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Adhesively Bonded Patch Repair in Polymer Composites: Effects of Reinforcement Configuration and Post-Cure Temperature

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Abstract

Adhesive patch repair technique has been identified as an effective and economical approach to repair damaged polymer composite structures that are used in aerospace, automotive, marine, wind energy, and many other high-performance engineering applications. Adhesive bonding offers superior stress distribution, reduced stress concentration, less structural weight and fatigue resistance, and thus increases the lifetime of the repair of composite structures when compared to the traditional mechanical attachment approaches. Performance and durability of the repaired laminate depend on the reinforcement arrangement of the repair patch and post-cure temperature at the time of bonding. This review will critically evaluate the latest studies conducted in adhesive patch repair of polymer composites focusing on the effect of different reinforcement arrangements such as glass fiber, carbon fiber, Kevlar, stitched, and hybrid fibers, as well as the effect of post-cure temperature. The complex relationship between reinforcement structure, adhesion characteristics, bonding at the interface, curing properties, residual stress evolution and failure modes is carefully examined in relation to their effect on tensile, compressive, flexural, impact and fatigue behavior of repaired composites. In addition, existing problems and gaps in current knowledge, along with the latest research trends and developments, are carefully evaluated with the aim to reveal potential approaches for optimization of repair process with regard to its efficiency, reliability and durability. In particular, optimization approaches that include optimization of reinforcement arrangement, choice of adhesives, curing processes and repair methods are carefully considered. The results obtained through this review can be used for a better understanding of the mutual effect of reinforcement configuration and post-curing process.

Keywords: Adhesively bonded patch repair; polymer composites; reinforcement configuration; post-cure temperature; hybrid fibre composites; mechanical performance; composite repair; structural durability

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INTRODUCTION

Polymer composites and especially fiber reinforced polymer (FRP) composites have become a very important engineering material due to the properties of high specific strength, rigidity, corrosion resistance, fatigue resistance, and low density. These qualities have made such materials widely used in the aerospace industry, automotive industry, marine industry, wind energy industry, civil engineering structures, and defense industry, where structural efficiency and high durability are of great importance. Although being highly efficient in mechanical terms, the composite structures are subject to different kinds of damage, such as impact damage, fatigue damage, delamination, matrix cracking, fiber breakage, and degradation from the environment during production, usage, or repair of such structures [1].

Among the existing repair strategies, patch repair using adhesives bond appears to be the most effective method for repairing composite structures. In contrast to mechanical joining, adhesive bond causes even distribution of stresses, reduction in the amount of stresses, preservation of structural integrity of the parent laminate, as well as decrease in additional weight. Besides, adhesively bonded repairs can be performed on complicated geometric configurations of composite parts and thin laminates for which fastening may cause additional defects and stresses. As a result, adhesively bonded patch repair has received a wide consideration in aerospace, marine, transportation and renewable energy industries.

The performance of adhesively bonded repairs depends on a number of design and process parameters among which the most important parameter is the reinforcement configuration which determines the effectiveness of load transfer, the ability of crack arrest, stiffness recovery, as well as repair durability. Several reinforcements such as glass, carbon, Kevlar fibre, stitched laminates, as well as hybrid systems were considered to increase mechanical performance of adhesively bonded repairs under tensile, compressive, flexural, impact and fatigue loadings. In particular, hybrid reinforcements have received a great consideration due to their combined advantages [2].

Post-cure temperature apart from reinforcement architecture plays an important role in determining the efficiency of adhesive repair. Post-cure helps to achieve better resin cross-linking, fibre-matrix adhesion, reduced stress generation and improved stability of repaired composites in terms of thermal and mechanical properties. On the other hand, improper post-curing procedure can deteriorate the properties of adhesive, generate thermal stresses and lower the efficiency of the repairs.

Though many experimental and numerical studies have individually focused on reinforcing mechanisms and curing procedures, there are very limited review studies on their combined effect on the performance of adhesively bonded patches. Recent advancements in composite technology in the form of hybrid fiber system, high-tech adhesives and optimization in post-cure process require an up-to-date review study [3].

Thus, in this review, a complete analysis is provided regarding the repair of polymer composites by adhesively bonded patches, especially focusing on the influence of reinforcement arrangement and post-cure temperature. Various aspects have been addressed in this review, which include the material used for the reinforcements, the approach adopted for repair, the process of curing, mechanical properties, failure mechanisms, existing problems, and possible future directions. This review is intended to guide researchers in developing repair systems that are dependable and efficient [4].

