



Natural fibre composite energy absorption structures

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ABSTRACT

Natural fibre composites represent an environmentally sustainable alternative to conventional glass and carbon fibre composites. Fibres derived from plants are renewable and have low levels of embodied energy compared to synthetic fibres. They are also low cost, low density, have high specific properties, are non-abrasive and less harmful during handling.

In motorsport the front and rear impact structures are required to act as both load-bearing members and energy absorption devices. The requirement to absorb large amounts of energy means that the specific energy absorption (SEA) of the material is critical to maintaining a low mass. This work focuses on the potential for natural fibres to replace synthetic fibres for future environmentally friendly energy absorption structures. Conical test specimens of jute, flax and hemp were manufactured using vacuum assisted resin transfer moulding (VARTM) and subjected to impact testing.

The natural fibre cones exhibited high values of SEA: unwoven hemp 54.3 J/g, woven flax 48.5 J/g and woven jute 32.6 J/g. The SEA was influenced primarily by fibre volume fraction (Vf) where a high Vf leads to high SEA. Significant variability in SEA resulted from the variation in fibre strength and Vf as a result of the VARTM manufacturing process. Natural fibre composites have the potential to be widely applied as low cost, sustainable energy absorption structures.

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1. Introduction

Composite materials offer higher specific strength, stiffness and energy absorption than metals which is driving their use across many industry sectors. They are used extensively in motorsport and increasingly in the automotive sector because of their potential to reduce mass. Impact structures in motorsport are required to act as both load-bearing members and energy absorption devices. The nose cone of a Formula 1 car must absorb 87.75 kJ of energy equivalent to 780 kg travelling at a speed of 15 m/s [1]. This high energy requirement means that the specific energy absorption (SEA) of the material is critical to maintaining a low vehicle mass. Carbon fibre composites currently have a maximum SEA of 70 J/g [2,3] compared with 19 J/g for metal structures due to the different energy absorption mechanisms [4].

During an impact a composite disintegrates both structurally and microscopically, absorbing energy through the fracture of fibres and matrix, debonding of the fibres from the matrix and delamination of layers. Metallic structures absorb energy through plastic buckling, a less efficient mechanism [5]. This work focuses on the potential for natural fibres to replace synthetic fibres for more sustainable energy absorption structures.

Current annual carbon fibre demand has reached a level of 27,000 tonnes [6]. Carbon fibre is energy intensive to manufacture

requiring 300 MJ/kg due to the numerous high temperature processes required [6,7]. End-of-life routes for carbon fibre composites predominantly consist of landfill, combustion for energy recovery or recycling which is now the subject of intense research [7]. A more environmentally sustainable option is to consider the use of natural fibre composites which may incorporate biodegradable resins to make them fully biodegradable at their end of life.

Plant fibres grow naturally, are renewable and require less energy to manufacture than synthetic fibres [8]. Recent life cycle analysis work has demonstrated that the spinning and subsequent weaving of flax fibres requires significant energy. Thus, woven flax may have a greater embodied energy than a glass fibre equivalent [9]. However, the environmental case is still unclear, it is known that natural fibre composites require a higher fibre volume fraction to match the strength and stiffness of synthetic composites. Hence, renewable fibres are replacing non-renewable resins. Additionally, natural fibre composites can be more readily used for energy recovery at end of life [8]. It is worthy of note that energy consumption is dominated by the in-use phase of transport related components e.g. automobile interior panels [10] and transport pallets [11]. Therefore, weight savings that are possible with low density natural fibres may aid in reduction of overall life cycle energy. Natural fibres are low cost, low density, have high specific properties, are non-abrasive and less harmful during handling. However, they have a low resistance to moisture and significant variability [12].

