Effects of impactors' shape on three-dimensional woven fabric composites at low-velocity impacts

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ABSTRACT – REZUMAT

Effects of impactors' shape on three-dimensional woven fabric composites at low-velocity impacts

This study investigated the fabric resistance of three-dimensional (3D) woven fibreglass composites generated by impactors of three shapes, i.e., hemispherical, conical, and ogival, on four types of composite structures. Composites were fabricated using the hand lay-up technique. Crimp and mechanical impact resistance tests were carried out in accordance with ASTM D2444 standards and ASTM D3883-04, respectively. The four-floating interlocked (4FLL) yielded the strongest fabric damage tolerance for all the three types of impactors' shapes with 6.3 kN for the hemispherical shape, 4 kN for the conically shaped, and 3.8 kN for the ogival shape. Additionally, the 4FLL generated a fabric crimp of 3.5% and 2.8% on both fabric directions. The post-impact damage showed that the ogival shape impactor penetrated samples of woven composites better than the conical and hemispherical shapes.

Keywords: *woven, composites, impact, impactors' shape, fibreglass*

Influența formei elementelor de impact asupra compozitelor țesute tridimensionale la impact cu viteză redusă

Acest studiu a investigat rezistența materialului compozitelor din fibră de sticlă țesute tridimensionale (3D) generate de elementele de impact cu trei forme, adică emisferice, conice și ogivale, pe patru tipuri de structuri compozite. Compozitele au fost fabricate folosind tehnica de întindere manuală. Testele de rezistență la ondulare și impact mecanic au fost efectuate în conformitate cu standardele ASTM D2444 și, respectiv, ASTM D3883-04. Țesătura de tip interlock cu 4 flotări (4FLL) a înregistrat cea mai ridicată toleranță la deteriorare pentru toate cele trei tipuri de forme de impact, cu 6,3 kN pentru forma emisferică, 4 kN pentru forma conică și 3,8 kN pentru forma ogivală. În plus, 4FLL a generat o ondulare a țesăturii de 3,5% și 2,8% pe ambele direcții. Daunele post-impact au arătat că elementul de impact cu formă ogivală a pătruns probele de compozite țesute mai bine decât cel cu formă conică și emisferică.

Cuvinte-cheie: *țesut, compozite, impact, forma elementelor de impact, fibra de sticlă*

INTRODUCTION

Woven composites are often created by combining technical textiles with dissimilar properties and adhering them together using polymer resin to create a superior product that can be utilised for a variety of technical applications [1]. The advancement of woven composite materials has been rapid due to superior features such as a high stiffness-ta high stiffness-to-weight ratioigue life. To date, both conventional two- (2D) and three-dimensional (3D) woven fabrics emerge as popular choices for various technical applications in sectors such as aerospace, shipping, and transportation.

In general, the 3D woven fabric is made by interlacing warp, weft, and z-yarn [2], with yarns assembled in the direction of the warp and weft. The yarn friction generated from this positioning is crucial in conferring the woven fabric agility against the smack of rupturing force [3]. 3D woven are made by interlacing yarns in lengthwise (X), crosswise (Y), and vertical (Z) [4]. The yarn's interweaving undulation movement has also caused another pertinent condition, i.e., the fabric crimp. Studies showed that the fabric crimp could significantly influence the mechanical strength, particularly on tensile and impact resistance performance, depending on the fraction of fabric crimp [5–7]. Through-thickness yarn plays a pivotal role in establishing the structurally intact three-dimensional fabric by binding non-crimp warp and weft yarn in the thickness direction [8]. Because 3D textiles are more resistant to delamination, the composite significance has progressed quickly [9, 10].

Meanwhile, minimising the damage against low-velocity impact has become one of the most crucial issues in fabricating the woven composite, especially in the application of aeroplane body parts. Low-velocity impacts against woven composite surfaces lead to matrix cracking, thus weakening the integrity of the structure. The damage is difficult to detect since it is not visible on the surface. If uncorrected, the structure's integrity will eventually fail and break apart, leading to catastrophic failure during its use.

