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A Low Velocity Impact Behavior of Fabric Reinforced Polymer Composites – A Review

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Abstract

The study of the low-velocity impact (LVI) performance of fabric-reinforced polymer (FRP) composites has drawn keen interest from the research community due to its application in various fields. In this direction, material designers and scientists have reported the behavior and performance of advanced composites subjected to LVI. In this paper, the existing literature and current research relating to LVI behavior and performance of fabric-reinforced polymer composites and nanocomposites are briefly reviewed. The impact behavior of some representative fabric reinforcements such as glass, carbon, Kevlar, Twaron, and hybrid fabric reinforcements in different matrix formulations have been discussed. The effect of fabric hybridization and nanofiller incorporation has also been reviewed. The fabrication methods, process parameters to achieve LVI application-centric fabric-reinforced polymer composites, their characterization methods, and testing standards are reported. Also, the failure mechanisms observed in FRP composites when subjected to LVI events are briefly discussed. Such information relating to LVI-resistant polymer composite materials has significant implications for the development of advanced composite systems and to achieve material sufficiency for a wide range of structural applications.

Keywords: Low-velocity impact; Fabric reinforced composites; Hybrid composites; Nanocomposites; Damage mechanisms; Penetration resistance.

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1. Introduction

In recent decades, the development and characterization of fabric-reinforced polymer (FRP) composites are increasingly becoming important due to the application of these composites in various ballistic, automotive, aerospace, and marine applications.[1–3] One of the prime reasons for choosing FRP composites for such applications is due to their flexibility to achieve required material properties and their ability to provide better energy absorption during impact events compared to metallic components.[4] They also provide enhanced structural, mechanical, and tribological properties coupled with weight reduction.[5] These polymer matrix composite components are exposed to projectile impact (both low and high velocity) during operational life. Impact events are considered to be low-velocity when the projectile impact velocity on the component is in the range of 1–10 ms^{-1}.[6] Low-velocity impact (LVI) events generally occur during the manufacturing, service life, or maintenance of these components.[7] The damage to structural components induced during LVI events may drastically reduce the stiffness and residual strength of the composites.[8] Thus, it is essential to study the extent of damage incurred by the components to increase their service life and enhance their impact strength. This can be achieved by improving the fabrication methods, or by hybridization with stronger reinforcements as fabric hybridization is said to improve energy absorption capacity and resistance to impact damage on FRP composites.[9]

The extent of damage experienced by the target components due to the impact depends on several factors such as; (i) impact velocity, (ii) material properties of the target and the impactor, (iii) projectile dimensions and mass, and (iv) target dimension. Laminated fabric composite components are also prone to damage and failure due to transverse contact and

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impact with foreign objects.[10] It is essential to study the effects of low-velocity impact on fabric-reinforced composite laminates, as these types of impacts induce barely visible impact damage (BVID),[11] which cause complex failure to the internal structure of the laminates with very minimal surface damage.[12] In light of the above discussion, it is obvious that the LVI performance of FRP composites is of significant importance. This is due to the wide range of important applications in which the material is subjected to low-velocity impact and the associated damage that may reduce dramatically not only the service life of the material but also the functionality of the components with time. In this review, several issues are covered extensively such as composites used for LVI resistance applications, manufacturing methods, LVI testing methods, correlation of LVI impact strength with mechanical properties of LVI materials, LVI failure mechanisms, and many other relevant points.

2. FRP Composites for LVI resistance applications

Various research studies have been carried out to experiment with new combinations of composite materials for low-velocity impact resistance applications. Reinforcement fabrics such as carbon, glass, Kevlar, Twaron, ultra-high density polyethylene (UHMWPE), kenaf, and hemp have been used with various matrix formulations such as epoxies of various grades, low-density polyethylene (LDPE), polypropylene (PP), unsaturated polyester resin (UPR), *etc.*, to fabricate composites for LVI resistance. Finite element modeling (FEM) of damage corresponding to LVI has been attempted by various researchers such as Shi *et al.*[13] Similarly, Hamdia *et al.*[14] and Bek *et al.*[15] studied the fracture toughness and elastic properties respectively of polymeric nanocomposites through FEM. Abir *et al*.[16] developed a finite element model to perform LVI on composites followed by a compression after impact (CAI) test. Maximum stress and Tsai Wu failure criteria were used to model the damage initiation. It was observed that failure in specimens subjected to the CAI test was due to buckling and delamination growth localized at the area of impact. The principal factors that affected the residual strength of composites were Mode-II interlaminar fracture toughness (ILFT) and fiber compressive fracture toughness. Also, it was reported that the increase in ILFT reduced the delamination size and increased damage tolerance. Good coordination between experimental and simulation results for the behavior of nanofillers in the matrix was reported. In this section, past and ongoing research related to the fabrication, LVI characterization, and results relating to various types of composites such as neat and hybrid fabric-reinforced composites, fabric nanocomposites, bulk polymer composites, ceramic matrix composites, *etc.* have been discussed.

2.1 Fabric-reinforced polymer composites

Composites consisting of a single type of fabric reinforcement have been applied for various structural and ballistic applications. Different fiber orientations such as unidirectional (UD), bi-directional (BD), twill, and other weave patterns have been tested by researchers in their works corresponding to impact resistance. Researchers reported that 0/90 bi-directional fiber orientation offered the best impact resistance compared to all other orientations such as UD and twill patterns.[17–19] Thus, the predominant usage of woven bi-directional fabric is observed in the literature reporting on structural and impact-resistant composites. Recent developments and research relating to FRP composites consisting of a single type of fabric have been tested against drop weight and quasi-static impact tests have been discussed in this section.

Low-velocity penetration resistance of para-aramid fabric laminates impregnated with shear thickening fluid (STF) was studied by Dorota *et al*.[20] using a spike indenter. STFs are fluids that exhibit a considerable increase in viscosity with an increase in the applied shear rate. They used Twaron fabric treated with STF solution containing nano-silica particles dispersed in polypropylene glycol. The rate of penetration was 5 mm/min (quasi-static indentation) and a displacement of 30 mm. The perforation ratio was then calculated which is the ratio of several perforated layers to the total number of layers in the sample. Similarly, non-treated Twaron fabrics were also subjected to the same test. From the tests, it was reported that the non-treated fabric specimen exhibited complete penetration of all layers, whereas, in STF treated specimen, the perforation ratio was only 24%, *i.e.* only 6 out of the total 22 layers were completely penetrated. It was concluded that the introduction of STFs improved the penetration resistance of the multi-layer composite by filling the voids between individual fabric yarns and at high shear rates these STFs offered high viscosity, thus resistance to penetration by the indenter. These materials are well suited to be used as personal armor, as they have lightweight and have low stiffness. Similarly, Bocian *et al*.[21] fabricated composite laminates using 12 layers of Twaron fabric reinforced in modified dicyclopentadiene (DCPD) matrix. The laminates were fabricated and cured by compression molding at 1.5 MPa pressure, at a temperature of 21 ºC for 12 hours. Drop-weight impact and high-velocity ballistic tests were conducted. The indenter for the drop weight test was in shape similar to that of a 9 mm parabellum bullet. The impact speed was maintained at 8.8 m/s and the impact-induced a force of 8.5 kN on the specimens. The kinetic energy of the impactor was kept constant (150 J) for the 6 specimens that were tested. It was reported that the energy absorbed by the laminate was ~ 92.9 J with a deformation of 21.95 mm in the laminates. The damage mechanisms were observed using scanning electron microscope (SEM) images, which revealed a shear failure in the fibers followed by delamination due to compressive stresses which led to matrix damage.

Twaron para-aramid fibers have high impact and penetration resistance properties as these fabrics offer better toughness and low brittleness. The performance of Twaron fabric composites against low-velocity impacts was compared with that of Kevlar fabric composites by Remon *et al*.[22] Samples were fabricated through vacuum assisted resin infusion process using 15, 20, and 25 plies of fabric reinforcement in an epoxy resin matrix. The flat specimens were subjected to quasi-static indentation (QSI) tests according to ASTM D6264-98[23] standard. The penetration and damage behavior of the laminate samples were investigated and reported. The rate of loading was maintained at 2 mm/min as per quasi-static test conditions. Results showed that Kevlar/Epoxy panels of all thicknesses were readily penetrated by the 12.5 mm diameter, hemispherical-shaped indenter while Twaron samples exhibited excessive deformation directly below the indenter, wrinkling in the adjacent areas and in the final stage complete perforation in some layers. It was clear that Twaron/Epoxy specimen exhibited better resistance to perforation compared to Kevlar/Epoxy sample, and the former requiring at least 200% more indentation force compared to the latter to completely perforate the laminate.

Finite element analysis of the LVI response of glass fiber composites was compared with the experimental results by Mars *et al*.[24] Laminates were fabricated using a polyamide matrix with varying glass fiber content (0, 10, 20, and 30 wt.%) by injection molding process and subjected to drop weight (1.265 kg) tests at 2 m/s impact velocity. The force *vs*. time (F-t) graphs were plotted and the results were analyzed. Increasing fiber content led to an increase in the ductility, load-carrying capacity, tensile strength, and modulus of the laminates. The initial fluctuation in the F-t curves was due to the initiation of damage in the region immediately below the indenter arising due to the low yield strength of these composites. The finite element simulations were carried out using the ABAQUS software platform and the results showed a good correlation with experimental results. Similarly, the impact of fiber content on the LVI response of E-glass/Epoxy composites was studied by Raghunath *et al*.[25] Fiber volume fractions varied between 40% and 60% in specimens fabricated by the vacuum bagging process. The 150 × 150 × 2 mm^3 laminates were subjected to instrumented failing weight tests using a hemispherical steel dart of 10 mm radius. It was noted that the best load-carrying capacity and resistance to indentation was observed in samples with 43 vol.% E-glass fabric. Below and above this volume fraction of fibers, both impact resistance and load-carrying capacity of the specimens retarded. For fiber volume fractions above 43%, the inter-laminar shear strength of the laminates decreased due to improper wetting of the fibers by the epoxy matrix.

Various architectures of UHMWPE fabrics in a linear low-density polyethylene (LLDPE) matrix were fabricated by Zhang *et al.*[26] by hot press compression molding technique and their LVI response was compared. Three types of UHMWPE fabrics, namely UD prepreg, 2D plain woven (2D-P), and 3D woven single ply (3D-S) fabrics were used in the study. Drop weight impact tests at 35 J impact energy were carried out on the three types of specimens, each using different fabric reinforcements. All laminates were fabricated to a thickness of approximately 3.5 mm, by varying the number of fabric plies. F-t curves for all three specimens showed a sudden drop in load during the initial phase of loading. It was due to the failure initiated on the specimens by the sudden impact of load, which caused inter-laminar delamination in all samples. This kind of incipient damage is known as Hertzian failure. The authors stated that better resistance to delamination and high-impact energy absorption was observed in the 3D woven single-ply fabric specimen compared to the other two fabrics. Due to the interlacing of fibers in warp and weft directions in 2D plain weaved fabric specimen, it's in-plane stiffness was very low, thus offering poor resistance to impact energy absorption and damage. The effect of matrix material on the impact performance of non-crimp carbon fabric was studied by Bhudolia *et al.*[27] They compared methyl methacrylate (MMA) thermoplastic and epoxy thermoset matrix-based carbon composites through low-velocity drop weight impacts at 25, 42, and 52 J. The carbon/MMA test specimens were fabricated by the vacuum-assisted resin transfer molding (VARTM) process. Their impact performance was compared with that of baseline carbon/epoxy composite. The impact energy absorption and load-carrying capacity in the carbon/MMA specimen were higher at impact energy levels of 42 and 52 J. These values were similar for both specimens at a lower impact energy of 25 J. In terms of failure mechanisms, the MMA matrix composite displayed plastic deformation unlike the epoxy composite with the brittle nature of the fracture. The epoxy composite had a larger delamination area due to weaker inter-laminar fracture toughness. In the case of carbon/MMA composite, the ductile nature of the matrix led to stable crack formation and hence smaller delamination area. Extensive debonding was observed in the carbon/epoxy specimen due to weak fiber/matrix bonding compared to strong interfacial bonding in the carbon/MMA specimen.

