EFFECTS OF THE NATURAL FIBER STITCHING ON THE IMPACT AND COMPRESSION AFTER IMPACT RESPONSE OF THE FLAX/EPOXY COMPOSITES

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Abstract
In this study, the influence of stitching with natural fibers on the impact and post impact properties of the flax fiber laminates were experimentally investigated. The twistless flax yarn and twisted cotton thread were used to stitch four layers of flax woven fabric together at an equivalent stitch density. Unstitched cross-plies $[0,90]_{4s}$ of continuous flax fibers were also manufactured at a similar thickness for benchmarking. The flax/epoxy composites were prepared by vacuum assisted resin infusion. The low-velocity drop weight impact test were conducted at two different energy levels to attain both non-perforation and full perforation impact, in order to assess the impact damage resistance and impact energy absorption behavior of the composite. The damage tolerance of the stitched and unstitched flax fibers composites were evaluated by means of the compression after impact test. The stitched laminates was found to absorb slightly more impact energy by facilitating formation of cracks in the laminates at non-perforation impact. They also showed lower residual effective stiffness compared to unstitched laminate. In the all laminates, fiber failure was the dominant failure mode under impact load.

1. Introduction

The use of natural plant fibers as reinforcement in the polymer composites is becoming more common due to their promising properties such as high specific stiffness, good acoustic insulation and vibration damping, and less environmental impacts [1]. Among the various plant fibers with such desirable characteristics, flax fibers possess the higher performance in terms of strength and stiffness per density, which makes them suitable reinforcing fibers for many applications. In order to utilize the maximum load carrying capacity of the flax fibers, it is necessary to use them in the form of long continuous uni-directional or textile woven by optimally twisted yarns in the laminate composites [2,3].

Generally, one of the most important failure modes in the laminate composites is the interlaminar failure or delamination. Through-the-thickness stitching of the fiber preforms is a convenient and cost-effective technique which is commonly used to improve the interlaminar properties of the laminates [4,5]. However, it can also influence on the other characteristics such as impact resistance and damage tolerance of the composites [6,7]. Unlike the man-made fiber reinforced composites, the influence of stitching on the properties of natural fiber composites is seldom reported. Rong et al. [8] carried out an investigation on the factors that influence in-plane mechanical responses and mode I interlaminar

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fracture toughness of unidirectional sisal/epoxy laminates stitched by Nylon and Kevlar threads. It was found that tensile and flexural properties were not significantly affected by stitching, while the delamination resistance was improved via an expanded fiber bridging zone.
In general, the performance of the structures made of composite laminates are susceptible to transverse impact damages caused by low velocity incidents such as tool dropping during manufacturing, stone or debris strike, etc. Hence, low-velocity impact behavior of composite laminates is one of the major design concerns of structures made of these materials. In this regards, the low-velocity impact response and post impact behavior of natural fiber composites laminates have been studied by some authors [9–19] to understand their functionality under impact loading. Dhakal et al. [15] showed that the low-velocity impact properties of non-woven hemp fiber laminates with higher volume fraction (V_f) in terms of impact energy absorption is comparable to the chopped mat E-glass fiber composites with equivalent V_f. Vasconcellos et al. [13] has reported the experimental results of the impact resistance of plain woven hemp/epoxy composite laminates at three different impact energies and the post impact behavior by means of tensile and tension-tension fatigue tests. They observed that the influence of impact damage on the residual tensile stiffness of the impacted specimens was very small. As of today, no previous work has been reported on the influence of through-the-thickness reinforcing on the low velocity impact performance of the NFCs in literature.
This paper presents an experimental investigation on the influences of stitching using natural fibers, firstly, on the impact behavior and secondly, residual compressive properties of the flax fiber laminates. The twist-less flax yarn and twisted cotton thread were used to stitch four layers of the flax woven fabrics at an equivalent and optimum stitch density. Unstitched cross-plies $[0,90]_{4s}$ of continuous flax fibers were also manufactured at similar thickness for benchmarking. The Low-velocity drop weight impact test were conducted at two different impact energies, 19.6J and 44.6J, to assess the impact damage resistance and impact energy absorption behavior. Finally, the influence of impact damage on the residual compressive properties were evaluated by compression after impact (CAI) test.