Extensive studies had been conducted to optimise the reduction of impact damages on woven fabric composites. Comparative studies showed that owing to the structure of the yarn interlacement', the 3D woven fabrics were able to maximise their impact resistance by eliminating the delamination. In this regard, the three-dimensional angle-interlocked is adequate for bulletproof protection, with delamination resistance higher than the laminated composite in the in-plane modulus [11]. Also, this composite showed higher resistance against impact owing to its ability to absorb a high capacity of energy by the z-direction fibres [12].

Meanwhile, the orthogonal weave attempts to move the warp at 90 degrees through fabric thickness for enhanced binding and organisational coherence structure [13]. This binder yarn increases modulus, resulting in greater shear and torsional strength and resistance to delamination [14]. Three-dimensional orthogonal composites, in particular, exhibited exceptional energy absorption for low momentum impact by spreading the damaging waves away from the impact zone more quickly [15]. Besides, this composite had a remarkable impact resistance since no delamination occurred when impacted with a conical cylindrical steel projectile owing to the presence of z-yarns in the direction of thickness [16].

The resistance of four different types of three-dimensional woven fabric fibreglass composites to a low-velocity drop-weight impact force was tested in this study. This study also determined the effects of impactors' shape on these three types of impactors (hemispherical, conical, and ogival). This study would significantly help optimise the yarn float length manipulation on 3D woven fabric–structure against impact resistance performance.

METHODOLOGY

Woven fabrics and composite fabrication

This study evaluated four types of 3D woven fibreglass fabrics: one-floating interlocked (1FAI), three-floating interlocked (3FALI), nine-floating interlocked (9FAI), and four-floating interlocked (4FLL), and figures 1, 2, 3, and 4 show their respective transversional view. The matrix of these fabrics comprised the Morcrete BJC39 epoxy resin and hardener HY225. Table 1 summarises the properties of the epoxy resin. The fibreglass mingled well with the epoxy, producing composites with robust and high mechanical performance.

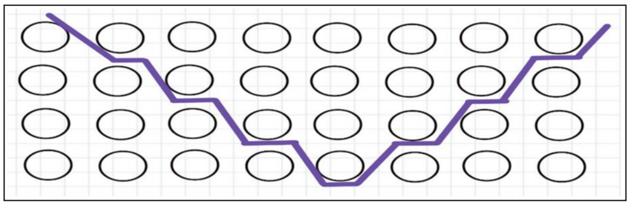

Fig. 1. The 1FAI

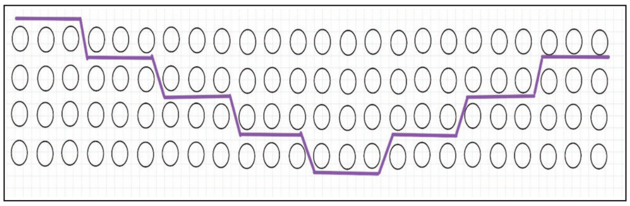

Fig. 2. The 3FALI

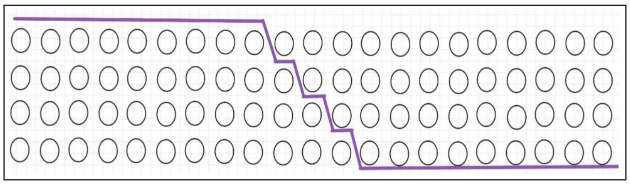

Fig. 3. The 9FAI

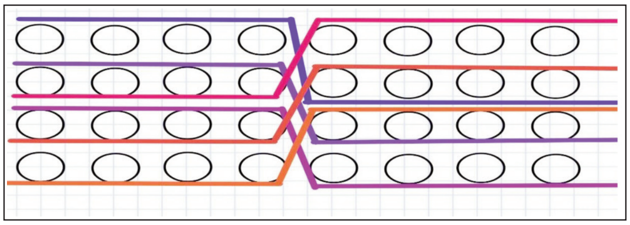

Fig. 4. The 4FLL

Table 1

CHARACTERISTICS OF THE EPOXY RESIN	
Epoxy: hardener ratio	3.5:1.25
Compression strength (MPa)	76
Curing hours	8 h
Curing temperature	Room temperature

Composites were fabricated using the hand lay-up approach. Each of the four woven textiles was cut into an 80 mm × 240 mm rectangle piece and placed in a mould. The resin, premixed with the hardener in a ratio of 3.7:1.3, was then applied to the fabrics and pressed along the fabrics with a roller. Together with the mould, the fabricated fabrics were cured in an oven with an initial temperature of 30°C. The temperature was continually increased by 20°C at every 30 min until it reached the maximum temperature of 100°C. The fabrics were then cured for another 3 h at the highest temperature. Altogether, 20 samples were prepared with five replicates for each type of fabric to minimise woven composite fabrication damage during processing while yielding average results.

