Post-impact flexural tests on jute/polyester laminates monitored by acoustic emission

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A number of industrial sectors, including automotive, building and leisure, have recently shown interest on natural fibers, as reinforcement for low-weight, environmental-friendly materials. The introduction of natural fiber composites in components for large volume applications requires studies aimed at predicting their in-service behavior, in particular fatigue and impact testing. Some recent investigations have raised concerns on the performance of these materials, especially when subjected to a high number of cycles, as an effect of a long-service life, in harsh environmental conditions [1–3]. The use of nondestructive testing techniques, such as acoustic emission, as monitoring methods during mechanical tests, proved useful in previous studies on mechanical characterization of natural fiber composites [4, 5].

Two approaches are used to predict impact damage on laminated composites reinforced with artificial fibers [6]. The first one is based on estimating the overall size of impact-damaged area and considering stress distribution in the region surrounding the impact point, whilst the second one is aimed at detecting the appearance of the first matrix crack, then the study of the initiation and propagation of delamination.

When dealing with plant-fiber composites, both approaches are viable, at least in principle: however, a number of difficulties can be perceived. First, the measurement of impact-damaged area has been revealed to be particularly difficult, as an effect of the fibers becoming loose and suffering early debonding around the impact point, even at low stress [7]. Second, the study of impact damage initiation is based on the assumption that the laminate shows limited presence of defects prior to impact and that the direction of impact, whether mono- or bi-dimensional, determines the damage propagation mode. However, in biological materials, such as plant fibers, the combined presence of stronger and weaker parts is a natural layout, aimed at obtaining the maximum possible impact resistance. In other words, natural materials work effectively through the limited and controlled occurrence of defects [8]. In plant fiber reinforced composites, because of the larger dimensional variability of fibers and fiber bundles, defects can more easily lead to disruptions in the laminate geometry than in glass fiber reinforced composites [9]. In addition, the capability of detecting defects and especially measuring their level of criticality is crucial to arrive to the possible production of components with plant fibers reinforcement. In this context, the acoustic emission (AE) technique can present some interest, for its capability of providing data from real-time monitoring during post-impact testing [10].

In the present work, plain woven jute fabric/polyester plates (100 mm × 100 mm), manufactured using a resin transfer moulding (RTM) process with a 60% wt. reinforcement content, have been impacted and then subjected to cyclic post-impact three-point bending tests. The impact energy was changed, by varying the mass of the hemispherical drop-weight steel impactor, whilst maintaining the impact velocity constant at 2 m/s (±5%). Impact tests were conducted on a CEAST Fractovis impact tower fitted with an anti-rebound device. The plates were divided into eight categories with five specimens in each category. One group of specimen was not impacted, while the remainder were impacted at energies of 5, 7.5, 10, 12.5, 15 and 20 J, and the last one was impacted to penetration according to ASTM D3763, always using a hemispherical impactor tip diameter 12.7 mm. Depending on the impact energy, the total mass of the impactor varied: 2.53 kg (5 J), 3.89 kg (7.5 J), 4.99 kg (10 J), 6.26 kg (12.5 J), 7.54 kg (15 J), and 9.97 kg (20 J). The penetration energy measured on these laminates was equal to 25 (±2.2) J.

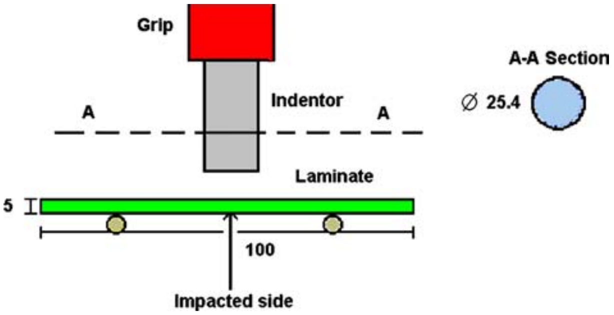

Figure 1 Set-up for the cyclic three point-bending test.

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On the impacted specimens, a 25.4 mm diameter indentor was used to undertake cyclic three-point bend tests, using an Instron 9400 universal testing machine, and following the scheme in Fig. 1. A loading rate of 4 mm/min was used. This condition was the highest loading rate that allowed one to monitor the whole test using acoustic emission technique without any loss of information due to system saturation. The acoustic emission apparatus employed was AMSY4, manufactured by Vallen Systeme GmbH, Icking, Germany. During acoustic emission monitoring, a threshold of 38 dB and an overall amplification of 36 dB with no internal amplification were employed. Four sensors were placed on the samples to form a 70 mm square grid to allow damage localization with a linear time of arrival technique. The sound velocity in the plates was measured via the acoustic emission sensors and was equal to approximately 2600 m/s.

