Contents lists available at [SciVerse ScienceDirect](http://www.sciencedirect.com)

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Post-impact static and cyclic flexural characterisation of hemp fibre reinforced laminates

Igor Maria De Rosa^{a,1}, Hom Nath Dhakal^b, Carlo Santulli^{a,*}, Fabrizio Sarasini^a, Zhong Yi Zhang^b^a Sapienza – Università di Roma, Department of Chemical Engineering Materials Environment, Via Eudossiana 18, 00184 Rome, Italy^b University of Portsmouth, Mechanical & Design Engineering, Anglesea Building, Anglesea Road, Portsmouth, Hants. PO1 3DJ, UK

ARTICLE INFO

Article history:

Received 14 May 2011

Received in revised form 23 August 2011

Accepted 28 September 2011

Available online xxxx

Keywords:

A. Polymer–matrix composites (PMCs)

B. Impact behaviour

D. Acoustic emission

D. Mechanical testing

Hemp fibres

ABSTRACT

The suitability for use of plant fibre composites after an impact event is still an open issue in literature. In this work, hemp fibre reinforced laminates have been subjected to cyclic flexural tests following falling weight impact at 12, 16 and 20 J. At these energies, still quite far from penetration, which was at about 40 J, damage starts to be increasingly apparent on both laminate surfaces. Post-impact flexural tests have been monitored using acoustic emission. Laminates with a sufficiently strong fibre–matrix interface have been obtained, as revealed from the impact hysteresis cycles and electron microscopy damage characterisation. However, a quite significant decrease of flexural properties and an increase of unrecoverable deformation after cyclical loading were also revealed with growing impact energies, in particular passing from 12 to 16 J.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

In recent years, the application of plant fibre composites to the production of semi-structural components has been widely considered as a possibility to reduce the carbon dioxide footprint of engineering materials [1].

In the specific case of hemp, this fibre has had a considerable history in terms of providing high tensile strength, especially in the use for roping, and in being part of a large productive system [2]. After a few decades of oblivion, due to drug production-related issues, the availability of varieties with low tetrahydrocannabinoids (THCs) content, allowed hemp production to resume [3]. It is therefore necessary in this moment to raise the profile of fibre use towards more engineered components, which may be of interest in a number of fields, including building, automotive and leisure sectors.

In this respect, the assessment of impact properties of hemp fibre reinforced laminates is a central topic [4]. In this regard, fibre architecture has a significant influence on impact properties of these laminates, as outlined in a number of studies [5,6]. Passing from random mats to woven tissues yields some value in terms of improved impact resistance, because of the more controlled fibre orientation: it is worthy to note, however, that tissue

crossovers can also act as possible propagators for delamination damage [5]. This suggests that also in comparison with woven structures, non-woven mats can still retain their full validity. This is especially true when considering that these simple structures can be viewed as an evolution towards more complex, but still cheap and effective non-woven structures, which have also been recently proposed for plant fibres, such as for example spunlaced flax [7]. To evaluate the influence of fibre architecture on impact resistance, falling weight impact tests are particularly significant, in that they supply a much more global indication of impact tolerance across the whole laminate thickness, rather than a bare value of work of fracture, as it is for Charpy or Izod impact tests. On the measurement of falling weight impact properties of plant fibre composites, some studies exist, which are based on the measurement of hysteresis cycles obtained during falling weight impact (IFW). Different approaches are possible and in a sense complementary to each other. In particular, linear stiffness i.e., the slope of the force vs. deflection curve during the test, is related to the rigidity of the laminate, when subjected to an impact loading [8–10]. This parameter can be measured as the interpolated slope of the quasi-elastic part of the impact loading curve, which terminates when the maximum load is reached: linear stiffness values are dependant on laminate thickness and impact velocity. Another possibility is for example analysing the energy absorbed during the impact event, by dividing it in elastic, plastic and damping energy [11,12].

An alternative approach to evaluate impact tolerance of a composite laminate is the assessment of its residual post-impact

* Corresponding author.

E-mail addresses: c.santulli@alice.it, carlo.santulli@uniroma1.it (C. Santulli).¹ Present address: Dept. Materials Science, University of California Los Angeles, E-V 2122, 410 Westwood Plaza, Los Angeles, CA 90095, USA.

