EXPERIMENTAL CHARACTERISATION OF THE IMPACT RESISTANCE OF FLAX FIBRE REINFORCED COMPOSITE LAMINATES

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Abstract

Natural fibres such as flax are a promising replacement for synthetic fibres in polymer composites and achieve comparable specific properties due to their low density. Recent developments in the production of technical flax fabrics allow the use of sustainable natural fibres in the manufacture of structural composite parts. While biocomposites have been demonstrated to satisfy design and structural integrity requirements, it is suspected that one of the limitations of natural fibre reinforced composites is their impact resistance. In this paper, the impact behaviour of biocomposites made of commingled flax and polypropylene fibres is investigated. Composite plates were manufactured using compression moulding process. Processing parameters such as temperature, pressure and time were optimized to improve the mechanical properties of composite plates. Impact tests were conducted using an instrumented drop tower at multiple energies. Qualitative assessment of the impact damage and the energy absorbed were used to identify the different modes of damage and to identify the critical energy for complete penetration. The experimental study was supplemented with impact modelling of the biocomposite laminates using a commercial finite element software. There is good correlation between the impact response and the FE model.

1. Introduction

Composite materials with glass and carbon fibre reinforcements have found extensive application in the transportation sector. In the rail industry, composite materials have been used for bogies, carbodies and for lids in freight wagons. Natural fibres have been studied as potential replacement to traditional composite reinforcements, specifically E-glass due to their low density, high specific properties, relative abundance, low cost of raw material, and positive environmental profile [1]. Extensive review articles have been published by Bledzki and Gassan [2] and Faruk et al. [3] on polymer composites reinforced with natural fibers up to 1999 and for the period 2000 to 2010, respectively. Bast fibres such as flax, hemp, kenaf, jute and ramie are used in applications with structural requirements due to their high cellulose content and microfibrils aligned in the fibre direction [4], that provide them excellent specific stiffness and strength. In particular, composites made of flax fibres (Linum usitatissimum) with thermoplastic, thermoset, and biodegradable matrices have exhibited good mechanical properties comparable to those of glass fibres [5]. Pil et al. [6] pointed that due to the lower density of flax, the specific longitudinal stiffness in tension is higher than that of glass fibres and in the case of plate bending, flax composites outperform steel and aluminium, and the specific bending stiffness is only 15–25% lower than that of carbon fibre composites. Shah et al. [1] proved the potential of flax as structural replacement to E-glass fabric with a case study of 3.5 m composite rotor blades manufactured from flax/polyester and E-glass/polyester composite.

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Bensadoun et al. [7] reported that the use of natural fibres for high performance applications has been limited by a lack of data on durability properties of these composites for loading conditions such as fatigue and impact. In transportation sector, impact loading can occur during the service life of freight wagons due to dropped tools, collisions with loading and unloading fixtures, ballast or cargo. Internal damage produced by impact loads, such as delaminations and back-face splitting can severely reduce the residual mechanical properties of the composite [8]. Many researchers have studied the impact resistance of natural fibre reinforced composites. Bos et al. [9] reported that the impact strength of short flax fibre compounds measured from unnotched Charpy tests were much lower than that of glass fibre. Bax and Mussig [10] compared the tensile and impact properties of PLA (polylactic acid) reinforced with Cordenka rayon fibres and flax fibres. Dhakal et al. [11] studied the low-velocity impact response of non-woven hemp fibre-reinforced polyester composites. The static and low velocity impact behaviour of non-woven flax fibre reinforced polypropylene was investigated by Hoang and Touchard [12]. Benevolenski et al. [13] investigated the effect of fibre hybridization on the impact resistance of flax mat reinforced polypropylene using both Charpy and falling weight impact tests. However, the focus of these articles is restricted to non-woven mat and there is limited literature on the drop mass impact tests on composite laminates with long continuous natural fibres. Scarponi et al. [8] studied the damage resistance and post-impact damage tolerance of plain weave hemp fabric reinforced bio-based epoxy composites subjected to low-velocity impact. Huber et al. [14] studied the puncture impact resistance of All Cellulose Composites (ACC) based on Cordenka fibres. Dhakal et al. [15] used an instrumented drop tower at low energies to characterise the damage performance of jute fibre reinforced unsaturated polyester composite for non-penetrating impacts. Santulli [16] developed a method to characterise the impact damage in flax-epoxy composites using hysteresis cycles. Bensadoun et al. [7] compared the impact resistance of flax based composites with thermoset and thermoplastic matrix and different fibre architectures and found that the thermoplastic composite outperformed the thermoset.

