Introduction

In this module we will be dealing with failure in unidirectional fibrous composites. We will look at the meaning of failure and damage in context of composites. We will be addressing the commonly used lamina/laminate failure theories used in the design of laminated composites. Further, we will address the difficulties envisaged in the development or extension of the theories for homogeneous, isotropic materials to heterogeneous and orthotropic composite laminates. We will deal with the popularly used failure theories in detail along with some numerical examples.

In the present module we will deal with failure and damage in context of unidirectional fibrous laminated composites.

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Failure and Damage

Failure of a structure or a system, in general, refers to the condition that the structure or system stops functioning satisfactorily. The criteria to decide the satisfactory functioning can be subjective or quantitative. In general, in engineering applications the failure is quantified using various criteria. The following are some of the criteria used to quantify a failure:

1. Strength
2. Form failure
3. Stiffness
4. Yielding
5. Fatigue life
6. Bending
7. Corrosion resistance
8. Impact resistance
9. Resistance to lightening
10. Resistance to hazardous environmental agents

However, the list is in-exhaustive with many such criteria. In general, failure is understood as complete de-functioning of the structure.

In case of composites, the failure of a lamina or laminate needs special attention. In case of laminates there are a number of local failures before it completely breaks into two or more pieces. The local level failure is called as “damage”. In case of fibrous composites the term “local” refers to the individual constituent phases – fibre and matrix. Thus, damage in case of fibrous composites is a micro level event.

It is important to note that the ultimate failure (rupture/breaking) of the laminate takes place by gradual accumulation of damage. In turn, this is manifested at the lamina or laminate level by some form of failure. Thus, the “first failure” in laminates does not mean the “final failure”. The development of additional local failures with increasing loads or time is termed as “damage accumulation”. The terms “damage growth” and “damage propagation” are equivalently used for damage accumulation. The branch of mechanics which deals with the study of initiation and accumulation of damage until and including complete rupture is called as “damage mechanics”.

In this lecture we are going to see the fibre-matrix level failure mechanisms in detail. The failure at lamina/laminate or macro-level is the ultimate result of the local failures. Thus, the understanding of these mechanisms is a key point in the development of a reliable and accurate failure theory for laminated composites. Further, this understanding also helps in developing new materials with higher strength.

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Defects in Composites

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

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

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. **In-field or service defects**

The defects in these two categories are listed below.

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

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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 further subcategorized based on constituent level as

i. Fibre level damage mechanisms
ii. Matrix level damage mechanisms and
iii. Coupled fibre-matrix level damage mechanisms

A. Micro-level Damage Mechanisms:

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

a) Fibre Level Damage Mechanisms:

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

1) Fibre Fracture/Breaking:

The fibre breaks into two or more pieces along its length when the axial tensile stress (or strain) in the fibre exceeds the axial strength (or maximum allowable strain) of the fibre. This kind of fracture occurs in brittle fibres. Such fractures are more catastrophic in nature than other modes of fibre failure.
The fibre fracture may also take place in shearing when the shear stress or strain exceeds the maximum allowable stress or strain.
The fibre fracture is depicted in Figure 6.1(a).

2) Fibre Buckling or Kinking:

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

It is seen that the kinking of fibres takes place in a sharply defined region. This region is called as kink band. In general, the kink band is oriented at an angle with respect to fibre direction.
This mechanism is one of the key failure mechanisms for laminates under compression. This failure mechanism triggers the other failure mechanisms leading to a complex and inter-related

mechanisms.

The fibre kinking is depicted in Figure 6.1(b).

***3) Fibre Bending*:**

The bending of fibre can take place under flexural load. The bending of fibres also depends upon the properties of fibre and matrix along with the fibre arrangement.
The fibre bending is shown in Figure 6.1(c).

***4) Fibre Splitting*:**

The fibre fails in this mode when the transverse or hoop stresses in the fibre exceeds the maximum allowable value. Further, this can also happen when these stresses in the interface/interphase region (region in matrix very close to the fibre) exceed the maximum allowable stress. The fibre splitting is elucidated in Figure 6.1(d).

***5) Fibre Radial Cracking*:**

The hoop stresses can also cause the radial cracking of the fibre. This type of cracking is seen in some of the fibres. The radial cracking of a fibre is shown in Figure 6.1(e).

