Evaluation of Fibre Reinforced Polymer Composites Using Non Destructive Testing: an Overview

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Abstract

Composite materials are able to substitute conventional structural steel due to its numerous advantageous properties. However, they suffer from one of the major drawback that is damages caused due to different impact events. The damages occur beneath the surfaces which are not visible to the naked eye. The damage progresses slowly and ultimately leads to catastrophic failure. It is very much essential to understand the damage and failure mechanism of advanced composite materials in order to obtain cost-effective, durable and reliable design components. Therefore, it is essential to determine the parameters that influence the impact response. This paper focuses on the types of impact, factors influencing the impact, damages caused due to impact and evaluation of composites using different non-destructive techniques (NDT).

Keywords: Impact damage; Low velocity impact; Delamination; Matrix damage; NDT methods

1. Introduction

Composites play a vital role in this present era. It not only makes progressive contribution to its widest application but its own characteristic properties like high strength, high stiffness, high fracture toughness , low density, good wear resistance, corrosion resistance etc. make it all together a very versatile and different material [1]. We can find an enormous potential of these composite materials starting from sports goods to aircraft components. It comprises of complex materials showing distinctive anisotropic properties. A composite material is composed of a reinforcing fibre and a matrix resin whose combination exhibits characteristic mechanical and physical property. It gets its strength and stiffness from the fibre which is considered to be the load bearing constituent and possesses modulus higher than the matrix. Matrix performs three fundamental functions that includes (a) load transfer to the fibres, (b) providing protection against destruction, and (c) stabilizing the fibres. Fibres can be either synthetic or natural. Commonly used synthetic fibres are Carbon, Glass (E-glass, C-glass, S-glass), and Kevlar. The natural fibres include jute, sisal, coir, hemp, basalt, and bamboo. Sometimes filler materials are also added to the matrix to improve the characteristic properties [2]. Composites are classified either on the basis of matrix or on the basis of fibres. On the basis of matrix following is the classification table 1.

Table 1. Composite classification on the basis of matrix.

Name	Composition	Examples
Polymer Matrix Composites (PMCs)	Fibres- Glass, Carbon, Kevlar etc. Matrix can be 1.Thermoplastics like PVC 2.Thermosets like epoxy.	CFRP, GFRP, KFRP etc.
Metal Matrix Composites (MMCs)	Fibres- Ceramic fibres Matrix- Al, Mg, Ti, Fe, Cu	Al-SiC, Al-Al_2O_3 etc.

Ceramic Matrix Composites (CMCs)	Fibres- Whiskers, short fibres. Matrix- Ceramic	SiC-SiC.

However different manufacturing processes or contact with foreign bodies or any kind of accidental impact of any working tools may lead to the development of superfluous defects such as distorted fibres, voids, inclusions, and resin rich zones [3]. This low velocity impact can result in serious damages which might not be visible to the naked eye. The low velocity impact results in loss of laminate strength but does not puncture the material [4].The impact damage generally commence with matrix cracking followed by fibre breakage and then it gradually progresses with delamination leading to the degradation of residual properties of the structure. Numerous parameters can display the extent of such damage which includes sequential stacking of fibres, properties of constituent parts, and prevailing environmental conditions [5].

Sometimes, the presence of individual reinforcing fibres in a composite material is not sufficient enough to meet the desired requirement. Hybridization is the only possible solution to achieve the desired properties by combination of two or more reinforcing fibres (natural/synthetic). They consist of combination of two or more fibres where some fibres are of high modulus and some are of low modulus type. Different combinations include interply, intraply, and intra yarn [5]. This method is basically adopted to increase the mechanical properties and also the damage tolerance behaviour of different structures. They provide improved properties while reducing cost [4].

The damages which the composites underwent due to impact or repeated kind of loads sometimes created hurdle in the extensive use of these materials and subsequently reduced the performance. Hence proper detection and effective monitoring of this defect is very much essential. Although obtaining accurate solution for a multi-layered material is difficult, different computational approach preferably finite element method [6] can be implemented. Numerous contributions have been made by different researchers and academicians on both experimental and numerical investigations [7]–[11].

In this current review paper, types of impact, factors influencing the impact, damages caused due to impact are investigated. A brief review on the capabilities of different non-destructive techniques for identifying defects is also discussed. Different advantages and disadvantages of various methods are also presented.

