**MECHANICAL BEHAVIOUR OF BONDED REPAIRED COMPOSITE PLATES**

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**ABSTRACT**

In this work the mechanical behaviour of adhesively bonded repaired composite plates, and the evaluation of their impact resistance to low-velocity impact were analysed. A combined experimental and numerical study was carried out. The influence of several parameters of the repair in the strength and stiffness of the plate were studied.

*Keywords*: Composite repair, bonded patch, damage, laminate.

**INTRODUCTION**

The use of composite laminates leads to measurable reduction of the structural weight as well as lower fuel consumption; such operational adjustments increase the efficiency of aircrafts, and reduce pollution emissions. Structural elements of aircrafts are susceptible to damage during their service life. Complete replacement of damaged components is not always feasible, due to the high level of integration and the big size of the structural components. Therefore, repair and subsequent put into operation of composite structures, can be cost-effective and less time-consuming that the replacement [1]. Bonded repairs can restore greater strength to a damaged composite structure and show some advantages as compared to bolted repairs. In addition, external bonded patches are suitable for repair thin composite laminates [2]. Consequently, the need to gain knowledge about their behaviour under service loading is readily apparent.

The repair process begins by removing the material from the damaged area, which causes a hole in the structure. An open hole on a composite structure produces a stress gradient that increases the stress field in its proximity. Damage usually appears in the laminate at points close to the hole-edge due to the stress concentration. The strength, the stiffness and the service life of a notched structure, suffer a considerable reduction compared with the unnotched structure. For this reason, this study starts by analysing the influence of a hole on composite structures. The Discrete Damage Mechanics model of Barbero-Cortes [3] was used to estimate matrix cracking evolution. This model was modified to include a fibre damage criterion to estimate failure initiation [4]. The influence of clusters of plies with the same orientation in failure strength and matrix cracking evolution were analysed.

As a first approach to adhesive patch repair, a single-lap bonded joint was analysed in order to validate the model developed in this work. This numerical model includes a Cohesive Zone Model (CZM) used to reproduce the behaviour of the adhesive layer in the patch. The model
was validated with experimental results from the literature. The influence of the cohesive law shape and the adhesive parameters in the response of the joint were analysed. Additionally, the laminate behaviour was modelled as linear elastic, applying the Hashin criteria [5] to predict the laminate failure. With this model, repaired laminates plates subjected to in-plane loads were studied. An analysis of the influence of patch geometry and size, and adhesive thickness was carried out.

Finally the low-velocity impact responses of patch-repaired were analysed. A broad range of impact energies was selected: from barely visible impact damage energy up to perforation, because the damage mechanisms that appear near the barely visible impact damage energy (EBVID) are different from those that appear near the perforation. Contact load, absorbed energy and damage differences were compared between intact and repaired laminates.

**MATERIAL AND EXPERIMENTAL PROCEDURE**

The laminates used in this study were manufactured in autoclave by INTA (Spain) from carbon/epoxy pre-peg (IM7/MTM-45-1) supplied by Hexcel Composite Materials. A quasi-isotropic symmetric stacking sequence was selected. The laminates tested in static conditions had 8 plies ([45/0/-45/90]_S, total thickness 1.024 mm), whereas in the impact tests a 16 plies laminates ([45/0/-45/90]_2S, total thickness 2 mm) was used. The adhesive used to bond the patch to the laminate was MTA-240 adhesive (0.13 mm thick). The patch was made from the same material as the laminate. In the single-patch specimens a laminate [45/0/-45/90]_S was used. In double-patch specimens, a laminate with stacking sequence [45/0/-45/90] was placed symmetrically on both sides of the laminate.

Tensile static tests were carried on intact and, repaired specimens using a universal testing machine Instron 8816. Specimen geometry was selected according to ASTM D3039M [6]. From these tests, force-displacement curves were obtained.

Low-velocity impact tests according to ASTM D7136M [7] were carried out using a CEAST Fractovis 6785 drop-weight tower, with computer data acquisition system DAS4000. The instrumented impactor provided force-time curves, from which the maximum displacement and energy variation can be estimated [8].

**NUMERICAL MODELS**

The Discrete Damage Mechanic model of Barbero-Cortes [3] with the addition of a fibre damage model was used to predict damage evolution in laminates with a hole. The fibre failure is estimated by the maximum stress criterion with a regularized degradation model which includes the Weibull distribution. This model was implemented in the Abaqus Software using a UGENS subroutine. An in depth description of the model can be found in [4]. The model has been validated with different laminates, geometries and lay-ups, showing a good accuracy in the estimation matrix cracking evolution and failure strength.

