*Journal of Advanced Research in Applied Mechanics* 123, Issue 1 (2024) 147-184

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

# A Review of Experimentation Numerical Simulation of Low-Velocity Impact Performances and Damages of Fiber-Reinforced Composites

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**ARTICLE INFO**

***Article history:***
Received 30 May 2024
Received in revised form 17 July 2024
Accepted 26 July 2024
Available online 30 August 2024

***Keywords:***
Fiber-reinforced composite; low-velocity impact, Performance and damage

**ABSTRACT**

Fiber-reinforced composites (FRCs) are extensively utilized in various industries due to their lightweight and high-strength properties, making the understanding of their response to low-velocity impact (LVI) crucial for ensuring structural integrity, performance and invisible internal damages that can compromise performance and safety. This paper critically examines the current state of research on the low-velocity impact behavior of FRCs, focusing on both experimental and numerical simulation approaches. The review comprehensively surveys on characterizing and modeling the response of FRCs to low-velocity impacts leading to damages. The effects of parameters including composites preparation; impact mechanics; testing methods; induced damages including assessment methods; different performance parameters including impact energy, force, load, impact resistance; post-impact damages and their resistance; performance and damage affecting different factors; numerical and simulation modeling are discussed. Current challenges and future prospects regarding the subject matter is highlighted. The comprehensive analysis presented in this review goals to consolidate current knowledge, identify research gaps, and guide future endeavors in enhancing the understanding of low-velocity impact (LVI) behavior in fiber-reinforced composites (FRCs).

## 1. Introduction

Composite materials are defined as the composition of more than one least two visually distinct materials which are combined to provide better desirable properties as a whole compared to the constituent's individual materials while retaining their respective chemical, physical, and mechanical properties. Different composites are applied for different purposes while fiber-reinforced composites (FRCs) are popular in applications due to different advantages compared to metallic and ceramic composites. FRCs consist of fibers with superior strength and modulus bonded to a matrix with distinct interfaces (boundaries) between them [1]. The properties of FRCs depend on types of matrices and reinforcement used, fiber volume fraction, fiber aspect ratio (fiber length/fiber

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https://doi.org/10.37934/aram.123.1.147184

diameter), fiber geometry, and interfacial adhesion between reinforcement and the matrix [2]. FRCs have gained significant prominence in various engineering applications including extensive use in aerospace, automotive, marine, and sporting goods industries, among others due to reduced weight, lifetime maintenance cost owing to corrosion and fatigue resistance, high specific strength and stiffness [3,4]. FRCs are used by stacking a number of thin layers of fibers and matrix and combining them into the required thickness where fiber orientation, stacking sequence determines the physical and mechanical properties [1]. As the demand for lightweight and high-performance structures continues to rise, understanding the behavior of fiber-reinforced composites under different loading conditions becomes imperative where one critical aspect that warrants thorough investigation is the response of these materials to different impacts loading like low velocity (large mass), intermediate velocity, high/ballistic velocity (small mass), and hyper velocity impact. These impact loadings are very important as extreme changes in energy transfer between the projectile and target, energy dissipation and damage dissemination mechanisms as the velocity of the projectile differs [5]. Among them, this review aims to provide a comprehensive overview of the experimental, modeling, and simulation studies conducted to date on the low-velocity impact response of fiber-reinforced composites produced during manufacturing, service life, or maintenance as it has profound implications on the structural integrity and performance through affecting mechanical properties and long-term durability. Besides, low-velocity impacts lead to significant damages often barely visible impact damages within the composite structures results reduction of the stiffness and residual strength followed to complex failure in internal structure with very minimal surface damage. Therefore, it is very crucial to poster this type of damages and to be able to predict origination of damage and its spread using different techniques to obtain the remaining lifespan under dynamic loadings [6]. In light of the above discussion, it is noticeable that the low-velocity impact performance of FRCs is of substantial importance because of the wide range of 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 [7]. Although the impact behavior of a composite structure can be assessed by experimental tests, a huge time and cost will be taken because of required skilled labors and material costs. Therefore, the numerical simulation by means of finite element method (FEM) has been extensively deployed to predict the induced damage modes subjected to dynamic impact loadings, especially at the early design stage when such simulation can minimize the risks prior to application of experiments and avoid waste of tests and components [8]. Besides, finite element simulation of drop weight and QSI tests are not widely presented in the literature and it will be advantageous to accomplish such studies to provide further evidence concerning to the behavior of thin FRCs under LVI [7]. Following the perspectives of experimentation, modeling and simulation; by synthesizing existing literature this paper intends to offer insights into the methodologies employed for experimentation, the development of predictive models, and the utilization of advanced simulation techniques to understand the intricacies of low-velocity impact on FRCs materials.

The first section of this review will delve into the experimental techniques employed to investigate the response of fiber-reinforced composites to low-velocity impact. This will include discussions on fiber-reinforced composite preparations, impact performance and damages assessment, performance assessment under low-velocity impact and affecting factors for performance and damage of FRCs under low- velocity impact experiments. The second section of the review will focus on the numerical simulation aspect, where numerical methods such as finite element analysis have been employed to simulate low-velocity impact scenarios like complex interactions between the impacting object and the composite structure, energy absorption mechanisms, deformation patterns, and damage evolution. Subsequently, development and validation of mathematical models will be explored which aimed at predicting the impact behavior. In conclusion, a holistic understanding of the low-velocity impact response of fiber-reinforced composites is essential for designing structures that can withstand real-world loading conditions. By synthesizing the wealth of knowledge accumulated through experimentation, modeling, and simulation, this review is to contribute to the on-going efforts of low-velocity impact on FRCs to enhance the performance and durability of fiber-reinforced composites in various engineering applications.

## 2. Body

### *2.1 Fiber-reinforced Composites (FRCs) Preparation*

Material selection is one of the most important factors in structural or mechanical design of FRCs as it is related to damage, failure, maintenance, repair, and replacement. Major materials of a FRCs are reinforcing fibers and matrix which acts as a binder of fibers. Besides those, the fabrication method and fiber architecture with construction types is also important factor for the whole process. Furthermore, other constituents may be used as and when required like coupling agents, coatings, fillers and ingredients of forming fiber-reinforced composites considering different architectures. Apart from this, as example researches on types of fiber, matrix and process used during FRCs preparation are described below.

#### *2.1.1 Fibers and matrix*

Fibers are the main constituents in a fiber-reinforced composite as they occupy the maximum volume fraction and share the major portion of the load so proper selection of the fiber type, configuration and orientation is very important along with volume fraction, length. There are different types of natural (abaca, flax, hemp, jute, coir, sisal) and synthetic fibers (aramid, glass, carbon, boron, ceramic, extended chain polyethylene) are used for composite preparation. Researchers have examined different fiber-oriented composites for different purposes. Among them, the use of aramid, glass, and carbon fiber-based composite have got attention and priority in different researches (shown in Table 1 and Table 2). Previous researches reveal that E-glass and HS glass are mostly used in glass composites because of low elastic moduli compared to other reinforcements, susceptibility to creep, and creep (stress) rupture, stiffer, stronger, better resistance to fatigue and creep, lower thermal and electrical conductivities including CTE. Similarly, carbon (graphite) fibers are used because of high stiffness, strength, low density, CTE, excellent resistance to creep, stress rupture, fatigue, corrosive environments while aramid, or aromatic polyamide fiber (mainly “Kevlar” 49 and “Twaron”) is used because of high-modulus with organic nature. Beside fibers, there is required of matrix which keeps the fibers in place, transfers stress between fibers, provides a barrier against adverse effects, and protects the surface from degradation in a fiber-reinforced composite. Matrix is classified as thermoset and thermoplastic. Among them thermoset polymers (also called epoxy/resins) are popularly used for FRCs (recent used matrix are shown in Table 1 and Table 2) because of their wide variety of properties, low shrinkage, resistance to chemicals and solvents, excellent adhesion properties, and absence of volatile matters in curing despite having cost and long curing time issues. In conclusion, 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. Similarly, according to Table 1 the best orientation of fibers is woven with plain or twill structure and according to Table 2 there are diverse configurations are used but researchers stated that 0/90 bi-directional fiber orientation presented the best impact resistance compared to all other orientation such as unidirectional and twill designs [7].

**Table 1**
Recent used fiber, orientation and resin matrix for composite preparation

| Reference | Fiber | Orientation | Resin |
|---|---|---|---|
| [9] | Carbon and Flax | - | Epoxy resin |
| [10] | E-Glass | Woven | Fumed silica nanoparticles |
| [11] | Carbon | Braided | Epoxy resin |
| [12] | Carbon | - | Epoxy resin |
| [13] | Carbon | Braided | Epoxy resin |
| [14] | Carbon and Flax | Woven | Epoxy resin |
| [15] | Aramid | Plain-woven | Epoxy resin |
| [16] | Carbon | - | Methyl methacrylate |
| [17] | Glass and Kenaf | - | Epoxy resin |
| [18] | E-Glass | - | Epoxy resin |
| [19] | Carbon and Aramid | Twill woven | Epoxy resin |
| [20] | Kevlar 29 | Woven | Polypropylene |
| [21] | Carbon | - | Epoxy resin |
| [22] | Ultrahigh Molecular Weight Polyethylene | Plain woven | Polyethylene |
| [23] | Carbon and S2-Glass | Woven | Epoxy vinyl ester |
| [24] | Basalt and Nylon 6 | Plain woven | Epoxy resin |
| [25] | E-Glass | Plain woven and knit | Vinyl ester resin |
| [26] | Carbon and Kevlar | Sandwich | Epoxy resin |
| [27] | Carbon and S2 Glass | Plain Twill | Epoxy resin |

**Table 2**
Recent used fiber, resin matrix and configuration for composite preparation

| Reference | Fiber | Resin Matrix | Configuration |
|---|---|---|---|
| [28] | Carbon | Epoxy | [(45/-45)/ (0/90)]3s; [(45/-45)/(0/90)]2s |
| [29] | Carbon | Epoxy | [45◦/-45◦/45◦]s; [0◦/90◦/0◦]s |
| [30] | Glass, Carbon | Epoxy | - |
| [31] | Carbon | Vinyl ester | [(0/ 90)30]s |
| [32] | Glass | Epoxy | [45◦/-45◦/45◦]s; [0◦/90◦/0◦]s |
| [33] | Carbon | Epoxy | [0/45/-45/90]2s |
| [34] | Carbon | Epoxy | [0/45/90/-45]4s |
| [35] | Carbon | Epoxy | 0◦, 30◦ , 45◦ , 60◦ , 90◦ |
| [36] | Carbon | - | [45/0/−45/90]4s |
| [37] | Carbon | Epoxy | [02/902]2s |
| [38] | Carbon | Epoxy | [−45∕45∕0∕90∕0∕45∕−45∕0∕0∕0∕90∕45]s |
| [39] | Carbon | Plastic | ([45/0/−45/90]3s |
| [40] | Glass | - | [0/90]2s |
| [41] | Carbon/graphite | Epoxy | [−45/0/45/90]3s; [−45/0/45/90]4s |
| [42] | Kevlar, carbon, glass | Epoxy | - |
| [43] | Carbon | Epoxy | [03/ 903]2s |
| [44] | Carbon, Glass | Epoxy | [02/ 903] |
| [45] | Carbon, Glass | - | [0/45/−45/90]2s |

### *2.1.2 Process for incorporating fibers into matrix*

The processes for incorporating fibers into a matrix can be divided into several categories. Like-fibers and matrices are processed directly into the finished product (filament winding and pultrusion) and fibers are incorporated into the matrix to prepare ready-to-mold sheets that can be stored and later processed to laminate (autoclave molding or compression molding). Besides, there are other different methods used for this process like bag molding process, resin transfer molding and structural reaction injection molding (liquid composite molding), resin film infusion, elastic reservoir molding, etc. [1]. The recent fabrication method for FRCs preparation is shown in Table 3 where it has been revealed that vacuum assisted resin transfer molding (VARTM) technique is being widely used for FRCs which is shown in Figure 1. This process is widely applied because it is difficult to control the void creation in compression molding compared to the VARTM process, through which voids can be reduced. Similarly, good repeatability, precision, and quality of the complete composite can be achieved in VARTM compared to hand lay-up and compression molding method [7]. Besides, other processes like filament winding, pultrusion, prepreg and autoclave are limitedly used because of the cost, void content, fibre volume content, large size requirements, damage creation and propagation considering specific composites of particular application.

