Influence of Preform Interlacement on the Low Velocity Impact Behavior of Multilayer Textile Composites

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ABSTRACT: Impact property of composite material is influenced not only by the type of fiber/matrix, but also by the woven structure of the reinforcement. Presence of 3D fibers in reinforcement is reported to enhance the performance of textile composites in an impact event. This article attempts to study the influence of interlacements in the multilayer woven interlocked 3D structures on the impact properties of the composite material reinforced with them. Low velocity impact testing was carried out on an instrumented drop weight impact tester to obtain load-elongation-time plots of the impact event. It has been observed that increased interlacement in the structure improves the impact resistance of the multilayer textile composites. Further, damage area maps have been developed to understand and analyze the interlacement effect on the impact behavior.

KEY WORDS: multilayer woven interlocked structures, interlacement index, low velocity impact behavior, damage area analyses.

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INTRODUCTION

TEXTILE STRUCTURES ARE preferred materials used for reinforcement in composite applications due to their uniqueness like handling, shapability, adaptability, and structural complexity [1]. Low velocity drop weight impact property of textile composites is a vital dynamic trait with respect to composites performance. Recent articles addressing the low velocity impact behavior of fiber reinforced composites point to susceptibility of these materials to localized impact loads [2–4]. Textile composites subjected to such impact load may cause invisible internal damages, which might render the composite material useless due to severely reduced structural integrity of the components [5]. Most textile composites absorb the impact energy through deformation and damage mechanisms; amongst them, delamination is considered as major failure mode [6,7]. Incorporation of fibers in the z-direction through the use of 3D structures and hybridization of high performance fibers in preforming are reported to be efficient ways to improve the impact performance of the textile composites [8].

Multilayer woven interlocked fabrics are distinctive class of 3D preforms, woven by selective interlacement and floats of yarns [9], which have been least explored to achieve interlocking of fabric layers during the weaving stage [10,11]. They provide the advantage of cost effective preform manufacture with control over layer interlocking density based on weave variations. These multilayer interlocked woven preforms with various architectures can be fabricated using variation of interlacements and floats in the structure. Orthogonal weave is a type of multilayer woven structure, where the yarns are arranged perpendicular to each other in X, Y, and Z directions without any interlacements. Apart from the orthogonal multilayer structures, the multilayer fabrics are further categorized into angle interlocked and layer interlocked structures. In angle-interlock structures, warp yarns of each layer interlace with the weft yarns of the adjacent layers, while in layer-interlock structures warp yarns interlace the top and bottom layer of the fabric. Design and structure of the multilayer interlocked woven preform determine its performance properties.

Structure-property relation in terms of factor or index using both interlacement and float becomes critical especially for fabrics with multilayered structures, for which structural factors have not been applied yet. An attempt has been made to study the consequence of interlacement variations in multilayer woven structures on the impact behavior of composites reinforced with them. Nine different multilayer interlocked woven structures with varying interlacements have been developed to study the influence of interlacement. Interlacement index (I) has been used to explain the influence of interlacements on the multilayer woven fabric properties [12].

Interlacement index is the ratio of number of interlacements in the given weave repeat to that of maximum possible contact field in the design given by Equation (1):

$$I = \left(\frac{i_{wp} + i_{wf}}{R_1 \cdot R_2} \right) \tag{1}$$

where i_{wp} and i_{wf} are interlacements in warp and weft respectively; product of warp repeat (R_1) and weft repeat (R_2) of a woven design gives the maximum possible contact fields in the woven design. Further, damage area maps have been developed based on the post impacted specimen image analyses, to analyze the influence of interlacement on impact behavior of the composite materials.