Long fibres sourced from the stem, leaves and seeds of a wide range of plants and trees can be extracted and processed into

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random mat and woven textile materials suitable for polymer reinforcement. This work focuses upon bast fibres which are categorised as fibres collected from the phloem of dicotyledonic plants. These are flowering plants with a pair of leaves in the embryo of the seeds. The specific fibres jute, flax, and hemp were selected due to the wide amount of research material currently available [13–17] and due to the worldwide availability of such plants. Bast fibre plants are grown in large quantities globally via low energy farming methods [8], with approximately 350,000 tonnes of flax fibre produced annually [18]. Bast fibres are obtained from plants grown in both temperate and tropical regions of the globe [13]. The worldwide use of these fibres, particularly in the manufacture of sustainable textiles and drying oil for painting and varnishing has been one of the primary forces driving their use in composites [13].

The mechanical properties of a composite are dependent on the strength of the bond between fibre and matrix [19–21]. This interface is the limiting factor of fibre-reinforced composite performance as it ultimately defines the amount of load that can be transferred from one fibre to the next by the matrix [22]. The strength of a fibre–matrix interface is dependent upon the degree of mechanical, chemical and electrostatic bonding and level of inter-diffusion between the matrix and fibres [23,24].

In carbon, glass and Kevlar composites the fibre–matrix interface is chemically enhanced using compatibilisers and sizing agents such as silane. Natural fibres adhere to the matrix solely through mechanical interaction; the roughness of the fibre surface causes adhesion between the two phases allowing it to transfer load to adjacent fibres. The lack of chemical bonding is due to the chemistry of natural fibres. Lignification processes within bast fibre plants lead to the creation of a complex three dimensional amorphous lignin polymer which is unique to each plant species [25]. These molecules are rich in functional groups and are therefore polar in nature, they are also strongly hydrophilic. As most polymer matrices are hydrophobic and apolar this results in poor compatibility and interfacial adhesion [26,27].

The natural fibres flax, hemp and jute all exhibit a specific modulus comparable with E-glass fibres but a lower tensile strength (1000 versus 3400 MPa) [8]. Bast fibres are a naturally derived reinforcing material and their material properties are shown to exhibit a high degree of variation relative to their synthetic parallels. This variability is a direct result of growing conditions experienced by each specific plant, the effect of processing operations and predominantly the degree of moisture present within the fibre samples. Stiffness reduction under wet conditions is attributed to the absence of hydrogen bonding within the fibres with stiffness values falling by a factor of 2–4 in relation to dry fibres [28].

Natural fibre composites have been demonstrated to absorb energy in both low speed [29] and ballistic [30] regimes. At low speed (2.5 m/s) increased volume fraction led to improved energy absorption and non-woven hemp reinforcement had comparable properties with chopped strand E-glass [29]. At high speed (300 m/s) the performance of hemp, jute and flax were similar although jute performed worst because of the low strength and brittleness of the fibres [30]. This work investigates the potential for natural fibre composites to be applied in sustainable energy absorption structures with a focus on motorsport.

2. Methodology

2.1. Materials

Test specimens were manufactured using vacuum assisted resin transfer moulding (VARTM). Natural fibre reinforcements were chosen because of their ready availability and included woven flax

(4–1 satin weave, 200 gsm, Foxtech Ltd.), woven jute (plain weave, 350 gsm, Aimplas, Spain) and chopped strand hemp mat (double needled, 450 gsm, Hemcore Ltd.) as shown in Fig. 1. In order to compare the SEA of natural fibre with a known material, three cones were manufactured using carbon fibre (plain weave, 375 gsm, Carr Reinforcements Ltd.). All samples used EP522 epoxy resin (Alchemie Ltd.) which was selected due to its low viscosity of 700 mPa/s at 25 °C for VARTM. This resin has tensile strength 43–53 MPa, elongation at break 3.5–5%, flexural strength 116–122 MPa, flexural modulus 2.5–3 GPa and heat distortion temperature of 104–108 °C.

Fabric was cut according to a standard layup schedule with the number of plies proportional to the areal weight of the material. The total ply mass in each case was approximately 26 g equivalent to five plies for flax and two for hemp. A closed aluminium mould was manufactured for the VARTM process. Component breakout was undertaken following a cure time of 24 h as specified within the product data sheet.