Fabric crimp

The fabric crimp is the product of yarn undulation through the yarn-yarn interlacement on the weave structure (citation). The standard method of the American Society of Testing and Materials (ASTM) D3883-04 was used to estimate the crimp fraction of the yarn that was pulled out from the woven fabric sample. The length of the straightening yarn (L_1) was compared with the woven fabric length (L_2). Equation 1 depicts the calculation of the fraction of yarn crimp.

$$Yarn\ crimp\ (\%) = \frac{L_1 - L_2}{L_2} \times 100 \qquad (1)$$

Impact testing

The impact of the fabric resistance was evaluated using an impact test machine (model: Instron Dynatup 9250 HV Tester) following the method of ASTM D2444. In this drop test, specimens were impacted by an impactor at low velocity until specimens ruptured or the limit of the extension was attained. All experiments were performed with a constant inceptive impact energy of 20 J via a mass of 3.29 kg at a distance of 0.6163 m between the impactor tup and specimen, and a velocity of 3.4901 m/s. The fabrics were tested with three types of impactors (12 mm diameter), i.e., conical, hemispherical, and ogival impactors (figure 5). All samples were cut into square pieces of 80 mm × 80 mm and fastened on the top of the round metal block to allow the impactor to pierce it. After the impactor perforated the textiles, the force imparted to the composites was calculated instantly.

Float Over Depth

The float over depth (FOD) is a ratio that measures warp length movement above weft yarns and then divided by how much it travels through fabric thickness, as shown by equation 2. The equation comprises where *f* is the measurement of float length while nl is the indication number of the layers that warp yarn travels through 3D fabric thickness:

$$Float\ over\ depth\ (FOD)\ ratio = \frac{f}{nl} \qquad (2)$$

where *f* is float length and *nl* – the number of layers.

RESULTS AND DISCUSSION

The compilation results of the low-velocity drop impact test based on four different woven fabric samples and three different impactor shapes were presented in this section.

Fabric crimp

Figure 6 shows the crimp percentage of different 3D weave structures, 1FAI, 3FALI, 4FLL and 9FAI.

At the warp direction, the 1FAI woven fabric displayed the highest crimp percentage, i.e., 6% followed by 3FALI, 4FLL, and 9FAI, and the yarn float length showed a direct relationship with the reduction of crimp percentage in both warp and weft directions. Longer float resulted in lower crimp percentage as well as shearing behaviour. In general, the warp yarn in 3D fabrics produced higher crimps compared to

