Review Articles

Low velocity impact behaviour of textile reinforced composites

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An attempt has been made to summarize the research progress on low velocity drop weight impact properties of textile reinforced composites. The paper mainly reports the impact test parameters and textile reinforcement along with matrix, interphase effects, impact failure modes and major evaluation techniques for impact damage analyses such as ultrasonic scanning and retention of strength after impact.

Keywords: Failure criterion, Impact behaviour, Post-impact damage evaluation, Textile composites

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1 Introduction

Man's quest for newer and better replacement materials has gained a major foothold with the advent of composite materials. Nowadays, composites are the most sought materials in terms of their utility, properties, adaptability and applications. Textile structures have long been known as prime reinforcement for fibre reinforced composite applications due to their unique properties, such as easy handling, shapability, adaptability and structural complexity.[1] Behaviour of composite materials to low velocity impact loading has gained importance as it emulates real world situations, for instance the impact events such as tool drops, bird hits, hail stone damage and contact with other materials, which can cause internal invisible or major visible damages. Due to the diversified use of textile reinforced composites, a major sector of research investigations is focused on understanding the impact behaviour, as low velocity transverse impact is said to be one of the common forms of loading event that results in failure mode, affecting the structural integrity of the composite structure.[2]

Evaluation of the effects of such impacts as well as the distribution of the stress due to impact as a function of time and space is highly complex due to the heterogeneous and anisotropic nature of the textile composites, which is further complicated by the loading parameters. The impact behaviour of textile composites is a diversified field with a wide range of parameters governing it, broadly classified into instrument parameters and composite material parameters. In the case of instrument parameters, the drop height (velocity), drop mass, angle of impact and impactor details such as type, size & geometry, and in the case of composite material parameters, the thickness, its fibre volume fraction (V_f), stacking sequence, elastic properties, resin system used, interphase and curvature details, all play a role in contributing towards the complexity of impact behaviour. Other than this, there is still the possibility of striker (impacting body) and target being either stationary or moving relative to each other. This review article reports the research development on low velocity drop weight impact behaviour of textile reinforced composites with emphasis on the effects of impact parameters and textile reinforcements.

Although a clear opinion does not exist, the impact phenomenon has been classified, based on the impactor velocity, into low (<0.25 km/s), medium (0.25-2 km/s), ballistic (2-12 km/s) and hyper velocity

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(>12 km/s) impacts.[3] In their review article on impact resistance of composite materials, Cantwell and Morton[4] have defined <0.01km/s as low velocity impacts considering different impact testing techniques, while Abrate[5] defined <0.1 km/s impactor speed as low velocity impact. According to Olsson[6], the definition of low velocity impact on composites is either the situation when the duration of impact is same as that of the time required for the flexural and shear waves to reach the boundary conditions (impactor of small mass with higher velocity) or when the impact duration is much larger than the time needed for the flexural and shear waves to reach the boundary (impacts caused by heavier masses at very low velocities). Although Olsson's approach for categorizing the impact phenomenon is reasonable as it considers the energy associated with impact and contact time, but populous view of considering <0.1 km/s as low velocity impact as suggested by Abrate is acceptable from impact testing view point and simplicity.

2 Effects of Test Parameters on Impact Behaviour

The impact behaviour of composite materials subjected to low velocity impact is influenced by the impactor issues and specimen specifics.[7] The impactor parameters mainly impinging impact behaviour are impactor material, mass, incident velocity, incident energy, impactor shape, drop mode and angle of impact. Test specimen factors include specimen thickness, history, specimen shape, clamping and specimen support.

2.1 Impactor Type and Geometry

Not all impact phenomena would be associated with the hard rigid impactors; aircraft composite structures often collide with soft body impactors such as bird strikes or hailstones. In such cases, the impactors are deformable and flow-over the structure, spreading the impact load. Bird strikes emulated by gelatinous impactors on the composite materials have been studied for gelatin flow during impact.[8] Hailstone impact studies by Kim and Kedward[9] has been done using an elastic–plastic ice model with solid elements for the ice projectiles. Johnson and Holzapfel[10] have discussed the recent progress on modeling and numerical simulation of such soft body impact on fibre reinforced composite structures. Both delamination and ply failures were found to be prominent during impact of soft bodies on composite structures in the velocity range 100–200 m/s,

depending on the impact energy levels. Mostly, the impact events involve rigid strikers on the composite structures and hence further discussion reported in this paper is based on the rigid type impactor.

Impactor shape has significant effect on the damage initiation. Low velocity impact tests on laminates with conical, flat, semi-spherical, and semi-cylinder impactors indicate that the impactor shape affects failure mechanism and energy dissipation capacity of the specimen. Flat and semi-spherical impactors display similar failure mechanisms and energy dissipation levels, but the internal damage caused by flat impactor is comparatively less. At the same time, surface damage on the laminate would be higher in flat impacted composite due to high contact area. Conical impactor exhibits local penetrations, resulting in lower impact energy dissipation.[11] Studies on effect of different impactor shapes on woven carbon/epoxy laminates convey similar effects with conical impactor.[12] Barely visible impact damage (BVID) was observed with semi-spherical impactor at 4J initial impact energy, whereas ogival and conical impactors produce permanent indentation and penetration.[12] During an impact event with semi-spherical impactor, the contact radius is proportional to the cube root of the impactor radius and the contact pressure will be less for a larger impactor at a given load.