**Table 3**
Fiber reinforced composite fabrication

| Reference | Fiber | Method | Curing |
|---|---|---|---|
| [9] | Flax/carbon fiber hybrid reinforced composites | Filament-winding | Room temperature for 48 hours, drying at 60◦C for 24 hours |
| [11] | 3D CFRP composites | Resin transfer mold | 70 ◦C, pressure 10 bar |
| [31] | Carbon fiber reinforced composite | Vacuum-assisted resin infusion | 23 ◦C, pressure 0.1 MPa |
| [32] | Glass/epoxy composite | Vacuum bag molding | 126℃ for 1 hour |
| [12] | CFRP filled with Nano clay | Vacuum infusion process | 24 hours at ambient temperature, 5 hours of post-curing at 60 ◦C. |
| [40] | Glass fibre reinforced polymer | Vacuum bag process | 130 °C, pressure 0.5 MPa |
| [42] | Hybrid (Kevlar, carbon, glass fabric reinforced) epoxy composite | Hand lay-up and compression molding | 100◦C, 13.85 MPa pressure for 30 min |
| [14] | Flax/carbon hybrid composite plates | Vacuum-assisted resin infusion | Room temperature for 48 hours, post-curing at 110 ◦C for 2 hours |
| [44] | Carbon/glass fibre reinforced epoxy composite | Vacuum injection process | 20◦C for 24 hour |
| [15] | Aramid/ epoxy nano composites | Hand lay-up method | 25 ◦C for 24 hours, pressure of 0.35 MPa, post-curing at 25 ◦C for 6 days |
| [18] | E-glass reinforced sandwich composites | Vacuum assisted resin infusion | 5-80 ◦C, pressure 0.625 MPa |
| [20] | Kevlar/polypropylene composites | Vacuum-assisted compression | 200 °C for 10 min, pressure 10 bar |
| [21] | CFRP | Prepreg lay-up | 135 ◦C, pressure 0.4 N/mm2 |
| [23] | 3D Woven composites by Carbon and S2 Glass | Vacuum infusion | Temperature raised at 2 ◦C /min up to 130◦C for 2 hours; then again up to 180 ◦C and held for 2 hours; pressure 2 bars and |
| [25] | E-glass composite | Vacuum-assisted resin-transfer molding | 4-8 hours, post-curing at 85 ◦C |
| [26] | Kevlar/carbon sandwich composites | Hand lay-up and Vacuum bagging | 600 mm Hg vacuum pressure for 9 hours |
| [27] | Carbon and S2 Glass hybrid composite | Vacuum assisted resin molding process | Room temperature |

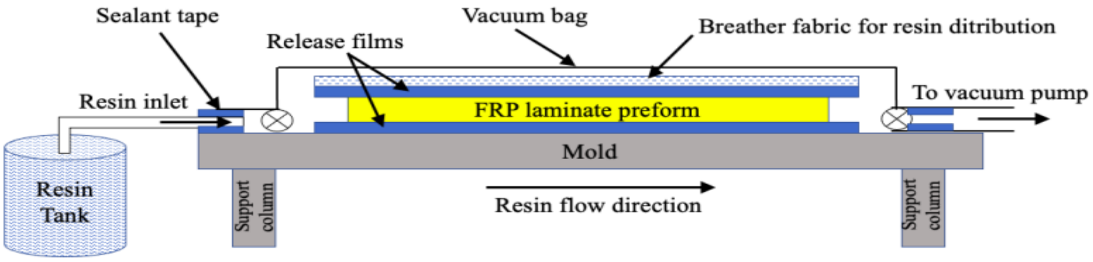

**Fig. 1.** Schematic sketch of the VARTM process [7]

### 2.2 Impact Mechanics, Testing Methods

The post-impact performance of the composites is evaluated by their properties and behavior or induced damages under different static or dynamic loading conditions in both normal and adverse test environments. To evaluate the properties and behavior of the composites important parameters to be considered are impact mechanics i.e., employed impact velocity ranges, impact testing methods with conditions, post impact properties specifically post impact induced damage and their evaluation. Following the perspectives, the issues are outlined below in general.

### 2.2.1 Impact mechanics

The impact property of a composite material is the ability of the material to resist the sudden release of load. All composites are expected to be retained during service because the composite is unsafe if its performance reduces under normal impact. Impact mechanics can be classified into four different categories, based on the velocity range [1] . Apart from this, researches argue with the velocity ranges for the specified velocity type which revealed the standard velocity ranges as stated in Figure 2.

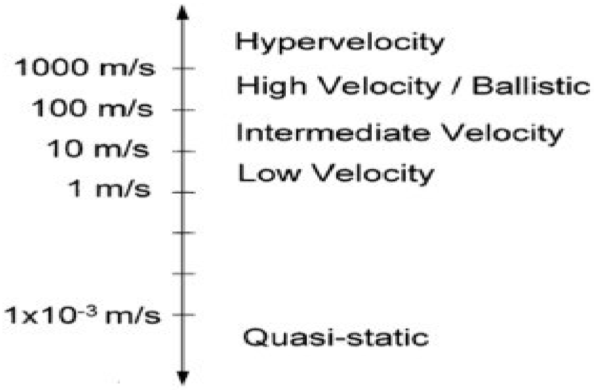

**Fig. 2.** Standard velocity classification of foreign object impact

### 2.2.2 Low-velocity impact (LVI)

Low velocity impact is defined as the impact property of a composite material which is the to resist the sudden release of load of 10 m/s. Low-velocity impact performance is one of the intensive areas of research for the next level by considering their huge potential applications in terms of structural that is aircraft, automotive, pressure vessels, piping, and also impact resistance applications [7]. Apart from this, some defined low velocity range which is being considered for impact related researches are shown in Table 4 where it has been observed that researches on defined low-velocity range for impact testing was 1-6 m/s. Besides, literature found for numerous research on the impact of ballistic velocity range velocity on the particular composites.

**Table 4**
Low-velocity range considered for FRCs impact mechanics

| Reference | Composite | Velocity (m/s) |
|---|---|---|
| [10] | Treated shear thickening fluid/3D glass fabrics composite | 2.6 |
| [46] | GFRP | Up to 4.43 |
| [47] | 3D Braided Composite | 1-6 |
| [43] | Carbon fibre reinforced epoxy composite | 1.68, 2.16, 2.56 |
| [45] | Carbon and glass reinforced composite | 5 |
| [20] | Kevlar/polypropylene composites | 4, 6 |
| [21] | Carbon fibre reinforced polymer | 1 |
| [23] | 3D Woven composites by Carbon and S2 Glass | Up to 4 |
| [25] | E-glass composite | Up to 5 |

### *2.2.3 LVI testing methods*

Impact test conditions should be aimed to pretend the loading conditions to which the particular composite materials are exposed in a functioning service and then reproduce the damage types, which are expected to occur. These are generally done by using falling weight or swinging pendulum and the latter using a gas gun or some other ballistic launcher. But for the low velocity impact response composite materials are tested by Charpy (Figure 3) and Izod pendulums (Figure 4), the falling weight features such as the Gardner and drop dart tests as well as hydraulic equipment premeditated to execute both in-plane and out-of-plane testing [48]. Researchers have hired various test methods to depict the LVI impact behavior of FRCs. Quasi-static indentation (QSI) test (Figure 5), drop weight test (Figure 6), and quasi-static penetration or stab test have been employed to study the effect of hybridization, stacking order, fiber constituents, impact energy, nano-filler concentration, indenter shapes under LVI [7].

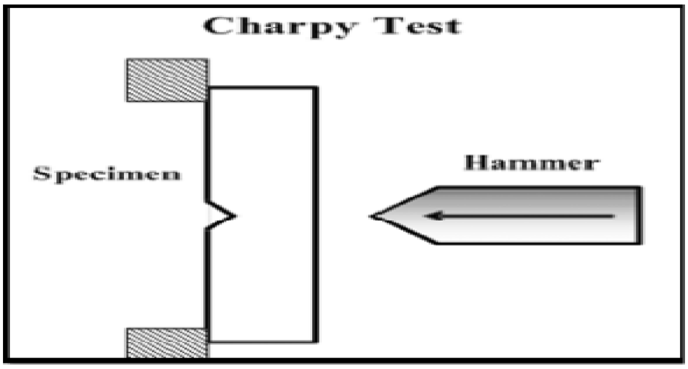

**Fig. 3.** Charpy impact test [48]

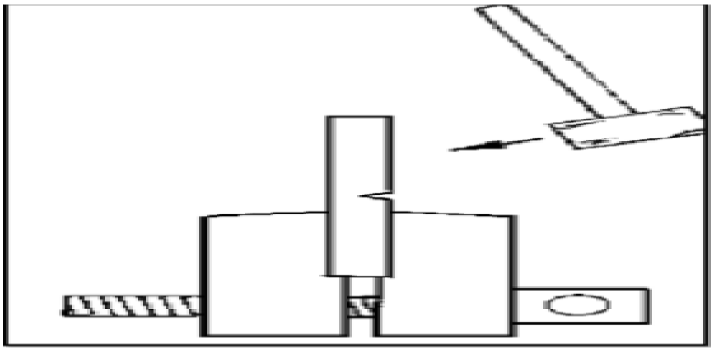

**Fig. 4.** Izod impact test [48]

Among them, drop or falling weight impact test is the most common and popular test method to assess low-impact which is shown in Table 5. It is widely being used because Izod and Charpy impact tests are comparatively relaxed to test which preferable to test the toughness of composite in dynamic state and it also infer the results with some demerits as limited for the thick and short samples so cannot be applied for accurate representation of common components [49]. Similarly, the drop weight impact test (Figure 6) is considered more useful than QSI for studying the damage mechanisms in impact-resistant composites because of using various impactors' shapes which imitates the impact events during operations. Furthermore, QSI tests are displacement controlled and the results correlate with drop weight tests which can assist to validate numerical simulation results [7].

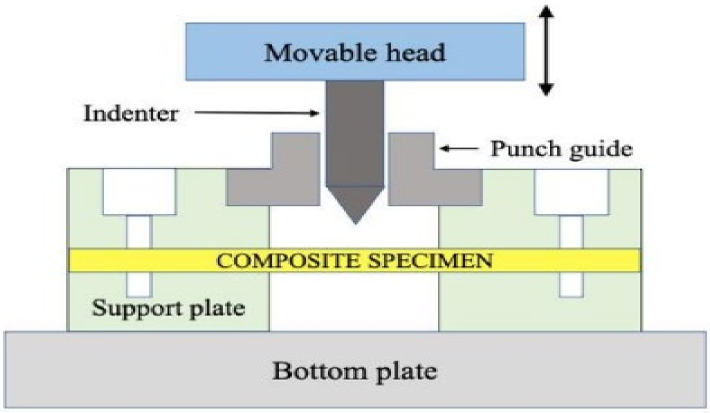

**Fig. 5.** Schematic diagram of quasi-static indentation test [7]

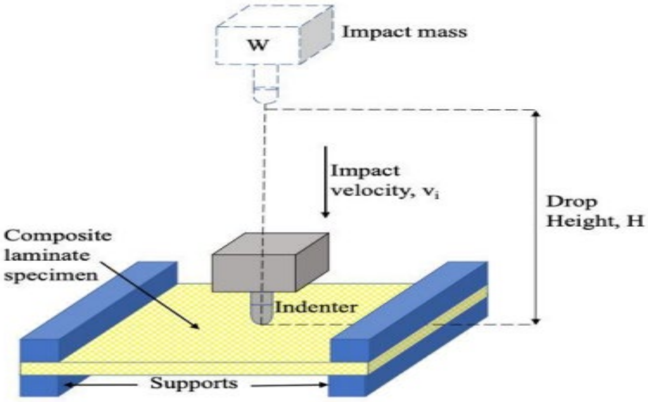

**Fig. 6.** Schematic diagram of drop weight impact test apparatus [7]

**Table 5**
Recent used LVI testing instruments for FRCs

| Reference | Composite | Instruments |
|---|---|---|
| [28] | Carbon fiber reinforced polymer composite | Drop weight impact machine |
| [29] | Carbon/epoxy composite | Drop weight impact machine |
| [50] | Carbon/epoxy composite | Airbus Industries Test Method |
| [30] | Glass- and carbon-reinforced polymer composite | Drop-weight impact testing machine, Universal testing machine |
| [9] | Flax/carbon fiber hybrid reinforced composites | Drop-hammer impact testing-Dynatup 9250HV, Electronic universal testing machine (Instron 3382) |
| [51] | Carbon fibre reinforced polymer composite | Drop weight impact machine |
| [31] | Carbon fiber reinforced composite | Drop weight impact machine, AM4113T Dino-lite premier digital microscope |
| [32] | Glass/epoxy composite | Instron CEAST 9350 impact testing machine |
| [33] | Carbon fiber reinforced plastic laminate | Impact tester (Instron, CEAST 9340) |
| [34] | Carbon fiber reinforced polymer laminate | LiShi drop weight impact testing machine |
| [35] | Carbon/epoxy composite | Instron Dynatup 9350HV drop weight test machine, universal testing machine |
| [36] | Carbon fiber composite laminate | Drop weight testing machine |
| [37] | Carbon-epoxy composite | Instron Dynatup 9250HV impact testing machine |
| [38] | Carbon fiber reinforced composite | Airbus Industries AITM 1-0010 standard (Drop Weight) |
| [39] | Carbon fiber reinforced plastic composite | CEAST 9350 drop weight impact test machine, Computer-controlled material testing machine for CAEI |
| [10] | Treated shear thickening fluid/3D glass fabrics | Dynamic rheometer (MCR301), Drop-weight impact machine, gas gun |
| [11] | 3D CFRP composites | INSTRON 9350 drop tower |
| [40] | Glass fibre reinforced polymer | Drop hammer impact tester, QBS- 100 KN servo-hydraulic tester |
| [41] | Carbon/graphite reinforced composite | Instron CEAST 9350 instrumented test tower, Servo-hydraulic test frame |
| [47] | 3D Braided Composite | Instron Dynatup 9250 drop hammer impact device |
| [42] | Hybrid (Kevlar, carbon, glass fabric reinforced) epoxy composite | Drop-weight testing machine (Instron, 9250 Series) |
| [12] | CFRP filled with Nano clay | Instrumented falling weight impact testing machine |
| [13] | 3D Carbon/epoxy composites | Drop-weight equipment |
| [46] | GFRP | A universal testing machine INSTRON 5900R, INSTRON CEAST 9350 drop-weight tower machine |
| [43] | Carbon fibre reinforced epoxy composite | Drop weight impact machine, Gas gun |
| [44] | Carbon/glass fibre reinforced epoxy composite | Drop weight impact machine |
| [45] | Carbon and glass reinforced composite | Drop weight impact machine |
| [52] | Carbon fiber reinforced composite | Drop weight testing machine |
| [14] | Flax/carbon hybrid composite plates | Universal test machine, drop-weight impact testing machine, hydrothermal aging tester |
| [15] | Aramid/ epoxy nano-composites | Drop weight impact test machine, non-destructive digital microscope |
| [16] | Carbon fibre composites with Methyl methacrylate | Instron Dynatup drop weigh impact testing machine |
| [17] | Glass/Kenaf Reinforced Epoxy Laminates | Drop weight impact test machine |

Again, as we know that, LVI is tested to define capacity to absorb and dissipate energies under impact loading. In practice, the impact condition can be different based on the velocities in specific applications during operations and maintenance results in different types of response of composites.