2. Experimental

2.1. Material preparation

2.1.1. Material

A low-viscosity thermo-set resin system Epolam 5051 (mixed viscosity: 200 mPa.s at 25℃) was used as polymer matrix. The fiber preforms were made by woven 4×4 hopsack standard fabric (Composite Evolution, UK) and UD flax fibres (LINEO, Belgium). Stitching of the preforms were conducted using 30tex cotton thread (Gütermann, Greece) and 250tex twistless flax yarn (Composite Evolution, UK).

2.1.1. Preform stitching and composite manufacturing

The stitching of woven preforms were carried out at an optimum stitch density using 250tex flax yarn and 30tex cotton thread [20]. The cotton thread stitching process were conducted using commercial sewing machine and the flax yarn stitching were performed manually. Stitching conducted at warp (x) direction at S_R =4mm (stitch row spacing) and (stitch length) S_L=3mm for cotton thread and S_R =8mm and S_L=8mm for flax yarn to achieve an equivalent stitch areal density. The stitch parameters were shown in Fig. 1.

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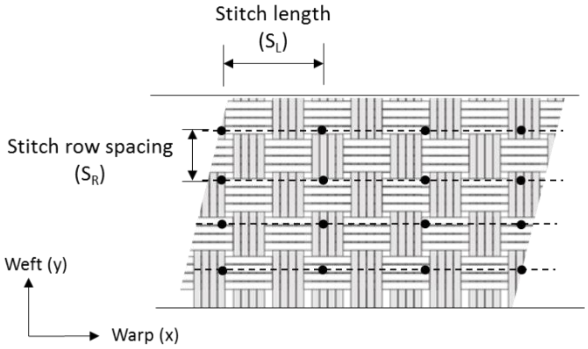

Figure 1. definition of the stitch parameters

The composites of the prepared preforms and the epoxy resin were processed by Vacuum Assisted Resin Infusion (VARI) technique. The detail information about the fabricated composite laminates in this study are presented in Table 1.

Table 1. Summary of composite lay-ups, notation and stitch parameters of the manufactured flax fiber laminates.

Flax Lamina preform	Laminate nomenclature	Areal density of lamina [g/m^2]	Layup	Stitch material	V_f (%)
4×4Plain Weave	PW0	500	$[0]_4$	-	30
	PWC		$[0]_4$	Cotton	
	PWF		$[0]_4$	Flax	
Unidirectional	UD0	110	$[0/90]_{4s}$	-	40

2.2. Specimen preparation and testing

The test specimens of 100x150 mm were cut from the original composite laminates using water-jet cut. The thickness of the laminates was 4±0.25 mm and the coefficient of variation for each specimen thickness measurement was less than 2%. Before testing, the specimens were placed in the oven for 24 hrs. at 60°C to dry the moisture induced during cutting process. The tests were conducted at temperature of 23°C and a relative humidity of 65%. All the specimens were exposed to test condition at least 48 hours. prior to testing.

2.3. Drop-weight impact test

Drop-weight impact test was performed to study the behavior of the unstitched and stitched woven fabric as well as cross-ply flax fiber laminated under low velocity impact in accordance with ASTM standard D7136. For each type of sample and energy level, three specimens were tested. The weight of the impactor was 9.99 kg with a striker diameter of 20 mm. The impact force-time history was obtained from impactor force sensor and the contact velocity was measured using high speed camera. The incident energy of 19.6J and 44.6J was chosen to induce non-perforation but visible damage and full perforation impact, respectively.

3. Results and Discussion

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3.1. Impact resistance

Impact resistance is defined as the ability of a material to resist permanent changes due to a loading event beyond the design load. In this study the low velocity impact resistance of flax fiber composite laminates is characterized using a drop weight impact test. The specimens after impact test were inspected visually to identify the external and visible damages.

