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MECHANICAL PERFORMANCE OF KNITTED TEXTILE COMPOSITES

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Abstract This paper investigates and contributes to the understanding of the mechanical behaviour of knitted textile composites having different knit architectures, and its relationship to their manufacturing parameters and thereby enhances the capacity to design, manufacture and deliver cost-effective impact resistant and tolerant structures. In-plane tension and compression properties were studied using both deformed and un-deformed fabrics. Impact and compression-after-impact properties were also studied to characterise the damage resistance and tolerance of these composite materials. It has been found that any change in the mechanical properties of the knitted composites with respect to architecture and knit-structural parameters are broadly related to the accompanying modifications to the state of the microstructural imperfections, *viz.* fibre bending and yarn crossover regions, and also to the relative fibre distribution along the two principal loading axes, in the knit structure.

Keywords: Knitted Composites, Biaxial, Damage Resistance, Damage Tolerance.

INTRODUCTION

Over the last decade, considerable research has been directed towards understanding the behaviour of composites made from textile preforms in an attempt to gain industrial acceptance. Well-developed, highly automated textile technologies, such as stitching, weaving, braiding, embroidery and knitting, with the incorporation of through-thickness advanced fibres, such as glass, carbon or aramid, combined with appropriate liquid-moulding consolidation techniques, have the potential of producing reliable and affordable high-quality textile composite structures and components with improved impact and delamination resistance. Recent researchers [Khondker *et al.*, 2000, 2001a, 2001b, 2001c, Ramakrishna 1995a, Ramakrishna *et al.*, 1995b, Phillips and Verpoest, 1995] have suggested that knitted composites could possess attractive properties for niche applications, such as those requiring high-energy absorption or good impact resistance. Previous work has shown that uniaxial deformation to a knitted fabric can alter the tensile [Leong *et al.*, 1999, Verpoest and Dendauw, 1992] and, to a lesser degree, compressive properties [Leong *et al.*, 1999] of knitted composites. It has been shown that knitted composites with an increased number of fabric layers demonstrated improved impact damage resistance [Ramakrishna *et al.*, 1995b] and fracture toughness [Karger-Kocsis *et al.*, 1996] in comparison with composites manufactured from a single layer of fabric. The strong intermingling of adjacent fabric layers within knitted composites effectively promotes fibre bridging and enhances interlaminar fracture toughness when compared to other textile composites [Huysmans *et al.*, 1996, Mouritz *et al.*, 1999].

To extend the understanding of how the structure of knitted preforms can be manipulated and controlled for desired properties, the present work investigates and reports the effects of knit-structural parameters namely loop length or stitch density, on the tensile, compressive, impact and compression-after-impact properties of the knitted composites.

EXPERIMENTAL

Fabric Materials and Composite Manufacture

The materials to investigate the properties of the knitted composites comprise unstretched fabrics of two plain (P61, P9), three 1×1 rib (R3, R61, R9), three Milano rib (M1, M3, M9) architectures. For the investigation of the composites reinforced by deformed fabrics, a different Milano rib knits having a nominal areal weight of 762 gm^{-2} were considered. These fabrics were produced on an 8-gauge V-bed knitting machine using 2×68 tex multi-filament E-glass yarns. Each of the former three groups of knits consists of a common architecture with different loop lengths and stitch densities, as summarised in Table 1. A total of thirteen different combinations of wale and course deformation were