Table 1
Falling weight impact testing parameters.

Test specimens	Height (mm)	Total energy absorbed (J)	Impact mass (kg)
Impacted up to penetration	475	39.39 ^a (40.06 J available)	8.6
50% of penetration energy	568	20	3.6
40% of penetration energy	454	16	3.6
30% of penetration energy	340	12	3.6

^a As measured from the hysteresis cycle.

properties [6,13,14]. This can be carried out using real time monitoring techniques, such as acoustic emission. Acoustic emission (AE) is widely used in industry to inspect and monitor the condition of composite materials. AE is a passive technique that monitors a structure while under loading. This technique cannot be easily applied, due to short timeframe involved, directly during impact loading, even when using embedded acoustic emission sensors [15], whose application may not be very practical on plant fibre composites.

The novelty of this work is trying to correlate the analysis of IFW hysteresis cycles with post-impact damage characterisation using acoustic emission monitoring on hemp fibre reinforced

Fig. 1. Photographs of impacted specimens (a 60 mm square region is shown).

Fig. 2. Typical load vs. time curves for the different impact energies.

Fig. 3. Impact force vs. deflection curve for a laminate impacted at 12 J, with linear stiffness (LS) obtained by interpolation, quasi-elastic energy (QEE) area and damage energy (DE) area.

laminates. This is alternative to other methods, which equally proved successful, such as the use of the so called “sentry function”, an energy ratio curve obtained as the ratio between the elastic energy measured in the hysteresis cycle and the AE energy [16]. While the sentry function is able to explain the nature of particular load drops occurring during the impact event, this analysis is capable of supplying a complete picture of impact damage characterisation on plant fibre composites. Recognising, as discussed above, that impact performance of plant fibre composites is a particular weakness suggests the usefulness of methods, such as the present one, aimed at the assessment of this property in order to establish the suitability of these materials to semi-structural applications.

2. Experimental

2.1. Materials

Fourteen layers of needle punched randomly oriented non-woven hemp fibre mat (330 g/m²), supplied by Hemcore Ltd.,

was used as the reinforcement, to a total laminate thickness of 6.7 mm. The matrix material based on unsaturated polyester (NORPOL 444-M888), was mixed with curing catalyst, methyl ethyl ketone peroxide (MEKP) at a concentration of 1.5% by weight, supplied by Reichhold UK Ltd. The fibre content was 50 ± 2 vol%.

2.2. Composite fabrication and preparation of test specimens

A compression moulding technique was used to fabricate the composite laminates of dimensions $230 \times 150 \times 6.7 (\pm 0.2)$ mm. A measured quantity of unsaturated polyester resin mixed with a catalyst (MEKP) for curing was poured on a pre-weighed amount of non-woven hemp fibre mat, which was placed in a mould. The mould was closed and the composite panel was left to cure in a hydraulic press at a temperature of 22 °C and at a pressure of 10 bar for 3 h. After being taken out from the hydraulic press, the panel was left to cure at a temperature of 22 °C for 24 h before being removed from the mould. Subsequently, post curing was carried out at a temperature of 85 °C for 3 h.

Fig. 4. Analysis of falling weight impact hysteresis cycles.

Table 2
Values of linear stiffness in a similar work on hemp fibre laminates [4] and in this work.

Laminate	Manufacturing method	Linear stiffness (N/mm)	Thickness (mm)	Reinforcement volume (%)
Hemp/epoxy [4]	Hand lay-up	341 ± 23	3.4	43
Hemp/polyester	Compression moulding	1468 ± 71	6.7	50

Fig. 5. Flexural strength and modulus of non-impacted and impacted laminates.

2.3. Impact testing

Impact test was performed on an instrumented falling weight impact testing machine Zwick/Roell (IFW 413) using a hemispherical impactor of 20 mm diameter. This diameter was also employed in a classical study, which was the first to attempt the analysis of impact hysteresis cycles on laminates including plant fibres (in that case flax) [17].

After setting the required height and mass to attain the required impact energy up to penetration, impact tests were performed on rectangular plates with dimensions of 230 × 30 × 6.7 mm, to serve

Fig. 6. Flexural loading-unloading cycles for impacted laminates loaded at 40% of the ultimate flexural stress.