IMPORTANCE OF THE STUDY

The rise in applications of fibre-reinforced polymer (FRP) composites in high-end engineering uses has generated a need for dependable and economically viable repair processes that are able to restore the integrity of the structures without resorting to replacement of all components. Adhesive bonded patch repair is one such repair method which has proven to be very effective due to its better load transfer capacity, lesser stress concentration, light weight and high efficiency when compared with the traditional mechanical fasteners. The effectiveness of the above repair process is greatly influenced by the choice of reinforcement arrangement and optimization of post-cure temperature [5].

While several studies on the effects of reinforcing materials and curing process have been conducted separately, there are very few reviews that have been done incorporating the two important parameters mentioned above. This results in the inability of scientists and engineers to come up with a unified theory regarding the effect of reinforcement arrangement and post-cure on repair effectiveness and structural behavior.

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This review will try to solve this problem through a thorough evaluation of recent advancements made in the field of adhesively bonded patch repair focusing especially on reinforcement arrangements, post-cure temperatures, mechanical response, failure mode and research potential. The information provided in this review is anticipated to offer a lot of help in developing reliable and efficient patch repair systems for modern day polymer composite structures [6].

RESEARCH METHODOLOGY

This study has been carried out through systematic and structured literature survey with an aim to have thorough knowledge about adhesively bonded patch repair in polymer composites with special reference to the influence of reinforcement configuration and post-cure temperature. Peer-reviewed articles related to the topic have been collected from international scientific databases that include Scopus, Web of Science, ScienceDirect, Springer Link, Wiley Online Library, and Taylor & Francis. In literature review, research articles published during last years were searched with the use of certain keywords such as adhesively bonded patch repair, polymer composites, fiber reinforced polymer, reinforcement configuration, glass fiber, carbon fiber, Kevlar fiber, hybrid composites, post-cure temperature, adhesive bonding, and composite repair.

After the process of screening was completed, the chosen studies were categorized into groups according to reinforcement materials, reinforcement structures, post-curing conditions, mechanical behavior, failure modes, and repair efficiency. Findings of the studies were carefully analyzed and compared to reveal the trends, challenges, knowledge gaps, and directions for further research [7].

Literature Selection and Classification

The literature that forms part of this review was chosen via systematic screening to ensure that quality literature has been included in this research. Journal articles from reputable databases have been used through careful selection of search words based on adhesive bond repair patches, polymer composites, configuration of reinforcements, adhesive bonding, hybrid fiber system, and post-cure temperature. Literature that concentrated on experimental analysis, numerical modeling, and reviews has been selected for this work [8].

After the first search, duplicates and unrelated articles were filtered out. The rest of the papers were assessed according to their scientific significance, relevancy, and quality. The chosen literature was grouped according to key research topics, such as reinforcement materials, reinforcement designs, post-curing regimes, mechanical properties, failure modes, and repairs optimization. This classification made it possible to compare existing papers systematically and to identify current trends, gaps, and directions for future research. The methodology used for the present literature review, including literature search, filtering, classification, and evaluation, is shown in Figure 1 [8].

Search Strategy

An extensive literature survey was performed using internationally acknowledged scientific databases like Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The time period of 2015 to 2025 was used in the literature search in order to get recent advancements regarding adhesively bonded patch repair of polymer composite materials. In the literature search process, various key words such as adhesively bonded patch repair, polymer composites, adhesive bonding, reinforcement pattern, carbon fiber, glass fiber, Kevlar fiber, hybrid composites, post cure temperature, mechanical properties, and failure modes were used [9].

Inclusion and Exclusion Criteria

The inclusion criteria consisted of literature associated with adhesively bonded patch repairs of polymeric composite materials, reinforcement layout, adhesive bonding, post-curing temperature, mechanical properties, and failure modes.