Yang *et al.*[28] compared the impact strength of various types of FRP composites such as Glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP), plant fiber reinforced plastics (PFRP), and silk fiber reinforced plastics (SFRP). The impact strength *vs*. fiber volume chart is illustrated in Fig. 1. GFRP and CFRP composites exhibited high impact strengths over 100 kJ/m^2 compared to SFRP and PFRP composites with considerably lower impact strengths. Glass and carbon synthetic fibers possess higher impact strength and toughness compared to natural fibers. The higher impact strength of GFRP and CFRP composites compared to SFRP and PFRP is owed to the fact that the tensile strength of synthetic fabrics such as glass and carbon is higher than that of natural fibers. Also, from Fig. 1, the impact strength of synthetic fiber-based polymer composites is noted to be dependent on the reinforcement volume fraction, while for natural fiber-based polymer composites, it is independent of fiber volume fraction. It can also be observed that epoxy matrix composites imparted better impact performance due to

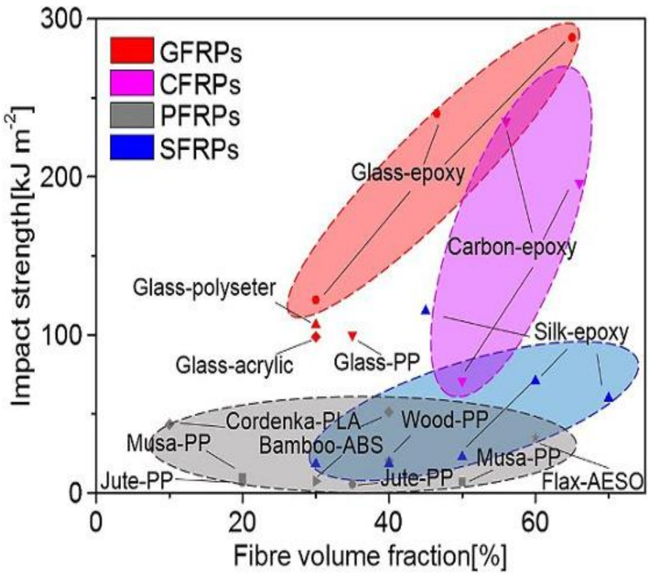

Fig. 1 Impact strength comparison for various FRP composites. Reproduced form the [28], Copyright 2017 The Author(s).

their high strength and toughness compared to thermoplastic matrix materials such as PP, polylactide (PLA), and acrylonitrile butadiene styrene (ABS). The impact behavior of silk fibers in the impact performance has also been studied by the authors and its impact strength is better than other commonly used natural fibers such as flax, and jute.

Most of the available literature is based on experimental studies on FRP composites. A finite element study of LVI on FRP composites was also conducted by researchers to validate the results with experimental findings.[29] The study of impact damage patterns using simulation tools is becoming increasingly popular as these tools reduce the cost of experimentation and help understand the basic performance of fabric composites under such impact events. Bozkurt *et al*.[30] conducted simulations of drop weight impact on CFRP composites using the Abaqus/Explicit platform. The model consists of a 150 × 100 mm^2 composite target attached to a rigid fixture and a hemispherical tipped impactor of 16 mm nose diameter. The impact was simulated at an initial energy of 15 J. During the initial stage of impact, matrix cracks developed in the bottom layer immediately as the impactor contacted the laminate, followed by crack propagation in the matrix, and initiation of delamination. In the later stage, the matrix damage expanded beyond the region of impact. This was due to energy absorption in the laminate. In the last stage, multiple vertical cracks in the direction of fibers and perpendicular to the axis of impact were developed in the specimen, and the complex matrix was damaged at the maximum impactor displacement.

Through various available literature on non-hybrid/neat fabric composites, it has been observed that these materials offer better homogeneity in terms of properties. The failure mechanisms can be well defined through impact tests on these composites unlike hybrid composites, where the explanation and analysis of damage patterns can become complicated due to the interaction of different fabric properties. Neat fabric composites are also easy to manufacture compared to hybrids, considering that different fabric types require distinctive curing conditions.

2.2 Hybrid fabric polymer composites

Polymer matrix composites with hybrid fabric reinforcements have tremendously enhanced the potential in terms of the development of cutting-edge composites which demand mechanical properties that are specific to the area of application. Thus, there is the widespread replacement of single synthetic fabrics with hybrid ones in fabric-reinforced polymer composites.[31] Various authors through their experimental findings have reported the advantages of hybrid fabric composites in terms of enhanced material properties and improved impact resistance offered by this class of materials.[32–35]

Bulut and Erklig[36,37] studied the effect of different fabric stacking sequences on the damage patterns and impact energy absorption when exposed to quasi-static indentation tests. The laminates were fabricated using 2-layer and 3-layer configurations. 12 different stacking patterns of Kevlar (K), Carbon (C), and Glass (G) fabrics in combination with epoxy resin matrix were used in the fabrication of specimens for the tests. A 12.7 mm diameter, the hemispherical projectile was impacted on the specimens at a speed of 1.25 mm/min. The specimens were completely perforated by maintaining a constant impactor displacement of 10 mm. From the impact test load-displacement curves, it was observed that due to the initial increase in load, matrix cracks developed in the samples, and delamination was initiated. Following penetration of the impactor, fiber failures and severe delamination occurred leading to reduced load-carrying capacity. During the final stages of penetration, friction between the specimen and impactor occurred due to the complete penetration of the latter. In terms of energy absorption by the laminates, it was reported that in a 2-layer configuration, hybrids C/K and K/C exhibited the best performance. In the 3-layer configuration, G/K/C showed the best energy absorption compared to other samples. Neat glass specimens exhibited the worst energy absorption in both configurations. The authors used mathematical models (Eqs. 1 and 2) to calculate the effect of hybridization on the impact behavior of the composite specimens;

$$h_e = \frac{F_h}{F_{(RoM)}} - 1 \quad (1)$$

$$F_{(RoM)} = \frac{1}{3}\left(F_C + F_K + F_G\right) \quad (2)$$

where, h_e represents the hybrid effect, denoting a positive or negative value. Indentation force is represented by F_h, and F_C, F_K, and F_G are maximum indentation load values on neat C/C, K/K, and G/G composites, respectively. The indentation load depends on the type of test and the impact apparatus used. In this study, an indentation load in the range of 3.7 to 5.91 kN was used for the impact tests. $F_{(RoM)}$ indicates the rule of mixture value of indentation load for neat composites. Positive

h_e values indicate a positive hybrid effect and vice-versa. Out of all specimens, only C/K and K/C in a 2-layer configuration, and G/K/C and K/G/C in a 3-layer configuration had a positive hybrid effect.

Similarly, Zhang *et al.*[38] fabricated low-velocity impact resistant (LVIR) composites using Glass (G) and Carbon (C) non-crimp fabric and epoxy resin matrix in neat (C/C/C and G/G/G), interlayer (C/G/C/G/C), sandwich (C/G/C), and intralayer configurations and subjected them to LVI at 30, 35 and 50 J energy using a hemispherical tipped 12.7 mm diameter indenter. None of the specimens were penetrated by the indenter. The E-T (Energy *vs*. Time) curves were split into 3 stages. In the first stage, the energy absorption by the laminates was low, due to the small indentation and distortion along the thickness of the specimen. In the next stage, an increase in the slope of the curve was observed, indicating higher energy absorption and a larger damage area due to increased contact with the indenter. Severe delamination was eminent at this stage. In the final stage, the energy absorbed remained constant and the elastic energy was released by the composite specimen leading to slight rebounding of the indenter. C/G/C exterior had the highest energy absorption among all specimens. This was 14% higher than G/G/G and 9% higher than G/G/G specimens. Computed tomography (CT) scan was conducted to analyze the damage patterns in various laminate orientations. C/C/C specimens exhibited shear cracks and crushing fractures due to compressive stresses and delamination between layers. In G/G/G, the front layers exhibited severe deformation due to impact and delamination in the rear surface due to bending stresses. Similarly, for C/G/C and C/G/C/G/C, fiber breakage was observed in the impact-facing layers and delamination in the bottom layers. In the sandwich specimen, the micro-cracks were higher compared to that of interlayer laminate, thus the latter configuration had a positive effect when considering impact resistance and lower damage propagation.

The effect of Carbon and Glass hybridization and their stacking sequence on the LVI response was also studied by Hung *et al.*[39] Four types of specimens were fabricated; (i) C_4/G_4, (ii) G_4/C_4, (iii) $G_2/G\ (\pm 45^o)_2$ / C_2 / $C\ (\pm 45^o)_2$ and (iv) $G_2/G\ (\pm 45^o)_2/C_4$. Each laminate had 8 layers of fabric with certain fabric layers with ± 45º orientation in specimen types (iii) and (iv). Drop weight tests were performed at 6, 8, and 10 J of impact energy. The impact damage in the specimens was observed using thermographic inspection. For all specimens, the damage on the impact side was localized around the area of impact. Type (i) had the smallest damage area on the impact face compared to other samples. Also, the flexural strength of the type (i) specimen was better than that of the other specimens. This is because of the high strength of the carbon fabric layer on the impact face. Based on the results, it is necessary to consider the stacking sequence of fabrics when designing composites for impact-bearing applications such as aerospace and automobiles as this parameter highly influences the impact resistance properties of fabric-reinforced composites.

While discussing materials for impact resistance, it can be generally observed that Kevlar offers the best penetration resistance, but hybridizing with carbon and glass fabrics provides better stiffness and cost benefits. Epoxy thermoset resin matrix has been used commonly due to its good corrosion resistance, thermal stability, and curing properties such as low shrinkage.[40]

2.3 Natural fiber-based polymer composites

In recent decades, researchers have also extensively used natural fibers in composites for LVI applications. These fibers are environment-friendly and recyclable, thus offering an ecological advantage over synthetic reinforcements.[41] Their low cost and low density compared to conventional reinforcement materials have incited interest among researchers to study their applicability in LVI applications.[42] For instance, Ismail *et al.*[43] studied the effect of hybridizing kenaf natural fabric with E-glass synthetic fabric in a diglycidyl ether of bisphenol A (DGEBA) epoxy matrix formulation. They fabricated kenaf/E-glass/epoxy hybrid specimens with reinforcement fabrics in the ratio 75:25 by weight of E-glass and kenaf fabrics, respectively. Drop weight impact tests were performed at 10, 20, 30, and 40 J of impact energy by varying the impactor drop height and the energy absorption was recorded. With increasing impact energy, energy absorption and deformation area of the specimens increased. Meanwhile, Dhakal *et al.*[44] compared the LVI performance of hemp fibers in an unsaturated polyester resin (UPR) matrix composite with that of E-glass/UPR specimens. Fiber volume fractions of 0, 0.06, 10, 15, 21, and 26% were used in the study. For E-glass/UPR specimen, 21% fiber volume content was used. Instrumented falling weight impact tests were performed using a 12.7 mm diameter hemispherical ended impactor at an initial energy of 11.47 J and 325 mm drop height. Experimental results suggested that as the hemp fiber content increased, the damage propagation phase improved, thereby improving the impact resistance of the composite. Comparing E-glass/UPR and hemp/UPR samples with 21 vol.% of fibers, the strength, and stiffness of the former were lower compared to the latter, whereas impact energy absorption was comparable in both specimens.