2.2 Impact Velocity/Energy

The drop weight impact can be elucidated from the impact energy E (J), projectile velocity V (m/s), impactor drop height h (m) and impactor mass M (kg) using the following equation, where g (9.81 m/s^2) is acceleration due to gravity:

$$E = M\,g\,h \qquad \qquad \ldots (1)$$

Impact studies on carbon/epoxy composites tested at small drop heights failed in a manner similar to those tested statistically, where with the increased drop height, multiple cracking and bending failures were reported.[13] Mili and Necib[14] have studied the impact behaviour of different glass/epoxy composite plates (0.43 V_f) at low impact velocities (<0.01 km/s). These studies on glass/epoxy composites under impact event validate that the impact forces and central deflections are proportional to the projectile velocity.

The work of fracture increases with increasing loading rate (impact velocity) due to the rate-

dependent fracture properties of the reinforced fibres. Increasing the loading rate increases fibre failure stress and as a result, the stored elastic energy. This, in turn, increases the crack bifurcation and results in formation of a larger damage zone during impact.[15] Response of fibre reinforced composite with impact velocity (V_o) and impactor mass (M) was proffered by a single factor called impact parameter (λ), as shown by the following equation[16]:

$$\lambda = \frac{(\alpha_p\, K^{2/5})(V_o\, M^3)^{1/5}}{h^2} \qquad \dots (2)$$

where α_p is the unit laminate thickness parameter; K, the Hertz-Sveklo factor; and h, the drop height. Maximum impact force, coefficient of restitution and time of contact during impact phenomenon can be determined in terms of impact parameter (λ). The coefficient of restitution (e) is laminate deflection recovery parameter during an impact event, given by the ratio of impactor velocity at separation to that of velocity at approaching. The coefficient of restitution (e) is dependent on λ and it decreases exponentially from 1 (elastic impact) to 0 (ref. 16) . Further, during drop weight impact event the maximum impact energy (E_{max}) imparted to the composite specimen is given by the following Eq. (3) (ref. 16). An estimate of energy loss (E_{loss}) during optimized impact phenomenon has been explained by the following Eq. (4) (ref. 17), where V_i & V_r are the impact and rebound velocities; and M, the impactor mass:

$$E_{max} = \frac{M V_o^2}{2} \qquad \dots (3)$$

$$E_{loss} = \frac{M(V_i + V_r)(V_i - V_r)}{2} \qquad \dots (4)$$

Based on the kinetic energy of the impactor (E_{max}), Cantwell and Morton [18] have ascertained the energy values of impact threats for composite structures that can arise from different causes at several places of the aircraft due to various types of risks (Table 1).[18] With low impact event energies ranging from 4J to 62 J at different sections, it can be inferred from Table 1 that most of the routine impact events occur in 10-40 J energy range.

Increased impactor mass and impact velocity result in higher peak contact force along with reduction in maximum displacement and unaltered maximum impact energy.[19] Glass/polyester, carbon/polyester

Table 1—Typical impact threat for an aircraft structure[18]

Section	Area	Impact risk	Impact energy, J
Upper wing skin	Inboard (near fuselage)	Falling tools	4
		Aircraft lifting equipment	20
		Refueling by gravity	20
Lower wing skin	Outboard	Falling tools	4
	Outboard + Inboard	Hail impact	30-35
	Outboard	Loading of pylons	16
Rear fuselage	Inboard Top	Runway debris	12-22
		Mounting of	
		Fin	57
		Rudder	10
		Hyd. reservoir	29
		Hyd. accumulator	28
		Airbrake	6
		Precooler	62
		Engine lifting equipment	44
		A/C lifting equipment	57
Sides		Ramming of service platform	19
		Mounting of	
		Hyd. reservoir	5
		Precooler	11
		Airbrake	6
		Engine lifting equipment	8
		A/C lifting equipment	20

and nylon/polyester composite materials properties have been probed for low velocity impact behaviour and it is recognized that when the material is not rate-dependent, static tests are sufficient to characterize composite materials dynamic behaviour.[20]

The impact damage-zone size decreases with the increase in impactor size for the same incident impact energy. At constant impact energy as the impactor size increases, more strength is retained in the impact zone.[21] The largest damage growth as well as the highest extent of damage would be caused by the smallest impactor having highest velocity at constant impact energy level.[21] The influence of the indenter size is significant when the contact load becomes very large, at which point the laminates get seriously damaged.[22]

2.3 Impact History and Repeated Impacts

Apart from total impact energy, the impact force history of the textile composite is the relevant

measure for direct composite material characterization. During low energy impact events, damage may not occur on a single hit. In fact, it is actually more important to determine the evolution of the damage produced solely, than the absorbed energy. A repeated drop test is one such test method in which a clear damaged region even when the impact energy is low. In such repeat impact event on glass/epoxy composites, the incident impact energy varies inversely [23] as to the number of drops to failure in the pattern (Fig. 1). Repeated drop tests were successfully used to understand the impactor mass effects on the impact behaviour of glass/epoxy composites. Figure 2 (ref. 24) illustrates the load-time-energy plot for 85th drop test conducted on the instrumented impact. machine (Dynatup 8250); numbers on the curves indicate impactor mass (kg). At lower incident energies, it is observed that heavier impactors cause more damage leading to earlier failures and the mass effect diminishes at higher incident energies.[24]