3.1.1. Non-perforation impact test (19.6J)

The impacted woven and cross-ply flax specimens are shown in Fig. 2. It was observed that for all woven flax fiber laminates (PW0, PWC, PWF), cross-shaped fiber breakage dominant crack formed at both the impact and the back surfaces of the specimens. Comparison between the unstitched and stitched specimens showed that the fracture mechanism were more or less identical. However, crack length along both directions were slightly longer for the stitched specimens. The difference in the crack lengths are about 10mm and 6mm in the longitudinal and transverse direction respectively. This can be attributed to the defects such as in-plane fiber damage and resin-rich spots created by stitching. For the cross-ply laminate of UD flax fiber (UD0), combination of matrix failure (transvers crack) and fiber breakage (longitudinal crack) formed cross-shaped damaged at the back surface of the specimens. At the impacted face, besides the superficial crushing at the impact location, a dominant matrix crack along the fiber direction as well as a visible peanut-shape delamination zone were observed.

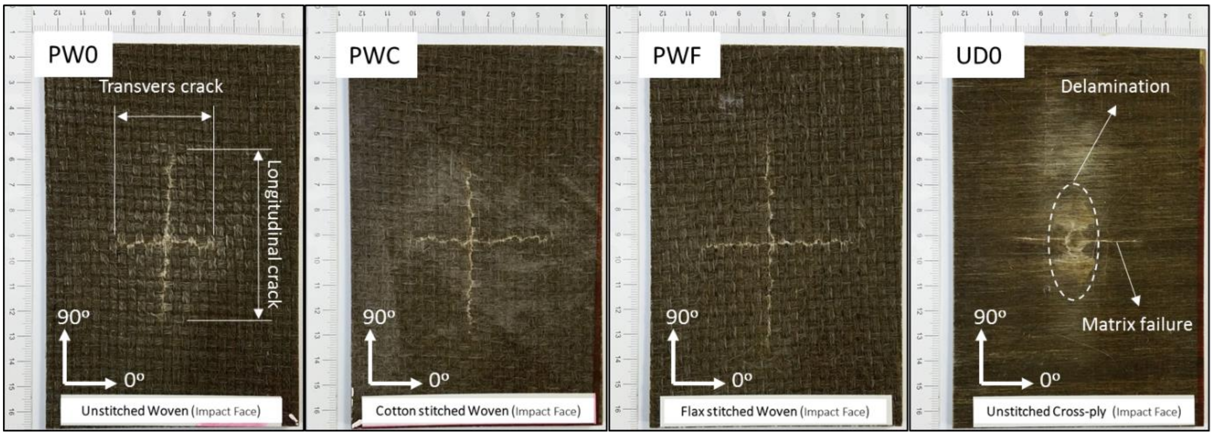

Figure 2. Damage on the impact face of the specimens under 19.6J impact energy (non-perforation).

3.1.2. Perforation impact test (45J)

Fig. 3 shows the impact faces of the specimens tested at 44.6J. It can be seen that the overall damage shape and size of the woven laminates were very similar. The damage formed was a circular hole with relatively big diameter created by the impactor. On the impact face of the cross-ply laminate, besides fiber and matrix failure, visible delamination was also observed. This means that part of the impact energy were dissipated by creating delamination.

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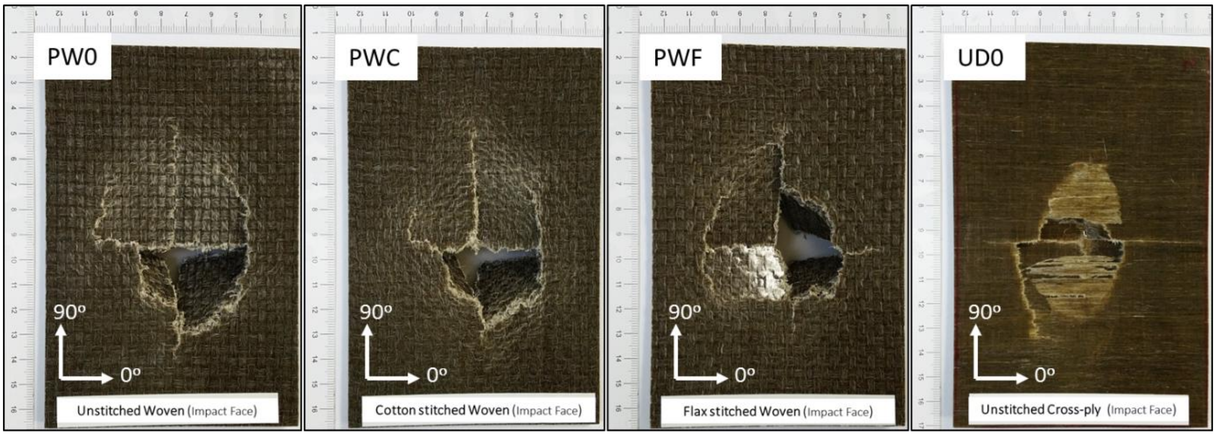

Figure 3. Damage on the impact face of the specimens under 44.6J impact energy (perforation).