Fig. 7. Typical localisation of AE amplitudes during monotonic flexural loading on non-impacted and impacted laminates.

for post-impact flexural testing, and on square plates with dimensions of $80 \times 80 \times 6.7$ mm, to allow the visualisation of impact damage characteristics. Both types of test specimens were removed from the composite laminate using a diamond-cutting wheel. The specimens were firmly fixed at all edges using annular clamps with inner and outer diameters of 50 and 75 mm, respectively. After the first impact of the specimen, a catcher mechanism was activated to prevent a second strike. During the impact in this system, the resistive force exerted by the specimen on the impactor was recorded by a load cell and stored in the computer for display and analysis. From the primary force-time information, the computer software calculated other important parameters, such as energy absorbed, and contact duration, while a motion sensor recorded the data related to impact velocity, which were all used to characterise the impact event.

2.4. Post-impact flexural tests

The impacted laminates were subjected to post-impact four-point bending tests having care to keep the impact point at the centre of the specimens loaded in flexure. The impacted surface was consistently in compression during bending loading of all laminates. Flexural tests were carried out in accordance with ASTM D 6272 (the configuration used was four-point bending). The dimensions of the specimens were selected in order to allocate space for two acoustic sensors at their extremities and also to contain the full area visually damaged by impact. These tests were performed

in an Instron 5584 universal testing machine using a support span length of 140 mm and a cross-head speed of 2.5 mm/min. Five specimens were tested for each impact energy, including non-impacted specimens, which served as reference materials, having the following dimensions: $230 \text{ mm} \times 30 \text{ mm} \times 6.7 (\pm 0.2) \text{ mm}$ ($L \times W \times t$). To assess post-impact flexural properties of the composites, tests were carried out using a step loading procedure, similar to the one adopted in [18]. In particular, the cyclic procedure adopted, aimed at simulating service life, consisted of consecutive steps, each including twenty loading-unloading cycles, performed between 0 and $\sigma_{\max}$. The maximum stress value was increased in the i th step with respect to the $(i-1)$ th step according to this rule: $\sigma_{\max-i} = \sigma_{\max-(i-1)} + 10\% \sigma_f$, until final fracture occurred.

2.5. Acoustic emission

Both monotonic and cyclic flexural tests were monitored by acoustic emission until final fracture occurred, using an AMSY-5 AE system by Vallen Systeme GmbH. The AE acquisition settings used throughout this experimental work were as follows: threshold = 35 dB, RT (Rearm Time) = 0.4 ms, DDT (Duration Discrimination Time) = 0.2 ms, and total gain = 34 dB. The PZT AE sensors used were resonant at 150 kHz. The sensors were placed on the surface of the specimens at both ends to allow linear localisation of detected damage. Vacuum grease was used as a couplant and the sensors were also fastened using adhesive tape.

Fig. 7 (continued)

2.6. SEM characterisation

A scanning electron microscope Hitachi S-2500 was used to investigate the fracture surfaces of composites. Prior to all observations, the specimens were graphite-coated to prevent charging.

3. Results and discussion

Impact testing parameters are summarised in Table 1. First the penetration energy was determined by impacting the samples with an energy that allowed penetration and measuring the absorbed energy from the hysteresis cycle. The falling weight tower being fitted with an anti-rebound device, the hysteresis cycle did refer only to the energy absorbed during the impact event. This was slightly less than 40 J, corresponding to approximately 119 kJ/m². This value obtained by dividing impact energy by the section of the part of the laminate included in the annular clamp and therefore left free to deform under the impact load: this is equal to 50 × 6.7 mm: this is a common practice for normalisation, used for example in [19]. This value is slightly exceeding what expected for hemp mat composites, as measured already by Chen *et al* in [7]. After this, three different energy levels, 30%, 40% and 50% of penetration energy, corresponding respectively to 12, 16 and 20 J, were used, with the idea of being around the value for visual appearance of damage, and not too close to penetration.