That's why different LVI testing conditions are employed when impact testing performed in mostly used drop weight impact testing machine based on impactor diameter, mass and impact energy to assess impact properties of composites which is shown in Table 6. According to the Table 6 for recent LVI testing of FRCs impactor diameter range was 12 to 25 mm, mass range was 5.277 to 30 kg and impact energy range was 1.35 to 100 J where the main target was to identify the impact behavior and post impact damage under low velocity including effects of different parameters like fiber content, laminate thickness, impact energy. Furthermore, it may be mentioned that based on the LVI tests the composites of carbon/epoxy and hybrid composite exhibits superior performance and widely used but it depends on particular applications. Similarly, use of nano-fillers in the composite fabrication enhances the performance.

**Table 6**
Recent LVI testing conditions

| Reference | Composite | Impactor Dia. (mm) | Impactor Mass (kg) | Impact Energy (J) | Target |
|---|---|---|---|---|---|
| [9] | Flax/carbon fiber hybrid reinforced composites | 12.5 | 7.28 | 5, 15 | Effects of fiber content and hybrid mode on the impact and residual compressive properties |
| [11] | 3D CFRP composites | 16 | 5.277 | 30, 65, 100 | LVI response and damage under different energies |
| [12] | CFRP filled with Nano clay | 10 | 7 | 10, 15, 20 | Effects of nano clay on the impact response |
| [13] | 3D Carbon/epoxy composites | 16 | 5.41 | 100 | Influence of the structural defects on the LVI damage mechanism |
| [46] | GFRP | 25.4 | 5.095 | 10, 25, 50 | Material thickness and impact energy influence on the residual flexural strength |
| [14] | Flax/carbon hybrid composite plates | 20 | 10.7 | 104 | Tensile, three-point bending, impact, water absorption property |
| [15] | Aramid/ epoxy Nano-composites | 12.7 | 10.3 | 16, 28, 40 | LVI response containing nano-interlayers with different thickness and stacking configuration |
| [16] | Carbon fibre composite with Methyl methacrylate | - | 7.86 | 25, 42, 52 | Low-velocity impact behavior |
| [17] | Glass/Kenaf Reinforced Epoxy Laminates | 16 | - | 3, 6, 9 | Low-velocity impact performance |
| [19] | Carbon–aramid/epoxy hybrid composite laminates | 12.7 | 6.5 | 26.8 | Low-velocity impact response of hybrid-laminate |
| [20] | Kevlar/polypropylene composites | 12 | 30 | - | Post impact response of different fabric architecture |
| [21] | CFRP | 14 | - | Up to 1.35 | Increase of the impact damage resistance by integrating a rubber layer |
| [28] | Carbon fiber reinforced polymer composite | 20 | 3.8 | 25,30 | Impact resistance with a negative Poisson ratio (NPR) with rubber protective layer and influence of cell angle and relative volume |
| [29] | Carbon/epoxy composite | 15.87 | - | 30 | Model to predict damage modes, locations, sizes, and damage |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | occurrence sequence |
| [50] | Carbon/epoxy composite | 16 | 4.3 | 32,42 | Model for LVI and CAI response of 3D woven layer-to-layer |
| [30] | Glass- and carbon-reinforced polymer composite | 5,8,11 | - | 25-40 | Hybrid methodology based on evaluation of results of the ultrasonic non-destructive testing |
| [51] | Carbon fibre reinforced polymer composite | 16 | 5.745 | - | Performance considering design for all aspects from on-set of damage |
| [31] | Carbon fiber reinforced composite | 16 | 5.5 | 16,283 | Experimental and numerical investigations into the dynamic response |
| [32] | Glass/epoxy composite | 20 | 10.81 | 50, 150 | Impact performance with S-type fold core |
| [33] | Carbon fiber reinforced plastic laminate | 16 | - | 3 | Model by considering lamb weave sensing |
| [34] | Carbon fiber reinforced polymer laminate | 20 | 2 | - | Impact response and damage mechanism under different rubber layer thickness and impact levels |
| [35] | Carbon/epoxy composite | 16 | 5.449 | 21.6, 47.6 | LVI damage of 3D considering different off-axis angles and impact energies |
| [36] | Carbon fiber composite laminate | 16 | 5.5 | 30 | A full-scale model for predicting LVI damage and CAI strength |
| [37] | Carbon-epoxy composite | - | 5.067 | 10 | Dynamic mechanical response and damage mechanism characterization under single and repeated LVI by considering the thickness effect |
| [38] | Carbon fiber reinforced composite | 16 | - | 30, 50, 60 | Numerical model for predicting the LVI resistance and tolerance of multi-directional laminates made of non-crimp fabric |
| [39] | Carbon fiber reinforced plastic composite | 16 | 5.565 | 4, 6, 8, 10 | Experiments and simulations with on-edge impact and compression after edge impact (CAEI) |
| [40] | Glass fiber reinforced polymer | 16 | 5.61 | 9.79,12.19,15.07 | Fatigue-driven residual strength model |
| [41] | Carbon/graphite reinforced composite | 25.4 | 5.439 | 15,35 | Simulation of the damage during an and prediction of remaining compression strength |
| [47] | 3D Braided Composite | 12.7 | 6.441 | 3.22, 12.88, 28.98, 51.53, 115.94 | LVI response and failure mechanism of 3-D braided composite |
| [42] | Hybrid (Kevlar, carbon, glass fabric reinforced) epoxy composite | 12.5 | 3.5 | - | Energy absorption due to LVI on non-hybrid and hybrid composite |
| [43] | Carbon fiber reinforced epoxy composite | 12.7 | 3.2 | 4.5, 7.5, 10.5 | Behavior of continuous polymer matrix composites |
| [44] | Carbon/glass fiber reinforced epoxy composite | 19.2 | - | 42.9, 54.9, 66.9, 78.9 | Synergistic effect of 3D orthogonal woven structure and asymmetric structure on impact response |

| | | | | | |
|---|---|---|---|---|---|
| [45] | Carbon and glass reinforced composite | 16 | 2 | 25 | Simulation and analysis of the low-velocity impact behavior and impact resistance |
| [52] | Carbon fiber reinforced composite | - | 2 | 6.7,16 | Effect of carbon nanotubes (CNTs) on the impact response |

### *2.3 LVI Induced Damages and Evaluation Methods*

#### *2.3.1 Damage types*

Impact leads to various types of damage in composites shown in Figure 4 which are caused by different stress components, namely bending, membrane, and contact stresses. These stresses cause different types of failure manifesting them as damage. These damages are often relevant in the field of maintenance and also affect the residual strength of a part resulting failure or lose of structural integrity. Furthermore, impact-induced damages can consist of macro and micro damages which can be sub divided into level of delamination, fibre, matrix and fiber-matrix coupled (Figure 7). Moreover, some damages are also not visible barely. So, the exact sequence of events for forming damages is difficult to ascertain because of the large number of parameters involved and the small duration of the phenomenon. However, in general damage occurrences in four stages with each absorbing different amounts of impact energy:

i) Localized contact damage dependent upon the magnitude of impact forces,
ii) Internal delamination due to the transverse shear stresses or strains,
iii) Matrix and fiber failure due to the compressive bending strains on the impact face, and
iv) Matrix fracture or fiber breakage caused by tensile bending strains on the lower face.

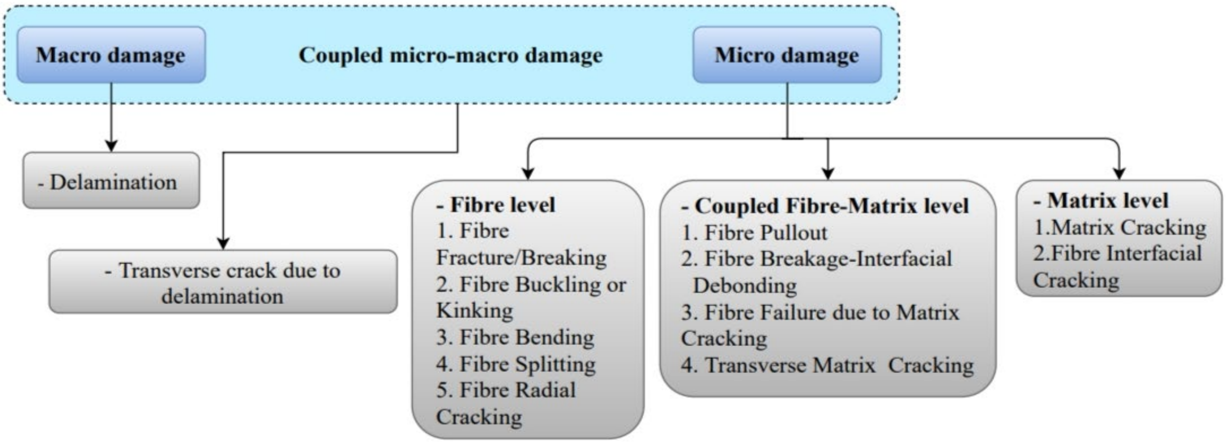

**Fig. 7.** Types of damage in composite structures [53]

Researchers identified and categorized different types of induced damages (Figure 8) for different composites which are originated and propagated by low velocity impact among the shown types of damages in Figure 7. Literature shows the following prospective damage types caused by LVI listed in Table 7. More precisely it can be stated that the prominent modes of damages caused by LVI are matrix mode, delamination mode, fiber mode and penetration (Figure 9). Among them the most profound mode is delamination.

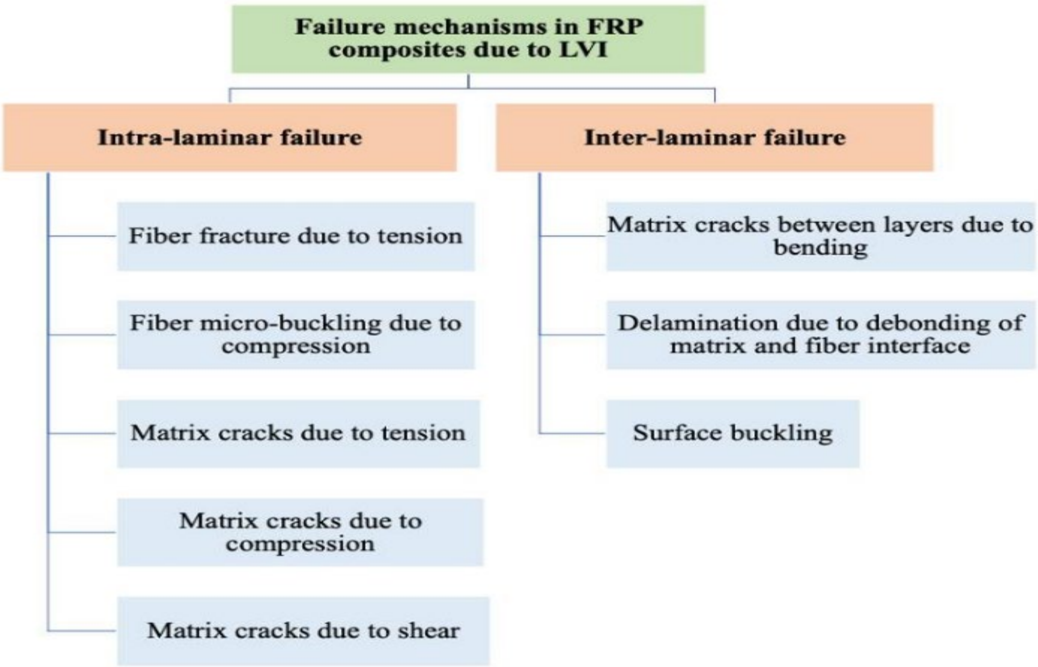

**Fig. 8.** Types of failure in FRP composites subjected to LVI [7]

**Table 7**
Prospective damage types due to LVI (cross ref.) [54]

| Sl. No. | Types of Damage |
|---|---|
| 01 | Delamination |
| 02 | Fiber Pull Out |
| 03 | Matrix Cracking |
| 04 | Damage/Dent at the location of Impact |
| 05 | Surface Buckling |
| 06 | Fiber Matrix Cracking |
| 07 | Inter-laminar Damage |
| 08 | Surface Buckling |

