1 Introduction

High performance composites, such as carbon-fibre reinforced plastic (CFRP) composites, are being increasingly used in the structures requiring high specific strength and stiffness. Nowadays, more and more these composites materials have been applied in automotive, marine, aeronautical and aerospace industries. Their wide acceptance introduces an issue related to the handling of these materials after damage arose from accidental impact, bird strike, hailstones and lightning strike or deterioration caused by the absorption of moisture or hydraulic fluid[1-2]. Due to the economical and ecological reason, repair of these structures should be evaluated instead of their disposal. 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 are considered as very attractive method due to their high efficiency, more uniform stress distribution and good fatigue behavior. This kind of repair can also be easily applied. The procedure of adhesive-bonded patched repairs consists of removing the damage part and bonding one or two patches [3]. This kind of repair is temporary, and also can be used as a permanent repair in lightly loaded and relatively thin structures [4]. In all of these types of repairs the main concerns are the prediction of the initial damage, the durability of the repaired laminate and the optimization of the patches. The work presented in this paper focuses on the damage propagation process in the open-hole composite plates repaired by external bonded patches under tensile loading. During the tests, strain gages, video extensometer and acoustic emission were used to investigate damage initiation and its propagation in the tested repairs. A finite element analysis was performed using LS-dyna software to simulate the damage process. Cohesive zone models (CZM) based on energy criteria in LS-dyna were used to simulate the interlaminar delamination behaviors. The objective of this work is to establish a numerical model which can predict the initial damage, its propagation until the final fracture.

2 Experimental study

2.1 Specimens and patches

Firstly static tensile tests were performed on the repairs in room temperature. Herein the composite plates were made of carbon/epoxy T600S/R368-1 with 8 plies quasi-isotropic laminate: [45/-45/0/90]s. The mechanical properties of this material are listed in Tab. 1. 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 (Araldite 2015) 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. Various patches with
different stacking sequence were used to understand its influence on the performance of the repairs. In this work, two series of patch configurations have been considered. The patches listed in Tab. 2 have different stacking sequence. Not only has the tensile stiffness of these patches varied in a large range, but also the ply angle in contact with the adhesive changes. The patches listed in Tab. 3 have the same stiffness, just the ply angle in contact with the adhesive changes. Three identical specimens were tested for each kind of patches in order to obtain average values.

2.2 Observation on fracture surface

In order to study the failure mechanism, photographs were taken on the fracture surface of the broken specimens. Three types of final failure modes can be concluded:

Mode A (Fig. 2(a)): this fracture mode was observed when the stiffness of the patches is very low, such as [90], and [75/-75]. The patches were always broken in the weakened section of the hole due to stresses concentration. The parent plate also broke apart along the transverse direction.

Mode B (Fig. 2(b)): this fracture mode was found on the specimens with the patches [45/-45].s. The patches always stick to the parent plate and were not broken. The fracture in joint was hardly found between the parent plate and the patches. The delamination was observed between the first two plies of the parent plate adjacent to the joint.

Mode C (Fig. 2(c)): this kind of fracture mode was observed on the specimen with the patches [0], and the patches in series II. The fracture in the adhesive seems to be the principle cause of this fracture mode. When the patches are sufficient stiff and strong, damages initiated and propagated in the adhesive joint because of the high shear and peel stresses in the adhesive near the patch edges. 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. The patches seem undamaged in this case.

2.3 Assessment of damage during the tests

In order to investigate the damage initiation and its propagation until the final fracture, strain gauges, video extensometer and acoustic emission sensors have been used during the tests.

2.3.1 Strain gauges

The location of the strain gauges used for every specimen was illustrated in Fig. 3. Fig. 4 presents the responses of the train gauges for a specimen repaired by the patches [0/90/45/-45]: the gauge 1 which was bonded to the parent plate shows a linear response until the final failure of the repair. It means that there was no damage in the parent plate far away from the zone repaired. The response of the gauge 1 was taken as a reference. The responses of the gauge 2 and 3, which stuck to the edge of the patch and the centre of the patch respectively, show a linear part at the beginning of the test until about 50% of the failure load. Then it began to present a nonlinear behavior because of the damage in the adhesive. The responses of gauge 2 allow detecting not only the plastic deformation in the adhesive, but also the partial detachment of the patch. It is noted that the strain measured by the gauge 2 and 3 tend to 0 as the patches were completely detached from the parent plate.