The loading programme for cyclic three-point bend tests was defined by using the average ultimate flexural stress values for laminates impacted at different energies are reported in Fig. 2 and were used to define a loading programme for fatigue testing. After 50 bending cycles at 10% of their average ultimate flexural stress for each impact energy, 50 bending cycles at 20% were performed and so on, until the specimen failed. The typical stress at which failure occurred for most specimens, normalized by the ultimate flexural stress, is shown in Table I. On some specimens, real-time characterization of the progression of impact damage at definite intervals during cyclic three-point bend tests was also carried out, using a thermoelastic stress analysis (TSA) system Deltatherm by Stress Photonics, based on the thermoelastic principle, first expressed by Lord Kelvin [11, 12].

TABLE I Percent of ultimate bending strength at which failure during cyclic tests occurred

Impact energy (J)	Bending strength for failure of impacted samples (%)
5	90
7.5	90
10	90
12.5	90
15	90
20	80

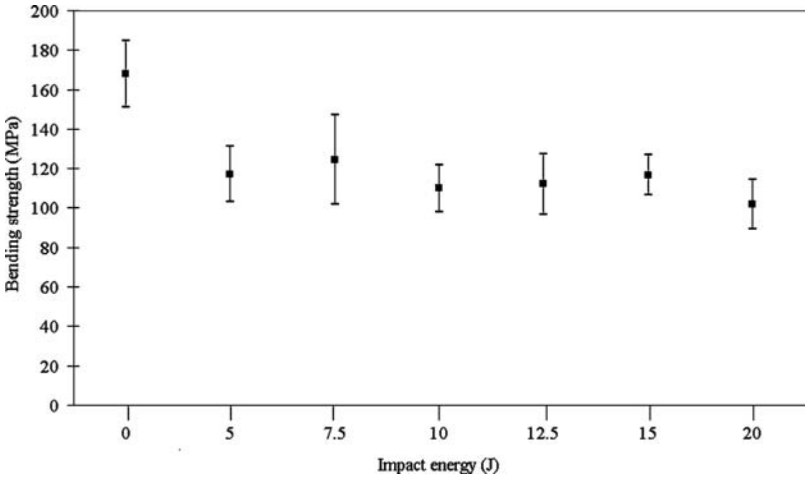

Figure 2 Bending strength of jute/polyester laminates impacted with different energies.

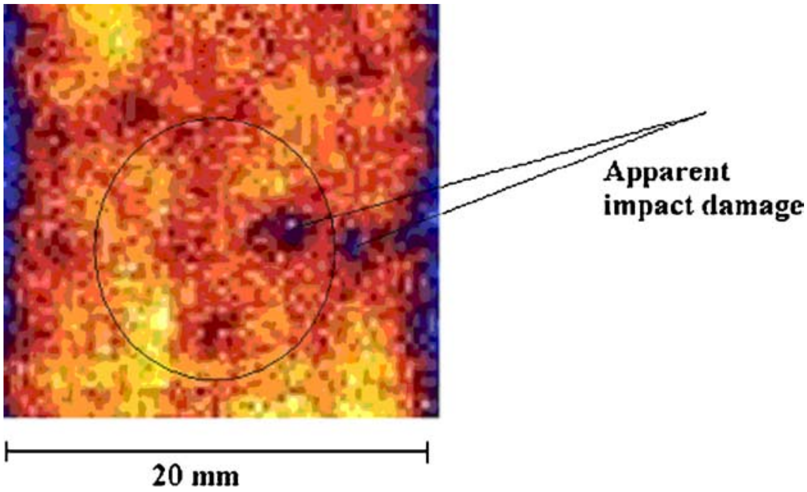

Figure 3 Thermoelastic stress measurement on a jute/polyester laminate impacted at 10 J during fatigue loading at 20% of their bending strength.