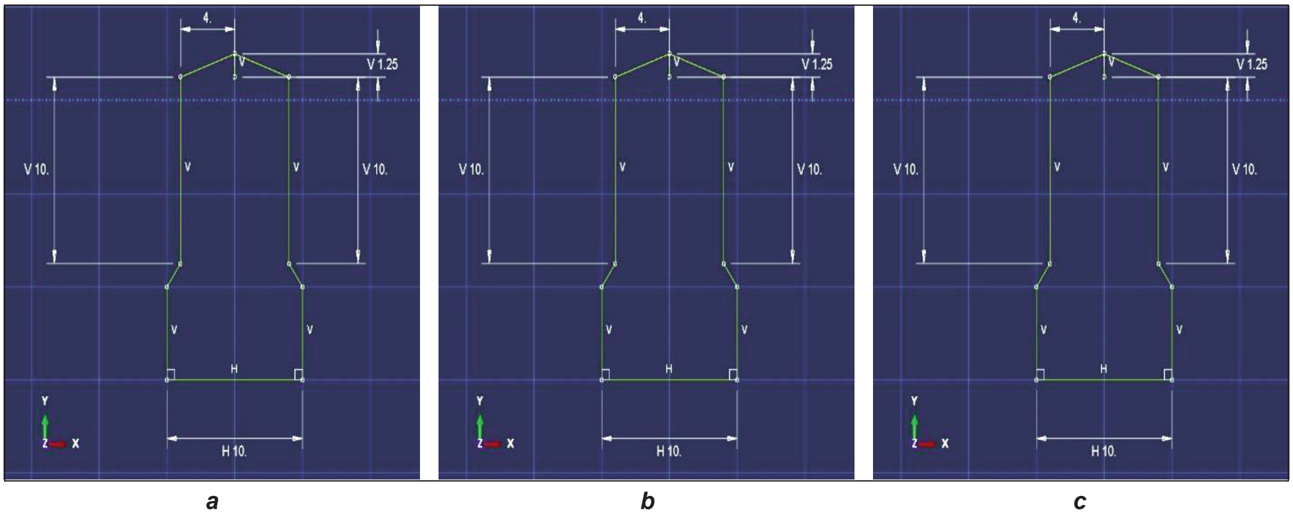

Fig. 5. Impactors shapes and dimensions in mm: *a* – ogival; *b* – hemispherical; *c* – conical

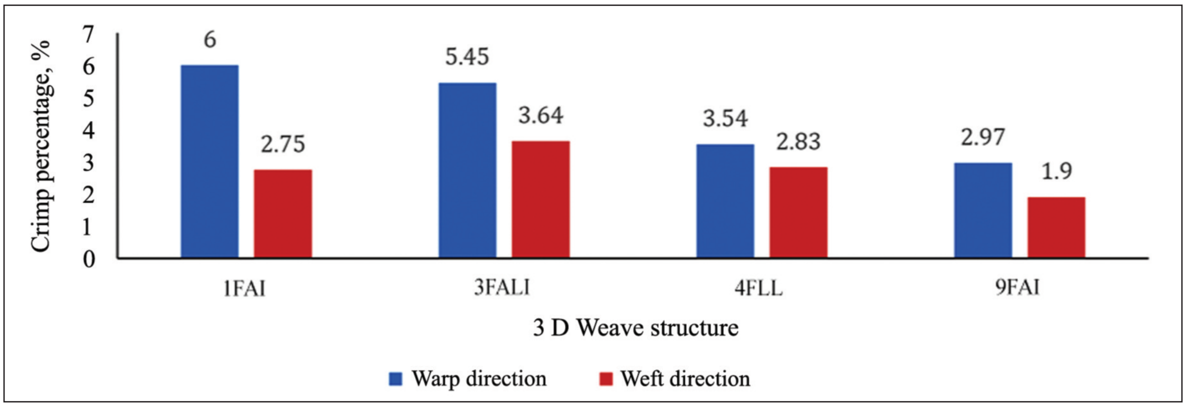

Fig. 6. Fabric crimp percentage

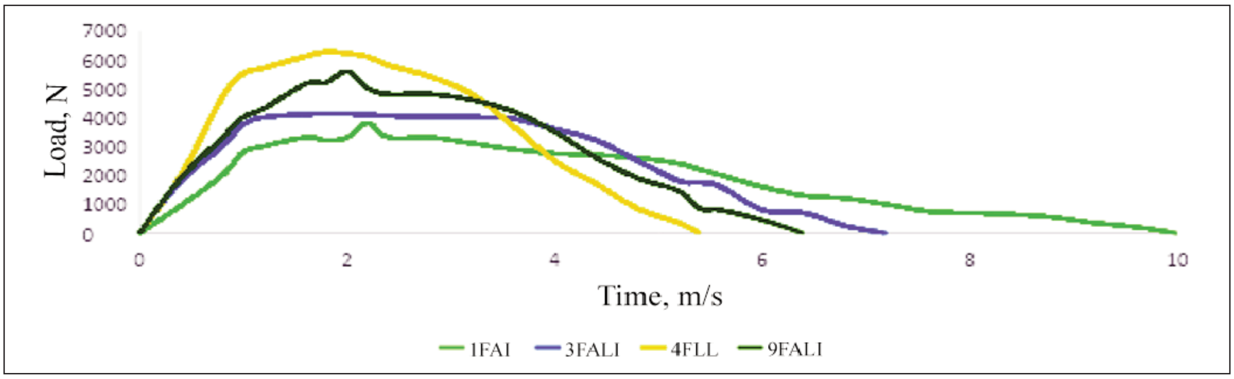

Fig. 7. Peak forces of the hemispherical impactor to rupture all composite samples

the weft yarn. This is because warp yarn had to move through the structures either layer to layer or through the structures.