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b) Matrix Level Damage Mechanisms:

There are two main damage mechanisms in matrix. These are: Matrix cracking and fibre interfacial debonding. These are explained below.

1) Matrix Cracking:

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

It is generally seen that the matrix cracks develop along the preferred directions in unidirectional lamina. The matrix cracks which are parallel to the fibre direction cause significant modulus degradation whereas the matrix cracks which are perpendicular to the fibre direction cause less degradation in modulus. The first mode of damage is very critical as one of them causes significant degradation. The second mode can go undetected sometimes. This is very dangerous from safety point of view. For example, for gas pipes leakage is an important criterion. If such damage is not detectable, it can lead to a catastrophe. This damage is shown in Figure 6.2(a), (b).

2) Fibre Interfacial Cracking:

When the in-plane transverse stresses in matrix are tensile in nature, the weaker interface between fibre and matrix is broken. A crack in the matrix region at this location is initiated. This crack grows along the fibre length. This leads to the debonding of the interphase between fibre and matrix. This mode of damage is also called **"transverse fibre debonding"**. This damage is shown in Figure 6.2(c).

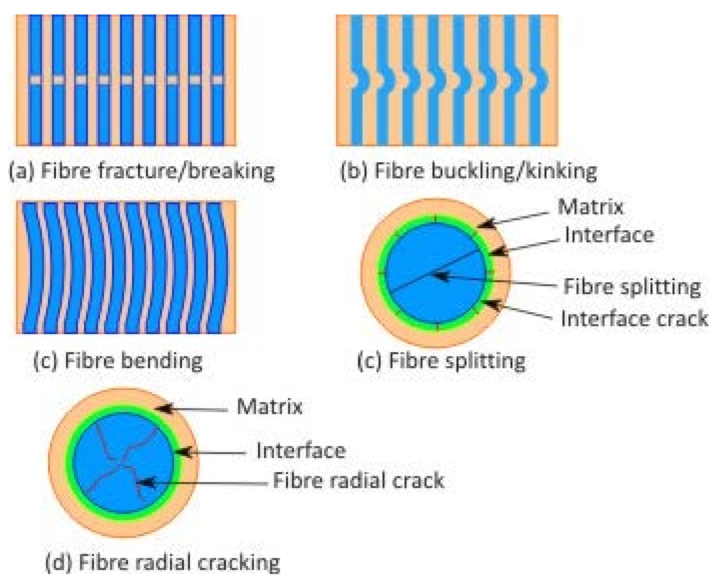

Figure 6.1: Fibre-level damage mechanisms

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c) Coupled Fibre-Matrix Level Mechanisms:

***1) Fibre Pullout*:**

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

The fibre pullout is shown in Figure 6.3(a).

***2) Fibre Breakage and Interfacial Debonding*:**

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

The fibre breakage leading to interfacial debonding is shown in Figure 6.3(b).

***3) Transverse Matrix Cracking*:**

The interface failure causing debonding (as in fibre breaking and interfacial debonding in above case) from the matrix may act like as a stress concentration site for the in-plane transverse tensile stress. When this stress exceeds the limiting stress in matrix, it leads to through thickness transverse crack in the matrix.

The through thickness transverse matrix cracking is shown in Figure 6.3(c).

***4) Fibre Failure due to Matrix Cracking*:**

The matrix cracks formed (as in matrix cracking case above) may terminate at fibre interface at low strains, while, at high strains, the stress at the crack tip may exceed the fracture stress of the fibres, leading fibre failure.

The fibre failure due to matrix cracking is depicted in Figure 6.3(d).

***5) Interfacial Shear Failure*:**

The fibre fracture or fibre failure due to matrix cracking may cause the matrix crack to propagate as macro-crack under opening mode until it hits an interface. The shear stresses may cause its propagation in sliding mode leading to a progressive failure of the interface.

The interfacial shear failure is shown in Figure 6.3(e).

