinus Sylvestris L.*) were tested as received (unreinforced) and after being reinforced with glass fiber reinforced polymers (GFRP). Each sample's dimensions were 95x150x3150 mm³, and small specimens of the same pine tree wood and cross section area (95x150 mm²) were cut to 570 mm long (for the bandwidth method tests).

A visual characterization was made according to European and Spanish standards UNE-EN 1912:2012, UNE-EN 14081-1:2006+A1 and UNE 56544:2007. Thus, every selected wood specimen was classified as structural timber elements or MEG (due to its Spanish acronym according to EN 1912:2012). They can be defined specifically as a C18 category, whose mean mechanical properties according to EN 338:2009 should be 9000 MPa and 18 MPa for the flexural elastic modulus and yielding point, respectively, as given in the standard.

The GFRP reinforcements were made using a bidirectional (0°-90°) woven type E glass fiber, with 440 g/m² weight (213/217), and an epoxy resin supplied by SICOMIN Composites, type SR 5550 and SD 5503. Table 1 includes the

mechanical properties of both materials (GF and resin), as given by the suppliers.

The resin/fiber volumetric ratio of the reinforcements was 3/1, which

corresponded to a 2/1 mass ratio, i.e. 2 kg of resin per each GF kg.

All reinforcements consisted on three GFRP layers for a total 3 mm thick

composite. Previously, the wood surface was cleaned in order to improve the

wood-resin bonding. Afterwards, the laminates were casted directly upon the

timber and the resin was applied using a metallic roller.

The properties of the GFRP laminate were measured before the reinforcement of

any timber beam. Three samples were tested according to ASTM

D3039/D3039M-08, and the laminate's average elastic modulus was $8673 \pm 1\%$

MPa, and its average tensile strength $115.0 \pm 6\%$ MPa.

Two different reinforcement configurations were tested, both of which were 2520

mm long for the complete beam tests. The first one was a longitudinal

reinforcement attached to the beam's lower side covering all the beam's width.

The second one also reinforced the lateral sides up to half the timber's depth, in

order to obtain a U-shaped laminate. In the latter, the inferior beam corners were

rounded in order to avoid undesirable local stresses in the composite. After being

reinforced the increase in the beam's mass was 3.3% and 9.1% for the inferior and

U-shaped layouts respectively, i.e. 2.00% and 5.15% of the total cross section

area.

2.2. Dynamic tests

The experimental program was divided into two different stages, where both static

and dynamic properties were analyzed. First the mechanical properties of

unreinforced timber, beams and small specimens, were characterized from a

dynamic point of view. Properties such as natural frequency, elastic modulus and

damping ratio were measured using non-destructive testing. Thus, the same timber

samples could be tested for both conditions (unreinforced and reinforced).

The dynamic characterization was based on the results of two different

techniques, logarithmic decrement technique and bandwidth method. The former

was used on the beams and the latter on small samples. Therefore, if both

techniques gave similar results, the analysis of the structural dynamic behavior

could be studied with small-scale specimens prior to the structure's retrofitting

with GFRP.

In the first technique, Fig. 2(a), the logarithmic decrement (δ) is defined as the logarithm of the ratio between two amplitudes (a fixed number of cycles apart) of the transient curve for a certain vibration mode (Chopra 2001). This variable (4) is directly related to the damping ratio according to (5), for the low damping ratios, typical of civil engineering structures, (4) can be simplified to (5).

$$\delta = \ln \frac{y_m}{y_{m+n}} = \frac{2 \cdot \pi \cdot n \cdot \xi}{\sqrt{1-\xi^2}} \quad (4)$$

$$\xi = \frac{\delta}{2 \cdot \pi \cdot n} \quad (5)$$

The bandwidth method, Fig. 2(b), is a frequency domain method, which can be used to calculate the material damping ratio, especially for low values (Lazan 1968). It is well known that from the frequency-amplitude curve the bandwidth corresponding to the $1/\sqrt{2}$ maximum amplitude (resonant frequency) is directly related to the damping ratio and the natural frequency (6) (Goldman 1999).

