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Effect of patch hybridization on the tensile behavior of patch repaired glass/ epoxy composite laminates using acoustic emission monitoring

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A B S T R A C T

This paper investigates the tensile response of damaged glass/epoxy composite laminates repaired using hybrid external patches. Hybrid external patches based on glass and Kevlar woven fabrics bonded on both faces of the damaged parent laminate were considered. Five different kinds of plain weave woven fabrics with a different ratio between glass and Kevlar fibers (100/0, 75/25, 50/50, 25/75 and 0/100) were used as the external patches. The intention of using these hybrid patches was to combine the excellent tensile stiffness of Kevlar fiber with the superior resin adhesion property of glass fiber. The virgin and damaged specimens were taken as the reference specimens for comparison of residual mechanical properties and damage mechanisms. Damage evolution and the failure progression of the repaired glass/epoxy specimens were monitored using real-time Acoustic Emission (AE) monitoring technique. The Acoustic Emission (AE) results depict different damage profiles and link them with mechanical test results to reveal the load to a change in failure mechanisms during mechanical loading concerning the influence of each hybrid patches on the performance of repaired glass/epoxy specimens. Good correlation of the acoustic emission results with the photographic images of fractured specimens was obtained. Specimens repaired with the equal volume fraction of glass and Kevlar fibers in the external patches presented the most favorable residual tensile response by effectively releasing the stress concentration in the damaged area.

1. Introduction

Fiber Reinforced Polymer (FRP) composites are extensively being used in automobile, marine and aerospace sectors due to their unique advantages over conventional metals in terms of high strength to weight ratio, better resistance to fatigue loading, tailorability to meet desired mechanical properties and improved corrosion resistance. Though laminated composites have numerous advantages, they are vulnerable and sensitive to low velocity impact loading due to the absence of fiber reinforcement in the thickness direction and poor interlaminar fracture toughness [1]. This impact loads on composite laminates can encourage various types of failure modes such as matrix cracking, fiber failure and fiber/matrix debonding, leading to a reduction of residual strength and stiffness of the laminates [2]. Furthermore, calamitous premature rupture may likely occur when such composite laminates are used in damaged condition [3]. The residual mechanical strength of the damaged composite laminate can be recovered either by repair or replacement of the laminate [4].

The choice of repair or replacement of the damaged laminate depends on several factors such as mechanical properties requirements, operation conditions (i.e. temperature, moisture, and pressure), location, damage area on the structure, aerodynamic requirements and financial constrains [5]. The residual mechanical properties of barely-damaged composite laminates can be economically recovered by repairing the damaged region since complete replacement of complexly integrated structures is costly, time-consuming and laborious [6]. Mechanical fastener repair technique and adhesively bonded repair technique are the two most conventionally practiced repair procedures in laminated composites [7]. Compared to mechanical fastener repair technique, adhesively bonded repair technique has several benefits such as high specific mechanical properties, low stress concentration, and better formability. These drawbacks exhibited by mechanical fastener repair technique on FRP laminates limit their use in many applications [8].

External patch repair and scarf repair are most commonly used adhesively bonded repair techniques in composite repair. In scarf repair, to ensure uniform transfer of load over and around the repair site, the damaged region is dressed by removing parent material from one side of the damaged laminate to produce a depression with optimized scarf angle and a small hole in the center. The scarf repair

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is avoided to repair damaged composite laminates of thickness less than 3 mm since it is difficult to perform better scarfing on thin laminated [9]. Studies have described that an adhesive scarf repair technique requires suitable equipment to expel the damaged area from parent laminate, to create optimum scarf angle and to consolidate the filled materials [10]. The dressed area is then repaired by filling the required number of plies by ensuring proper fitting into the depressed region of parent laminate and further consolidating by utilizing a hot press operated under the aid of pressure. In most cases, a scarf angle of less than 3° is necessary for the scarf repair of fiber reinforced polymer matrix composite laminates [11]. On the other hand, for repairs with a low scarf angle a long scarf is needed, and such long scarves are intricate to produce. Moreover, the application of a long scarf requires the machining of a large area of undamaged parent laminate. There are also cases in which enough repair area cannot be machined on a laminate for which a low scarf angle is needed. Scarf area is a function of the thickness of the laminate. In most cases, taper ratios for thick laminates are 30:1 (length: thickness) and 50:1 for thinner laminates. This scarfing process necessitates a higher level of proficiency than the external patch repair.