It has been reported elsewhere that a significant improvement in impact properties can be obtained using hemp mat to reinforce polyester matrix, resulting in particular in a substantial increment of peak load and total energy absorbed, even by the introduction of a small volume of hemp fibres [4]. However, an open question remains as to evaluating which is the level of degradation which these materials undergo as an effect of growing impact energies. Images reported in Fig. 1 indicate that visible damage on the impacted surface clearly grow between 12 and 16 J, and with lesser evidence, between 16 and 20 J, and that even the highest level of impact applied, 20 J, is not sufficient to produce spalling i.e., loss of material at rear, which is a typical occurrence on plant fibre composites when subjected to high strains [20]. Spalling has been observed in other studies on hemp mat reinforced laminates for energies quite close to the penetration energy [5].

What observed above does suggest that the evolution of damage with impact energy in these materials appears to be gradual, a small increase of impact energy resulting obviously in further degradation, but not in an abrupt change of fragmentation characteristics. This involves the formation at rear of an elongated crack, corresponding approximately to the dimension of the impactor, which then propagates along different directions, being diverted quite unpredictably by the random orientation of reinforcement fibres.

The study of hysteresis impact cycles has been performed, starting from load vs. time curves, as those reported in Fig. 2. From

Fig. 8. Typical localisation of AE durations during monotonic flexural loading on non-impacted and impacted laminates.

these and from double integration of the acceleration measurements, load vs. deflection curves have been obtained, such as the one depicted in Fig. 3.

Variables obtained from impact hysteresis cycles are reported in Fig. 4. Linear stiffness values are comparably high, with respect to data measured on hemp mat laminates with similar reinforcement volume in another work, even taking into account the different thickness of the laminates. The compared values are reported in Table 2 (characteristics from this study are in bold). In addition, linear stiffness values do not substantially change with growing impact energies in the interval considered in this study. This suggests that the material does not undergo a substantial reduction in stiffness between the lowest and the highest impact energy applied. Also, the higher value of peak load for 20 J impacted samples appears to indicate that more energy is elastically absorbed by the laminate, therefore that it still shows some damage tolerance at this level of energy.

In practice, damage energy (DE), defined as the energy absorbed after the impacted laminate has passed its peak load and therefore starts showing irreversible damage, does remain appreciably constant within a few percents for all impact energies applied to the laminates. This implies that no substantial variation in the mode of damage absorption can be observed between the different impact energies: this is also reflected in the aforementioned absence of spalling.

The loss of properties at the maximum impact energy applied, which corresponds, as stated above, to approximately 50% of the

penetration energy, is in the order of 20% in terms of modulus and in the order of 23% in terms of strength, as reported in Fig. 5. It may be suggested that impact damage does produce a significant number of fibre fracture events, in addition to delamination. In presence of a sufficiently sound interface, as it is likely to be the case here for the manufacturing method employed, the effect on stiffness is lower.

In post-impact cyclic flexural tests, every subsequent loading-unloading cycle results in some unrecoverable deformation, which had been observed already in a study on plant fibre composites, where it was more pronounced on kenaf fibre reinforced laminates than on jute fibre reinforced ones [21]. Here, unrecoverable deformation becomes more apparent for laminates impacted with higher energies: for comparison, tests performed on impacted laminates loaded at 40% of the ultimate flexural stress are shown in Fig. 6, in that this is the maximum level of stress which does not result in the failure of any tested laminate.

It needs also to be noticed that the degradation of flexural properties in relative terms is still considerably higher in plant fibre composites than in glass/plant fibre hybrids, such as e.g., the one studied in [14], which included jute fibres. There are no studies to our knowledge on post-impact residual mechanical properties of hemp/glass fibre hybrids to allow for comparison, although some work on these hybrids have been recently produced [22].

Acoustic emission (AE) analysis has been performed following both monotonic and cyclical tests in real time. In previous studies concerned with measurement of post-impact properties of plant

Fig. 8 (continued)

fibre composites and hybrids [14,15,23], analysis of AE data concentrated on different features, which can be divided in two general categories: they may be based on AE events localisation, which allows measuring the damaged area with some accuracy, or concentrate on time history during post-impact testing to discern changes of laminates behaviour during testing. This would allow for example establishing stress limits for use indicated by the “knee” of AE cumulative counts curve, or revealing that some mode of damage become predominant e.g., fibre failure, often linked to the detection of higher amplitude events, or delamination, which is likely to be indicated by high duration events.

