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A Review of Experimental and Numerical Methodologies for Impact Testing of Composite Materials

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Abstract: This review provides an overview of experimental impact testing and numerical impact simulations for composite materials in terms of a complementary combination of both techniques. It discusses the significance of impact testing, describes experimental methods such as drop-weight testing, pendulum testing, and ballistic testing, and explains numerical alternatives including finite element analysis. Relevant standards for impact testing are outlined, and a comparison of experimental and numerical research findings is presented. It highlights that numerical simulations are cost-effective and efficient for initial composite material development and prototype stages of structures, but may be less accurate compared to experimental approaches. Experimental testing is recognised for providing more accurate results, although it can be time-consuming and costly. The importance of a combined approach is emphasised to demonstrate that numerical simulations complement experimental testing and vice versa to obtain a comprehensive understanding of composite material behaviour under impact. This integrated approach can ensure safer and more efficient use of composite materials in demanding applications, contributing to the prevention of failures and improvement of the reliability of composite structures.

Keywords: composites, impact testing, ASTM and ISO standards, numerical simulation, finite element method

1 Introduction

Over the last decades, composite materials have rapidly increased in popularity and are now used intensively in various domestic and industrial applications, including aerospace (Castanie et al. 2020), automotive (Sarfraz et al. 2021), and marine (Rubino et al. 2020) manufacturing sectors. It has been recently reported (Research and Market 2022) that the compound annual growth rate of the composite material industry is expected to be 7% for a period from 2022 to 2030.

Composite materials are highly demanded by manufacturers due to their exceptional properties based on the mix of high stiffness, toughness, corrosion resistance, and lightweight (Callister and Rethwisch 2018; Hale 1976). Such advanced characteristics are achieved by combining two or more materials with complementary properties to form a structure in which the reinforcement material is embedded in a matrix. As a result, the composite material shows unique properties that are very different from the properties of the original materials used to build the composite (Rajak et al. 2019). Unlike homogeneous materials, such as metal alloys, the reinforcement and matrix of composites remain separate and do not combine.

Although composites offer advanced properties compared to the parent materials, the internal stresses induced in the reinforcement or/and matrix make the composites vulnerable to a wider range of damage and failure modes. To evaluate the reliability and predict the behaviour of the composites, extensive testing is required, particularly in industries where structural failure can lead to catastrophic consequences. Impact testing is an important technique applied to assess the exact operational performance of composites under physical collisions. The aerospace, automotive, marine, and other industries heavily relying on composites have adopted impact testing as a crucial part of their quality control processes; (Safri et al. 2018; Brown et al. 2023).

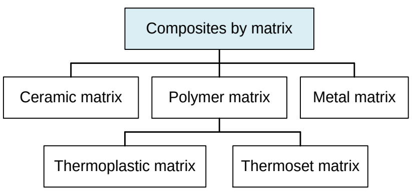
Experimental impact testing involves exposing a composite material to an impact from a specified distance, angle, and velocity, and then measuring the resulting force and displacement (Wu et al. 2020; Mitrevski et al. 2006). Following the safety requirements, the impact testing is performed in a controlled environment, such as a test facility, using specialised impact and measurement equipment. The data obtained from the impact tests are collected and analysed to assess the resistance to damage and the ability of the composite material to absorb the energy of the impact (Hu et al. 2019; Mitrevski et al. 2005).

Due to the advanced developments in software and the increase in computational resources available for software processing over recent years, numerical modelling using finite element analysis (FEA) has also become increasingly popular for the simulation of the impact testing of composites. FEA procedures involve modelling the composite and simulating the impact scenario using various parameters similar to the physical impact test, including impact angle, velocity, and material properties. The software simulation is capable to produce a detailed output of the composite's behaviour during the impact, including force and deformation. The verified results obtained from the simulation are crucial for the analysis and optimisation of the composite structure design, material selection, and manufacturing process.

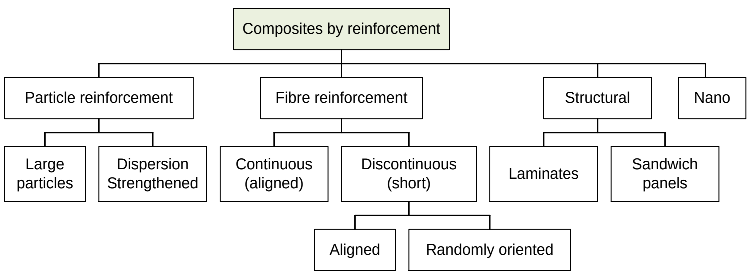
In the design process of composite materials and composite parts, it is typical to use both experimental impact testing and impact test simulation in combination to complement each other. The appropriate combination of numerical simulation and experimental testing can provide a more comprehensive understanding of the impact behaviour of composite materials. This article aims to review and evaluate experimental impact testing and numerical simulations of impact tests applied for analysis as a combination of both testing approaches. It outlines the advantages and limitations of using the combination of tests in terms of efficiency, accuracy, results correlation, and complexity. It is expected that this review will provide information to researchers and engineers working in the area of composites to make informed decisions about selecting the appropriate combination of experimental and numerical testing techniques.

2. Composites Overview

Composites are a large group of materials that can be classified into different categories according to material characterisation and applications. There are several classification systems for composite materials; however, the most common system organises the composites in terms of matrix and reinforcement type.



(a)



(b)

Figure 1. Classification of composites by (a) matrix and (b) reinforcement.

According to typical classifications (Jose and Kuruvilla 2012), composite materials are divided by matrix into ceramic matrix composites (CMC), polymer matrix composites (PMC), and metal matrix composites (MMC) as can be seen in Figure 1(a). The second category can be further subdivided into thermoplastic and thermoset.

Figure 1(b) shows the classification of composites by reinforcement. Initially, a differentiation is made between the four groups particle-reinforced, fibre-reinforced, structural, and nanocomposites. Specifying further, particle-reinforced composites are divided into large particle and dispersion reinforced. Fibre-reinforced composites are either continuous or discontinuous, whereby the latter can be aligned or randomly oriented. Structural composites are divided into laminates and sandwich panels. In addition, the fibre phase of fibre-reinforced composites can be distinguished between wires, fibres, and whiskers (Callister and Rethwisch 2018).

2.1 Material Utilised for Composites

PMCs are typically made of thermoplastic or thermosetting polymers. However, a thermosetting matrix is preferred over a thermoplastic matrix due to its higher thermal resistance (Dang et al. 2012). The reinforcement used in PMCs usually consists of synthetic fibres, such as carbon, glass, or aramid fibres (Rajak et al. 2019). When carbon fibres are used, the resulting PMC is called a carbon fibre-reinforced polymer (CFRP), whereas glass fibres produce a glass fibre-reinforced polymer (GFRP). Hapuarachchi et al. (2007) reported that natural fibres, such as bamboo, hemp, sisal, kenaf, and flax, have gained popularity as an environmentally friendly alternative. In the automotive industry, these natural fibres are already being used in seatbacks, door panels, dashboards, headliners, trunk liners, and package trays (Puglia et al. 2005). However, natural fibres are not as impact-resistant as synthetic fibres, which has led to the development of hybrid composites that combine both types of fibres (Faruk et al. 2012). PMCs are generally inexpensive and relatively simple to manufacture (Rajak et al. 2019).