MATERIAL AND METHODS

The 2-ply and 3-ply multilayer fabric samples were woven on 4 harness, flexible rapier automatic loom (Dornier), at 400 rpm with 24 ends/cm and 12 picks/cm setting. 5 meter length each of four varieties of Nylon 2-Ply fabrics (N2P1, N2P2, N2P3, and N2P4) along with five varieties of 3-ply fabrics (N3P1, N3P2, N3P3, N3P4, and N3P5) were woven for the present studies using high tenacity Nylon-6 filament yarn (96 Tex, fiber diameter 27.2 µm). These nine structures were chosen for the present study as these designs represent combined variations in the 2-layer & 3-layer structures having layer interlock, angle-interlock, and orthogonal multilayer structures. Also they represent least to maximum interlaced design variations possible among the multilayer structures which can be easily formed on any weaving loom fitted with 4 harnesses (healds). The graphical representation of the woven design and the line diagrams of 2-ply and 3-ply multilayer woven structures are represented in the Figures 1 and 2. Among these multilayer structures N2P1, N2P2, N2P3, N3P1, N3P2, and N3P3 are the orthogonal structures, N3P4 and N3P5 are layer interlock structures where as N2P4 is an angle interlock structure. Nylon 6 plain woven (half the aerial density of multilayer fabric), was used as reference sample for comparison of results of the above mentioned multilayer samples. The general construction characteristics of the fabric samples made are provided in the Table 1, where n_1, n_2 denote ends/cm, picks/cm, c_1, c_2 represent warp, weft crimp % values and I is the interlacement index of the structure.

Composites were prepared with these preforms by hand-lay-up method using unsaturated polyester resin cured for one day at ambient temperature

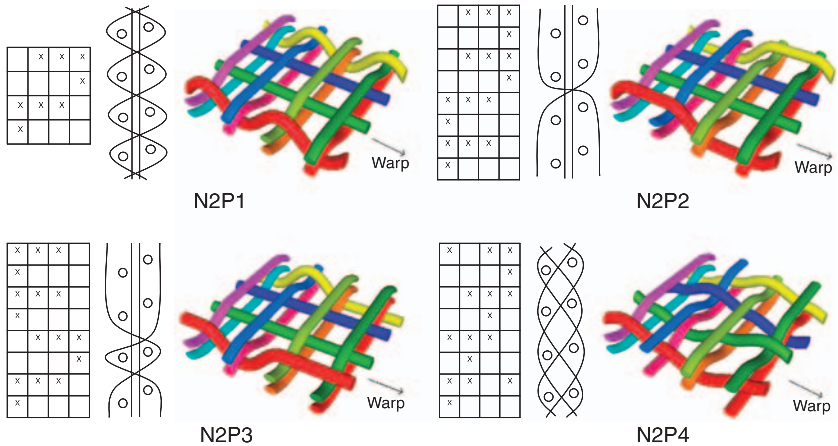

FIGURE 1. 2-Ply multilayer woven structures.

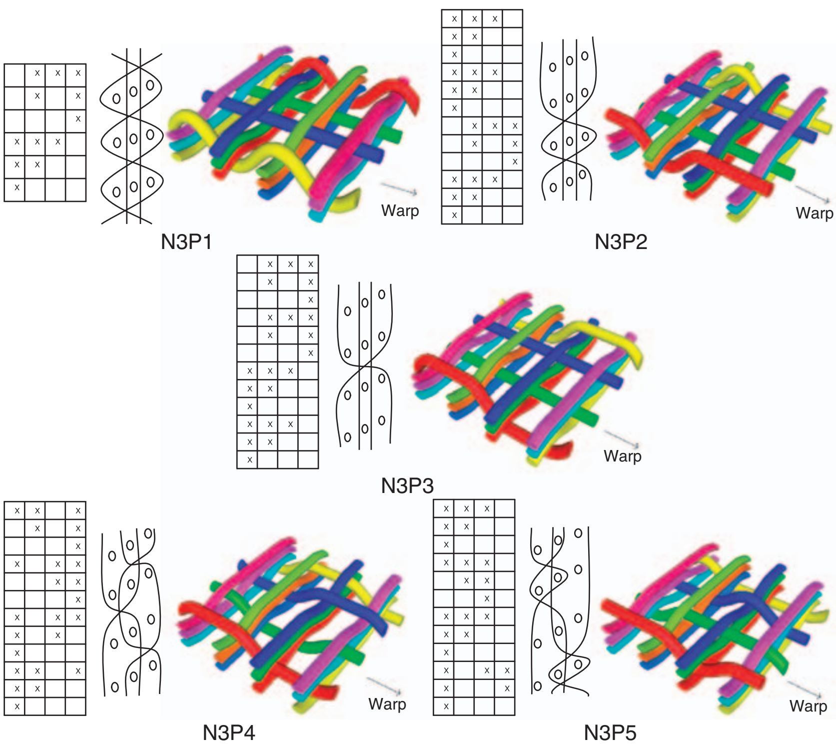

FIGURE 2. 3-Ply multilayer woven structures.

