1 Introduction

Nowadays, more and more composites materials have been applied in aerospace, automotive and marine structures. Due to the high cost of the composite structure, it could not be able to replace the damage part arose from accidental impact, bird strike, hailstones and lightening strike or deterioration caused by the absorption of moisture or hydraulic fluid [1]. As a result, maintenance and repair techniques have drawn considerable attention and repair techniques have been used widely in recent years due to the economical and ecological reason. In this context, it is extremely important to find an efficient repair method to satisfy the requirement of restore the mechanical strength and assure the functionality of the structure.

In contrast to fastened joints, adhesive-bonded patched repairs present very attractive due to their high efficiency, more uniform stress distribution and good fatigue behavior. What's more, it can be easily applied. The adhesive-bonded patched repairs consist of cutting a circular hole to remove the damage part and then the patches are bonded on one side or both sides of the laminate. This kind of repair is temporary, and also can be used as a permanent repair in lightly loaded and relatively thin structures [2].

In all types of repair, the main concerns are the prediction of initial damage, of the durability of the repaired laminate and to optimize the patches. Analytical studies, experimental method and finite element method (FEM) are the most common methodologies of analysis. This work presents a study of the tensile behavior of carbon-fiber reinforced plastic (CFRP) laminates repaired by external bonded patches. A finite element analysis was performed using LS-dyna software to understand the damage process in the tested repairs. The stresses, strains as a function of the applying load during the damage propagation. Cohesive zone models (CZM) based on energy criteria in LS-dyna were used to simulate the interlaminar delamination behaviors.

2 Experimental study

2.1 Specimens and patches

The parent plates [45/-45/0/90]S and patches used in the experiments were fabricated from the prepreg T600S/R368-1. The mechanical properties of this material are listed in Table 1[3]. The parent plate has 250 mm long by 50 mm wide and the thickness of 1.6 mm. To simulate the cleaning of damage zone in the structures, a circular hole of 10 mm in diameter was drilled at the center of the parent plate, and circular patches of 35mm in diameter were bonded on both sides by using epoxy adhesive (PERMABOND ESP 110) of 0.2mm thickness, as shown in Fig 1. The geometry of tabs which were made of glass fiber composite is 50 × 50 × 2.5 mm.

All of specimens were loaded in longitudinal tension at a rate of 0.5 mm/min. In this work, two series of patch configurations have been considered. The patches listed in Table 2 have different stacking sequence. Not only can the tensile stiffness of these patches be varied in a large range, but also the ply angle in contact with the adhesive changes. The patches listed in Table 3 have the same stiffness, just the ply angle in contact with the adhesive changes. The patches with or without coupling have all been considered. In order to obtain average values, three identical specimens were tested for each kind of
patches.

2.2 Strain gauges

Because of the slide between the tabs and the clamps, the displacements of the machine recorded during the test were not accurate, so impossible to be used to valid numerical results. In order to measure correctly the strains at certain positions, four strain gauges were used: two of them were placed on the patch; the others were fixed on the parent plate as shown in Fig 2.

2.3 Fracture modes

In order to study the failure mechanism, photographs were taken on the specimens broken. After inspect all the specimens, it was concluded that there were two principal failure modes in the tests:

Mode A (Fig 3): When the patches are sufficient strong, because of the high shear and peel stresses in the adhesive or/and in the parent plate near the patch edges, damages initiated and propagated in the adhesive ply or/and in the first ply of the parent plate. As the patches and the parent plate were partly separated, the patches could not give a reliable support to parent plate so that it could not take more loads and broke apart along the transverse direction through the hole. In general the patches were undamaged in this case.

Mode B (Fig 3): This fracture mode was observed when the strength and the stiffness of the patches is too low to resist to load. The patches were broken at the lever of the hole due to stresses concentration. The parent plate also broke apart along the transverse direction.

Details of fracture mode of two series of patches are listed in Table 4.

3 Numerical study

To avoid the limitation of 2-D models and to investigate the failure mechanism at layer level, a three-dimensional finite element model was adopted.

3.1 Failure criterion for composite

In FEM, Solid elements MAT059 were utilized to simulate the parent plate and patches. Each ply was considered as a orthotropic material with their real fiber orientation. Based on the stresses calculated eight criteria were implemented in the code to predict the various in-plane damage mechanisms [4].