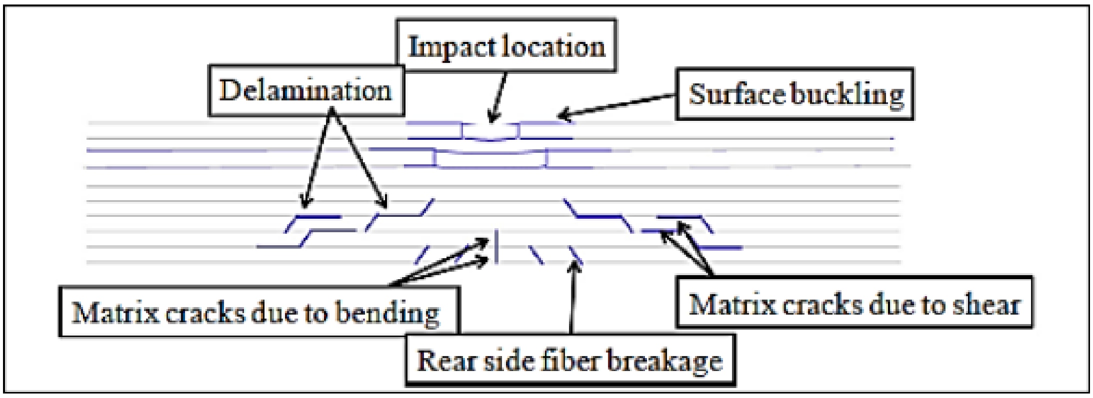

**Fig. 9.** Damage due to LVI and its internal structure [55]

### *2.3.2 Damage evaluation methods*

Different reliable damage detection and monitoring techniques shown in Figure 10 are employed to avoid such damages and failures. Among them non-destructive testing (NDT) is one of the most common methods in which the damages are identified and characterized without cutting or modifying the material [56]. In previous researches, various NDT techniques have been employed to detect damage in composites to evaluate manufacturing defects or delamination caused by impact. Among them acoustic emission is used to monitor the formation and growth of damage, specifically for fiber fracture; thermography and thermo-elastic stress analysis is used to correlate damage and surface strains. These methods have limitations regarding type, size and orientation of damage in simultaneous nature; fine-scale failure events (e.g., fiber/matrix debonding), sensitiveness to certain types of damage (e.g., fiber fractures), detailed 3D representation of damage. In view of these, X-ray computed tomography (CT) is now a powerful technique to inspect the interior of a material for hidden flaws for multiscale (macro, meso, micro and nano-scale) imaging of composite architectures, manufacturing defects, and in-service damage [57].

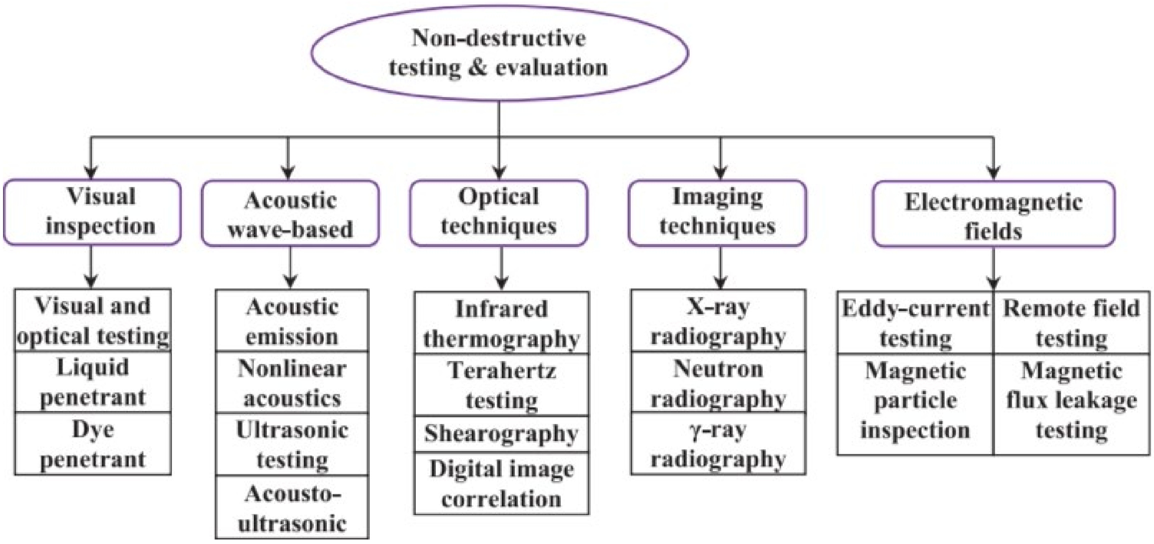

**Fig. 10.** Categories of non-destructive testing and evaluation techniques [58]

Again, depending on the type of damage and defects formed during manufacturing and in service life of composites different types of NDT techniques can be employed for fruitful assessment which is shown in the Figure 11. Apart from this; advantages, limitations, and ranges of applications of different NDT techniques including recent advancements in structural health monitoring of composite structures is reviewed [53]. Similarly, the application of different non-destructive testing and evaluation techniques of composite materials/structures are reviewed in [58] and for fiber reinforced composites reviewed [59]. Apart from this, some examples of applying damage evaluation method is presented in Table 8. Based on the existing literature it can be stated that X-ray computed tomography (CT), thermography and ultrasonic testing are the most appropriate NDT methods for damage identification in composite materials under LVI which are worked by applying short-wavelength electromagnetic radiation, providing images from thermal patterns on the surface of an object and studying the propagation of ultrasonic waves respectively.

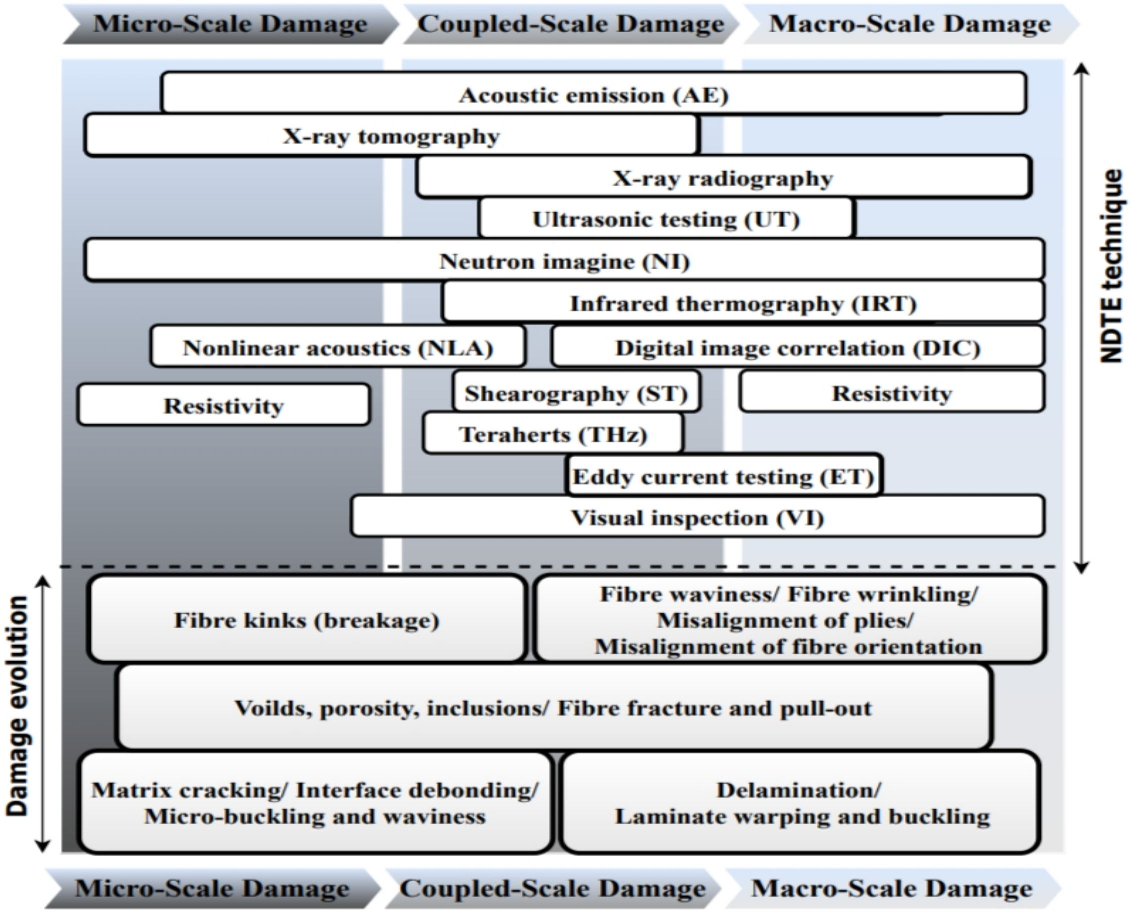

**Fig. 11.** Range of damage for NDT techniques application along with manufacturing damage evolution [53]

**Table 8**
Recent application of damage assessment method for FRCs

| Reference | Composite | Assessment Method |
|---|---|---|
| [9] | Flax/carbon fiber hybrid reinforced composites | Acoustic emission |
| [10] | Treated shear thickening fluid/3D glass fabrics | Fourier transform infrared spectroscopy |
| [11] | 3D CFRP composites | Micro-computed tomography |
| [12] | CFRP filled with Nano clay | Field-emission scanning electron microscopy |
| [13] | 3D Carbon/epoxy composites | X-ray micro-computed tomography |
| [15] | Aramid/ epoxy nano-composites | Scanning electron microscopy |
| [16] | Carbon fibre composites with Methylmethacrylate | Data acquisition system |
| [19] | Carbon–aramid/epoxy hybrid composite laminates | Ultrasonic C-scan |
| [20] | Kevlar/polypropylene composites | Data acquisition system |
| [22] | Ultrahigh Molecular Weight Polyethylene | 3D-topographies |
| [23] | 3D Woven composites by Carbon and S2 Glass | X-ray micro tomography |
| [24] | Basalt and nylon intra-ply hybrid composites | Visual inspection and ultrasonic C-scan |
| [25] | E-glass composite | Photographic analysis |

### *2.4 Performance Parameters*

The performances of FRCs under low-velocity impact are investigated based on the following parameters which are achieved from experimental tests results.

#### *2.4.1 Impact force*

The seemingly straightforward concept of impact force, generated by the collision of two objects, reveals a captivating world of intricacies when applied to fiber-reinforced composites (FRCs). It can be defined as the generation of impact force resulting from the collision of two objects is a transient force characterized by a brief duration. This force is intricately tied to the relative velocity of the colliding objects, a parameter directly proportional to their motion. Upon collision, one object typically absorbs the majority of the impact, undergoing deformation and subsequently dissipating the energy in the form of heat or other forms of energy release [60]. While its influence depends directly on the relative velocity of colliding objects, the true story lies in the complex interplay of material properties, fiber matrix interactions and properties, damage mechanisms, testing methods, and environmental factors. Studies show a direct correlation between impact energy and the location of damage [61], with carbon/epoxy laminates often succumbing to partial penetration and back-face splitting [27]. However, material composition paints a nuanced picture. A five-ply PSTF-impregnated composite, for instance, absorbs more impact force than its TSTF counterpart under the same mass fraction, while a 3D glass fabric with TSTF impregnation exhibits a lower peak force [10]. This highlights the critical role of fiber-matrix interactions and their influence on energy dissipation. Further complexities emerge when considering the relationship between force and deformation. While impact force generally increases with increasing impact energy [12], increasing toughness and maximum displacement can lead to reduced peak force under low-velocity impacts [15]. This trade-off underscores the importance of considering not just absolute force values, but also the material's ability to absorb and distribute energy. Material type also plays a significant role. Glass/epoxy composites often exhibit high peak load with minimal displacement, while kenaf/epoxy display the opposite behavior [17]. Bio-fiber reinforced composites like BFRPs, with their inherent toughness, often outperform their carbon counterparts [62]. Additionally, hybridization within the composite itself influences response. Non-hybrid carbon/epoxy laminates generally exhibit the highest peak load, while non-hybrid aramid/epoxy laminates show the lowest [19]. Testing methods also require careful consideration. Load responses, captured in terms of peak load and maximum displacement, can be highly accurate, with reported errors less than 5% [63]. However, parameters like fiber volume fraction can significantly impact peak load, with a 10% increase leading to a 2.28-fold increase in peak load for five-layered hemp/polyester composites [64]. Environmental factors further add to the complexity. The impact resistance and duration of abaca/epoxy composites, for instance, are higher than their abaca/rubber hybrid counterparts, while the impact energy of the hybrid is higher [65]. This suggests that the properties of the matrix phase, particularly its rubberiness, play a crucial role in both energy absorption and damage resistance [11,16,21]. Hybridization itself can complicate the picture. Composites with a bilinear ductile stress-strain curve and high strain to failure often exhibit the lowest impact energy [66]. Additionally, thick-ply arrangements tend to absorb less impact energy compared to thinner ply configurations [49]. In summary, the seemingly simple concept of impact force in FRCs unveils a captivating world of intricate relationships and complex material interactions which is dictated by constituent properties and interfacing. Load histories can be modeled with reasonable accuracy. Hybridizing with ductile components and reducing ply thickness are potential routes to enhance impact performance. Understanding these complexities, including the influence of material composition, environmental factors, and testing methods, is paramount for the rational design of impact-resistant composites and the development of reliable engineering solutions. This journey beyond the raw numbers of force and displacement (typical diagram shown in Figure 12) unveils the true story of how FRCs respond to impact, paving the way for innovative materials that can withstand the demanding realities of engineering applications.

