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# Design and optimization of bonded patch repairs of laminated composite structures

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ABSTRACT

The present study proposes a method for design optimization of external patched repairs. The tensile behavior of notched specimens with patched repair was studied using finite element analysis and compared with experimental results. It was found that high stress concentrations along the transverse edges of circular patches and/or at the longitudinal edges of the hole leads to early damage initiation in the parent plate. The damage initiation site and its propagation depend on the patch in-plane stiffness. The optimal patch design can be characterized by a strength ratio $R^*$. The overall design of the patch repair can be considered using a dimensionless design parameter $K$.

## 1. Introduction

The wide applications of composite structures, particularly in the transport industry (aeronautical, automotive and marine), pose questions about the repair of damaged composites structures. In many applications, the composite elements which were partially damaged by low-speed impacts will have reduced mechanical performance [1]. Frequently, the cost of complex composite structure is too high to systematically replace damaged ones [2,3]. A local repair can be considered as a good solution for economical and mechanical reasons and one of the repair methods often used by industry consists in bonding composite patches to the damaged areas. In order to guarantee the load transmission, the process of local scarf repair used in industry is actually quite difficult to realize: a great amount of material in the damage area will be firstly removed associated with a very low scarf angle, and then the holed zone will be filled with a patch bonded in layer-by-layer fashion [4–9]. Although the results are satisfactory, the method requires special equipment and is very time-consuming.

Another more practical method of local repair is developed using external bonded patches. Up to now, a lot of attention has been paid on the patch conception concerning the geometry, overlap length, patch thickness, patch stacking sequence, adhesive thickness, parent plate thickness, etc. Design and optimization of this type of repair have been shown to be very complex [10–13]. It was observed that each parameter has its own influence on the final performance of the repair and optimization is a complex function of these factors [14]. For instance the early works of Soutis et al. [15–17] examined the compressive behaviors of patched CFRP laminates and showed that repair performance depends strongly on the structural coherence between patch and parent material and the type of adhesive. Caminero et al. studied one side and both sides bonded patch repairs in composite panels under tensile loading [9,18]. In particular, several nondestructive testing methods were used for damage monitoring and analysis: Digital Image Correlation (DIC), Ultrasonic guided waves (Lamb waves), X-ray radiographs and ultrasonic C-scanning. Liu and Wang [19] investigated composite laminates with external patches under static tensile loading using finite element analysis (FEA). In the study of composite structures, FEA has been shown to be essential for design and simulation [14,20–22].

The aim of this present study is to develop an easy-to-use design tool for optimizing any external patched repair. This is achieved through a combined approach consisting of experimental observations, finite element simulations, and analysis.

In experimental work [23,24], the tensile behaviors of notched specimens repaired with two series patches, one with different stiffness and the other with the same in-plane stiffness but different stacking sequence, were investigated. This work allowed us to determine the way of load transfer from the parent plate to the patches, to identify the critical zones in the repaired system, and

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to establish the influence of individual parameters on repair performance. A model describing three modes of damage and failure process of repaired systems was proposed.

3D finite element modeling was used to analyze stress and strain distribution in patch repaired systems. The correlation between numerical and experimental results allows us to define a strength ratio parameter, $R^*$, which is critical to optimal patch designs. Finally, a dimensionless design parameter $K$, very easy to determine, has been proposed.

## 2. Experimental specimen

The parent composite plates were laid up to give a quasi-isotropic structure with the following stacking sequence: $[45/-45/0/90]_s$. The carbon fiber/epoxy prepreg was composed of Torayca T600S fiber and Structil R368-1 resin, cured at 125 °C. Patches were made from the same material but with varying stacking sequences. A toughened single part epoxy adhesive with a controlled 0.2 mm thick bond line (*MASTERBOND ESP 110*) was used. Material properties are presented in Table 1, where $E$ and $G$ refer to the Young's modulus and shear modulus, and $\nu$ is the Poisson's ratio. Subscripts 1, 2, 3 correspond to the longitudinal and the two transverse directions, respectively. $X$, $Y$, and $S$ refer to longitudinal, transverse and shear strength respectively. Subscripts $t$ and $c$ denote tensile and compression.

The configuration of repaired specimens is shown in Fig. 1. The 10 mm diameter hole in the parent plate is to simulate a damaged zone that has been cleaned up. The circular patches, cut from plate material, are bonded symmetrically to each side of the specimen using the standard bonding procedure. In practical terms the holes are filled with adhesive. Glass/epoxy tabs are bonded to the specimens in the grip area.

