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Partial replacement of E-glass fibers with flax fibers in composites and effect on falling weight impact performance

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The environmental advantage of using cellulose-based natural fibers in place of glass fibers as reinforcement for composite materials has been recognised in a number of LCA (Life Cycle Analysis) studies [1–3]. In automotive components, natural fiber composites are able to improve fuel efficiency, reducing emission of pollutants during component service. Moreover, natural fibers production presents lower environmental impacts than glass fiber production, and end-of-life incineration of natural fibers results in recovered energy [4]. It has also been recently estimated that carbon dioxide emissions would decrease by 3.07 million tonnes (4.3% of total USA industrial emissions) and crude oil consumption by 1.19 million m^3 (1.0% of total Canadian oil consumption) only by substituting 50% of glass fibers with natural fibers in North American automotive applications [5].

One of the principal requirements for a possible replacement of glass fibers with natural fibers in the automotive industry would be to obtain a sufficient crashworthiness of the final component. In this regard, falling weight tests are essential to measure materials resistance to impact. There is little coverage on literature about falling weight impact tests of natural fiber composites: initial work on jute fibers reinforced composites confirmed concerns on the inadequate impact performance unpredictability of impact damage patterns for these materials [6, 7]. In this context, partial substitution of glass fibers with natural fibers may have validity in itself, since the material will offer still environmental advantage when compared with glass fiber composites, while permitting to obtain a mechanical performance higher than using pure natural fiber composites. E-glass/natural fiber hybrid laminates were first studied several decades ago, alternating jute/polyester with glass/polyester layers [8]. More recently, a number of cellulose-based fibers have been coupled with glass fibers, providing sufficient static properties. However, the natural fibers were used mainly to reduce the weight of the laminate, and the route selected to obtain adequate impact properties was rather based on the improvement of matrix properties [9]. Other concerns over deceiving impact performance were raised when applying natural fibers layers to glass fibers reinforced laminates to improve the adhesion of glass fiber composites in bonded joints [10]. However, it might still be the case that the reduced impact properties obtained adding natural fibers to a glass fiber reinforced composite could be compensated, e.g., by modifying the component geometry or by improving the manufacturing process. If this proves feasible, the optimal design of natural fiber composites would result in a compromise between weight gain i.e., volume of natural fibers introduced, and final crashworthiness of the component.

The study of hysteresis cycles obtained during falling weight impact tests proved useful to compare damage tolerance of different laminates [11] and suitable also to the examination of natural fiber composites [12]. As suggested in [13], an impact event on thick composite laminates consists of four phases: *stress wave propagation during elastic loading, squashing, hinge rotation*, and *elastic recovery* before the striker rebounds. If the energy is sufficient to produce damage on the non-impacted face or even penetration, the final phase results in structural closure, resembling a severe forming process.

Flax-epoxy laminates (dimensions 250 × 25 × 10 mm) were obtained by hand lay-up using different flax thread sizes (0.2, 0.9, and 2.3 mm). The maximum fiber content in weight obtained was dependent on the thread used, being 31% with the 0.2 mm, 55% with the 0.9 mm, and 56% with the 2.3 mm thread. To allow for a comparison, also E-glass/epoxy laminates were manufactured using the same procedure: in this case up to 67% wt. glass fibers were introduced.

Initially, quasi-static three-point bending tests have been performed on an INSTRON 4302 testing machine, using a 10 kN load cell. The specimens were supported in a three-point bending rig with a 200 mm span and impacted with a 12.7 mm impactor. Using the same bending rig also falling weight impact tests were carried out, using a Rosand IFW5 impact tower with height varying from 0.5 to 1 m, using masses from 2.5 to 10.5 kg. From force vs. deflection hysteresis cycles, a number of variables were measured. These included the slope of the elastic part of impact curve (*linear stiffness*), the *maximum load*, reached at the end of the elastic phase, and the *final load drop*, obtained during hinge rotation, which indicates damage severity on the laminate and depends on how long the squashing phase was protracted.