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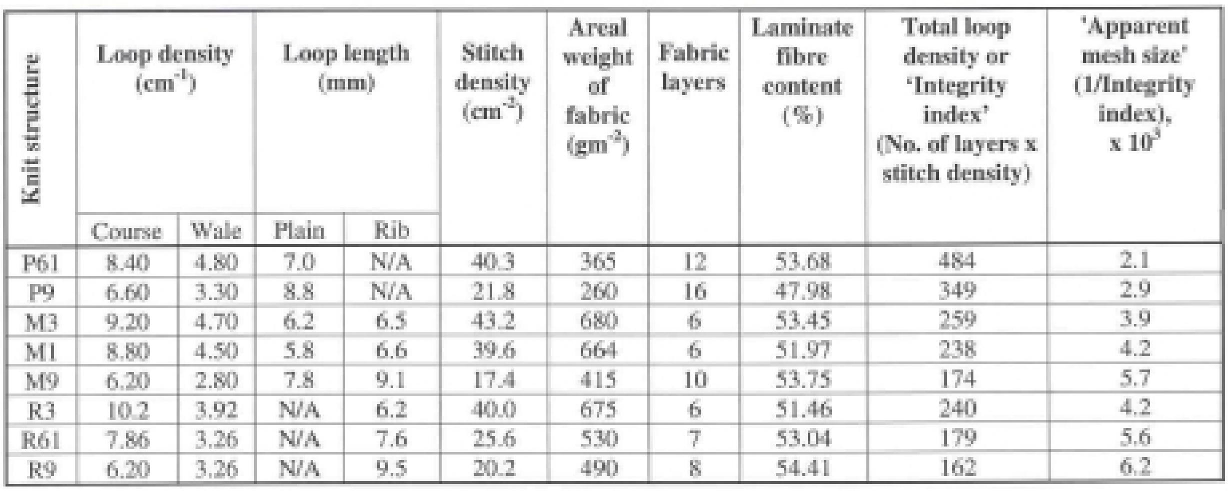
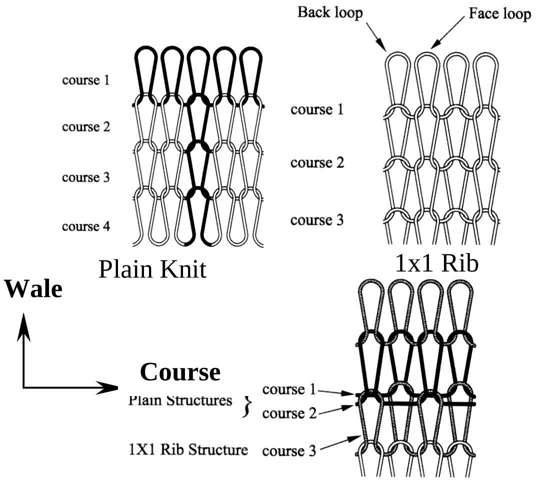
Table 1: Summary of weft knit structures of the undeformed fabrics



Knit structure	Loop density (cm^{-1})		Loop length (mm)		Stitch density (cm^{-2})	Areal weight of fabric (gm^{-2})	Fabric layers	Laminate fibre content (%)	Total loop density or 'Integrity index' (No. of layers x stitch density)	'Apparent mesh size' (1/Integrity index), x 10^3
	Course	Wale	Plain	Rib						
P61	8.40	4.80	7.0	N/A	40.3	365	12	53.68	484	2.1
P9	6.60	3.30	8.8	N/A	21.8	260	16	47.98	349	2.9
M3	9.20	4.70	6.2	6.5	43.2	680	6	53.45	259	3.9
M1	8.80	4.50	5.8	6.6	39.6	664	6	51.97	238	4.2
M9	6.20	2.80	7.8	9.1	17.4	415	10	53.75	174	5.7
R3	10.2	3.92	N/A	6.2	40.0	675	6	51.46	240	4.2
R61	7.86	3.26	N/A	7.6	25.6	530	7	53.04	179	5.6
R9	6.20	3.26	N/A	9.5	20.2	490	8	54.41	162	6.2

investigated. It should be noted that in the present work any increase in loop length is accompanied by a decrease in stitch density. Figs. 1 shows schematic diagrams of various knit architectures.



Plain Knit

1x1 Rib

Milano Knit

Fig. 1 Schematic diagrams of the weft-knit architectures

Flat composite panels were manufactured from the knitted fabrics using the resin transfer moulding (RTM) technique. The fabrics were placed into the RTM tool and injected with Derakane™ 411-C-50 vinylester resin. For the deformed case, a special rig was developed to maintain the fabric in its biaxially stretched state, while being enclosed in the main moulding tool for resin infusion. The fibre volume fraction (V_f) of the knitted composites for the undeformed and deformed conditions was maintained fairly constant at approximately 50±3% and 55±3% respectively by varying the number of fabric layers used for each structure. This was to minimize the effect of V_f on the mechanical properties.