2.2. Experimental procedure

2.2.1. Fibre testing

Individual fibres were extracted from yarns of each material and the maximum tensile strength and modulus were measured for each material at gauge lengths of 10 and 20 mm according to ASTM D3379-75. Thirty fibres of each material and gauge length were tested for statistical significance in an Instron 5800R with a 10 N load cell and Instron fibre grips. Average fibre diameter was determined through the use of a Zeiss Sigma scanning electron microscope. Microscopy was undertaken with an acceleration voltage of 10 kV and use of the secondary electron signal. Fibre diameters were determined through use of SmartSEM imaging software.

2.2.2. Static testing

Quasi-static testing was carried out on an Instron 5800R configured for static compression testing. Statically crushed specimens were tested at a platen speed of 1 mm/min. Compressive force and displacement were recorded and testing was halted prior to total compression of the test specimen.

2.2.3. Dynamic testing

Dynamic testing used a bespoke Instron impact tower with a maximum impact energy of 11 kJ. Test energy varied from 500 to 1000 J based upon predicted energy-absorption capabilities. During the impact test, resistive force offered by the test specimen was recorded by the system load cell at 50 ms intervals throughout the duration of the crushing regime.

The test specimen was designed to absorb 1000 J of energy (Fig. 2). A cone angle of 15° allows for the maintenance of vertical crush resistance and a wall thickness of 3 mm helps develop progressive crushing without unnecessary instability caused by excessively thick or thin walls. The dependence of SEA on the composite's thickness is significant, because it influences the bending strength. SEA decreases with increasing cone angle due to the increase of the bending momentum of the layer [31]. Crush initiation of a fibre-reinforced composite requires a deliberate weakness in the structure. On tubes a chamfered end is utilised to perform this function. However, specific geometries such as a cone automatically ensure the presence of an initiator, and so they are often used to compare impact properties of like materials.

2.2.4. Sample analysis

Optical microscopy was used to determine fibre volume fraction and presence of voids. Microscopy of the fracture surface allowed examination of the fracture mechanisms for each fibre type. Samples of each specimen were cut to size and encased in 30 mm

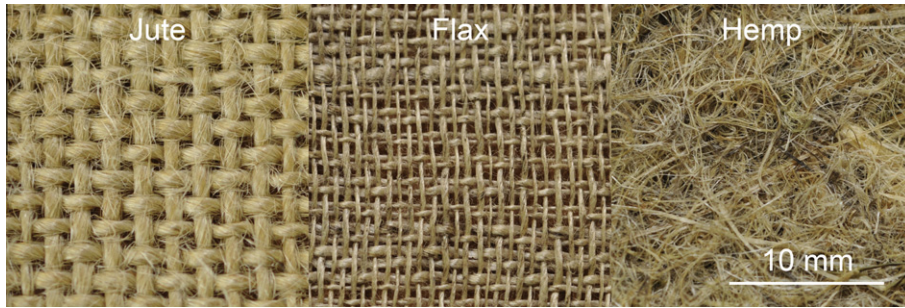


Fig. 1. Macroscopic detail for each fibre type.

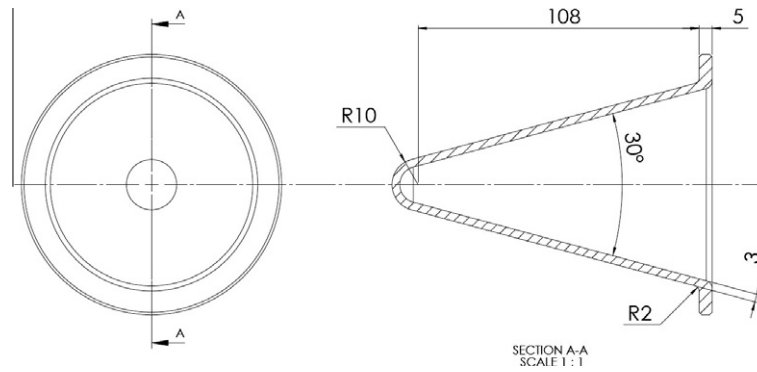


Fig. 2. Engineering drawing of VARTM cone.

diameter sample cups with Buehler Epokwik. Samples were removed after the specified 1 h cure time and then subjected to a three-phase grinding process with silicon carbide abrasive discs at grit value of 300, 600 and 1200. Samples were then polished using a 0.3 μm Alumina paste to achieve suitable surface quality.