MMC materials have a metallic matrix, which is primarily made up of aluminium. However, other metals and alloys, such as copper, magnesium, titanium, iron, nickel, silver, and beryllium, can also be used. Typically, ceramics such as silicon carbide, aluminium oxide, boron carbide, titanium carbide, and titanium boron, are used as reinforcements (Hunt 2000). Metals such as tungsten, lead, and molybdenum, are also suitable as reinforcement materials. Aluminium-based MMCs are widely used as reinforcing compounds in the aerospace and automotive industries. Due to their stiffness and abrasiveness, they are more difficult to machine, which is reflected in their cost (Rajak et al. 2019).

CMCs were developed to overcome the brittleness drawback of monolithic ceramics. CMCs have a matrix made of technical ceramics, such as zirconia, silicon nitride, aluminium nitride, aluminium oxide, and silicon carbide. Carbon, silicon carbide, mullite, and aluminium oxide are commonly used as fibre materials. CMCs are ideal for use in extreme environments due to their high mechanical strength and thermal resistance. For example, CMCs are commonly used in rocket propulsion and high-temperature furnaces. The fabrication and machining of CMCs require specialised processes and tools, resulting in high production costs.

2.2 Functional Principles

PMCs have a relatively soft and ductile matrix in which high-strength and stiff reinforcement is embedded (Rajak et al. 2019). The reinforcement is crucial for carrying loads and achieving ultimate strength, whereas the matrix functions as a medium for transferring stress to the fibres. In addition, the matrix protects the reinforcement from damage caused by environmental factors, such as chemical reactions, surface damage, and mechanical abrasion (Callister and Rethwisch 2018). Strong adhesion must exist between the reinforcement and the matrix. This can be achieved by pre-treating the reinforcement with resin before embedding (Gay 2015).

Similarly, MMCs have a stiffer reinforcement embedded in a more ductile matrix, leading to a desirable combination of high strength and plasticity (Balci et al. 2019). Unlike the previous two types, CMCs are reverse composites having a tougher matrix and a more ductile reinforcement. As a result, the matrix has a lower failure strain than the fibres and fails first (Rajak et al. 2019).

2.3 Reinforcement Concentration and Fibre Orientation

The distribution, concentration, and orientation of fibres have an immense influence on the load-bearing capacity of fibre-reinforced composite materials. To achieve optimum mechanical stress parameters such as strength and stiffness, the composite requires a maximum fibre volume of approximately 60% (Askeland et al. 2018). A higher volume risks incomplete matrix encapsulation of fibre. By controlling the fibre orientation, the load-bearing capacity of the composite material can be modified in different stress directions. For example, randomly oriented discontinuous short fibres demonstrate a relatively isotropic behaviour similar to that of homogeneous materials. Anisotropic behaviour is achieved by stacking plies of continuous fibres in the same direction, providing excellent load-bearing properties in the direction parallel to the fibres but weak load-bearing properties perpendicular to the fibres, as shown in Figure 2(a) representing a unidirectional case. If the composite material has to effectively absorb loads in multiple directions, the fibre plies are stacked with an angle offset. For example, the stacking sequence shown in Figure 2(b) achieves a quasi-isotropic state. These stacking sequences are simplified and referred to as [0/0/0/0]s and [0/90/45/-45]s, where "s" stands for symmetrical.

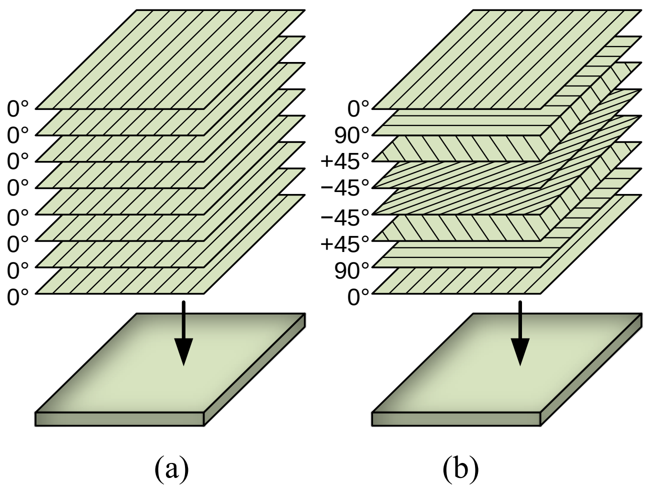
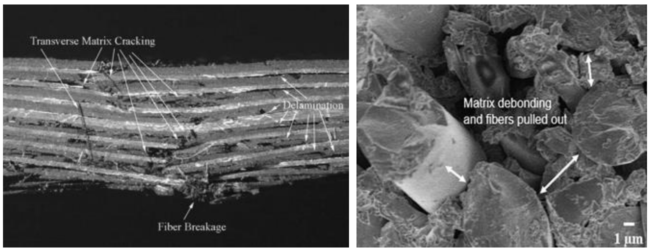


Figure 2. Ply stacking sequence of a fibre-reinforced composite: (a) unidirectional, (b) cross-plied quasi-isotropic.

2.4 Damage and Failure Modes

The impact strength of composites depends on fibre loading and fibre length (Shrivastava et al. 2017). Impact failure modes are affected by parameters such as type of fibre, resin, lay-up, thickness, type of impactor, and velocity (Ghasemnejad et al. 2010). The impact performance can be classified into low- and high-velocity impacts. At low-impact velocities, the composite material is damaged but often remains functional to a reduced degree. High-velocity impact often leads to penetration or perforation, thus destroying the composite material (Hogg and Bibo 2000). Low-velocity impact damage is further subdivided into clearly visible impact damage (CVID) and barely visible impact damage (BVID), with most of the damage occurring in the latter category (Duell 2004; Ouyang et al. 2021). For example, delamination often occurs between the plies, which can not be detected on the surface (Meola and Carlomagno 2010).

The initial form of low-velocity impact damage typically produces matrix microcracks (Nairn 2000), which then evolve into delamination, matrix and fibre cracks, debonding, and fibre pull-out, as shown in Figure 3. Delamination is one of the most common types of failure, whereby the individual plies of the composite separate from each other (Schoeppner and Abrate 2000). Moreover, matrix and fibre cracks provoke and favour the occurrence of delamination (van der Meer 2015). The debonding between the matrix and the fibres negatively influences the mechanical properties of the composite material (Saeedifar et al. 2018). If the fibre matrix adhesion becomes insufficient, for example, due to debonding, fibre pull-out may occur (Hernandez et al. 2017).



(a) (b)

Figure 3. Damage and failure modes of composite materials; (a) delamination, matrix cracking, and fibre breakage (Saeedifar et al. 2018), (b) matrix debonding and fibre pull-out (Hernandez et al. 2017).

3 Experimental Impact Testing

3.1 Classification of Impact Testing

Experimental impact tests are crucial to determine how composite materials perform under different impact conditions. Tests enable the evaluation of the resistance of the material, its ability to absorb energy, and the failure modes occurring in the composites. Moreover, impact tests simulate real-life scenarios in which composite materials may experience various types of impacts.

