



HAL
open science

Low velocity impact damage assessment in natural fibre biocomposites

Karthik Ram Ramakrishnan, Stéphane Corn, Nicolas Le Moigne, Pierre Slangen

► **To cite this version:**

Karthik Ram Ramakrishnan, Stéphane Corn, Nicolas Le Moigne, Pierre Slangen. Low velocity impact damage assessment in natural fibre biocomposites. ICCM21 - 21st International Conference on Composite Materials, Aug 2017, Xi'an, China. hal-03753375

HAL Id: hal-03753375

<https://imt-mines-ales.hal.science/hal-03753375v1>

Submitted on 17 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

LOW VELOCITY IMPACT DAMAGE ASSESSMENT IN NATURAL FIBRE BIOCOMPOSITES

Karthik-Ram Ramakrishnan¹, Stéphane Corn¹, Nicolas Le Moigne¹, Pierre Slangen²

¹ Centre des Matériaux des Mines d'Alès (C2MA), Ecole des mines d'Alès, Alès, France

Email: karthik-ram.ramakrishnan@mines-ales.fr

² Laboratoire de Génie de l'Environnement Industriel (LGEI-ISR), Institut Mines Telecom, France

Email: pierre.slangen@mines-ales.fr

Keywords: biocomposites, flax, impact, drop tower, finite element, high speed camera

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 flax-epoxy and commingled flax and polypropylene fibres is investigated. Composite plates were manufactured using compression moulding process and impact tests at several energies were conducted using an instrumented drop tower. Force and displacement data were obtained from accelerometer measurements and a high speed camera setup was used to observe the bottom surface of the plates during impact. A crack tracking algorithm was developed to identify the initiation and propagation of cracks. The force-displacement curves and high speed camera results were compared for the flax-PP and flax-epoxy composites. The experimental study was supplemented with the finite element modelling of the impact response of biocomposite laminates. There was a good correlation found between the impact measurements and the FE simulations.

1. INTRODUCTION

Biocomposites with 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 fibres. Bast fibres such as flax, hemp, kenaf, jute and ramie are used in applications with structural requirements as their high cellulose content and microfibrils aligned in the fibre direction provide excellent specific stiffness and strength [4]. 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 [5-6]. 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. However, 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. Internal damage produced by impact loads during the service life of freight wagons due to dropped tools, collisions with loading and unloading fixtures, ballast or cargo can severely reduce the residual mechanical properties of the composite [8]. Many researchers have studied the impact resistance of natural fibre reinforced composites [8-16]. 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. The static and low velocity impact behaviour of non-woven flax fibre reinforced

polypropylene was investigated by Hoang and Touchard [10]. Benevolenski et al. [11] investigated the effect of fibre hybridization on the impact resistance of flax mat reinforced polypropylene. 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. It is evident that the structural potential of plant fibres as reinforcing agents can only be realized when the highest reinforcement efficiency is employed and this is typically achieved with twistless long continuous fibres.

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. 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. [12] studied the puncture impact resistance of All Cellulose Composites (ACC) based on Cordenka fibres. Dhakal et al. [13] 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 [14] developed a method to characterise the impact damage in flax-epoxy composites using hysteresis cycles. Zivkovic et al. [15] analyzed the damage mechanisms occurring after impact testing of dry and conditioned composite specimens prepared by a wet hand lay-up laminating process and concluded that hybrid composite structures with flax and basalt can provide markedly improved impact behaviour.

The aim of this work is to study the impact resistance of biocomposites reinforced with flax fabrics and to assess the evolution of damage using high speed imaging. Usually, the assessment of impact damage is done after the impact using visual inspection, ultrasonic C-scan or other NDI methods. The evolution of damage is identified from the force-displacement curve obtained from the impact experiment, which typically exhibits a loss of stiffness followed by the force drop, but this experimental data is rarely correlated to the actual creation and propagation of cracks. However, recent developments of ultra-high speed cameras, enhancement in imaging technologies, and powerful and affordable PCs for image processing have facilitated the use of high speed DIC for dynamic event testing [16-17]. In this paper, a method is presented to correlate the force-displacement data from the sensors to the slow motion tracking of the cracks propagation during an impact event on natural fibre reinforced composites.

The experimental results are compared with a finite element model created in LS-Dyna. The numerical modelling of FRP composites is possible at different scales: micro, meso and macro scale. The Representative Element Volume (REV) approach, used in modelling at the microscopic and mesoscopic scale uses the properties of the constituent materials and allows the modelling of the interaction between the fibre and the matrix. Wang et al. [18] noted that local damage evolution in natural fibre reinforced composites will determine their fracture toughness, stiffness loss and ultimate failure, and that the connection between the microstructural scale and the macroscopic scale is nontrivial. Sliseris et al. [19] used the microstructure of short flax fibre and flax fabrics in their numerical model and demonstrated that the simulation was able to predict the main damage mechanisms of the composite. Adam et al. [20] used an incremental formulation based on mean-field homogenization method and an interface between Digimat and Ls-Dyna solver to perform multi-scale FE analysis of the impact properties of fibre reinforced structures. In our study, a Ls-Dyna model of the impact tests is developed and simulation results are compared with the force-displacement data from the drop tower. A qualitative comparison of the damage in the biocomposite is also provided.