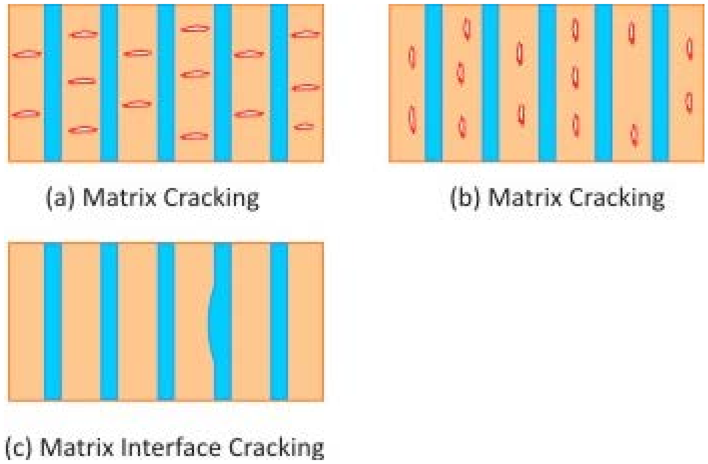

Figure 6.2: Matrix-level damage mechanisms

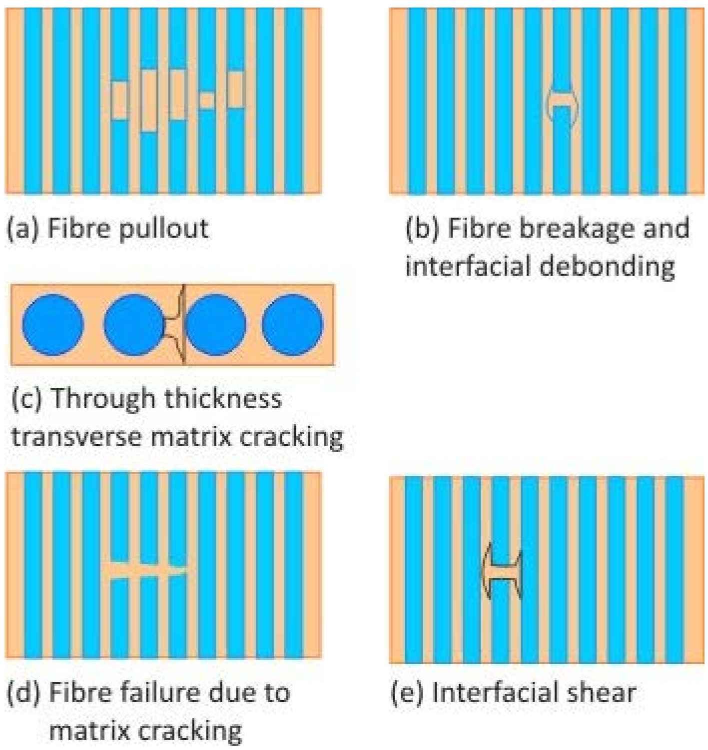

Figure 6.3: Fibre-matrix coupled failure mechanisms

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B. Macro-level Failure Mechanism:

The macro-level mechanisms are laminate level mechanisms. Here, we are addressing the delamination. It is seen that the adjacent layers are bonded together by a thin layer of resin between them. This interface layer transfers the displacement and force from one layer to another layer. When this interface layer weakens or damages completely, it causes the adjacent layers to separate. This mode of failure is called delamination. It is shown in Figure 6.4.

Delamination reduces the strength and stiffness and thus limits the life of a structure. Further, it causes stress concentration in load bearing plies and a local instability leading to a further growth of delamination which results in a compressive failure of the laminate. In these two cases delamination leads to a redistribution of structural load paths which, in turn, precipitates structural failure. Hence, delamination indirectly affects the final failure of the structure thus affecting its life. Therefore, delamination is known as the most prevalent life limiting damage growth mode.

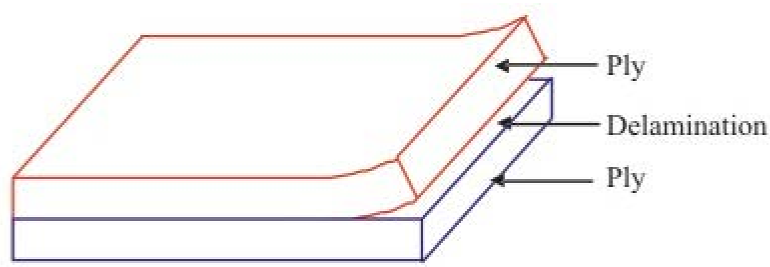

Figure 6.4: Macro-level damage mechanism (Delamination)

Causes of Delamination:

Delamination can occur due to variety of reasons. The situations which can lead to delamination initiation and its growth are explained below.

a) Manufacturing Defects

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

b) Loading Generating Transverse Stresses

The interface is weaker in transverse strength as compared to the layers. Hence, its failure is dominated by the transverse stresses. The interface generally fails under tensile load applied normal to it (see Figure 6.5(a)). Also, the delamination can take place due to compressive stresses in its inplane direction causing buckling, which in turn, causes delamination.