To model the patch-repaired laminates, a numerical model than combines a failure criteria for the laminate and a CZM for the adhesive was implemented. The laminate was modelled assuming an orthotropic linear elastic behaviour. In order to predict the intralaminar failure at ply level, the Hashin Criterion [5], which includes different equations to estimate fibre and matrix failure modes, was implemented in a VUMAT subroutine. The out-of-plane failure in the adhesive was predicted using a Cohesive Zone Model. The damage initiation criterion applied was the quadratic nominal stress criterion (QUADS) [9]. To model the damage
evolution, a linear traction-separation law was selected after a preliminary study carried out on single-lap bonded joins.

The material properties and the model parameters were obtained from the literature and from characterization tests.

RESULTS

The crack density evolution in laminates plates with a centred hole subjected to a tensile load was studied. Several stacking sequences containing plies at 0º and 90º with several clusters of plies at 90º were selected, Figure 1.

In all the cases, the crack density evolution is similar: first the crack grows fast after initiation, later the grown is almost linear until the applied load is close to the failure load when an increment of the grown rate is observed. The damage starts at lower applied load as the number of plies in the cluster increase. Also, the rate of growth decrease. The numerical model was able to predict a reduction of the failure load when the cluster is thicker, as has been observed experimentally [10]. Also the position of the cluster modifies the crack density evolution. Clusters located close to the surface of the laminate produce a damage onset at lower loads and a lower damage grown rate.

The influence of patch geometry and size, adhesive thickness, patch stacking sequence, on failure force and damage evolution was analysed. Plates with single and double patch configurations subjected to tensile loads were selected. An increment of the patch size, for the same level of damage in the laminate, produces higher overlap length and increase the failure load. An optimum thickness of the adhesive layer was found, for thicker layer the failure load is reduced. This thickness is similar for all geometries and configurations analysed. Stacking sequence of the patch has not significant influence on the failure load. Only when a patch with all plies at 90º was used, a big reduction of failure load when the load is applied in
longitudinal direction was observed. A change in stacking sequence modifies the damage evolution in the patch. Patches containing a high number of plies at 0º produce a higher damage area. In all the cases tested, the single-lap patch laminates showed lower failure loads than double-lap patch laminates.

In order to study the impact resistance of double-patch repaired plates, a comparison between the low-velocity impact behaviour of repaired specimens and intact laminates was carried out. The obtained results were analysed for a broad range of impact energy, evaluating differences in contact load, damage area and absorbed energy.

Significant differences between intact and repaired specimens appear in all the variables analysed, for example in damage area and shape (Figure 2.). For repaired specimens, damage is much more localised and rounded than in intact specimens. The repair delays the initiation of the damage with respect to the intact specimens, also higher damage growth rate was detected in this specimens. The initiation of damage is observed in in the load-time history by the appearance of high frequency oscillations. These oscillations appeared at lower impact energies in the intact specimens. The contact force is lower in the latter specimens, related to the lower stiffness of the intact laminates. An influence of the impact energy was observed in the delamination threshold load (DTL). This fact differs from the behaviour observed by other authors, who postulate an independence of this variable with impact energy. The ratio between DTL and peak load is similar in all the range of impact energies studied. When the impact energy increases, the intact specimens absorb significantly more energy than the repaired laminates.

![Fig. 2 - Extension of damaged area vs. impact energy for all different specimens.](image)

**CONCLUSIONS**

In this work the behaviour of patch-repaired composite laminates was analysed. The main conclusions of the study are as follows:

- The cluster position and size modify the failure load and damage evolution on laminates with centred holes subjected to tensile loads. Thicker clusters reduce the failure load and the onset of matrix cracking. The position of the cluster modifies the behaviour of the laminate only when they are located on the surface of the laminate.
The response of a repair plate subjected to in-plane loads is highly influenced by the combination of the geometric parameters such as repair configuration (single- and double-lap), adhesive thickness, patch size, patch stacking sequence and its geometry. The most relevant parameters are patch size, adhesive thickness and repair configuration.

For the studied impact energy range, DTL varies with the impact energy and its value is higher in repaired specimens than in intact laminates, due to the higher stiffness of the repaired configuration, which increases the load needed to produce the onset of delamination. At low-impact energies energy absorption in repaired specimens was higher than the one given in intact laminates, although the measured damage area was found to be greater in the former configuration. For higher impact energies, both damage area and energy absorption in intact specimens were greater than in repaired laminates.

The differences observed in the impact behaviour in the intact and repaired samples in the range of impact energies considered clearly shows the need to select the largest possible range of energies, since the behaviour differs depending on the failure mode that is activated for a given impact energy.

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