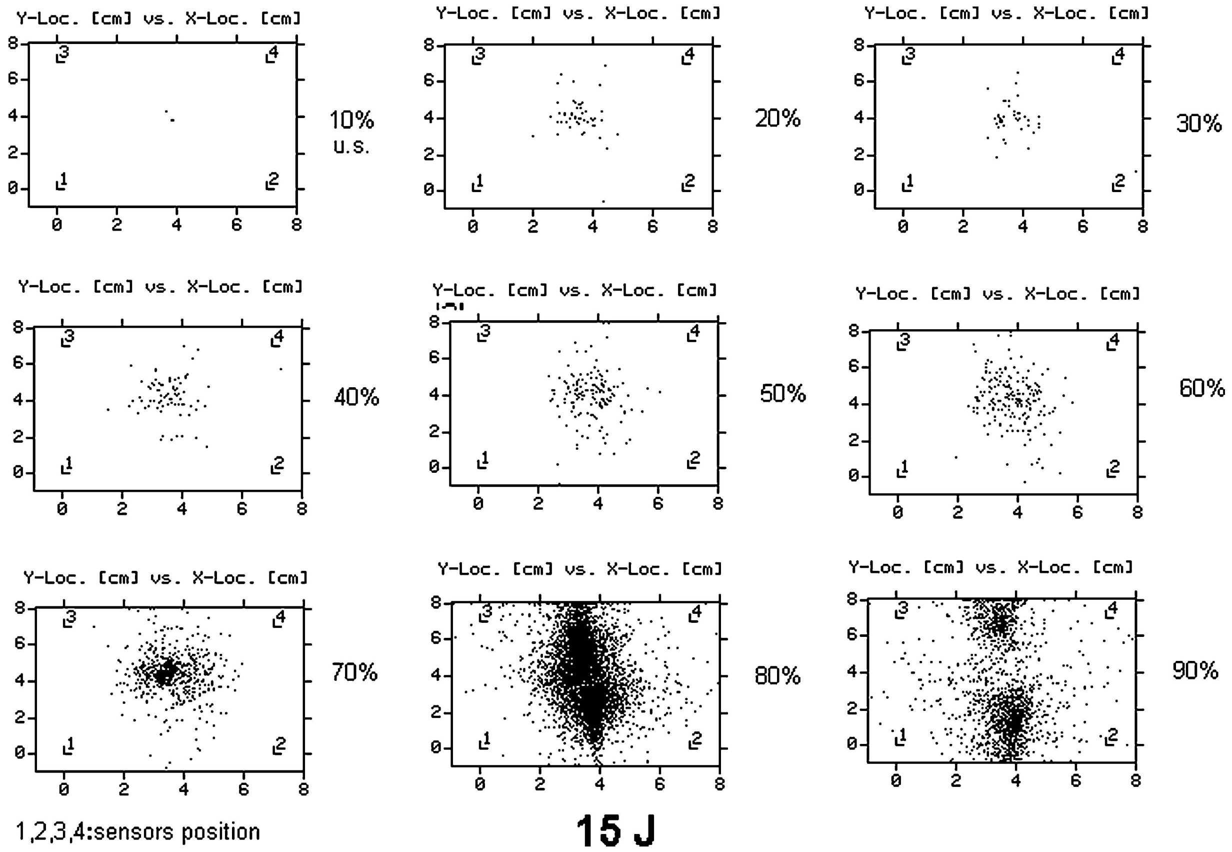

Figure 4 AE events localization plots during bend tests at different stress levels (% of bending strength) on an impacted jute/polyester laminate.