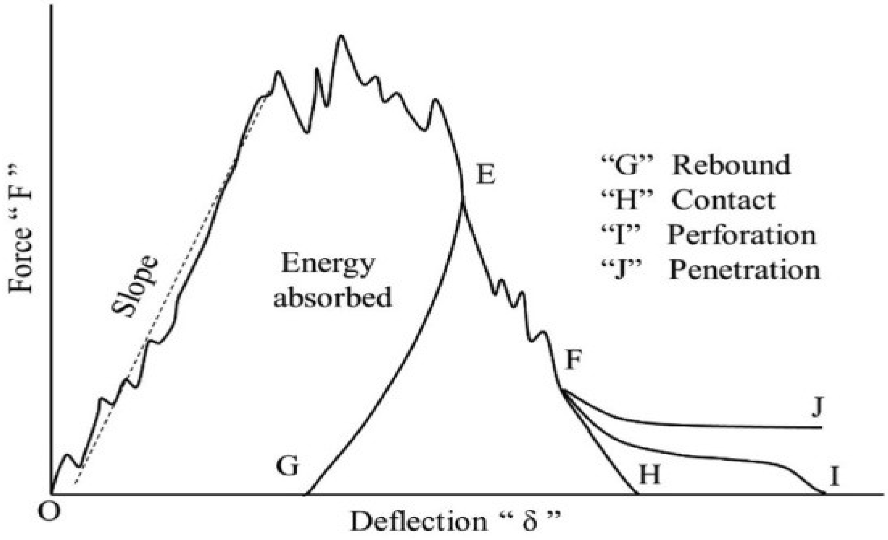

**Fig. 12.** Typical schematic diagram of force versus deflection or displacement [67]

### *2.4.2 Energy absorption*

Energy absorption is defined as the energy absorbed per unit mass of material. Energy absorption emerges as a critical determinant of structural safety under impact, quantified as the surface beneath the load-displacement curve (refer to Figure 12). Energy absorption f FRCs under low-velocity impact is reviewed and summarized below with respect of materials and mechanics, impact, force, hybridization.

### *2.4.2.1 Materials, mechanics of impact energy absorption*

Impact energy absorption in fiber-reinforced composites (FRCs) reveals an appealing symphony of material properties, mechanical responses, and diverse failure modes. This complicated interplay dictates the way FRCs responds to impact, shaping their ability to withstand and dissipate energy. Studies highlight the intricate interweaving of forces at play. While impact energy and absorbed energy often exhibit a linear relationship, the correlation between impact energy and specific failure modes adds another layer of complexity [31]. This suggests that different materials not only absorb energy differently but also experience distinct damage patterns under impact. For instance, most hybrid composites tend to absorb more energy than their reinforced counterparts, demonstrating the synergistic effect of combining different fiber types [45]. However, this comes at a cost, as evidenced by flax specimens absorbing more energy but also exhibiting greater damage extension at lower energy levels compared to glass/flax composites [68]. Material selection further enriches the performance spectrum. Studies show that CF/PEEK consistently outperforms CF/Epoxy in terms of impact resistance under low-velocity impacts [43], highlighting the influence of matrix materials on energy dissipation. Similarly, Kevlar-based composites showcase a fascinating interplay of fiber arrangement and energy absorption. K/K/K composites boast the highest absorption potential compared to G/G/G and K/G/K, while three-fabric hybrids underperform compared to neat Kevlar and two-fabric sandwich composites [69]. This tricky arras of fiber combinations and their arrangement within the laminate underscores the importance of considering not just individual fiber properties but also their synergistic effects. Again, regarding stacking sequence a study involving basalt and Kevlar composites, the H-1 composite, featuring an alternating layer arrangement, absorbed more energy than both the Kevlar polypropylene and H-2 composites with contrasting stacking sequences [70]. This underlines the critical role of fiber placement in optimizing energy dissipation pathways within the composite structure. In summary, complex interplay of material choices, failure modes, and energy dissipation mechanisms plays a vital role for tailoring FRCs to withstand diverse impact scenarios, paving the way for innovative materials that excel in both energy absorption and damage resistance. This journey beyond the simple numbers reveals the true story of how FRCs respond to impact, opening doors to engineering solutions that can thrive in the face of real-world challenges.

#### *2.4.2.2 Impact and energy absorption*

Energy absorption plays a vital role in protecting structures under impact conditions. It is quantified by the area under the load-displacement curve shown in Figure 13 and depends on parameters like average load, specific energy absorption, and volumetric energy absorption. Studies highlight the diverse roles of material properties [71]. Under low-velocity impact, while basalt (100B) exhibits the highest maximum force, nylon (100N) boasts the lowest; showcasing the unique mechanical signatures of different fiber types. This underscores the importance of considering the material's inherent response to impact. Furthermore, the trend of total absorbed energy can diverge from that of elastic energy, indicating distinct mechanisms at play in energy dissipation [24]. Hybrid composites often hold promise for enhanced energy absorption. FCFCF and CFFFC flax-carbon hybrids, for example, outperform non-hybrids by 13.25% and 28.89% respectively demonstrating the synergistic effect of combining fibers [14]. Similarly, 3D fiber-oriented laminates consistently outshine their 2D counterparts, regardless of reinforcement type, highlighting the influence of fiber architecture in distributing and dissipating impact energy [23]. Within material categories, further nuances emerge. Single-ply 3D orthogonal woven fabrics exhibit superior energy absorption compared to unidirectional or 2D plain-woven fabrics due to efficient stress transfer between yarn orientations in the matrix [22,25]. However, the incorporation of nano clay or nano-fibers can surprisingly decrease impact energy absorption [12,15]. Beyond material composition, processing and configuration play a vital role. Increasing fiber volume fraction can significantly boost total energy absorption [64], while stacking sequence influences the dynamic response of composite plates [58]. Environmental factors also contribute to the complexity. Cavitation within the composite before major failure can significantly contribute to energy absorption [16]. and matrix type can influence energy dissipation, with flax-MAPP composites exceeding epoxy-based ones in perforation resistance [72]. In summary, multiscale design factors ranging from materials selection to topological arrangements govern energy absorption under impact, necessitating integrated modeling-experimental efforts to significantly improve tolerance.

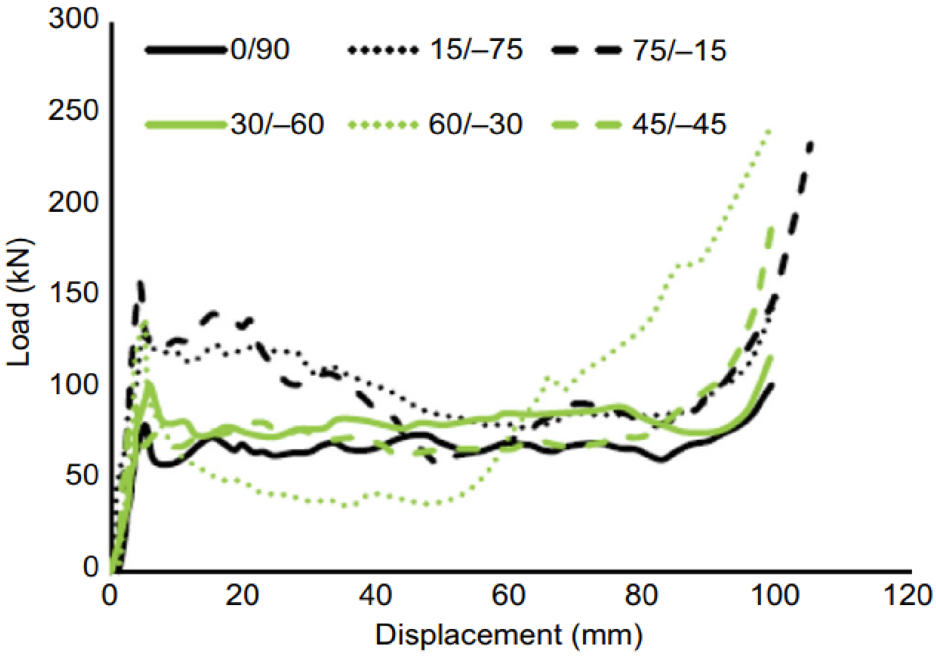

**Fig. 13.** Typical average load-displacement curves for each fiber orientation of the composite tubes tested using quasi-static crushing tests [71]

### *2.4.2.3 Force and impact energy absorption*

The relationship between impact force and energy in fiber-reinforced composites (FRCs) depends on the combination of different factors i.e., applied force, energy absorption, and damage progression. Studies illuminates that impact energy and peak force generally share a positive correlation, but the threshold load, marking the onset of significant damage, often remains remarkably constant even as energy levels rise [51]. This suggests a critical force level beyond which energy absorption accelerates, while initial impacts may cause little visible surface damage [73]. Further complicating the equation, projected residual strength mesas beyond a certain impact energy (BVID), even as energy levels continue to climb [51]. These interesting findings underscore the material's ability to absorb and dissipate damage, maintaining a degree of structural integrity. Hybrid structures introduce a further layer of complexity. As impact energy increases, both the threshold load and energy absorption of hybrid structures typically tend to rise [34]. This suggests a synergistic effect, where different material components work together to distribute and dissipate energy more effectively. However, higher energy comes at a cost. Increased energy levels typically lead to a greater peak force, a shorter impact duration, and more severe interlaminar damage within the composite [74]. Even the location of impact plays a role. Low-energy impacts at nodal points on a composite sandwich structure can trigger localized crushing damage, which, despite consuming high energy, leads to efficient energy absorption [32]. This highlights the importance of considering not just overall force and energy, but also the specific damage mechanisms at play. In summary, the relationship between force and energy in FRCs under low velocity impact depends on complex material interactions, dynamic damage progression, and complex energy dissipation mechanisms.

### *2.4.2.4 Hybridization and impact energy absorption*

The notion of simply combining different fibers in an FRC to maximize impact resistance is challenged by the intricate interplay of material interactions and energy dissipation mechanisms. While hybridization offers potential benefits, its impact on energy absorption reveals a fascinating dance of synergy and trade-offs. Studies highlight the nuanced effects of fiber combinations. For instance, the hybridization of flax and carbon fibers can minimize impact energy absorption in non-perforation events, despite the higher energy dissipation capacity of carbon plies compared to flax [74]. This suggests a complex interplay between fiber properties and their arrangement within the composite, where the flax fibers might act as a sacrificial layer, mitigating damage to the more energy-absorbing carbon plies. Similarly, incorporating carbon nanotubes (CNTs) into the laminate can enhance overall impact energy absorption compared to pure fiber composites [75]. This underscores the potential of nano-materials to improve energy dissipation mechanisms, although the specific effects depend on their orientation and volume fraction within the composite. Again, laminate thickness also plays a crucial role. Thinner laminates tend to scatter impact energy through intra-laminar damage, while thicker ones absorb energy primarily through delamination under the same impact conditions [37]. This suggests a trade-off between energy dissipation mechanisms and plate thickness, with thicker laminates potentially offering increased energy absorption but also suffering from more severe damage modes. Furthermore, the impact of repeated loading adds another layer of complexity. Unlike the initial impact, subsequent impacts can lead to a reduction in energy absorption due to changes in plate thickness and dominant damage modes [37]. This highlights the importance of considering the cumulative effects of impact in real-world applications. Finally, the stacking sequence within the composite can significantly influence its dynamic response to impact [76].This emphasizes the need for careful design and optimization of the entire composite system, considering not just individual fiber properties but also their arrangement and interaction within the laminate. In summary, the relationship between hybridization and impact energy absorption in FRCs is a complex issue which depends on material interactions, energy dissipation mechanisms, and environmental factors. Understanding these is crucial for to optimize energy absorption while minimizing damage and ensuring long-term structural integrity.