Impact tests are classified according to the velocity of the impact. The four classifying categories are corresponding to low, medium, high, and hypervelocity. In low-velocity impact tests, the impact velocity is typically less than 10 m/s, where the materials may be damaged, but can still function to some extent. Medium-velocity impact tests are conducted with impact velocities ranging from 10 m/s to 50 m/s. Materials under medium velocity impact experience significant damage, which can lead to partially or completely inoperable conditions. In high-velocity impact tests, the impact velocity is typically greater than 50 m/s, and materials may receive damage in the form of penetration or perforation. Hypervelocity impact tests have even higher velocities comparable to the speed of meteorites or space debris (Vaidya 2011; Ismail et al. 2019). The impact tests classified on the base of the impact velocity are listed in Table 1.

Table 1. Classification of impact tests

Impact Test	Impact Velocity (m/s)	Impact Test Method
Low velocity	< 10	Drop weight Pendulum (Charpy, Izod) Inertia wheel
Medium velocity	10 – 50	Inertia wheel Servohydraulic Gas gun
High velocity	50 – 1000	Gas gun Electromagnetic launcher
Hyper velocity	2000 – 5000	Light-gas gun Electromagnetic launcher

3.2 Experimental Impact Testing Methods

Specific impact testing methods are generally related to testing velocity classification, as shown in Table 1. The listed methods simulate impact incidents that can occur in a real-life scenario. No impact testing method is clearly preferred over the others, as each method has its own limitations and potential errors. Although each method provides similar results, some are easier to prepare and perform and have a higher tolerance for errors (Pai et al. 2021).

The drop weight impact test method, as shown in Figure 4(a), raises the impactor to a certain height and releases it, causing a test specimen to be impacted by the drop. This method is the most popular for low-velocity impact testing since it does not require test specimens with standardised dimensions (Mustafa et al. 2019), unlike pendulum impact testing methods. Therefore, more complex components and geometries can be tested using this method (Vaidya 2011). During impact, three different scenarios can occur (1) free fall and stop, (2) free fall, stop, and rebound, and (3) free fall, stop, and perforation (Pai et al. 2021).

Other low-velocity impact testing methods include Charpy and Izod, which use a pendulum hammer to strike and fracture a test specimen from a fixed height, as shown in Figure 4(b). The difference between Charpy and Izod lies in the clamping of the specimen and the striking position. In Charpy, the specimen is clamped at the ends and struck in the middle, while in Izod, the specimen is clamped on the bottom half and struck on the upper half (You et al. 2020). These tests are primarily used to determine the impact toughness of composite materials and compare different material designs (Vaidya 2011).

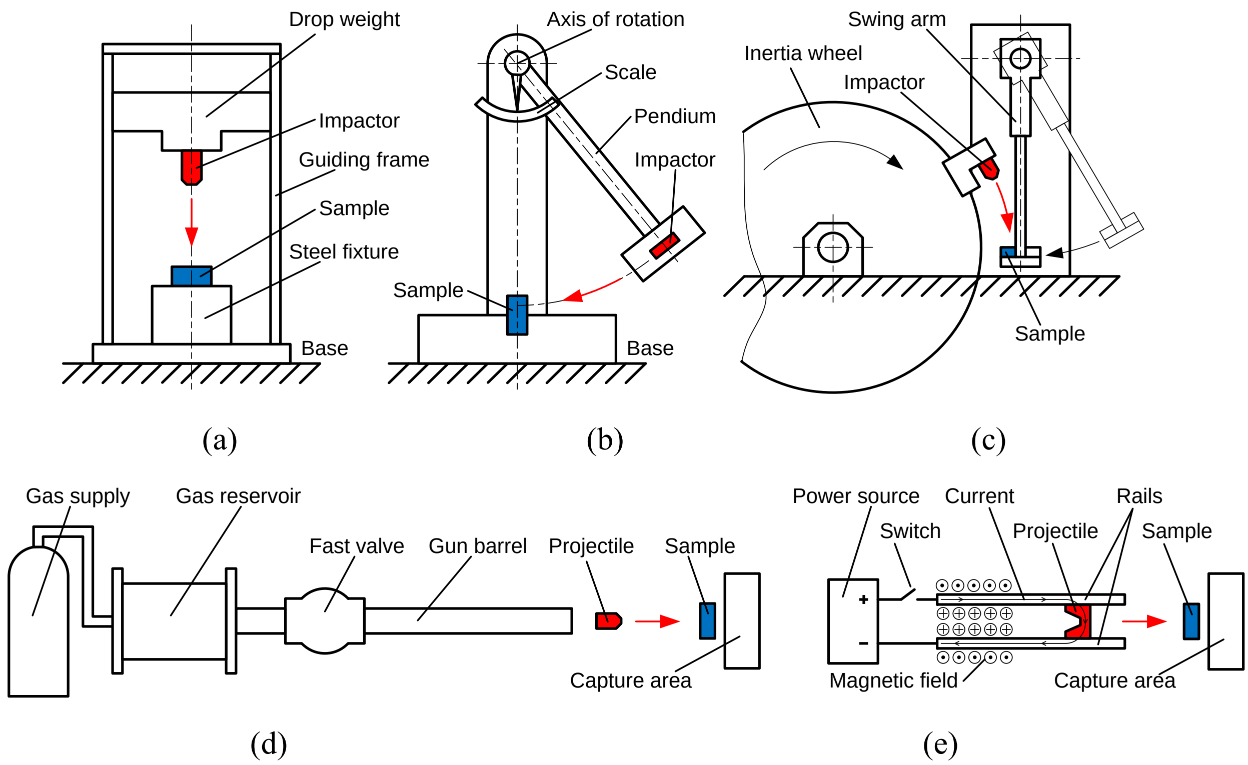


Figure 4. Schematic of impact testing methods; (a) drop weight impact testing, (b) pendulum impact testing, (c) inertia wheel impact testing, (d) gas gun impact testing, (e) electromagnetic launcher impact testing.

The inertia wheel impact testing method shown in Figure 4(c) is similar to the pendulum testing method, but it provides more consistent and higher impact velocities of up to 20 m/s. This method is able to conduct medium velocity impact testing (You et al. 2020; Loureiro et al. 2010).

Another method of achieving higher impact velocities of up to 25 m/s is the servo-hydraulic method, which has a design similar to the drop weight method, but the gravitational acceleration is replaced by servo-hydraulics (Bardenheier and Rogers 2006).

To perform high-velocity impact testing, the gas gun impact testing method is a suitable option as shown in Figure 4(d). In this method, a rigid or flexible projectile is launched from a barrel towards the test specimen. The pressure necessary to accelerate the projectile is achieved by compressing the air (Kamarudin and Abdul Hamid 2017). A modification of the gas gun method that can achieve even higher velocities up to the hypervelocity classification is the light-gas gun. This method uses compressed helium or hydrogen because these light gases can reach higher maximum velocities than propellant charges or compressed air (Tang et al. 2020).