MECHANICAL TESTS

Tensile and compressive tests were conducted on a MTS 100kN hydraulic mechanical testing machine under a nominal test speed of 0.5mm/min. The tests were terminated with the first onset of failure, coincident with a significant drop in the load-carrying capacity of the specimens. An extensometer was used to measure the tensile strain. An abrasive open mesh emery cloth (Screenbak^{TM}- 360 grit) was used in the gripped areas instead of end tabs for all the tests and this appeared to be effective in ensuring failure within the gauge length and reducing the likelihood of failure in the grips. The compression test rig used was a simplified version of the Celanese/IITRI test rig, where the load was introduced predominantly by end loading, with the ends of the specimens clamped to prevent brooming. At least 5 test specimens were tested both in the wale and course directions for each knit structures.

Using an instrumented drop-weight test rig, low-to-medium-energy impacts were carried out at controlled and measured energy levels on the specimens. The relative impact damage resistance was evaluated from the extent of damage sustained. CAI tests were conducted with the impacted specimens on a test rig modified for use with thin laminates subject to buckling, at a nominal displacement rate of 0.5 mm per min. The relative impact damage tolerance was determined by their residual compressive strength.

RESULTS AND DISCUSSIONS

Tensile and Compressive Properties (Undeformed Fabric Reinforced Composites)

As evidenced in Figs. 2, tensile failure initiates from the highly stressed crossover points in the knits. For this reason, the plain knit composites which have a relatively simple structure proves to be superior over the rib and Milano counterparts (Figs. 3). Further, by increasing loop length and decreasing stitch density, better tensile strengths are also achieved for all the three architectures (Figs. 3). This is coincident with a reduced number of, and an expected relief of stresses at, crossover points, as well as a relaxation of the overall bending stresses in the knitted loops. Therefore, a relatively simple structure with high loop radius of curvature and a small number of crossover points is preferable for good tensile strength. These characteristics are enhanced with increased loop length and reduced stitch density.

Fig. 2 Representative SEM micrographs of the tensile tested specimens

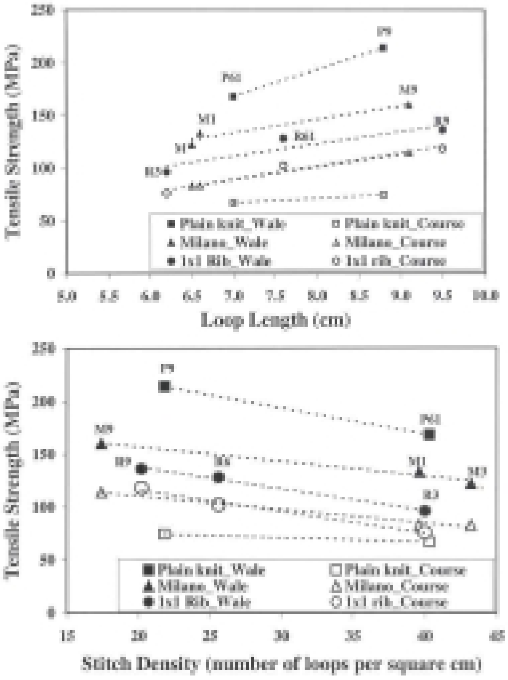


Fig. 3 The effect of weft-knit architectures on the composite tensile strength

As observed in Figs. 3, the three architectures were clearly anisotropic in their tensile strength. A quantitative assessment of the relative contribution of the fibres in the wale and course directions, obtained through a mapping technique, confirmed that the higher average net fibre content in the wale direction compared with that in the course direction, and the lower wale-to-course lineal loop density and, hence, the number of fibre crossover points, or failure nuclei, both contributed to this anisotropic behaviour of knitted composites.

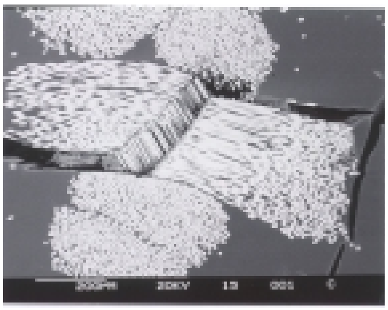


Fig. 4 Representative SEM micrograph showing fibre collapse and kink formation leading to ultimate compressive failure

Compressive strength is virtually insensitive to knit architecture as it is highly dominated by the properties of the matrix [Khondker *et al*., 2001a]. Nevertheless, ultimate failure of the composites in compression is preceded by fibre tow collapse (Fig. 4). Hence, better compressive strengths are achieved with longer loop lengths and smaller stitch densities, which increase the radii of curvature of the knitted loops, thus enhancing fibre buckling loads [Khondker *et al*., 2001a]. In other words, the "S" shape of the knitted loops that are susceptible to fibre collapse by microbuckling is minimized by an increased loop length and reduced stitch density, thus improving compressive strength.