### *2.4.3 Force and displacement under impact*

Force and displacement have been considered as important parameters to assess mechanical properties of composites which are presented in Figure 12. Studies highlight the diverse roles these parameters play. While impact energy often exhibits a linear relationship with maximum displacement, particularly for CFRPs with protective layers [28,31]; the response of peak force to velocity, time, and displacement can vary depending on the material and configuration. Hybrid structures, for instance, tend to exhibit an increase in both maximum displacement and impact energy as the impact energy increases [34]. However, this trend may not hold true for all hybrid configurations, as evidenced by the unique behavior of CCCG laminates [45]. Beyond simple trends, the location of impact also plays a crucial role. Localized loading under impactors can produce larger deflections compared to distributed loading [78]. Similarly, material properties like the inclusion of CNTs can significantly influence peak force, with CNT-reinforced composites exhibiting higher peak forces compared to their neat counterparts [75]. Auxetic laminates, with their unique negative Poisson's ratio, showcase a fascinating behavior, exhibiting consistently reduced maximum displacements at elevated impact energies [79]. The impact history of the material also adds another layer of complexity. Repeated impacts can lead to increased peak force and maximum displacement, with the extent of this increase depending on the plate thickness [37]. Additionally, the relationship between velocity and displacement is not static, with increasing velocity leading to larger thickness displacements [47]. This highlights the importance of considering not just the material itself but also its configuration and interaction with other materials within the composite structure. Finally, even the stacking sequence within the composite can significantly impact its resistance to impact. Studies have shown that K/K/K Kevlar-based composites outperform other configurations in terms of impact resistance, showcasing the importance of optimizing the arrangement of fibers within the laminate [69]. In summary, the force and displacement responses of composites under impact depend on parameters including energy, velocity, indentor geometry, stacking sequence, hybridizing, and introducing auxetic or nano-scale features. Tailoring these factors enables tuning sensitivity to damage initiation and energy absorption across service conditions.

### *2.4.4 Impact resistance beyond material choice*

The magnetism of fiber-reinforced composites (FRCs) lies in their strength and lightness, but their true test lies in their ability to withstand the unforgiving realm of impact. Studies highlight the delicate interplay between material properties and impact resistance. Natural fiber composites, for instance, fall short compared to their glass counterparts due to the inherent limitations of their fiber strength [80]. Similarly, the brittleness of carbon fibers translates to poorer impact resistance compared to the resilience of basalt/glass hybrids [81]. However, this simplistic narrative is further complicated by the nuanced world of hybridization and configuration. Beyond just the constituent materials, the type of hybridization and stacking sequence play a critical role. While K/G/K hybrid composites offer a compelling 21% reduction in material cost compared to the K/K/K configuration, they also showcase superior impact resistance and energy absorption [42]. This underscores the importance of optimizing the synergistic effects of different fibers within the laminate. Further complexities arise when considering the influence of impact parameters. Increasing impact energy often pushes the material beyond its threshold load, necessitating protective layers to enhance energy absorption and prevent catastrophic failure [28]. Similarly, the impact response of GFRPs is highly sensitive to both thickness and the level of impact energy [82]. This emphasizes the need for tailoring the FRP architecture to match the specific demands of the anticipated impact scenario. Intriguingly, even the location of fiber placement within the laminate can significantly influence impact resistance. Replacing the glass fiber on the non-impacted side with stiffer and stronger carbon fiber has been shown to enhance energy-absorbing capacity and penetration threshold, highlighting the potential of strategic material distribution [44,74]. In summary, the enigmatic performance of FRCs under impact reveals itself as a captivating tapestry woven with intricate material interactions, environmental factors, and configuration nuances.

## *2.5 Post-impact Damages*

After the impact test in specific conditions, the specimen is visually as well as non-destructively inspected for internal and surface damages (e.g., SEM images of failure mechanisms in Kevlar, carbon, and glass hybrid composites shown in Figure 14). There are different techniques of non-destructive tests (NDT) are applied by the researchers to assess the post-impact damage of FRCs under low-velocity which are reviewed below.

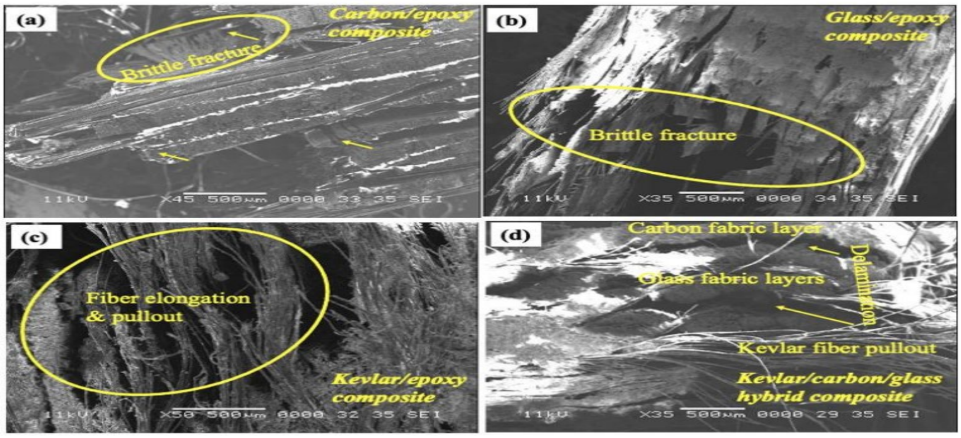

**Fig. 14.** SEM images of failure mechanisms in Kevlar, carbon, and glass hybrid composites [7]

### *2.5.1 Damage mechanisms and influences*

The damage diagnostics are typically the correlation between mechanical properties and applied loading. Previous research has categorized various types of damage, like delamination, matrix cracking, fiber breakage, and fiber-matrix debonding [42,83,76], a closer look reveals a dynamic interplay between these mechanisms, influenced by a multitude of factors. Delamination reigns as the most common culprit, often intertwined with a reduction in energy absorption and load-bearing capacity [84]. However, its behavior exhibits intriguing complexities. Studies suggest a linear relationship with impact energy and location-specific patterns [61]. Damage distribution can be symmetrical, circular around impact zones, or even morph into zigzag patterns at higher velocities [11,36,47]. Adding another layer of intricacy is the temporal sequence of damage. Matrix cracks often precede fiber breakage, typically initiating in the 90° layer and propagating upwards with increasing impact energy [12]. This sequence, coupled with the interplay of tensile and compressive damage modes, shapes the overall failure behavior of the composite [28]. Material choices and design configurations significantly influence the type, severity, and location of damage. 3D braided composites without defects, for instance, exhibit higher damage volumes compared to their defect-free counterparts [13] . Similarly, the type of fabric used in hybrid structures can impact damage patterns, with carbon fabric exhibiting smaller average damage areas than aramid fabric [19]. Even seemingly minor details like fiber angle, stitching presence, and stacking sequence can play a crucial role [12,20,85]. Material composition also plays a vital role. HFRPs, due to the presence of carbon fibers, exhibit more severe internal damage and reduced compressive strength compared to flax skin composites [86]. Similarly, the type of resin used can influence the damage profile, with studies suggesting better damage tolerance for epoxy resins compared to bismaleimide under impact [74]. Impact parameters like energy level further add to the intricacy. While most studies report an increase in damage area and volume with increasing energy, some materials exhibit a peak resistance at a specific energy level [11,17]. Understanding these non-linear relationships is crucial for optimizing material selection and design for specific applications. In summary, a range of progressive damage modes occur under impact with differing dominance and complex relationships to impact conditions. From which the complex relationships between diverse damage mechanisms, material properties, and impact parameters is paramount for designing impact-resistant FRCs that can withstand the challenges of real-world applications.

### *2.5.2 Damage resistance*

The consideration of damage resistance stands as a pivotal parameter in the preparation of composites for specific conditions or purposes, given their varied responses. Woven laminates, for instance, offer a shining example of superior resistance compared to their unidirectional counterparts. Their complicated, multidirectional weave pattern distributes and dissipates impact forces more effectively, resulting in smaller deformation areas and enhanced damage tolerance [81]. Again, adhesives play a crucial role in composite structures, but their own vulnerability can compromise overall resilience. Fortunately, research suggests that optimizing scarf angles, adhesive thickness, and patch off-axis angles can significantly resist adhesive damage and the dreaded delamination at the interface [87]. Another fascinating revelation concerns the thickness of individual plies. Studies demonstrate that thinner plies within a composite laminate lead to improved damage resistance [36]. This finding highlights the complex interplay between fiber distribution and stress concentration within the material while material composition also plays a significant role. The addition of carbon nanotubes (CNTs) to composite matrices has been shown to drastically reduce damage susceptibility [75]. These microscopic reinforcements act as energy dissipaters, effectively shielding the composite from harmful impacts. Lastly, the stacking sequence of layers within a laminate offers powerful levers for tuning damage resistance. Introducing ±45° layers within carbon fiber laminates, for instance, can significantly enhance the peak force the laminate can withstand while shrinking the total area of damage, absorbed energy, and damping index [45]. This issue of the internal architecture unlocks exciting possibilities for customized damage resilience. In summary, damage resistance in FRCs is far from a massive property. Recognizing the interplay between factors like laminate type, adhesive design, ply thickness, material composition, and stacking sequence empowers the specific applications. Here it may be further mentioned that, improvements in one aspect can adversely affect other performance metrics.

## *2.6 Factors Affecting Performances and Damages*

Different factors affect performances and damages of FRCs under low velocity impacts which are outlined in the Figure 15. Among them few factors affect only performances and few affect damages of FRCs. Again, few factors affect both performances and damages which is summarized and reviewed in this section.

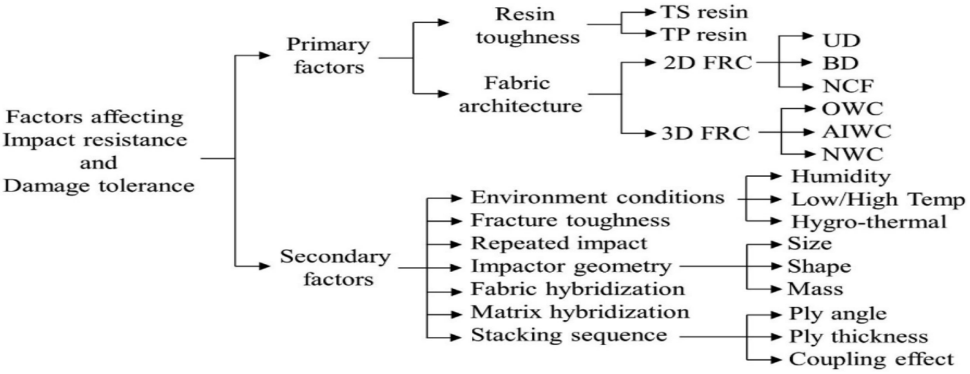

**Fig. 15.** Factors affecting impact resistance and damage tolerance of FRC [67]

### *2.6.1 Factors affecting performances*

The factors influencing damage in FRCs is crucial, a complete picture demands exploring those that enhance their performance under low-velocity impact. The intricate relationship between interfacial properties and impact performance offers a fascinating example. Studies suggest that adding 10% MAg-PP to PP improves the Kevlar fabric/PP matrix bond, while surprisingly, decreasing interfacial strength can lead to better impact performance [20,88]. This counterintuitive finding underscores the complex interplay between materials and highlights the need for precise optimization. Fiber surface modification, number of layers, and thickness have emerged as potent tools for improving the properties of kenaf/glass hybrid composites [89]. Similarly, incorporating nanoparticles can significantly enhance low-velocity impact strength [90]. These findings pave the way for exploring novel material modifications and configurations to unlock latent performance potential. Manufacturing processes also hold untapped potential. Modifying the BFRP production process has been shown to improve impact behavior [62], while silica modification and high-concentration TSTFs can bolster ballistic resistance in specific scenarios [10]. This emphasizes the importance of considering the entire value chain when engineering high-performance FRCs. The ability to tailor failure modes is another exciting avenue. Increasing the nylon/basalt fiber ratio, for instance, can shift the primary failure mode from fiber breakage to extended delamination, potentially increasing material resilience [24]. This knowledge empowers designers to manipulate FRC behavior for specific applications. Areal density normalization unveils further nuances. Studies reveal that 3D systems exhibit superior damage tolerance compared to their 2D counterparts, highlighting their potential for lightweight, impact-resistant structures [25]. Hybrid structures also offer captivating possibilities. Adding Kevlar to the face sheet of a composite can maximize absorbed energy and minimize post-impact strength reduction, even if elastic moduli decrease [26]. Conversely, incorporating S2-glass fabrics in the back surface can enhance impact response, while overall damage tolerance benefits from hybridization in general [27]. These findings showcase the synergy achievable through strategic material combinations. The choice of resin further adds to the mosaic of performance. Thermoplastic resins, for instance, are often favourable in applications demanding impact resistance, tolerance to damage, and overall performance [49]. This highlights the importance of material selection in optimizing FRC behavior for specific needs. In summary, property enhancements under impact are feasible spanning constituent tailoring to process innovations to architectural manipulations in composites. However, improvements along certain axes can detrimentally affect other performance metrics.

### *2.6.2 Factors affecting damages*

There are different factors like layer thickness, hybrid mode, reinforced fiber type, inclusion of other materials etc. which affect damages. Layer thickness, for instance, dances with impact energy to orchestrate the location of delamination in CFRP laminates [34]. By adjusting the rubber layer's thickness, we can influence the battleground where this crucial damage type takes root. Hybrid materials, where multiple fiber types join forces, offer a fascinating counterpoint. Studies reveal that hybridizing three fiber types allows the damaged area to undergo a larger deformation, distributing the stress and potentially delaying catastrophic failure [81]. This approach highlights the potential of synergy in mitigating damage. Through-thickness negative Poisson's ratio, a seemingly esoteric property, can also hold the key to damage mitigation. Research suggests that it consistently reduces matrix and fiber tensile damage in auxetic laminates, though its influence on delamination remains elusive [79]. This finding opens doors for exploring novel material properties to combat specific damage types. The interplay between compression and tension forces within the composite plays another captivating role. While fiber tension and compression lead to damage, matrix compression surprisingly exhibits minimal detrimental effects [77]. This point is to the importance of understanding the diverse responses of different material components to various loading conditions. The inclusion of carbon nanotubes (CNTs) adds another layer of complexity. While they initially reduce damage in composite plates, exceeding a critical threshold can lead to a sudden drop in impact tolerance, particularly concerning delamination [52]. This finding emphasizes the need for careful optimization to harness the benefits of CNTs without compromising resilience. Finally, the very orientation of fibers in 3D woven composites dictates the directionality of impact damage. Studies show that damage typically initiates at the bottom of the impacted area and expands outwards and upwards, influenced by the loading direction and weft or warp orientation [35]. This knowledge empowers us to tailor the fiber architecture for specific applications, minimizing the vulnerability to damage in critical directions. In summary, impact damage progression depends on multiscale design factors ranging from layer thickness and hybridization to material properties and fiber orientation, each factor plays a crucial role in dictating the material's response to impact.