The aim of this work is to study the impact resistance of polypropylene thermoplastic composites reinforced with flax fibre fabrics. The impact resistance is characterised via a drop weight impact test as it represents a more realistic loading case than Izod or Charpy tests. The progression of damage in the composite was observed using high speed photography. The experimental results are compared with a finite element model created in LS-Dyna.

2. Materials and methods

2.1. Manufacturing of composite specimen

Flax/thermoplastic fabric supplied by Composites Evolution as Biotex Flax/PP was selected for the project. Various investigations of flax fiber/polypropylene composites have been conducted [17-19]. The woven Flax/PP fabrics are commingled textiles with surface density of 400g/m2 made from twistless natural flax fibre and polypropylene (PP) fibre in a balanced 2x2 Twill architecture. The fabrics are moulded into rigid fibre-reinforced thermoplastic composite parts by simply applying heat and pressure to melt the thermoplastic, wet-out the flax and consolidate. The composites were fabricated using a compression moulding method. The fibres were cut to 300 mm x 300 mm and were placed between the two rigid steel plates in a hydraulic press. A square frame was used as a spacer in between the steel plates to control the thickness of the composite plate. For our study, 10 plies of the Flax/PP fabric was used for final consolidated thickness of 3.1 mm± 0.05mm. Teflon sheets were used on both the steel plates as a mould release surface. The advantage of this thermo-press process is that it was possible to obtain good surface quality on both sides of the composite as well as repeatable thickness of the laminates. A thermocouple was used to measure the temperature at the middle of the composite plate during the consolidation.

The thermo-press system used for the fabrication of the plates is shown in Figure 1. The composite plates were manufactured using the same experimental parameters; the press was preheated to

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temperature of 210 °C which corresponded to the measured temperature in the middle of the composite to 190 °C. The temperature used was about 20 °C higher than the melting temperature of the polymer measured using DSC test. A constant pressure of 20 bar was applied for three minutes before the heating element was turned off. The composite was allowed to cool down gradually under the pressure applied by the thermopress until the temperature dropped to 100 degrees when the composite was demoulded.

Figure 1. Manufacturing of the Flax-PP composite using thermopress

2.2. Experimental setup for low velocity impact testing

Low velocity impact testing is typically accomplished using a drop tower with velocities below 10m/s. Impact testing at this low velocity allows the whole structure to respond and there will be more elastic absorption. Applications for flax composites in the transport industry are expected to mainly be in this velocity regime. The drop tower Instron CEAST 9340 setup, shown in Figure 2 consists of an instrumented impactor that is secured to a carriage that falls along guideposts and collides with the plate. The weight of the impactor was 3.1 kg with a hemispherical impactor of diameter 20 mm. The square composite target plate of 100 mm is clamped with a circular ring of internal diameter 40 mm. The drop height is varied from 0.2 m to 0.3, 0.35, 0.4, 0.5 and 0.7 m to give a range of impact energies while the mass of the impactor is kept constant. The initial velocities varied from 1.98 m/s to 3.71 m/s corresponding to kinetic energy of the impactor of 6 J to 21 J. The highest energies led to the complete perforation of the plates, which allowed assessing the absorbed energy behaviour of flax composites. At least 2 specimens were tested at each condition, due to limited material. A Phantom V711 (Vision Research) high speed camera was used for slow motion observation of the bottom surface of the composite plate during the impact event. The images were acquired at a frame rate of 13000 fps and resolution of 600 x 800 for the entire field of view. A pair of photoelectronic switches acted as the trigger for the camera and were also used to measure the initial velocity and rebound velocity of the impactor.

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Figure 2. Drop tower setup used for low velocity impact testing

3. Results of drop tower impact testing

Figure 3 shows the front and rear surface of the flax composite plate after impact at various energies from 6 J to 21 J. It can be observed that the amount of damage sustained by the composite increases with increasing energy and there is complete penetration of the composite for initial energy of 15 J and 21 J. At lower energies, there is matrix cracking around the point of impact as revealed by the change in colour. The fibre fracture forms a crack that is aligned with the fibre direction of 0 and 90°. However, the composite material does not behave as a purely brittle material and some plastic deformation is noticeable. The impact tested samples with penetration exhibited a typical pyramidal-type failure of woven fabric composites, despite the circular boundary condition.