Apart from kenaf and hemp, there are various natural fibers such as sisal,[45] flax,[46] jute,[47] ramie[48], *etc.* that offer good mechanical properties and have been subjected to research in composite material applications. Even though they offer good durability, some of the limitations such as poor compatibility with matrix formulations, poor fire retardancy, and high moisture absorption have made their use limited to few applications. But increasing demand to use eco-friendly and biodegradable materials necessitates research of natural fiber composites.[49]

2.4 Fabric-reinforced polymer nanocomposites

The incorporation of nanofillers in fabric-reinforced polymer composites is gaining attention in recent years due to their ability to enhance the impact performance of these materials. These secondary reinforcements offer a large interfacial area, which is said to improve interaction at the matrix-reinforcement interface. The surface area of the nanomaterials decides the level of van der Waals interaction between the polymer matrix and the secondary reinforcement, thus enhancing material properties such as fracture toughness.[50,51] This can be done by the addition of nanofillers such as aluminum oxide (Al_2O_3), silicon carbide (SiC),[52] graphite fluoride (GrF),[53] multi-wall carbon nanotubes (MWCNT),[54], *etc.* which act as crack arrestors and also improve the bonding between the matrix and the fabric, which plays an important role in improving the overall fracture toughness of the nanofiller incorporated composites otherwise known as nanocomposites.

Mourad *et al.*[52] conducted damage assessment of KM2Plus Kevlar/epoxy composite laminates reinforced with SiC, Al_2O_3, and MWCNT nanofillers in varying concentrations apart from the neat specimen. A 5 mm diameter impactor with a 20 kg strike mass was dropped onto the test specimen from a height of 1 m. Neat Kevlar/epoxy showed penetration in all the layers, whereas nanofiller reinforced specimens showed better penetration resistance with a maximum of 5, 5, and 4 fabric layers penetrated in SiC, Al_2O_3, and MWCNTs reinforced specimens, respectively. Considering the effect of nanofiller concentrations, for SiC and Al_2O_3 reinforced specimens, 3 wt.% nanofiller concentration exhibited the best penetration resistance compared to 1 wt.% and 2 wt.%. But for MWCNTs reinforced specimens, the best impact resistance was observed in specimens with 0.5 wt.% nanofillers compared to 0.25 wt.% and 1 wt.%. The addition of nanofillers enhanced inter-laminar shear strength (ILSS), and damage resistance in the composites. The damage was localized around the edge of the impacted zone. Laminate with 0.5 wt.% MWCNTs had the least damage area due to better impact resistance offered by the matrix.

Carbon fiber-reinforced composites commonly used for automotive applications in the past decade have also been studied by researchers to enhance their durability by incorporating secondary reinforcements into the matrix. Leng *et al.*[53] studied the influence of adding nano graphite fluoride (GrF) in the LVI resistance behavior of CFRP composites. Drop weight impact tests were performed on neat carbon/epoxy specimens followed by specimens with 0.5, 1, 2, 3, and 4 wt.% GrF nanofillers. The impact resistance was highest for 1 wt.% GrF concentration. Above this, there was a gradual reduction in impact resistance. The compression after impact (CAI) test also showed the best results for 1 wt.% GrF concentration. CT scan images were used for post-damage failure analysis. The neat sample exhibited a smooth fracture surface and the crack initiation was completely due to the brittleness of the matrix. In GrF-filled specimens, the delamination area was larger as the concentration was increased. This was due to microvoids generated by the addition of the nanofiller. The authors also concluded that the presence of the microvoids is the reason for the retardation of fracture toughness in specimens with filler concentration above 1 wt.%.

Similarly, Moumen *et al.*[55] added carbon nanotubes (CNTs) in varying concentrations in carbon fabric-reinforced epoxy matrix composites and subjected them to low-velocity impacts at 3, 7, and 12 m/s. The concentration of CNTs was 0, 1, 2, and 4 wt.%. At 3 m/s impact velocity, there was no plastic deformation in the impact specimens. At 7 m/s, the damage modes such as matrix cracking and delamination were observed in the panels, while at 12 m/s impactor speed, all specimens were completely perforated. It was reported that the best impact resistance and energy absorption were observed in samples with 1 wt.% CNTs compared to neat and other specimens. At higher concentrations, agglomeration of CNTs was observed through post-failure SEM images. Apart from using CNTs (0.3 wt.%), Mahdi *et al.*[56] also tested nanoclay (2 wt.%) and hybrid fillers (2 wt.% nanoclay and 0.1 wt.% MWCNTs) in carbon/epoxy laminates and reported their LVI response at 30, 40, and 50 J impact energies using a hemispherical shaped impactor through drop weight test. Post-impact damage analysis showed slight indentation in specimens just below the impactor contact region at 30 J impact. Complete perforation of all specimens was observed at 50 J impacts. In hybrid nano-filled specimens, the extent of delamination was lesser compared to neat and other specimens. Overall energy absorption and peak load across all impact energies were highest in the case of the hybrid filler carbon/epoxy specimen (32% and 16% respectively compared to the control specimen). Similarly, the impact damage area in hybrid filler specimens was 80% lesser compared to control samples. The authors concluded that the study of hybrid fillers can enormously elevate the performance of impact-resistant composites.

Soliman *et al.*[57] used COOH functionalized MWCNTs in plain woven BD carbon fabric reinforcement and epoxy matrix to fabricate composites and subjected them to drop weight impact tests. Neat CFRP laminates followed by specimens with COOH-MWCNTs in concentrations 0.5%, 1%, and 1.5% by weight of matrix were used in the experiments. Various impact energies of 15, 24, 30, 60, and 120 J were used for the LVI tests. The concentration of carbon nanotubes was observed to have an effect on the impact penetration height on the laminates for impact energies of 15 and 24 J, whereas no effect was found for higher impact energies. In general, CFRP laminates with COOH-MWCNTs exhibited enhanced LVI behavior for BD fabric composite laminates under impact.

Afrouzian *et al*[58] dispersed nano silica particles in the epoxy matrix to fabricate E-glass reinforced composites to study the effect of nanofiller addition in the LVI performance of these materials. The nanofiller concentrations were 0, 0.5, 1, and 3 wt.% in specimens consisting of 12 fabric layers. The specimens were subjected to tensile, flexural, QSI, and high-velocity impact (HVI) tests. LVI energy absorption was highest in specimens with 0.5 wt.% nano silica compared to other specimens. The high impact energy absorption in nanocomposites in the elastic region compared to control samples is due to the inclusion of nano-silica, which contributes to the increased stiffness of the laminates. Thus, nanofillers play a significant role in the perforation resistance of composites.

Recent research studies also emphasize on chemical modification of fillers and fabric reinforcements using reactive coupling agents to enhance the filler-matrix interactions and overall mechanical properties of the nanocomposites. Tasic *et al.*[59] studied the effect of chemical modification of oxidized MWCNTs (O-MWCNT) using diallyl amine (DAA), hexamethylenediamine (HDA), and p-phenylenediamine (PDA) on the filler-loaded nanocomposite. Recycled polyethylene terephthalate (PET) was used in the production of unsaturated polyester resin (UPR) in the study. The neat UPR specimen and nanofiller-loaded composite specimens such as O-MWCNT/DAA/UPR, O-MWCNT/PDA/UPR, and O-MWCNT/HDA/UPR were subjected to tensile tests, and their tensile strength, tensile elongation at break, and elastic modulus were determined. It was observed that tensile strength was considerably improved in specimens with chemically modified MWCNTs. For 2.5 wt.% nanofiller concentration, the increase in tensile strength was 97.4%, 119%, and 139% for O-MWCNT/DAA/UPR, O-MWCNT/PDA/UPR, and O-MWCNT/HDA/UPR specimens respectively compared to pure UPR sample.

Through various available literature, the effect of various nanofillers and their concentration in fabric-reinforced composites on their impact resistance has been substantiated. At optimum concentrations, pure and chemically modified nano reinforcements have enhanced the performance of composites substantially, but at higher concentrations, agglomeration of fillers due to van der Waals force[55] leads to retardation in impact performance and also increases brittleness in these composites.

2.5 Bulk polymer and ceramic matrix composites

Very limited efforts are available in the literature related to studying LVI and HVI resistance of non-polymeric composites (without fabric reinforcements) such as metal and ceramic matrix composites and bulk composites. They have not been utilized in ballistic and structural applications due to their low flexibility and highly brittle nature. The properties of matrix materials play an important role in the outcome.

Pandya *et al.*[60] subjected pure DGEBA epoxy resin and MWCNT dispersed DGEBA epoxy resin to quasi-static shear penetration tests using a cylindrical flat-ended punch of 12.5 mm diameter. At peak shear plugging load, both types of specimens failed catastrophically due to brittle fracture. It was observed that the shear plugging force increased as the tip displacement of the punch increased. Shear plugging was observed to be the main mode of impact energy absorption. Dispersion of nanoparticles and compression during impact was also reported to absorb energy. MWCNT dispersed epoxy sample exhibited 17% higher shear plugging strength compared to the neat specimen. Shear plugging led to the initiation of radial cracks around the edge of the indenter. During the final stages of impact, these radial cracks initiated catastrophic failure in the specimen. Similarly, from HVI tests conducted on the samples, it was reported that dispersion of MWCNTs led to an increase in ballistic limit velocity and energy absorption by 5% and 10% respectively compared to neat samples. Nanofillers helped retard the growth of cracks and enhanced shear strength in the matrix material leading to its improved LVI and HVI performance.

Herb *et al.*[61] conducted experimental and finite element analysis of QSI tests on silicon carbide (SiC) fabric-reinforced SiC ceramic matrix composite (SiC/SiC). The test results were used to analyze the damage mechanism in these composites and also evaluate the influence of indenter diameter, D_p (4.5, 9, and 16 mm), and central hole, D_s (18, 32, and 80 mm) of the specimen support fixture. There was found to be no correlation between D_s and the impact energy absorbed by the composite from the indentation tests. Whereas with increasing D_p, the energy absorbing ability of the laminate increased, given larger the indenter size, the more the damage to the laminate. For complete penetration of all the layers, the laminate required an energy absorption of 0.8, 2.1, and 5.5 J for D_p of 4.5, 9, and 16 mm respectively. The 3D architecture of the SiC fibers minimized the delamination area and the damaged area was localized in the region just below the indenter.

Based on the literature reviewed in the above sections relating to the various types of composites used for LVI resistance applications, a few selected materials with their impact conditions and performance are listed in Table 1. Various types of fiber reinforcements and matrix materials have been used in the fabrication of FRP composites for LVI applications and subjected to drop weight and QSI tests as shown in Table 1. Reinforcement fabrics such as Kevlar, glass, carbon, Twaron, UHMWPE, kenaf, and hemp in different fiber architectures have been studied and results reported. It can be observed that the impact energy absorption in FRP composites improved with the introduction of different types of nanofillers. At constant laminate thickness and impact velocity, carbon/epoxy specimen offers better indentation resistance compared to Kevlar or glass samples.[38] Considering fabric architecture, 3D woven fabrics offer enhanced energy absorption compared to 2D and UD fiber orientations UHMWPE laminates.[26] Similarly, the hybridization of high-strength fabrics such as Kevlar with cheaper glass fabrics shows enhanced impact performance.[62] Thus, it can be stated that the dispersion of nanofillers, the architecture of fiber or fabric, and the hybridization of reinforcements can have a considerable effect on the impact behavior of FRP composites. The parameters that affect the LVI behavior of FRP composites that have been studied by various authors have been highlighted in Table 2.

Table 1. Impact performance of various LVI composites.