Microscopy was undertaken through use of a Nikon Eclipse LV100D-A universal design microscope. Fracture surface imagery was captured with a 3 Megapixel U-Eye digital imaging camera. Buehler Omninet modular digital imaging software was used to determine fibre volume fraction, voidage and create fracture surface imagery.

3. Results and discussion

3.1. Fibre testing

The peak tensile strengths for each fibre are presented in Fig. 3 using simple Gaussian statistics with error bars at ± 1 standard deviation, not Weibull statistics as they have been shown to yield similar results [26]. The undamaged portion of each tested fibre was viewed using a Zeiss Sigma SEM (Fig. 4) and the mean fibre diameters were measured as: flax – 18.63 μm , jute – 48.64 μm and hemp – 38.74 μm . Fibres were assumed to be cylindrical. All fibre types exhibited significant variability in fibre strength. This scatter is known to be as a result of natural variability in the plant due to growing conditions and moisture content as well as damage during processing [32]. As the effectiveness of a fibre-reinforced material is determined by the mechanical properties of the reinforcing fibres and their adhesion to the matrix material, fibre strength variation will affect both the strength and toughness of the final composite.

Fig. 3 reveals excellent correlation between mean fibre strength at both gauge lengths. It is expected that a longer fibre has a greater number of defects and would therefore fail sooner. In the case of

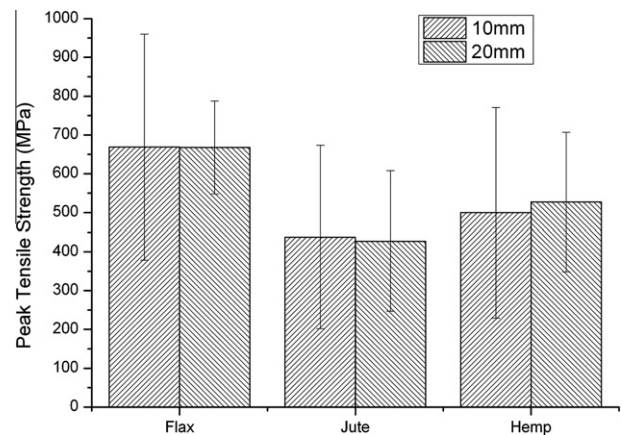


Fig. 3. Mean tensile strength for all fibres at 10 mm and 20 mm gauge length, error bars at ± 1 standard deviation.

natural fibres there are so many defects in the fibres, as seen in Fig. 4, that there is little difference between the 10 and 20 mm samples. The fibres would need to be tested at considerably shorter gauge lengths in order to obtain their theoretical maximum strength. The mean tensile strength for flax fibre (~667 MPa) is comparable with previous research which found mean tensile strength for 10 mm samples to range from 600 to 766 MPa and 20 mm samples from 470 to 630 MPa [32]. Equally, the results for jute (~430 MPa) are comparable with previous research which ranges from approximately 350 to 450 MPa [15].