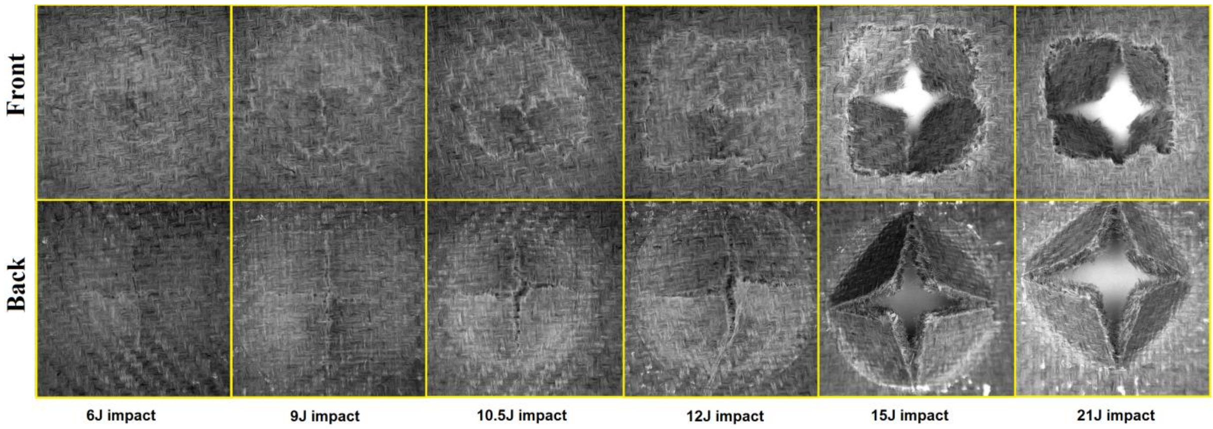

Figure 3. Front and back surface of Flax-Polypropylene composite after impact

The assessment of the impact damage in the composite is usually accomplished in terms of the impact energy (Ei) and absorbed energy (Ea) [8]. Impact energy is the kinetic energy of the impactor right before contact with the composite plate, whereas absorbed energy is the energy dissipated by the system through the several mechanisms occurring during impact, like plastic deformation, friction, and failure of the material. Composite plates such as the flax fibre reinforced polypropylene undergo failure mechanisms such as matrix cracking, debonding, pull-out and fibre breakage. In the cases where there is no full penetration, such as in the lower energy impacts, the impactor rebounds with some kinetic energy (Er). The absorbed energy is the difference between the kinetic energy before and

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after the impact. An energy ratio is defined as the ratio of this difference (Ei-Er) to the initial impact energy (Ei). Figure 4 shows the energy ratio plotted against the kinetic energy of the impactor. There is no rebound when there is complete penetration and all the energy of the impactor is dissipated. This results in an energy ratio of 1. It can be seen that the energy ratio approaches 1 at the impact energy of 12 J and it can be surmised that this represents the penetration limit for the flax-polypropylene composite.

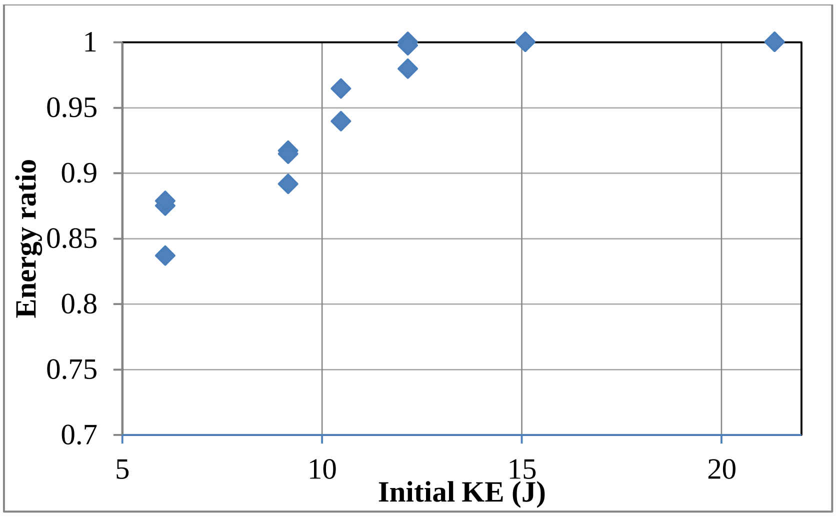

Figure 4. Energy ratio vs. Initial Kinetic energy of the impactor

The progression of the impact damage observed by the images captured by the high speed camera are shown for an impact of 12J in Figure 5. It can be seen that at time of 1.5 ms, there is localized damage at the point of impact. Radial cracks begin to propagate along the two fibre directions. The polypropylene matrix is a compliant matrix and exhibit extensive deformation as observed by the bulged surface and fibre pull-out. In this case there is no penetration of the plate and the impactor rebounds after reaching maximum displacement at 7.7 ms.