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TABLE I Impact and flexural failure energies on laminates (average on 5 specimens)

Flax thread diameter (mm)	Fiber content (% in weight)	Impact penetration energy (J)	Static flexural energy (J)
Flax/epoxy (0.2 mm thread)	31	16	15.9
Flax/epoxy (0.9 mm thread)	53	17.8	16.6
Flax/epoxy (2.3 mm thread)	50	16	15
E-glass/epoxy	67	78	69.1

TABLE II Variables obtained from the impact hysteresis cycle analysis on flax-epoxy specimens, all impacted at 15 J

Flax thread diameter (mm)	Linear stiffness (N/mm)	Max. load (N)	Load drop (% Max. load)
0.2	113.4	1514	76.6
0.9	162.8	1954	10.3
2.3	115.5	1583	88.1

For a preliminary assessment of static and impact properties on flax/epoxy laminates and E-glass/epoxy laminates, penetration energies from impact tests were compared with energy at failure obtained by integrating flexural force vs. deflection curves. Penetration energy values measured on all flax/epoxy laminates closely matched static flexural energy values (Table I). This is likely to indicate a low strain rate effect for the material, although of course the absolute values measured are not comparable with those yielded by the E-glass/epoxy laminates, where moreover the introduction of a larger volume of reinforcement was possible. The 0.9 mm thread conferred a slightly superior impact resistance to the laminates, resulting in the penetration energy value being approximately 10% higher, as confirmed by the results obtained from hysteresis cycles (Table II).

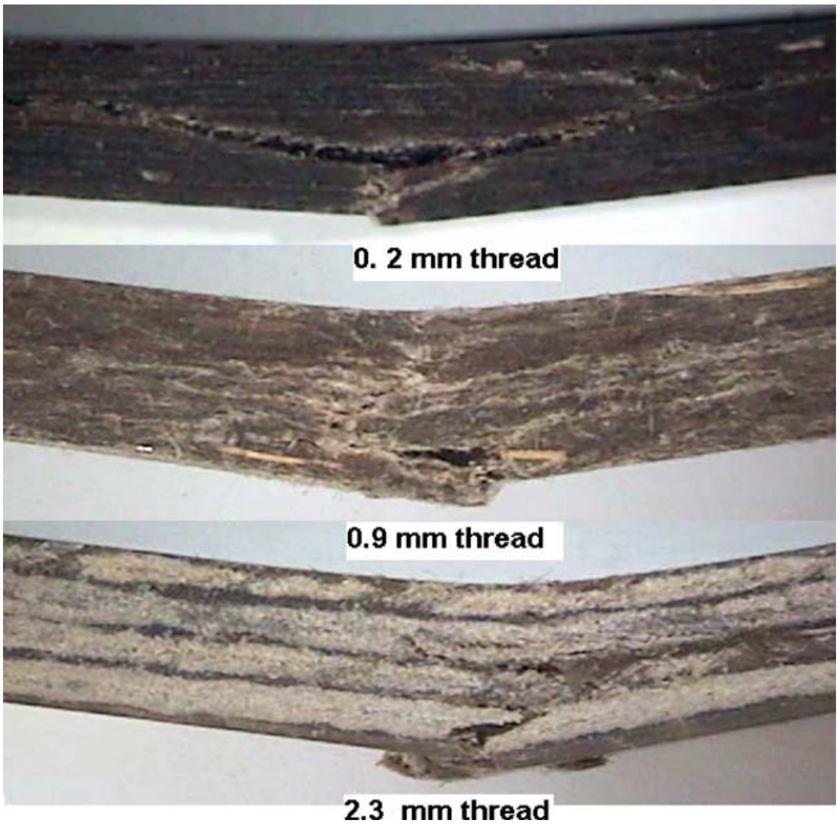


Figure 1 Progression of impact damage on flax-epoxy laminates manufactured with different thread diameters.

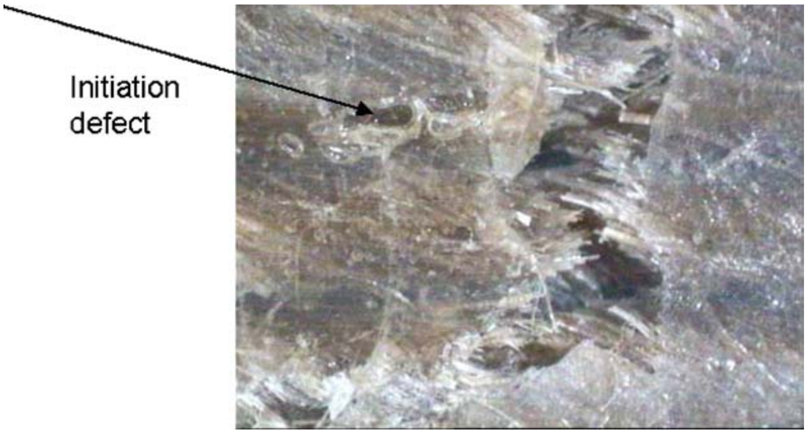


Figure 2 Propagation of impact damage in flax-epoxy (0.9 mm thread) laminate from a sub-surface defect.