Type of specimen	t (mm)	Type of Impact	V (mm/min)	J_i (J)	J_{ab} (J)	Ref.
(i) Carbon/Epoxy (ii) Carbon/Kevlar/Epoxy (iii) Kevlar/Epoxy (iv) Glass/Epoxy	2.7	Quasi-static indentation	1.25	-	38.24 35.15 32.40 16.95	[36]
SiC/SiC	1.2		0.2	-	5.5	[61]
Carbon/GrF/Epoxy	2.5	Drop Weight	-		12.4	[53]
(i) UD-UHMWPE/LDPE (ii) 2-D Plain UHMWPE/LDPE (iii) Single ply 3-D orthogonal UHMWPE/LDPE	3.44 3.50 3.56		-	35	19.60 16.68 21.34	[26]
E-glass/Kenaf/Epoxy	-		-	40	23.23	[43]
(i) E-glass/Epoxy (ii) E-glass/Kevlar/epoxy	4		-	50	11.11 21.01	[62]
Twaron/DCPD	4.4		-	150	92.9	[21]
(i) E-glass/Epoxy (ii) E-glass/Graphite/Epoxy	2		-	15.7	13.01 13.861	[63]
(i) Carbon/Epoxy (ii) Carbon/Nano clay/Epoxy (iii) Carbon/MWCNT/Epoxy (iv)Carbon/Nanoclay/MWCNT/Epoxy	2.4		-	40	12.95 13.87 15.58 17.14	[56]
(i) Neat Epoxy (ii) MWCNT/Epoxy	4.3	Quasi-static shear punch	1	-	6.1 7.4	[60]

t-laminate thickness, J_i-impact energy, J_{ab}-absorbed energy, and V-impact speed.

Table 2. Effect of various parameters on the LVI behavior of composites.

Author, Year, Ref.	Composite	Parameter/s Studied	Effect on LVI behavior
(i) Mankarious, 2017, [22]	Kevlar/epoxy, Twaron/epoxy	Laminate thickness	The depth of penetration is reduced with an increase in laminate thickness.
(ii) Reddy, 2019, [64]	E-glass/epoxy		Displacement decreased by 50% as thickness doubled.
(i) Cao, 2020, [65]	Carbon/epoxy	Indenter shape	For constant impact energy, the energy absorption and final displacement of the laminate increase with the increase in impactor diameter.
(ii) Icten, 2012, [66]	Glass/epoxy		The displacement values increase with decreasing impactor nose diameter and conical angle.
(iii) Whistler, 2012, [67]	Glass/epoxy		The impactor of a larger radius (152.4 and 50.8 mm) required more impact energy to cause deformation in the laminates compared to a smaller (12.7 mm) radius impactor.
(i) Gemi, 2018, [68]	Carbon, Glass, epoxy hybrids	Impact Energy	Energy absorption by laminates increased with an increase in impact energy (5 J, 10 J, 15 J, and 20 J).
(ii) Zaera, 2005, [69]	Carbon/epoxy		Energy absorption by the laminates was observed to be proportional to the impact energy.
(i) Bulut, 2017, [36,37]	Carbon, Glass, Kevlar, epoxy hybrids	Fabric stacking sequence	C/K and K/C in 2-layer configurations and G/K/C in 3-layer configurations exhibited the best penetration resistance.
(ii) Hung, 2018, [39]	Carbon/Glass/epoxy		The best flexural property and least damage area were observed in samples with a Carbon layer on the impact side and glass in the rear face of the laminates.

3. Manufacturing methods

The most common methods in the fabrication of hybrid and non-hybrid FRP composite laminates are the hand lay-up process followed by curing by compression molding, vacuum-assisted resin infusion (VARI), vacuum-assisted resin transfer molding (VARTM), pultrusion, filament winding, and prepreg/autoclave methods. These techniques are discussed briefly in the following sections.

3.1 Hand lay-up followed by compression molding

Hand lay-up and compression molding are one of the most common and simple methods to fabricate FRP composite specimens.[70] It is a very flexible process in terms of controlling the required process parameters and it is also a cost-effective method. A high rate of success in terms of fabrication has led many researchers to utilize this technique to fabricate composite samples for studying their impact performance. Researchers such as Shivamurthy *et al*.[71] and Mourad *et al.*[72] use compression molding techniques to fabricate FRP composite laminates for impact resistance applications. These specimens are subjected to tensile, flexural, and hardness tests, and also the effect of nanofillers such as SiC, Al_2O_3, and CNTs on the mechanical behavior of such composites is studied. Other researchers such as Boria *et al*.[11] and D. Zhang *et al*.[26] fabricate PP and UHMWPE-based composites respectively by compression molding technique and subject them to drop weight impact tests. In Table 3, the selection of compression molding process parameters for the fabrication of composites by various researchers is listed.

For UHMWPE/LLDPE and PP/PP composites being thermoplastic, the curing temperature used in the fabrication is low due to the curing of these materials at a lower temperature compared to thermoset materials. Similarly, the curing pressure used in the fabrication of PP/PP is higher as the matrix is in the form of thin films. Fig. 2 shows the hand lay-up followed by the compression molding process in the fabrication of FRP composite laminates.

3.2 Vacuum-assisted resin infusion (VARI) / transfer molding (VARTM)

The VARTM method is used to fabricate various FRP composites to avail better bonding between the fabric and the matrix interface, and also minimize voids within the laminates. Fig. 3 presents the schematic description of the VARTM process. Also, using VARTM ensures identical properties and quality in all finished samples of the same type.[36] In this process, the matrix-wetted fabric is vacuum bagged to remove excess resin and allow uniform matrix content within the laminate. Jogi *et al*.[62] used the VARTM process to fabricate neat E-glass/epoxy and E-glass/Kevlar/epoxy hybrid specimens for experimental LVI tests. Similarly, vacuum pressure is also used in the VARI method to infuse resin into the reinforcement fabrics, in this method, the matrix mixture is injected into the reinforcement only during the vacuum bagging process. Sun *et al.*[73] fabricated composite laminates that consisted of glass fabric, shape memory alloys, and epoxy

Table 3. Compression molding process parameters used in various composites.

Specimen	P (MPa)	t (minutes)	T (°C)	Ref.
E-Glass/Graphite/LY556 Epoxy	0.5	120	140	[71]
Kevlar/SiC/AY105 Epoxy Kevlar/Al_2O_3/AY105 Epoxy Kevlar/CNT/AY 105 Epoxy	0.386	15	175	[72]
UHMWPE/LLDPE	10	180	120	[26]
PP fiber/PP film matrix	10	120	130	[11]

P-Curing pressure, T-Curing temperature, and t-Curing time.

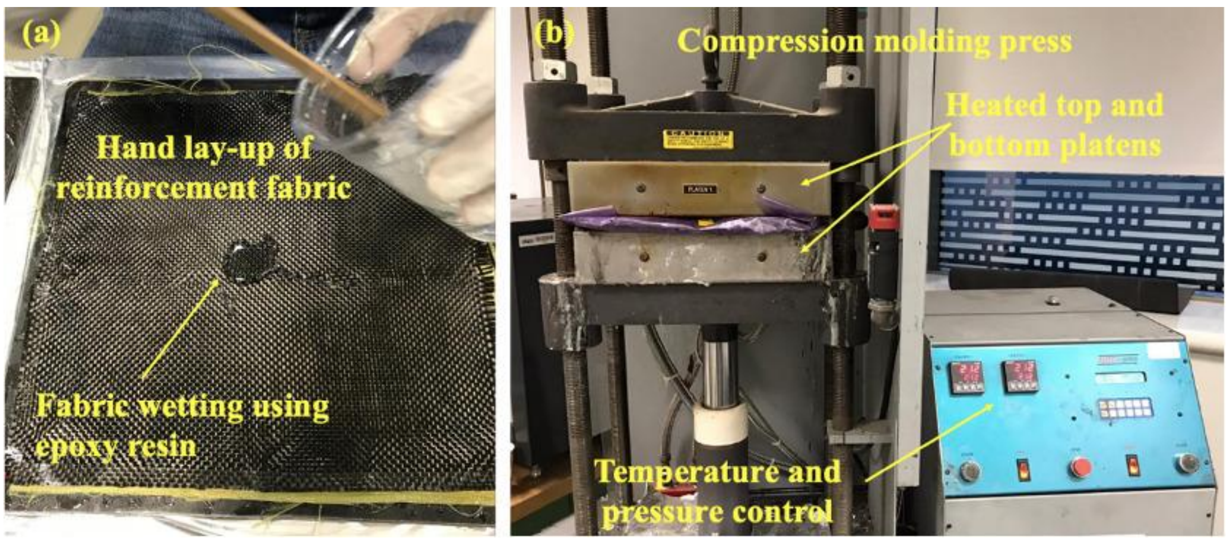

Fig. 2 Hand lay-up and compression molding method for fabrication of FRP composites.

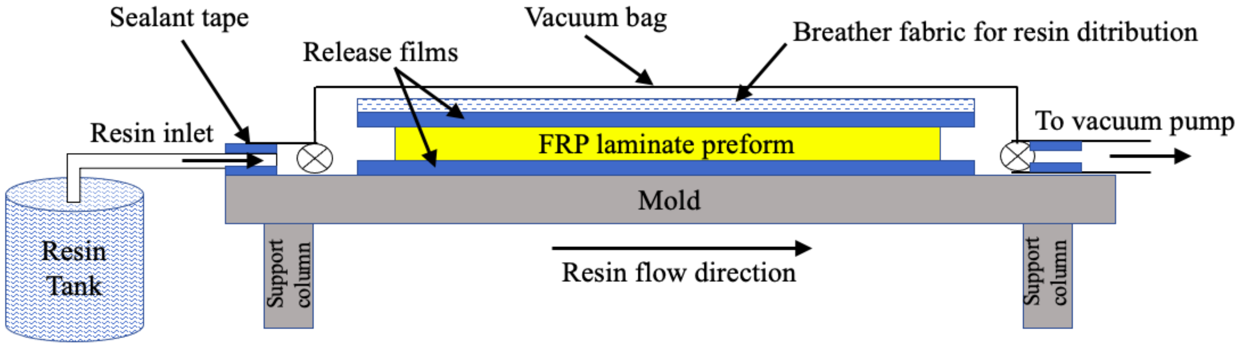

Fig. 3 Schematic sketch of the VARTM process.

resin by the VARI process for LVI applications. Similarly, Swolfs *et al.*[50] used this process to fabricate carbon/glass/epoxy hybrid composite specimens.

3.3 Pultrusion

The pultrusion technique has also been used apart from the above-discussed fabrication methods to manufacture automobile, aerospace, and structural composites.[74] Through this technique, high fiber content greater than 70% can be achieved in components apart from delivering high-quality products at high production rates. Pultrusion is widely used to produce glass and carbon fiber-reinforced composites[75] Li *et al.*[76] fabricated GFRP composites in an unsaturated polyester resin matrix by pultrusion process using alternating layers of glass fabric roving with glass fiber mat between them. The 10 mm thick laminate consisting of 5 layers in total was subjected to drop weight impact tests using a hemispherical impactor of 20 mm diameter and impact mass of 5.5 kg. Impact energies of 16.75, 33.50, 50.25, and 67 J were used in the impact tests conducted as per ASTM 7136[77] standard. The damaged area increased with increased impact energies. Load-displacement and deflection-time curves were plotted to study the impact performance of the composites. Pultruded composites experienced multiple modes of impact-induced damage such as delamination, matrix cracking, and fiber breakage similar to components fabricated by other processes. In the top and bottom roving layers, the matrix cracks are initiated along the direction of fibers. Shear cracking was predominant in samples subjected to higher energy levels. Finite element modeling of LVI was conducted and results were compared to experimental tests and both results showed a good correlation.