Tensile and compressive moduli are on the whole unaffected by varying any of the parameters studied in this research. The ultimate tensile and compressive strains, on the other hand react in a similar manner to loop length and stitch density variations where, for the plain knit composites, increasing loop length and decreasing stitch density are advantageous, but for the rib and Milano composites there is, apparently, an optimum loop length and stitch density for maximum ultimate strain to be achieved [Khondker *et al*., 2001a].

Tensile and Compressive Properties (Deformed Fabric Reinforced Composites)

The effects of simultaneously deforming a weft-knit Milano rib fabric on the overall composite tensile and compressive properties has been studied for a number of wale-course stretch ratios. At a particular wale deformation, the changes in modulus and ultimate strain with course deformation are dependent on the wale deformation (Fig. 5 and 6). This is also true for the strength in the wale axis but the strength along the course axis is improved with course deformation, irrespective of how far the fabric is stretched in the wale direction (Fig.- 7).

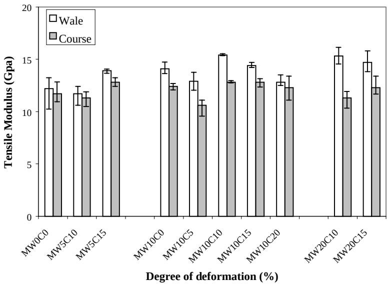


Fig. 5 The effects of course deformation at a constant wale-deformed state on the composite tensile modulus

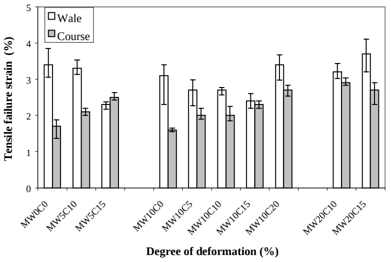


Fig. 6 The effects of course deformation at a constant wale-deformed state on the composite tensile strain to failure

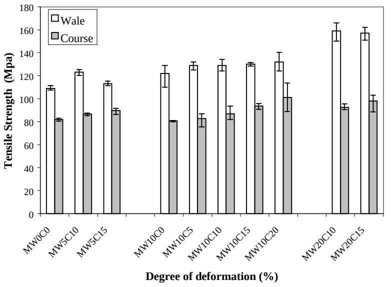


Fig. 7 The effects of course deformation at a constant wale-deformed state on the composite tensile strength

At a particular course deformation, both strength and modulus along the wale axis show signs of improvement with wale deformation, but are relatively unaffected along the course axis (Fig. 8 and 9). Whilst the ultimate strain at a constant course deformation is affected by increasing the degree of wale deformation, there is no obvious trend (Fig. 10). Scanning electron microscopy revealed that tensile failure was caused by fibre breakages occurring predominantly at yarn crossover regions (similar to that of Figs. 2), although specimens subjected to low amounts of deformation also showed signs of failure at sinker loops, which coincide with cross-sections of minimum fibre content.

Generally, compression properties of weft-knit composite structures appeared to be close to isotropic and relatively insensitive to fabric deformation [Khondker *et al.*, 2001b]. This phenomenon was believed to be due to the fact that under compression, knitted composites are highly dominated by the properties of matrix. Fractographic studies indicated that the compression failure mode involved yarn collapse by way of kink formation (similar to that of Fig. 4) due to yarn buckling, which was a direct result of the highly curved loop architecture of the knits. As expected, these tow kink failures occurred at the yarn crossover regions that experience high stress concentrations. These regions are also resin rich and offer only limited lateral support to the yarns. Failure was associated with cracking of the matrix in these areas and a linking of such local failure regions to produce a diagonal fracture.