2. MATERIALS AND METHODS

2.1. Manufacturing of composite specimen

The thermo-press system used for the fabrication of the biocomposite plates is shown in Figure 1. Flax/thermoplastic fabric supplied by Composites Evolution as Biotex Flax/PP was selected for the

project. The woven Flax/PP fabrics are commingled textiles with surface density of 400g/m^2 made from twistless natural flax fibre and polypropylene (PP) fibre in a balanced 2x2 Twill architecture. Dry flax woven fabrics also supplied by Composites Evolution were chosen for the manufacture of Flax-Epoxy composites. The thermoset matrix chosen was a two part epoxy resin supplied by Resoltech (1800 epoxy resin and 1805 aliphatic amine hardener). The resin and the hardener are mixed in the ratio of 100:17 by weight. The flax fabrics were dried at $60\text{ }^\circ\text{C}$ for 24 h before the manufacturing process in order to minimize the moisture content.



Figure 1. Manufacturing of the Flax fibre biocomposites using thermopress

The fibres were cut to $300\text{ mm} \times 300\text{ mm}$ and were placed between the two rigid steel plates in a hydraulic press. Teflon sheets were used on both the steel plates as a mould release surface. The thermoplastic composites were fabricated at a temperature of $210\text{ }^\circ\text{C}$ and pressure of 50 bars for duration of 10 minutes. 10 plies of the Flax/PP fabric was used for final consolidated thickness of $3.1\text{ mm} \pm 0.05\text{ mm}$. For the thermoset composite, 5 plies of flax woven fabric were stacked and impregnated by 140 g of the epoxy resin/hardener mixture. 5 plies were chosen instead of 10 plies used in the Flax-PP composite. Even though the areal density of the flax fabric is the same as the Flax-PP commingled fabric (400 gsm), the commingled fabric were mixed in the ratio of 40:60 (i.e. effectively, the areal density of the flax fibres were only 160 gsm). The flax-PP and flax-epoxy composites have similar thickness. The laminated flax/epoxy composites were hot-pressed under a constant pressure of 20 bars and a constant temperature of $60\text{ }^\circ\text{C}$ for 21 hours (curing 6 hours and post-curing 15 hours).

2.2. Experimental setup for low velocity impact testing

Low velocity impact testing is typically accomplished using a drop tower with velocities below 10 m/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 low velocity impact tests were conducted using a CEAST instrumented drop tower. The drop tower 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 which is clamped in a 40 mm internal diameter fixture. The weight of the impactor was 3.1 kg with a hemispherical impactor of diameter 20 mm . A Phantom V2512 high speed camera, coupled with long distance macro-zoom lens, was used for slow motion observation of the bottom surface of the composite plate during the impact event. A mirror setup placed at 45° below the composite plate allowed the camera to safely capture the impact event without fear of damage and also to shine about 15000 lumens from superLEDs cold light device. The images were acquired at a frame rate of 39000 fps and exposure time of $25\text{ }\mu\text{s}$ with a

resolution of 786 x 786 pixels. The scale factor or magnification (M), which depends on the focal lens and the distance between the camera and object, was fixed to 69 μm per pixel. Photoelectronic switches used to measure the initial velocity and rebound velocity of the impactor also acted as the trigger for the image acquisition in rolling buffer FIFO memory mode. The drop height varied from 0.1 m to 0.3, 0.35, 0.4, and 0.5 m to give a range of kinetic energies of 3 J to 15 J. The upper bound energy was chosen in order to get experimental results up to the full perforation of the plate. Three specimens were tested at each condition to ensure the repeatability of the experiment.

