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Health monitoring of timber beams retrofitted with carbon fiber composites via the acoustic emission technique

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ABSTRACT

This paper proposes a methodology for monitoring of timber beams retrofitted with CFRP (Carbon Fiber Reinforced Polymer) via the acoustic emission technique (AE). The work proposes the use of multi-resonant sensors linearly distributed along the element. The spectral energy of the located AE events is proposed to separate the signals into two groups, depending on the predominant frequency band, between two resonant bands of the used sensor. To avoid the influence of the attenuation, the spectral energy is corrected by the attenuation curves empirically determined. By means of bending tests on beams with two retrofitting layouts, it is demonstrated how the signals grouped into the high-frequency group are located at the areas where the final CFRP-wood delamination took place or where the final failure of the element is concentrated. This result is very promising for health monitoring of retrofitted timber elements in real scenarios.

1. Introduction

The use of FRP for retrofitting and repair of wooden structures as an alternative material to steel has been booming for several years. Its high strength and deformability and the low weight added to the structure are its main attractions. In particular, the use of carbon fiber pultruded laminates and fabrics (CFRP), already at reasonable and competitive prices in the market, provide excellent results in terms of strength, stiffness and ductility.

Numerous experimental, analytical and numerical works have demonstrated the high capacity for retrofitting and repair conferred by different layouts of CFRP [1–11]. Among them, those published by our research group recently, in which the effectiveness of different layouts were compared on old timber beams with more than 200 years in service, demonstrating their effectiveness in a real on-site performance in a historic building of Granada city [12–14].

However, at present, the use of codes and standards for the calculation and design of FRP reinforcement systems on timber beams, unlike in the case of concrete, are still scarce or nonexistent. This gap generates in the professionals of architecture and civil engineering and in the owners of wooden structures, both private and administrations that own many historic buildings, certain reluctance to use them. In general, the use of steel as a traditional system for the reinforcement of wood structures continues to be opted for.

To generate confidence about its operation in situ, as well as to do a continuous follow-up that establishes the pertinent structural alerts, the in-situ and real-time monitoring of structures [15] is an efficient strategy (Structural Health Monitoring), which can be of great utility to the case of FRP-retrofitted or repaired timber structures. In particular, acoustic emission (AE) method is an efficient technology for structural monitoring especially suitable for this purpose [16–18]. There are not, as far as the authors of this work know, previous publications about the AE monitoring of timber structures reinforced with CFRP. The method has been, however, widely used for wood and CFRP, individually [19–24]. There are also some works on the AE monitoring of concrete elements retrofitted with CFRP [25–29].

The acoustic emissions are the elastic waves suddenly released by changes in the strain field of a material. Part of the energy is released in the form of an elastic wave, which can be collected on the surface of the structure by piezoelectric sensors, and converted into an electric signal. Moreover, on the basic of seismology, a location of AE sources can be done. In the case of wood, however, two problems arise when applying this technique: a) Its high heterogeneity, which confers a very high distortion to the waves. Multiple reflections and other propagation phenomena of the wave, alter in a very considerable way the shape of the wave, making its ulterior analysis very complicated and unreliable; b) The high attenuation of the material, which entails a closer location of the sensors, and the almost loosing of information at higher frequencies.

To overcome both inconveniences, this paper proposes a double strategy for the AE data analysis. Firstly, all the AE data analysis is done only on a

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very narrow window of the signal, just after the threshold crossing, including only one cycle of the waveform. This action largely avoids the effect of reflections and other propagation phenomena. Secondly, the proposed method includes a correction of the signal in the frequency domain, which attempts to compensate the attenuation losses. This correction is stronger and more relevant as the frequency increases.

Using this double strategy, the work proposes the use of signals whose spectral energy is predominant within a band of high frequencies. By means of the experimental analysis, the work correlates these signals as coming from the resin-wood failure. This failure is the precursor of CFRP-wood delamination, which generates the final failure of the structure. The appearance, detection and location of these AE signals serve as a real-time alert of final element failure. The proposed methodology has been validated on two different retrofitting layouts. First, by using only a pultruded CFRP laminate placed on the traction face. Second, by using an additional fabric partially wrapping the timber element. Both layouts have a completely different mechanical behavior and failure pattern, but the AE methodology provides successful results in both cases.

2. Specimens descriptions

All the timber beams used in this work were extracted from the last rehabilitation carried out on the roof of the Faculty of Law of the University of Granada. They are *pinus sylvestris* beams from the forests of the south of Spain, which had been in service for more than 200 years. They were cut and sanded with a final cross-section of (147 ± 11) × (222 ± 6) mm^2 and a length of 4500 ± 2.4 mm.