2.4 Specimen Thickness and Rigidity

The composite specimen thickness has a significant effect on the local indentation during impact.[25] Naik et al.[26,27] have studied the damage initiation behaviour of composite plates subjected to low velocity drop weight impact, observing in-plane failure of the layers in the form of matrix cracking and delaminations. They showed a linear relationship between the peak contact force and the composite thickness. The maximum plate displacement was stated to increase with the decrease in plate thickness. Also, the duration of impact increases as the composite plate thickness increases. A representative plot (Fig. 3) deciphers the exponential increase in number of drops
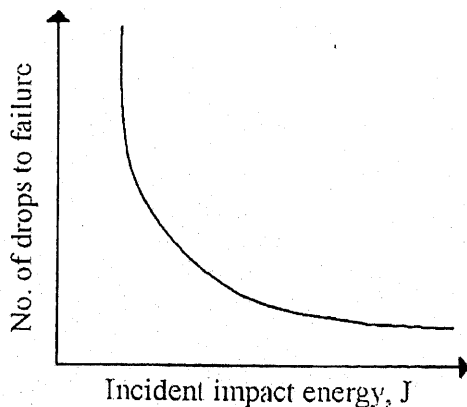
to failure with the increase in laminate thickness, as observed for carbon, Kevlar and glass fibres reinforced in epoxy matrix, tested on instrumented impact tester having semi-spherical impactor of 0.765 kg mass and 0.5 m drop height.[28] Change in composite thickness has slight influence on impact velocity threshold but significantly affects maximum damage size. Thicker the composite, the smaller is the damage area at specific impact velocity; this could be due to the lesser displacement on the thicker composites.

In an impact event, peak force and contact duration are important factors influencing impact characteristics. Stiffer composite specimens show shorter contact durations and higher peak forces than their softer counterparts.[29] Other factor strongly influencing impact performance is the history of composite laminate, which is greatly influenced by the overall rigidities of the plate, governed by the elastic properties of the material (E_1, E_2, γ_{12}, G_{12}).
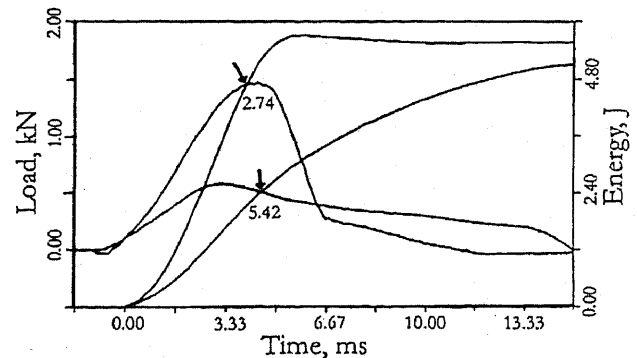

Fig. 2—Instrumented drop impact plots of glass–epoxy composite, Load–time–energy trace for 85th drop number (E_{imp} – 5.3 J) [24]

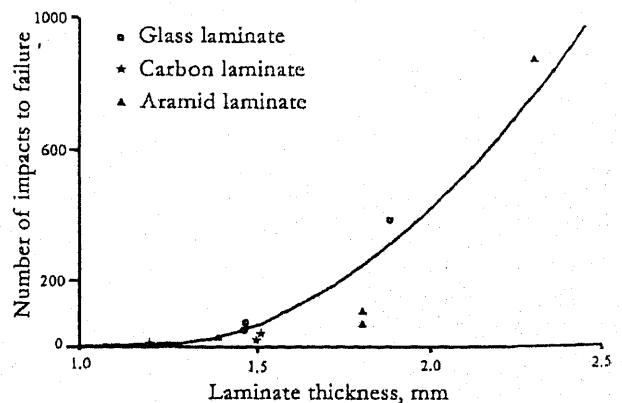Fig. 1—Repeat impact performance of glass/epoxy composites [23]

Fig. 3—Variation in number of drops to failure with laminate thickness [28]

Transverse modulus (E_2) has a major influence on the contact stiffness. Lowering the contact stiffness lowers the contact forces and increases contact area, which, in turn, affects the stress distribution under the impactor.[5] In the specimen under impact, larger the width of the rectangular specimens, higher will be the peak force and shorter will be the contact durations. Therefore, the delamination area of the small rectangular specimen is slightly less than the other specimens. Nevertheless, the thickness of the composite is most dominant parameter in the specimen that governs the dynamic response and damage mode of impact event.[29] Demuts *et al.*[30] have assessed that the impact damage is not only dependent on the impactor shape and laminate thickness but also on its structural support and impact history.

In this part, low velocity impact test and specimen parameters influencing impact performance of textile composites have been discussed. Semi-spherical, rigid type of impactor has been prevalently employed for the instrumented low velocity impact tests. Although the instrumented impact tests are centered on impact velocity, edification and analyses based on impact energy provides better understanding of textile composites impact performance. Among the various factors deliberated in this section, the incident impact energy, specimen thickness, rigidity and previous history of the composite are the most influential parameters for low velocity drop weight impact properties.

3 Influence of Composite Constituents on Low Velocity Impact Behaviour

Properties of the constituent elements, i.e. fibre, matrix and the interphase, have distinct effect on the impact behaviour of the composite material, which is discussed in this section.

