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A Study on Different Failures of Composite Materials

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Abstract — Composites are the important engineering materials made from two or more different materials, which has significantly different physical and chemical properties and which also remain distinct and separated at the microscopic level within finished structure. This material provides better mechanical properties than the parent metals. Composite materials have shown boundless engineering application where strength to weight ratio, cost effectiveness and ease of fabrication are mainly required. Composites include a wide range of the products for different application ranging from aerospace, sports, electronics industries, construction, automobile components, furniture and insulation panels made from different fibers, and textiles.

It is observed that many defects which may arise from composite materials in fibers, matrix and lamina. These defects, if they exist include misalignment of fibers, cracks in matrix, non uniform distribution of the fibers in the matrix, voids in fibers and matrix, delaminated regions, and initial stress in the lamina as a result of its manufacture and further treatment. These defects tend to propagate as the lamina is loaded creating an accelerated rate of failure. This paper presents a study and analysis of different failures commonly seen in different composite materials.

Keywords- Composite material, imperfections, delamination, fiber, matrix.

1.INTRODUCTION

Two or more chemically different constituents combined macroscopically to yield a useful material which is called composite material. One constituent is called reinforcing phase and the one in which the reinforcing phase is embedded is called matrix.

Composite material offers to engineers many advantages that are especially appealing for engineering applications. They are made up of combining two or more materials in such a way that the resulting materials have improved properties then their parent materials . The composite materials consist of high specific strength, high specific stiffness, more thermal stability, more corrosion and wear resistance, high fatigue life. When designed properly, the new combined material exhibits better properties than would each individual material. The requirement of composite material has gaining momentum in these days due to these properties. Apart from defense and automotive industries, aircraft industries also using composites largely in the present days for reducing the weight of the aircraft and improved strength. The addition of high strength, high modulus refractory particles to a ductile metal matrix produce a material whose mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement.

1.1Advantages of Composite Materials

Composites can be very strong and stiff, yet very light in weight, so ratios of strength-to-weight and stiffness-to-weight are several times greater than steel or aluminum. The few important advantages are as under.

- High specific strength and
- High specific stiffness Long fatigue life
- High creep resistance
- o Low coefficient of thermal expansion
- o Low density
- Low thermal conductivity
- Better wear resistance
- Improved corrosion resistance
- o Better temperature dependent behaviour

Disadvantages and Limitations of Composite Materials

•Properties of many important composites are anisotropic - the properties differ depending on the direction in which they are measured, this may be an advantage or a disadvantage

•Many of the polymer-based composites are subject to attack by chemicals or solvents, just as the polymers themselves are susceptible to attack

•Composite materials are generally expensive

•Manufacturing methods for shaping composite materials are often slow and costly.

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1.2Functions of the Matrix Material

•Provides the bulk form of the part or product made of the composite material

•Holds the imbedded phase in place, usually enclosing and often concealing it.

•When a load is applied, the matrix shares the load with the secondary phase, in some cases deforming so that the stress is essentially born by the reinforcing agent.

1.3Functions of the Reinforcement

Function is to reinforce the primary phase. Imbedded phase is most commonly one of the shapes Fibers ,Particles, Flakes. In addition, the secondary phase can take the form of an infiltrated phase in a skeletal or porous matrix Example: a powder metallurgy part infiltrated with polymer.

2. Different Damages seen in Composite Materials

The following are the types of defects that generally occur in a composite

- 1.Fibre-matrix debonding
- 2) Matrix cracking and crazing
- 3) Fibre misalignment
- 4) Density variation (due to resin distribution)
- 5) Cut or broken fibres
- 6) Improper curing of resin
- 7) Delamination
- 8) Impact damage (tool drop)
- 9) Inclusions
- 10) Abrasion and scratches
- 11) Voids and blisters
- 12) Machining problems
- 13) Wrinkles

Following are the most commonly seen defects.