The highest velocities for high and hypervelocity impact tests can be generated using an electromagnetic launcher (EML). As shown in Figure 4(e), a magnetic field is generated by the current flow through the rails and the projectile, which is initially part of the circuit. This causes an electromagnetic force, also known as Lorentz force, that accelerates the projectile and launches it towards the test specimen (Kim et al. 2019a; Kim et al. 2019b).

3.3 ASTM and ISO Standards

Composite materials and their testing require standardisation to ensure a consistent degree of quality, which is necessary for free trade and liability aspects. Following the advancement in globalisation, various standardisation systems employed by different countries become increasingly harmonised. For example, in the field of composite materials impact testing, many of the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) standards have been harmonised. Although these standards are represented by different codes, their technical content share common specifications and parameters. Harmonisation leads to cost savings, simplification of evaluation, and comparability. Over time, EN standards of European countries have been replaced by equivalent ISO standards. Western countries tend to follow ASTM or ISO, whereas Asian countries prefer ISO or their national standards (Sims 1999; Raj et al. 2021).

Table 2 lists the relevant ASTM and ISO standards for impact testing. ASTM D256 and its equivalent ISO 180 recommend Izod as the standard testing method over Charpy for low-velocity impact testing (Raj et al. 2021). For high-velocity impact testing, the damaging surface is more localised, so the structural response is less important, and therefore equal dimensioning is not relevant. Thus, no standardisation exists for the test specimen dimensions used in high-velocity impact tests (Duell 2004).

In addition to the detailed description of ASTM and ISO standards for impact testing, it is imperative to acknowledge their limitations. One significant limitation is the scope of these standards, which may not encompass all types of composites or impact scenarios, potentially leading to gaps in testing protocols. Furthermore, practical challenges in standard implementation, such as the need for specialised equipment or the complexity of procedures, can hinder their widespread adoption. Criticisms within academic and industry circles also point to a lack of flexibility in these standards, which may not keep pace with rapid advancements in composite materials technology.

Table 2. Relevant ASTM and ISO standards for experimental impact testing

Standard	Content	Accordance and Differences
ASTM D5628 (2001) ISO 6603 (2000)	Describes the method for dropping weight tests on a flat specimen.	For compliance with ASTM and ISO the test specimen shall be 60 mm in diameter or a 60 mm side length square with a thickness of 2 mm. A minimum of 30 test specimens must be tested.
ASTM D2444 (1999) ISO 3127 (1994)	Describes the method for drop weight tests on pipe specimens.	ASTM test specimens must have an outer diameter equal to their length. However, the length must not be less than 152 mm. ISO test specimens allow varying outside diameters, but the length shall be 200 mm.
ASTM D7136 (2012)	Measuring damage resistance of PMCs to drop weight impact.	Currently, no ISO equivalent exists.
ASTM D6110 (2008) ISO 179 (2000)	Describes the method for the Charpy impact test.	ASTM test specimens have a maximum length of 127 mm, a width of 3 to 12.7 mm, a thickness of 12.7 mm, and a notch of 45°×2.54 mm with a radius of 0.25 mm. ISO test specimens have a length of 80 mm, a width of 10 mm, a thickness of 4 mm, and a notch of 45°×2 mm with a radius of 0.25 mm. Several different shapes of test specimens exist.
ASTM D256 (2010) ISO 180 (2000)	Describes the method for the Izod impact test.	ASTM test specimens have a maximum length of 64 mm, a width of 12.7 mm, a thickness of 3.2 or 6.4 mm, and a notch of 45°×2.5 mm with a radius of 0.25 mm. ISO test specimens have a length of 80 mm, a width of 10 mm, a thickness of 4 mm, and a notch of 45°×2 mm with a radius of 0.25 mm.
ASTM D8101 (2017)	Measuring penetration resistance of composites to blunt projectile high-velocity impact.	Currently, no ISO equivalent exists.
ASTM D618 (2000) ISO 291 (1997)	Describes the atmosphere for conditioning and testing.	For compliance with ASTM and ISO the test specimen shall be conditioned at 23°C and 50% relative humidity for a minimum of 40 hours prior to the test. Testing shall be conducted in a standard laboratory atmosphere at 23°C and 50% relative humidity.

4 Numerical Impact Testing

4.1 Numerical Simulation as Experimental Alternative

The continuous improvement of computer performance has made computer-aided engineering (CAE) an increasingly cost-effective solution for numerical simulations of impact testing. However, conducting CAE requires a deep understanding of both the simulation setup and the real processes that are being simulated. If successful, this methodology can provide an excellent alternative to experimental testing. CAE approach is much cheaper in comparison to experimentation and can provide results which are difficult or impossible to obtain from experimental testing, albeit slightly less accurate due to its simplification of reality. To conduct an impact simulation, the following steps must be executed chronologically: (1) the creation of the test setup in a computer-aided design (CAD) program, (2) the definition of material properties and behaviour in the simulation software, (3) mesh generation of the test setup and (3) execution of the explicit FEM Solver setup with the specification of boundary conditions.

4.2 Numerical Approach and Appropriate Software

A suitable numerical method for addressing physical challenges is the finite element method (FEM). FEM is divided into implicit and explicit methods, with the implicit method only suitable for static and quasi-static loadings. In contrast, explicit finite element method solvers have been utilised for time-dependent issues, which arise when acceleration effects can not be neglected. Explicit-based methods are suitable for dynamic loadings where the sum of all forces equals the mass multiplied by acceleration. Since impact testing is always time-dependent, acceleration always matters, and loads never occur statically, an explicit FEM solver is required. Several competitive explicit FEM solvers have been established on the market, most of which are included in software packages, but some are also available as stand-alone versions. For modelling composites, it is essential to use CAD software that is specifically configured for matrix and reinforcement design. A listing of such software can be found in Table 3.

Table 3. Software capable of composite impact testing

Software Package	Composite Modelling	Explicit FEM Solver
Abaqus Unified FEA (Dassault Systèmes 2023)	Abaqus/CAE Composite Modeler (CMA) ANSA[a] ESAComp[a] MultiMech[a] Digimat MF & FE[a]	Abaqus/Explicit CZone (CZA)
Altair One (Altair 2023)	HyperMesh ANSA[a] ESAComp[a] Digimat MF & FE[a]	Altair Radioss
Ansys Workbench (Ansys 2023)	Ansys LS-PrePost Composite PrepPost (ACP) ANSA[a] ESAComp[a] MultiMech[a] Digimat MF & FE[a]	Ansys LS-DYNA Ansys Autodyn Explicit Dynamics
COMSOL Multiphysics (COMSOL 2023)	Composites Material Module	Model Builder
Hexagon (Hexagon 2023)	Patran Laminate Modeler ANSA[a] Digimat MF & FE[a]	MSC Nastran
Simcenter 3D (Siemens 2023)	Femap NX Laminate Composites ANSA[a] MultiMech[a]	NX Nastran
ESI Group[b] (ESI Group 2023)	PAM-Composites ANSA[a] Digimat MF & FE[a]	PAM-Crash

[a] Compatible with explicit FEM solvers. However, not included in the software package;
[b] Producer of the software, programs are not bundled into a software package.