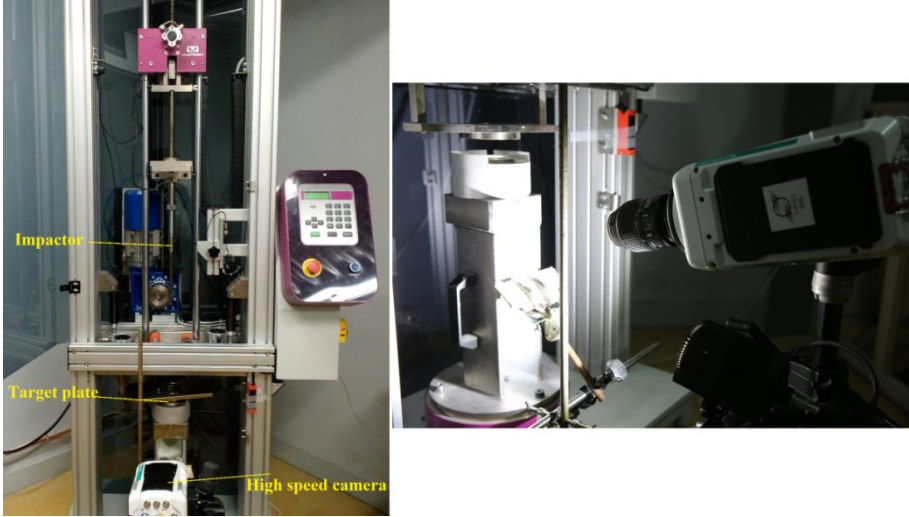


Figure 2. Drop tower setup used for low velocity impact testing

3. RESULTS OF DROP TOWER IMPACT TESTING

The instrumentation in the drop tower allows the measurement of force and displacement history of the impactor during the impact from accelerometer data. Figure 3 a shows the typical force history for flax/PP composite plates during a 3 J impact. It can be observed that the force curve is a bell-shaped curve that starts with the linear increase in force up to 1000 N and then there is non-linear material behaviour up to peak force of approximately 1550 N followed by unloading or fracture of the composite. Figure 3 b shows the energy history obtained from the force-displacement data. During the impact, the kinetic energy of the impactor is transferred to the plate and dissipated through the various damage mechanisms. It can be seen that during the eventual rebound phase, not all the energy transferred to the plate is returned to the impactor and the energy gap corresponds to plastic deformation and damage in the composite.

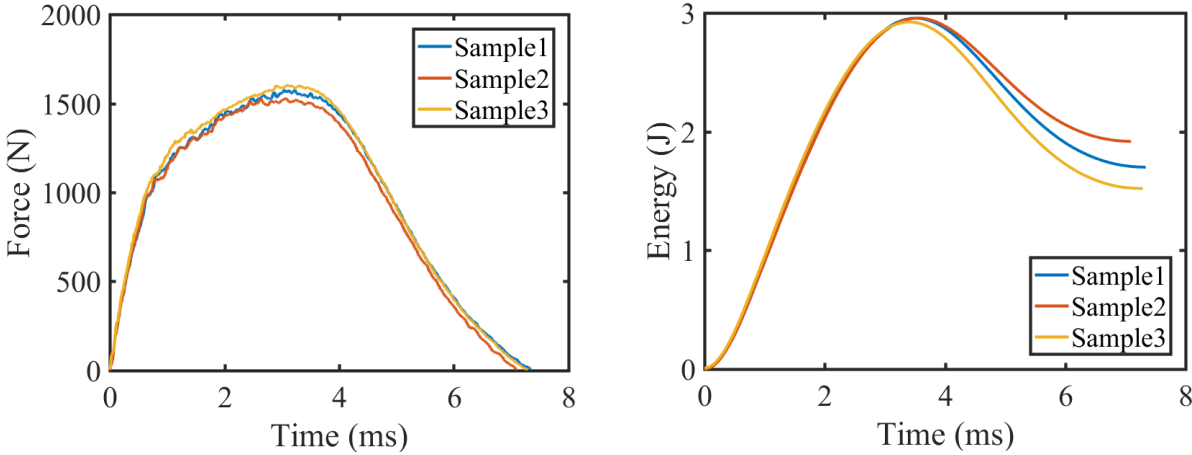


Figure 3. Typical force-time and energy-time history for 3J impact of Flax/PP composite

Figure 4 shows the force–displacement curves for impact at different initial impact energies for both the flax/PP and flax-epoxy plates. The impact energy varies from 3 J for the low energy/low damage impact to 15 J for full penetration impact. It can be seen that the initial stiffness of the plate is identical for all the loading conditions and that with increasing energy, there is increasing trend of residual displacement. For impact at 15 J, there is complete perforation of the plate and there is no rebound. The tail in the 15 J impact is the residual contact force at the end of impact due to friction between the impactor and the hole in the plate.

