Numerical analysis of damage evolution in adhesive of bonded composite Material

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Abstract— Adhesives play important roles in bonded composite repair as it ensures the transfer of load between the composite patch and the cracked aluminum component. Also, it holds the two structures together. The damage of the adhesive can thus reduce significantly the efficiency and the durability of the bonded composite repair. The adhesive damage models using critical zone have proven their effectiveness due to simplicity and applicability of the damage criteria in these models. The scope of this study is the estimation of the adhesive damage and failure in bonded composite repair of aircraft structures using modified damage zone theory. The effect of this damage on the repair efficiency was analyzed. In order to achieve these objectives, non-linear finite element analyses of adhesive joints considering the material nonlinearity of the adhesive layer were performed. The obtained results show that adhesive damage is principally located at the free edges of the patch and over the crack region. The damage zone ratios depends on the applied load, it affects the repair efficiency when its value approaches the critical value of 0.22.

Index Terms— damage zone theory, composite repair, crack, cohesive failure, finite element method, damage ratio, stress intensity factor.

I. INTRODUCTION

Bonded composite repairs of metallic structure have become a useful aircraft structural life extension solution over the last two decades. These repairs provide an efficient method for restoring the ultimate load capability of the structure. They also offer several advantages over bolted repairs, including minimal changes to aerodynamic contours, weight savings, reduced cost, and formability to complex shapes. This technology can also be used very effectively to reinforce under-designed undamaged structures where there is risk of fatigue cracks initiations. Several design parameters play important roles in bonded composite patches which include: patch size, shape and taper, materials selection, fiber reinforcing/mediation phase in order to allow the widespread use of bonded repair with carbon fiber reinforced composites. The adhesive properties have focused a particular importance in the literature. Gkikas et al. [1] introduced small weight fraction of multiwall carbon nano–tubes in a polymer adhesive film used for bonded composite repair. They concluded that this reinforced adhesive be employed as a reinforcing/mediation phase in order to allow the widespread use of bonded repair with carbon fiber reinforced composites. About the effect of the patch shape, Bachir Bouiadja et al. [2] compared the rectangular and trapezoidal patch shapes. They showed that the trapezoidal shape improves the repair efficiency and durability. Ramji et al. [3] tested several patch shapes and they concluded that the extended octagonal patch shape performs better in case of stress intensity factor reduction. Hosseini et al. [4] established that as the thickness of the composite patch is increased, fatigue crack propagation of
repaired stiffened panel is also increased. Aminallah et al. [5] used the finite element method to estimate the intensities of the thermal stresses in bonded composite repair of aircraft structures, they concluded that These stresses lead to an increase of the stress intensity factor what cause the reduction of the fatigue life of the repaired structures.

The majority of works on the analyses of adhesively bonded composite patch repairs [6–10] have avoided analyzing the nonlinearity of geometry and materials. Generally, these investigations assume that the base–plate have linear elastic material properties. This assumption allows applying of linear elastic fracture mechanics concepts to analyze the repaired structures. Albedah et al. [6] and Bachir Bouiadjra et al. [7] analyzed the performances of double symmetric patch by applying the concepts of elastic fracture mechanics. Wang et al. [8], Albedah et al. [9] and Mhamdia et al. [10] analyzed the effects of thermal stresses by considering behavior of all materials (aluminum, composite and adhesive) linear and elastic.