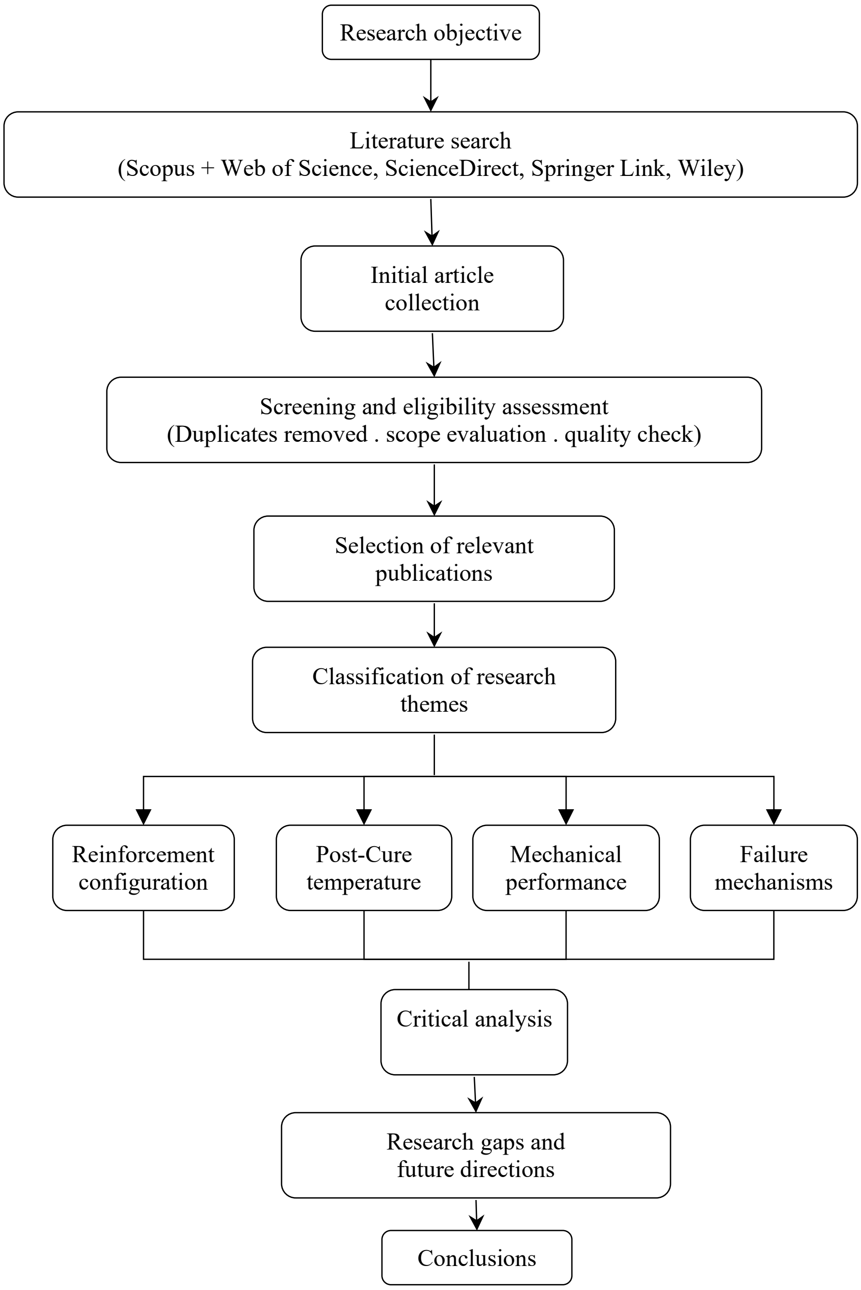

Figure 1. Methodological framework adopted for the present review.

The experimental, numerical, analytical, and review studies that appeared in reputable scientific journals were taken into account in order to provide a holistic view on the topic under discussion. Articles not dealing with composite repair, those not written in English, duplicates, conference papers with inadequate technical content, and papers irrelevant to the aims of this review were discarded.

REINFORCEMENT CONFIGURATIONS IN ADHESIVELY BONDED PATCH REPAIR

Selection of reinforcement architecture is one of the most critical criteria which determine the structural behavior of patch repairs in adhesive bonded joints in composite structures. Reinforcement architecture has direct effect on load transfer capability, stress distribution, crack resistance, interfacial bonding, and durability of the repaired structure. Properly designed reinforcement architecture not only helps in restoring the mechanical properties of damaged composite laminates, but it also makes them fatigue resistant and environmentally resistant.

Table 1. Comparison of different reinforcement materials used in adhesively bonded patch repair.