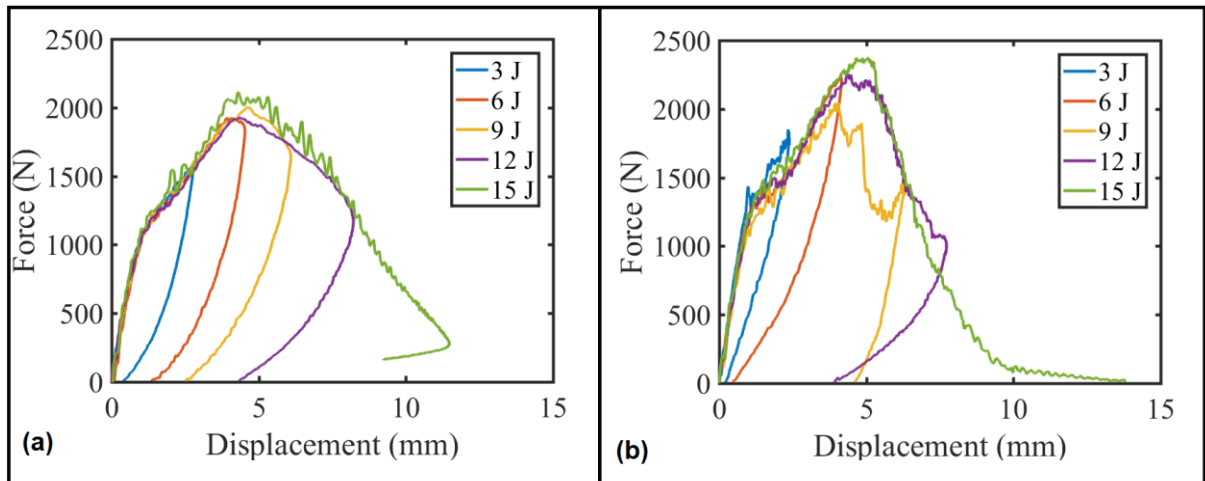


Figure 4. Comparison of the force-displacement curves for different initial impact energies (a) Flax-PP composite and (b) Flax-Epoxy composite

Figure 5 shows an example of the high speed camera images of the bottom surface of a flax/PP plate for a 6 J impact. The initiation and propagation of macro-cracks at different moments of the impact are observed. It can be seen that at time of 0.77 ms, there is localized damage beneath 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 full penetration of the plate and the impactor rebounds at the end of the impact. A macro was written in ImageJ software [21] to measure the length of cracks from each image. The crack tracking algorithm has several steps beginning with the conversion of a reference image to 8-bit and running median and gaussian blur filters to the image. Then each image from the high speed camera was treated with similar filters and subtracted from the reference image to isolate the cracks. The binary image is dilated and eroded to highlight the fissure and then a skeletonisation algorithm is used to trace the crack length with 1-pixel wide lines.

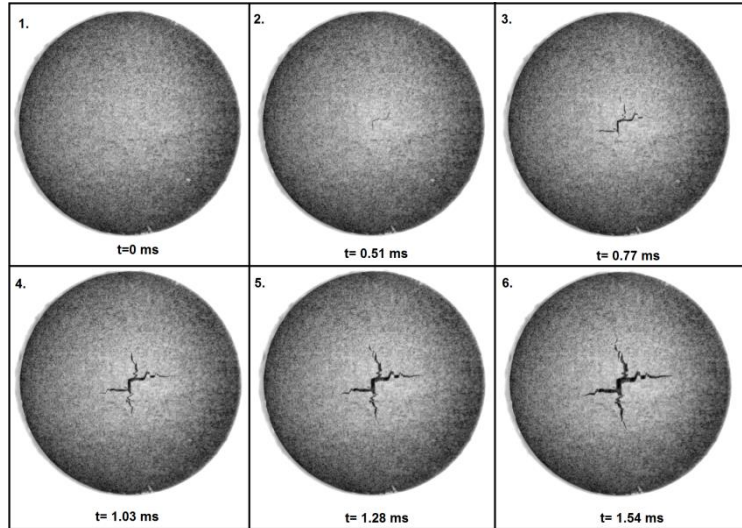


Figure 5 High speed images of initiation and progression of cracks in Flax-PP during 6J impact

The total length of the cracks is measured at each time interval and the evolution of damage observed in the plate was correlated to the mechanical response of the composite plate. For clear colour composite, no preparation of the samples is required as dynamic range of the V2512 is really high. Figure 6 shows the evolution of crack length correlated to the force –time history obtained from the sensors. It can be observed that the force response has an initial linear region followed by yielding and finally an unloading phase after reaching the peak. The crack initiation occurs close to the stiffness change at critical force of 1100 N. The total crack length reaches a maximum at the end of the loading phase.