Recently, some studies have taken into account the effect of the material plasticity. Albedah et al. [11] studied the elastic–plastic behavior of repaired cracks with bonded composite patch, their results show that the plastic zone sizes around the crack tip decrease significantly when the patch is bonded. This is due to the fact that a part of the plastic strain around the crack tip is absorbed by the composite patch. In another study, Oudad et al. [12] investigated the influence of the patch parameters on the size of the plastic zone at the tip of repaired cracks. They showed that the presence of the composite patch reduces considerably the size of the plastic zone ahead of the crack. This reduction is very important so that the concepts of linear fracture mechanics can be applied for repaired cracks. The adhesive disband during the repair process has focused special attention in the literature. Recently, several papers describing the effects of the adhesive disband on the repair efficiency were published [13–16]. Bachir Bouiadjra et al. [17] analyzed the effect of adhesive disband on the performances of bonded composite repair in aircraft structures. Their investigations showed that the presence of the adhesive disbonds increases the stress intensity at the tip of repaired cracks which can reduce the repair efficiency. In the case of double symmetric composite patch, the presence of double adhesive disband accentuates its negative effect on the repair efficiency and increases the risk of adhesive failure between the bonded structures. Ouinas et al. [18] studied the behavior of progressive edge cracked aluminum plate repaired with adhesively bonded composite patch under full width disband. It was shown in this study that the reduction of the stress intensity factor at the crack tip increases with the patch thickness for disband width higher than crack size. Bachir Bouiadjra et al. [19] analyzed the effect of the adhesive disband for inclined cracks repaired with boron/epoxy patch. It was concluded that the booth mode I and mode II stress intensity factors are negatively affected by the presence of the adhesive disband. Caminero et al. [20] used different on–line monitoring Technology, such as Digital Image Correlation (DIC) and Lamb waves, in order to study the performance and damage detection in bonded composite repairs. Critical zone criteria were proposed [21] [22] to analyze the adhesive damage and failure. These criteria states that the material will fail once the measured stress exceeds the ultimate strength of the material everywhere within a critical distance or zone. The adhesive damage occurs when the adhesive strains or stresses are locally greater than the ultimate material properties. Adhesive fracture does not occur by the propagation of cracks, but rather by the initiation and propagation of a damage zone in the adhesive containing defects such as micro–cracks or voids [23]. Sheppard et al. [22] introduced a critical failure zone for composite and aluminum single–lap and double–lap joint. The critical area, where the on Mises strain exceeded a maximum strain allowable, was determined at the point of the experimental failure load joints considering the presence of singularities at the free ends of the joint. This model was extensively used in the literature to predict the adhesive failure. Magalhães et al. [23] have observed that the damage propagates inside the adhesive, but near the interface adhesive—adherend. The failure, that appears to be adhesive, is in fact cohesive because a thin adhesive layer can be observed on the adherend surface. Ban et al. [24] introduced modifications on the damage zone model of Sheppard et al. [22], the damage zone ratio was suggested for the failure load prediction of the adhesive joint. For The Structural FM 73 epoxy adhesive, it was shown that that the damage zone ratio corresponding to the failure of this adhesive is about 0.247. Apalak et al., [25] al used the damage zone theory to analyze the effects of thermal stress in bonded composite tee joint with double support. They showed that the joint failure can be expected along the composite plates surfaces as well as inside the adhesive fillets in cases where toughened adhesives are used. All these studies are limited to analyze the failure in adhesively bonded joint. The scope of this paper is to use the modified damage zone models in order to analyze the adhesive damage in bonded composite repair of aircraft structures and to estimate the effect of this damage on the repair efficiency. The finite element method was used for the composite repair simulation and for the estimation of the damage zone ratio in the adhesive. This ratio gives the relationship between the damaged zone of the adhesive and the total bonded area.

II. GEOMETRICAL AND FE MODELS

The basic geometry of the cracked structure considered in this study is shown in “Figures I”. Consider a rectangular aluminum 2024–T3 plate with the following dimensions: height $H_p = 254$ mm, width $W_p = 254$ mm, thickness $t_p = 2.5$ mm, with a central crack of length $2a$. The plate is repaired with single and double boron–epoxy patch of dimensions: $H_f = 75$ mm, $W_f = 130$ mm and $e_f = 1.5$ mm, the plies in the patch had unidirectional lay–up where the fibers are oriented along
the specimen length direction (parallel to the direction of load). The patch is bonded by 0.15 mm thick film of FM 73 epoxy adhesive “Fig. 1”. The plate is subjected to a remote uniaxial tensile load of amplitude $\sigma$. The elastic properties of the different materials are given in Table 1.

### TABLE I. ELASTIC PROPERTIES OF THE DIFFERENT MATERIALS

<table>
<thead>
<tr>
<th>Properties</th>
<th>Aluminium alloy T3</th>
<th>Brön/epoxy</th>
<th>Adhesive(FM73)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Young modulus $E_1$(GPa)</td>
<td>72</td>
<td>200</td>
<td>4.2</td>
</tr>
<tr>
<td>Transversal Young modulus $E_2$(GPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transversal Young modulus $E_3$(GPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Poisson ratio $\nu_{12}$</td>
<td>0.33</td>
<td>0.3</td>
<td>0.32</td>
</tr>
<tr>
<td>Transversal Poisson ratio $\nu_{13}$</td>
<td></td>
<td>0.28</td>
<td></td>
</tr>
</tbody>
</table>

The stress–strain curves of the FM 73 epoxy adhesive is presented in “Fig. 2”. “Figure 3” presents the multi–linear stress–strain curve of the FM73 adhesive for determining its ultimate strain.