$$\xi = \frac{f_2 - f_1}{f_1 + f_2} \quad (6)$$

Where f_1 and f_2 correspond to the frequencies below and above the resonant frequency (f_r), whose amplitudes are $1/\sqrt{2}$ lower than the maximum amplitude. As both methods are non-destructive tests, each sample could be measured before and after being reinforced. First of all, mechanical parameters of the whole beams, such as natural frequency, elastic modulus and damping ratio, were obtained for the axial (longitudinal) mode - according to ASTM E1876-09 – and the bending (transverse) mode according to ASTM D6874-09. All dynamic tests were repeated three times. Fig. 3(a) includes schemes of both test's configurations, which were used in order to measure the natural frequency and elastic modulus of each beam. Simply supported beams with elastomeric supports in each end section were used for the bending mode. In addition, a third support in the middle section was included for the longitudinal mode (to avoid the effect of bending mode). All these tests were repeated once the GFRP reinforcement had been made.

In order to control the excitation of the structures, a constant impact intensity level was achieved using an impulse force hammer, Kistler model 9728A20000. The impact point, see Fig. 3(a), was located at the middle point of the upper side (1575 mm away from each support) for the bending mode, and at the center of an end face of the beam for the longitudinal one. The accelerations induced by the

1 hammer were measured with a model PCB 333B50 accelerometer located at the
2 opposite end face of the impact point. The sensor's sensitivity was 1000 mV/g and
3 the sampling frequency 1 kHz. The data were registered with a data acquisition
4 device model Kyowa PCD-320 and a signal conditioner model PCB 482A22 was
5 used. The signal was analyzed applying a FFT in the free vibration range and a
6 Hanning window function. Afterwards, the damping ratio was calculated in time
7 domain using the logarithmic decrement technique for a 20 cycles distance
8 (Goldman 1999).
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10 The bandwidth method measures were made in two 95x150x570 mm³ specimens
11 for each laminate configuration (i.e. unreinforced, lower and U-shaped). In this
12 case, tests were made on an Erudite MKIV (PC1004) analyzer, and therefore the
13 same parameters (natural frequency, elastic modulus and damping ratio) were
14 obtained in the frequency domain, according to the formulation included in
15 ASTM C215-08. The experimental setups corresponding to each tested vibration
16 mode (longitudinal, bending and torsion) are represented in Fig. 3(b). Moreover,
17 signal's intensity was fixed at 0.5 V for the longitudinal mode or 0.1 V for
18 transverse and torsion modes. In this case, each measure was repeated 30 times in
19 order to minimize the possible experimental error.
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33 **2.3. Static mechanical tests**

34 The static counterparts were also evaluated in the timber samples, both reinforced
35 and unreinforced. Wood moisture content was measured according to UNE-EN
36 13183-1:2002 prior to any mechanical testing. For this purpose, small specimens
37 of dimensions 150x95x54 mm³ were dried at 105°C until constant weight
38 (difference between mass measures lower than 0.1% after two hours). Fig. 4
39 includes the mass loss curves for each specimen, where an average moisture
40 content of 11% was calculated, once the oven drying process was complete.
41 Hence, the conditions included in the European standard, which allows a 12%
42 maximum moisture content, were fulfilled and the strength tests could be made.
43 Four point bending tests were made according to UNE-EN 408:2004 (see Fig. 5
44 for test setup) in order to measure the bending elastic modulus and the flexural
45 strength. In this case, specimens of each reinforcement configuration were tested,
46 i.e. unreinforced, lower and U-shaped reinforcements. For this purpose two LVDT
47 were located at each lateral side of the central cross section to measure the middle
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span deflection. A constant 0.2 mm/s deflection rate was fixed for every test until the material's failure. Therefore, bending strength, elastic modulus and ductility were calculated. Moreover, ambient conditions (21°C and 55% RH) were maintained stable during all tests.

3. Experimental results and discussion

3.1. Analysis of dynamic properties

The dynamic behavior analysis was the main objective of the research as explained above. First of all the dynamic properties were measured with the complete beams (3150 mm long). The natural frequencies were obtained with a free vibration method, while the damping ratios were calculated applying the logarithmic decrement technique. Table 2 and Table 3 include the experimental results for the longitudinal and bending modes respectively. Each test was repeated three times, so only mean values and relative standard deviations (RSD) of each parameter are included. Moreover, as this is a non-destructive test, the same specimens could be tested before and after casting the GFRP.