Impact resistance based on the impactor shape

Figure 7 depicts the maximum force required by the hemispherical impactor to rupture all composite samples. The 4FLL fabric showed the greatest resistance towards the impact requiring an average force of 6250.0 N to rupture it and followed by 9FAI, 3FALI, and 1FAI fabrics requiring average forces of 5581.0, 4528.0, and 3800.0 N, respectively. The contact time for all composites attaining the peak force ranged between 1.8 and 2.2 m/s.

Figure 8 shows the peak force that the conical impactor needed to break all composite samples. The greatest peak force obtained by the 4FLL fabric was 4000.1 N, followed by the 9FAI, 3FALI, and 1FAI fabrics, with the maximum force typically reaching between 3.7 and 4.6 m/s, except for the 4FLL, which reached the peak force at 2.0 m/s. The conical impactor, with a smaller interacting surface area, could penetrate fewer layers of the composites compared to the hemispherical impactor, thus requiring a longer impacting time to rupture the fabrics.

Figure 9 shows the peak force that the ogival impactor needed to puncture all composite samples. Similar to the previous two impactors, the 4FLL fabric showed the highest resistance with an average force of 3750.7 N and followed by 9FAI, 3FALI, and 1FAI fabrics requiring an average force of 3411.0, 3342.6, and 2647.3 N, respectively. The contact time for all composites attaining the peak force ranged between 3.6 and 4.6 m/s.

Overall, the 4FLL composite consistently gave the most robust fabric resistance with the highest peak force, followed by 9FAI, 3FALI, and 1FAI fabrics. In general, the hemispherical impactor tup, with a generally larger surface area, required a higher force at the shortest contact time (5.6 m/s) to break the fabric, while the ogival impactor, with the smallest surface area, penetrated easier (less force but a longer contact time, i.e., 7.6 m/s) as more pressure was exerted on the composites. The findings of this study were consistent with the modelling results reported in another study [17, 18], i.e., the ogival impactor required the smallest peak force to puncture the fabrics. However, the ogival impactor generated more friction between the impactor and composite, thus increasing the contact time.

The hemispherical impactor yielded a broader damaged area without penetrating the composite but with matrix cracking. In contrast, the ogival impactor penetrated the composite with matrix cracking encircling the pierced hole due to the fibre breakage. Penetration was observed in the impact of the conical impactor but with a smaller damaged area than the ogival impactor but larger than the hemispherical impactor. In general, damages on the rear surface area were dependent on the shape of the impactor.