Figure 3 Sub-surface defects in a flax-epoxy laminate.

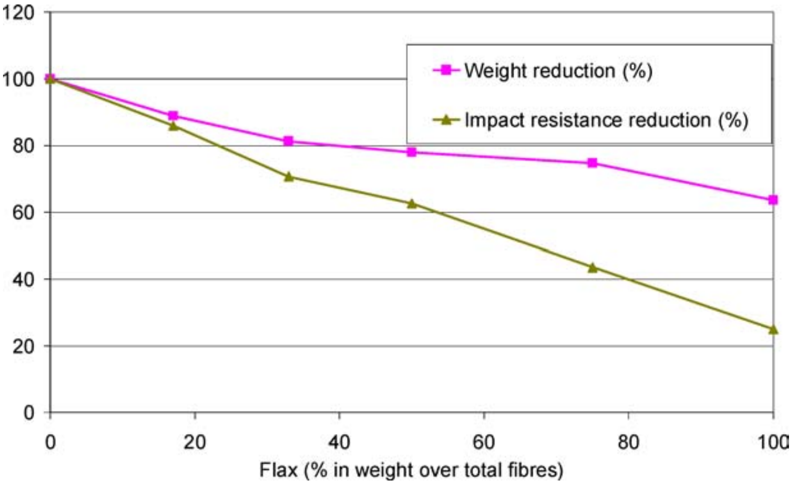


Figure 4 Weight gain and impact resistance reduction for replacement of E-glass fibers with flax fibers.

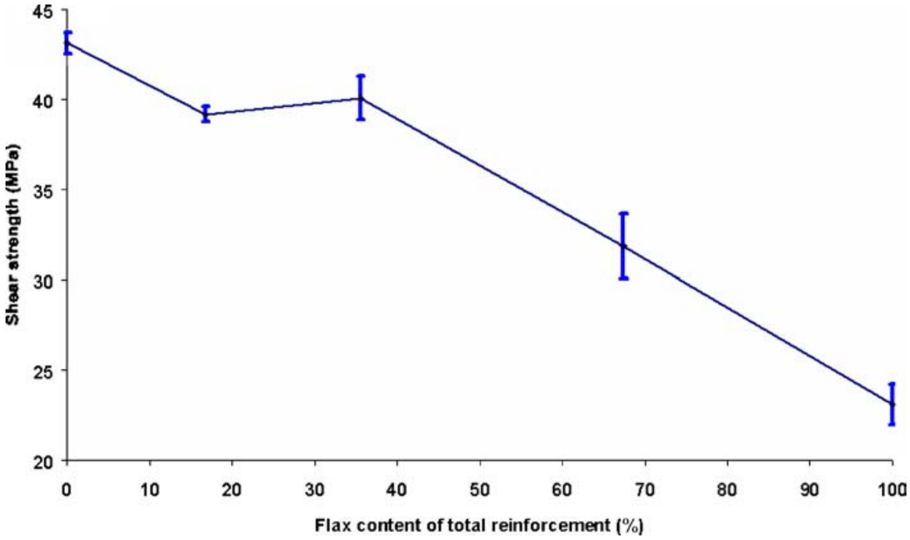


Figure 5 Shear strength of hybrid laminates with different flax fiber content.