2.3.2 Acoustic emission

In this work, three acoustic emission sensors were employed to detect when and where damage initiation occurred and follow their propagation. One sensor is placed on the center of the patch and two sensors on the parent plate. The distance between every two sensor is 40 mm, as shown in Fig. 5.

2.3.3 Video extensometer

Actually, the displacements of the machine recorded during the test were not accurate due to the slipping between the tabs and the clamps, and so it is impossible to be used to compare to the results obtained by numerical simulation. A video extensometer with two laser points (Fig. 6) was so used during the tests to record the relative displacement of a 50mm calibrate length as a function of the applying load.

3 Numerical simulation

The behavior of the repairs was simulated by using software Ls-dyna.

3.1 Continuum damage model for composite

Plate and the patches in composite were simulated by using a continuum damage mechanics model (MAT058) with thick shell element. This kind of material model takes into account the influence of
Numerical simulation of composite structure repaired by external bonded patches under tensile loading using cohesive elements

the damage on the stiffness and the strength of the material with a damage variable. This variable varies between 0 and 1, which correspond to an initial state without damage and a complete damage state respectively. The failure criterions, as shown in Eq (1)-(3), were implanted in this model [5, 6]:

\[
f_{11} = \frac{\sigma_{11}^2}{(1-w_{1c,t})^2} X_{c,t}^2 - r_{1c,t} = 0 \quad (1)
\]

\[
f_{22} = \frac{\sigma_{22}^2}{(1-w_{2c,t})^2} Y_{c,t}^2 - r_{2c,t} = 0 \quad (2)
\]

\[
f_{12} = \frac{\epsilon^2}{(1-w_{12})^2 S^2} - r_s = 0 \quad (3)
\]

Where \( w_{1f}, w_{2f} \) and \( w_{12} \) are the damage variables in the fiber direction, the transverse direction to fiber and the shear direction in the fiber plan, respectively. \( r_i \) is the threshold which measure the size of the elastic region. The evolution of the damage is controlled by an exponential law as following:

\[
w_i = 1 - \exp \left[ - \frac{1}{m_i} \frac{\epsilon}{\epsilon_{\beta}} \right] \quad (4)
\]

Where \( \delta_f \) is the final strain related to the complete damage. \( m_i \) is a parameter which is computed internally and describes the development of the different failure modes like tension, compression and shear in the various directions depending on the strains.

3.2 Mixed mode cohesive zone models

The interlaminar fracture named delamination is one of the most common and early detected failure mechanisms in composite materials. It can even determine the performance of a composite structure. In the last decade years, cohesive zone model has been well developed to simulate composite delamination. In this work, zero-thickness cohesive elements with the material model MAT186 in LSDyna were employed to model the interfaces. The cohesive elements are inserted between two solid/shell elements and are controlled by a Traction Separation Load Curve (TSLC), as shown in Fig. 7. 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 \( G_{IC} \) and peak traction stress in normal direction \( T \) for mode I, critical energy release rate \( G_{IIc} \) and peak shear stress in tangential direction \( S \) for mode II and the load curve for both modes. The failure displacements \( \delta_{IF} \) and \( \delta_{II,F} \) for pure mode I and pure mode II are given respectively by:

\[
\delta_{IF} = \frac{G_{IC}}{A_{TSLC,T}} \quad (5)
\]

\[
\delta_{II,F} = \frac{G_{IIc}}{A_{TSLC,S}} \quad (6)
\]

Where \( A_{TSLC} \) is the area under the normalized TSLC. For mixed-mode I+II the criterion proposed by Gong and Benzeggagh [7, 8], known as BK’s law [9] was used. The ultimate displacement is so defined as:

\[
\delta_f = \frac{1 + \beta^2}{A_{TSLC} (T + \beta^2 S)} \left[ G_{IC} + G_{IIc} \left( \frac{\beta^2 S}{T + \beta^2 S} \right)^{3/2} \right] \quad (7)
\]

Where \( \beta = \delta_{II}/\delta_{I} \) is the mode mixity.

