Impact Factor Value 4.046 **e-ISSN: 2456-3463**

International Journal of Innovations in Engineering and Science, Vol. 3, No.4, 2018

A Review on Delamination Failure Analysis and Performance Enhancement of Hybrid Polymer Composite Laminates

Dhananjay G. Pardhi[1], Prashant M. Khanorkar[2]

[1]*Lecturer in Mechanical Engineering,*
Government Polytechnic, Bramhapuri, India, 441206
[2]*Lecturer in Mechanical Engineering,*
Government Polytechnic, Bramhapuri, India, 441206

Abstract – *Delamination is one of the most critical failure modes in* ***hybrid polymer composite laminates****, occurring when adjacent layers separate at their interfaces due to weak interlaminar bonding, manufacturing defects, or mechanical loading. In laminated composite structures, different fiber materials and polymer matrices are combined to achieve improved mechanical performance. However, the mismatch in mechanical and thermal properties between layers often generates interfacial stresses that initiate and propagate delamination. This phenomenon significantly reduces the structural integrity, stiffness, and load-carrying capacity of composite materials. This review paper examines the mechanisms, causes, and analysis of delamination in hybrid polymer composites. Key contributing factors such as manufacturing imperfections, void formation, impact loading, and environmental effects are discussed. The study also highlights the importance of mechanical characterization techniques, including Mode I and Mode II fracture tests, for evaluating interlaminar fracture toughness. Various mitigation strategies, including interlaminar toughening, fiber hybridization, and optimization of manufacturing parameters, are also discussed. These approaches contribute to improving the mechanical performance and long-term reliability of hybrid polymer composite laminates.*

Keywords: Delamination, hybrid polymer composites, Manufacturing Parameters, Mechanical testing

I -INTRODUCTION

Originating from early agricultural societies and being almost forgotten after centuries, a true revival started of using lightweight composite structures for many technical solutions during the second half of the 20th century. After being solely used for their electromagnetic properties (insulators and radar-domes), using composites to improve the structural performance of spacecraft and military aircraft became popular in the last two decades of the previous century. First at any costs, with development of improved materials with increasing costs, nowadays cost reduction during manufacturing and operation are the main technology drivers. For instance, Smith et al. (2018) conducted experimental investigations into how different loading conditions affect delamination, revealing essential insights into the mechanics of hybrid composites. The orientation of fibers within these composites also plays a pivotal role in delamination initiation and propagation, as shown by Brown and Lee (2019). Utilizing advanced techniques like finite element modeling, Gupta et al. (2020) predicted delamination growth in carbon-glass hybrids, enhancing the understanding of failure mechanisms in complex composite systems. Moreover, analytical approaches to detect and characterize delamination have been comprehensively reviewed by Chen and Wang (2021), indicating the need for robust diagnostic methods. Interfacial adhesion is another critical factor affecting delamination, with Jiang and Li (2022) demonstrating its significant impact on polymer-based hybrid laminates. The arrangement of plies and their stacking sequences have been investigated by Garcia et al. (2019), showing how these factors contribute to delamination resistance. Environmental influences, such as moisture absorption, can also degrade interlaminar fracture toughness, as discussed by Lee and Kim (2020). Recent advancements in material modifications, including the use of nanofillers to improve interlaminar fracture toughness, have shown promising results (Tanaka et al., 2021). Other innovative strategies, such as stitching and z-pinning techniques, have been validated experimentally for their effectiveness in mitigating delamination (Nguyen et al., 2019). The integration of functionalized nanotubes has also proven effective in enhancing interfacial bonding (Wang et al., 2022). Furthermore, multi-scale modeling techniques (Liang & Zhang, 2018) and damage mechanics-based models (Park et al., 2019) are increasingly employed to predict delamination behavior under various loading scenarios. The synergistic effects of combining natural and synthetic fibers to counteract delamination have been explored by Mishra et al. (2022), emphasizing the potential of hybrid composites in engineering applications.

Composite materials offer many advantages in aircraft applications when compared to conventional materials such as metals. Increased strength, increased stiffness, reduced weight, reduced part count, and longer lifespan through greater fatigue limits and better corrosion resistance are benefits that can be achieved by replacing metals with composites. The use of composites also opens up more options for the design geometry of aircraft structures since they are particularly well suited for compound curves and organic shapes such as engine cowlings, wheel fairings, and wing tips. Aircraft that can fly higher, faster, and farther while carrying greater payloads are made possible through the use of composite materials. Many of the advancements that have occurred in aerospace over the past several decades have been made possible through the adoption of composite materials.

II -CLASSIFICATION OF COMPOSITE MATERIALS

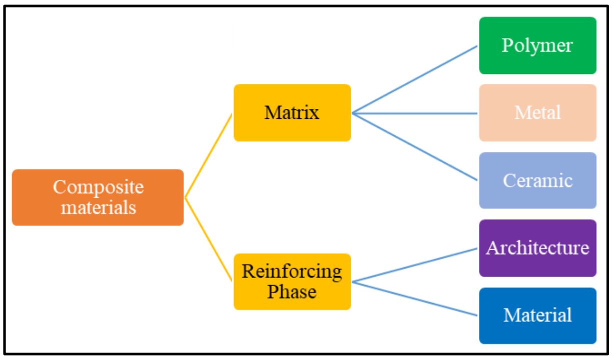

Fig 1. Classification of composites based on the matrix and reinforcement

Composite materials are commonly classified at following two distinct levels. The first level of classification is usually made with respect to the matrix constituent. The major composite classes include

(Fig-03) Organic Matrix Composites (OMCs), Metal Matrix Delamination failure in hybrid polymer composites occurs when the layers or plies within the composite material start to separate along their interfaces. This type of failure is particularly significant in laminated composites where layers of different materials (hybrid composites) are bonded together. Delamination failure in hybrid polymer composites is a critical issue that affects the structural reliability and performance of these materials, requiring careful attention during design, manufacturing, and maintenance phases to mitigate its occurrence. Figure 2. depicts delamination and debonding failure mode of composite laminates. onding failure mode of composite laminates.