2. Impact on composite specimen

The growth of our industries is largely hampered due to one of the most important aspect that is the damages caused to the composites due to impact. Behaviour of the structure or components due to impact is of great concern today as it hinders the strength significantly. Most of the time damage occurs inside the specimen due to which they are not visible from the surface of the specimen. Generally impact loading can be divided into the following categories:-

1. Low velocity impact lies in the range of (1- 10) m/s [12]. It does not always lead to the complete puncture of the material but expected to occur during the service life and manufacturing of the component [13]. Any tool drop in the shop floor to bird strike, there is possibility of occurrence of low velocity impact. Different aircraft, automobile, and marine components are exposed to this low velocity impact. The drop weight impact test, Izod and Charpy test equipments are used to assess the impact resistance property of the material. There are different parameters which affect the impact property of the composite materials like the kind of reinforcing fibre, stacking sequence of fibres, type of matrix, thickness of the specimen, etc. Matrix cracking, fibre splittings, delamination are the major failure modes observed in the composite material [14], [15].
2. High velocity lies in the range of 10-100 m/s. Localised damages are observed when the specimen is subjected to high velocity impact [16]. Runway debris hitting the aircraft during landing or take-off, hail strike, etc. is typical examples of high velocity impact. Compressed air gun and Gas gun equipment are used for conducting high velocity impacts. The shape and mass of projectile, material properties and thickness of specimen greatly influence the impact properties. Delamintaion, interfacial debonding, fibre fractures are some of the prominent damage modes observed in the specimen [17], [18].
3. Ballistic impact lies above 500 m/s. The ability of a material to withstand high velocity impact without getting perforated defines the ballistic limit. Ballistic impact occurs when a material is subjected to high velocity impact by certain projectiles in defence and military applications. The impact tests can be conducted using Projectile and Gas gun assembly. Various factors are responsible for influencing the impact resistance properties of materials like shape, size, hardness and density of projectile, different mechanical properties, ductility, strength, hardness, microstructure and thickness of the target plate. Fibre pull-out, breakages and delamination are some of the prominent failure modes [19]–[21].

4. Hypervelocity impact lies above 2000 m/s. Here projectile energy is more prominent and the influence of the shape parameter is also seen. Under this category, it is essential to understand the impactor and target materials behaviour to study the damages evolved. Typical examples include space shuttle orbit and anti-ballistic missiles. Different testing equipments include Plasma and Electrostatic dust accelerators, Light gas guns, Exploding foil/wire accelerators. Here projectile velocity, shape and energy including target plate's strength, hardness, ductility and microstructure are important factors which greatly influence the impact properties. Fibre breakages and perforations are the major failure modes observed in the impacted specimen [22]–[24].

2.1 Factors affecting impact properties

There are several factors which influence the impact properties are as follows [25], [26]:-

1. The energy absorption characteristic of a composite structure is greatly influenced by the type of reinforcing fibre. Higher is the strain to failure behaviour of the fibre, greater is the energy absorbing capability. The increase in specific energy absorption occurs with decrease in the density of the reinforcing fibres [27]. The energy absorption capability also varies with the change in stiffness of reinforcing fibres.
2. The fracture toughness of the thermoplastic matrix causes an increase in energy absorbing capabilities. In ductile materials, the increase in matrix failure strain results in decrease in energy absorbing capability while increase in energy absorption occurs for brittle fibre reinforcement. Any change in matrix stiffness leads to failure of brittle materials in various modes while there is small change in energy absorption for ductile materials.
3. When the orientation of fibre (θ) increases, the absorption of energy decreases nonlinearly and brittle fracture is observed particularly for carbon fibre reinforced polymer composites while for glass fibre reinforced composites, it decreases nonlinearly with lamina bending.
4. The nose shape of the projectile also greatly affects the energy absorption capability of the composite materials. At low velocity, blunt projectiles can penetrate the target more efficiently than hemispherical and conical projectiles. Similarly at high velocity, conical projectiles are more effective in perforating the targets with minimum energy.
   Thus, deformation in target plates is greatly affected by the nose shape of the projectile.

2.2 Damage Progression under impact loading

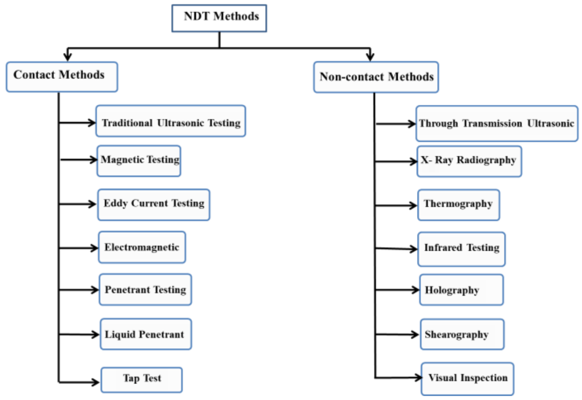
Various damage modes observed on the specimen under low velocity impact are:-