3.4 Filament winding method

Complex and large axisymmetric composite components are fabricated using the filament winding method. A high fiber volume content of about 80% can be achieved by this method. Thermoset resins are the most suited for this type of fabrication due to lower viscosity and fiber rovings are the common reinforcements negating the requirement of an autoclave for the curing process.[78] Soykok *et al*.[79] fabricated glass/epoxy composite tubes by filament winding process using fiber winding angles of 30º, 45º, 60º, and 75º. The tubular specimens had a length of 170 mm and a wall thickness of 2 mm. These specimens were subjected to drop-weight LVI tests using a hemispherical impactor at energy levels of 2.5, 5, and 7.5 J. The post-impact specimens were then subjected to torsion tests. Samples subjected to 2.5 J impact energy showed no reduction in torsional stiffness compared to non-impacted specimens. In 5 J impacted samples, the deterioration in torsional stiffness of 40.2% and 13.2 % were observed in samples fabricated with fiber orientation of 60º and 75º respectively. Similar trends were also observed for samples impacted at 7.5 J, with not much effect in fiber winding angles of 30º and 45º. The highest impact energy absorption and torsional stiffness were exhibited with 60º fiber angles. The process flow in the filament winding method is presented in Fig. 4.

3.5 Prepreg and autoclave method

The Prepreg method is used to fabricate high-quality composites for aircraft structures such as wing skins, wing spars, and fuselage frames. A fiber volume fraction of around 60% is achievable using the prepreg method with a void content of less than 1%. This method is cost intensive as large autoclaves are required to accommodate composite components and to cure them effectively. Thus, large batches of components have to be fabricated to make the process cost-effective. The curing process parameters need to be kept constant when components of similar shape and size are manufactured, thus the parameters need to be scheduled and maintained well to achieve the desired quality of composites.[80] Meredith *et al.*[81] studied the impact energy absorption behavior of prepreg carbon/epoxy composites. Six specimens were fabricated using UD and 2 × 2 twills, high-strength carbon fiber prepregs of areal densities 200 gsm and 660 gsm. Five samples were autoclave cured and one oven cured. The cone-shaped specimen was manufactured to resemble missile and rocket cones. LVI tests at 10 m/s velocities, drop mass of 78 kg, and impact energy of 4000 J was conducted on the specimens. Impact damage and defects in the specimens were analyzed using fractography and optical microscopy respectively. It was reported that oven-cured samples had a higher concentration of void defects compared to autoclave-cured ones. Samples of the same thicknesses

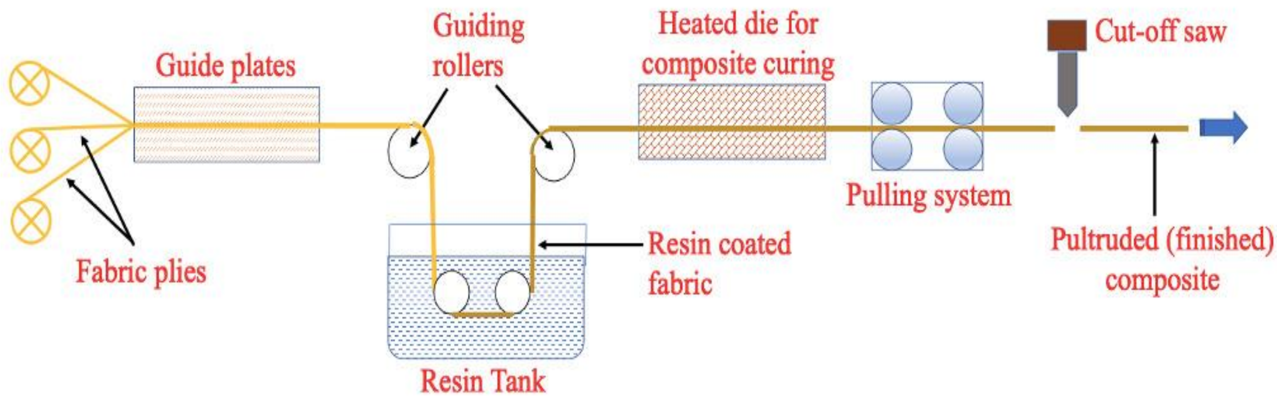

Fig. 4 Schematic representation of filament winding process.

fabricated with 200 gsm areal density exhibited better energy absorption compared to 660 gsm fabrics.

3.6 Comparison of various fabrication processes

Zhang *et al.*[82] studied the effect of fabrication processes such as autoclave and quick steps on the fracture toughness of the CFRP laminates. They reported that the fracture toughness of laminates for autoclave and quickstep processes were 564 and 527 J/m^2 respectively. Remarkable improvement in fracture toughness was observed for hot compression molded specimens due to the simultaneous application of heat and pressure during fabrication leading to better fiber/matrix bonding. At 783 J/m^2, the mode I fracture propagation toughness of quickstep specimens was 1.5 times higher compared to laminates fabricated by the autoclave process. Gollins[83] conducted LVI tests using the drop weight method on GFRP specimens to compare the impact performance of samples fabricated by using different fabrication methods such as compression molding and VARI. It was reported that GFRP composite laminates fabricated by the compression molding process had 20% higher fiber density compared to the VARI process. Compression-molded specimens exhibited a higher strength-to-weight ratio and better tensile strength compared to the others. The LVI performance of compression molded specimens degraded with the addition of nanoclay reinforcement due to an increase in brittleness, compared to samples fabricated by VARI. But, the delamination area in compression molded samples was smaller than those of VARI samples.

FRP composites are used in numerous applications due to their design flexibility, remarkable mechanical properties, high specific strength, corrosion resistance, *etc.* These composites tend to deviate from their designed properties due to the material defects as an effect of the fabrication process, leading to retardation in the mechanical properties of these materials. Such defects include fiber misalignment, waviness, fiber rupture, and void formation within the matrix. An increase in void content in the composite by a mere 1% leads to a decrease in tensile strength by 10–20%, flexural strength by 10%, and ILSS by 5–10%. This retardation in the mechanical properties can be alleviated by optimizing the process parameters of the fabrication process.[84] In the compression molding technique, it is difficult to control the void formation compared to the VARTM process, through which voids can be minimized. Similarly, good repeatability, accuracy, and quality of the finished composite can be achieved in VARTM compared to hand lay-up and compression molding. The comparison of various composite fabrication methods and their parameters is presented in Table 4.

4. LVI Testing methods

Researchers have employed various test methods to characterize the LVI impact behavior of FRP composites. QSI test,[22,60] drop weight test[26,38,52,53], and quasi-static penetration/stab test[14] have been used to conduct LVI analysis to study the influence of hybridization, stacking sequence, fiber content, impact energy, nanofiller concentration, indenter shapes, *etc.* which can help develop LVIR composites with enhanced mechanical and impact properties. Post-impact damage analysis using drop weight tests is tedious and cost-intensive, and experimental results seem to have poor repeatability. While replicating an LVI event through QSI tests, the damage initiation and crack propagation in fabric-reinforced polymer composites can be easily identified, and deformation can be quantified accurately.[85]

4.1 Quasi-Static Indentation Test

QSI is a displacement-controlled test method and acts as an LVI test. But, the final damage to the composite specimen can be characterized only through impact testing. The force vs. displacement (F-d) curves acquired through QSI of LVI-resistant materials need to be analyzed further to measure their indentation resistance. These are one of the most common types of LVI tests used by researchers to analyze the impact performance of composite components that are subjected to impact loads. The apparatus consists of an indenter that is targeted on the composite target at very low loading rates.[86]

Table 4. Comparison of various composite fabrication processes and parameters.

Composite fabrication method	Parameter					Ref.
	Curing Pressure (MPa)	Curing Temperature (°C)	Curing time (min)	Fiber content (vol. %)	Fabrication cost	
Hand layup & Compression molding	13.85	100	30	65-73	Low	[32]
VARTM	0.2-0.7	25	1440	50-60	Moderate	[62]
Pultrusion	-	188	-	60-70	High	[75,87]
Filament winding	-	80	240	80	High	[78,79]
Prepreg & Autoclave	0.64	180	120	70-75	High	[82]
Prepreg & Quickstep	0.098	180	120	70-75	High	[82]

Various shapes of indenters such as conical and hemispherical-shaped tips can be fitted to the apparatus based on the experimental conditions. Fig. 5 illustrates a schematic representation of an ideal indentation test apparatus.

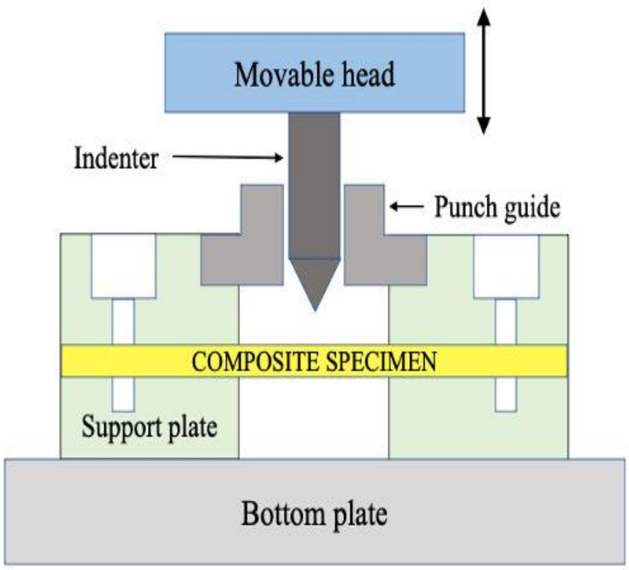

Fig. 5 Schematic diagram of quasi-static indentation test.

The duration of interaction between the indenter and the target during LVI events is much higher than the time taken by the shock waves to reach the periphery of the component, thus such impacts can be considered a QSI problem. Thus, QSI tests are advantageous to analyze the damage patterns and the interactions between them.[88]

4.2 Drop weight impact test

Drop weight tests (Fig. 6) are considered more useful compared to QSI tests when studying the damage mechanisms in impact-resistant materials. The damage observed in composite specimen post-drop weight tests is more comparable to impact events during the operational life of composites. Authors such as Mourad *et al*.[52] and Hung *et al.*[39] had used drop weight testing corresponding to ASTM 7136[77] standard to measure the impact resistance of Kevlar/epoxy and carbon/E-glass specimens respectively of different fiber orientations. Similarly, Stephen *et al*.[89] performed drop weight tests on hybrid composites consisting of Kevlar, carbon, and glass fabrics in different stacking arrangements, and compared their energy absorption behavior. Through the low-velocity impact tests, they observed that, by hybridizing cheaper fabrics in high-impact resistant Kevlar fabrics, the cost of the composites can be reduced without sacrificing their impact response. Also, drop weight tests have proven to be a successful method to investigate the impact damage resistance in FRP composites for various applications.

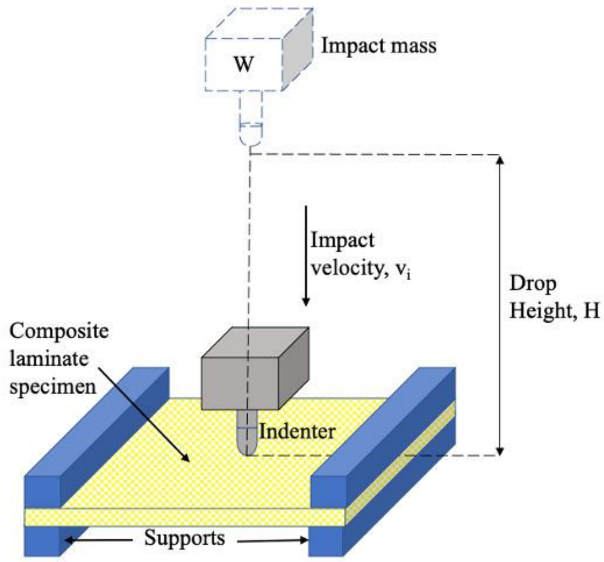

Fig. 6 Schematic diagram of drop weight impact test apparatus.