Reinforcement	Advantages	Limitations	Typical Applications
Glass Fibre	Low cost, corrosion resistance, easy fabrication	Lower stiffness	Marine, automotive, civil structures
Carbon Fibre	High stiffness, excellent fatigue resistance	High cost, brittle	Aerospace, high-performance structures
Kevlar Fibre	High toughness, impact resistance	Moisture sensitivity, difficult machining	Defence, impact-resistant components
Hybrid Fibre	Balanced strength and toughness	Complex manufacturing	Multi-functional composite repairs
Stitched Fibre	Improved delamination resistance	Higher fabrication complexity	Thick composite laminates

Several reinforcing materials have been considered for repair in composites, such as glass fibers, carbon fibers, Kevlar fibers, stitched reinforcements, and hybrid fiber reinforcements. Every type of reinforcement has some unique mechanical properties which make them applicable in certain environments. Glass fibers are used widely in the repair due to their low cost, good corrosion resistance, and good mechanical properties. Carbon fibers are known for their stiffness and fatigue resistance. Due to these properties, carbon fibers are used extensively in aerospace structures. Kevlar fibers are characterized by good toughness, high impact resistance, and good energy absorption capability [10].

Research in the recent past has shown increased interest in using hybrid reinforcement designs comprising two or more fiber types to take advantage of the benefits provided by each material used. Hybrid reinforcement systems have been found to provide higher levels of stiffness, strength, toughness, and ability to stop cracks when compared to systems with a single fiber material. Moreover, the stitched reinforcements increase through thickness reinforcement and minimize interlaminar delamination, thereby enhancing the durability of repaired composites.

The performance of a reinforcement design is influenced not only by the choice of the fiber material but also by other parameters like the fiber orientation, the stacking sequence of fiber layers, patch geometry, the nature of adhesive, and the compatibility of the patch with the parent structure. Therefore, optimization of the reinforcement design is a key topic in research which seeks to maximize repair efficiency while minimizing the added weight.

While glass fibres continue to be the cheapest of all reinforcement fibres due to their resistance to corrosion and ease of manufacture, their stiffness and fatigue behavior are usually inferior to those of carbon fibers. Carbon fibers have higher load carrying capacity and stiffness and therefore are used for applications requiring good performance, though being expensive, may limit their usage. Kevlar fibers have high resistance to impacts and energy absorption, but lower compressive strength and poor machinability. Reinforcement fiber hybrids are the combination of different kinds of fibers which provide the best ratio of strength, toughness, and durability, though making their production more difficult. The properties and applications of various reinforcement materials employed in adhesively bonded patch repair are summarized in Table 1, enabling a comprehensive comparison of their performance.

Glass Fibre

Glass fibre-reinforced polymer (GFRP) is one of the most commonly used reinforcing materials in adhesive bonding patch repairs due to its superior combination of mechanical properties, corrosion resistance, lightweight nature, and economical value. The patch repairs made of glass fibre can effectively recover the load-bearing capability of damaged composite laminates along with improving the tensile, flexural, and impact properties. The high compatibility of glass fibre with epoxy adhesives enhances the effective stress transfer capability and bonding strength at interfaces. Due to their reliability and ease of fabrication, GFRP repair systems are widely used in aerospace, marine, automotive, and civil engineering fields. However, glass fibres are less stiff and fatigue resistant than carbon fibres [11].

Carbon Fibre

Carbon Fibre Reinforced Polymers (CFRPs) are highly popular due to their high strength to weight ratio, high stiffness, and excellent fatigue performance characteristics and thus are one of the most favoured reinforcement materials used in adhesive patch repairs. The CFRPs successfully restore the structural integrity of the damaged composite laminate by promoting improved load transfer and minimizing the stresses on the damaged region. Their superior mechanical properties make them an ideal choice for applications such as aerospace and automotive industries. However, their increased costs and relative brittleness of carbon fibres may act as a hindrance in some cases [12].

Kevlar Fibre

The use of Kevlar fibre in the patch repair through adhesive bonding results from its high toughness, high impact resistance, and high energy absorbing capability. Kevlar fibre has a higher damage tolerance capacity and crack arrest capability compared to glass and carbon fibres, thus making it the appropriate choice for repair work on composite material that has undergone impact and dynamic loading. The lightness of weight and high tensile strength also increase the durability of the repaired laminate. The compressive strength of Kevlar fibre is, however, low and its machinability and bonding are poor when compared to glass and carbon fibres.

Hybrid Fibre

The concept of Hybrid FRP materials is that these materials comprise of more than one fibre type like glass/carbon or glass/Kevlar composites that are designed to give better performance in terms of mechanical characteristics. The main objective of using hybrid systems is to take advantage of all the fibres used in the system, thus offering increased stiffness, strength, toughness, and impact resistance. Hybrid reinforcements are useful in adhesive patch repairs where they offer improved load transfer and tolerance to damage.