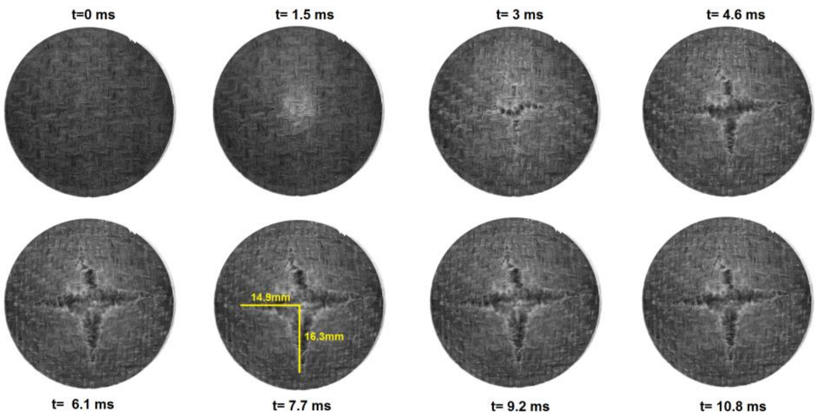

Figure 5. Progression of impact damage for composite plate impacted at 12 J

4. Finite element modelling of impact damage in flax composite

The response of the composite plate to impact loading was examined using the Finite element method. Commercially available Finite Element software LS-Dyna was used for the numerical modelling. LS-Dyna is the desired FE code for the low velocity impact analysis of composite structures as it is a general-purpose finite element code for analysis of large deformation dynamic response of structures based on explicit time integration [20]. The numerical modelling of FRP composites is possible in different scales: micro, meso and macro scale [21]. The Representative Element Volume (REV)

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approach allows the modelling of the interaction between the fibre and the matrix and is used in modelling at the microscopic and mesoscopic scale. Sliseris et al. [22] used the microstructure of the short flax fibre and flax fabric in their model and demonstrated that the simulation was able to capture the main damage mechanisms of the composite. However, the requirements related to industrial problems have necessitated the choice of a macroscopic approach.

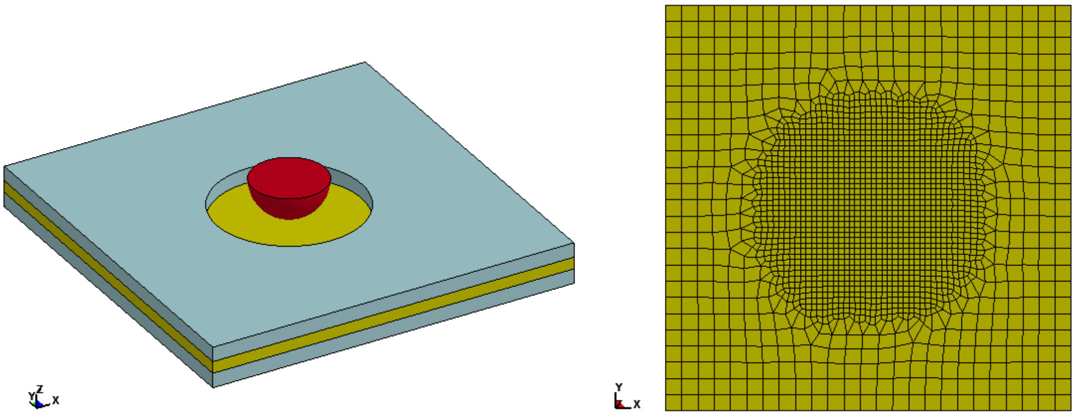

Figure 6. Finite element model of the low velocity impact test of composite plate

The FE model developed in LS-Prepost for the simulation of the impact of composite plate is shown in Figure 6. The dimensions of the square plates were 100 mm x 100 mm. The 3.1 mm thick Flax-PP composite with 10 layers of balanced 2x2 Twill fabric were modelled as a Thick shell which enables a simplified method for defining composite layups. The Thick shell elements (Type 3) are shell-like solid elements that uses assumed strain 2x2 quadrature in the shell plane and co-rotational formulations. The constitutive law is fully 3D based and the thickness change come naturally from corresponding degrees of freedom. The hemispherical impactor was modelled with 6355 tetrahedral elements, while the Flax composite was represented by 3974 thick shell elements. The Thick Shell formulation allows defining each layer of the composite as an integration point and the fibre orientation in each ply was defined using an ICOMP function. The mesh on the composite plate was refined to have an adequately fine enough mesh in the central region of interest, that is, areas where there are high stress gradients or large deformations. This element size was the best compromise between calculation time and accuracy of the local material fracture representation. The composite plate has a clamped boundary condition along a 40 mm diameter hole of the support fixture similar to the one used in the experiment.