1. Matrix Failure
   Damage is initiated in the form of matrix cracks that occurs due to mismatch of the properties of the reinforcing fibre and matrix under transverse impact loading. In case of unidirectional layered composites, matrix cracks in a plane parallel to the orientation of fibres.
2. Delamination
   This mode of failure is very important as it can cause sub-surface damage which might not be visible from the impacted side. Delamination occurs due to change in fibre orientation between the adjacent layers. The greater is the mismatch in the orientation of fibres, greater will be the delamination area which in turn will affect the stacking sequence, laminate thickness and material property. Delamination is induced by shear and bending cracks.
3. Fibre failure
   Fibre breakage occurs at a later stage of the damage progression after matrix cracking and delamination. It appears at the non-impacted/back side of the specimen due to high tensile bending stresses.
4. Penetration
   When failure of reinforcing fibres reaches a critical point, then penetration of the specimen is observed. This type of failure is considered to be macroscopic in nature.

3. Damage Detection Methods

Non-destructive methods are considered to be important for evaluating the composites. They are always in demand because of its unique speciality, reliability and rapid applicability [20]. They prove to be most advantageous in detecting, localizing and determining the extent of damage in the materials. The damage detection is considered to be ideal when it is easy to use and capable enough to identify almost all the failure modes in the concerned material.

In this section, some of the Non Destructive Testing Techniques and Destructive Testing Techniques are discussed. Basically there are two methods of NDT that is Contact and Non-Contact Methods which is classified below.



(a)Tap Test:-
The experimental setup consists of a clamp to fix the specimen as a cantilever beam, connecting cables, accelerometer, laptop and an accelerometer data reader. The beam specimen was fixed to the clamp with a given length of beam free to hang. At the free end, an accelerometer was mounted. The accelerometer data reader collected vibration acceleration data and showed it in the software. The specimen is given some displacement in the vertical direction and released such that it vibrated freely and got damped on its own. The vibration data are collected from the laptop through the installed software. Three sets of readings corresponding to each test were taken.

(b)X-Ray Radiography:-
X-Ray is used to detect internal defects or fractures in materials that allow X-Ray penetration, without having to manipulate the material. In this way, the material remains in the same physical condition before and after the test. Penetrant like Zinc-iodide is mostly used due to its wide scale availability. Delamination is visible in this type of testing if its direction is not upright to the x-ray beam. Different types of radiography are available and each is having its own subsequent applications [28].
1. Film radiography [29]
2. Computed radiography [30]
3. Computed tomography [31]
4. Digital radiography [32].

(c) Ultrasonics Testing:-
In order to detect flaws relating to surface and sub-surface, cracks, shrinkage, discontinuities, flakes, and faults can be easily achieved using this test in which the working frequency range is around 5 MHz or below. Here, the required specimen is subjected to ultrasonic signals and then for maximum energy transmission it is either coated with gel or is immersed in water. A transducer is kept at the back in order to assess the quality of the specimen as shown in figure 1. Generally, there is conversion of ultrasonic signal into an electrical signal which is amplified and subsequent displayed on an oscilloscope [3]. Three forms of scans are available that is scan A, B, C. C scan is ideally found to be suitable for delamination detection. B-scan typically tells about the depth of the damage and C-scan helps in determining exact location of the damage. One advantage is the accurate determination of the depth of damage and one disadvantage is the long-time which it takes in analysing the results in comparison to thermography and shearograph [33], [34].

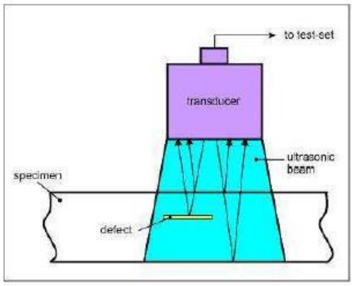


Fig.1: Ultrasonic Testing Method

(d) Thermography Testing:-

This technique depends solely on the absorption and heat dissipation in a composite structure which is basically damaged. Active and Passive thermography are the two methods available. The former involves an uninterrupted heat flow whereas the later involves a sudden rise in temperature on the surface of the component. Delaminations caused due to impact loading can be easily detected by this technique and also causes a change in thermal radiation of the area [35]. However if the defect is deep enough then it cannot be inspected by this testing. Vibrothermography [36] is another approach where vibrations of low amplitude are focussed to create heating zone locally in a specimen and then an IR camera collects the required data. Similarly IRT (Infrared Thermography Testing) is based on the recording of the thermal radiation emitted by a surface of a specimen by means of an infrared camera [37].