Impact damage characterization indicated also that the use of 0.9 mm thread resulted in better fiber impregnation, as reflected in the presence of the reversed-pine pattern of impact damage cracks, typical of a sufficiently strong fiber–matrix interface [14]. This is in contrast with what shown by the other laminates, which present more localized cracks, due to not sufficient fiber impregnation and presence of voids in the matrix: mode of failure in the three laminates are compared in Fig. 1. In spite of its better performance, the 0.9 mm thread laminate was not exempt from defects: Fig. 2 shows a sub-surface processing defect, which acted as initiator for impact failure. Because of the large stress concentrations in the vicinity of the defect, they can give rise to the propagation of cracks into the matrix, eventually triggering the delamination of lower layers [15]. Interlaminar strength did not appear to have a clear relation with impact resistance. In practice, it has been noted already that in plant fiber reinforced composites improving the adhesion between layers does not always

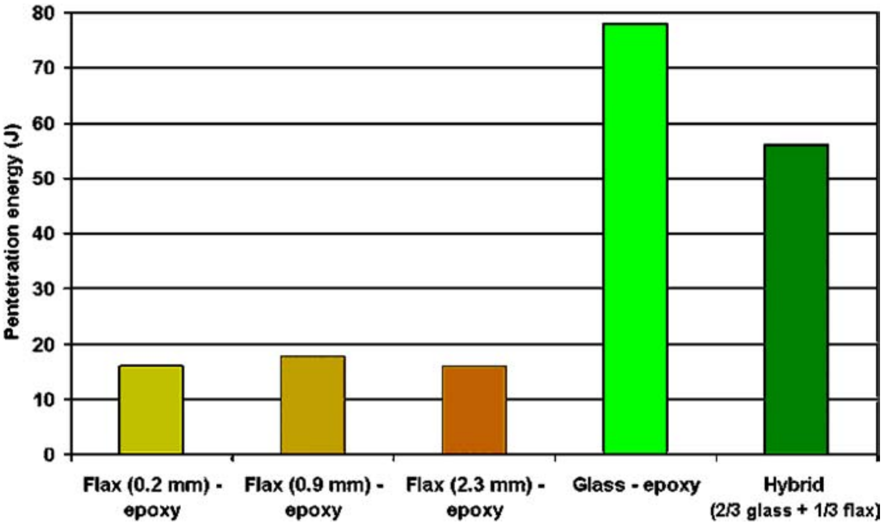


Figure 6 Comparison of impact resistance in different laminates.

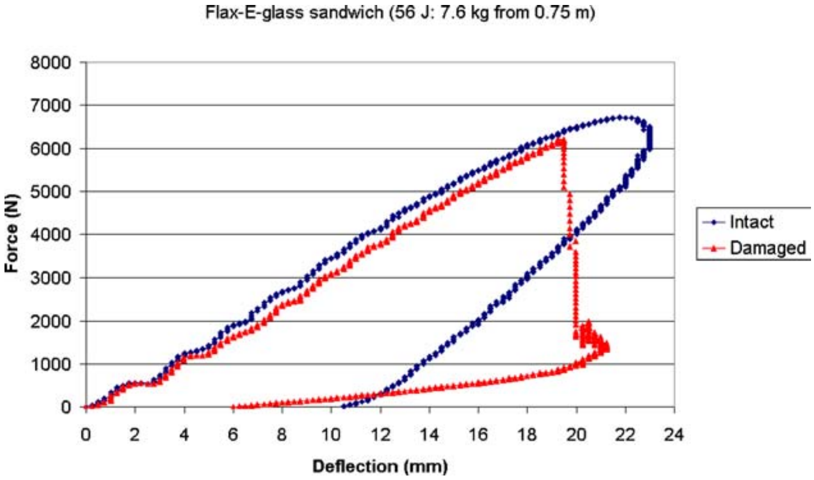
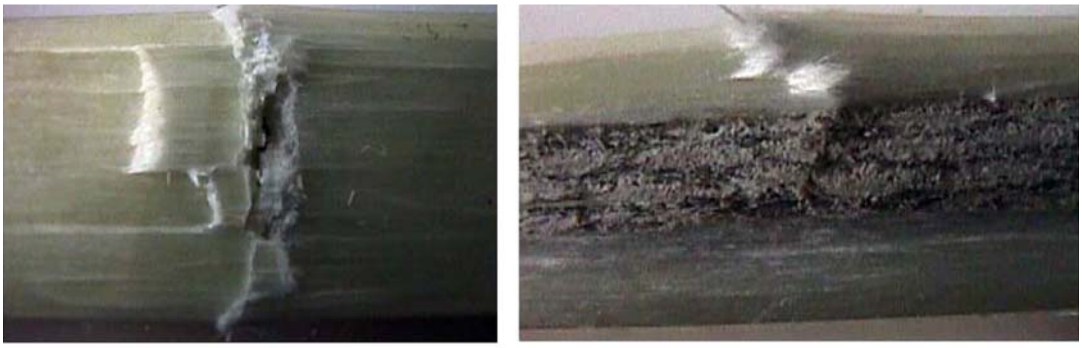


Figure 7 Force vs. deflection curves on two hybrid laminates both impacted at 56 J, one intact and one previously impacted at 42 J (80% of penetration energy).