In particular, six beams were reinforced with CFRP by using two different layouts named as LR (longitudinal) and BR (braided), respectively. They are represented in Fig. 1. For LR layout a pultruded CFRP lamella was adhered on the bottom face of the beam, i.e. at the maximum tensile stresses zone. In the case of BR reinforcement, an additional CFRP fabric was wrapped onto this lamella. It was distributed discontinuously along the beam, in order to save CFRP material. Furthermore, two beams without reinforcement (NR) were used as control specimens.

As is shown in Fig. 1, the CFRP lamella of both layouts partially covered the beam width. In particular, the width was set at w_{frp} = 100 mm. In all cases, the CFRP lamella was installed all along the entire length of the beam between the two supports (4000 mm) used for the bending tests. In the case of the BR layout, the CFRP fabric height was set at h_{frp} = 150 mm and the length of each piece of fabric was set at l_{frp} = 100 mm. More details regarding the mechanical properties of the wood, carbon composite, adhesives and bond procedure, can be found in [13–15]. Table 1 summarizes the specimen description.

3. Acoustic attenuation measurement

Before the mechanical tests, the acoustic attenuation of the eight beams was measured. To do that, one AE sensor was placed at the center of six intervals of length [-60, 60] cm. These intervals covered

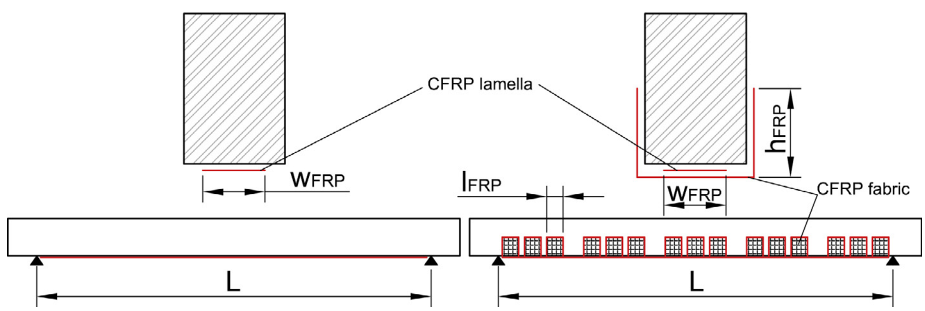

Fig. 1. LR (left) and BR (right) reinforcement layouts.

Table 1
Test program of bending tests. NR denotes the non-reinforced beams, LR the longitudinal reinforced and BR the braided reinforced ones [12–14].

Reinforcement layout	CFRP type	CFRP Thickness (mm)	Fiber Volume Content (%)	Carbon Grammage	Number of specimens	Short name
Non-Reinforced **NR**	–	–	–	–	2	NR
Longitudinal reinforcement **LR**	Lamella	1.2	70	–	3	LR
Braided Reinforcement **BR**	Lamella + Fabric	0.111	–	200	3	BR

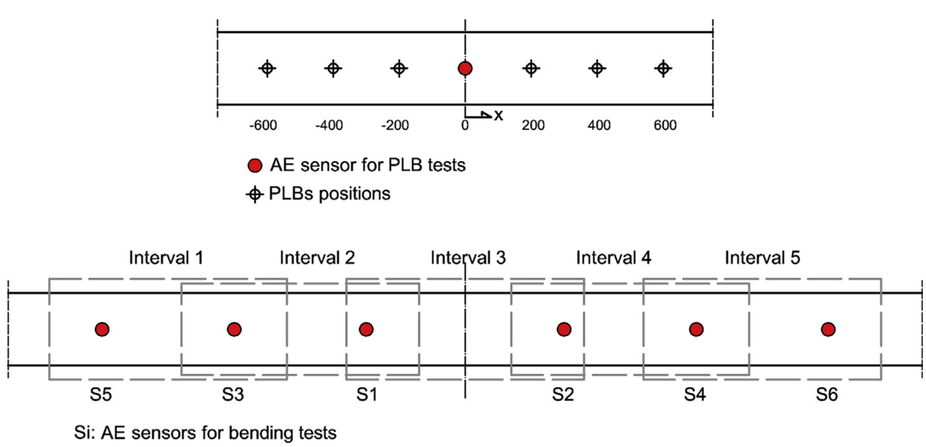

Fig. 2. Attenuation tests procedure.