3.1 Effect of Textile Reinforcement
3.1.1 Fibre Content and Properties

Fibres being the principal load-bearing element of the composite structure contribute significantly for its strength and stiffness. The elastic modulus of the high performance fibres used in the composite is much higher than that of the matrix, hence under low velocity impact situations, fibres exhibit rigidity and initial damage is more matrix and interphase dominated.[31]

Fibre's ability to store energy elastically is the fundamental parameter influencing the low velocity impact response of the composite.[4] Glass fibres, although have lower strength and stiffness, show better impact resistance than carbon fibres in the composites due to higher strain to failure.[32] Reinforcements with high strain to failure fibres, such as ultra high modulus high density polyethylene (UHMWPE) and aramid fibres like Kevlar 49, are known to impart high resistance to impact damage.[33,34] Carbon fibres, being most brittle, show poor resistance to impact damage in composite form which has been validated in comparison to glass[32] and Kevlar reinforced composites.[35] Maximum load increases with the increase in impact energy up to 20J and carbon/epoxy composites under low velocity impact would not be able to withstand dynamic peak load beyond 3.6 kN (ref. 36). Reinforced fibre dimensions influence the composites response to impact loading. The increase in diameter of the reinforced fibre would enhance low velocity impact response, but increased toughness of the composite and reduced fibre failure strain result in overall loss of strain energy absorbing capacity.[4]

The maximum impact force is an increasing function of fibre volume fraction (V_f). During low velocity impact event, the maximum deflection of the composite plate and contact time of the impactor with the laminate continuously decreases with increased V_f.[16] Studies based on instrumented impact tests for glass/polypropylene thermoplastic composite show a non-linear dependence of fibre initial modulus on the fibre content; the maximum modulus is in the range of 40–50 fibre weight %. Impact properties are reported to increase initially with the increase in glass content but decrease when the glass fibre weight content is increased beyond 50 % (ref. 37).

3.1.2 Fibre Hybridization

Hybridization of high performance fibres has been reported to be an efficient way to improve the impact performance of the composite materials.[38-41] Among the high performance fibres used for hybridization, one would be high modulus, high strength fibre such as carbon and the other would be a low modulus fibre like Kevlar or glass.[40] Advantages in few properties may also result in disadvantageous side effects such as mismatch of modulus, which have to be balanced while designing the composite. Hybridization studies on carbon-glass epoxy composites have yielded higher impact resistance as compared to virgin types, evident by about 83% post impact compressive strength retained in carbon-glass hybridized laminates as compared to 73% in virgin carbon composite.[42]

The fibre having lower modulus should be used at the composite surface to enhance the low velocity impact performance of hybrid composites.[43] Inclusion of woven glass fabric layers at the top and bottom surfaces for carbon/epoxy composites is recommended, which delay the penetration of the indenter and prevent the splitting damage. Also, with the use of glass fibres in that case, damage initiation could further be delayed with very little increase in the overall weight of the structure.[36] Addition of glass fibre to carbon/epoxy and boron/epoxy composites is reported to improve the impact strength by a factor of 3-5 as compared to unhybridized laminates.[44] An optimal solution for fibre hybridization has been suggested by Rahul et al.[45,46] Finite element method, Island model parallel genetic algorithm and Sequential genetic algorithm have been used by them to obtain optimum laminate particulars in terms of minimizing the cost, weight or both cost and weight of carbon/epoxy, Kevlar/epoxy hybrid laminates while maximizing the strength.

3.1.3 Reinforcement Geometry

Fibre orientation is an important parameter wherein unidirectional, bi-directional and 3D preformed composites have been constantly investigated for their impact performance.[47,48] Compared to CSM (chopped strand mat) and nonwoven reinforced laminates, overall impact behaviour is better in bi-directional laminates due to the presence of interlacement and fibre crossover points.[49] Figure 4 presents the traced damage area of composites with different textile reinforcements subjected to low velocity impact (10J) tested in-house on instrumented impact tester (Dynatup 8250) with semi-spherical impactor, illustrating the influence of fibre orientation on impact load distribution and damage propagation. It is observed that the rational mixing of unidirectional and woven layers helps in decreasing the overall failure function, thus to improvise impact damage resistance.[49]

Among the textile composites, woven laminates possess large toughness with respect to the initiation of interlaminar cracks [50] and due to these interlacements these composites offer excellent resistance to impact damage through the cross-over points, which act as stress distributors. Plain woven reinforcements with highest interlacement per woven design repeat [36] offer excellent dissipation for impact load, thus possess better impact property.[50,51] Plain woven textile laminates subjected to impact loading
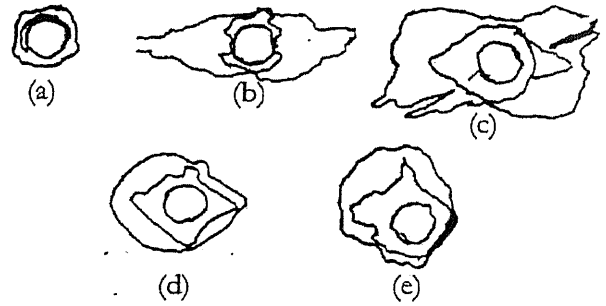

Fig. 4—Impact damage area of GFRP laminates with different textile reinforcements [(a) CSM, (b) UD, (c) multi-axial warp knit (d) plain woven, and (e) twill woven]

beyond threshold energy level show crack initiation within the ply which tries to propagate through the thickness, but has to cut through the fibre in the warp direction wherein the resistance is offered due to high interlacement. Unless the energy available is high enough to fracture the fibre tow, the growth of crack is arrested. Hence, the delamination initiation and progression will be suppressed. This will help in considerably reducing the delamination damage.