Regarding the natural frequencies, before any GFRP had been casted, all specimens showed similar frequencies with relative deviations of lower than 4.6% for both modes. Thus, the origin of the tested samples can be verified, especially if the average mass value ($24 \text{ kg} \pm 5\%$) is also considered, i.e. beams with similar masses and natural frequencies should come from the same wood type.

Both vibration modes present similar patterns after casting the composites, e.g. the frequencies tend to be higher for the reinforced beams. This increase was higher for the U-shaped laminate in the longitudinal mode, while the bending mode showed just the opposite trend, as the lower laminate frequency was the highest. This change of behavior can be explained due to the combined effect of mass and stiffness; a higher mass would decrease the natural frequency, while a higher stiffness (i.e. modulus) would tend to increase it. In Fig. 6 the dynamic parameters increase for each reinforcement type are plotted. The U-shaped GFRP had higher influence almost on every property, especially on the final mass (with a 9.1% mass increase versus the 3.3% of the lower composite), and on the longitudinal stiffness (21.6% versus 10.7%). However, the complete composite section contributed to the stiffness improvement only in the axial mode. Whereas if the

bending mode was excited, only the inferior part of the reinforcement would be actually working. Thus, there is almost no difference between the two reinforcement bending stiffness, and therefore the change in the bending frequency is lower for the U reinforcement, as the mass influence prevails. Regarding the material's damping ratio, different trends were detected for each vibration mode. The axial mode was not affected by the GFRP, as only small variation on the damping ratio were measured. On the contrary, the damping ratio values for the bending mode decreased for the reinforced samples. This damping loss was between 25 and 40% (with respect the unreinforced beam's value) for the U-shaped and lower composites respectively. However, these results may be related to the initial damping capacity, which was especially low for the U reinforcement.

A secondary objective was to assess the possibility of using small samples to obtain dynamic mechanical parameters, which later could be correlated with the behavior of the structure. This method, based on the bandwidth method, has been successfully used in previous researches on stone-like materials, e.g. rocks or concrete, ([Giner et al. 2011](#) and [2012](#)). Table 4 includes all the experimental results obtained with 95x150x570 mm³ samples for three vibration modes, axial, bending and torsion, Fig. 5(b). Mean and relative standard deviation values have been calculated for the natural frequencies, elastic modulus and damping ratio of each mode.

The effect of the GFRP composite in the dynamic properties follow similar trends as their counterparts measured in beams. Generally, higher reinforcement amounts resulted in higher modulus and lower frequencies and damping ratios. Moreover, a good repeatability was achieved as almost every measure showed dispersion below 10% for the mean value of two samples. If each sample is considered separately, the repeatability is even better and the thirty measures made on each probe was only 3%. However, some problems were detected for the bending damping ratio, with RSD up to 26% depending the type of reinforcement. This accuracy issue may be related to the experimental configuration for the transverse measures, because it did not appear in the other two modes.

3.2. Static mechanical properties

The static characterization consisted on two different tests to measure the elastic modulus and bending strength, according to UNE-EN 408:2004. The elastic modulus was measured in the same samples before and after being reinforced with GFRP. All the results for the four point bending tests are included in Table 5.

First, an improvement in both modulus and strength was observed for both laminate layouts, as it was expected. This property enhancement was more noticeable in the flexural strength. The improvement in the ultimate load was up to 40% with respect to the unreinforced timber, while the stiffness was increased less than 14%.

Besides the bending strength and stiffness, a ductility factor was determined as the relationship between the plastic and elastic energies (which were evaluated using the load-versus-deflection curves of each test). The mechanical behavior of wood elements corresponds to an elasto-plastic material upon compression and elastic material with brittle failure upon tension. Usually the material reaches its ultimate strength before developing all its compressive plasticity ([Bru et al. 2014](#)). Hence, the ductility of the unreinforced beam was very low, as it broke when the lower fibers reached their tensile strength. When a GFRP reinforcement was attached, the ductility was highly increased, especially in the lower laminate, which ductility was twice as much than the U-shaped composite. However, further analysis were made based on the failure modes observed in images of the broken samples (Fig. 7). Each one of the specimen showed a different type of failure.