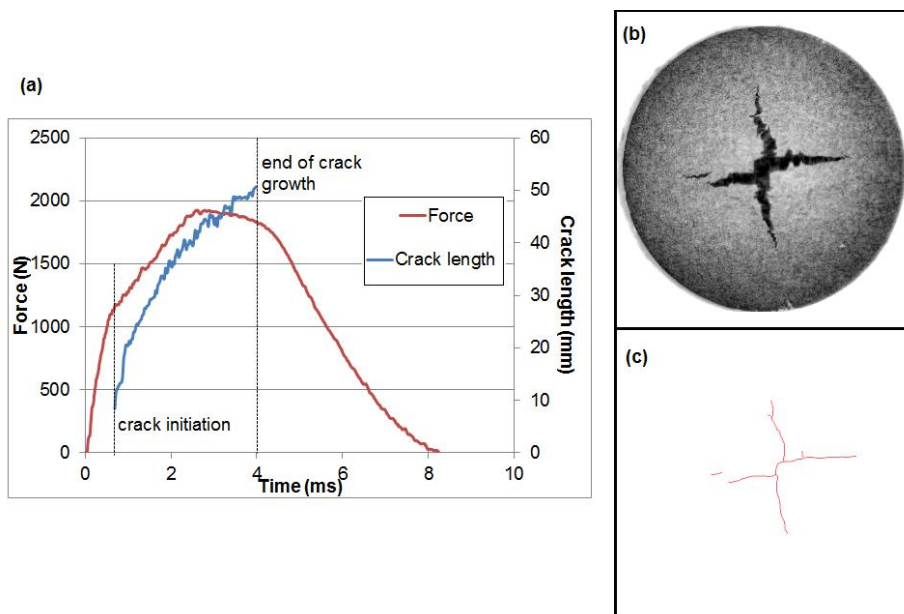


Figure 6 (a) Force – displacement curves for 6 J impact on Flax-PP composite; (b) Real time high speed image of the plate at maximum displacement; (c) Skeletonised image of the crack

A comparison of the visual inspection of the composite samples impacted at energies of 6 J and 12 J are shown in Figure 7. It can be observed that the increasing crack length is an indicator of the amount of damage sustained by the composite. At lower energies, there is matrix cracking around the point of impact as revealed by the whitening near the centre. 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. There is complete penetration of the

composite for initial energy of 12 J for the Flax/PP composite while the flax-epoxy composite impacted at the same energy shows less plastic deformation. The polypropylene matrix is a compliant matrix and exhibit extensive deformation as observed by the bulged surface and fibre pull-out. However, it can be seen that the crack nearly reaches the edge of the clamping fixture for the flax-epoxy composite.

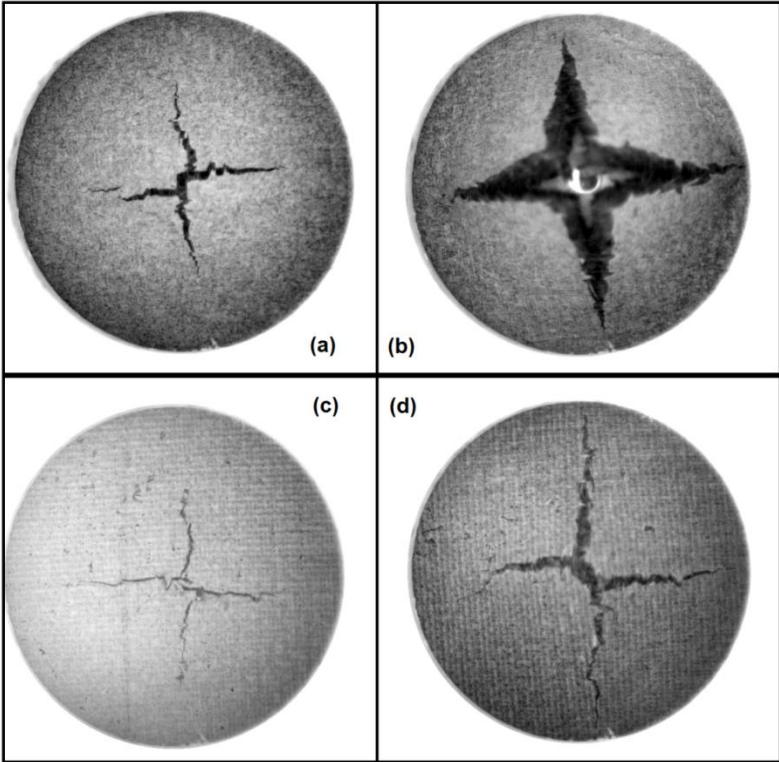


Figure 7 Bottom surface of the composite plate after impact: **(a and b)** 6 J and 12 J impact on Flax-PP composite; **(c and d)** 6 J and 12 J impact on Flax-Epoxy composite

A comparison of the force-displacement data for 6 J and 12 J impact for the flax/PP and flax-epoxy composite is shown in Figure 8. It can be seen that the initial stiffness of the flax-epoxy plate is marginally higher than the flax/PP composite. It is also evident from the curves that the flax/PP composite has higher maximum displacement for both load cases.