The inplane loads applied to angle ply laminate can cause delamination in it. This is because the bending-stretching coupling can give rise to transverse stresses in the interface. A schematic illustration of how axial tensile loading of angle ply laminates cause rotation of the plies is shown in Figure 6.5(b). This rotation of the plies generates the interlaminar shear stresses, which is one of the crucial factors in delamination.

***Note*:** The Inter-laminar stresses are the stresses in the interface between two adjacent layers. The existence to these stresses is shown in various references. Further, these stresses can be very high locally depending upon various situations. We will also see the existence of these stresses in a later chapter.

c) *Laminate Geometry*

The geometry of the laminate can lead to a three dimensional state of stress locally in the interface leading to high interlaminar stresses. Some of the geometries of the laminate and structures are shown below in which delamination damage will be a major damage mode.

i. **Free Edge:**
The free edges of the laminate have very high transverse normal (σ_{zz}) and shear (τ_{xz}, τ_{yz}) stresses. It is shown that significant interlaminar stresses are induced in regions near the laminate free edges. Interlaminar stresses near the free edges can be controlled to an extent through the choice of materials, fibre orientations, stacking sequence, layer thickness and the use of functionally graded materials. However, when free edges are present, interlaminar stresses can be completely eliminated through the use of a homogeneous material, locally. The delamination shown in Figure 6.4, infact, is an edge delamination.

ii. **Notch:**
Notch in the laminates acts like an external crack giving rise to high three dimensional stress state in the vicinity of the notch (See Figure 6.5(c)).

iii. **Cut-out:**
Cutouts are inevitable in structures. Cutouts are made to pass electric wires; fluid passage as in the wings, doors and windows in the fuselage of an air vehicle. These are, especially in aerospace vehicles, made also to reduce the weight of the component. The cutout boundaries act like free edges leading to significant transverse stresses. This is one of the most common site for onset of delamination. A laminate with cutout is shown in Figure 6.5(d).

iv. **Ply Drop/Termination:**
The optimum design of composite structures in air vehicles is important. As a result of the optimization (e.g. weight minimization) process or sometimes purely due to geometric requirements/constraints, one or more of the plies have to be terminated (also known as “ply drop”) inside the laminate. The region of ply termination acts like a region of high stresses for neighbouring laminae which can be a reason for delamination of the plies adjacent to the ply drop region. A ply drop in laminate is shown in Figure 6.5(e).

v. **Bonded Joints:**
Sometimes laminates are bonded together using resin. Improper bonding leads to weaker joints. When such weak joints are subjected to serve loading conditions delamination can occur. A bonded joint in composite is shown in Figure 6.5(f).

vi. **Bolted Joints:**
Sometimes it is required to attach the composite structures to metallic structures. In such situations, bolted joints are imperative. The free edges of the cutout made in composite and additional load applied by tightening of the joint leads to a complex local state of stress. When these composite structures are *T* or *L* sections carrying additional loads, the situation is the worst. In such a situation delamination starts at cutout edges or at the curved edges of the *T*

or *L* sections. A *L*-bolted joint is shown in Figure 6.5(g).

vii. **Doublers:**
These are needed due to geometric or functional requirements in the structures. In this case a laminate is split into two or more set of laminae (or vice a versa). Thus, at the bifurcation laminae (or where the laminae join together to form laminate) give rise to high stresses. These locations are potential zones for delamination initiation. Typical doublers are shown in Figure 6.5(h).

Suppression of Delamination:

Several possible design changes are suggested for delaying/suppressing the onset and growth of delamination.