Longitudinal tension:

\[
\left( \frac{\sigma_1}{S_{ca}} \right)^2 + \left( \frac{\sigma_4}{S_{ba}} \right)^2 + \left( \frac{\sigma_6}{S_{cb}} \right)^2 > 1 \tag{1}
\]

Transverse tension:

\[
\left( \frac{\sigma_4}{Y_{t}} \right)^2 + \left( \frac{\sigma_6}{S_{ca}} \right)^2 > 1 \tag{2}
\]

Through-thickness shear (combined with long. Tension):

\[
\left( \frac{\sigma_1}{X_{t}} \right)^2 + \left( \frac{\sigma_6}{S_{ca}} \right)^2 > 1 \tag{3}
\]

Delamination (through-thickness tension):

\[
\left( \frac{\sigma_3}{Z_{t}} \right)^2 + \left( \frac{\sigma_5}{S_{cb}} \right)^2 + \left( \frac{\sigma_6}{S_{ca}} \right)^2 > 1 \tag{4}
\]

Through-thickness shear (combined with transverse tension):

\[
\left( \frac{\sigma_5}{S_{cb}} \right)^2 > 1 \tag{5}
\]

Longitudinal compression:

\[
\left( \frac{\sigma_1}{X_{t}} \right)^2 > 1 \tag{6}
\]

Transverse compression:

\[
\left( \frac{\sigma_4}{S_{ca}} \right)^2 + \left( \frac{\sigma_6}{S_{cb}} \right)^2 + \left( \frac{\sigma_{11}}{S_{ca}} \right)^2 > 1 \tag{7}
\]

Through-thickness compression:

\[
\left( \frac{\sigma_3}{S_{ca}} \right)^2 + \left( \frac{\sigma_5}{S_{cb}} \right)^2 + \left( \frac{\sigma_{11}}{S_{ca}} \right)^2 > 1 \tag{8}
\]

3.2 Mixed mode cohesive zone models

It is well known that the interlaminar fracture named delamination is one of the most common and early detected failure mechanisms in composite materials. In order to simulate composite delamination, zero-thickness cohesive elements were employed to model the interfaces between each ply.

In this work, the material type MAT186 is chosen...
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for CZM. It includes three general irreversible mixed-mode interaction cohesive formulations. Furthermore, the traction-separation law with an arbitrary shape can be used in this model. The traction-separation behavior of this model is mainly given by critical energy release rate $G_i^c$ and peak traction stress in normal direction $T$ for mode I, critical energy release rate $G_{II}^c$ and peak shear stress in tangential direction $S$ for mode II and the load curve for both modes. The failure displacements $\delta_{IF}^F$ and $\delta_{II}^F$ for pure mode I and pure mode II are given respectively by:

$$\delta_{IF}^F = \frac{G_i^c}{A_{TSLC} T}$$

$$\delta_{II}^F = \frac{G_{II}^c}{A_{TSLC} S}$$

Where $A_{TSLC}$ is the area under the normalized traction-separation curve. For mixed-mode I-II the criterion proposed by Gong and Benzeggagh [5, 6], known as BK’s law [7] was used. The ultimate displacement is so defined as:

$$\delta^F = \frac{1 + \beta^2}{A_{TSLC} (T + \beta^2 S)} \times $$

$$\left[ G_i^c + \left( G_{II}^c - G_i^c \right) \frac{\beta^2 S}{T + \beta^2 S} \right]$$

Where $\beta = \delta_{II} / \delta_{IF}$ is the mixed mode ratio. Several authors have proposed different shapes for the traction-separation laws [8, 9, 10, 11], such as bi-linear, tri-linear, trapezoidal, and exponential. In this study a cohesive law shown in Fig 4 was chosen to simulate the delamination behavior.

3.3 Validation of CZM

In the present work, the values of $G_i^c = 0.516 N/mm$ and $G_{II}^c = 1.88 N/mm$ for the composites used were measured by DCB mode I and ENF mode II tests respectively, the cohesive laws of the interfaces in pure mode I and II were estimated by an inverse data fitting procedure on DCB and ENF tests. Table 3 presents respectively the cohesive parameters of pure mode I and II used to simulate the delamination. For validation CZM, DCB and ENF tests were simulated, as shown in Fig 5 and Fig 6 which indicate that the simulation has a good agreement with the results of experiments, the used CZM reproduces accurately the delamination behavior.

4 Results and discussion

In the following sections, the results of simulation with CZM are presented and compared with the experimental results.