Impacted face

Side

Figure 8 Impact damage in E-glass/flax fiber reinforced hybrid laminate.

result in a tougher material, the effect of defects being much more critical [16]. A number of sub-surface defects are for example highlighted in Fig. 3. This is even more difficult when dealing with impact properties, which are very sensitive to the presence of defects, especially if they are large enough to result in appreciable disruptions of the laminate geometry [17].

In view of its better properties, 0.9 mm flax thread was exclusively used to produce hybrids, using different proportions of flax/epoxy layers as core sandwiched between E-glass/epoxy skins. As suggested above, hybrids manufacturing was intended primarily to compare decrease in impact properties with weight reduction in the laminate, due to the introduction of flax fibers. In this regard, introducing some flax fibers (in proportions up to $1/3$) resulted in a moderate reduction of impact properties, but still in a considerable weight gain (Fig. 4). In this proportion, flax fibers in the core proved able to protect the non-impacted side from delamination up to impact energies approaching 50 J. However,

TABLE III Variables obtained from the impact hysteresis cycle analysis on hybrid laminates (2/3 glass/epoxy + 1/3 flax/epoxy)

Impact energy	Condition	Linear stiffness (N/mm)	Max. load (N)	Load drop (% Max. load)
52 J	Not impacted	277.4	5650	6.2
52 J	Previously impacted at 40 J	270.3	5690	52
56 J	Not impacted	247.4	5979	74.8
56 J	Previously impacted at 45 J	242.9	5807	76.1

exceeding that amount of flax fibers has a more severe effect on impact strength, partially due to the manufacturing process adopted, which does not allow sufficiently high volumes of untreated flax fibers to be introduced. This is confirmed by the interlaminar shear strength results (Fig. 5), which suggest that an introduction of flax fibers not exceeding 40% of total amount of reinforcement does not lead to a significant decrease in shear properties. In practice, hybrids obtained with $2/3$ glass fibers + $1/3$ flax fibers show a reduction of impact properties of approximately 25% with an average weight gain of 12% (Fig. 6).

On the $2/3$ glass + $1/3$ flax hybrids, the aspect of post-damage residual impact properties has also been considered: Fig. 7 shows the effect of a previous impact on a hybrid laminate, resulting in a decrease by more than 10% of the maximum load the material is able to withstand. As a matter of fact, previous results in literature suggested that untreated plant fibers, like the one used in this investigation, are more prone to debonding in correspondence with defects, and this reduces their resistance to repeated impacts [6]. In this case, their unsatisfactory performance was ascribed to an imperfect mould closure, which resulted in a scarce thickness control on the laminates. This was addressed by slightly modifying the mould: as a consequence, following mouldings did not show this problem, so that here the effect of previous impact loading on final performance appears to be modest, as depicted in Table III. In addition, as shown in Fig. 8, the vertical matrix crack appears to lead to efficient stress redistribution in the flax core, so that the energy dissipated is sufficient in this case (impact at 50 J) to hinder damage propagation in the whole of the sandwich.

Conclusive observations should refer to the fact that, in spite of limitations owed to the manufacturing procedure employed, the flax fiber reinforced core in the hybrid laminates showed an appreciable action of impact damage dissipation. This may suggest that limited substitution of flax fibers to glass fibers is a strategy practicable in structural components, after addressing material processing and fiber extraction issues. Flax-epoxy laminates and hybrid E-glass/epoxy-flax/epoxy laminates provided a sufficient impact performance with a considerable weight reduction with respect to fiberglass. Areas of concern for these laminates are the need for control over void content and defects, and the requirement of further studies on the effect of damage on performance, especially when the material undergoes repeated impact events.

Further work should therefore involve using more refined manufacturing technologies, e.g., vacuum-assisted resin transfer molding or injection molding, for a more accurate dimensional control over the composite. Moreover, using enzyme-retted fibers would result in improved matrix–fiber compatibility, while reducing the penalty of mechanical deterioration and limiting chemical treatments and associated costs.

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