4.3 Quasi-static Stab Test

Zielinska *et al.*[20] are among the very few researchers to have used quasi-static stab resistance tests using the type of apparatus using a spike-type indenter. They analyzed the stab resistance of Twaron fabric specimens consisting of STF-impregnated fabric and non-impregnated specimens using a stab hit to simulate low-velocity penetrative impact. Fig. 4 shows the loading test apparatus. The spike indenter was fixed to the testing machine pointing towards the fabric specimen placed on a backing device designed corresponding to National Institute of Justice (NIJ) Standard 0115.00.[90] This test was a deformation-controlled process in which the spike penetrated the fabric at a loading rate of 5 mm/min and a maximum displacement of 30 mm. The non-STF-treated specimens were completely perforated during the test while the restricted movement of individual fibers in the STF-treated fabric specimen hindered penetration.

Among the various LVI tests discussed in this section, drop weight tests are the most ideal to recreate low-velocity impacts on aerospace or other structural applications. Various impactor shapes can be fitted to the drop weight tester to imitate impact events that may occur during the service life of composite components. Various literature is also available on LVI tests through QSI tests which provide researchers with data on the penetration behavior of FRP composites. Even though QSI tests are displacement controlled, the results correlate well with drop weight tests. The information gathered through QSI tests can aid in validating numerical simulation results to discuss failure patterns in composites.[91] Finite element simulation of drop weight and QSI tests are not widely available in the literature and it will be beneficial to perform such studies to provide further information relating to the behavior of thin FRP composites under LVI loads.

4.4 LVI test standards

The standards corresponding to different methods of LVI tests that are performed by various researchers in their study on the impact performance of composites are listed in Table 5.

Table 5. LVI Test methods and corresponding standards.

Test Type	Standard	Ref.
Drop weight test	ASTM D7136	[52]
Quasi-static stab test	NIJ Standard 0115.00	[20]
QSI test	ASTM D6264-98	[22]
Quasi-static shear punch	ASTM D732-02 [92]	[60]
Falling weight impact test	ISO 6603-2 [93]	[50]

4.5 LVI test Indenter/Impactor Size, Specimen Dimensions, and Standards

Various indenter shapes and sizes are available and used in LVI testing by various researchers.[65–67] Standard shapes and sizes corresponding to various test methods have been listed in Table 6. The shape and size of indenters are said to have a considerable impact on the failure mechanisms of composites, and this was studied by Mitrevski *et al.*[94] They used conical, hemispherical, and ogival-shaped indenters of 12 mm diameter similar to the ones shown in Fig. 7 for impact testing of CFRP laminates. The failure patterns and damage areas were analyzed using C-scan images. It was reported that the damaged area in specimens was highest for hemispherical-shaped indenters, followed by ogival. The least damage to specimens occurred while conical-shaped indenters were used. In terms of penetration depth, impacts by conical impactor produced the highest penetration followed by ogival and least by the hemispherical indenter. Similarly, the post-impact specimen thickness at the impact region was larger for the conical indenter than for ogival and hemispherical shapes. This can be attributed to the extensive damage to the rear face of the laminate subjected to impact by the conical indenter. Also, Pandya *et al.*[95] in their study on the impact behavior of hybrid composites, noted that the kinetic energy, size, and shape of the impactor had a considerable influence on the impact performance of composites.

Authors like Karakuzu *et al.*[96] studied the effect of impactor mass, impact energy, and velocity on the maximum contact force, deformation, energy absorption, and impact damage area in E-glass/epoxy composite laminates, experimentally and numerically. They fabricated 2.9 mm thick laminates using 8 fabric layers, each 0.36 mm thick and having an orientation of 0/30/60/90. The impactor mass used in the study were 5, 10, 15, and 20 kgs, whereas the impact energies

Table 6. Indenter dimensions and loading parameters for LVI tests.

Type of Test	Test standard	L×W (mm^2)	Type of Indenter	D (mm)	V (mm/min) (*m/s)	m (Kg)	F (kN)	Type of composite	Ref.
Quasi-static Indentation test	ASTM D6264-98	152×152	Hemispherical tipped	12.5	2	-	41	K/E Twaron/E	[22]
Quasi-static shear plugging test	ASTM D732-02	125×35	Cylindrical, flat tipped	12.5	1	-	10	DGEBA/E DGEBA/E/MWCNTs	[4]
Drop Weight Impact	ASTM D7136	48×48	Cylindrical, Pointed	5	4.4*	5-20	-	K/E K/MWCNT/E K/Al_2O_3/E K/SiC/E	[52]
Drop Weight Impact	ASTM D7136	100×100	Hemispherical nosed	20	-	2.9	2.5	C/E C/GrF/E	[53]
Drop Weight Impact	ASTM D7136	150×100	Hemispherical nosed	12.7	-	6.5	-	UHMWPE/LLDPE	[26]
Drop Weight Impact	ISO 6603-2	100×100	Hemispherical nosed	20	4.4*	26.7	20	C/E G/E C/G/E	[50]

L×W = length ×width of the specimen, D-diameter of indenter, V-loading rate, m-mass, F-Peak load, K–Kevlar, C–carbon, G–glass, E-epoxy.

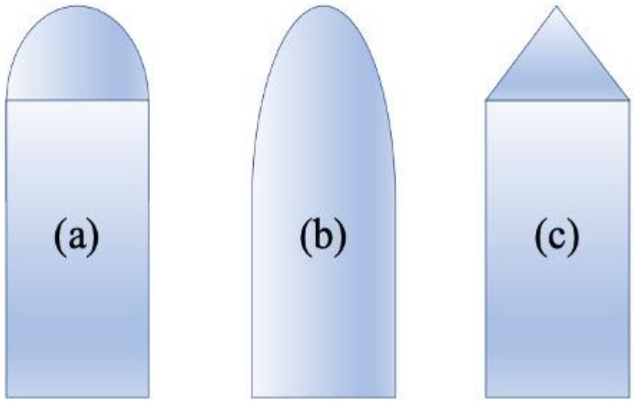

Fig. 7 Indenter shapes used for LVI tests: (a) Hemispherical, (b) Ogival, and (c) Conical.

were 10, 20, 30, and 40 J. The impact velocity, impact energy absorption, and deflection was calculated using a software platform Visual IMPACT. During LVI tests, firstly, the mass of the impactor was kept constant, varying the impact energy, in the next set of experiments, the velocity of impact was maintained constant, and impact energy was varied. Finally, the impact energy was kept constant and the impactor mass was varied. Through test results, it was reported that energy absorption in the composite specimens was higher for constant velocity compared to constant mass conditions. Higher delamination was caused by higher impact mass compared to lower mass. Similarly, the delamination area in impacted specimens was more when high-impact mass was coupled with low-impact velocity compared to the delamination area when low-impact mass was coupled with high-impact velocities. It was observed that delamination increased in specimens up to an impact mass of 15 kgs, above this the delamination area reduced and damage was mainly due to matrix cracking and fiber failure.

5. Correlation of LVI impact strength with Mechanical Properties of LVI materials

In hybrid fabric composites, the properties of the matrix formulation have a great impact on their impact resistance, while the degree of failure depends upon the orientation of fibers.[97] Several other factors like fiber properties, volume fraction, and the stacking sequence of fabrics also affect the impact behavior to a great extent.[7] Through their study on tensile and compression test performance of carbon and E-glass fabrics, Ikbal *et al.*[98] reported the effect of fabric hybridization in enhancing the failure strain of composites which made them more tolerant to impact damage, *i.e.*, enhancement in impact properties while reducing the cost of designing advanced composite materials. Inter-laminar shear strength is another very important property required in composite laminates to withstand impacts. Even though reinforcement fibers have high tensile and compressive strength, they are weak in shear. Predominantly, loads during any impact events are of shear mode, the necessary shear strength is offered by the matrix system. The matrix material offers bonding between the reinforcing fibers and transfers load between the fibers by providing a better shear response.[99] Similarly, the fracture toughness of fabric-reinforced composites has a huge impact on the LVI performance of these materials. Epoxy-based matrices are generally vulnerable to cracks and highly brittle due to their cross-linked structure.[100] The addition of nanofillers such as CNTs has been shown to improve the fracture toughness of epoxy matrix by up to 43% at a concentration of 0.5 wt.%. At 0.25% CNT concentration by weight, the enhancement in fracture toughness observed by Rafiee *et al*.[101] for epoxy was observed to be 11% compared to control samples. Similarly, Park *et al.*[102] reported considerable toughening in epoxies by incorporating graphene into the matrix. Crack pinning and deflection were observed to increase with the concentration of graphene which led to improved fracture toughness in the matrix system.

Karahan *et al.*[9] performed LVI experiments on non-hybrid and hybrid composites fabricated using Twaron, Kevlar-29 woven fabric, UD Kevlar-29, and UD UHMWPE reinforcements in the LDPE matrix. Force *vs*. displacement data for the specimens subjected to the LVI tests was analyzed to interpret the effect of reinforcement properties and the hybridization on the impact strength of the composites. Apart from energy absorption, the bending stiffness of the specimens was also calculated. They reported that the bending stiffness of the composites was an important property in evaluating the damage resistance of these materials, especially the delamination in laminates. This property was reported to be highly influenced by the hybridization of reinforcement fabrics. The bending stiffness was calculated as the slope of the force *vs*. displacement curve in the elastic region. Dikshit *et al*.[103] noted that the delamination resistance of composite laminates could be measured by their inter-laminar fracture toughness (ILFT) properties. ILFT of multilayer composites is influenced by their stacking sequence and fiber orientation, fabrication method,[104] laminate thickness[105], and environmental factors.[106]

6. LVI failure mechanisms

Failure mechanisms of the FRP composite structures are classified into two phases (i) elastic failure, and (ii) damage at specific stress. The elastic failure is barely visible during the physical inspection and the second phase of failure is visible.[107,108] The multi-layered woven fabric and filler-loaded polymer matrix composites also called hybrid composites are used extensively in aeronautical structures. This is due to more flexibility in design for required multi-functional and structural properties and ease of manufacturing. In such composites, the LVI is more common and assessment of damage due to LVI is a complex problem. But the damage assessment is of utmost importance due to the required high reliability.