The presence of third directional fibres in 3D textile preforms (orthogonally woven, multi-axial warp knitted, multi-layered woven-interlocked and stitched) not only hinders crack propagation but also increases the impact resistance and damage tolerance of the composites reinforced with them.[52,53] Delamination prone ply interphases can also be eliminated in multi-directional weaving such as multi-axial warp knit preforms [54] and 3D orthogonal weaves.[55] Many related research studies have shown that the composites reinforced by 3D woven and multi-axial warp knits outperform 2D woven laminates under impact not only by sustaining substantially less shear damage but also by exhibiting better resistance to penetration.[56-59]

The thickness reinforcement in the form of pinning and stitching to improve the damage resistance and tolerance has been studied by many authors.[60-62] Stitched preforms are commercially more important class of 3D preforms currently used, in which stitching all the layers by high performance fibre such as Kevlar or glass makes the 2D preform to perform the 3D function. However, the studies have indicated the role of stitching in altering the material in-plane mechanical properties.[62,63] Tensile strength of the stitched laminates has been reported to be either slightly improved, unchanged or 30-45% reduced,

whereas the compressive strength shows a loss magnitude of 5-55%. This influence in mechanical properties due to stitching is dependent on other factors like type of fibre, fibre orientation, stitching parameters and testing method.[63]

Knitted textile preforms, compared to woven counterpart, distribute the stress better throughout the structures and the composites reinforced with them are better impact resistant due to higher isotropic behaviour.[64] Knitted reinforced composites, compared to the braided, uni-fabric and prepreg tape composites, show superior retention of compressive strength after impact event. The occurrence of greater damage resistance during the impact event is due to homogeneous distribution of reinforcement -in the matrix which results in a better ply nesting and intermingling of knitted loops within the fabric layers, thus suppressing the propagation of crack or delamination growth.[65] Sugun and Rao[66] have compared the drop weight impact properties of knit preforms with woven fabric laminates and opined that the rib knit preforms with added reinforcements in the course direction possess superior energy absorbing capabilities compared to equivalent woven fabric composites.

Preform stacking sequence influences not only the impact performance of composites but also the pre and post-impact compressive strengths along with the total delamination area.[67] Strait *et al.*[68,69] in their studies on carbon fibre reinforced epoxy-polyether sulfone resin composites, found that the quasi-isotropic laminates have better overall impact resistance than cross-ply laminates. Choi *et al.*[70-73] have observed higher initial damage resistance with more uniformly dispersed ply sequence in laminate. They have also inferred that the impact damage is less sensitive to laminate thickness than to stacking sequence and the impact energy threshold is strongly affected by ply-orientations and laminate thickness.

The influence of fibrous reinforcement on the low velocity impact behaviour has been discussed in this section. It is evident from the above deliberations that the type of fibre, fibre hybridization, fibre volume fraction, reinforcement geometry, stacking sequence and fibre orientation in the reinforcement influence the impact behaviour of the composite. Critical factors on which preform engineering has been concentrated are fibre's strain energy storage capacity and 3D preforming with respect to improvement in low velocity impact performance of the composite material.

3.2 Effect of Matrix Properties

In the textile composites, matrix performs the function of gluing the fibrous structure together, thus the strong and stiff fibres are able to embrace most of the stresses whilst the resin distributes the external load to all the fibres and prevents fibre buckling under compressive forces. Although resin does not contribute to the strength and stiffness of the composite, the role of matrix in impact behaviour of composite is still very critical, as damage to the matrix can reduce the load bearing ability of composite to 50% (ref. 74).

3.2.1 Thermoplastic Matrices

Both thermoplastic and thermoset type matrices are abundantly used for composite preparation; in comparison to thermoset, thermoplastics offer advantages like reduced cycle times, improved toughness, and potential for recycling [75], but low thermal stability, chemical resistance, poor interfacial properties and creep problems are major hindrances for their high end applications in composites.[76] Comparative low energy impact damage on both thermoset and thermoplastic fibre reinforced composites indicates better damage tolerant behaviour of thermoplastic systems.[77] Effect of cooling rate on impact damage performance of carbon/polyether ether ketone (PEEK) thermoplastic composites shows that the ability to resist damage initiation upon impact is higher in the fast cooled (20°C/min) laminates as compared to the slow cooled (1°C/min) laminates. Also, these carbon/PEEK composites show better impact resistance compared to the equivalent carbon/epoxy thermoset laminates.[78] Studies on the matrix controlled damage by Wang and Vu Khank [79] in carbon/PEEK composites with cross lay-up sequence have reported the observation of matrix transverse cracks in the laminates at 0.5-1.0 J impact energy.

3.2.2 Thermoset Matrices

Although broadly similar, there exist subtle differences between the impact damage modes of the epoxy and polyester matrix composites. Studies on glass fibre reinforced polymer (GFRP) composites with orthopthalic polyester and epoxy matrix systems show similar impact behaviour, but the polyester laminates absorbed marginally higher impact energy compared to the epoxy composites.[80] Also, the front face delamination and the back face fibre damage was observed more in epoxy than in the polyester

laminates, which could be due to the brittleness of the epoxy system, but the internal delamination in epoxy laminates was smaller and first seen at a higher incident energy as compared to polyester laminates. The variant of the particular resin system becomes important as commercial grade polyester resin, which is used abundantly for many GFRP composites, does not exhibit the above inference. Epoxy matrix (LY556/HT972) out performed the commercial polyester matrix composites, both reinforced with plain woven glass fabric (4 mm laminate thickness, 0.65 V_f), when tested inhouse on Dynatup instrumented impact tester for number of drops to failure, with all other parameters being the same. Epoxy composites took 48 and 7 impact blows for penetration failure at 6J and 20J impact energies, whereas polyester laminates could only bear 18 and 3 blows respectively, as represented by impact energy vs. number of drops to failure curves (Fig. 5).