It is observed that silicon carbides and epoxy shows a 91.43% less fracture toughness than that of aluminium alloy. SiC/Al2O3 and SiC/SiC have 27% and 30 % less fracture toughness than aluminium alloy.

Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term organic matrix composite is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and carbon matrix composites commonly referred to as carbon carbon composites. The second level of classification refers to the reinforcement form - fibre reinforced composites, laminar composites and particulate composites. Fibre Reinforced composites (FRP) can be further divided into those containing discontinuous or continuous fibres. Fibre Reinforced Composites are composed of fibres embedded in matrix material. Such a composite is a discontinuous fibre or short fibre composite if its properties vary with fibre length. On the other hand, when the length of the fibre is such that any further increase in length does not further increase, the elastic modulus of the composite, the composite is considered to be continuous fibre reinforced. Fibres are small in diameter and when pushed axially, they bend easily although they have very good tensile properties. These fibres must be supported to keep individual fibres from bending and buckling. Laminar Composites are composed of layers of materials held together by matrix. Sandwich structures fall under this category. Particulate Composites are composed of particles distributed or embedded in a matrix body. The particles may be flakes or in powder form. Concrete and wood particle boards are examples of this category.

Figure 1. Shows a classification of composites based on the matrix and reinforcement

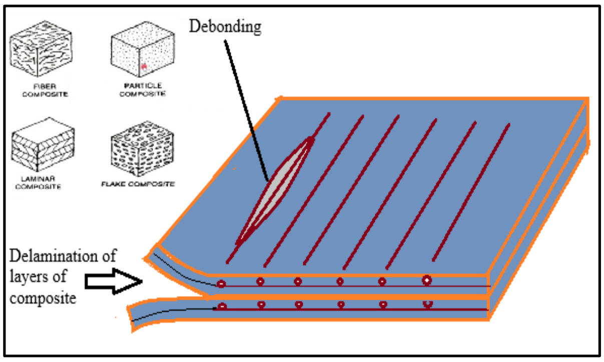

Fig 2- Delamination and debonding failure mode of composite laminates

III - DELAMINATION FAILURE

Delamination is a type of layer deformation in laminated composite materials, and it is due to continuous stress and pressure on the material. This form of failure can result in faulty performance during the use of these materials. The inadequate curing methods form irregular pressure on the different areas, generating areas of delamination. The formation of these delaminated areas in composite materials can significantly reduce the composite's strength during compressive loading. This is because of the buckling effect of the laminated structure.

One of the most prevalent failure forms of composite materials is delamination. Due to imperfections during the manufacturing process or the effects of external factors during the working life of composite laminates, i.e., the impact of foreign items, the phenomenon of delamination may occur. This failure also happens due to the high inter laminar stresses that are connected, typically, to the lowest through-thickness strength. This is caused by the fibers that lie in the laminate plane that do not reinforce the thickness, so the composite must rely on the nearly weak matrix to transport loads in that direction.

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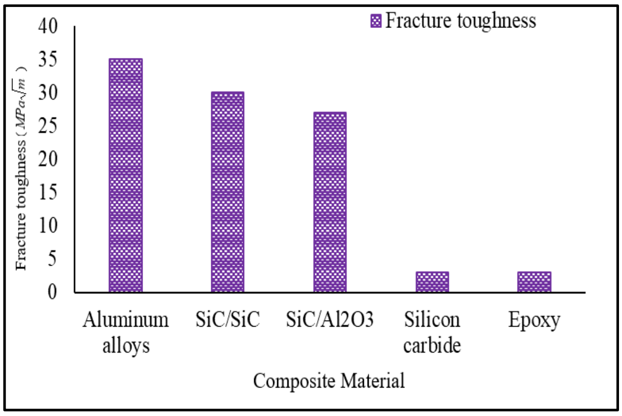

Fig 3. Comparison of typical fracture toughness of different matrix composites

IV- CONCLUSIONS

The widespread applicability of composite polymers is driven by their ability to combine the desirable properties of different materials, resulting in tailored solutions that meet specific performance requirements across diverse industries.

- Studies on surface preparation techniques to improve bonding between polymer matrices and reinforcing materials have been addressed to the limited extent.
- Incorporation of natural fibre with synthetic fibre along with hybridization at the level of matrix and their synergistic effect against the environmental degradation has a scope of exploring to the further level.
- A very few studies have been carried out on the degradation of hybrid polymer composites over extended periods in real life applications under harsh environments.
- Delamination failure in Hybrid Polymer composite and its mitigation for Performance improvement have been addressed to a very limited extent.

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