In this study a bilinear cohesive law was chosen to simulate the delamination behavior. According to our previous study [10, 11], the parameters for cohesive element between the plies in the composite and adhesive/adherents were illustrated in Tab. 4.

3.3 Numerical model of the repairs

In order to investigate the damage initiation and its propagation until the final fracture in the repairs, the parent plate and the patches were simulated ply by ply and the cohesive zone models were inserted to all the interfaces, as shown in Fig. 8. The adhesive (Araldite 2015) was considered as isotropic material with bilinear elastic-plastic behaviour illustrated in Fig. 9. In this work, MAT003 was employed to simulate the adhesive. The Properties of the adhesive from the literature [12-14] are listed in Tab. 5. In order to guarantee an accurate simulation, Turon et al [15] propose that at least three elements have to be within the cohesive length, which is defined as the distance from the crack tip to the point where the interface strength is reached. According to our previous study [10, 11], a mesh size of 0.25 mm is used for the critique zones, such as at the edge of the patches and the hole in the
centre. Fig. 10 presents the numerical mesh model used in our simulation.

3.4 Results and discussions

3.4.1 Load-displacement curve

Fig. 11 compares the results of the numerical simulation with experimental load-displacement curve measured by the video extensometer for a specimen repaired by the reference patches [90/0/-45/45]. Generally, it is shown that the stiffness predicted by the simulation is in very good agreement with experimental value, but the numerical prediction for remote failure load is lower about 10% than measured one.

3.4.2 Remote failure strength

Analyse of experimental observation shows an influence of the stiffness and the stacking sequence of the patches used on both of the performance of the repairs (Fig. 12) and their failure mode. The result of series I indicated that the reference patch [90/0/-45/45] 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 an earlier failure occurs. This observation is in accordance with the conclusion in references [16, 17]. For the patches of series II which have the same membrane stiffness, the specimen repaired by the patches [0/90/45/-45], whose fiber direction adjacent to the adhesive is 0°, gives the best performance. The specimens repaired by the patches [45/-45/90/0] which has the same fiber direction adjacent to the adhesive as the parent plate present the worst performance. Fig. 12 show a comparison between the remote failure stresses obtained numerically and experimentally for the two series of the tests. It is shown that this model can predict the best and the worst performance for both two series of the tests, although the numerical results are always lower than experimental ones. For most of the cases, the error is inferior to 10%.

3.4.3 Damage process

With the help of the sensors of acoustic emission (AE), we can obtain the information about the damage initiation and its propagation up to the final fracture. Take the specimen repaired by the patches [0]₄ as an example. By analyze acoustic emission signals in Fig. 13, which present the energy of AE as a function of X position of the event, the damage appears at the edge of the hole when the force is about 30% of failure load (Fig. 13(a)). According to the numerical results, the initial damage appears at this moment and is located at the surface of the patch in the transverse direction (matrix and fibre/matrix interface damage) at the edge of the hole. But the response of the strain gauge 3 (Fig. 14) was always linear when the force was 30% of the failure load. That means there should be no important damage on the patch surface at this moment. So this numerical model can predict the moment when the damage takes place, but it cannot give the correct information on the location of the initial damage.

When the force is up to 85% of the failure load, all kinds of damage except delamination such as fiber breakage, matrix failure and shear failure predicted by the numerical model take place in the central zone of the patches. The delamination at the interfaces between adhesive//plate (Fig. 15(b)) and adhesive//patches (Fig. 15(c)) is located at the edge of the patch in longitudinal direction. This information is in good agreement with the results obtained by acoustic emission (Fig. 15(a)).

When the force is up to 100% of the failure load, according to Fig. 16(b)-(e), the delamination was well spread in the parent plate, especially at the interface adhesive//plate. Then the patches detach more and more so as to reduce their capacity of load transfer and accelerate the damage propagation in the plate. The final fracture occurs after fiber breakage at the ply 0° in the plate (Fig. 16(f)). Compared with the fracture surface (Fig. 16(g)), the numerical results show a close correspondence with the experimental results.

4 Conclusions

In this study, both experimental tests and numerical study are carried out to investigate the influence of different stacking sequence of patches on the ultimate failure strength and the damage process in a repair structure.