Stitched Fibre

Stitching of fibre reinforcement increases the interlaminar resistance of composite laminates due to reduced occurrence of delamination failures and improvement in the integrity of the structure. In the case of stitch reinforcement, the resistance to crack propagation is increased and durability of the repair with adhesive bonding is improved when subjected to fatigue and impact loading. Stitched reinforcement of composite laminate is most suitable for use in thick laminates in aircraft and maritime applications where delamination is one of the main modes of failure. However, stitching may cause local fibre distortion [13].

EFFECT OF POST-CURE TEMPERATURE

Post-cure temperature is very important in ensuring the mechanical strength and durability of adhesively bonded patch repairs of polymer composites. Proper post-cure ensures proper resin cross-linking, improved fiber-matrix interfacial bonding, reduction of residual stresses, and improvement in tensile, flexural, and fatigue characteristics of the patched laminates. Proper post-cure also helps in improving the thermal stability and environmental resistance of composite structures. On the other hand, too much high post-cure temperatures may lead to thermal degradation, introduction of residual stresses, and reduction in adhesive properties, thereby reducing repair efficiency. Hence, proper selection of post-cure temperature is extremely important in order to ensure good bonding, improved mechanical performance, and longer life of repaired polymer composite parts. The effect of post-cure temperature on the performance of adhesively bonded patch repairs is shown in Figure 2. Proper post-cure will ensure proper resin cross-linking, improved fiber-matrix interfacial bonding, reduction of residual stresses, and finally improved mechanical performance and durability of polymer composite structures. But at the same time, improper post-cure may adversely affect adhesive properties, thus reducing repair efficiency. Though high post-cure temperatures are useful in ensuring proper resin cross-linking and interfacial bonding, they may introduce thermal degradation and residual stresses at the same time.

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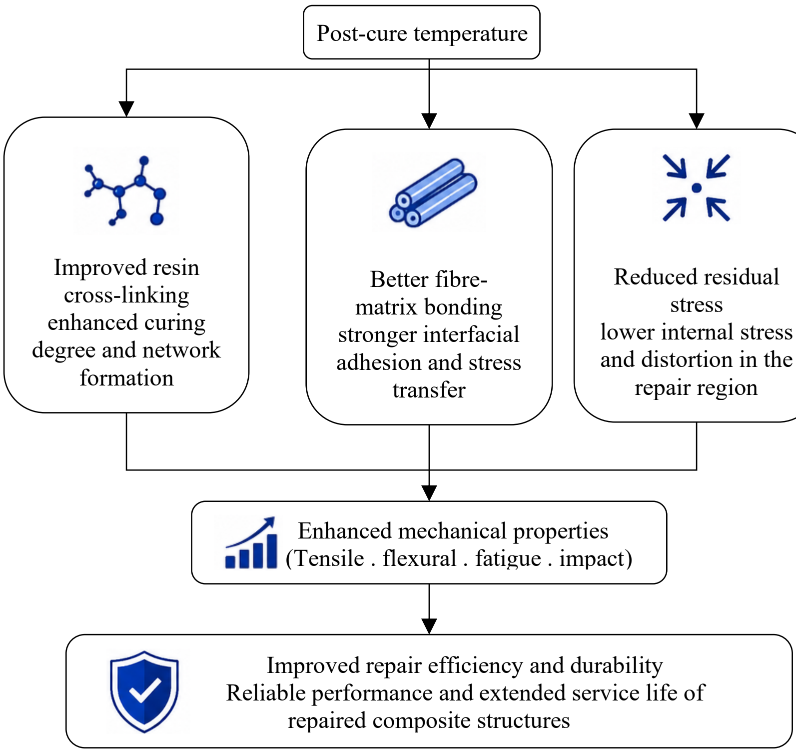

Figure 2. Influence of post-cure temperature on the mechanical performance of adhesively bonded patch repair in polymer composites.

MECHANICAL PERFORMANCE OF REPAIRED POLYMER COMPOSITES

The mechanical performance of adhesively bonded patch repairs relies upon the interactions between reinforcement arrangements, adhesive characteristics, and post-curing factors. Effective designs of repair procedures greatly enhance the tensile, flexural, compressive, impact, and fatigue properties of damaged polymer composites [18]. Effective load transfer within the adhesive interface and high fibre-matrix interfacial bonding are among the factors that help increase the stiffness, strength, and durability. Besides, optimal post-curing increases cross-linking of resins and decreases residual stress, thus improving the structural performance of repaired laminates in the long run.