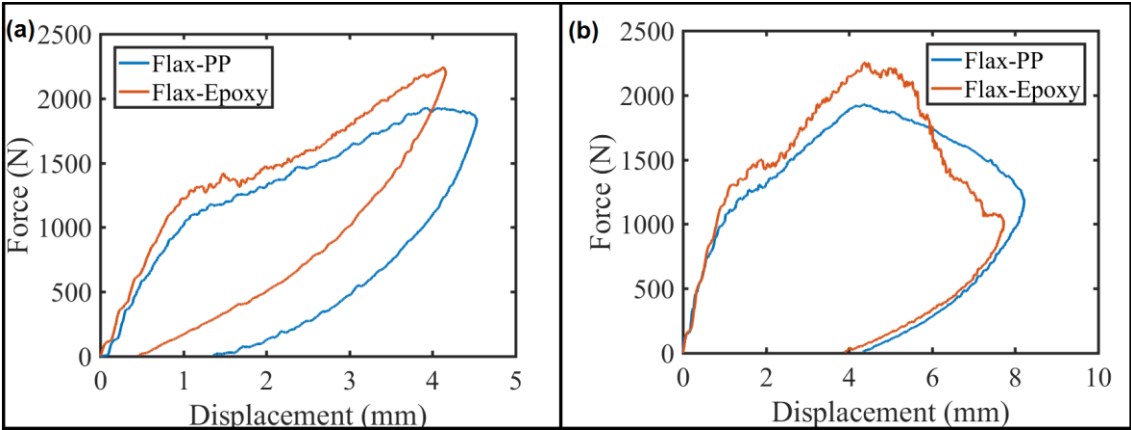


Figure 8. Comparison of Force – displacement curves for (a) 6 J and (b) 12 J impact

4. FINITE ELEMENT MODELLING OF IMPACT DAMAGE

The response of the composite plate to impact loading was examined using the Finite element method. 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 [22]. Mean Field Homogenisation and FE modules of Digimat [23] are capable of predicting the properties of RVE including the effect of fabric architecture. Flax fibres reinforced PP or epoxy matrix have highly nonlinear mechanical behaviour and display nonlinear stress-strain curve even for small strains in tensile tests. An advanced yarn model, which considers inclusions of infinite aspect ratio, was used to model the woven flax fabric in Digimat. However, since a yarn is actually made from a set of individual fibres, extra input parameters such as yarn density and fibre diameter were provided to the model. The homogenisation can be understood to take place in two steps; one for the fibres within the yarn and the second for the yarn in the matrix including the effect of weave architecture and crimping.

The homogenized model developed in Digimat was used in LS-Dyna to perform multiscale finite element analysis of the flax composites taking into account the local microstructure and anisotropic, nonlinear stress-strain behaviour of the material. The FE model developed in LS-Prepost for the simulation of the impact of composite plate is shown in Figure 9. The model also includes the clamping fixture to simulate the boundary conditions of the experiment. 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 use assumed strain 2x2 quadrature in the shell plane and co-rotational formulations. The constitutive law is fully 3D based and the thickness change comes naturally from corresponding degrees of freedom.

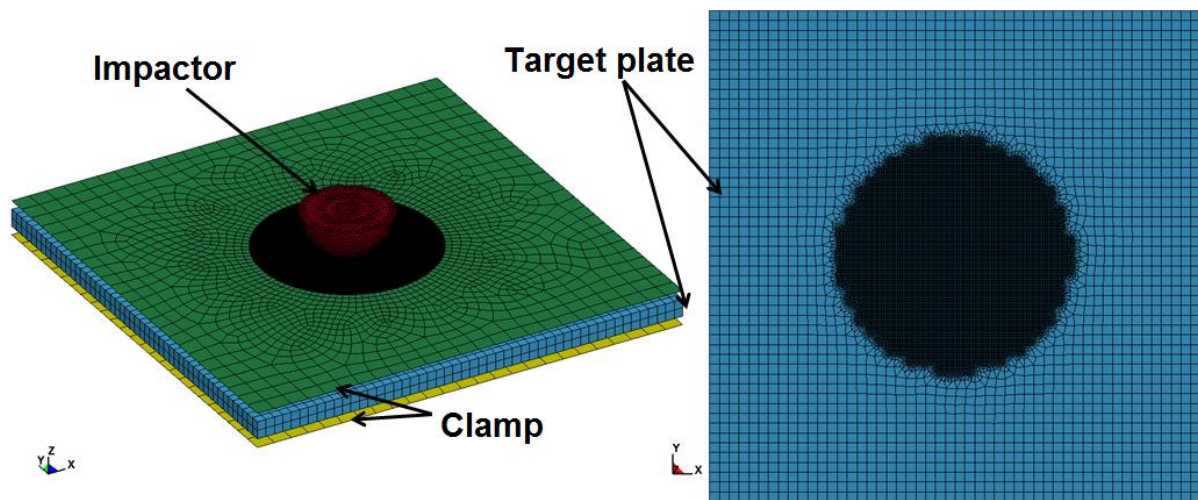


Figure 9. Finite element model of the low velocity impact test of composite plate