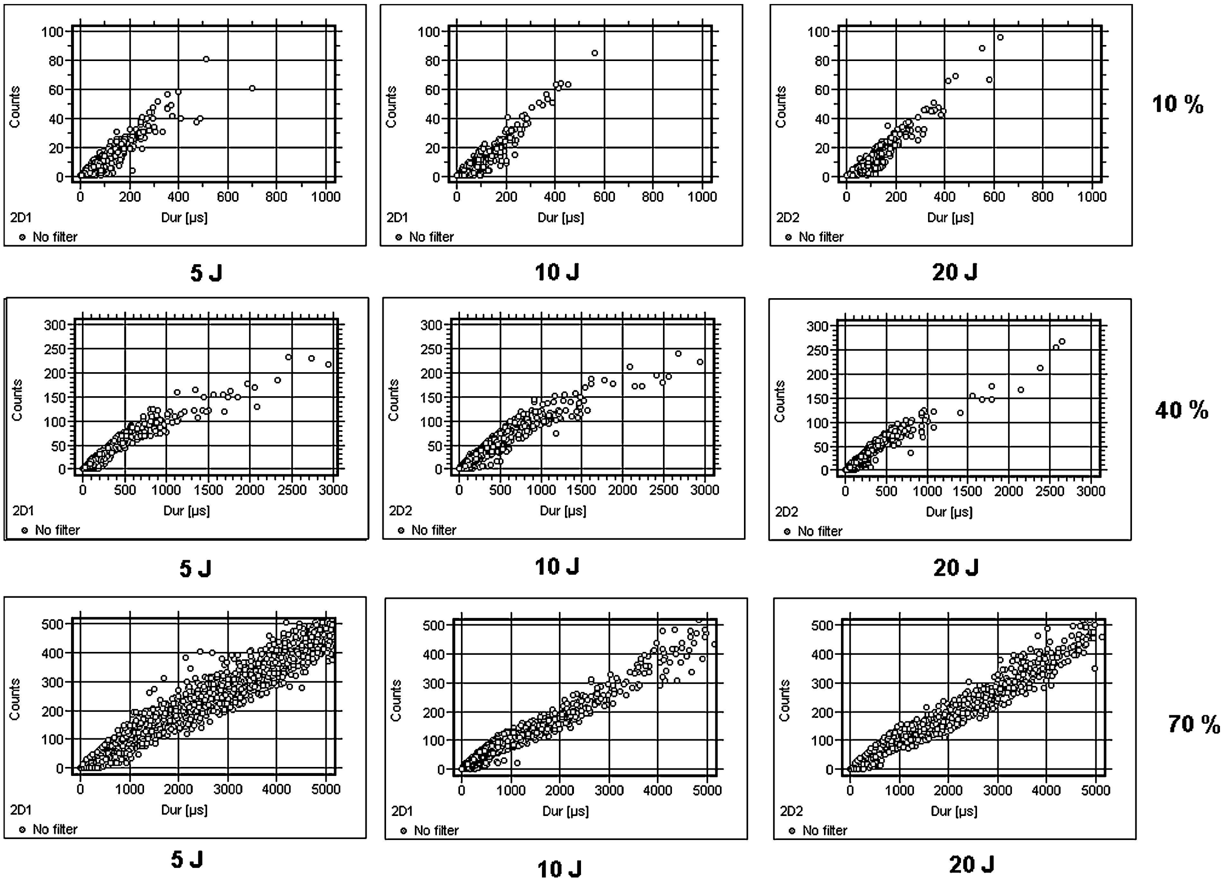

Figure 5 AE counts vs. duration plots at different impact energy and flexural stress levels.

The real time characterization of impact damage progression during three-point bend tests via thermoelastic stress analysis showed that damage in natural fiber reinforced laminates progresses as far as the defects present in the laminate reach a critical energy that allow them to develop. It is also likely, as previously observed [13], that these defects are going to coalesce, triggering the final failure of the laminate. In this process, increasing the impact energy causes more damage, mainly by allowing defects to propagate easily via the higher stress concentration induced by the impact energy. As a result, impact damage typically appears to be concentrated in a few regions aligned along the centre of impact, depending on defects already present in the material (Fig. 3).

Fig. 4 shows the acoustic emission localization plots during flexural tests at different stress levels on a jute/polyester specimen (impact energy=15 J). At low stress level (not exceeding 40% of the bending strength), damage appears prevalent on the impact line, whilst it tends to be more dispersed over the specimen, also for the higher deflection reached, for higher stresses. At stresses approaching failure, as it can be observed for the graph at 80% of the bending strength, the events tend to be redistributed, concentrating in the region where the failure is going to occur.

Previous studies on the residual properties of damaged composite materials have shown that the dimension of the discontinuities D present in the laminate and the residual material strength σ_c are linked to define the critical stress intensity factor K_{Ic}: $K_{Ic} = \sigma_c(\pi D)^m$, where m is a constant [14]. The stress intensity factor K_I of the laminate and the critical stress intensity factor of the laminate containing discontinuities are in turn function of the cumulative counts N_t of the acoustic emission activity as follows: $N_t = f(K_I/K_{Ic})$ [15].

In Fig. 5, an alternative representation of the above relation is represented, as the event counts are plotted against the event duration. Here, the characteristics of the curves,