Table 1. Multilayer woven perform properties.

	$n_1 \times n_2$ (/cm)	c_1 (%)	c_2 (%)	Thickness (mm)	Aerial density (g/m^2)	I
N2P1	24 × 13	7.8 (6.4)	3.6 (2.3)	1.12	432.6 (2.8)	1.25
N2P2	23 × 11	6.9 (9.3)	3.2 (3.8)	1.18	411.4 (3.1)	1.125
N2P3	23 × 11	5.3 (8.2)	2.1 (2.9)	1.20	407.6 (5.3)	1.125
N2P4	24 × 12	4.3 (3.8)	2.6 (3.2)	1.25	412.2 (4.7)	1.00
N3P1	25 × 12	6.3 (7.6)	3.1 (3.0)	1.22	422.2 (2.9)	1.0833
N3P2	24 × 12	4.4 (6.7)	2.1 (4.1)	1.34	420.1 (3.2)	0.9583
N3P3	24 × 12	5.6 (7.8)	3.0 (1.9)	1.32	438.5 (2.5)	1.00
N3P4	24 × 13	6.5 (3.9)	4.0 (3.3)	1.27	436.8 (1.4)	0.9167
N3P5	25 × 12	6.8 (4.8)	3.6 (4.4)	1.41	437.2 (2.9)	0.8333
NP-control	12 × 6	7.3 (4.2)	4.6 (2.3)	0.71	212.3 (4.5)	2.00

Note: CV % values are given within parenthesis.

Table 2. Properties of multilayer reinforced composites.

	Thickness (mm)	V_f	Void (%)
N2P1	1.62 (4.8)	0.31	2.46 (3.6)
N2P2	1.61 (2.4)	0.32	2.35 (4.8)
N2P3	1.63 (4.5)	0.28	1.65 (3.4)
N2P4	1.64 (3.8)	0.30	1.73 (6.1)
N3P1	1.65 (2.3)	0.28	2.97 (7.5)
N3P2	1.64 (3.1)	0.27	2.29 (4.3)
N3P3	1.64 (4.2)	0.28	1.84 (3.6)
N3P4	1.65 (4.0)	0.28	1.90 (5.3)
N3P5	1.63 (3.8)	0.32	2.55 (6.8)
NP-control	1.62 (5.4)	0.31	3.91 (9.7)

Note: CV % values are given within parenthesis.

with thickness spacer of 1.6 mm. The physical properties of the laminates prepared are presented in Table 2. Fiber volume fraction (V_f) of the composite was calculated using the Equation (2), with fiber density (σ_f), composite density (σ_c), data from density gradient tests along with weight (gsm) of fabric (W_f), and composite (W_c). Void (percentage) was estimated by image analysis using optical microscopy technique as per the method suggested by Purslow [13].

$$V_f = \frac{W_f/\sigma_f}{W_c/\sigma_c} \tag{2}$$

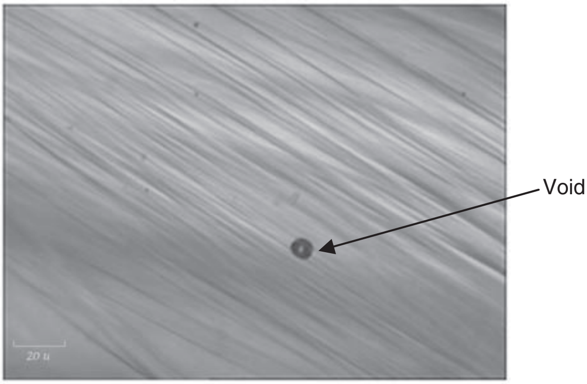

FIGURE 3. Void estimation by image analysis. Image of N3P3 composite (40×).

Table 3. Composite tensile and flexural test results.