The hemispherical impactor was modelled with 31505 tetrahedral elements, while the Flax composite was represented by 77768 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. A mesh sensitivity study was done to determine the element size that was the best compromise between calculation time and accuracy of the local material fracture representation. An element size of 0.2 mm at the centre of the plate was chosen. 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 adjusted 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. Because tensile testing of flax-polypropylene samples indicated that the behaviour is nonlinear, the Piecewise Linear Plasticity model available in the material library as MAT24 was used for the composite. The homogenized Young's modulus of 9.2 GPa was defined for the flax-polypropylene composite and a stress vs. plastic strain curve was defined for the post-yield response. The anisotropy was included by means of the composite layup, defining the fibre orientations in each ply. After the defined yield stress, there is an onset of non-linearity due to plastic deformation and subsequent increase in stress with strain is associated with the effects of strain hardening. In this non-linear region, the total strain is considered to be the sum of a recoverable elastic component and a plastic component, which is non-recoverable. The hardening curve was defined in the form of yield stress with plastic strain where the first pair corresponds to the initial yield stress at zero plastic strain. Additionally, an effective plastic strain criterion was used to define the erosion of elements.

The model is validated by comparison with experimental force-displacement response for 6 J impact. The evolution of damage observed by the Digital Image correlation of the high speed images is also compared with the results obtained from the simulation. The results of the Finite element model developed in LS-Dyna is shown in Figure 10. The comparison of the force – displacement curves obtained from the experiment and the LS-Dyna simulation for the 6J impact show the nearly linear increase of the force until yield and then nonlinear behavior. The creation of cracks results in the loss of stiffness.

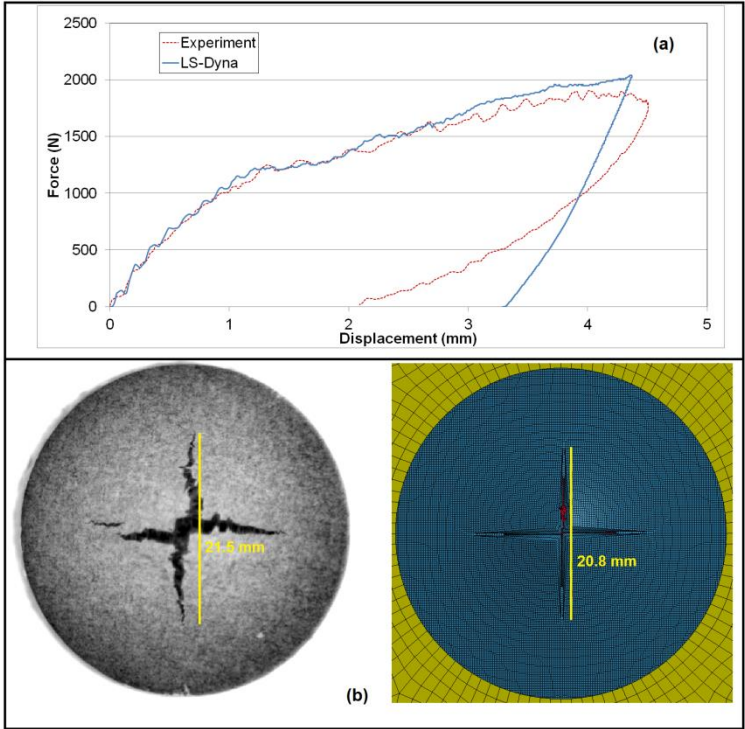


Figure 10. (a) Comparison of LS-Dyna model and experiment data of Force-displacement curves for 6J impact (b) cracks in the centre of the composite plate for 6J impact from high speed camera and simulation respectively

The cracks, shown in Figures 10(b) correspond to the point of maximum displacement. The cracks are aligned in the fibre directions similar to the observed cracks in the experimental test. It can be seen that the crack lengths at maximum displacement obtained from the simulation (20.8 mm) corresponds with the 21.5 mm crack length measured from the drop tower test. The unloading part of the force – displacement curve is not accurately captured in the model which results in larger residual displacement of 3.2 mm in the model compared to 2.1 mm for the experiment. 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.

5. CONCLUSIONS

The aim of the paper was to investigate the impact response of thermoplastic and thermoset biocomposites reinforced with flax fibres. Composite plates were manufactured using compression moulding and impact tests were conducted using a drop tower system at multiple energies. Force and displacement were measured using accelerometer 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 composite. Comparison of the impact response of flax-epoxy and flax-PP composite shows that the thermoplastic composite exhibits more ductile behavior and absorbs more energy. 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 both in terms of comparison of force-displacement curves as well as the qualitative comparison of impact damage and crack length. 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.

ACKNOWLEDGMENTS

This project was funded by the European Union's Horizon 2020 Programme (HERMES project, grant agreement n° 636520).