### *2.6.3 Diverse factors affecting performances and damages*

#### *2.6.3.1 Fiber constituents*

The appeal of FRCs lies in their remarkable strength and lightness, but true mastery lies in understanding the relationship between fiber content, performance, and damage. Research paints a captivating picture, revealing that altering fiber constituent levels unveils a symphony of consequences with each note dictating the material's resilience. Increasing carbon fiber content in HFRPs, for instance, shades a complex representation. While specific energy absorption (SEA) and permanent damage deformation rise, the impact load threshold unexpectedly plummets [86]. This seemingly paradoxical dance highlights the delicate balance between strength and brittleness inherent in high fiber concentrations. Fortunately, studies offer a guiding rhythm. Optimizing fiber content and orientation can unlock the full potential of FRCs, leading to significantly higher impact strengths [89]. The mantra seems clear: find the sweet spot in the fiber volume waltz to maximize both load-bearing capacity and resistance to damage. Material composition further adds to the melody. FRPs impregnated with short-fiber thermoplastic (STF) materials exhibit superior performance under impact [91]. This secret lies in the increased surface area exposed to the hammer striker, allowing for more efficient energy dissipation and minimizing concentrated stress points. Ultimately, fiber volume acts as the conductor of this intricate orchestra. Higher concentrations prolong the contact time with the impacting object, boosting the peak load but also amplifying the damage propagation – a double-edged sword demanding careful consideration [64]. In summary, fibers govern key energy absorption modes and damage progression in composites under transverse impact loading. Improving fundamental understanding of constituent-level dynamics and interactions with parameters like content, orientation, length/diameter ratios, and hybridizing is essential to predict mechanisms linked microstructure-manufacturing-property relationships.

#### *2.6.3.2 Miscellaneous*

Different factors affect performance and damages of FRCs under low-velocity impact. Like-material properties, thickness, type of fibres, hybrid nature, fiber constituents, orientation, layer etc. Researches on the mentioned factors revealed that, material properties and laminate thickness emerge as the first brushstrokes on this canvas, dictating the dynamic response to impact forces in which projectile characteristics like weight, shape, and incident angle add another layer of complexity, demanding careful consideration during design [5]. Next, the interplay of fiber selection reveals fascinating possibilities. High-strength synthetic fibers reign supreme in terms of both performance and damage tolerance, often outshining their single-fiber counterparts [90]. However, hybrid composites, like kenaf reinforced with glass fiber, unlock a symphony of enhanced performance beyond what individual fibers can achieve [89]. Furthermore, the strategic manipulation of fiber orientation and layer count within hybrid laminates allows for further fine-tuning of absorbed impact energy, empowering engineers to tailor the material response for specific needs [49]. Environmental factors, too, leave their mark. Excessive water uptake, temperature fluctuations, and fiber chemical composition changes can undermine the delicate dance between fiber and matrix in plant-based fibers, impacting interface strength and ultimately leading to performance degradation [92]. Similar nuances dictate the impact behavior in rubber-composite systems. Softer rubber compounds, for instance, offer superior damage resistance, while the tolerable impact energy can vary significantly depending on the position of the rubber ply within the laminate [21,65]. Delving deeper, the intricate interplay between fiber type, fiber-matrix interface strength, and laminate thickness reveals its influence on low-velocity impact resistance [93]. Yet, intriguing findings emerge – flax and cotton stitched composites, despite differing stitch type and thickness, exhibit surprisingly similar impact responses [85]. This highlights the importance of not only considering individual factors but also understanding their complex interactions. Finally, the burgeoning realm of 3D-woven composites adds another dimension to the tapestry. Here, z-yarns act as invisible threads, reinforcing structural integrity and promoting deeper indentation during impact. 3D-O woven composites with S2 glass fibers and PE binders showcase superior performance in terms of maximum load and energy dissipation, leaving their 2D counterparts lagging behind [22,23]. In conclusion, a multiplicity of factors spanning hierarchical material structure, processing history, and testing conditions dictates impact response and damage in composites.

### *2.7 Numerical Models with Simulation*

Numerical modeling with simulation is one of the reliable and popularly used approaches to validate the existing theory of practice in research findings. As simulation method is one of the widespread approaches nowadays to find the best possible solutions to researchable engineering problems to minimize the time and save the cost as well. Researchers investigated the low-velocity impact and induced damages of fiber-reinforced composites by simulation techniques to predict the appropriate composite materials' properties. In composite research number of modeling approaches through finite element analysis (Typical FEA model of carbon fiber composite laminates with rigid impactor shown in Figure 16) are applied combined with simulation (shown in Table 9 and Table 10 respectively) by the researchers which are reviewed in contrast to the present study. According to Table 9 the most used mechanics of damage are cohesive zone technique and continuum damage technique effectively predict matrix cracking or splitting and appropriately capture the damage process and eventual damage extent under low velocity impact loadings respectively. Furthermore, ABAQUS is mostly used software for finite element analysis by Hashin and Puck model.

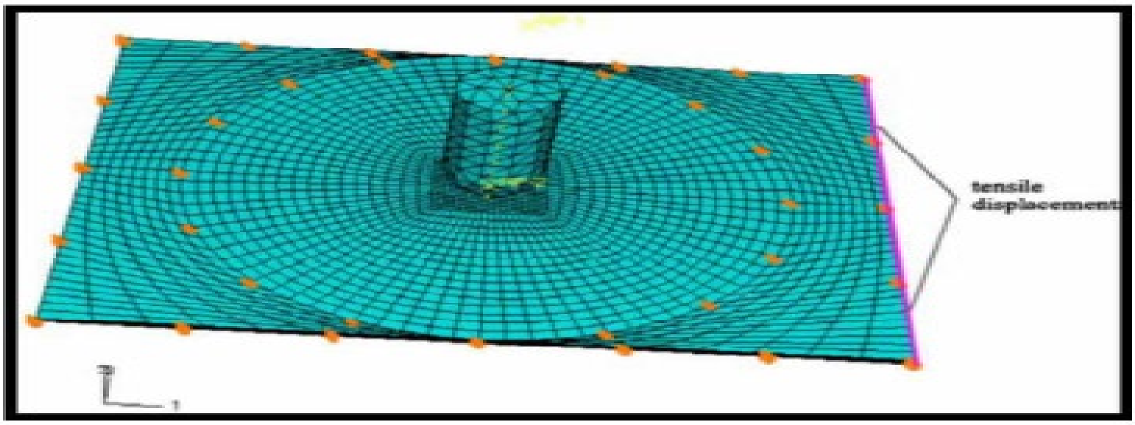

**Fig. 16.** Typical FE model of carbon fiber composite laminates with rigid impactor [48]

**Table 9**
Damage model deployed for FEA

| Reference | Composite | Software | Model/Criteria |
|---|---|---|---|
| [50] | Carbon/epoxy composite | ABAQUS/Explicit | Intra-laminar damage model |
| [29] | Carbon/epoxy composite | ABAQUS/Explicit VUMAT | Continuum damage mechanics (CDM), 3D Hashin Criteria, cohesive zone model (CZM) |
| [28] | Carbon fiber reinforced polymer composite | ABAQUS/explicit VUMAT | Puck damage model |
| [31] | Carbon fiber reinforced composite | ABAQUS/Explicit | 3D Hashin failure criterion |
| [32] | Glass/epoxy composite | ABAQUS/Explicit- VUMAT | 3D progressive damage model |
| [37] | Carbon-epoxy composite | ABAQUS (Explicit) VUMAT | Cohesive zone model |
| [38] | Carbon fiber reinforced composite | ABAQUS Explicit | 3D Hashin failure criteria, surface-based cohesive behavior |
| [39] | Carbon-fiber reinforced plastic composite | ABAQUS/Explicit | Continuum shell elements, Hashin failure criteria |
| [40] | Glass fibre reinforced polymer | ABAQUS/Explicit | Fatigue progressive damage model |
| [41] | Carbon/graphite reinforced composite | Abaqus explicit solver | Impact model |
| [43] | Carbon fibre reinforced epoxy composite | Abaqus/Explicit 2018 | Hashin’s 2-D theory |
| [45] | Carbon and glass reinforced composite | ABAQUS-VUMAT | Progressive damage model, cohesive zone model |
| [52] | Carbon fiber reinforced composite | ABAQUS/Explicit | Hashin’s criterion, cohesive zone model |

**Table 10**
Simulation information for FEA

| Reference | Meshing node | No. of element | Element Size (mm) | Friction Coefficient |
|---|---|---|---|---|
| [50] | 8-node C3D8R (ply) | 45000 | 1 | 0.3 |
| [31] | 8-node C3D8R (layer) | 327840 | 0.5 | 0.2 |
| [32] | 3D solid C3D8R (layer), S4R (impactor) | - | 0.5 × 0.5 × 0.25 | 0.2 |
| [35] | 4-node C3D4(ply), 8-node C3D8R (impactor, base) | 971670 (ply), 1280 (impactor), 380 (base) | - | - |
| [37] | 8-node C3D8R(ply), COH3D8 (inter layer damage) | 53792 (ply), 47608 (inter-layer damage) | 0.8 x 0.8 | - |
| [39] | 8-node SC8R (ply) | 32 | 0.5 | 0.3 |
| [40] | 3D C3D8R (ply), R3D4 (impactor), C3D8R (base) | 56259(ply),1726 (impactor),6738(base) | 0.1 | - |
| [41] | 4-node SC8R (ply), 10-node 3D C3D10(indenter) | 83000 | 1 x 1 | - |
| [43] | Continuum shell (layer) | - | 1 x 1 | 0.25 |
| [45] | 3D 8-node C3D8R (ply), 3D 4-node R3D4 (impactor) | Carbon=82889, Glass=48000 | (1.2×0.9×0.5), (1 × 1 × 0.8) | - |
| [52] | 3D 8-node SC8R (ply) | 8064 | 0.5 | - |

### *2.7.1 Predictive models for impact behavior*

Predicting the mechanical and impact performance of FRCs under low-velocity impact has long been an attractive field for researchers. Researchers have worked on different models, each striving to capture the relationship between mechanical properties and impact response. The review of this part aims to unveil the strengths and limitations of these models, paving the way for more accurate and reliable predictions. One set of models, exemplified excel at predicting fatigue life after impact, demonstrating a strong correlation with experimental data [40]. However, dynamic simulations, while capturing the general load-time response, often struggle with accurately portraying flexural stiffness [94]. Similarly, discrepancies between simulated and measured load-carrying capacity can arise, as observed in previous study, where predicted values fall slightly below experimental results [82]. Other models focus on validating force and displacement graphs, offering valuable insights into the laminate's response under varying impact energies and boundary conditions [95]. These parametric studies provide a deeper understanding of how different factors influence the material's behavior. Simplifying the numerical model can also yield benefits, as demonstrated in previous study. By neglecting the delamination failure mode in FFRPs, the model becomes computationally efficient while still providing reliable energy absorption predictions [80]. This highlights the importance of finding the right balance between model complexity and accuracy. Multi-scale failure analysis methods, offer a promising avenue for capturing the intricate interplay between impact and CAI damage processes [74]. This approach holds significant potential for predicting not just the immediate impact response but also the long-term consequences of damage. Finally, models that focus on specific aspects of impact behavior, such as residual velocity prediction [69] or the response and failure mechanisms of 3D braided composites [47] , offer valuable tools for tailoring material design and optimizing performance for specific applications. In conclusion, the landscape of predictive models for FRC impact behavior is a vibrant mosaic of successes and challenges. While no single model reigns supreme, each contribution adds a valuable piece to the puzzle. By understanding the strengths and limitations of these models, researchers can continue to refine and develop new tools.