Two series of patches were considered to investigate the influence of their membrane stiffness and the stacking sequence. Under tensile load, there are
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mainly three kinds of fracture mode. Too low and high membrane stiffness could bring about an earlier failure. The best performance is found in the repairs with the patches having the same stiffness as that of the parent plate. With the same membrane stiffness, the specimen repaired by the patches [0/90/45/-45], whose fiber direction adjacent to the adhesive is 0°, gives the best performance, while those repaired by the patches [45/-45/90/0] which has the same fiber direction adjacent to the adhesive as the parent plate present the worst performance.

The stiffness of the curve force-displacement and the remote failure strengths predicted by the numerical model show a good agreement with the experimental results. By the comparison between the numerical results and the information of acoustic emission, it is concluded that our numerical model is capable to predict the moment of the initial damage and the damage pattern during the damage process. But it has to be improved because the prediction of the location of the initial damage has not been verified by experimental observation.

Tab. 1 Mechanical properties of composite materials

| E11 (GPa) | 103 | E12, E22 (GPa) | 7 |
| v12 | 0.34 | v23 | 0.30 |
| v31 | 0.023 | G12, G13 (GPa) | 3.15 |
| Xc (MPa) | 2100 | G23 (GPa) | 2.75 |
| Yc, Zc (MPa) | 1500 | Yt, Zt (MPa) | 55 |
| Yt, Zt (MPa) | 180 | S12, S13, S23 (MPa) | 80 |

Tab. 2 Stacking sequence of patches used in series I

<table>
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<td>7</td>
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<td>1-2</td>
<td>[75/-75]s</td>
<td>6.2</td>
<td>7</td>
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<td>[45/-45]s</td>
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<td>1-5</td>
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Tab. 3 Stacking sequence of patches used in series II

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Tab. 4 Properties of cohesive element

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<td>Interface strength T for mode I</td>
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<td>Interface strength S for mode II</td>
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<td>Interface stiffness for mode I</td>
<td>K_{01}</td>
<td>2×10^5 N/mm^3</td>
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<tr>
<td>Interface stiffness for mode II</td>
<td>K_{01}</td>
<td>2×10^5 N/mm^3</td>
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<tr>
<td>XMU for mixed mode</td>
<td>0.85508</td>
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<td>Fracture energy for mode I</td>
<td>G_{IC}</td>
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<tr>
<td>Fracture energy for mode II</td>
<td>G_{IIC}</td>
<td>1.89 N/mm</td>
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Tab. 5 Properties of adhesive

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<td>Young’s modulus: E (Mpa)</td>
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<td>Poisson ratio</td>
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Fig. 1 Geometry of the specimen

Fig. 2 Fracture surfaces of the tested specimens
(a) Mode A
(b) Mode B
(c) Mode C

Fig. 3 Location of the strain gauges

Fig. 4 Responses of the strain gauges for the specimen with patches [0/90/45/-45]

Fig. 5 Location of the acoustic emission sensors

Fig. 6 Calibrate length defined by two laser points on the specimens

Fig. 7 Cohesive zone model (CZM)
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Fig. 8. Numerical model for repairs with CZM

Fig. 9 Behavior of adhesive

Fig. 10. Mesh model of the repairs

Fig. 11 Comparison between the experimental and numerical F-δ curves

Fig. 12 Comparison between the experimental and numerical remote failure stresses

(a) Energy of acoustic emission signal as a function of the x position at 30% of the failure load

(b) Matrix and interface damage in the patch

Fig. 13 Damage initiation for the patches [0]4
Fig. 14 Responses of the strain gauges for the specimen with patches $[0]_4$.

(a) Energy of acoustic emission signal as a function of the $x$ position at 85% of the failure load

(b) Delamination adhesive // parent plate

(c) Delamination adhesive//patch

Fig. 15 Damage propagation (force=85% failure load)

(a) Energy of acoustic emission signal as a function of the $x$ position at 100% of the failure load

(b) Delamination between $-45^\circ$/0° in the plate

(c) Delamination between 0°//90° in the plate

(d) Delamination between 90°//90° in the plate
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