Here, the analysis has been concentrated on the linear localisation of AE events during monotonic tests, in particular focusing on amplitudes (Fig. 7) and durations (Fig. 8). In contrast, during cyclical loading tests, time histories have been analysed, showing the evolution of AE activity with loading, focusing on amplitudes (Fig. 9), durations (Fig. 10) and linear localisation (Fig. 11). To try to clarify how amplitudes change in relation to durations with growing impact energies, the two variables are plotted against each other in Fig. 12.

In linear localisation of events during monotonic tests (Figs. 7 and 8), it can be observed that in non-impacted specimens the acoustic emission activity is clearly distributed in two regions not far from the middle line of the laminates. This may suggest that both damage due to fibre failure, represented by higher amplitudes (Fig. 7), and damage due to delamination, represented by higher durations (Fig. 8) tend gradually to concentrate in an area centred

on the impact point with growing impact energy. The limited number of AE events shown in the central part of the non-impacted laminates is likely to indicate that impact has a considerable effect in concentrating damage. Since AE is sensitive to damage development, this may imply that flexural loading does not lead to a substantial aggravation of damage in that area.

It needs also to be noted from AE localisation plots that the extension of the damaged area due to impact is likely to exceed the dimension of the fixture used for impact testing (50 mm internal diameter), although some more damage is obviously produced during bending, particularly under the loading pins. This suggests a non-negligible influence of the boundary conditions on the test, an occurrence noticed already in [18].

During post-impact flexural loading, all the laminates fail during the very first cycles performed at a higher level of stress, this being equal in most cases to 60% of the ultimate flexural stress. The detail of the levels of failure for all tested laminates is reported in Table 3.

It is significant to observe in Fig. 9 that high amplitude events, which are usually related with fibre failure [24], are more frequent at higher level of stresses and during the first cycles of each loading step. In general, during final stage of loading of 16 J and 20 J impacted laminates, high amplitude events are less present than in the case of 12 J laminates, which suggests that the higher impact energies produced a more severe damage.

It has been also suggested, always following [18], that high duration events which are not associated with a high amplitude,

Fig. 9. Typical AE amplitude history on post-impact cyclical flexural loading.

but with low or intermediate ones, are usually associated with delamination and debonding. More specifically, this happens as an effect of macro-cracks due to flexural loading, as proposed in [25]. In a previous work concerning cyclic loading of impacted E-glass/jute hybrid laminates, a long-duration event was defined as exceeding 1 ms [14]: in this case, the much higher damping of plant fibre laminates, as observed e.g., in [26], suggests that a suitable limit for that purpose would be much lower, in the order of

$10^2 \mu\text{s}$. Adopting this criterion, as highlighted in Fig. 10, the evolution of AE durations during loading cycles shows that the presence of high duration events only slightly grows with impact energy and appears to be more affected by the level of flexural load applied. Also the persistence of events with the same duration at fixed intervals in time, as it is more clearly observable for the 12 J laminate (one case is shown by an arrow), reflects the presence of a delamination opening and closing during cyclical loading, an event

Fig. 10. Typical AE duration history on post-impact cyclical flexural loading.

which has been observed already on polymer composites using acoustic emission [27]. It is likely that for higher impact energies, the growing amount of damage i.e., the larger number of AE sources present in the region of the laminate surrounding the impact point would increase the duration of the events over time:

this may also indicate that the geometrical dimensions of the delamination are growing.

The occurrence of AE events produced by crack closure is further confirmed in Fig. 11, where at a definite location events are detected above a given percent of ultimate strength, which

Fig. 11. Typical AE localisation history on post-impact cyclical flexural loading.

suggests that a delamination is gradually opening. The linear locations at which this happens (as highlighted by arrows) are at no more than 20 mm from the impact centre (approximately assumed at $x\text{-loc} = 11$ cm).

The increase of impact energy is likely to produce also some change in the mode of damage propagation in the laminates. This

is reflected in the AE amplitude vs. duration diagrams (Fig. 12), where the distribution of the events gradually changes towards higher amplitudes and lower durations with growing impact energy. This may suggest that substantial delamination already took place during impact and that more serious cracks are opening in the material as an effect of cyclical loading.