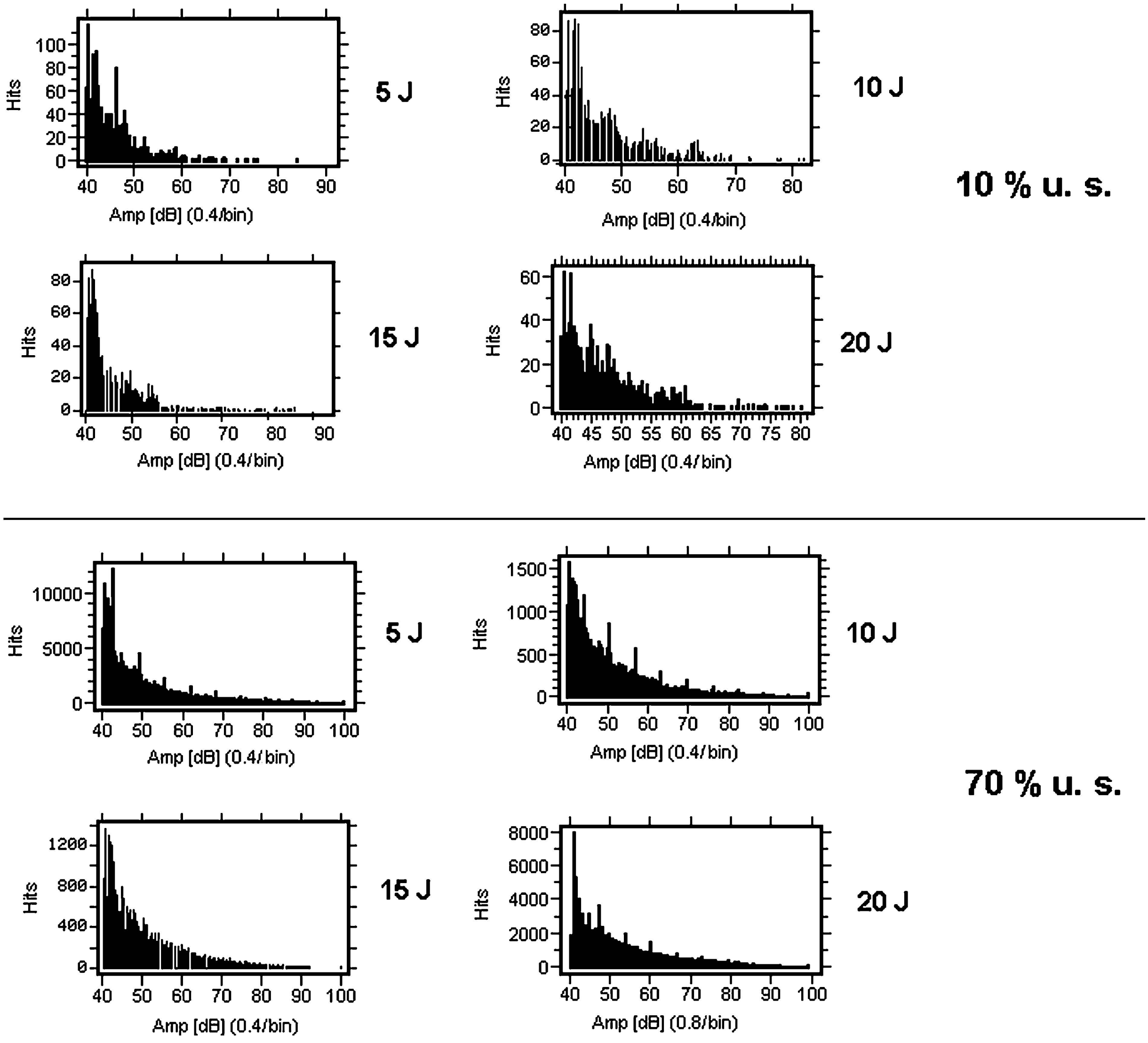

Figure 6 AE amplitude distributions at different impact energy and flexural stress levels.

especially the presence of large duration events, appear to be dependant on the applied bending stress (10, 40, and 70% of the laminate bending strength) rather than on the impact energy applied on the laminate. An explanation of this can be that the flexural damage affects the value of K_{Ic} and then of σ_{c} much more than the previous impact damage. This would justify the inconsistent reduction in bending strength reported in Fig. 2 when increasing impact energy from 5 to 20 J, whilst a substantial decrease is observed passing from intact specimens to those impacted with the lowest energy, 5 J.

This is substantially confirmed from amplitude distribution histograms (Fig. 6), which suggest once again that the influence of flexural damage is particularly significant. Acoustic emission activity, comparing laminates tested at the same flexural stress, but previously impacted with different impact energies, appear to vary randomly, depending on the presence of defects in the single laminate. This suggests that damage is substantial even for impact at the lowest energy, 5 J: increasing the energy does not markedly increase the level of damage obtained for a 5 J impact, until a value sufficient for the penetration of the laminate is reached.

The results obtained suggest that impact damage and residual properties of jute fiber reinforced composites are mainly defects-driven characteristics. This means, as confirmed by the acoustic emission analysis, that there is no real dependence of the damage produced on the energy applied. However, it indicates also that no impact, even at very low energy, can be deemed to result in negligible damage, in that it may allow pre-existing defects to deteriorate.

More in general, this study confirms that there is scope for the investigation of residual properties in natural fibers reinforced composites using monitoring techniques, such as acoustic emission and thermographic techniques. These can be useful not only to detect defective areas, but also to predict the occurrence of failure and characterize it. Future work would require extending the assessment of residual properties using monitoring techniques to hybrid glass fiber-plant fiber reinforced laminates, whose application appear more viable in structural components.

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