(e) Electromagnetic Testing:-

This is another method of NDT technique which comprises of many sub-groups as:

1. Eddy Current Testing
2. Remote field Testing
3. Flux leakage Testing
4. Alternate current field measurement Testing
5. Microwave Testing.

Out of the above sub-groups, eddy current method is widely used [37]. This technique uses the concept of electricity and magnetism to identify and detect the defects or any faults underlying the specimen. Inside the test specimen electric current, magnetic field or both is induced and corresponding electromagnetic response is observed.

(f) Acoustic Emission Testing:-

Acoustic Emission testing is an important method for studying the characteristic behaviour of materials subjected to stress. This is a passive method in comparison to other NDT methods. It is based on the detection and conversion of high frequency elastic waves into electrical signals. When a component or structure is subjected to stress, flaws or discontinuities are produced thereby releasing energy. Transducer then receives this energy in the form of high frequency waves and transforms into a voltage which is subsequently amplified and refined as AE signal data with the help of timing circuits. Received signal is analysed corresponding to its intensity, frequency count and its location. It includes a wide range of application starting from structural health monitoring to predictive diagnosis. It can also be used for detecting faults and pressure leaks in tanks, vessels, pipes, as well as for monitoring the progression of corrosion in welding [38]. Baskov et al. [39] studied the analysis of acoustic-emission signals generated due to ultrasonic waves propagating in a polymer composite material. Arumugam et al. [40] identified various failure mechanisms in bidirectional glass/epoxy laminates loaded in tension using acoustic emission (AE) analysis.

(g) Shearography Testing (Speckle Shearing Interferometry):-

Shearography is a laser based optical technique for determining deformations present on the surface. It measures derivatives of surface displacements, thus eliminating the need to numerically differentiate displacement data to yield strains. It eliminates the reference beam of holography, which leads to the development of simplified optical setup, reduced coherence length requirement of laser, and not requiring special vibration isolation. These advantageous factors have rendered shearography a practical measurement tool. Consequently, it has received wide industrial acceptance for nondestructive testing [41].

(h) Holography Testing:-

Holography provides a 3d image by means of interference [42]. It consists of two steps:- 1. Recording a wavefront and 2. Reconstruction of wave. Here fringe pattern is obtained as a result of interference of the deformed and undeformed wavefronts of the same object. It requires only coherent light instead of any lenses or other imaging device. The only difference between shearography and holography is the yielding of information. Shearography describes the derivative of surface displacement while holography represents the surface displacements [42].

Table 2. Few developments in the study of hybrid composite structures using various NDT techniques.

Ref Nos.	Inspection Type	NDT Method used
2000 [43]	Delamination evaluation of CFRP, GFRP, KFRP composite materials.	Ultrasonic Testing
2001 [44]	Impact damage of CFRP	Scanning Acoustic

	laminates(CF/Epoxy and CF/PEEK) at low and hih temperature	microscopy(SAM)
2002 [45], 2017 [46],2021 [47], 2022 [48]	Damage detection of carbon epoxy laminate when subjected to low velocity impact.	X-ray and deply technique, Active thermography and digital signal processing, EMW-NDT, Edge illumination X-ray phase contrast imaging
2004 [49]	Impact damage assessment of carbon/epoxy and hybrib(carbon/glass/Kevlar epoxy) for comparative study.	Air coupled ultrasonic C-scan and X-ray radiography
2005 [50]	Carbon fibre/epoxy laminates of square cross-section at low temperature(20 to -150^{o}C)	C-Scan Ultrasonic inspection and Optical and Scanning Electon Microscopy
2009 [51]	Damage detection of military aircraft wings and body panels made of sandwich structures	Acoustic detection system
2012 [52]	Detection of impact damage on carbon fibre reinforced epoxy laminates	Electronic speckle pattern interferometry(ESPI), Shearography, X- radiography , ultrasonic testing
2015 [53]	The inspection of three types of specimens namely (a) GFRP plate (b) Al-GFRP-Al (c) CFRP.	PZT sensing technique, Ultrasonic scanning, Pulsed Thermography, Vibration based inspection.
2021 [54]	Damage detection in composite materials	Tap test

Different Destructive Testing techniques include Thermal deplying, Optical Microscopy, Scanning Electron Microscopy.

4. Conclusion

The current research paper attempted to study the impact response of fibre reinforced polymer composites and various parameters influencing the impact response. The damages and the different modes of failure caused due to the low velocity impact loading are also studied. Fibre reinforced polymer composites are widely used in aerospace and automobile industries. Understanding the damage mechanism is very much essential to predict the failure and also to come up with cost-effective and reliable product design. Evaluation of composite materials using non-destructive testing becomes demanding and crucial. Various advantages and disadvantages of NDT methods in identification and determination of defects are also investigated.

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