4.3. CAD Modelling of Test Setup

The test setup is modelled using a CAD program having compatible composite material design within the software package or imported from an external source. To save computational resources during simulation, it is advisable to simplify the test setup. It is not necessary to model the complete experimental impact test, such as drop weight or pendulum. It is sufficient to model only the impactor and the target specimen. However, some researchers tend to include fixtures or supporting surfaces in simulation models.

4.4. Material Properties and Modelling

To obtain realistic results, it is essential to define the material behaviour as precisely as possible in the software. Such material properties are typically provided by material manufacturers or can be found in research publications. In case of unavailability, for example, due to new material development, destructive mechanical testing methods such as tensile, compression, shear, bending, and torsion must be performed to determine the material properties and stress-strain curves.

It is important to specify whether a material exhibits isotropic, orthotropic, or anisotropic elasticity behaviour. Randomly aligned short-fibre composite materials behave isotropically, while aligned long-fibre composites behave orthotropically or anisotropically. Various computational material models are applied to accurately simulate the different stress-strain curves of the impactor and composite material, which can be classified into linear elastic, linear elastic with plasticity hardening, viscoelastic, hyperelastic, and equation-of-state (EOS) models. The latter is often used for high-velocity bird strike impact simulations.

4.5. Meshing of Test Setup

In the subsequent step, the test setup must be meshed, where the CAD geometry is divided into a computational mesh. There are various types of mesh, including Lagrangian, Eulerian, Arbitrary Lagrangian-Eulerian (ALE), and Smooth Particles Hydrodynamics (SPH) (Ramirez et al. 2022). These are suitable for impacts on composite materials. Lagrangian is the most widely used and preferred for solid materials due to its accuracy, versatility, and low computational time. However, under impact modelling, Lagrangian type mesh is deformed with the material and large deformations can result in strong mesh element distortion, leading to energy errors and slow computational time. With Eulerian, the mesh remains stationary and the material moves through it, allowing for multiple materials in one mesh element. However, tracking the material's behavioural history is difficult. The ALE model tries to combine the advantages of Lagrangian and Eulerian and compensate for their disadvantages but at a higher computational cost. In contrast, SPH is a mesh-free model based on Lagrangian principles, where instead separated particles represent the material (Bi 2018). This model is preferably used in high-velocity bird strike impact simulations, where strong deformations of the flexible projectile occur.

A mesh element can have different sizes and geometries, such as tetrahedrons, hexahedrons, and prisms, to accurately reproduce the meshed geometry. If the mesh is too coarse, the geometries will not be accurately represented, and the calculations may become inaccurate. On the other hand, if the mesh is too fine, the simulation time may increase excessively without significantly improving accuracy. Therefore, it is reasonable to design the mesh to be finer at the impact position and coarser towards the outside. An indicator of mesh quality is provided, for example, by ANSYS, which defines threshold values for element quality, aspect ratio, and skewness (Sunar 2021), which the generated mesh should not exceed.

4.6. Explicit FEM Solver Setup

Subsequently, the boundary conditions of the simulation are specified in the explicit FEM solver. This includes assigning materials to the corresponding CAD bodies, defining the impactor's velocity and direction of motion, setting the simulation duration, and assigning support types to surfaces to prevent free movement. Finally, the desired solutions are specified, and the simulation is ready to be computed.

4.7. Result Validation

Different solvers use varying mathematical formulas for the same purpose, leading to differences in results even under the same boundary conditions. This highlights the fact that simulations should never be blindly trusted without comparing the results with reality. Therefore, performing a validation case prior to impact simulations is crucial. By calibrating simulations based on the conducted experiments, it can be ensured that the results correspond to or closely approximate reality. Validation can be carried out using similar scenarios from reported research publications, self-conducted experiments, or calculations. Additionally, a mesh dependency study can be conducted in parallel to investigate the most accurate size and shape of mesh elements, while considering computational time.

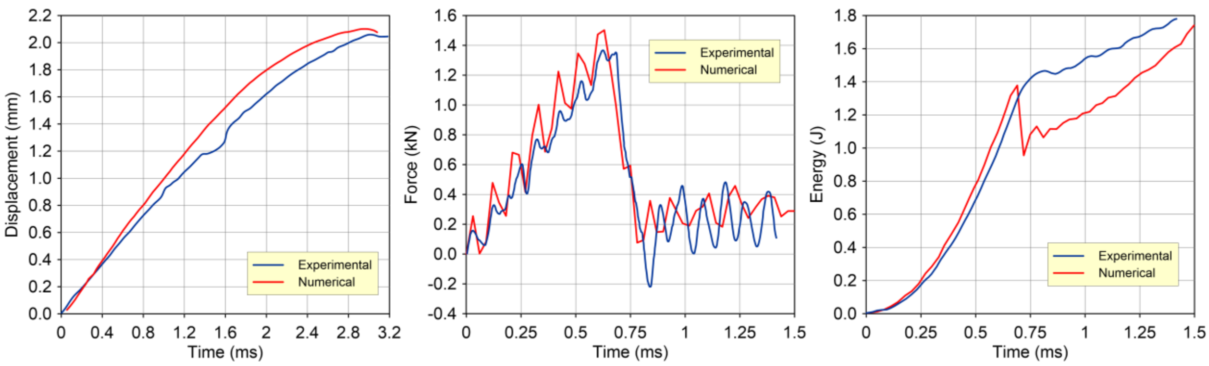
5 Test Results Collection

5.1. Measuring Systems

In order to obtain accurate and detailed results, complex and sophisticated measuring systems are necessary for experimental impact tests. High-speed cameras are suitable for recording the impact (Sommer et al. 2022). Digital image correlation (DIC) can be used to determine the displacement and strain of the test specimen (Shyamsunder et al. 2022). Alternatively, displacement can also be measured using laser displacement sensors (Seifoori et al. 2021) and displacement transducers, while strain gauges can provide strain data (Hu et al. 2016). The impact force can be measured using a load cell in the impactor (Hufenbach et al. 2008). Alternatively, an accelerometer can be used in combination with a high-speed data acquisition system, triggered by an impact event (Perillo et al. 2014). A velocimeter is suitable for measuring high-velocity projectiles (Long 2021).

5.2. Results Comparison

As mentioned above, impact tests on composite materials are dynamic and time-dependent. Therefore, it is required to measure different variables such as the time history of displacement (Long 2021), strain (Fernie and Warrior 2002), impact force (Liu et al. 2020), projectile velocity (Shyamsunder et al. 2022), damaged area (Ullah et al. 2013), as well as absorbed, dissipated, and kinetic energy (Sommer et al. 2022). Figure 5 provides examples of displacement, force, and energy in experimental and numerical comparisons for GFRP laminate plates. While Figure 5(a) and Figure 5(b) show a consistently good correlation for curved and flat GFRP laminate plates respectively, Figure 5(c) only exhibits a close correlation over a period of time for the flat laminate. It was explained by the fact that in the numerical model, the friction coefficients affect absorbed energy and may be the cause of this difference. Despite the deviation, the result is significant and useful over the period of the close correlation, and this could be used to predict the impact behaviour. Other result types include force versus displacement (Hufenbach et al. 2008), absorbed energy versus stacking sequence (Ullah et al. 2013), residual versus initial impactor velocity, absorbed energy versus kinetic energy (Yang et al. 2022), strain versus stress (Nunes et al. 2019), and delamination area versus impact energy (Perillo et al. 2014).