First, the unreinforced beam failed at the loading point, where a high concentration of knots can be observed, Fig. 7(a). In this case the ductility was not developed, as explained above. Second, the lower laminate reinforcement, Fig. 7(b), failed by the GFRP composite, which cracked but with a ductility improvement. Finally, the U-shaped laminate, Fig. 7(c), also showed high ductility, but only half than the other reinforcement, i.e. the U-GFRP allowed the timber section to develop a nonlinear behavior despite knots. Fig. 7(c) shows a hidden knot that was detected after the test, and explains the difference in the ductility factor between both laminates.

3.3. Comparison of methods and reinforcement efficiency

Finally, some comparisons have been made between the three methods used in this research to measure the elastic properties of GFRP reinforced timber beams. Fig. 8 includes the bending elastic modulus for each technique (static or dynamic) and reinforcement type. In general, the dispersion for the same parameter was small for all three methods. For example, between both dynamic techniques, standard deviations were again below 10%. The bandwidth method on short samples actually showed the best results related to the longitudinal elastic modulus, especially for low reinforcement ratios. The difference between the static and dynamic measures has been studied based on confidence intervals. For each reinforcement type the 95% confidence interval of the mean value of the static modulus has been calculated (according to UNE 66040:2003). Based on this analysis, there is almost no difference between static and dynamic values. However, in some cases the dynamic elastic modulus is slightly lower than its static counterpart.

The efficiency of each reinforcement type has been compared in the graphs included in Fig. 9. The increase of each parameter (with respect to the unreinforced sample measure) is represented in Fig. 9(a). The U-shaped composite resulted on higher stiffness improvements, whichever method (static or dynamic) was used to assess it, but of course with a higher total mass also. However, the lower reinforcement showed better ductility and strength, probably due to the existence of a hidden knot in the middle section of the U-shaped specimen. For example, the bending elastic modulus improvement for the U-shaped composite was 13.6%, while it was only 3.0% for the lower GFRP. These results are perfectly reasonable with regard to existing literature, where a direct relationship between bending stiffness and wrapping reinforcement layouts has been pointed ([Buell and Saadatmanesh 2005](#)).

In addition, the relative property increase has been calculated, as the property improvement with respect to the mass increase, i.e. the total amount of composite material necessary. These ratios have been included in Fig. 9(b) and in this case the lower laminate was better in any case but the static elastic modulus. The effectiveness of these lower composite was especially high with regard to the beam's ultimate strength. Therefore, the most efficient reinforcement used in this study was made by three GFRP layers attached to the low side of the beam.

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However if this composite was widened up to half of the beam's depth, increases in all mechanical parameters and strength were observed despite the existence of hidden knots, which would put at risk the structural performance.

4. Conclusions

The effect of GFRP reinforcement on the dynamic behavior of structural timber elements was analyzed by different dynamic methods. After this experimental program the following conclusions could be drawn.

Static and dynamic techniques used during the current research showed a suitable correlation in order to obtain the elastic modulus, even if shorter samples were dynamically tested. Besides, similar results regarding the transverse damping ratio were assessed whichever dynamic method was used.

In the comparison between both dynamic techniques, the bandwidth method applied on short samples showed better results due to its lower dispersion.

The timber stiffness was higher for higher amounts of reinforcement. However, a decrease on the damping factor for both longitudinal and bending vibration modes was also observed. Nevertheless, this damping loss, together with the low change in bending stiffness, are not too important for the GFRP reinforced beams in order to fulfill the service state limits, which are usually required in the structural design codes.

Moreover, in both types of reinforcement, the ductility was highly improved due to the use of GFRP, especially for the lower laminate. However, the U-shaped composite was capable of controlling the cracking problems of timber when hidden knots were present.

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Fig. 1 Dynamic Magnification Factor versus frequency ratio (r) for different damping ratios (ξ).

Fig. 2 Dynamic methods to assess the damping ratio: (a) logarithmic decrement; (b) bandwidth method.

Fig. 3 Experimental setup to measure dynamic properties: (a) logarithmic decrement tests; (b) bandwidth method tests.

Fig. 4 Mass loss of small samples of each beam when dried at 105°C.

Fig. 5 Four point bending test according to UNE-EN 408:2004.

Fig. 6 Dynamic properties increase of reinforced timber beams with different GFRP layouts.

Fig. 7 Types of failure mode for different GFRP reinforcements: (a) unreinforced beam; (b) lower laminate; (c) U-shaped composite and (d) detail of a hidden knot in the U-reinforced beam.