### *2.7.2 Numerical models for damages*

Numerical modeling has emerged as a powerful tool for predicting and understanding the complex relationship between impact forces and induced damage. The failure or damage criteria or model for composites can be ordered in various ways. The first is whether they are based on the fracture mechanics bearing in mind initiation and propagation of the failures/damages in a macroscopic or microscopic scale or whether they are founded on strength theories. Another option is to divide based on the fact that they are applied to a global, complex failure, or only for a specific failure mode. The literature provides many theories only the most popular criteria will be introduced here which are shown in Table 11 and Table 12. Furthermore, there is no fixed theory that considers all of the factors and mechanisms common in composites. This fact leads to the blend of various models that predict their fracture or damage behavior [96]. So, this review aims to critically analyse the current landscape of such models, highlighting their strengths, limitations, and potential for future advancements. One of the most promising avenues lies in capturing the intricate interplay between lamb waves and impact damage. Models in studies by Chen *et al.,* [33] and Li *et al.,* [36] validate this approach, demonstrating accurate reproduction and investigation of various damage types. Another model, showcased in $^{o}$ne study, takes it a step further, simulating layer-by-layer damage progression with impressive accuracy (less than 10% error) across various parameters like matrix cracking, fiber breakage, delamination size, and overall energy dissipation [29]. Compacted fiber simulations also exhibit promising results. In study by Millen *et al.,* [50], the predicted damage area under low-velocity impact aligns closely with experimental data (within 2% on the impacted side, 6% on the non-impacted side), showcasing the potential for this approach in various applications. Physically based constitutive damage models and kinematic modeling with material-aligned meshes offer another exciting direction. These models, exemplified by Falcó *et al.,* [51], excel at simulating failure mechanisms, permanent indentation, and fracture energy dissipation with remarkable accuracy. Additionally, models like study by Liu *et al.,* [43] highlight the potential for predicting damage differences between different composite materials (e.g., CF/Epoxy vs. CF/PEEK) under low-velocity impact. The ability to validate undamaged laminates against experimental data and accurately predict damage zone size and number based on deflection values (as demonstrated in another crucial milestone [79]. Delamination prediction also shows promising results, with models in study by Kurşun *et al.,* [98] achieving 10-17% error for two different stacking sequences, showcasing the potential for tailoring material design to minimize this critical damage type. Linear-orthotropic damage models, while valuable, can benefit from further development. As highlighted, incorporating cohesive behavior to predict delamination and utilizing continuum damage mechanics offer promising avenues for improvement [70]. Other models demonstrate the effectiveness of these approaches, achieving good agreement between numerical and experimental results in terms of damage area and impact force history [73]. Challenges remain, however. Some models struggle with accurate damage zone and shape prediction despite good correlations in force and energy-time data (e.g. [98]). Others require further validation to confirm their accuracy across various impact scenarios [99]. Overall, numerical modeling for FRC damage under low-velocity impact is vibrant and rapidly evolving. From capturing complex interactions like lamb waves to predicting specific damage types and material behavior, these models offer invaluable insights for material design, optimization, and performance prediction.

**Table 11**
Fiber failure criteria for tension and compression mode [96]

| Criteria | Tensile | Compression |
|---|---|---|
| Hashin 2D | $\left(\frac{\sigma_1}{x_T}\right)^2 + \left(\frac{\tau_{12}}{s_{12}}\right)^2 \geq 1$ | Not applicable |
| Hashin 3D | $\left(\frac{\sigma_1}{x_T}\right)^2 + \frac{1}{S^2{}_{12}}(\tau^2{}_{12} + \tau^2{}_{13}) \geq 1$ | Not applicable |
| Chang-Chang | $\sqrt{(\frac{\sigma_1}{x_T})^2 + \frac{\tau^2{}_{12} / 2G_{12} + \frac{3}{4}\alpha\tau^4{}_{14}}{s^2{}_{12_{IS}} / 2G_{12} + \frac{3}{4}\alpha S^4{}_{12_{IS}}}} \geq 1$ | Not applicable |
| Puck | $\frac{1}{\varepsilon_{1_T}}(\varepsilon_1 + \frac{v_{f12}}{E_{f1}} m_{f\sigma}\sigma_2) \geq 1$ | $\left\lvert\frac{1}{\varepsilon_{1T}}(\varepsilon_1 + \frac{v_{f12}}{E_{f1}} m_{f\sigma}\sigma_2)\right\rvert \geq 1 - (10_{\gamma 21})^2$ |
| Max Stress | $\sigma_1 \geq x_T$ | $\sigma_1 \geq x_C$ |
| Max Strain | $\varepsilon_1 \geq \varepsilon_{1T}$ | $\varepsilon_1 \geq \varepsilon_{1C}$ |

**Table 12**
Matrix failure criteria for the tension and compression modes [96]

| Criteria | Tension | Compression |
|---|---|---|
| Max Stress | $\sigma_2 \geq Y_T$ | $\sigma_2 \geq Y_C$ |
| Max Strain | $\varepsilon_2 \geq \varepsilon_{2T}$ | $\varepsilon_2 \geq \varepsilon_{2C}$ |
| Hashin-Rothem | $(\frac{\sigma_1}{Y_T})^2 + (\frac{\tau_{12}}{s_{12}})^2 \geq 1$ | $(\frac{\sigma_1}{Y_C})^2 + (\frac{\tau_{12}}{s_{12}})^2 \geq 1$ |
| Hashin 2D | Not applicable | $\frac{\sigma_2}{Y_c}\left[(\frac{Y_c}{2S_{23}})^2 - 1\right] + (\frac{\sigma_2}{2S_{23}})^2 + (\frac{\tau_{12}}{s_{12}})^2 \geq 1$ |
| Hashin 3D | $\frac{(\sigma_2 + \sigma_3)^2}{Y^2{}_T} + \frac{\tau^2{}_{23} - \sigma_2\sigma_3}{S^2{}_{23}} + \frac{\tau^2{}_{12} - \tau^2{}_{13}}{s^2{}_{12}} \geq 1$ | Not applicable |
| Chang-Chang | $\sqrt{(\frac{\sigma_1}{Y_T})^2 + \frac{\tau^2{}_{12} / 2G_{12} + \frac{3}{4}\alpha\tau^4{}_{14}}{S^2{}_{12_{IS}} / 2G_{12} + \frac{3}{4}\alpha S^4{}_{12_{IS}}}} \geq 1$ | Not applicable |
| Puck | $\sqrt{(\frac{\tau_{21}}{s_{21}})^2 + (1 - \frac{P^{(+)}{}_{1\square}Y_T}{s_{21}})^2(\frac{\sigma_2}{Y_T})^2} + \frac{P^{(+)}{}_{1\square}\sigma_2}{s_{21}} \geq 1 - \left[\frac{\sigma_1}{\sigma_{1D}}\right]$ | for 2D plane stress mode B, $\theta_{fp} = 0°$<br>$\frac{1}{s_{21}}\left(\sqrt{(\tau^2{}_{21} + P^{(-)}{}_{\perp\square}\sigma_2)^2 + P^c{}_{\perp}i^3\lvert\sigma_2\rvert}\right) \geq 1 - \left\lvert\frac{\sigma_1}{\sigma_{113}}\right\rvert$<br>for mode C, $\theta_{fp} \neq 0°$<br>$\left[(\frac{\tau_{21}}{2(1 + P^{(-)}{}_{\perp\perp}s_{21}})^2 + (\frac{\sigma_2}{y_c})\right]\frac{Y_c}{(-\sigma_2)} \geq 1 - \left[\frac{\sigma_1}{\sigma_{1D}}\right]$ |

### *2.7.3 Models validation for damages*

The review of this part aims to contribute on the progress made in this field, highlighting the validation of various models against experimental data which is mainly on the basis of comparison of impact damage between experimental and FEM simulation shown in Figure 17 as an example. Apart from this; one model, showcased in study by Mahmoud *et al.,* [100], stands out for its impressive versatility. It demonstrably replicates the behavior of FRCs under low-velocity drop weight impact across a range of variables. From material properties and stacking sequences to thicknesses and impact velocities, its predictions of load-displacement curves and damage extent align closely with experimental results. Similarly, the model presented in another study captures the impact responses and deformations of rubber layers with remarkable accuracy, furthering our understanding of these crucial elements [34]. The ability to predict specific impact properties, such as impact force and energy absorption, is another valuable contribution. For instance, the model in study by El Moumen *et al.,* [75] while another developed model describes the structural response of the samples over the entire range of impact energies in terms of size and shape of delamination excels at predicting these parameters in CNT-reinforced composites, offering valuable insights for tailoring materials for optimal impact resistance. Moreover, the model developed in other study delves deeper, accurately describing the structural response of FRCs across a spectrum of impact energies [101]. This detailed understanding of delamination size and shape paves the way for precise damage mitigation strategies. In conclusion, the validation of various models against experimental data underscores the significant strides made in modeling low-velocity impact damage in FRCs. From offering benchmarks for future model development (as emphasized in [102]) to pinpointing specific impact properties and damage characteristics.

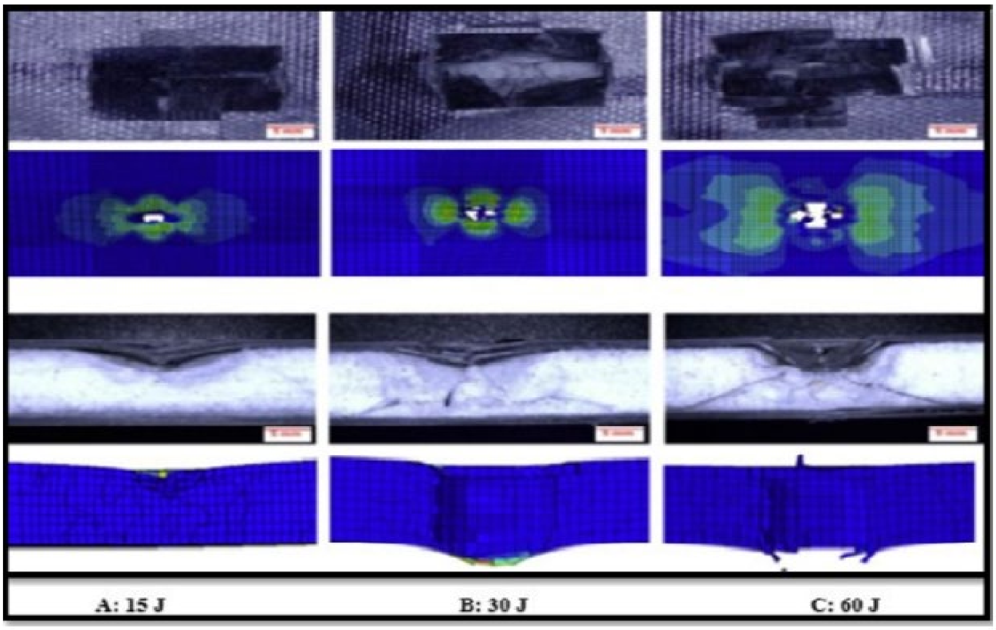

**Fig. 17.** Comparison of impact damage between experimental and FEM simulation of foam sandwich composite with cross-ply face sheet [48]

## 3. Conclusion

This review synthesizes prosperity of knowledge on the experimentation and numerical simulation which reveals the intricate interplay between various factors and mechanisms governing the low-velocity impact (LVI) performances and damages in fiber-reinforced composites (FRCs). Experimental studies utilizing methods ranging from basic drop tests to advance in situ X-ray monitoring have connected impact parameters and laminate characteristics to damage modes and extents. The conclusions can be drawn as:

i) Composites fabricated by VARTM process containing carbon, glass and Kevlar fiber with thermoplastic resin having proper stacking sequence provides good LVI resistance in applications.
ii) Hybridization and nano-fillers have good effects on composites in terms of impact resistance.
iii) Drop weight impact tests are most suitable to evaluate LVI, having specific impactor diameter, mass and energy despite limitations of standards of test and availability of instruments.
iv) LVI causes various damages like delamination, matrix cracking, fiber breakage and coupled of fiber and matrix breakage but delamination is the main one.

v) NDT is the most effective method of damage evaluation, from which ray, ultrasonic and thermography technique is most used techniques to evaluate damages caused by LVI.
vi) Area of damages increases with respect of impact energy as it has a profound influence on energy absorption and peak force.
vii) LVI induced response and damage progression depends on multiscale design factors like thickness, hybridization of material properties, fiber orientation, fiber content, count, processing history and testing conditions.
viii) Efforts have developed finite element models and analytical methods with reasonably good predictive capability for LVI
ix) Most applied mechanics of damage are cohesive zone technique and continuum damage technique while ABAQUS is mostly used software and models are Hashin and Puck.
x) Additionally, there is no concrete theory that considers all of the factors and mechanisms. This leads to the blend of various models that predict fracture or damage behavior.

## 4. Future Prospects

It is evident that challenges and gaps persist, particularly in standardizing testing procedures and refining numerical simulations for accurate prediction of complex damage patterns and residual mechanical properties to better capture real-world scenarios. To overcome the challenges and advance our understanding of low-velocity impact, future research can focus on several promising areas:

i) Incorporating complex damage mechanisms like fiber bridging, interfacial debonding, and fatigue crack growth into numerical simulations will enhance their accuracy and predictive capabilities.
ii) Coupling micro and macro-scale models will allow for a more comprehensive understanding of how microstructural features influence the overall impact response.
iii) Developing testing methods and simulation tools accounting moisture, temperature and fatigue loading will provide a realistic picture of performance in real-world applications.
iv) Implementing machine learning to analyze experimental data and guide the development of robust damage models can accelerate the optimization process for impact-resistant.
v) Exploring the potential of self-healing mechanisms and damage-tolerant matrix can lead to the development of FRCs with enhanced impact resistance and extended service life.

## Acknowledgement

This research was supported by Ministry of Higher Education of Malaysia (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2023/TK04/UTHM/02/1).

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