	Tensile strength (MPa)		Flexural strength (MPa)	
	Warp	Weft	Warp	Weft
N2P1	115.7 (3.3)	75.1 (6.7)	48.5 (2.1)	26.6 (3.9)
N2P2	119.3 (4.1)	68.5 (2.9)	47.1 (4.3)	21.6 (1.4)
N2P3	115.0 (2.8)	64.3 (3.4)	54.7 (3.2)	33.6 (4.1)
N2P4	111.2 (4.9)	63.8 (2.1)	42.4 (1.5)	21.0 (2.4)
N3P1	116.2 (3.8)	66.4 (5.2)	39.6 (3.3)	31.0 (2.1)
N3P2	114.8 (4.3)	64.9 (3.7)	49.8 (1.4)	29.1 (2.8)
N3P3	116.8 (5.4)	66.7 (4.4)	50.1 (2.9)	31.7 (3.5)
N3P4	116.0 (4.2)	66.9 (2.4)	51.4 (2.3)	31.6 (4.6)
N3P5	117.2 (2.1)	71.8 (5.5)	51.1 (2.1)	30.0 (4.2)
NP-control	108.3 (6.3)	63.1 (8.2)	50.1 (7.6)	30.6 (5.2)

Note: CV % values are given within parenthesis.

In this method 50 images of each composite were captured using Leica microscope (40×) fitted with digital camera and representative image of the N3P3 reinforced composite sample is given in Figure 3. The images were analyzed for presence of void and average void was calculated from the ratio of total void area to the area of composite.

Composite Mechanical Properties

The tensile properties of the composite samples were evaluated as per ASTM D 3039 standard on Instron universal tester. Flexural tests on the composites were carried out on the same Instron tester as the ASTM

Table 4. Low velocity impact test results.

	5 J		15 J		25 J	
	Max. load (kN)	Total energy (J)	Max. load (kN)	Total energy (J)	Max. load (kN)	Total energy (J)
N2P1	1.47	5.38	2.13	10.72	2.27	11.43
N2P2	1.43	5.40	1.93	10.78	2.17	10.66
N2P3	1.42	5.37	1.98	9.37	2.14	10.13
N2P4	1.42	5.13	2.00	9.93	2.10	10.65
N3P1	1.44	5.47	2.01	11.05	2.12	10.08
N3P2	1.40	5.38	1.86	9.91	1.93	10.09
N3P3	1.42	5.25	2.01	12.12	1.97	11.03
N3P4	1.40	5.55	1.76	10.08	1.88	10.59
N3P5	1.36	5.44	1.71	10.67	1.85	10.20
NP-control	1.30	6.02	1.32	10.44	1.62	10.17

Note: CV % values <3.

Standard D 790. Table 3 provides the tensile and flexural tests results conducted on the composite samples.

Low velocity impact drop weight tests with semi-spherical indenter (2.2 kg) were conducted on the composites at three different impact energy levels of 5 J, 15 J, and 25 J using a DYNATUP GRC model with 830-I data acquisition software. Three tests were conducted on the multilayer composites samples of size 9 cm × 9 cm at each impact energy level.

RESULTS AND DISCUSSIONS

Impact result shows interesting observations with multilayer reinforced composites. Table 4 provides the impact test results for three levels of impact energy. Figure 4 presents the select images of the composite samples under study subjected to impact test at the 5 J, 15 J, and 25 J impact energy levels. It can be observed from the impacted specimens that at 5 J impact energy the control sample shows distinct fiber failure while the multilayer textile composite (N3P3) has absorbed the impact energy without fiber damage. At 15 J and 25 J impact energy, both control and multilayer samples display fiber failure and larger extent of damage has been observed with the control sample. Figures 5–7 illustrate the impact performance curves (Load–Time–Energy) for these composite samples obtained from the instrumented impact test at 5 J, 15 J, and 25 J impact energy levels respectively. Figure 8 represents a typical impact curve which has been used to explain the impact behavior of these multilayer composite samples.