References

- [1] D. U. Shah, Peter J. Schubel, Mike J. Clifford, Can flax replace E-glass in structural composites? A small wind turbine blade case study, *Composites Part B: Engineering*, 52: 172-181, 2013
- [2] A.K Bledzki, J Gassan, Composites reinforced with cellulose based fibres, *Progress in Polymer Science*, 24(2): 221-274, 1999
- [3] O. Faruk, A.K. Bledzki, Hans-Peter Fink, Mohini Sain, Biocomposites reinforced with natural fibers: 2000–2010, *Progress in Polymer Science*, 37(11): 1552-1596, 2012
- [4] K.L. Pickering, M.G. Aruan Efendy, T.M. Le, A review of recent developments in natural fibre composites and their mechanical performance, *Composites Part A: Applied Science and Manufacturing*, 83, 2016
- [5] Libo Yan, Nawawi Chouw, Krishnan Jayaraman, Flax fibre and its composites – A review, *Composites Part B: Engineering*, 56: 296-317, 2014
- [6] Lut Pil, Farida Bensadoun, Julie Pariset, Ignaas Verpoest, Why are designers fascinated by flax and hemp fibre composites?, *Composites Part A: Applied Science and Manufacturing*, 83: 193-205, 2016
- [7] F. Bensadoun, D. Depuydt, J.Baets, A.W. Van Vuure, I. Verpoest, Influence of fibre architecture on impact and fatigue behaviour of flax fibre- based composites, 19th International Conference on Composite Materials Montreal, July 28 – August 2, 2013
- [8] C. Scarponi, F. Sarasini, J. Tirillò, L. Lampani, T. Valente, P. Gaudenzi, Low-velocity impact behaviour of hemp fibre reinforced bio-based epoxy laminates, *Composites Part B: Engineering*, Volume 91: 162-168, 2016

- [9] H.L. Bos, J. Müssig, Martien J.A. van den Oever, Mechanical properties of short-flax-fibre reinforced compounds, *Composites Part A: Applied Science and Manufacturing*, 37 (10): 1591-1604, 2006
- [10] T.Q. Truong Hoang and Fabienne Touchard, Non-woven Flax Fibre Reinforced Polypropylene: Static and Low Velocity Impact Behaviour, *Polymers & Polymer Composites*, 21(5), 2013
- [11] O. I. Benevolenski, J. Karger-Kocsis, K. -P. Mieß, and T. Reubmann, Instrumented Perforation Impact Response of Polypropylene Composites with Hybrid Reinforcement Flax/Glass and Flax/Cellulose Fibers *Journal of Thermoplastic Composite Materials*, 13: 481-496, 2000
- [12] T. Huber, S. Bickerton, J. Müssig, S. Pang, M.P. Staiger, Flexural and impact properties of all-cellulose composite laminates, *Composites Science and Technology*, 88: 92-98, 2013
- [13] H.N. Dhakal, V. Arumugam, A. Aswinraj, C. Santulli, Z.Y. Zhang, A. Lopez-Arraiza, Influence of temperature and impact velocity on the impact response of jute/UP composites, *Polymer Testing*, 35: 10-19, 2014
- [14] Carlo Santulli, Falling weight impact damage characterization on flax/epoxy laminates, *Int. J. Materials and Product Technology*, 36: 221-228, 2009
- [15] Irena Živković, Cristiano Fragassa, Ana Pavlović, Tommaso Brugo, Influence of moisture absorption on the impact properties of flax, basalt and hybrid flax/basalt fiber reinforced green composites, *Composites Part B: Engineering*, Volume 111, Pages 148-164, 2017
- [16] Madhu S Kirugulige, Hareesh V. Tippur, Thomas S. Denney, Measurement of transient deformations using digital image correlation method and high-speed photography: application to dynamic fracture. *Applied Optics*, 2007, vol. 46, no 22, p. 5083-5096.
- [17] Tiwari et al., Application of digital image correlation in impact testing. SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Portland, June 2005
- [18] Fang Wang, Xue Li, Junqian Zhang, Lu Li, Leon M. Keer, Micromechanical modelling of the progressive failure in unidirectional composites reinforced with bamboo fibres, *Mechanics of Materials*, Volume 94, 2016
- [19] Janis Sliseris, Libo Yan, Bohumil Kasal, Numerical modelling of flax short fibre reinforced and flax fibre fabric reinforced polymer composites, *Composites Part B: Engineering*, Volume 89: 143-154, 2016
- [20] L. Adam, R. Assaker & R. Ramaya, Multi-Scale Modeling of the Impact and Failure of Fiber Reinforced Polymer Structures using Digimat to LS-Dyna Interface, 6th European LS-Dyna users' conference, 2007
- [21] Ferreira T and Rasband WS. "ImageJ User Guide — IJ 1.46", imagej.nih.gov/ij/docs/guide/, 2010—2012.
- [22] Livermore Software Technology Corporation, LS-Dyna Keyword Users Manual, Volume- II (Material Models), LSTC (April 2012)
- [23] Digimat manual, eXstream engineering, Release 2017.0, www.e-Xtream.com, January 2017