However, poor bonding, unsuitable reinforcement materials, or inappropriate curing can decrease repair efficiency and promote structural degradation. Thus, the effective optimization of repair conditions is vital for obtaining reliable and durable composite repairs. The main factors affecting the mechanical performance of adhesively bonded patch repairs are shown in Figure 3 below. Table 2 is a summary of relevant research on the adhesively bonded patch repairs for polymer composites, which includes the reinforcement systems, adhesives used, results obtained, and research areas yet to be investigated by recent research [14]. The mechanical properties of polymer composites after repairing cannot be explained by only one factor. Reinforcement system, nature of adhesives, patch geometry, and post-curing process collectively affect the repair effectiveness. Hence, future optimization approaches should take into account these factors collectively.

RESEARCH GAPS AND FUTURE PERSPECTIVES

While many achievements have been made in the field of adhesively bonded patch repair for polymer composites, there are still several issues that need to be addressed. Most previous studies have concentrated on one type of reinforcing material and certain curing conditions; however, no research has been done on the joint effect of reinforcement arrangement and post-curing temperatures under real-world operational conditions. Moreover, long-term durability, environment aging, fatigue performance and the application of intelligent structural health monitoring tools require more study.

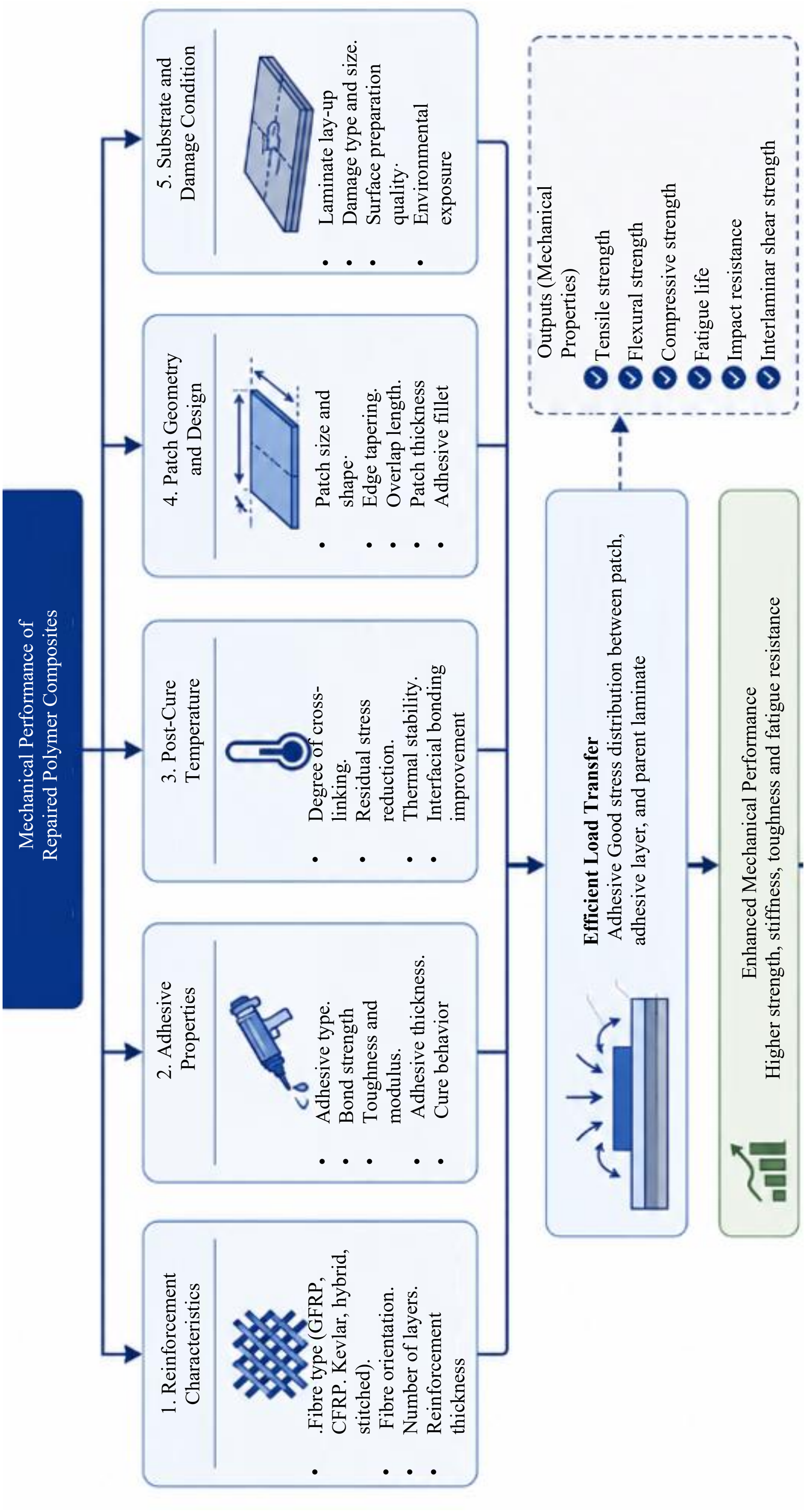

Figure 3. Factors influencing the mechanical performance of adhesively bonded patch repairs in polymer composites.

Table 2. Summary of representative studies on adhesively bonded patch repair of polymer composites.

Author (Year)	Reinforcement	Adhesive System	Key Findings	Research Gap
Fernandes et al. (2025)	CFRP composite patch	Epoxy adhesive	Developed adhesively bonded composite patch repairs for load-bearing aerospace structures, demonstrating improved structural integrity and repair efficiency.	Limited validation under long-term environmental exposure and fatigue loading.
Ghafafian and Seidlitz (2025)	Composite repair systems (multi-material)	Structural adhesives	Reviewed repair strategies across aerospace, marine, wind energy, and automotive sectors, highlighting the importance of repair standardisation.	Need for unified repair procedures and long-term durability assessment.
Yashiro et al. (2025)	Variable stiffness composite patch	Epoxy adhesive	Demonstrated that variable stiffness patches improved stress distribution and reduced stress concentration in repaired laminates.	Limited experimental validation under complex loading conditions.
Budhe et al. (2018)	Bonded composite repairs	Epoxy adhesive	Reviewed environmental effects on bonded composite repairs and reported significant influence of temperature and moisture on joint durability.	More research required on environmental ageing and service-life prediction.