Toughness of the matrix in the composite is a vital factor influencing the impact behaviour of the composite material. Brittle laminates tend to fail by extensive delamination whereas the tougher systems fail by transverse shear near the impact locations. Also, the mode II (forward shear) properties of the matrix determine the level of damage incurred during the impact event.[4] During impact damage, single-step cured samples lose 82 % of its initial toughness, indicating lower brittleness while multi-step curing reaches lesser losses (67%), indicating higher brittleness.[81]

3.2.3 Modified Matrices and Additives

Incorporation of plasticizers and elastomeric components in the resin formulation has been attempted to reduce the matrix damage due to impact and to improve the fracture toughness of the thermoset composites.[82] The impact response of carbon fibre composite with modified bismaleimide (MBMI) compared to epoxy resin shows that the toughening effect of the modified MBMI matrix leads to higher energy absorption during impact event due to enhanced fibre/matrix adhesion and the plastic deformation in the matrix.[83] Morii et al.[84] studied the impact property and damage tolerance of matrix hybrid composite laminates consisting of the lamina with a conventional epoxy resin and the lamina with a flexible epoxy resin modified from conventional resin. They concluded that the energy absorption increased exponentially with the increased flexible resin fraction with its presence on the impacted face.
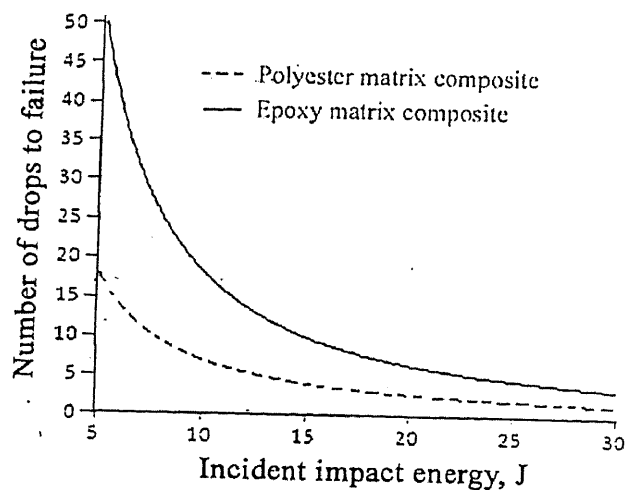

Fig. 5—Impact performance of polyester and epoxy matrix GFRP laminates

However, the detrimental effects of matrix's property modification on other mechanical properties of the composite have also been conveyed.[4, 85]

3.3 Influence of Interphase

Apart from the fibrous reinforcement and polymeric matrix in the composite materials, a third constituent (the interphase) is now known to drastically affect the performance of the composite.[5] The interphase is a region of finite mass located at the fibre/matrix boundary. Though it is well known that the bond strength between fibre and matrix significantly influences the mechanical properties of composites, very few studies have been done on the influence of interphase on the impact behaviour of composites.[86] Kevlar fibres are known to have poor interphasial bonding with the matrix material in the composite. An investigation on the Kevlar/epoxy composites low velocity (1.8 m/s) impact behaviour after fibre treatment with phosphoric acid has indicated marginal reduction in impact performance with enhanced interfacial properties.[87] Depending on the type of reinforcing fibres, composites with poor fibre/matrix interphase absorb more energy under impact loading because of extensive delamination and debonding processes. The influence of fibre/matrix adhesion on the energy absorption ability of glass fibre reinforced composites has been studied by Morii et al. [88] and El-Habak.[89] Both opined that the fibre treatment strongly influences the impact behaviour and inferred that the laminates with decreased fibre/matrix adhesion absorb more energy.

In this section, the influences of matrix and interphase on low velocity impact performance of

composite material have been elaborated. Matrix toughness plays significant role in the impact behaviour wherein brittle laminates tend to fail by delamination while the tougher systems fail by transverse shear. The thermoplastics are more impact damage tolerant than the thermoset matrix composites due to higher toughness. Among the commonly used polyester and epoxy matrix composites, epoxies perform better than polyester matrices under low velocity impact. Stronger interphase between the fibre and the matrix has negative effect on the low velocity drop weight impact performance of textile composites.

4 Failure of Textile Composites Subjected to Low Velocity Impact

Mode of failures in composites is an important factor in damage analyses as it provides information not only on impact event but also on the residual strength of impacted composite. Textile composites subjected to low velocity impact dissipate the imparted energy through several interacting damage modes rather than simple deformation.[90] Failure during the impact event on fibre reinforced composite can be deciphered by the load-time-energy curves obtained by instrumented impact tester. The characteristic points of such typical impact curve (Fig. 6) have been discussed by Ghasemi and Parvizi.[91] They observed the incipient damage point (IDP) as first sudden load drop and/or a change of slope in the ascending portion of the load vs time or load vs deflection impact curves.

Incipient damage point, also termed as Hertzian failure, is a consequence of internal delamination and/or fibre/matrix interface failure which usually takes place close to the back surface of the impacted panels.[92,93] The incipient load (P_i) and energy (E_i) are denoted in the Fig. 6. Impact damage gets initiated as matrix crack extends to the interphase of two lamina and progresses as delamination. Matrix cracks can initiate as either tensile or shear cracks. In both the cases, the crack will initiate transverse to the fibres within a ply.[94] These cracks propagate through the thickness and when they come across stiffer fibres in the ply, it leads to development of delamination. Under low-velocity impact, textile composite systems sustain damage and the majority of failures are reported to be due to delamination.[91,94,95] The extent of delamination will depend on the portion of impact energy available to fracture the interphase.