3.2. Static testing

Fig. 5 illustrates the static behaviour of the cone specimens where the area under each curve indicates the amount of energy

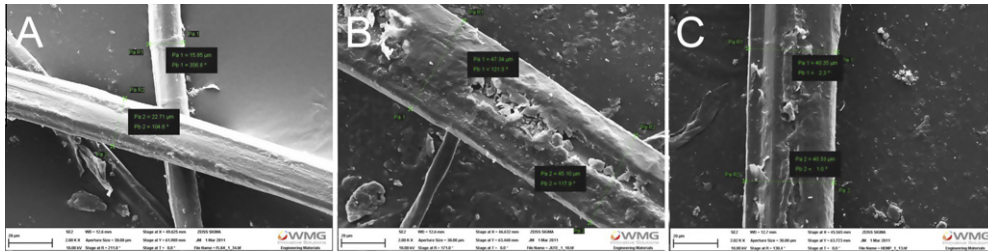


Fig. 4. SEM images of individual fibres flax (A), jute (B) and hemp (C).

absorption. The flax sample crushed progressively for the duration of the test. The jute sample failed after 35 mm and the hemp sample after only 8 mm. The base of the cone was not constrained during this test and so it merely serves to highlight the tensile properties of each material as the jute and hemp samples failed in tension around their base.

3.3. Dynamic testing

Table 1 displays the dynamic testing experimental results. The critical results are the SEA values which were: flax (45.3 J/g), jute (32.6 J/g), hemp (54.3 J/g) and carbon (55.7 J/g), these are plotted in Fig. 6. The behaviour of each specimen was captured through the use of high-speed video equipment enabling a more detailed discussion of the fracture mechanisms at work (Fig. 8). These results highlight a number of areas for further discussion: the large amount of variability in the results, the high SEA achievable by natural fibre composites, and the ability of non-woven hemp to achieve similar properties to woven carbon fibre.

The variation in SEA within each material is a function of the raw materials and the manufacturing process. Variation due to manufacturing may arise from the fibre orientation during the lay-up process, the packing density imparted during moulding process and overall specimen porosity. The method for laying up material into the mould was kept constant, thus fibre orientation for each specimen was the same. Equally, the weight of fibre inserted into the mould was the same in each case. Thus the variation experienced is due to the raw material and porosity introduced during the VARTM process where small vacuum leaks can introduce porosity into the specimens.

The fibre volume fraction for a three samples of each material type was measured using optical microscopy and the results are shown in Table 1. Voidage for all specimens ranged from 6% to 8%. Fibre volume fraction (Vf) was observed to have a significant

effect on SEA as shown in Fig. 7. A high Vf results in a high SEA. The Vf is affected by the amount of material compression in the mould. The Vf for unwoven hemp (43.5–52.5%) is higher than might be expected for an unwoven material as a result of this.

The dependence of progressive fracture behaviour and high SEA upon Vf is significant, as displayed in Fig. 7. The availability of energy dissipation pathways is directly related to Vf. Jute specimens were observed to have the lowest Vf (30.27–31.6%) and the correspondingly lowest SEA values (30.25–34.83 J/g). Conversely, those specimens constructed of hemp exhibited the highest fibre volume fractions (43.51–52.52%) with correspondingly high values of SEA (49.23–58.06 J/g).

Higher Vf composites have less resin available to fracture, thus reducing energy dissipation through resin cracking. Increasing resin toughness reduces the length of the central crack, increases the support of the fibres and therefore increases SEA due to fibre breakage and higher energy matrix failure. However, an excessive quantity of weak resin rich areas within the specimen leads to premature fracture of the lamina bundle fronds reducing the total level of SEA. A high SEA is dependent upon a balance of in-plane and through thickness properties [33].

Constraint of the base during dynamic testing allowed for the development of longitudinal cracks and lamina bundle fronding without catastrophic failure of the test specimen. The development of a debris wedge along with the other energy dissipation sources led to the observed values of SEA. The dynamic behaviour of each material is presented in Fig. 8. The level of SEA attributable to each specimen is dependent upon the fracture mechanisms for each material and the corresponding energy dissipation pathways.