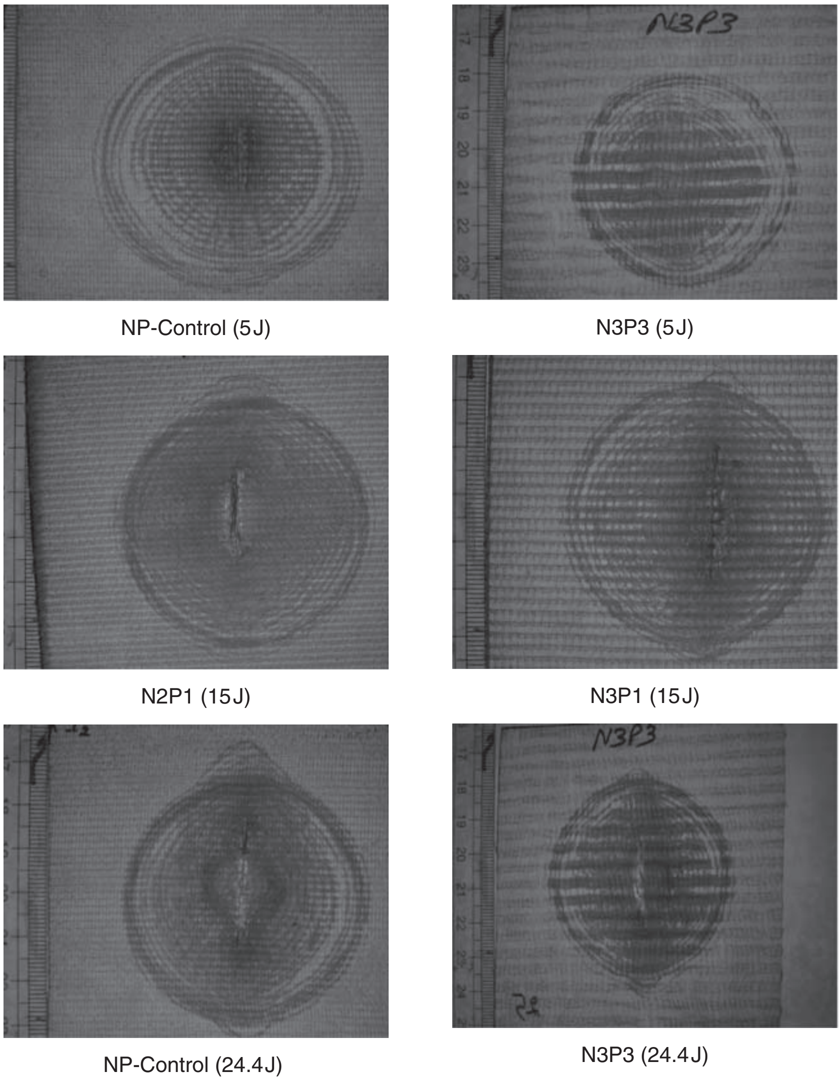

FIGURE 4. Images of composites impacted.

Multilayered structure of the reinforcement has significant influence on the impact performance of the composites under investigation, with all the multilayered composite samples performing better than the control specimen at both impact energy levels. Figure 8 represents a typical impact curve obtained from instrumented impact tester. In textile reinforced composites

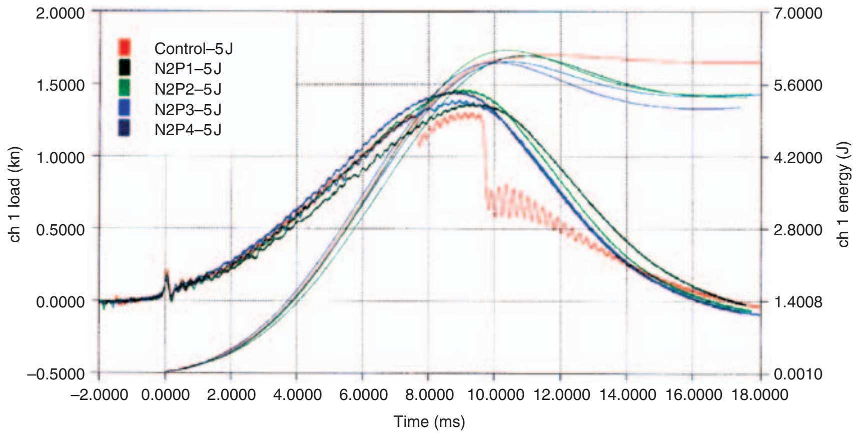

FIGURE 5. Impact plot of 5 J on 2-ply multilayered composite specimens.