3.2. Energy absorption

The energy absorbed by the specimen with time was measured by calculating the area under the force-displacement curve. This value of absorbed energy refers to the total amount of energy dissipated by the specimen through damage formation in the composite. Fig. 4 shows the absorbed energy per total impact energy ($E_{absorbed}/E_{impact}$) in percentage for both non-perforation and peforation impacts. At the non-perforation impact level (19.6J), it was observed that the absorbed energy per total impact energy ratio of the two stitched woven composite specimens were about 12-18% higher than that of the unstitched woven laminates. This corresponds to the longer crack lengths being observed in the stitched woven laminates (Fig. 2). In the case of full perforation impact, the energy absorption behavior of the all types of woven laminates are almost identical. This result is in consistent with the similar damage size of the woven laminates when subjected to high impact energy (Fig. 3). Unlike conventional glass or carbon fibre reinforced composites where low impact energy cracking tends to propagate through the matrix-rich inter-ply planes between the fibre layers, the strengths of the impregnated flax fibre and matrix are rather similar ([20,21]) which led to both fibre breakage and matrix cracking mechanisms to dominate in the transverse impact of natural fibre composite laminates. In full perforation impact,

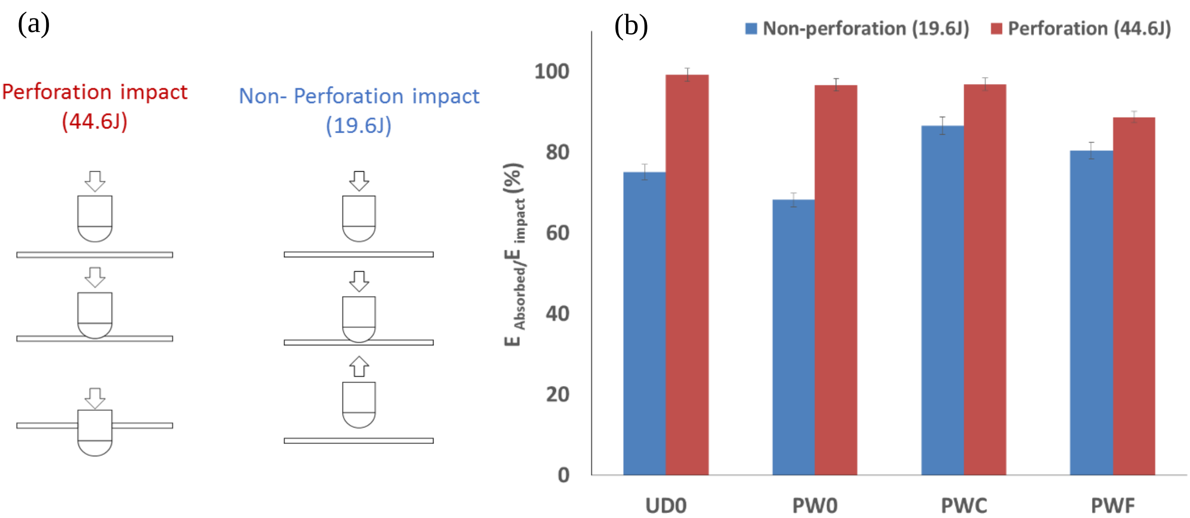

Figure 4. (a) Perforation versus non-perforation impact; **(b)** Absorbed energy per total impact energy of non-perforation and perforation impact.

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3.3. Force response

The typical force-time history of flax fiber laminates under drop-weight impact are shown in Fig. 5(a). The impact force increases linearly until reaches a characteristic force P_1 at which a change in the stiffness characteristics of the specimen occurs. P_1 is another indicator for the ability of a material to resist damage initiation [22]. Beyond P_1, the behavior of the impact force can be attributed to the damage development or delamination within the laminate.