(a) (b) (c)

Figure 5. Experimental and numerical comparisons of displacement, force, and energy versus time; (a) spherical impact on curved GFRP composite plate, data from (Seifoori et al. 2021), (b) cylindrical impact on [0/90]3s GFRP laminate plate, data from (Boukar et al. 2022), (c) cylindrical impact on [0/90]3s GFRP laminate plate, data from (Boukar et al. 2022).

As demonstrated in Figure 5, achieving a perfect correlation between experimental and numerical results is impossible. Boukar et al. (2022) reported the impact force and energy values, whereas Seifoori et al. (2021) provided only displacement results. Table 4 provides a list of minimum and maximum experimental and numerical deviations reported in research. The deviations were calculated by dividing the peak experimental value by the corresponding numerical value at the same moment in time, with deviation ranging from excellent 1% to impractical 31%.

Table 4. Deviation of experimental and numerical testing results

Reference	Impact Velocity	Explicit FEM Solver	Result Type	Exp. – Num. Deviation [%]
(Boukar et al. 2022)	Low	Abaqus/Explicit	Force	9.0 – 22.6
			Energy	9.3 – 16.4
(Perillo et al. 2014)	Low	Abaqus/Explicit	Force	2.7 – 19.0
			Energy	1.1 – 2.9
(Ullah et al. 2013)	Low	Abaqus/Explicit	Force	7.5 – 10.9
(Miao et al. 2022)	Low	Abaqus/Explicit	Toughness	0.9 – 31.3
(Hamamousse et al. 2019)	Low	Explicit Dynamics	Force	4.5 – 9.9
(Seifoori et al. 2021)	Low	Explicit Dynamics	Displacement	2.3 – 11.1
(Hu et al. 2016)	High	LS-DYNA	Strain	2.9 – 27.8
(Shyamsunder et al. 2022)	High	LS-DYNA	Displacement	9.0 – 13.8

Furthermore, the examination of the tested composite materials is of great interest. For example, Figure 6 shows delamination and matrix tension failure of different composite plies after impact, while in Figure 7(a) front side total deformation and in Figure 7(b) rear side von Mises stress contours are displayed. The numerical approach offers the advantage of being able to analyse each moment in time during the impact, not just the post-impact result. In addition, the evaluation of individual plies is easier, as they can be easily separated virtually.

Simulations can provide results that can not be measured experimentally. For example, Figure 8(a) illustrates a simulated Charpy impact test and Figure 8(b) shows the corresponding experimental test specimen before and after impact. The simulation provides a deeper understanding of the fracture process and shows the maximum principal stress distribution of the MMC particles and matrix.

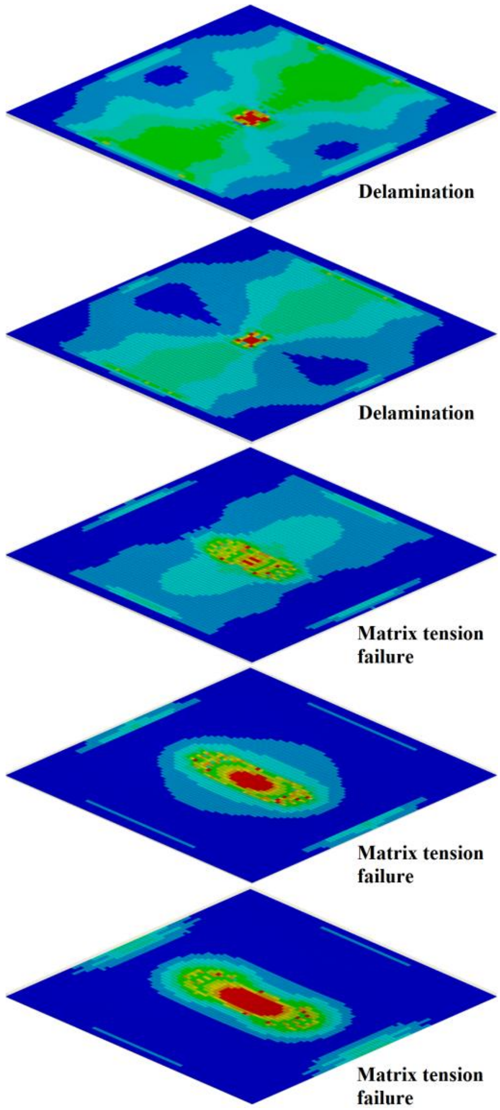
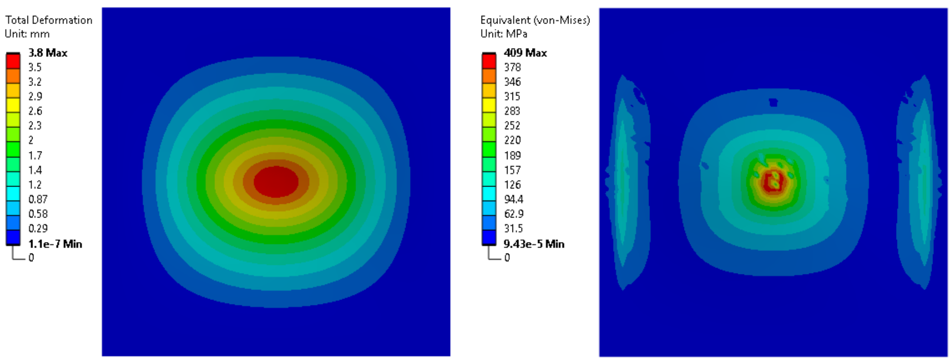
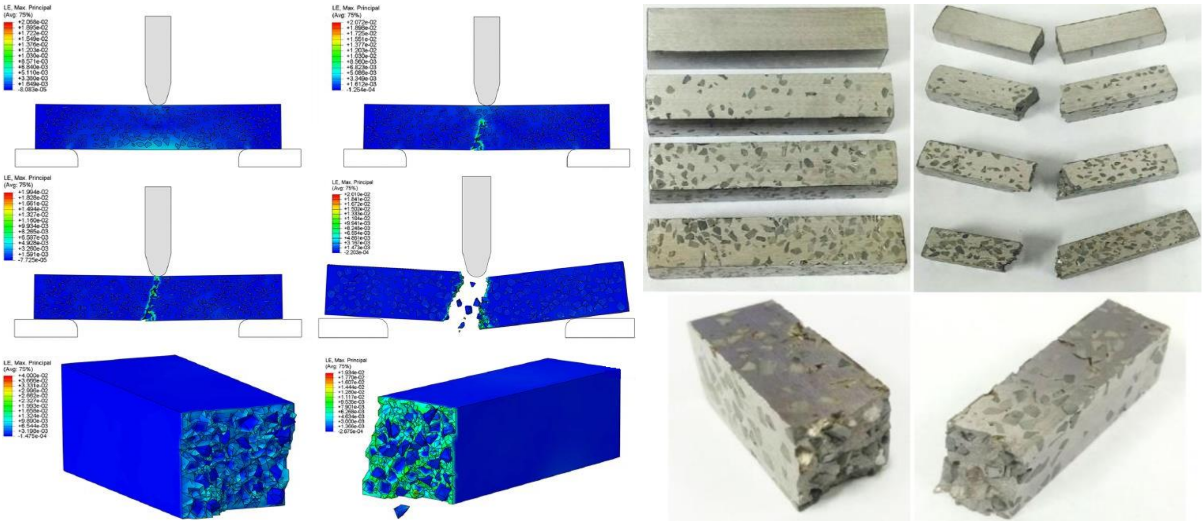


Figure 6. Composite laminate failure of different unidirectional plies after spherical impact from above.