The primary cause of delamination is the low interlaminar fracture toughness. This is due to brittle nature of most resins (epoxy) used as matrix material, which have low mode I fracture toughness. The suggested models for improving this property are:

a. Adding thermoplastics, interleafing soft and hard layers, increasing length of cross-links

b. Adding second phase materials to matrix like rubber; chopped fibre, fibrils, etc.

c. Through thickness reinforcement by 3*D* braiding or stitching

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C) Coupled Micro-Macrolevel Failure Mechanisms:

The transverse matrix cracking of a lamina as shown in Figure 6.3(c) is an important failure mechanism. The through thickness transverse crack may propagate to neighbouring lamina causing it to break.

There can be another scenario that this crack terminates at the neighboring interface. This crack front act as a stress concentration site for interface between the adjacent layer causing it to weaken, thus initiating a delamination crack in the interface. This delamination growth can lead to failure of the laminate. This is depicted in Figure 6.6(a).

A third scenario is also possible in which the transverse through thickness crack leads to interface crack in adjacent layer causing partial delamination. This delamination may cause a transverse crack in the next layer. Then this crack initiates a interfacial debonding of that layer and so on causing the failure of laminate.

The coupling between the transverse cracking of lamina and delamination is depicted in Figure 6.6(b).

Thus, the transverse cracking of lamina and delamination are strongly coupled.

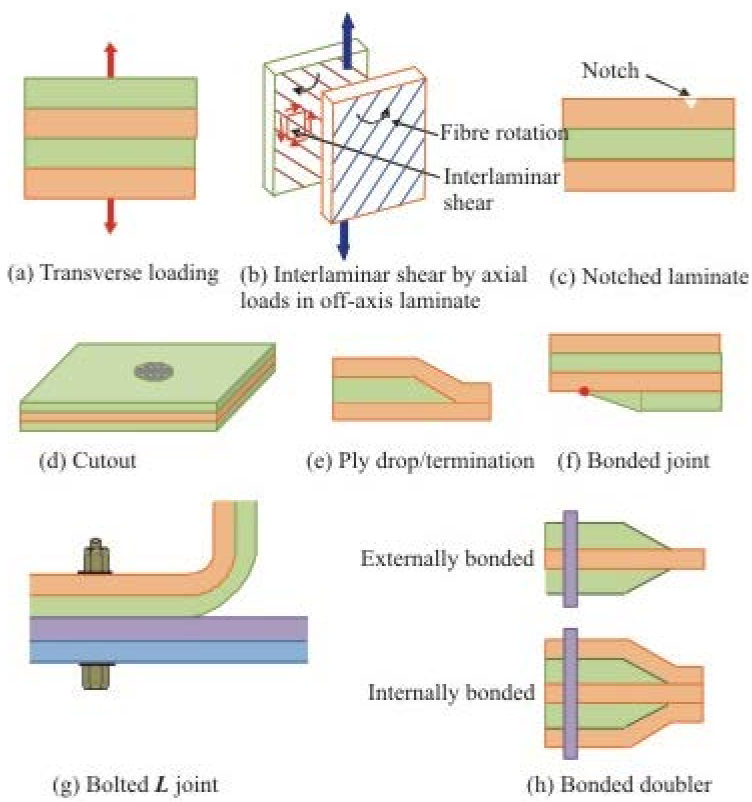

Figure 6.5: Situations conducive for delamination

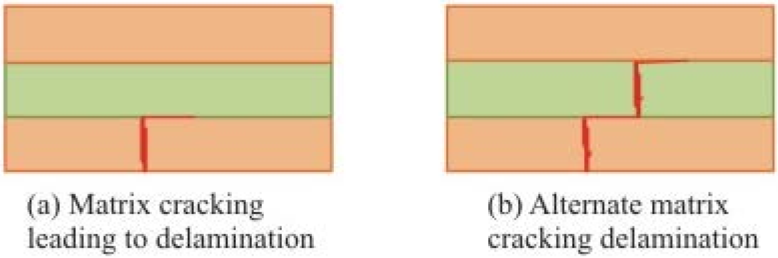

Figure 6.6: Coupled micro-macro damage mechanisms

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Home Work:

1. What is meant by failure and damage?
2. Why is the study of damage mechanisms and their mechanics important for fibrous composites?
3. What are the defects in a composite?
4. What are the sources of defects in a laminated composite?
5. What are the damage mechanisms in a fibrous laminated composite?
6. What are the causes of delamination?
7. What are the remedies to suppress the delamination?

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