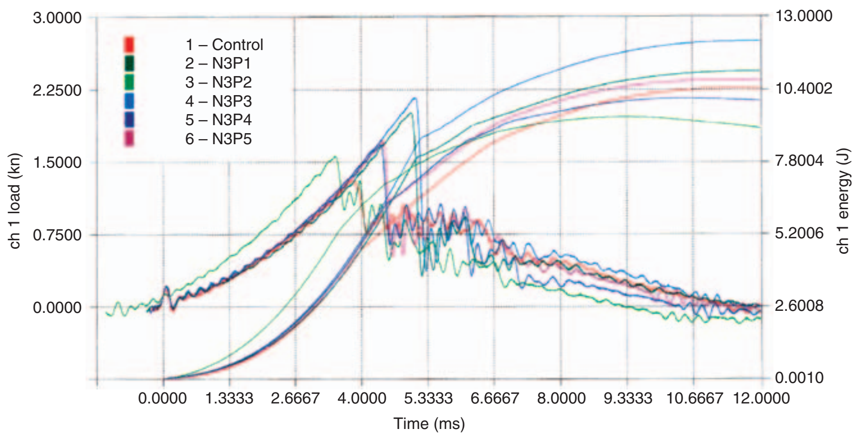

FIGURE 6. Impact plot of 15 J on 3-ply multilayered composite specimens.

there is very little plastic deformation and impact energy is initially absorbed through elastic deformation till a threshold. The maximum load point (MLP) or this threshold value is the peak impact load that a laminate can tolerate before undergoing major damage. At the MLP, a major fiber breakage occurs through the laminate thickness. The maximum load (*Pm*) and the required energy (*Em*) at the maximum load are shown in Figure 8.

From the impact load-time curves it can be seen that the 2-ply NP-control sample has failed catastrophically distinctly at maximum load point, while

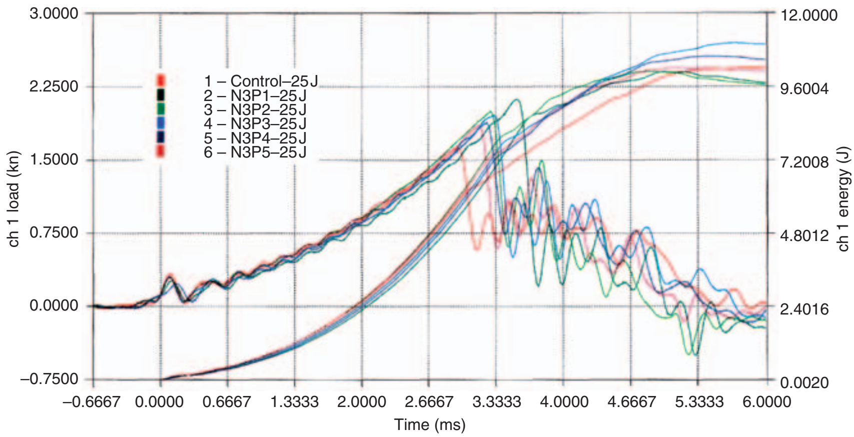

FIGURE 7. Impact plot of 25 J on 3-ply multilayered composite specimens.

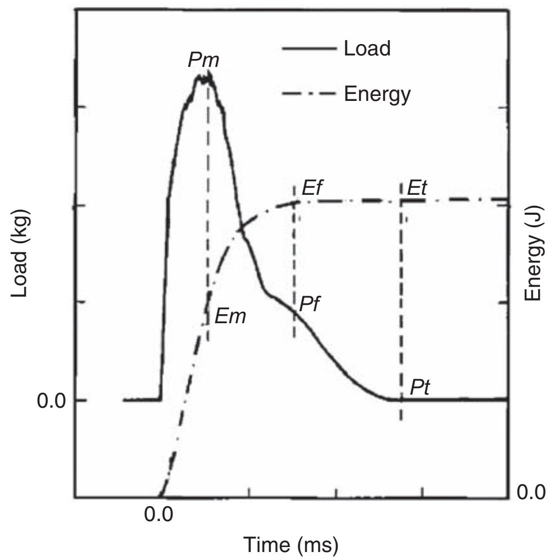

FIGURE 8. Typical instrumented impact curve.