(a) (b)

Figure 7. Total deformation and von Mises stress contours during impact on unidirectional composite laminate: (a) front side total deformation; (b) rear side von Mises stress.



(a) (b)

Figure 8. Charpy impact test on particle reinforced MMC test specimen (Miao et al. 2022): (a) simulated fracture progress; (b) experimental specimen and fracture.

6. Discussion

6.1. Using Impact Testing Methods

Table 5 presents samples of reported investigations in the area of impact testing on composite materials for comparison. These studies typically involve both experimental and numerical approaches, followed by a comparison of the results. It has been observed that only a few research publications, such as Ullah et al. (2013), have utilised the Izod impact testing method. For low-velocity impact testing, drop weight testing is the most commonly used method, while gas guns are popular for high-velocity impact testing.

Table 5. Comparison of the reported studies on experimental/numerical composite material impact testing

Reference	Test Method	FEM Solver	Material	Test Geometry	Impactor Shape	Standards	Exp. – Num. Correlation
(Boukar et al. 2022)	Drop weight	Abaqus/ Explicit	GFRP	Flat plate	Rigid: Cylindrical	ISO 179	Good prediction of peak force, absorbed energy, and delamination area.
(Perillo et al. 2014)	Drop weight	Abaqus/ Explicit	GFRP	Flat plate	Rigid: Spherical	ASTM D7136	Good prediction of impact behaviour for different energies and stacking sequences.
(Seifoori et al. 2021)	Drop weight	Explicit Dynamics	GFRP CFRP	Curved plate	Rigid: Blunt, Conical, Spherical	ASTM D760	Good prediction of mid-point deflection time histories.
(Sommer et al. 2022)	Drop weight	LS-DYNA	CFRP	Tube	Rigid: Blunt	-	Excellent prediction of material behaviour and damage mechanisms.

(Hufenbach et al. 2008)	Charpy	LS-DYNA	CFRP	Flat plate	Rigid: Blunt	ISO 179	Good prediction of forces and failure modes.
(Hynes et al. 2022)	Charpy	Abaqus/ Explicit	FML[a]	Flat plate	Rigid: Blunt	ASTM D256, D638, D790	Good prediction, helped to understand how the experimental trials behave.
(Miao et al. 2022)	Charpy	Abaqus/ Explicit	PRMMC[b]	Flat plate	Rigid: Blunt	GB/T[c] 9096	Good prediction, helped to study the effect of particle volume fraction on impact resistance.
(Ullah et al. 2013)	Izod	Abaqus/ Explicit	CFRP	Flat plate	Rigid: Blunt	ASTM D4812, D3518	Good prediction of damage sequence and pattern. Reasonable agreement of transient response.
(Yang et al. 2022)	Gas gun	LS-DYNA	GFRP	Curved plate	Rigid: Blunt, Spherical	GB/T[c] 1447, 1448, 1449, 1450.1	Satisfactory prediction of residual impactor velocity and sequential plate deformation.
(Long et al. 2021)	Gas gun	Abaqus/ Explicit	CFRP	Wing leading edge (Laminate/ Foam sandwich structure)	Flexible: Spherical	-	Good prediction of dynamic response and ultimate failure characteristics.
(Hu et al. 2016)	Gas gun	LS-DYNA	CFRP	Helicopter cockpit (Honeycomb sandwich structure)	Flexible: Spherical	-	Good prediction of deformation. Helped to enhance structure stiffness.
(Nunes et al. 2019)	Gun	LS-DYNA	AFRP	Flat plate	Rigid: Blunt, Spherical	ASTM D3039, D6641, D7078, D2344, D638	Good prediction of residual velocity and damage. Deviations when impact velocity approaches the ballistic limit.

[a] Fibre metal laminate; [b] Particle reinforced metal matrix composite; [c] China national standard.

6.2. Utilised Explicit FEM Solvers

When it comes to the choice of explicit FEM solvers for composite material impact testing, Abaqus/Explicit and LS-DYNA are the most commonly used options, as shown in Table 5. The report by Seifoori et al. (2021) is one of the few studies that have utilised Ansys Explicit Dynamics. Other potential explicit FEM solvers listed in Table 5 have received limited attention from researchers in the field of composite material impact testing.

6.3. Geometry of Test Specimen

Charpy and Izod test specimens are typically flat plates due to compatibility requirements. Similarly, flat plate specimens are commonly used in the drop weight method. However, other geometries are also possible in the drop weight method due to the absence of a strictly required method applied for the specimen clamping. For example, Sommer et al. (2022) tested tubes, while Seifoori et al. (2021) tested curved plates. Curved plates were also tested in high-velocity gas gun impact tests by Yang et al. (2022). In high-velocity impact tests, there is often enough space available to test entire structures, such as a wing leading edge as demonstrated by Long et al. (2021), or even a full-scale helicopter cockpit as shown by Hu et al. (2016).

6.4. Impactor Shapes

In low-velocity impact tests, rigid and blunt impactors are typically used. However, Boukar et al. (2022) utilised a cylindrical impactor in the drop weight method, while Perillo et al. (2014) used a spherical impactor. Seifoori et al. (2021) employed a conical impactor in their study. In high-velocity impact tests, Long et al. (2021) and Hu et al. (2016) used flexible and spherical projectiles to replicate bird strikes. For impacts involving rigid projectiles, such as those conducted by Nunes et al. (2019) for military purposes, blunt projectiles were also included.

6.5. Impactor Modelling

Impactors are typically modelled as solid bodies in simulations. However, Perillo et al. (2014) employed a shell surface model for the impactor, which reduced computational time due to the lower number of mesh elements, while still achieving a good correlation between numerical and experimental results.

6.6. Compliance with Standards

There is a clear trend towards compliance with ASTM standards in the field of impact testing on composite materials. Boukar et al. (2022) and Hufenbach et al. (2008) are the only studies that followed ISO standards, while Miao et al. (2022) and Yang et al. (2022) applied Chinese national standards. Standards are widely accepted in low-velocity impact tests such as Charpy and Izod, where the test specimen is clearly defined. However, the adherence to standards decreases for the drop weight method, and standards are often not considered necessary for high-velocity impact tests. The standards applied by Yang et al. (2022) and Nunes et al.