The woven flax and jute samples exhibit characteristics of brittle fracture. The formation of multiple longitudinal cracks upon impact is followed by the initiation of lamina bending. The jute displays a large longitudinal crack upon impact which suggests that the dominant energy dissipation feature is that of crack propagation through resinous areas. The woven nature of the jute specimen ensures that longitudinal crack propagation is resisted by the reinforcing fibres allowing for the initiation of lamina bundles. The longitudinal cracks propagate less effectively in flax signifying the importance of woven fibre density upon composite toughness. The Lamina bundles are observed to fracture under the influence of transverse bending forces, limiting energy absorption due to lamina bundle bending. The extent and dimensions of fracture material suggest low circumferentially orientated fibre toughness.

In contrast, the unwoven hemp exhibits characteristics attributable to progressive collapse. There is no indication of terminal longitudinal crack formation upon crush initiation. The initiation of, and continued development of lamina bundles illustrates the dominant influence of crack growth limitation upon fracture mode. Lamina bending dominates the crushing regime with little material consumed through brittle fracture. The extent of material fronding indicates heightened energy dissipation and thus SEA capability in comparison to woven jute and flax.

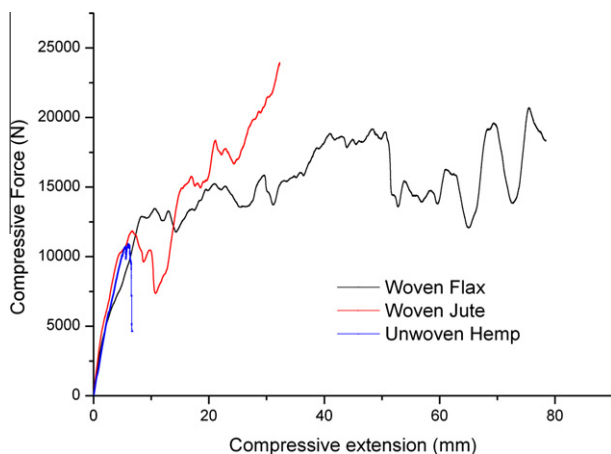


Fig. 5. Load versus extension for statically tested flax, hemp and jute samples.

Table 1
Test matrix for static, dynamic and sample analysis results.

Fibre type	Impact velocity (m/s)	Absorbed energy (J)	Mass lost (g)	Fibre volume fraction (Vf)	Specific energy absorption (J/g)
Flax	5.86	566.60	8.79	–	64.46
Flax	6.38	671.62	15.21	–	44.16
Flax	4.72	794.22	22.68	33.7	35.02
Flax	4.8	821.38	16.07	41.79	51.11
Flax	4.67	777.49	16.19	35.6	48.02
Jute	6.38	671.62	16.44	–	40.85
Jute	6.5	697.13	22.11	–	31.53
Jute	6.68	736.27	25.03	29.8	29.42
Jute	5.36	1024.21	34.72	30.27	29.50
Jute	4.8	821.38	25.86	31.6	31.76
Hemp	3.71	490.69	9.01	52.52	54.46
Hemp	4.78	814.55	14.33	43.51	56.84
Hemp	4.73	797.59	15.42	44.39	51.72
Carbon	5.42	484.7	8.59	–	56.43
Carbon	6.70	740.7	13.49	–	54.91
Carbon	6.54	705.73	12.67	–	55.70

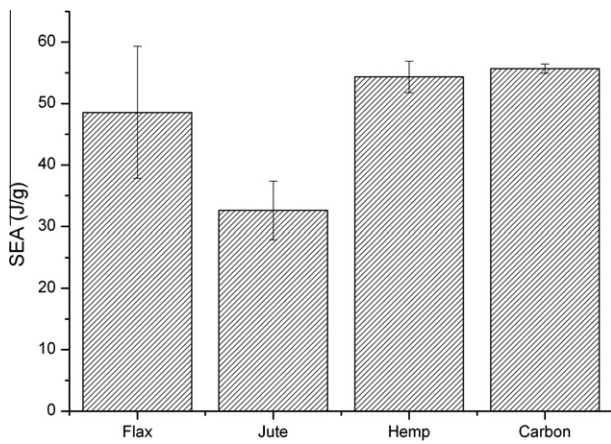


Fig. 6. Plot of specific energy absorption range versus fibre type, error bars at ± 1 SD.