Fig. 5(b) shows the damage initiation loads (P_1) for the different composite laminates. It can be seen that the value of P_1 of various specimens follows a similar pattern for both non-perforation and perforation impact tests. Impact on the cross-ply UD laminates generate a higher P_1 than (unstitched and stitched) woven laminates, suggesting that for laminates of similar thicknesses, the cross-ply unstitched UD fibre orientation offers the highest protection against impact damage initiation. This can be largely attributed to the higher fiber volume fraction (V_f=0.4) of the UD0 laminate that resulted from the more compact packing of cross-ply UD fibres, which translates to higher tensile properties, stiffness and strength over the lower V_f woven laminates.

For the three woven composites which are of similar V_f (=0.3), the stitched specimens regardless of the type of stitching fibre used (cotton thread or flax yarn) always led slightly lower values of P_1. It has been well documented that stitching could disrupt the in-plane fibre alignment and increase the matrix-rich regions between the woven fibre tows [23]. Although the effect is expected to be less detrimental in natural fibre composites due to the lower fibre strengths, Fig. 5(b) shows that these stitch-induced defects could still lead to damage initiation at lower loads under transverse impact loading. The drop in P1 of 8% is however less significant than for high strength fibre reinforced polymer composites.

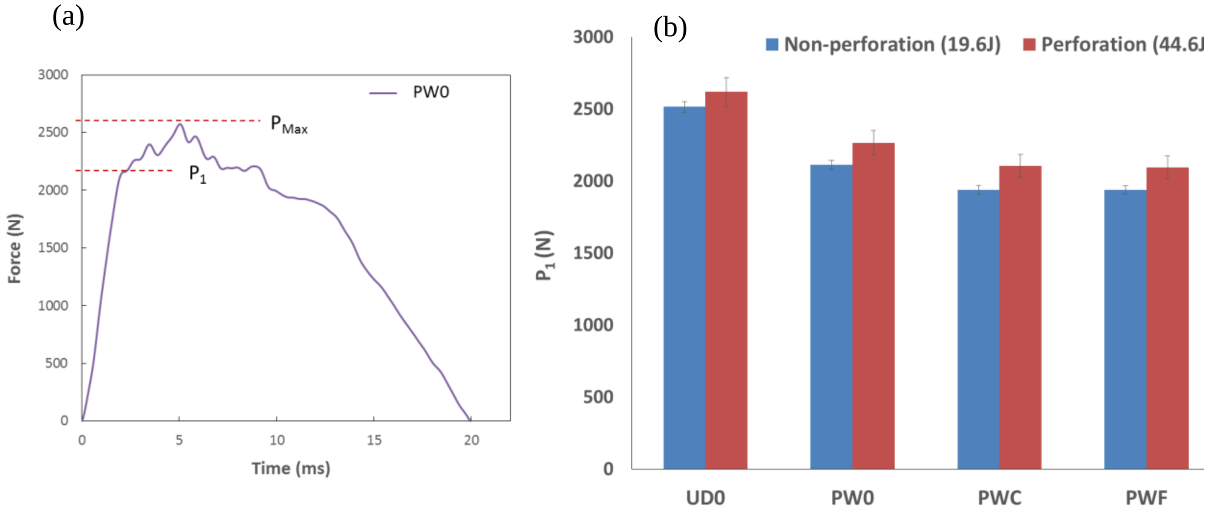

Figure 5. (a) Typical impact force-time response of a flax fiber composite; **(b)** Damage initiation force (P_1) for the different laminates subjected to non-perforation and perforation impact.

3.4. Compression after impact (CAI)

The Compression After Impact (CAI) test as shown in Fig. 6(a) were carried out to investigate the structural behavior of the flax fiber composite after being damaged by low velocity impact. The effective compressive stiffness against the impact energies are plotted in Fig. 6(b). Undamaged specimens (i.e. intact panels that were not subjected to impact tests), showed a range of effective stiffness from 4.5-6.5 GPa, with the highest values coming from the woven (PW0) and flax stitched woven (PWF) panels. For the non-perforated panels from the 19.6J impact tests, it is evident that the reduction in the effective stiffness for stitched specimens is larger than unstitched laminates, particularly for the flax stitched woven (PWF) panels. This is likely due to the more extensive damage sustained earlier from the impact

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tests. For the perforated panels from the 44.6J impact tests, all specimens exhibit lower, but similar values of the effective stiffness of 3-4GPa. This can be due to two factors: firstly, the size of damage zone for the all specimens is almost identical, and secondly, the boundary effects of the support fixture are significant, because the area of impact-induced damage is large respect to the total area of the specimen.