all multilayer woven interlock reinforced composites exhibit damage tolerance at 5 J impact energy (Figure 5). At 15 J and 25 J impact energy levels, it has been observed that all the multilayer composite samples have displayed superior peak impact load for fiber failure compared to the

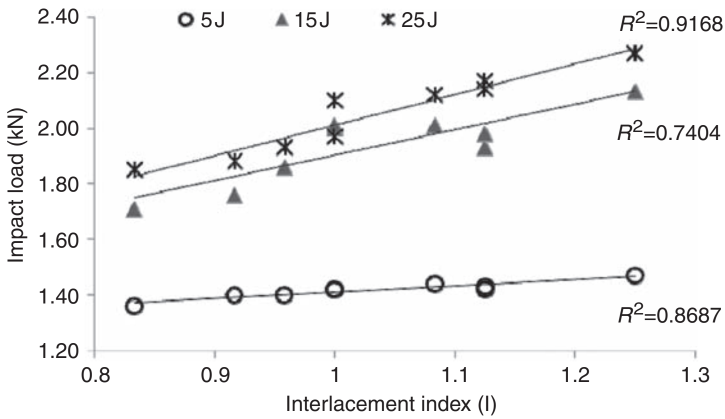

FIGURE 9. Interlacement index vs max. impact load for multilayer composites.

control samples (Figures 6 and 7). N2P1 and N3P1 composite samples have shown higher impact strength with maximum impact load for failure whereas N2P2 and N3P1 samples have demonstrated higher impact resistance through absorption of maximum impact energy at 15 J impact. Similar to the 15 J impact behavior, N2P1 and N2P2 composite samples have shown higher impact strength with maximum impact load for failure at 25 J impact energy, while N2P1 and N3P3 samples have demonstrated higher impact resistance through absorption of maximum impact energy at 25 J impact.

A plot of interlacement index with maximum impact load to failure of multilayer textile composites under investigation, infers that impact strength of these composite materials increase with increased interlacements in the woven reinforcement as shown in the Figure 9. Higher interlacement indexed N2P1 composite demonstrates maximum impact load to failure and similarly least impact strength is displayed by N3P5 reinforced composite having least interlacement index (0.8333). Overall it could be assessed that the orthogonal structures have performed superior, layer interlock structures have inferior impact property whereas the angle interlock structure (N2P4) has almost similar impact performance as those of orthogonal structures among the multilayer structures presently studied for impact behavior.

Post impacted specimens were subjected to image processing technique using ImageJ® software to analyze the damage area during impact event. A typical impacted damage area map is represented by Figure 10, which illustrates the fiber failure, interphase or interface failure, and matrix failure regions in the impact damage traced image. Table 5 presents the segregated

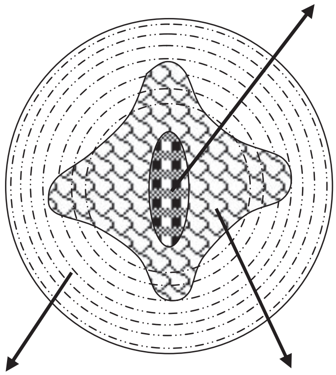

FIGURE 10. Traced image displaying damage area map in impacted specimen.

Table 5. Impacted specimen damage area (cm^2).

	Fiber failure		Interphase failure		
Composite	15 J	25 J	5 J	15 J	25 J
N2P1	0.31	0.58	4.92	5.45	6.44
N2P2	0.40	0.63	4.87	4.90	5.37
N2P3	0.42	0.64	4.69	4.79	5.33
N2P4	0.54	0.66	4.47	4.66	5.00
N3P1	0.53	0.62	4.51	4.64	5.28
N3P2	0.59	0.64	4.23	4.45	4.71
N3P3	0.49	0.63	4.46	4.67	5.29
N3P4	0.62	0.69	4.21	4.29	4.18
N3P5	0.72	0.72	3.86	4.10	4.04
NP-control	1.41	0.77	3.24	4.09	7.28

areas of the impacted specimens into these regions and Figures 9 and 10 illustrate the influence of reinforcement structure (interlacement index) on the damage area of the impacted composite samples.

It can be seen from Figure 11 that increased interlacement in the multilayered reinforcement results in decreased fiber failure zone in the composite. Higher interlacement in the structure increases the load transfer efficiency of the reinforcement through these interlacements which act as joints in the structure. Hence higher the interlacement lower would be the fiber failure region.