The main failure mechanism due to LVI in multi-layered hybrid polymer composites is classified as intra-laminar failures and inter-laminar failures.[109] The detailed types of failure in such composites are shown in Fig. 8. The intra-laminar damage in the FRP composites is fiber fracture and fiber buckling under tension and compression load respectively. The fiber fracture influences the residual strength of the composite laminate. The matrix failure by tension or compression, and shear failure of the matrix are also intra-laminar failures. This influences the load transfer capacity from matrix to fiber due to decreased integrity in the composite. In addition, inter-laminar failures such as matrix microcracks develop initially at the interface between fiber and matrix. Further, microcracks will continuously grow as the load increases and the separation of fiber from matrix occurs. Continuation of the growth due to the propagation of cracks and crack bridging leads to fiber-matrix debonding and delamination. This significantly reduces the compressive strength of the composite laminate.[110]

The polymer matrix holds the fibers in place, transfers the impact loads to the fibers, and protects them from damage in FRP composites. The matrix is the barrier between the projectile and the fibers, it also protects them against adverse environmental effects. For most ballistic and structural composites, epoxy resins are used to meet the required strength. However, it is also reported that epoxy resin is brittle and has poor resistance to crack growth, thus delamination failure is commonly observed in epoxy resin-based fabric composites. In addition to this brittleness combined with heterogeneous and anisotropy are major drawbacks of FRP composites which makes them more sensitive to LVI. Hence, majorly failure modes of FRP laminates subjected to LVI are mentioned by many researchers as discussed above classified as (i) matrix mode, (ii) delamination mode, (iii) fiber mode, and (iv) penetration mode.[111] The matrix and delamination modes are the first types of failure modes also due to material property mismatch between fiber and matrix. The shear matrix cracks developed on the upper layer and middle layers start under the edge of the impactor due to high transverse shear stress which is related to contact shear force and contact area.[112] The matrix cracks developed in the bottom surface and bottom layers of the FRP composite subjected to LVI are closely related to the flexural deformation of the laminate and observed in thin samples. Whereas the matrix cracks at the upper layer are observed in thick samples of shorter length.[113] Further, the delamination mode of failure is developed by the growth of matrix crack. In addition to this bending stiffness mismatch between adjacent layers due to various orientations of fibers in the neat or hybrid layers, resin-rich zones between the layers act as bending stress risers, and the localized bending-induced stress causes the delamination. The delaminated area is directly proportional to the bending stiffness mismatch of adjacent layers. Also, the stacking sequence, laminate thickness in addition to material property

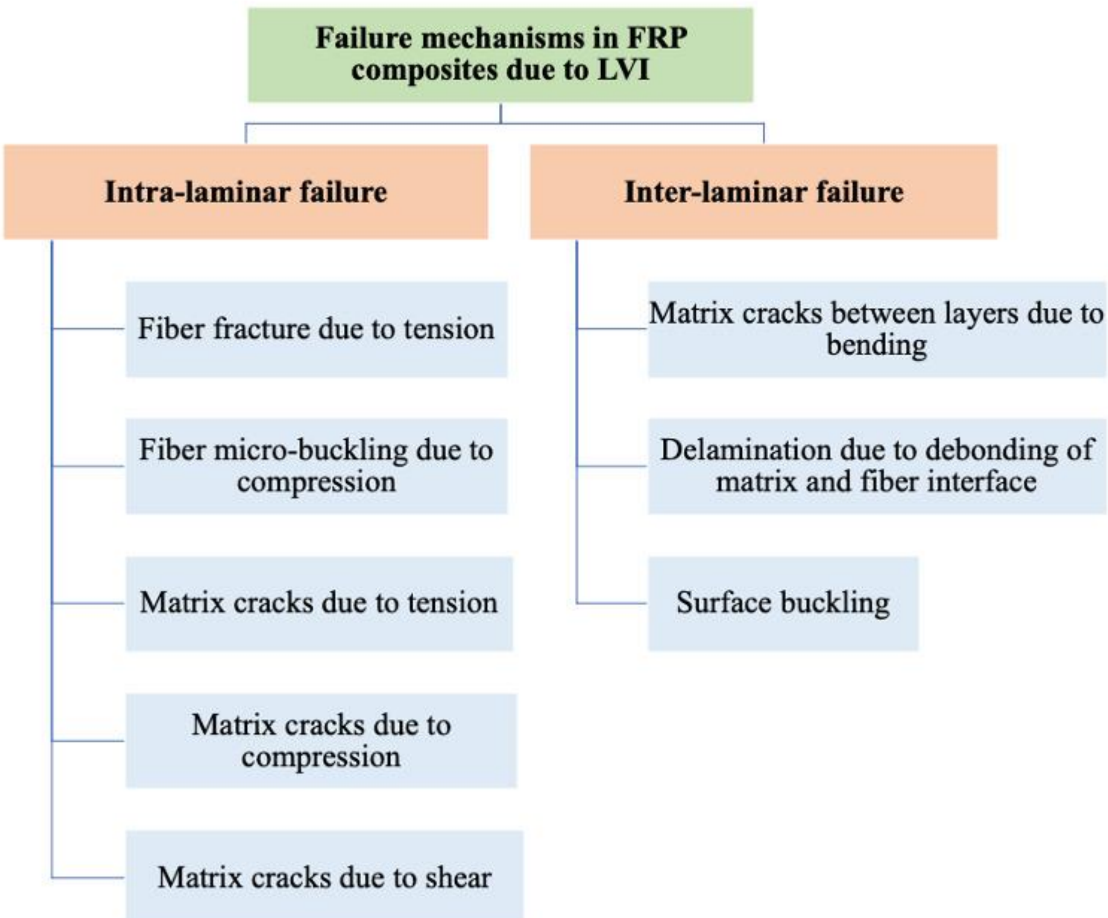

Fig. 8 Types of failure in FRP composites subjected to LVI.

influence on delamination mode of failure when FRP laminate is subjected to LVI. The delamination causes a significant reduction of residual compressive strength of the laminates due to reduced stiffness as compared to the original laminate and whole laminate subdivided into multiple laminates and acts as an individual due to delamination and they have less resistant to buckling. The fiber damage of FRP laminates subjected to LVI is later staged as compared to matrix failure. The fiber fracture is caused due to localized high stress and indentation effect of the LVI indenter at the point of contact. The fiber fracture in the bottom layers of the FRP laminate is caused due to high bending stress. The residual tensile strength of composites is significantly reduced by fiber fracture. Further, fiber failure reaches a critical stage, and penetration of the indenter causes a macroscopic failure.

High-specific strength FRP pipes are noncorrosive and possess attractive structural properties, thus, gaining demand across the globe for diverse applications, leading to significant market growth in recent years.[111] In this consideration Khan *et al.*[114] studied the LVI response of filament wound FRP pipes using a drop weight impact test and reported the failure mechanism. They studied load versus time, load versus deflection, and energy versus time response for glass fiber-reinforced epoxy and glass fiber-reinforced vinyl ester pipes. They found in each type of pipe two responses such as elastic deformation and initiation and propagation of crack led to major damage as plastic deformation. Gross damage was reported during elastic deformation, and reported observation of initiation and propagation crack to major damage was in plastic deformation. They reported lower energy to peak load and deflection at peak load values for epoxy matrix pipes and concluded it was due to the brittle property of epoxy as compared to vinyl ester. Sun *et al.*[73] carried out drop weight impact studies on UD glass fabric reinforced epoxy matrix composites of 3.2 mm thickness consisting of 16 layers of fabric in 0º/90º orientations. Weak interfacial bonding between the glass fibers and matrix led to fiber pull-out during the event of an impact. In the top layers of the laminate, directly facing the impactor, matrix cracks were initiated and these cracks were oriented in planes parallel to the direction of fibers. Also, debonding was observed at the fiber-matrix interface during fiber pull-out. In the later stages of the impact process, fiber breakage occurred finally leading to catastrophic penetration of laminates. Delamination was caused by the transverse impact load above a threshold energy level, and it was observed to develop due to the presence of matrix cracks. Similarly, Habibi *et al.*[115] studied the effect of LVI impact on residual tensile strength and residual compressive strength of UD flax fiber composites. The 2.95 mm thick composites laminates were subjected to impacts at energy levels between 0-5 J and impact angles between 15º-60º. The laminates did not show any damage on the rear face at or below the energy threshold value of 2 J. The damage was restricted to matrix cracks in the direction of fibers. As the impact angle was increased, more was the delamination area and matrix cracks, leading to reduced strength of the composite. Post-impact tensile tests showed that for samples impacted at 5 J of energy, the residual strength was reduced by 41%. Similarly, the residual compressive strength of composites was reduced by 40% at an impact energy level of 5 J and an impact angle of 60º.

Sayer *et al.*[116] performed an LVI study on hybrid fabric composites consisting of carbon, glass, and Kevlar fabrics and reported that delamination and fiber breakage on the rear face of the laminates away from the impact as the major failure patterns. A similar study was also conducted by Bulut and Erklig[36,37] who carried out QSI tests on hybrid fabric multi-layer composites systems made up of glass, Kevlar, and carbon fabrics in different stacking sequences. The force versus displacement curves for the various composite specimens subjected to quasi-static loading was generated and it was represented in Fig. 9. Part 1 of the curve relates to the region of elastic deformation in the laminates due to the applied load. At the beginning of Part 2, a sudden drop in force corresponds to the matrix cracking due to the indenter impact, and during this section, delamination builds up, penetration of laminates is initiated and stiffness of the specimen begins to retard. Part 3 is the final stage of penetration during which catastrophic damage and complete penetration occur.

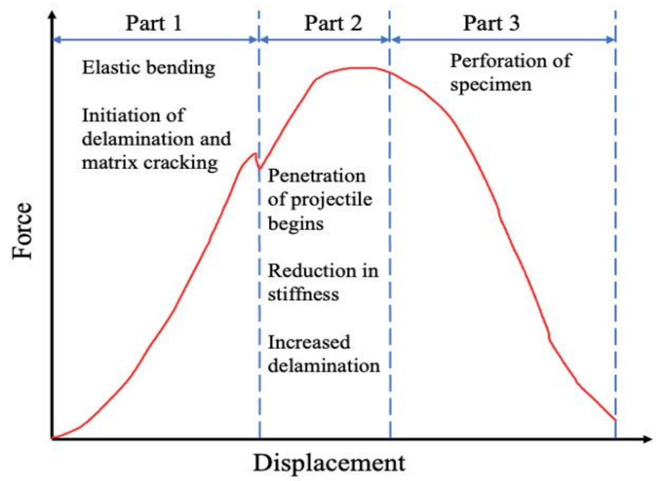

Fig. 9 Force vs. displacement curve for QSI on FRP composites.

In Fig. 10, various damage mechanisms such as fiber breakage, matrix-fiber debonding, and matrix cracks induced in hybrid composites consisting of Kevlar, carbon, and glass fabrics upon LVI loading can be visualized through the SEM images.

The development of LVI-resistant materials involves the selection of fibers or fabric with good strength, and stiffness to avoid fiber breakage, the matrix material must be selected such that it provides good wetting of fabric and imparts toughness to the composite to negate matrix cracking. The addition of secondary reinforcements such as high aspect ratio nanofillers improves ILSS, ILFT, and fiber-matrix interfacial bonding, and arrests the propagation of micro-cracks during

LVI events.

6.1. Analysis of failure using NDT

Post-impact failure analysis is essential in the study of the impact behavior and failure modes in LVI-resistant composites. Researchers have tried to inspect and characterize the damage patterns in the composite specimens by subjecting the post-impact specimens to a range of Non-Destructive Test (NDT) methods. Among them are CT-scan, X-ray, Ultrasound, Optical Thermography, and SEM to understand the micro-level damage behavior in individual fibers, the interface region between the fibers and matrix as well as the matrix damage patterns. In operational situations, LVI damage is hardly visible during the physical inspection, but internal damages can be severe and could lead to catastrophic failures. Such NDT methods can aid in understanding micro, and internal damages and ways to enhance the damage resistance of fiber-reinforced composites.[117]

Pagliarulo *et al.*[118] performed LVI experiments on carbon/epoxy laminates using drop weight apparatus and analyzed the damage mechanisms using various NDT methods. Load *vs*. deflection curves were used to measure various energy levels when the specimen was impacted. The depth of indentation on the specimen was measured using confocal microscopy. Ultrasound was then used to measure the damage on the top face and the internal layers of the specimen. The ultrasound results were compared using another NDT technique lock-in thermography. The damaged surface features were also studied using a relatively new method known as Electronic Speckle Pattern Interferometry (ESPI) to measure the displacements, cracks, and defects on the post-impact surface. It was reported that in terms of the delamination area, all the NDT techniques showed results that were in good agreement with each other. The finite element analysis results of the impact damage were comparable with those of NDT. Even though the ESPI method is relatively new in the study of LVI damage, it is reported to be an effective tool for such studies.