Oshima and Iwahori (2025)	Adhesively bonded composite joints	Structural adhesive	Reviewed common failure mechanisms including adhesive debonding, matrix cracking, fibre breakage, and delamination affecting repaired structures.	Limited predictive models for failure progression and durability evaluation.

However, elevated post-cure temperatures may cause residual thermal stresses and degrade adhesives; thus, repair efficiency may be decreased. This means that to achieve high efficiency of the repair, it is important to optimize not only reinforcement architecture and adhesive properties but also post-cure temperature.

FAILURE MECHANISMS IN ADHESIVELY BONDED PATCH REPAIR

The long-term effectiveness of repair patches in adhesively bonded patches depends on a range of failure modes that occur due to mechanical and environmental loading. Adhesive debonding, fibre fracture, matrix cracking, interlaminar delamination, and cohesive failure of the adhesive joint are some typical failures that reduce the effectiveness of load transfer and result in failure of the structure when left uncontrolled [15]. The nature and severity of failures vary depending on the reinforcement pattern, adhesive characteristics, curing conditions, and operating environment. Thus, an important issue to address is that of identifying the failure modes that can be predominant in a particular case and help improve the effectiveness of repair designs. The typical failure modes in adhesively bonded patch repairs and their effect on structural performance are depicted in Figure 4 below.

The future research work should pay special attention to sustainable repair materials, intelligent bonding systems, hybrid reinforcement systems and predictive numerical models in order to increase repair efficiency, structural reliability and service life. This will make a significant contribution to the implementation of adhesive bonded patch repair technology into next generation polymer composite structures. Future researches should be concerned about the optimal combination of reinforcement arrangements, adhesives and curing conditions through the application of advanced numerical simulations, machine learning methods and SHM tools [16].

CONCLUSIONS

Adhesive patch repair technology has proved to be an efficient and affordable means for restoring the structural stability of the polymer composite structures employed in the aerospace, automobile, marine, and civil engineering sectors. This paper emphasizes the fact that the behavior of the repaired composite structures depends significantly on the type of reinforcement, nature of the adhesive, and temperature during post-cure. Different types of reinforcements such as glass, carbon, Kevlar, hybrid, and stitched fibers have their own advantages depending upon the loading condition.