The tensile tests were run at room temperature on an MTS DY-36 universal test machine fitted with a 100 KN load cell. The loading speed was 0.5 mm/min and at least five specimens were tested in each configuration. The specimens were divided into two series so as to more clearly understand the impact factors on repair behavior.

Series I patches are designed to vary the in-plane stiffness over a wide range. These characteristics are shown in Table 2 where $A_{11}$ refers to the in-plane stiffness in the loading direction and $h$ is patch thickness. It should be noted that the fiber angle of the patch lay-up in contact with the parent plate also varies with the stacking sequence.

For Series II patches the ratio $A_{11}/h$ was held constant but the stacking sequence was varied in order to determine the importance of this variable on the performance of repaired systems (Table 3).

**Table 1**
Mechanical properties of materials.

| Material | T600S/R368-1 | MASTERBOND ESP 110 |
|---|---|---|
| $E_1$ (GPa) | 103 | 3 |
| $E_2$, $E_3$ (GPa) | 7 | |
| $\nu_{12}$ | 0.34 | 0.3 |
| $\nu_{23}$ | 0.30 | |
| $\nu_{31}$ | 0.023 | |
| $G_{12}$, $G_{13}$ (GPa) | 3.15 | |
| $G_{23}$ (GPa) | 2.75 | |
| $X_t$ (MPa) | 2006 | |
| $X_c$ (MPa) | 1500 | |
| $Y_t$, $Z_t$ (MPa) | 44 | |
| $Y_c$, $Z_c$ (MPa) | 140 | |
| $S_{12}$, $S_{13}$ (MPa) | 65 | 40 |
| $S_{23}$ (MPa) | 32.5 | |

## 3. Finite element modeling

3D FEA using MSC.Patran with a Marc 2005 solver was carried out to determine the stress/strain distribution in the patches and parent plates. A previous study had shown that this software is well suited to the analysis of composite materials [25].

Due to symmetry considerations, only one half of the repaired test specimen is modeled in the FEA (Fig. 2). Boundary conditions are simulated by fixing one end and applying a constant displacement in the longitudinal direction at the other. It was confirmed that the constant displacement gives rise to a constant reaction at the boundary since the repaired zone is sufficiently far from the fixed end. The adhesive bondline is simulated as being isotropic with an elastic–perfectly plastic behavior. The composite is assumed to be elastic. The patches and the parent plate are meshed using the real stacking sequences with hexahedron 20-node brick elements. Convergence testing was performed in high stress concentration areas. A 9384-element mesh model was adopted because it had been proved to be sufficiently accurate in terms of describing the damage initiation zones observed in the test specimens [23]. The same model was used in all repaired configurations.

In this study, only static strength analysis was performed. Patches I-1 and I-2 were found to be too soft to reconstitute the strength of specimens, and therefore they were not considered further.

## 4. Results and discussions

### 4.1. Parent plate fracture model

The fracture surfaces were examined by low magnification photography. Fig. 3a presents the typical failure morphology of the specimens repaired by $[45/-45/0/90]$ patches (Series I-4 in Table 2). A large amount of fiber breakage and delamination can be seen near the edge of patch, denoted as A. The patches were partially or even completely separated from the parent plate. Furthermore, some broken fibers from the parent plate were still attached to them. This implies that the top layer in the parent plate, which was adjacent to the adhesive, was particularly damaged and delaminated before the ultimate specimen failure. Specimens with the patches $[0]_4$ (Series I-5 in Table 2), who have the highest value of $A_{11}$, showed a similar failure surface. It appears that, with rigid patches, the damage tends to initiate in the top layer adjacent to the patch edge A. As the delamination progresses, the amount of fiber breakage in this area increases. Final failure occurs by concentrated damage of the parent plate on each side of the hole.

In the case of the specimens using $[45/-45]_s$ patches (Series I-3 in Table 2), the fracture surface were considerably different from the previous examples but in fact very similar to that of notched specimens with no repair, as seen in Fig. 3b. Here the fracture surface in the plane perpendicular to the load direction is located in the section weakened by the hole. Signs of delamination and fiber breakage are much less visible near the patch edge, suggesting that the damage is initiated at the edges of the hole in the parent plate, denoted as C in Fig. 3b. In this case, a rapid damage growth leads to the final failure along the transverse direction through the hole.

These observations were used to validate the FEA model.

### 4.2. Method of determining an optimization parameter

#### 4.2.1. Prediction of damage onset and repair failure

Since the load transfer path is from the parent plate through the adhesive joint and into the repair patch, the overall performance depends on the choice of adhesive and the surface preparation before bonding. It has been shown that the critical plastic strain