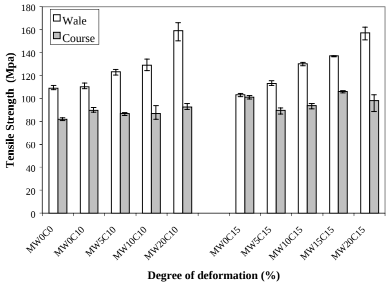


Fig. 8 The effects of wale deformation at a constant course-deformed state on the composite tensile strength

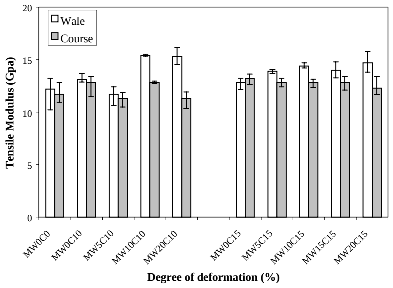


Fig. 9 The effects of wale deformation at a constant course-deformed state on the composite tensile modulus

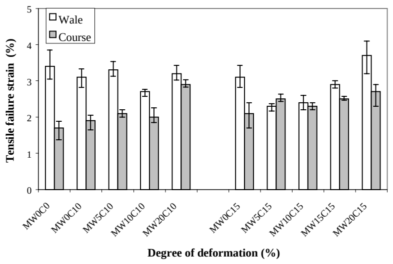


Fig. 10 The effects of wale deformation at a constant course-deformed state on the composite tensile strain to failure

Impact Damage Resistance and Tolerance

The damage area created by the impact event gives an indication of the composites ability to resist impact, i.e. small damage areas demonstrating good resistance, and a superior damage tolerance is demonstrated by a large retention in compressive strength of the damaged material. Figs. 11 shows the typical impact damage.

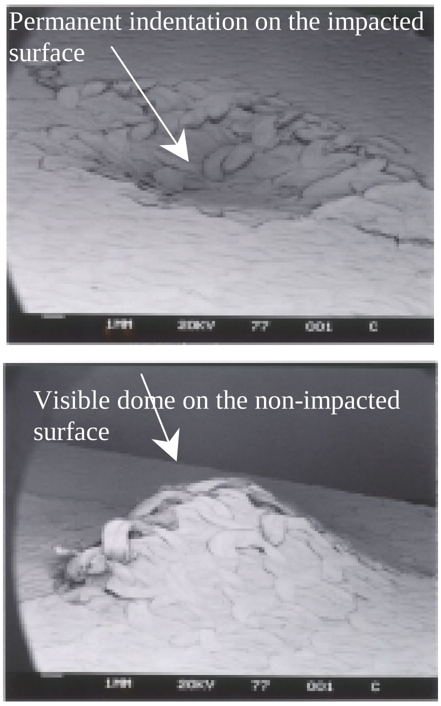


Fig. 11 Typical SEM micrographs showing impact damage (impact energy 8.18 Joule/mm)

It was quite noticeable from the results that the better damage tolerance demonstrated by a particular knit structure was derived from the greater damage resistance of the structure during the impact loading. Two new parameters are proposed (refer to Table 1) in order to explain the difference in the impact damage resistance and tolerance behaviour of composite materials manufactured from knitted fabrics of different styles and different structure parameters. A knit structure with a higher value of 'total loop density' effectively reduced the 'apparent mesh size' defined as the apparent stress transfer unit [Karger-Kocsis *et al*., 1996] of the knit, which provides better through-thickness-strength in the reinforcing materials [Khondker *et al*., 2001c]. Because of a better knitted-mesh generation, the structural integrity of the composites is greatly enhanced, giving rise to an improved interlaminar fracture toughness value [Karger-Kocsis *et al*., 1996]. It was obvious that, a tougher composite specimen offered better resistance to the damage caused by the impactor, and consequently the better damage tolerance. On the other hand, the knit structure showing inferior damage tolerance exhibited a higher value of undamaged compression strength [Khondker *et al*., 2000]. This was attributed to the fact that the radii of curvature of the loops are generally reduced for the knits with longer loop lengths or larger 'apparent mesh size', which could mean higher fibre buckling loads and, hence better undamaged compressive strength. The performance of knitted composites was compared with specimens made from 2-D braid, unidirectional fabrics and prepreg [Falzon, 1997].It was found that it would be necessary to remove more material in order to repair a structure manufactured from unidirectional prepreg tape compared with one made using knitted fabrics [Khondker *et al*., 2000].