Fig. 8 Comparison of the elastic modulus measured using three different methods: static bending test, dynamic logarithmic decrement test and dynamic bandwidth method. In each reinforcement type two limits have been drawn, which represents the 95% confidence interval for the mean value of the static modulus.

Fig. 9 (a) Effect of the GFRP layout in different properties, all increments are expressed as % by the unreinforced measure: Δm (mass increase); ΔE (static modulus); Δf_u (ultimate strength); ductility (ductility factor = plastic energy/elastic energy); ΔE_{long} (dynamic modulus for longitudinal mode); ΔE_{bend} (dynamic modulus for bending mode). (b) Property changes relative to mass increase of each GFRP layout.

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Table 1 Mechanical properties of laminate's components: GF and epoxy resin. Average values as provided by the suppliers.

	Density (kg/m ³)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Strain at failure (%)
Glass Fiber	2600	3400	72400	4.5
Epoxy Resin	1000	48	2810	7.3

Table 2 Dynamic properties for the axial vibration mode on complete beams (RSD means relative standard deviation).

Longitudinal Mode	Specimen 1 Unreinforced	Specimen 2 Lower laminate*	Specimen 3 U-shaped laminate*
Frequency, f (Hz)	203.12	222.65 [230.47]	210.94 [222.65]
RSD	0.00	0.00 [0.00]	0.00 [0.00]
Damping ratio, ξ (%) (%)	2.54	2.22 [2.43]	2.13 [2.08]
RSD	0.04	0.06 [0.27]	0.10 [0.14]
Modulus of elasticity, E (MPa)	10362.0	10971.5 [12143.6]	8837.4 [10742.6]
RSD	0.00	0.00 [0.00]	0.00 [0.00]

* [values in brackets correspond to reinforced specimens]

Table 3 Dynamic properties for the transverse vibration mode on complete beams (RSD means relative standard deviation).

Bending Mode	Specimen 1 Unreinforced	Specimen 2 Lower laminate*	Specimen 3 U-shaped laminate*
Frequency, f (Hz)	30.76	30.92 [31.74]	32.71 [33.04]
RSD	0.00	0.01 [0.01]	0.00 [0.01]
Damping ratio, ξ (%)	2.14	2.36 [1.40]	1.63 [1.25]
RSD	0.07	0.05 [0.01]	0.08 [0.02]
Modulus of elasticity, E (MPa)	10736.6	11489.8 [12501.9]	11539.1 [12842.8]
RSD	0.00	0.02 [0.00]	0.00 [0.02]

* [values in brackets correspond to reinforced specimens]

Table 4 Dynamic properties for GFRP reinforced timber elements using short samples, average value $\pm$ standard deviation is given.

Type	Mode*	E (MPa)	f (Hz)	ξ (%)
Unreinforced	L	13232.8 ± 192.6	4393 ± 175	1.59 ± 0.10
	B	12487.1 ± 1270.0	1862 ± 37	1.95 ± 0.10
	T	855.5 ± 83.0	929 ± 9	2.33 ± 0.16
Lower laminate	L	12583.7 ± 250.6	4007 ± 80	0.77 ± 0.06
	B	12917.9 ± 640.8	1774 ± 15	1.16 ± 0.30
	T	1030.2 ± 70.1	955 ± 27	2.34 ± 0.20
U-shaped laminate	L	13481.0 ± 851.2	4301 ± 213	1.13 ± 0.06
	B	12846.8 ± 529.3	1837 ± 18	1.82 ± 0.38
	T	924.1 ± 53.6	938 ± 9	2.32 ± 0.14

* Vibration modes: L (longitudinal); B (bending); T (torsion).

Table 5 Mechanical static parameters: E_{un} elastic modulus of the bare timber sample; E_r elastic modulus of the reinforced sample; and f_u bending ultimate strength.

Type	E_{un} (MPa)	E_r (MPa)	f_u (MPa)	Ductility factor*
Unreinforced beam	12204 ± 358	---	47.06	0.73
Lower laminate	12662 ± 19	13010 ± 253	66.00	8.17
U-shaped laminate	11844 ± 176	13449 ± 58	57.95	3.59

*(plastic energy/elastic energy)

line figure 5
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line figure 8
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