(2019) do not specifically refer to impact testing, but rather to the acquisition of material properties using tension, compression, shear, and bending mechanical testing methods.

6.7. Experimental and Numerical Correlation

In general, the researchers have reported a good or excellent correlation between experimental and numerical results. Only Yang et al. (2022) described their correlation as satisfactory. In terms of damage mechanisms and failure modes, several studies including Boukar et al. (2022), Sommer et al. (2022), Hufenbach et al. (2008), Ullah et al. (2013), Long et al. (2021), and Nunes et al. (2019) achieved good prediction through simulation. However, Nunes et al. (2019) reported disagreements when the impact velocity approached the ballistic limit, and Ullah et al. (2013) claimed to have achieved only reasonable agreement in transient response. Seifoori et al. (2021) achieved good numerical predictability of deformation, as did Hu et al. (2016), who used these predictions to improve the structural stiffness of the helicopter cockpit. Forces were successfully simulated by Boukar et al. (2022) and Hufenbach et al. (2008). Simulations also helped Hynes et al. (2022) understand the behaviour of experimental trials, and Miao et al. (2022) used simulations to study the effect of particle volume fraction on impact resistance.

7. Recommendations

For very slow impact simulation up to 10 m/s, a transient implicit approach may be feasible, as it takes time-dependent loads into consideration. However, as impact velocities increase, leading to higher loading rates and shorter impact durations, the implicit approaches provide more inaccurate results and become less reliable. An example of an implicit transient FEM solver is Ansys Transient Structural. Although implicit transient approaches can provide more accurate results, it requires a significant increase in computational resources and is challenging in terms of operational stability, as achieving convergence becomes more difficult. However, for faster impact velocities and large deformation issues, there is no alternative to explicit FEM solvers.

Ansys Explicit Dynamics, Ansys Autodyn, and Abaqus/Explicit are FEM solvers with a wide range of applications. Ansys Explicit Dynamics can handle both linear and non-linear material behaviour and enables complex contact simulations through advanced contact algorithms. As Ansys Explicit Dynamics utilises a modified version of Ansys Autodyn, both techniques behave similarly. Abaqus/Explicit provides sophisticated contact algorithms to simulate complex contact scenarios, as well as advanced material models to simulate fracture and failure.

PAM-Crash was originally developed for automobile crash simulations but is also used in other industries where impact safety is crucial. Similarly, LS-DYNA has a good reputation in the automotive industry and has been extensively validated for crash simulations, but is also widely used for other types of impact scenarios. Altair Radioss is another popular automotive crash safety solver that can also be used for drop testing and impact simulations. All three solvers provide advanced material models to simulate metal plasticity, foam degradation, and composite failure, as well as sophisticated contact algorithms to simulate airbag deployment and other impact scenarios. They also include tools to simulate restraint systems and pedestrian impact.

CZone (CZA) excels in the dynamic analysis of rigid and flexible multibody systems subjected to shock, vibration, and impact. It can handle large models including various contact algorithms and supports complex material models.

COMSOL Model Builder enables multiphysics simulations that include structural mechanics, acoustics, fluid mechanics, heat transfer, and electromagnetics, making it similar to MSC/NX Nastran in its application. Model Builder provides a user-friendly interface for creating and solving complex models and includes a wide range of physics modules and material models. The Nastran solver is capable of handling large and complex models, contains a wide range of material models and solver algorithms, and supports various optimization and fatigue analysis techniques.

However, for high-velocity impacts such as bird strikes or bullet impacts, Nastran may not be suitable as it does not provide equation of state (EOS) material models. Additionally, Nastran, CZone (CZA), and PAM-Crash do not support a Smoothed Particle Hydrodynamics (SPH) modelling approach, which may render them unsuitable for scenarios with large impactor deformation during impact.

7. Conclusion

Impact testing of composite materials is crucial for determining material properties and behaviour. Only with this knowledge can composite materials be safely applied in aerospace, automotive, and marine applications. Various experimental test methods have been developed for testing at low, medium, high, and hyper-impact velocities. For low-velocity impact testing, drop weight, Charpy, and Izod tests are available. Medium-impact velocities can be achieved with the aid of an inertia wheel or servo-hydraulic systems. For high-velocity impact tests, gas guns, light gas guns, and electromagnetic launchers are used instead. Standards ensure comparability, but the harmonisation of different systems is progressing slowly. Alternatively, impacts on composite materials can be numerically simulated using composite material design compatible CAD software and explicit FEM solvers. The combination of both experimental testing and numerical simulations provides a more comprehensive understanding of the impact behaviour of composite materials, offering insights that may not be achievable by using only one approach.

The following are the main conclusions of this review.

- Different experimental impact testing methods have the potential to achieve similar results, but the preparation, performance effort, and error tolerance may vary. While gas guns are popular for high-velocity impact testing, Charpy, Izod and drop weight tests are normally utilised for low-velocity laminate testing. The drop weight method allows testing curved composite shapes. However, Charpy and Izod impact tests are limited to composites with flat geometries.
- ASTM standards are the most widely followed standardisation system by researchers, although standards are occasionally ignored. However, the review of ASTM and ISO standards reveals significant limitations in their scope and adaptability. These standards, while providing a necessary framework for testing, do not fully encompass the diversity of composite materials and impact scenarios, potentially leading to gaps in testing protocols.
- As an alternative to experimental testing, numerical simulations of impacts on composite materials are feasible using various software options available in the market. However, Abaqus/Explicit, LS-DYNA, and Ansys Explicit Dynamics have been primarily adopted by researchers as explicit FEM solvers.
- Simulations are generally less expensive than experiments, as there is no need for expensive machines, measurement equipment, and a series of prepared test specimens with potentially complex geometries.
- Since simulations are simplifications of reality, the results are approximations and subject to a certain degree of inaccuracy. However, correlation with experimental data is possible within a few percent of deviation (0.9% is the lowest deviation reported in the literature studied).
- Simulations can provide a wider variety and more detailed results than experimental measurements, as they are observable at every moment during the impact.

- The numerical approach is excellent for the development of composite materials and for prototype stages of structures, while the experimental approach provides the most accurate results. Thus, both approaches have their own significance and can not fully replace each other. In simulations, the impactors can be modelled as solid bodies or a shell surface model, but the latter showed a reduced computational time with good correlation results. It is important to conduct an analysis of composite material behaviour under impact using both numerical simulation and experimental testing in order to achieve a precise and comprehensive solution.

Future research should focus on developing more inclusive and adaptable standards, capable of accommodating a broader range of materials and impact conditions. Such advancements are crucial to ensure that testing protocols remain relevant and effective against the backdrop of rapidly evolving composite material technologies. Additional research directions could include investigating less commonly used explicit FEM solvers and comparing their results for different composite material applications. A review of composite material design compatible CAD software and its capabilities and limitations would also be of great interest. Furthermore, it is noticeable that most reported research focuses on PMCs as materials, while MMCs and CMCs are less commonly studied. Therefore, more research in these composite material categories would be beneficial. Finally, additional research into the impact on different sloped or curved surfaces could be conducted to investigate their influence on the extent of damage and patterns.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Data Availability

The data used to support the findings of this study are included within the article.

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