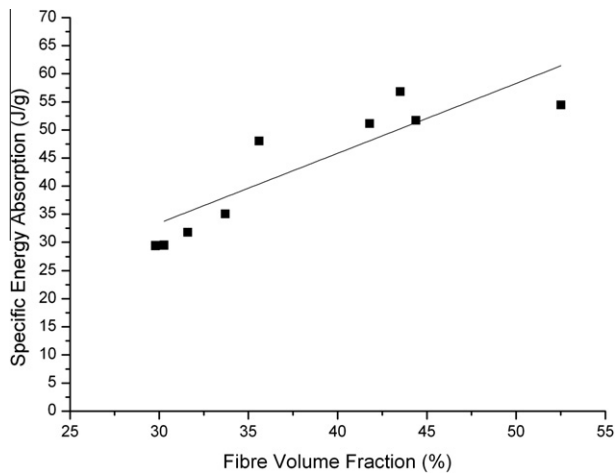


Fig. 7. Strong correlation observed between specimen fibre volume fraction and degree of SEA.

3.4. Sample analysis

Optical micrographs are provided in Fig. 9 which illustrates the dynamic fracture surface of each material. Fracture characteristics are highlighted with letters. (A) High degree of longitudinal cracking within resin rich areas, resulting in energy dissipation and preferential formation of lamina bundles. (B) Propagation of

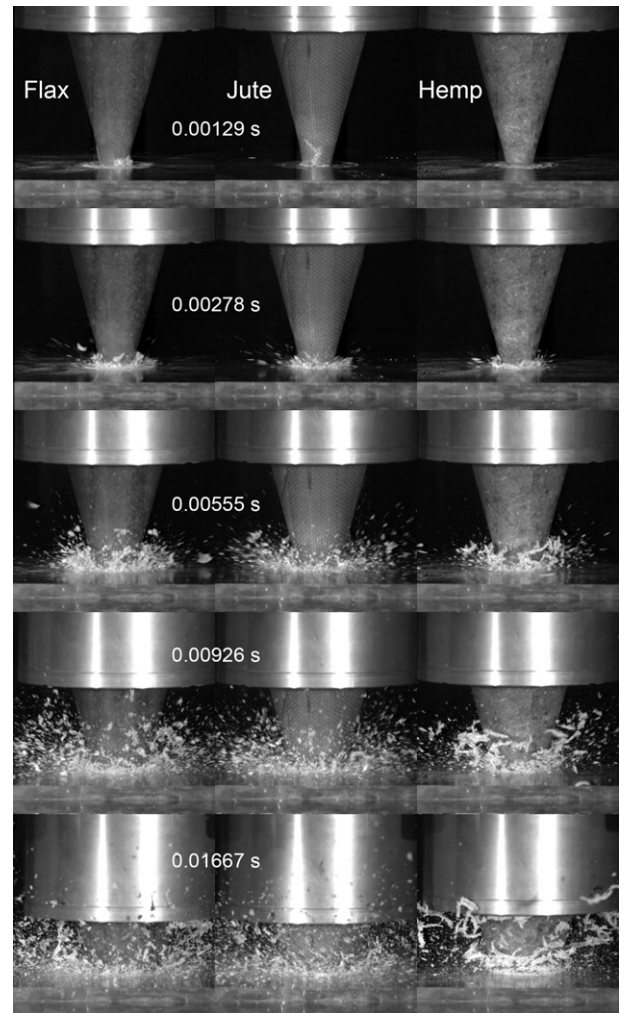


Fig. 8. Comparison of all samples at different time points during impact tests.