In textile reinforced composites, there is very little or no plastic deformation and impact energy is
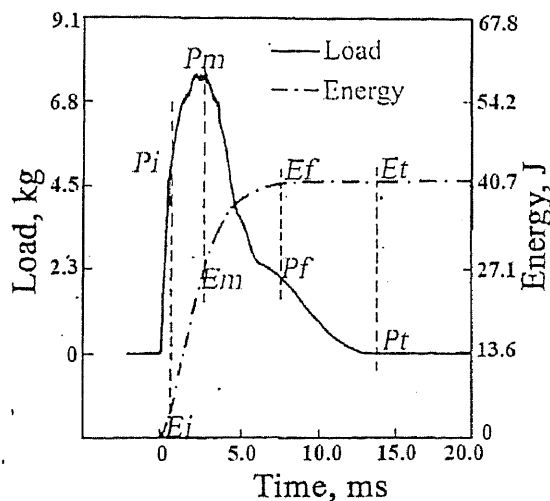

Fig. 6—Typical instrumented impact tester load-time-energy curve[91]

initially absorbed through elastic deformation till a threshold. The maximum load point (MLP) or this threshold value is the peak impact load that a panel can tolerate before undergoing major damage. At the MLP, a major fibre breakage occurs through the laminate thickness. The maximum load (P_m) and the required energy (E_m) at the maximum load are shown in Fig. 6. Relevant to the present discussion is the work by Davies *et al.* [96], who showed that in carbon/epoxy composite laminates there is a threshold value of the impact energy below which delamination is not generated, as given by the following equation:

$$P_m^2 = \frac{8\pi^2 Eh^3 G_{IIc}}{9(1-v^2)} \qquad \qquad \dots (5)$$

where P_m is the threshold load; E, the equivalent in-plane modulus; v, the Poisson ratio; h, the laminate thickness; and G_{IIc}, the critical strain energy release rate. The model indicates that the square of the critical force threshold is proportional to the cube of the laminate thickness. Above that threshold, delamination increases suddenly, affecting an area that increases with increasing impact energy. At the failure point (FP), the composite loses its structural integrity; it fails completely and can sustain no more load. At this point, the load starts to drop to the zero load level (or minimum load level after the MLP) with a constant slope in the impact curve (Fig. 6); the failure load (P_f) and the corresponding energy (E_f) at the FP are shown in the figure. Dorey [97] gave a following simple equation for the impact energy (E) required for fibre failure and penetration:

$$E = \frac{\sigma^2 wtL}{18\, e_f} \qquad \qquad \dots (6)$$

where σ is the flexural strength; e_f, the flexural modulus; w, the width; L, the unsupported length; and t, the specimen thickness. Threshold load method as mentioned by Eq. (5) is reported to be the simplest method which provides accurate results for impact induced delaminations in the composite.[98]

The total point (TP) is the point where the impact event ends (end of the duration time), the load returns to zero (or a minimum level after the MLP) and energy has a constant value. The load (P_t) and energy (E_t) at this point are shown in Fig. 6; E_t denotes the total energy absorbed by the composite. The difference between E_t and E_m is a measure of the energy required to propagate the damage and is denoted by E_p (i.e. $E_p = E_t - E_m$).

This section was focused on failure modes occurring in the textile composites subjected to low velocity impact. Textile composites under impact event dissipate energy through elastic, plastic deformation and through creation of new surfaces by failure. Interacting failure modes initiating from matrix cracks, delamination, fibre damage and finally laminate penetration failure have been discussed. Characterization of such failure modes plays a significant role in damage analyses and modeling the impact behaviour.

5 Evaluation of Impact Damage in Textile Composites

The complexity of comprehending the impact behaviour from the point of view of designing the composite structure is well conveyed by Bibo and Hogg.[58] A good understanding of the characteristics of low velocity impact induced damage, including the damage formation and development features becomes essential to quantify the impact induced damage and to evaluate the post impact load bearing capabilities.[99] At times the low velocity impact induced damages could be very dangerous because in many instances they cannot be detected visually and may lead to structural failure at loads well below design levels.[100] Evaluating the properties of the impacted specimen becomes critical issue in this regard. In many fibre reinforced composite impact situations, the level of impact at which barely visible impact damage occurs is much higher than the level at which substantial loss of residual properties occurs.[101-103] Even when no sign

of impact damage is observed at the surface, matrix cracking and delamination can occur beneath the impacted surface, which affect the performance of the composite. Hence, the evaluation of impact damage becomes critical in these situations and various evaluation techniques are available to assess the damage after impact, which can be broadly classified into destructive and non-destructive evaluation tests.

Destructive techniques generally involve microscopic investigations and impact damage tolerance studies based on residual strength parameters such as tensile, compression and flexural strengths. Many microscopic studies have been tried for characterizing the impact damage by visual image analyses. Chai and Babcock[104], using the shadow moiré technique, performed optical measurements on composites subjected to low-velocity out-of-plane impact. Epstein et al.[105] used dynamic moiré interferometry to measure the deflection of impacted composite plates. Microscopic investigations on the structural properties of GFRP composites[106] report that no delamination occur in the samples examined in this work when the energy of impact is <9 J. For E-glass non-crimp (multiaxial) woven and non-woven reinforced composites, metallographic microscopy was used to observe the damage characteristics of the perpendicular cross-section of the low velocity impacted laminates after a micro-powder polishing treatment.[107] The load–time and the energy–time histories have been compared with the fractographics and it is found that the fibre breakage occurs prior to the major damage. When the impact energy increases over the threshold energy of the major damage, matrix cracking, delamination, and fibre breakage are observed at the back surface, below a nearly undamaged zone, which is attributed to the bending stresses.