-A matrix crack typically found where there is a high stress concentration or can be associated with thermal shrinkage during manufacture especially with the more brittle high temperature adhesives.

-Debonding observed when an adhesive stops adhering to an adherend or substrate material. Debonding occurs if the physical, chemical or mechanical forces that hold the bond together are broken.

-Delamination is a failure in a laminated, often a composite, which leads to separation of the layers of reinforcement or plies. Delamination failure can be of several types, such as fracture within the adhesive or resin, fracture within the reinforcement or debonding of the resin from the reinforcement.

-A void or blister is pore which remains unoccupied in the composite material. A void is typically result of imperfection from the processing of the material and it is generally undesirable. Because a void is non uniformity in a composite material, it can affect the mechanical properties and its lifespan. Blisters are generated in outermost layers. ---Porosity is caused by volatile entrapment during the curing of the resin

-Wrinkles are common when adding new layers; it is significant to eliminate them as they can weaken the composite. --The inclusion of foreign bodies in the composites can include backing film, grease, dirt, hair to finger prints, which can lead to areas rich or deprived of resin.

-In the lamina scale three basic failure modes (Unidirectional) can be distinguished:

1.brittle

2.brittle with filament pullout

3.staggered failure, i.e., brittle failure with filament pullout and matrix shear or debonding along the fibers

2.1 Longitudinal Compression

The characteristic modes of failure are:

- (1) Filament micro buckling with matrix elastic- fully bonded.
- (2) Matrix yielding or interfacial debonding followed with filament micro buckling.
- (3) Panel micro buckling,
- (4) Shear failure.
- (5) Ply separation because of transverse tension.

2.2 Transverse Tension

In this case, failure of composite is dominated from the high strain concentration in matrix. The primary failure modes are tensile matrix failure and then fiber debonding. A great amountl of analytical and experimental work has been reported on the stress distributions in transversely loaded unidirectional composites. The most significant result is the strain concentration in tile matrix at fiber-matrix interface .

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2.3 In-Plane Shear

The failure mechanism under this type of loading are matrix shearing, fiber debonding or a combination of the two. The intralaminar shear strength can be determined by the dividing shear strength of the matrix with the shear stress concentrations because of voids and fibers. In many composites the intralaminar shear strength is approximately equal to the inter laminar shear strength. A fairly good correlation is found between the latter and the transverse tensile strength

2.3 Biaxial Loading

Under biaxial stress conditions one or more of the failure modes discussed may be activated. Macroscopic and microscopic failure criteria are proposed. Macroscopic criterias are based on maximum strain or distortional energy. Heterogeneous microscopic failure criteria taking into consideration nonlinear response have been studied.

2.4 Progressive Damage

Both matrix controlled and fiber controlled types of failure can be separately and sequentially seen during the loading of the various lamina within a laminate. At some point so much damage accumulated in the form of these local failures that the laminate can no longer able to sustain load. This then comprises the ultimate load, failure in the broad and total sense.

2.5 Micro-damage in composite materials

The first damage occurring requires here low energy consumption (interface or matrix failure), while the last stages (fiber breakage) requires more significant energy level. The first step of damage begins logically at zones of lower strength like the matrix fibre interfaces and matrix itself, with failure over small distances which are intralaminar cracks. Intralaminar damages mainly seen in the areas where fibres are not oriented in axis of the load, when the strain in the matrix reaches its breaking strain.

2.6 Fatigue damages in composite materials

It is important to note that fatigue strength may change in function of the composite (composition, layer, anisotropy, etc) and so fatigue characterization is needed to study for each material. The fatigue damage criterion is also a main factor and depends on the use, the function of the composite part.