Wang et al. [12] numerically showed that considerable amount of materials are removed (between 26% and 76%) by performing conventionally designed scarf repairs. Compared to the external patch repair, scarf repair results in the machining of large amount of undamaged parent material for the attainment of a optimum scarf angle that will make certain the strength and stiffness recovery. Soutis and Hu [13] carried out a 3D finite element analysis to evaluate the stresses in a scarf repaired composite under uniaxial loading for prediction of optimum scarf angle. They observed that simple scarf-joint analysis misjudges the residual strength of scarf repair by over 40% and envisages an optimum scarf angle of 4° compared with a scarf angle of around 7°. Moreover, they reported that a 4° scarf angle would machine larger amount of undamaged material and reduce the strength of repaired laminate. Kumara et al. [14] reported that the residual strength of scarf joint with small scarf angle (2–3°) have higher values compared to the larger scarf angles. They reported that small scarf angle necessitates very long repair lengths, which induced laminate failure mainly by fiber failure and pull-out. For instance, minimum scarf angle of 5° results in a scarf length of 57.15 mm. Xiaoquan et al. [15] investigated the effect of specimen width and scarf angle on residual strength of scarf repaired composite laminates. They observed that larger amount of material removal from a constant width specimen turns it weaker as only minor amount of parent material is remaining on the sides of scarf opening in case of smaller scarf angles. In conclusion, despite the fact that scarf repair offers satisfactory results, this technique is on the other side very tedious, laborious, time consuming and further requires costly equipment to perform the repair.

On the other hand, adhesively bonded external patch repair is compatible to repair thin as well as thick laminates. In adhesively bonded external patch repair technique, the damaged site in parent laminate is dressed by cutting a hole, the dressed area is then filled with neat resin and then FRP patches are wrapped externally. Literature shows that adhesively bonded external patch repair is frequently adopted technique to repair damaged laminates, since it is less time consuming, economic and highly free from local stress concentration. These distinct characteristics make adhesively bonded external patch repair a simple and effective repair method in fiber reinforced laminated composites, as confirmed by the increasing attention that they are progressively gaining within the research community. So far, many investigations have been carried out to optimize the patch thickness, patch orientation, and patch shape of the adhesively bonded external patch repairs under different loading conditions using experimental, analytical or numerical approaches, and the information regarding their residual mechanical behavior can be observed from many previous pieces of literature. Numerous investigations in the area of patch repair of the laminated composite have been constrained for secondary load bearing components taking into consideration adhesive parameters (i.e. adhesive material, adhesive thickness), patch thickness, patch orientation, and patch shape as the major feature influencing the mechanical behavior of these repaired laminates [16,17].

Furthermore, the previous literature shows that the fiber reinforcement used to fabricate the external patches were identical to that of the fabric used to fabricate the parent laminate [12–17]. Due to high specific mechanical properties, carbon and glass fibers are the fiber reinforcements of choice in aerospace sectors. However, the toughness of glass and carbon fibers are considerably low and the maximum displacement to failure property is quite poor [18,19]. Repairing high stress concentrated damaged region with fiber reinforcements of least toughness induces premature failure of the structure well below the design limit of the structure. So as to overcome this problem it is becoming crucial to build up a patch that facilitate to produce adhesively bonded external patch repaired composite structures with a high strain to failure, minimum thickness and residual strength nearly close or similar as that of virgin or normal components. Hybrid external patches can be employed alternatively to produce adhesively bonded external patch repairs of minimum thickness without reducing the design mechanical properties of the repaired structures significantly.

Unlike homogeneous external patches which are appropriate to encounter a specific or exact mechanical property, hybrid external patches are heterogeneous material prepared by reinforcing two or more different types of fibers in a common matrix system to bid a range of different characteristics than the homogeneous patches [20]. They present a broad range of mechanical properties that cannot be enacted with a single type of fiber system. Hybridization process allows the designer to alter the patch mechanical properties to meet the specific requirements of the repair under consideration. In this view, Kevlar fibers are the best choice from the viewpoint of availability and cost, and hybrid glass/Kevlar fiber reinforced polymer matrix composites have consistently showed superior damage tolerance under mechanical loading than their glass fiber complements [21]. In terms of density, the three conventional fibers (Kevlar, carbon and glass) depict a considerable difference. Kevlar fiber reinforced composites are very lighter, carbon is next and the glass is the heaviest. The tensile strength of glass, Kevlar and carbon fibers is comparable. Specifically, any component where we necessitate a particular tensile strength can be smaller, or thinner and lighter if fabricated using Kevlar fibers than if made out of glass and carbon. The compressive strength of Kevlar is 1/10 of its ultimate tensile strength. Since, the aerospace structures are subjected to different types of service loading conditions, Kevlar fibers are not preferred to fabricate primary and secondary load carrying members. Hence, in addition to improving on the toughness, Kevlar fibers can only provide better specific tensile strength [22]. Even though, the importance, characteristics and applications of hybridization are examined by numerous researchers, the influences of adhesively bonded hybrid external patches on the residual mechanical properties of repaired composite laminates are not studied in detail yet. So far, no investigation has been conducted on adhesively bonded external patch repairs in damaged laminated composites using hybrid patches.

In fiber reinforced composite laminates, the combination of numerous damage modes like fiber/matrix debonding, matrix cracking, delamination and fiber breakage influence the structural integrity of the laminates. The damage in heterogeneous laminates is indeed developed by an association of numerous micro failure mechanisms. Hence, it is necessary to identify and reckon the individual failure modes to examine the predominance of each failure mode in influencing the ultimate failure of the laminates. The distinct failure mechanisms and damage propagation behavior of the hybrid patches can alter the structural response of the repaired laminates under mechanical loading. Understanding the damage mechanisms and their mutual