An initial velocity is defined to the nodes in the hemispherical impactor. The density of the steel impactor is modified to obtain the same kinetic energy as in the experiment. Two initial velocities, 1.98 m/s and 2.8 m/s were simulated that correspond to the 6 J and 12 J impact. To reduce the runtime, all simulations commenced with the impactor situated just 0.5 mm above the plate. An Automatic Surface to Surface contact was defined between the impactor and the composite plates. Modelling at the macroscopic scale considers the layer as homogeneous and therefore the phenomena occurring within the layer must be defined implicitly through the material law. The simplest models only consider the elasticity of the composite but tensile testing of the flax-polypropylene composite indicates that the behaviour is nonlinear. LS-Dyna has more specific material laws in its library that consider phenomena such as damage and viscoplasticity but with higher computational cost. A compromise solution is the use of Piecewise Linear Plasticity model available in the material library as MAT24. Young's modulus of 8.2 GPa was defined for the flax-propylene composite and a stress vs. plastic strain curve was defined for the post-yield response. An effective plastic strain criterion was used to define the erosion of elements.

The results of the Finite element model developed in LS-Dyna is shown in Figure 7. The force – displacement curves obtained for the 6J and 12 J impact show the nearly linear increase of the force until yield and then nonlinear behavior. The sharp drop in the force corresponds to the loss of stiffness due to the creation of cracks. The cracks are aligned in the fibre directions similar to the observed cracks in the experimental test. The cracks, shown in Figures 7(b) and (c), correspond to the point of maximum displacement. The impactor rebounds after the impact for both the 6J and 12J impact case with rebound velocity of 0.78 and 0.5 m/s respectively. This rebound velocity from the LS-Dyna simulation has good correlation with the measured rebound velocities of 0.8 and 0.4 m/s respectively from the drop tower tests. More tests are needed to validate the model but the results shown provide promising first results on the modelling of biocomposites with a macroscopic model.

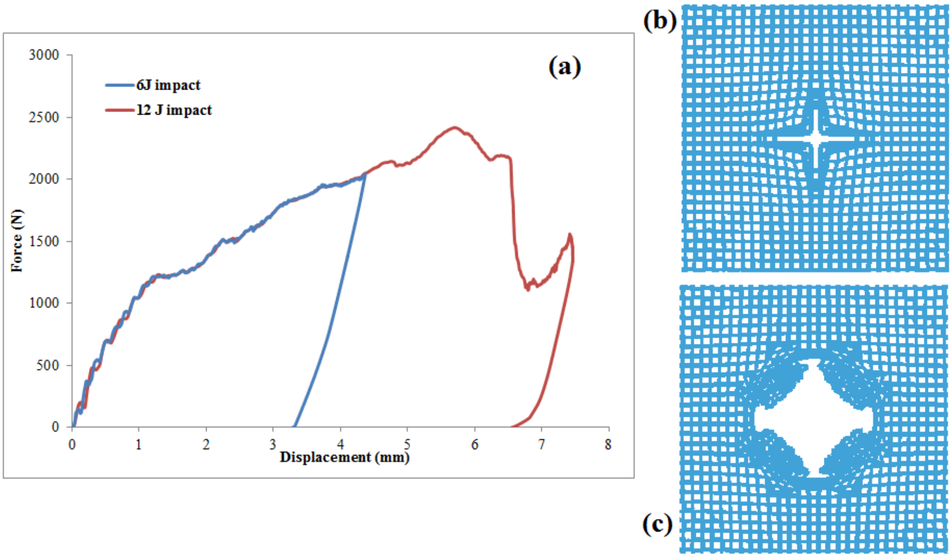

Figure 7. Results of LS-Dyna model: (a) Force-displacement curves for 6J and 12 J impact, (b) and (c) cracks in the centre of the composite plate for 6J and 12J impact respectively

4. Conclusions

The aim of the paper was to investigate the impact response of biocomposites of flax fibres reinforced polypropylene. Composite plates were manufactured using compression moulding of commingled flax and polypropylene fibres. Impact tests were conducted using a drop tower system at multiple energies and high speed camera was used to observe the propagation of impact damage in the composite. The different modes of damage and the critical energy for complete penetration were identified for the Flax-PP composite. A finite element model was developed to simulate the behavior of the biocomposite to impact loading using LS-Dyna. Good correlation was obtained between the drop tower impact test and the FE model in terms of qualitative comparison of impact damage and residual velocity measurement. Impact resistance has a great influence on the service life and durability of biocomposites and this study is a crucial addition to the research on sustainable composites for structural applications.

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