Fig. 12. AE amplitude vs. duration distribution in the whole of cyclical flexural loading.

Table 3

Level of flexural stress for laminate failure during post-impact cyclical loading.

Impact energy (J)	Failed at 50% u.s.	Failed at 60% u.s.	Failed at 70% u.s.
12	1	2	2
16	–	3	2
20	1	4	–

This is confirmed by post-impact flexural failure patterns (Fig. 13). These show that the influence of impact over fracture propagation is increasing with growing impact energy: in particular, more cracks are spreading on the rear surface in correspondence with the impact point at the higher impact energies. Going into more depth in the investigation of failure patterns, as reproduced by SEM micrographs, it is clear that flexure produces a limited amount of mode I fibre fractures to failure (Fig. 14), which

Fig. 13. Photographs of impacted samples after their failure by flexural loading.

suggests that leading events are debonding and pull-out: this is expected when using untreated hemp fibres as the reinforcement. This is partially contrasted by the diffuse fibrillation of hemp fibres, which has been reported as a factor for obtaining a stronger interface in hemp fibre composites via the creation of a larger contact surface between fibre and matrix [28]. On the other side, it needs to be noted that fibrillation also reduces the resistant section of the fibre, hence having a detrimental effect on impact damage tolerance.

4. Conclusions

The fabrication of hemp-polyester laminates with a compression moulding procedure yielded composites of considerably improved quality with respect to similar laminates produced by hand lay-up, with a volume of reinforcement approaching the maximum which is technologically possible for an effective impregnation. This is demonstrated by the study of falling weight impact hysteresis curves.

Despite this, still a quite significant decrease of flexural properties after impact loading was revealed. This is in the order of 20% in terms of modulus and in the order of 35% in terms of strength at the maximum impact energy applied, which corresponded approximately to 50% of the penetration energy. In particular, also small differences in impact energy, such as those applied here, representing 10% of penetration energy, may produce a significant degradation of material properties. This is confirmed by acoustic emission data and post-impact flexural damage modes, which show that crack propagation quite abruptly involves more complex patterns passing from 30 to 40% of the penetration energy i.e., from 12 to 16 J, which are further developed at 20 J.

The final consideration is on the difficulty of predicting the evolution of impact damage with growing energy on hemp fibre laminates: this suggests that a significant effort needs to be put in further studies into the determination of an energy limit for the possible continued use or possible repair of these materials after the impact event.

Fig. 14. (a) Flexural fracture surfaces of non-impacted sample. (b) Flexural fracture surfaces of sample impacted at 20 J.