longitudinal crack resisted by reinforcing fibres and potentially by the presence of stress relievers in the form of small pores. (C) Indications of lamina bending within all test specimens to varying degrees which suggests energy dissipation paths may depend upon front bending and the effects of friction. (D) Evidence of premature lamina bundle fracture suggesting low circumferentially orientated fibre toughness and reduced SEA for jute and flax. Hemp

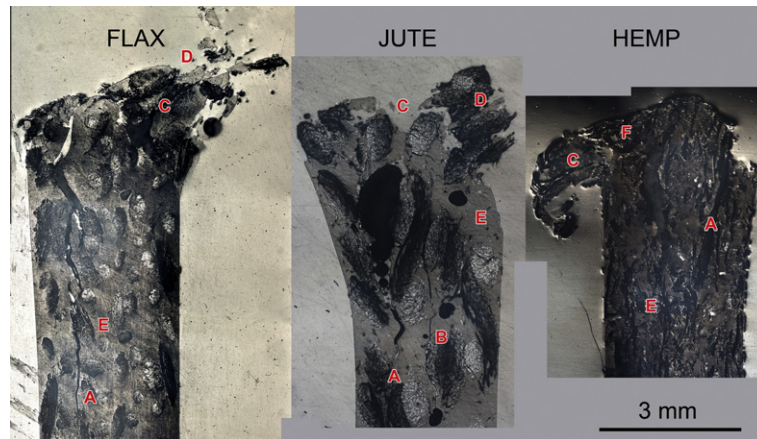


Fig. 9. Fracture specimen optical micrographs.

displays extensive fronding indicating increased energy dissipation. (E) Vf differences evident between all samples. (F) Debris wedge formation in hemp specimens leads to additional energy dissipation through friction.

The proportion of resin rich areas available for longitudinal crack growth is directly dependent upon Vf. This is evident in Fig. 9A where longitudinal cracking is present within each of the specimens, being most prevalent in the jute specimens observed to have the lowest Vf. The large plain weave of the jute samples decreases the Vf whereas the tight weave in the flax samples give a higher Vf. This leads to development of a single interlaminar crack in flax, as opposed to the numerous fractures experienced in jute samples. Hemp samples with the highest Vf, developed longitudinal cracks which progressed at a rate that allowed subsequent development and bending of lamina bundles.

The properties of the fibre influence the degree to which circumferentially orientated fibres can withstand the forces introduced into the specimen during lamina bending. However, the continued bending of these bundles and corresponding energy absorption through frond bending and frictional action is influenced in a greater part by the ease of crack growth through resinous areas. While jute samples display established bend formation in comparison to flax, images from the high-speed footage (Fig. 8) illustrate how excessive longitudinal cracking results in premature lamina bundle fracture. The specimens tested are therefore more sensitive to Vf than fibre properties.

Progressive collapse is dependent upon the availability of energy dissipation sources in the form of frond bending, inter and intralaminar fracture and dissipation via frictional action. The presence of these fracture characteristics within specimen micrographs suggests fibre volume fraction variations have a direct influence upon the observed fracture behaviour. All specimens show indications of frond bending and inter-laminar cracking, although to varying degrees. Whilst longitudinal cracking within resin rich areas is a source of energy dissipation, insufficient attenuation prevents dissipation via higher level pathways such as lamina frond bending.

This initial examination of natural fibre composites for energy absorption structures has demonstrated the potential of these materials. Further work will concentrate on larger specimens using prepreg materials in order to manufacture high quality test specimens.

4. Conclusions

Natural fibre composites have the potential to be widely applied as low cost, sustainable energy absorption structures. Unwoven

hemp exhibited an SEA value (54.3 J/g) comparable with carbon fibre (55.7 J/g). Woven flax had an SEA of 48.5 J/g and woven jute 32.6 J/g. The specific energy absorption was influenced primarily by fibre volume fraction (Vf) where a high Vf results in a high SEA. Significant variability in SEA resulted from the variation in fibre strength and Vf as a result of the VARTM manufacturing process. Unwoven hemp with its low embodied energy is a promising candidate for sustainable energy absorption structures.

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