Similarly, Gaudenzi *et al*.[119] compared the analysis results of various NDT methods on the impact damage on UD CFRP laminates subjected to drop weight tests. Impact energy of up to 20 J was used in the tests which cause BVID which could only be analyzed through NDT methods. In this study lock-in thermography, transient thermography, and sonic infrared techniques were used apart from the ultrasonic method to analyze the area of damage. It was observed that the ultrasonic

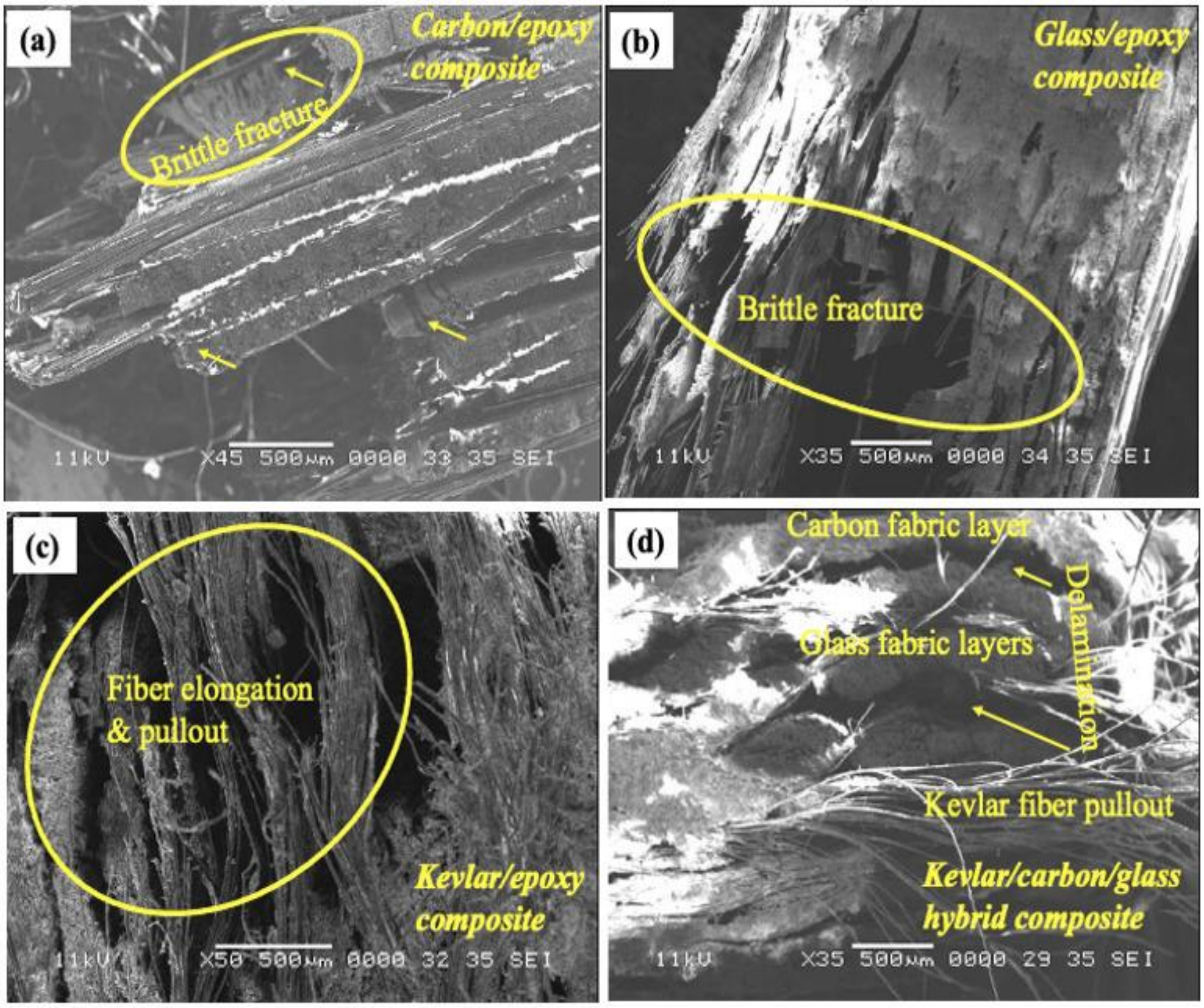

Fig. 10 SEM images of failure mechanisms in Kevlar, carbon, and glass hybrid composites.

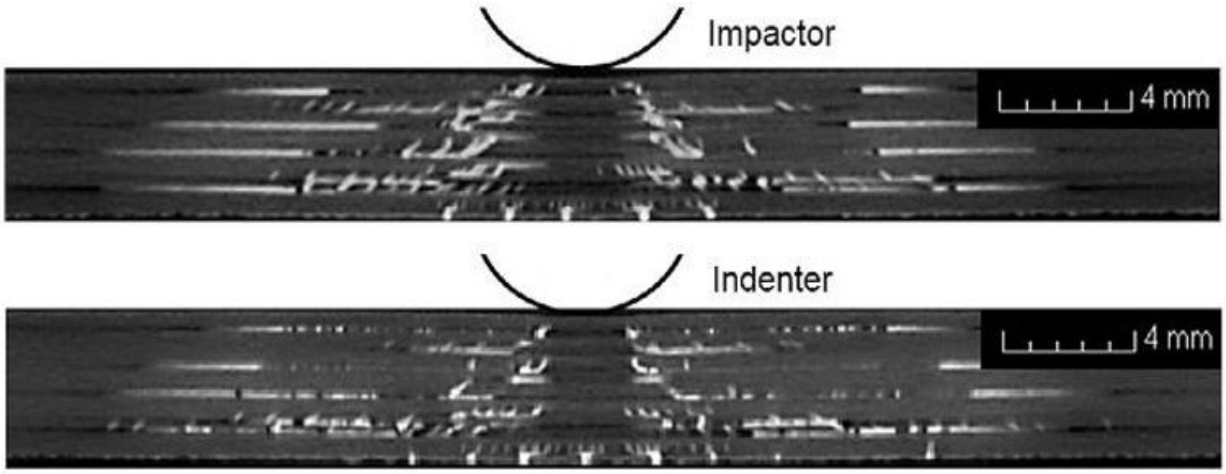

Fig. 11 X-Ray image showing the variation in damage due to (a) the Drop weight impact test and (b) the QSI test. Reproduced with permission from [86], Copyright 2015 Elsevier.

method was more accurate compared to transient thermography in mapping the area under impact damage. Also, sonic infrared thermography was reported to be a fast and accurate process to study the impact damage throughout the specimen and ultrasonic testing was carried out to validate the results obtained through the sonic infrared technique.

Kapadia[120] reported that the selection of the NDT technique in analyzing damages and defects in polymer matrix composites is an important task. Thermal techniques involving excessive heat might lead to melting or charring of thermoplastic and thermosetting matrix respectively. For composites such as GFRP which offer less thermal conductivity, vibrothermography was proposed, and for high thermally conductive composites such as CFRP, thermal pulse thermography was recommended. Void content affects the ILSS of composites and ultrasonic testing can be used to gauge voids accurately by measuring the reduction in wave amplitude as it passes through the laminate. Similarly, acoustography is one NDT method that has been widely used to measure impact damage, delamination area, and void content in polymer matrix composites.

Figure 11 shows X-ray morphology images for similar composite laminates after impact studied by Abisset *et al*.[86] It can be observed that the delamination patterns for both QSI and dynamic drop weight from the X-ray images are similar. No evident differences could be spotted through damage morphology. Whereas in the case of hybrid composites high resolution imaging especially SEM helps to observe the damage to fibers and matrix upon impact and also to analyze the effect of adding nanofillers to the composites.

7. Conclusion

A detailed insight into the recent research studies shows that there is a growing inclination towards both synthetic and natural fiber-based FRP composites by researchers for various applications. Comprehensive scientific explanations and systematic analysis presented in this work indicate that hybrid fabric polymer composites have a huge potential to take composites to the next level in terms of structural and LVI resistance applications. They offer improved mechanical properties and impact strength, and weight reduction compared to conventional composites. The fabrication of hybrid composites involving the usage of nanofillers and different types of fabric reinforcements is challenging in terms of achieving the best material properties. Homogeneous dispersion of nanoparticles in the matrix liquid, proper bonding at the reinforcement-matrix interface, and proper curing of laminates without voids or other defects are a few challenges facing researchers. Fabrication methods currently in use to produce composite laminates, such as hand lay-up, compression molding, VARI, VARTM, pultrusion, and filament winding are still dependent on human skill to achieve better quality laminates until a more viable technique is available to manufacture such components on a commercial scale. The availability and selection of standard LVI testing methods and equipment is another major challenge posed by this field of research.

This review also illustrates that the research work relevant to the LVI performance of bio-composites and natural fiber composites is lacking. Also, it can be noted that laminated FRP composites having numerous applications, such as aircraft structures, automotive, pressure vessels, and piping have been characterized through thermo-mechanical tests. However, either LVI or HVI performance which is extremely important for such applications has not been conducted. LVI performance studies of graphene-reinforced fiber composites are also very minimal in the literature though the importance of using 2D materials such as graphene or graphene oxide as fillers for improved characteristics due to their unique properties. Few related works are available in the literature.

8. Future Prospects

The necessity for impact-resistant materials for structural, aerospace, and automotive applications demands the design and development of hybrid and non-hybrid fabric composites with high specific strength and specific modulus. Components made of such composites must be protected against impacts during their service life or maintenance, which has the potential to retard their performance and at times such impacts are not visible during the physical inspection and can cause severe sudden catastrophic failures. Hence, the development of fabric-based composite materials towards this goal is necessitated. The addition of nanofillers to composites as secondary reinforcements has been shown to have enhanced ILSS, ILFT, and other mechanical properties of these materials greatly. So is the effect of chemical modifiers added to nanofillers to improve interaction at the filler-matrix interface? Another crucial area of discussion among the research community is the dispersion of nanofillers into the matrix and the interface bonding between nanofiller and the matrix and the effect of such bonding on the physical and mechanical performance of the resultant composite materials. The future holds a huge potential in terms of the development of such advanced materials with good impact-resistant properties and this area of multi-disciplinary research has the potential for the design and development of such smart materials through cutting-edge technological advancements in terms of technically robust manufacturing processes and characterization methods that are eco-friendly and sustainable.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

Abbreviations

2D – 2 dimensional
3D – 3 dimensional
Al_2O_3 – Aluminium dioxide
BD – Bidirectional
BVID – Barely visible impact damage
C – Carbon
CAI – Compression after Impact
CFRP – Carbon fiber reinforced plastic
DCPD - Dicyclopentadiene
DGEBA – Diglycidyl ether of bisphenol A
ESPI – Electronic speckle pattern interferometry
FEM – Finite element modelling
FRP – Fabric reinforced polymer
G – Glass
GFRP – Glass fiber reinforced plastic
GrF – Graphite fluoride
HVI – High velocity impact
ILFT – Inter-laminar fracture toughness
ILSS – Inter-laminar shear strength
K – Kevlar
LDPE – Low density polyethylene
LLDPE – Linear low-density polyethylene
LVI – Low velocity impact
LVIR – Low velocity impact resistant
MMA – Methyl methacrylate
MWCNT – Multi walled carbon nanotubes
NDT – Non-destructive test
PP – Polypropylene
QSI – Quasi-static indentation
SEM – Scanning electron microscope
SiC – Silicon carbide
STF – Shear thickening fluid
UD – Unidirectional
UPR – Unsaturated polyester resin
UHMWPE – Ultra high molecular weight polyethylene
VARI – Vacuum assisted resin infusion
VARTM – Vacuum assisted resin transfer molding

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