References

- [1] Wambua P, Ivens J, Verpoest I. Natural fibres: can they replace glass in fibre reinforced plastics? *Compos Sci Technol* 2003;63(9):1259–64.
- [2] Hill C, Hughes M. Natural fibre reinforced composites: opportunities and challenges. *J Biobased Mater Bioenergy* 2010;4(2):148–58.
- [3] Lachenmeier DW, Kroener L, Musshoff F, Madea B. Determination of cannabinoids in hemp food products by use of headspace solid-phase microextraction and gas chromatography-mass spectrometry. *Anal Bioanal Chem* 2004;378(1):183–9.
- [4] Dhakal HN, Zhang ZY, Richardson MOW, Errajhi OAZ. The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites. *Compos Struct* 2007;81(4):559–67.
- [5] Santulli C, Caruso AP. Effect of fibre architecture on the falling weight impact properties of hemp/epoxy composites. *J Biobased Mater Bioenergy* 2009;3(3):291–7.
- [6] Yuanjian T, Isaac DH. Impact and fatigue behaviour of hemp fibre composites. *Compos Sci Technol* 2007;67(6):3300–7.
- [7] Chen Y, Müller DH, Nießen K, Müssig J. Spunlaced flax/polypropylene nonwoven as auto interior material: mechanical performance. *J Ind Text* 2008;38(1):69–86.
- [8] Scarponi C, Pizzinelli CS, Sanchez-Saez S, Barbero E. Impact load behaviour of resin transfer moulding (RTM) hemp fibre composite laminates. *J Biobased Mater Bioenergy* 2009;3(3):298–310.
- [9] Alvarez V, Vázquez A, Bernal C. Fracture behavior of sisal fiber–reinforced starch-based composites. *Polym Compos* 2005;26(3):316–23.
- [10] Santulli C, Janssen M, Jeronimidis G. Partial replacement of E-glass fibers with flax fibers in composites and effect on falling weight impact performance. *J Mater Sci* 2005;40(13):3581–5.
- [11] Santulli C. Falling weight impact damage characterisation on flax/epoxy laminates. *Int J Mater Prod Technol* 2009;36(1–4):221–8.
- [12] Santulli C, Jeronimidis G, De Rosa IM, Sarasini F. Mechanical and falling weight impact properties of unidirectional phormium fibre/epoxy laminates. *Express Polym Lett* 2009;3(10):650–6.
- [13] De Rosa IM, Santulli C, Sarasini F, Valente M. Post-impact damage characterization of hybrid configurations of jute/glass polyester laminates using acoustic emission and IR thermography. *Compos Sci Technol* 2009;69(7–8):1142–50.
- [14] De Rosa IM, Santulli C, Sarasini F, Valente M. Effect of loading-unloading cycles on impact-damaged jute/glass hybrid laminates. *Polym Compos* 2009;30(12):1879–87.
- [15] De Rosa IM, Sarasini F. Use of PVDF as acoustic emission sensor for in situ monitoring of mechanical behaviour of glass/epoxy laminates. *Polym Test* 2010;29(6):749–58.
- [16] Minak G, Morelli P, Zucchelli A. Fatigue residual strength of laminated graphite–epoxy composite circular plates damaged by transversal loads. *Compos Sci Technol* 2009;69(9):1358–63.
- [17] Benevolenski OI, Karger-Kocsis J, Mieck KP, Reubmann T. Instrumented perforation impact response of polypropylene composites with hybrid reinforcement flax/glass and flax/cellulose fibers. *J Thermoplast Compos Mater* 2000;13(6):481–96.
- [18] Santulli C. Post-impact flexural tests on jute/polyester laminates monitored by acoustic emission. *J Mater Sci* 2006;41(4):1255–60.
- [19] Dear JP, Brown SA. Impact damage processes in reinforced polymeric materials. *Compos Part A Appl Sci Manuf* 2003;34(5):411–20.
- [20] Wambua P, Vangrimde B, Lomov S, Verpoest I. The response of natural fibre composite to ballistic impact by fragment simulating projectiles. *Compos Struct* 2007;77(2):232–40.

- [21] Akil Md H, De Rosa IM, Santulli C, Sarasini F. Flexural behavior of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission. *Mater Sci Eng A – Struct* 2010;527(12):2942–50.
- [22] Panthapulakkal S, Sain M. Injection-molded short hemp fiber/glass fiber-reinforced polypropylene hybrid composites. Mechanical, water absorption and thermal properties. *J Appl Polym Sci* 2007;103(4):2432–41.
- [23] Minak G, Ghelli D. Influence of diameter and boundary conditions on low velocity impact response of CFRP circular laminated plates. *Compos Part B Eng* 2009;39:962–72.
- [24] Huguet S, Godin N, Gaertner R, Salmon L, Villard D. Use of acoustic emission to identify damage modes in glass fibre reinforced polyester. *Compos Sci Technol* 2002;62(10–11):1433–44.
- [25] Woo SC, Kim DJ, Choi NS. Acoustic emission characteristics of single-edge-notched glass fiber/aluminum hybrid laminates. *Key Eng Mat* 2006;306–308(1–2):19–24.
- [26] Di Landro L, Lorenzi W. Mechanical properties and dynamic mechanical analysis of thermoplastic-natural fiber/glass reinforced composites. *Macromol Symp* 2009;286(1):145–55.
- [27] Prasse T, Michel F, Mook G, Schulte K, Bauhof W. A comparative investigation of electrical resistance and acoustic emission during cyclic loading of CFRP laminates. *Compos Sci Technol* 2001;61(6):831–5.
- [28] Mutjé P, Gironès J, López A, Llop MF, Vilaseca F. Hemp strands: PP composites by injection molding: effect of low cost physico-chemical treatments. *J Reinf Plast Compos* 2006;25(3):313–27.