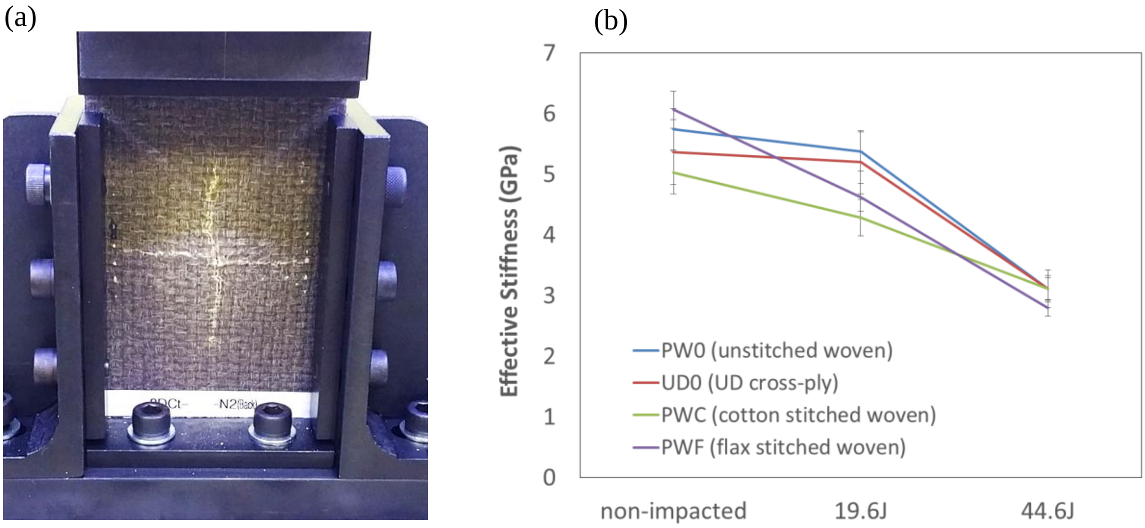

Figure 6. (a) Compression after impact (CAI) test of flax fiber composite; **(b)** Effective stiffness of composite panels against impact energy.

3. Conclusions

This study experimentally investigates the effects of natural fiber stitching on low-velocity impact response and compression after impact (CAI) stiffness of the continuous flax/epoxy composite laminates. The flax and cotton stitched composites showed similar impact response despite differences in fiber type and thickness. The initiation force (P_1) for stitched woven flax laminates were lower than the unstitched one, which was attributed to lower crack resistance of the resin-rich regions that reside between the stitch loops. However, stitched laminates did led to >10% higher energy absorption during non-perforation impact testing and longer cracks were observed. At higher impact energies in the full perforation case, the efficiency of absorbed energy over impact energy all exceeded 90%, and very similar degree of perimeter damage joining the transverse and longitudinal crack tips were observed. The CAI test results were in good alignment with the impact damage incurred, where lower effective stiffnesses were measured for samples with larger damage zone, and a convene of values were observed for the 44.6J impact damaged specimens with similar energy absorption efficiencies.

References

[1] Dicker MPM, Duckworth PF, Baker AB, Francois G, Hazzard MK, Weaver PM. Green composites: A review of material attributes and complementary applications. Compos Part Appl Sci Manuf 2014;56:280–9.
[2] Goutianos S, Peijs T, Nystrom B, Skrifvars M. Development of Flax Fibre based Textile Reinforcements for Composite Applications. Appl Compos Mater 2006;13:199–215.
[3] Shah DU, Schubel PJ, Clifford MJ, Licence P. Fatigue life evaluation of aligned plant fibre composites through S–N curves and constant-life diagrams. Compos Sci Technol 2013;74:139–49.