3. Sources of Defects and Damages in Composite

There are two main sources which can introduce defects and/or damage in a composite. These two sources are:

- 1. Fabrication or processing defects and
- 2. Service defects

1.Fabrication or Processing Defects:

The defects that can occur during fabrication or processing are listed below:

- 1. Abrasions, scratches, dents and punctures
- 2. Cut fibres
- 3. Knots and kinks in fibres
- 4. Improper splicing (joining) of layers
- 5. Voids (due to poor processing, high humidity)
- 6. Inferior quality of the materials used
- 7. Improper curing of resin
- 8. Resin rich or resin lean areas due to improper distribution of resin
- 9. Inclusions and contamination
- 10. Mandrel removal problem
- 11. Machining problems
- 12. Improper tooling
- 13. Tool drop causing low energy impact which results in impact damage

2. In-field or Service Defects:

The defects that can occur during in-field or service are listed below:

- 1. Shock
- 2. Environmental cycle of temperature and humidity
- 3. Exposure to hazardous chemicals
- 4. Exposure to radiations
- 5. Bacterial degradation
- 6. Vibrations
- 7. Improper handling and storage
- 8. Tool drop

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- 9. Abrasions, dents and punctures
- 10. Corrosion
- 11. Erosion due to sand and dust
- 12. Improper maintenance or repair

4. Damage Mechanisms in Fibrous Composites

The damage mechanisms in a fibrous composite are broadly categorized as:

- 1. Micro level damage mechanisms
- 2. Macro level damage mechanisms and
- 3. Coupled micro-macro level damage mechanisms
- The local level mechanisms are subcategorized based on constituent level as
- i. Fibre level damage mechanisms
- ii. Matrix level damage mechanisms and
- iii. Coupled fibre-matrix level damage mechanisms

4.1. Micro-level Damage Mechanisms:

First, we will look at the micro-level mechanisms in detail as follows:

4.1.1 Fibre Level Damage Mechanisms:

The fibre failure mode is considered the most catastrophic mode of failure in laminates. This is due to fact that the fibre is the load carrying constituent. The failure of fibres can take place because of various stress components. The damage mechanisms of fibre are explained below in detail.

4.1.2 Fibre Fracture/Breaking:

The fibre breaks into two or more pieces along its length when the axial tensile stress (or strain) are in the fibre exceeds the axial strength (or maximum allowable strain) for the fibre. This kind of fracture seen in brittle fibres. Such fractures are more catastrophic in nature than other modes of fibre failure. This fibre fracture may also take place in shearing when shear stress or strain exceeds the maximum allowable stress or strain.

4.1.3 Fibre Buckling or Kinking:

This type of failure observed when the axial load on the fibre is compressive in nature. The axial compressive stress responsible for the fibre to buckle. This form of fibre failure is called as fibre kinking. The critical stress at which kinking takes place is function of material properties of fibre , matrix properties and the distribution of fibres in the matrix. In general, the fibre kinking first starts at the place of fibre misalignment or local defects.

4.1.4 Fibre Bending:

The bending of fibre can starts under flexural load. The bending of fibres also depends upon various properties of fibre and matrix along with the fibre arrangement.

4.1.5 Fibre Splitting:

The fibre fails in this way when the transverse or hoop stresses in this fibre exceeds the maximum allowable value. Further, this can also be happen when these stresses in the interface/inter phase region -region in matrix very close to the fibre, exceed the maximum allowable stress.

4.1.6 Fibre Radial Cracking:

The hoop stresses can also create the radial cracking of the fibre. This type of cracking is seen in some of the fibres.

4.1.2 Matrix Level Damage Mechanisms

.1 Matrix Cracking:

When the stress in the matrix exceeds the strength of this matrix, matrix cracks are developed. There are two types of matrix cracks that developes in a unidirectional lamina. The cracks are either perpendicular or parallel to the fibre directions. In the first type, the cracks are developed when axial stress in lamina is tensile in nature. In the second type, the cracks are developed when the in plane transverse stress in lamina is tensile in nature.