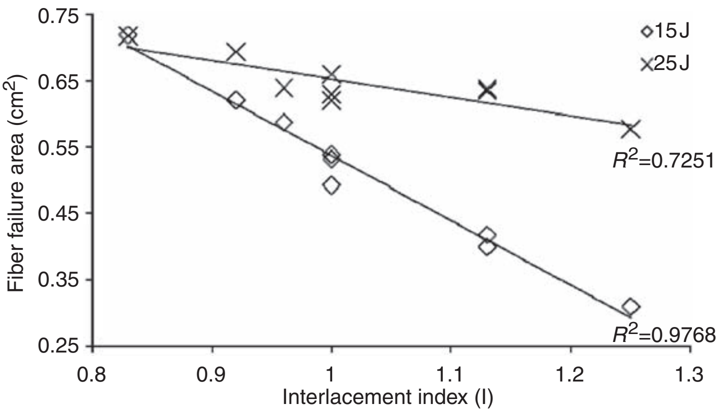

FIGURE 11. Fiber failure area vs interlacement index for impacted multilayer composites.

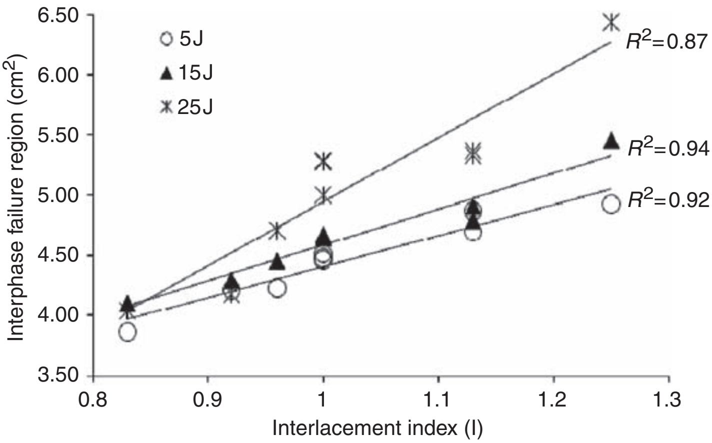

FIGURE 12. Interphase failure area vs interlacement index for multilayer composites.

Figure 12 shows the influence of reinforcement structure in terms of interlacement index on the interphase failure region. It can be assessed that increased interlacements in the multilayer structure cause higher interphasial failure regions in the composites which can also be attributed to better dissipation of load in the multilayer structure through interlacement points. Also lower interlacement in the structure would result in lack of load transferability in the composite which could further result in stress accumulation at the zone of impact. Thus higher fiber failure are effected as evinced by the results of layer interlocked structures N3P4 and N3P5 reinforced composites.

During an impact event, the interlacements in the reinforcement act as binding points which transmit the impact load from one fiber to other. A higher interlacement index of the structure increases the ability of the composite to withstand higher load with better dissipation of the impact load, thus reducing the fiber failures in the composite material as evident from the Figures 9 and 11. During such impact load dissipation, fibers tend to deform from their position thereby causing interphasial debonding with the matrix thus resulting in debonding with the matrix which absorb significant amount of impact energy to create failure regions. Hence with increased interlacement in the reinforcement, lower would be the fiber failure and higher would be the interphasial failures as observed from the results of the impact behavior of multilayer composites in this study (Figures 9, 11, and 12). With better understanding of important role played by the interlacement in the multilayer woven composites, the task of designing impact damage tolerant structure would be much helpful.

CONCLUSIONS

Multilayer structures have significant influence on the impact behavior of composites reinforced with them. Interlacements in the multilayer reinforcement has been represented by the Interlacement index (I), to correlate the structural geometry on the impact performance. Higher interlacement index of the reinforcement results in better impact strength of the composite material. Damage area analysis through image processing has been successively tried to understand the influence of interlacement on impact performance of the multilayer reinforced composites. Increased interlacements in the multilayer structure cause lower fiber failure regions and higher interphasial failure regions in the composites, which are due to better dissipation of load in the multilayer structure through interlacement points.

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BIOGRAPHY

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