Excerpt from ISBN 978-3-00-053387-7

[4] Tong L, Mouritz AP, Bannister M. 3D Fibre Reinforced Polymer Composites. Elsevier; 2002.
[5] Tan KT, Watanabe N, Sano M, Iwahori Y, Hoshi H. Interlaminar Fracture Toughness of Vectran-stitched Composites - Experimental and Computational Analysis. J Compos Mater 2010;44:3203–29.
[6] Lopresto V, Melito V, Leone C, Caprino G. Effect of stitches on the impact behaviour of graphite/epoxy composites. Compos Sci Technol 2006;66:206–14.
[7] Tan KT, Watanabe N, Iwahori Y. Effect of stitch density and stitch thread thickness on low-velocity impact damage of stitched composites. Compos Part Appl Sci Manuf 2010;41:1857–68.
[8] Rong MZ, Zhang MQ, Liu Y, Zhang ZW, Yang GC, Zeng HM. Effect of Stitching on In-Plane and Interlaminar Properties of Sisal/Epoxy Laminates. J Compos Mater 2002;36:1505–26.
[9] Scarponi C. 12 - Impact behavior of natural fiber composite laminates. In: Zafeiropoulos NE, editor. Interface Eng. Nat. Fibre Compos. Maximum Perform., Woodhead Publishing; 2011, p. 341–82.
[10] Dhakal HN, Skrifvars M, Adekunle K, Zhang ZY. Falling weight impact response of jute/methacrylated soybean oil bio-composites under low velocity impact loading. Compos Sci Technol 2014;92:134–41.
[11] Petrucci R, Santulli C, Puglia D, Nisini E, Sarasini F, Tirillò J, et al. Impact and post-impact damage characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion. Compos Part B Eng 2015;69:507–15.
[12] Liang S, Guillaumat L, Gning P-B. Impact behaviour of flax/epoxy composite plates. Int J Impact Eng 2015;80:56–64.
[13] de Vasconcellos DS, Sarasini F, Touchard F, Chocinski-Arnault L, Pucci M, Santulli C, et al. Influence of low velocity impact on fatigue behaviour of woven hemp fibre reinforced epoxy composites. Compos Part B Eng 2014;66:46–57.
[14] Dhakal HN, Zhang ZY, Bennett N, Reis PNB. Low-velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites: Influence of impactor geometry and impact velocity. Compos Struct 2012;94:2756–63.
[15] Dhakal HN, Zhang ZY, Richardson MOW, Errajhi OAZ. The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites. Compos Struct 2007;81:559–67.
[16] Scarponi C, Pizzinelli CS, Sánchez-Sáez S, Barbero E. Impact load behaviour of resin transfer moulding (RTM) hemp fibre composite laminates. J Biobased Mater Bioenergy 2009;3:298–310.
[17] Caprino G, Carrino L, Durante M, Langella A, Lopresto V. Low impact behaviour of hemp fibre reinforced epoxy composites. Compos Struct 2015;133:892–901.
[18] Santulli C, Caruso AP. Effect of Fibre Architecture on the Falling Weight Impact Properties of Hemp/Epoxy Composites. J Biobased Mater Bioenergy 2009;3:291–7.
[19] Bensadoun F, Depuydt D, Baets J, Vuure V, Willem A, Verpoest I. Influence of fibre architecture on impact and fatigue behaviour of flax fibre-based composites. 19th Int. Conf. Compos. Mater. ICCM19 Montr. Can. 2013, 2013.
[20] Ravandi M, Teo WS, Tran LQN, Yong MS, Tay TE. Effect of through-the-thickness stitching and fibre architecture on the interlaminar properties of flax/epoxy laminates. Proc. 20th Int. Conf. Compos. Mater. ICCM-20 Cph. Den. July 19-24, 2015.
[21] http://www.axson-na.com/TDSs/TDS - Epolam 5015 System. Epolam 5015-5014-5016 n.d.
[22] D30 Committee. Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. ASTM International; 2012.
[23] Yudhanto A, Watanabe N, Iwahori Y, Hoshi H. Effect of stitch density on tensile properties and damage mechanisms of stitched carbon/epoxy composites. Compos Part B Eng 2013;46:151–65.

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