2 Fibre Interfacial Cracking:

When the in-plane transverse stresses for matrix are tensile in nature, the weaker interface between fibre and matrix is broken. A crack in this matrix region at this location is initiated. This crack grows along fibre length. This leads to the debonding of the inter phase between fibre and matrix. This mode of damage is called "transverse fibre debonding"

4.1.3 Coupled Fibre-Matrix Level Mechanisms

1 Fibre Pullout:

The fibre pullout takes place when the bonding between fibre and matrix becomes weak and fibres are subjected to tensile stress. If this fibres are already broken then they just slide through the matrix and come out of it. This phenomenon is called fibre pullout.

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2 Fibre Breakage - Interfacial Debonding:

When these fibres break the interface close to tip of broken fibre, they act as a site of stress concentration. The interface may fail then, leading to debonding of fibre from matrix.

3Fibre Failure due to Matrix Cracking:

The matrix cracks formed here may terminate at fibre interface at low strains, while at the high strains, the stress at the crack tip may be exceed the fracture stress of the fibres, leading fibre failure.

4 Transverse Matrix Cracking:

The interface failure causing debonding from the matrix can act like as a stress concentration site for in-plane transverse tensile stress. When these stresses exceeds the limiting stress in matrix, they lead to through thickness transverse crack in the matrix

4.2. Macro-level Failure Mechanism:

The macro-level mechanisms are laminate level failure mechanisms. Here we are studying the delamination. It is seen that the adjacent layers are bonded together by thin layer of resin between them. This interface layer transfers displacement and forces from one layer to another . When this interface layer becomes weak or damages completely, causes the adjacent layers to separate. This mode of failure is called delamination. Delamination decreases the strength and stiffness and so limits the life of a structure. Further it creates stress concentration in load bearing plies and a local instability leading to the further growth of delamination which results in the compressive failure of the laminate.

4.2.1 Manufacturing Defects

It is the most common reason for the delaminations in a laminate. Improper laying of laminae, insufficient curing temperature, pressure, duration of curing, air pockets and other inclusions are some of the reasons responsible for the manufacturing defects causing delamination.

4.2.2 Loading which creates Transverse Stresses

The interface is always weaker in transverse strength as compared to the layers. so its failure is dominated from the transverse stresses. The interface generally fails under tensile load applied normal to it . Also delamination can take place due to compressive stresses in its inplane direction causes buckling, which in turn, causes delamination. The in plane loads applied to the angle ply laminate may cause delamination in it.

4.2.3 Laminate Geometry

The geometry of laminate may lead to the three dimensional state of stress locally in the interface leading to the high inter laminar stresses.

4.3Coupled Micro-Macrolevel Failure Mechanisms:

The transverse matrix cracking of a lamina is the important failure mechanism. The through thickness transverse crack may propagate to the neighboring lamina causing to break. There can be another scenario that the crack terminates at neighboring interface. This crack front act as stress concentration site for interface between a adjacent layer causing it to weaken, so initiating a delamination crack in the interface. This delamination growth may lead to failure of the laminate. Another scenario is also possible where the transverse through thickness crack leads to interface crack in the adjacent layer causing partial delamination. This delamination can cause the transverse crack in the next layer.

5. CONCLUSION

Due to the challenges of development of material with better properties in advance engineering fields, composites have shown cost and energy advantages over traditional materials. The combination of different particles as rainforcement found to give better mechanical and physical properties.

In this paper, a brief study and analysis of some of the common failure detection methods of composites materials systems are discussed. In different applications of composites it is important to understand the presence nature and extent of damage by nondestructive testing. Knowledge of the physical failure mechanisms will enable one to select or develop better fabrication technique.

Several limitations must be overcome in order to exploit the full potential of Metal matrix composites. At first proper manufacturing process should be developed and implemented. Secondly properties of composites are greatly depended on the volume percentages of rainforcement particles. The current challenge is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composites industry.Failure criteria, empirical or theoretical can be discussed to correlate amount of damage with residual strength of a component.

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