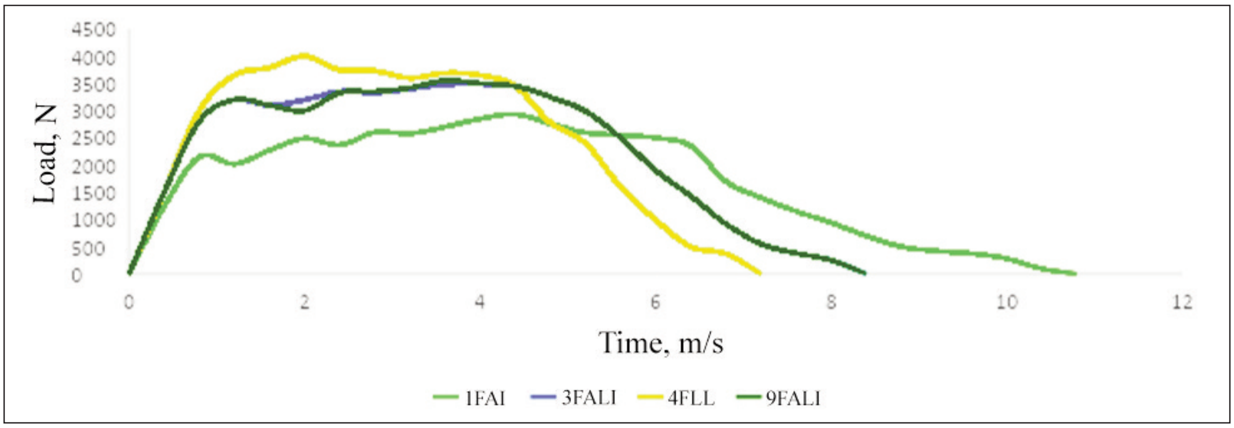

Fig. 8. Peak forces of the conical impactor to penetrate all composite samples

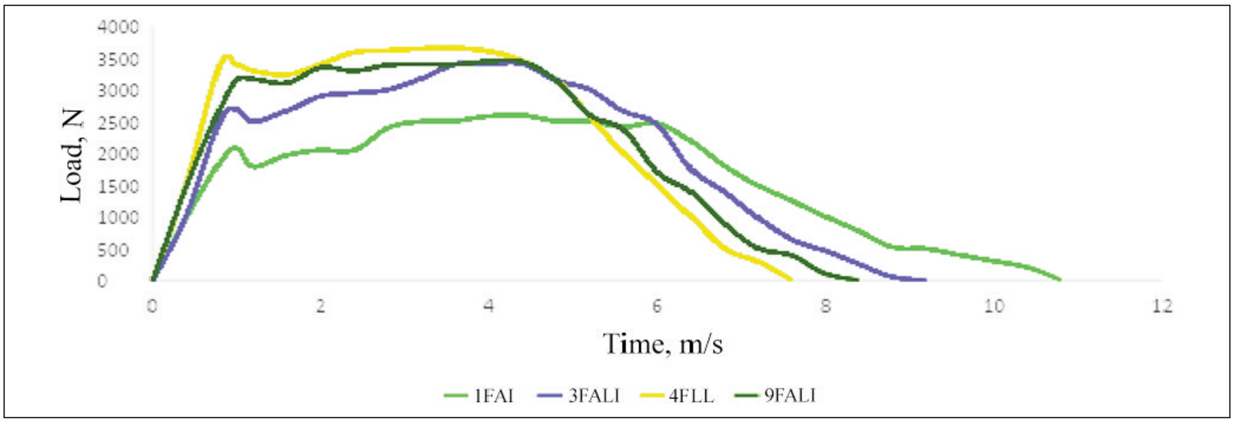

Fig. 9. Peak forces of the ogival impactor to pierce all composite samples

Table 2

FLOAT OVER DEPTH RATIO ACCORDING TO DIFFERENT IMPACTOR SHAPES AND WEAVE STRUCTURE

Fabric	FOD ratio	Conical Impactor (N)	Ogival Impactor (N)	Hemispherical Impactor (N)
1FAI	0.25	2850.0	2647.3	3800.0
3FALI	3	3478.9	3342.6	4528.0
4FLL	4	4000.1	3750.7	6250.0
9FAI	2.25	3490	3411.0	5581.0

Float over depth ratio

Further analysis was carried out to investigate the role of floats and layers in chosen 3D woven fabric structures during the impact and damage process. Table 1 showed that fabric 4FLL reported the highest results for conical, ogival, and hemispherical impact values as well as float over depth (FOD) ratio. The longer yarn float with minimal interlacing depth resulted in higher impact performance. The float-over-depth ratio for each type of fabric is presented in following table 2.

CONCLUSION

The impact damage of four different types of 3D woven textiles was investigated in this study. The 4FLL composite yielded the most robust resistance against impact followed by 9FAI, 3FALI, and 1FAI fabrics. The longer warp length above weft with lower depth was able to provide greater resistance during impact. This was shown by 4FLL capability to respond for higher impact within a 2 seconds time frame and delayed maximum impact force (N) for hemispherical and conical impactors. Meanwhile, the ogival impactor, with a smaller surface area, required a slightly lower force and a shorter time frame within 1 second to break the composite compared to blunter impactors, such as the conical and hemispherical impactors. Future investigations on post-damage woven composite characteristics could be studied using physical and computer simulations to determine the suitability of technical applications based on the type of weave structure against different impactor shapes.

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