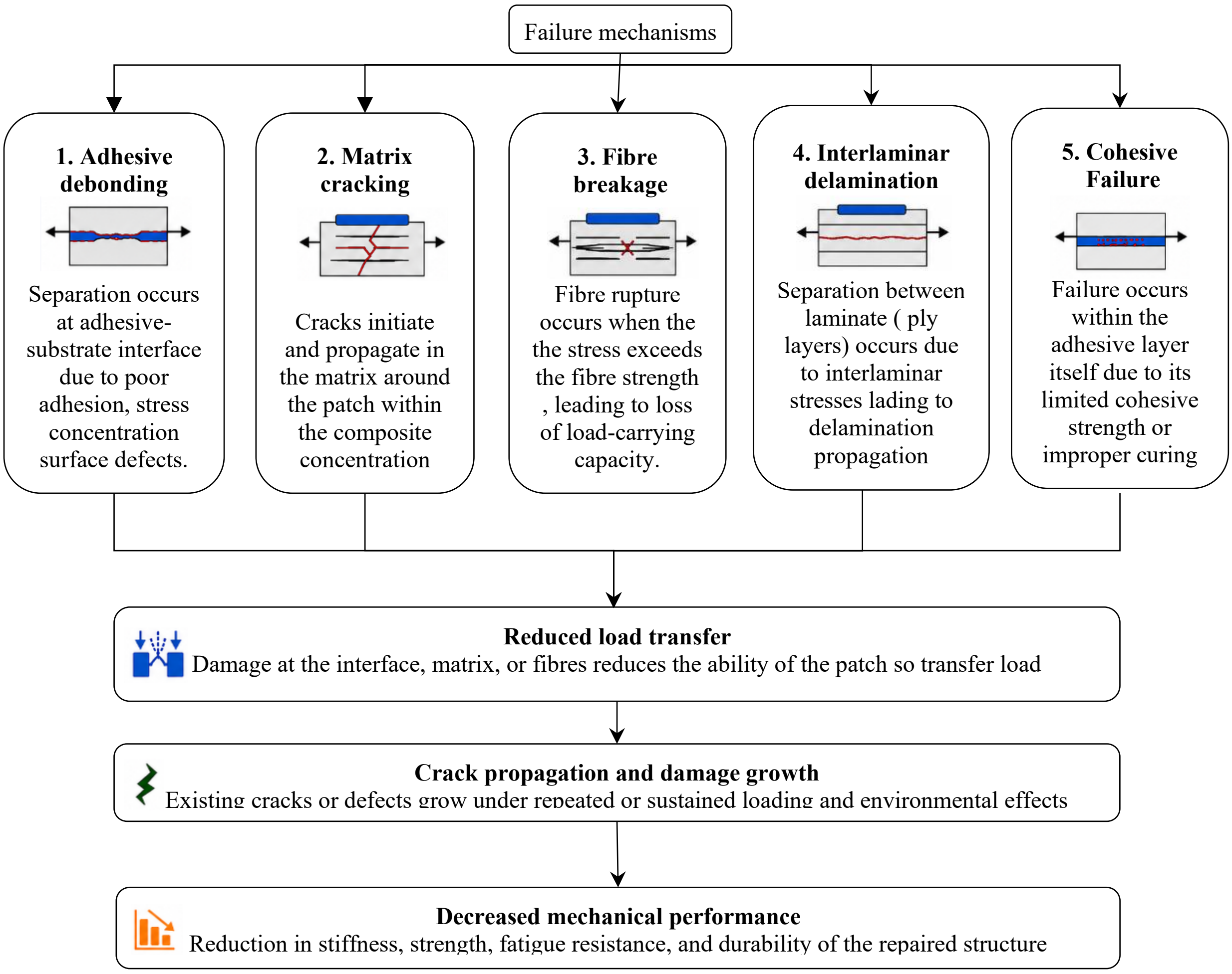

Figure 4. Common failure mechanisms in adhesively bonded patch repair of polymer composites.

Proper post-curing helps in increasing the crosslinking of the resin and also improves the interfacial bonding between fiber and matrix.Moreover, gaining insight into the mechanisms of failure of the repairs such as debonding of the adhesive, cracking of the matrix, fiber rupture, and delamination plays an important role in enhancing the reliability of repair. Even though considerable work has been done in this area, there is still a need for more studies in areas such as long-term durability, environmental aging, optimization of hybrid reinforcement, and intelligent repair technologies.

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