4.1 Finite element models

The finite element model of the repairs in LS-dyna was illustrated by Fig.7. In this model, the specimen was modeled ply by ply with 8-node solid element MAT059 for the part of composite, where each interface is modeled by zero-thickness cohesive element (ELFORM=19) MAT186 with the normalized traction-separation law described by Fig. 4. The adhesive layer is considered as elastic-plastic behavior with hardness (Table 6).

4.2 Comparison between the numerical and experimental results

For the repairs studied, the predicted ultimate strengths by finite element analysis were compared with the experimental results in Fig 8 and 9. The result of series I indicated that [45/-45]s patch gives a best performance of the repairs. The increase of membrane stiffness of patches does not always lead to the increase of the failure load. The much too high membrane stiffness can result in a higher shear and peel stress in the adhesive or and in the first ply of the parent plate near the edge of patch where a earlier failure occurs. It can give us an instruction to optimize the patches. For the patches of series II which have the same membrane stiffness, no significant effect of the stacking sequence on the failure load have been observed. Fig 10 to 13 show a comparison between the strains obtained numerically and experimentally for the repairs using patches [90/0/-45/45]. It was found that the for the patch of series II and series I-3 and I-5, the interlaminar delamination occurred only on the interfaces of parent plate, whilst there was no delamination in the patch. But for the patch [75/-75]s and [90]4, the interlaminar delamination was found in both parent plate and the patches.
5 Concluding remarks

In present study, both experimental tests and numerical study are carried out to understand the influence of different stacking sequence of patches on the ultimate failure strength and the damage process of the repairs. Two series of patches were considered to investigate the influence of their membrane stiffness and the stacking sequence. Under tensile load, there are mainly two kinds of fracture mode. Too high membrane stiffness could bring about an earlier failure. With the same membrane stiffness, the stacking sequence does not have a significant influence on the failure load.

With $G^C_1$ and $G^C_2$ values measured by the experiments, an inverse data fitting procedure was used on DCB and ENF simulation to obtain the properties of the interface cohesive element which are necessary for the model of reparation. With this model, DCB and ENF tests were accurately reproduced.

For simulating composite delamination, the use of CZM at each interface of the repaired system is necessary and efficient. The results of the simulation show a good agreement with the experiment data.

<table>
<thead>
<tr>
<th>Table 2 Stacking sequence of patch in series I</th>
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<tbody>
<tr>
<td>No</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1-1</td>
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<tr>
<td>1-2</td>
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<tr>
<td>1-3</td>
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<tr>
<td>1-4</td>
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<td>1-5</td>
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<th>Table 3 Stacking sequence of patch in series II</th>
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<tbody>
<tr>
<td>No</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>2-1</td>
</tr>
<tr>
<td>2-2</td>
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<tr>
<td>2-3</td>
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<th>Table 4 Final failure modes of two series of patches</th>
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<tbody>
<tr>
<td>[90]4, [75/-75]s</td>
</tr>
<tr>
<td>[45/-45]s, [90/0/-45/45], [0]4</td>
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<tr>
<td>[45/-45/90/0], [0/90/45/-45]</td>
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<th>Table 5 Properties of cohesive element</th>
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<tr>
<td>Mode I T=15MPa ( G^I_I = 0.516N/mm )</td>
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<tr>
<td>Mode II S=80MPa ( G^{II}_{II} = 1.888N/mm )</td>
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<th>Table 6 Properties of adhesive</th>
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<tr>
<td>Shear modulus</td>
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<tr>
<td>Plastic hardening modulus</td>
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<tr>
<td>Yield stress 40MPa</td>
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<tr>
<td>Failure strain 0.08</td>
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Fig 1 Geometry of the specimen
Fig 2 Location of the four strain gauges

Fig 3 Mainly failure mode of the tested specimen

Fig 4 Normalized traction-separation law for CZM

Fig 5 Comparison between numerical and experimental results for DCB tests

Fig 6 Comparison between numerical and experimental results for ENF tests

Fig 7 Finite element model in Ls-dyna

Fig 8 Predicted ultimate strength in function of A11 vs experiment data for the patches in series I

Fig 9 Predicted ultimate strength vs experiment data for the patches in series II
6 References


[5] Gong XJ , "Rupture interlaminaire en mode mixte I+II de composites tariifs unidirectionnels et multidirectionnels verre/epoxy".PhD thesis, Université de Technologie de Compiègne, France