Damage tolerance studies based on tensile and compressive strengths have gained prominence as the reduction in tensile strength depends mainly on the extent of fibre breakage, whereas in compression, the delamination failure is induced by local buckling instability due to the presence of inter-laminar and intra-laminar shear cracks. Figure 7(ref.108) illustrates the post impacted tensile and compression strength plots, implying the significance of impact properties for structural applications. The delaminations at low impact energies cause little effect on the tensile strength but significantly reduce the compressive strength of the textile composite.
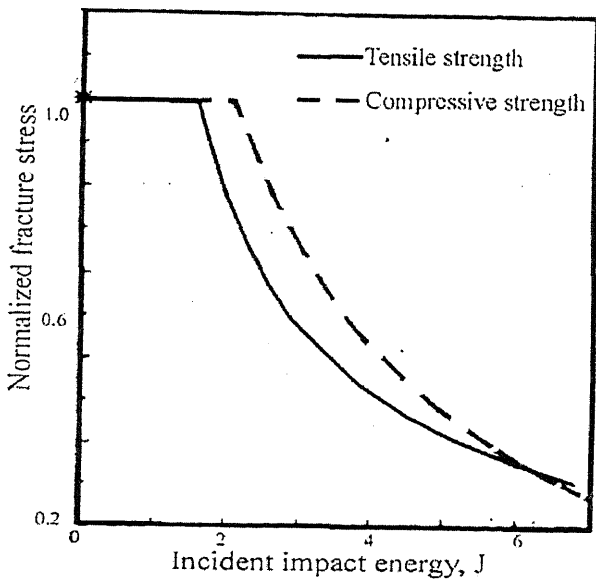
Fig. 7—Tensile and compressive strength reduction after impact [108]

Few standard tests provide detailed test procedures to evaluate the post impact compression strength of composite materials; these include ASTM[109,110], BSS[111], SACMA (suppliers of advanced composite materials association)[112], FAA[113] and AECMA[114].

Ultrasonic (C-Scan) techniques have become one of the most popular nondestructive testing techniques because of their versatility and ease of operation. They can easily detect internal cracks and inclusion-type defects in homogeneous or layered materials, but cannot penetrate inside highly oriented materials like fibres and epoxy resins. Only relatively low frequency ultrasonic waves are observed to propagate through these materials[115], although simpler ultrasonic approach to assess the maximum spatial extent of the impact damaged GFRP volume has been reported.[106] The evaluation of the damage spatial extent obtained by this method was found to correlate well with that recovered by direct microscopic investigation. Ultrasonic C-scan pulse-echo immersion method was effectively adopted for low velocity (3-30J) impact damage analyses of CFRP laminates of 10 different cross-ply lay-up of different thicknesses. Projected delamination was obtained by placing a gate over the back wall echo, layer wise distribution was obtained by successive time delay from the front wall to the back wall echo covering each interphase. Delamination areas were quantified accurately by processing the raw image data using a digital image processing technique. Based on the data obtained, an

empirical relationship was also established by curve fitting technique between the delamination area and the impact energy, as given below[116]:

$$D = (E - E_{id})m_1 \quad for\ E_{id} < E_L^d \qquad \ldots (7)$$

$$D = D_L + (E - E_L^d)m_2 \quad for\ E_L^d < E \qquad \ldots (8)$$

where D is the delamination damage (mm^2 mm^{-1}); E, the normalized impact energy (J mm^{-1}); E_{id}, the impact energy for damage initiation (J mm^{-1}); E_L^d, the impact energy beyond which damage increases marginally (J mm^{-1}); DL, the delamination corresponding to E_L^d (mm^2 mm^{-1}); m_1, the slope for phase II between E_{id} and E_L^d (mm^2 J^{-1}); and m_2, the slope for phase III beyond E_L^d (mm^2 J^{-1}).

The above discussion as well as a number of recently published papers suggest that objective evaluation of impact behaviour and post-impact damage characterizations of textile composites subjected to low velocity drop weight impact possess potential for research and development. Residual compression strength after impact, microscopic cross section investigation by fractography and ultrasonic scanning techniques are the most relevant techniques for post impact damage evaluation of the textile composites presently.

6 Conclusions

Textile composites under impact demonstrate different modes of failure through several interacting damage modes amongst which delamination failure is considered most decisive. Impact damage assessment by residual strength-compression after impact, microscopic studies and ultrasonic scan are imperative for the evaluation of low velocity impacted textile composites.

Given the diversified variables of the impactor and the target as mentioned above, it is not possible to definitely conclude upon the effects of any or all of the test parameters on the impact response of textile composites, except in select situations. A sort of compartmental research is discerned, wherein the influence of a particular parameter is focused upon and conclusions drawn, overlooking or at least temporarily ignoring the effects by the other factors. Another issue faced by researchers is the scaling effect; unlike quasi-static tests (such as tensile test) the data obtained at the coupon level could not be merely used to predict the structure's impact response

at the component level. Therefore, the low velocity impact performance of the textile reinforced composites is still an open research arena to design composite structures for particular end use applications.

Presently, research information is available on the behaviour of textile structures subjected to low velocity impact, but the research focus should progress towards development of newer reinforcements and preforms for composites with desired impact damage tolerance through preform engineering. The other issue that needs to be explored is the method of designing composites with impact damage tolerance. This becomes critical when the composite is used for aerospace/transport applications, in which the structure has to undergo impact damage during emergency and needs to provide safety without catastrophe. As of now, impact design data for composites is obscure which is further complicated by large variations available and other issues. One possible solution would be that, for routinely used constructions, simulative studies should be carried out along with the design data based on past experience. However, except in select situations, when it comes to designing composites with impact damage tolerance, a case to case basis approach seems practical with experiments carried out in laboratory.

Acknowledgement

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