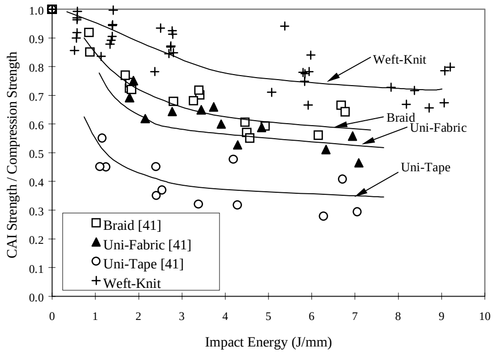


Fig. 12 Plot of CAI strength to undamaged compression strength ratio versus incident impact energy for various composite structures

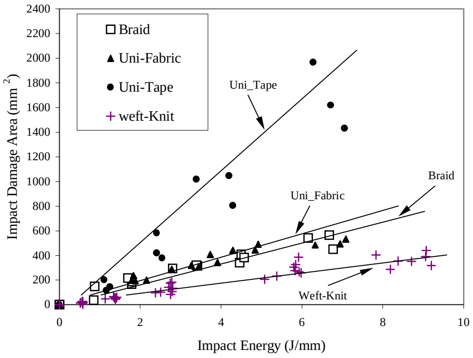


Fig. 13 Impact damage resistance of various composite structures with respect to damage area

In comparison with the braid, uni-fabric and prepreg tape composites, knitted structures showed a superior retention of its compressive strength, which confirmed the better damage tolerance of the weft-knitted composite (Fig. 12). This was believed to be derived from the greater damage resistance during the impact event **(**Fig. 13). This behaviour was attributed to a more homogeneous distribution of the knitted reinforcement in the matrix, resulting in a better ply nesting and intermingling of knitted loops within the fabric layers, which suppress the propagation of crack or delamination growth. The compression failure mechanism in damaged knitted specimens was observed to be dominated by kink band formation or shear crippling, the same as that observed for undamaged specimens (Similar to that of Fig. 4). Optimisation of the knit architecture in regards to damage tolerance and in-plane mechanical performance may make it possible to increase the design allowables.

CONCLUSIONS

An experimental investigation was carried out to study the effect of weft-knit architecture and knit/structural parameters on the tensile and compressive properties of knitted composites reinforced with both undeformed and deformed fabrics. Tensile strengths in the wale direction were higher than those in the course direction for all the knit structures under investigation. A relatively simple structure with high loop radius of curvature and a small number of crossover points are preferable for better tensile strength. These characteristics are achievable with increased loop length and reduced stitch density. Compressive strength is virtually insensitive to knit architecture as it is highly dominated by the properties of the matrix. Tensile failure initiates from the highly stressed crossover points in the knits whereas the compression failure mode involved yarn collapse by way of kink formation due to yarn buckling, which was a direct result of the highly curved loop architecture of the knits. As expected, these tow kink failures occurred at the yarn crossover regions that experience high stress concentrations. These regions are also resin rich and offer only limited lateral support to the yarns.

Contrary to the case for uniaxial deformation, fabrics undergoing biaxial deformation do not exhibit significant change in the knit structure. Nevertheless, it is believed that the changes in mechanical properties are related to the re-distribution and re-orientation of the fibres resulting from stretching the fabric, thereby altering the relative contents and/or directionality of the fibres in the composites. Failure of the knitted composite are concentrated at the highly stressed crossover points of a knit structure, where stretching could unlock or, alternatively, further increase the induced stresses at these point thereby affecting the overall strength of the composite. This work highlights the importance of controlling the amount and distribution of stretch in a knitted fabric during preforming to ensure an adequate distribution of the composite properties. In particular there is a possibility of creating soft and hard spots in the composite component, as a result of local biaxial stretching. A better understanding of the manner in which knitted fabrics behave when subjected to deformation and of the mechanical properties of the resultant composites, will assist the designer account for anomalies due to preforming and will pave the way for the development of more accurate predictive tools.

On the other hand, a knit structure with the higher value of 'total loop density' effectively reduced the 'apparent mesh size' of the knit, which made the resultant composite stiffer because of a better mesh generation, giving rise to a highly improved fracture toughness value. It was obvious that, a stiffer composite specimen offered better resistance to the damage caused by the impactor, and consequently the better damage tolerance.

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