The analysis involves a three–dimensional finite element method by using the commercially available finite element code ABAQUS [26]. The finite element model consisted of three subsections to model the cracked plate, the adhesive, and the composite patch. Due to symmetry, only one quarter of the repaired plate was considered. The plate had four layers of elements in the thickness direction, the adhesive had only one layer of elements through thickness and the patch had two layers of elements through thickness. The mesh was refined near the crack tip area with an element dimension of 0.067 mm using at least fifteen such fine elements in the front and back of the crack tip. “Fig. 4” shows the overall mesh of the specimen and the mesh refinement in the crack tip region.
The procedure used in the finite element analysis is as follows: the tensile stress was applied to the grip specimen. General static “STEP” option was used for analysis with ABAQUS. Automatic increment of step was used with maximum number of increments of 100. Minimum increment size was 10^-5. Maximum increment size was 1. Nevertheless, the ABAQUS solver code could override matrix solver choice according to the “STEP” option. The Von-Mises criterion is used as plasticity criterion. Incremental plasticity theory is introduced to model the material non-linearity. The Newton-Raphson iterative method is used as an approach for resolving non-linear finite element equations. The Stress intensity factor at the crack front was computed using the virtual crack closure technique (VCCT). The VCCT is based on the energy balance. In this technique, the stress intensity factors are obtained for three fracture modes from the equation:

\[ G_i = \frac{K_i^2}{E} \]  

Where \( G_i \) is the energy release rate for mode \( i \), \( K_i \) the stress intensity factor for mode \( i \), \( E \) the elastic modulus.

### III. Damage Zone Theory

The theory’s main assumption is that both adhesive and adherent crack initiation in adhesively bonded joints will occur after a damage zone develops. Under low load, localized damage will occur at the end of the joint. This damage occurs because the material is locally subjected to strains greater than the ultimate material strain. Under medium load, the damage zones will grow in size and the concentration of points of specific damage will increase. As the failure load is reached the damage zone in either the adhered or the adhesive will grow to a critical size and the individual components of damage will coalesce and form a crack.

The damage zone will be identified by marking elements for which a failure criterion is exceeded on the element. The adhesive used in the analyzed joints is a toughened ductile adhesive which is expected to suffer a yielding failure. Consequently, the failure criterion used for cohesive failure of the adherent will be the equivalent Von Mises strain criterion.

\[ \varepsilon_{equiv} = \frac{1}{\sqrt{2(1+\nu)}} \left( \varepsilon_{p1} - \varepsilon_{p2} \right)^2 + \left( \varepsilon_{p2} - \varepsilon_{p3} \right)^2 + \left( \varepsilon_{p3} - \varepsilon_{p1} \right)^2 \]  

Where \( \varepsilon_{equiv} \) is the equivalent stain, \( \varepsilon_{p1} \) are the plastic strains in the different directions and \( \nu \) is the Poisson ratio.

This criterion is satisfied when the maximum principal strain in the material reaches the ultimate principal strain. For each failure criterion an ultimate strain will be defined and the corresponding damage zone size at failure determined. For the FM 73 epoxy adhesive, the damage zone was defined as an area in which the strain exceeded the ultimate strain of 7.87\% [24] see “Fig. 3”.

Under damage zone theory, we assume that the adhesive joint fails when the damage zone reaches a certain reference value. The damage zone can be defined by either the stress or the strain criterion. The strain criterion is more appropriate when the adhesive exhibits significant nonlinearity. There are two modes of failure relevant to the adhesive joints: interfacial and cohesive failure. In the interfacial mode, the failure load of the adhesive joint depends on the interfacial stress near the interfaces between the adhesive and the adherend [24]. However, the adhesive fails when cohesive failure occurs in the joint. Since cohesive failures certainly occurred in the adhesive joint, we recommend using the adhesive failure criterion for the damage zone. The failure criterion, for isotropic materials, such as the Von-Mises and Tresca criteria can be used to better understand adhesive failures. We can also predict the failure of the adhesive joints by using the damage zone ratio method. The damage zone ratio \( DR \) is defined as follow:

\[ D_R = \frac{\sum A_i}{L_w} \]  

\( DR \) is the damage zone ratio, \( A_i \) the area over which the equivalent strain exceeds 7.87\%, \( L \) the adhesive length and \( w \) is the adhesive width. The plate is subjected to a remote uni-axial tensile load of \( \sigma = (100,250) \) MPa. It was shown that he FM 73 fails when the DR value reached 0.2474 [24].

### IV. Results and Discussion

This study was carried out in order to determine the evolution of the damage zone in the adhesive layer in aircraft structures repaired with bonded composite patch. The damage zone theory was used to achieve the objectives of the analysis.
First, the area of the damaged zone was computed for different crack lengths with an applied stress of 100 MPa. “Fig. 5” presents (in gray) the contour of the damaged zones in the adhesive layer for a crack length a=5mm (relative small crack). From this figure, it can be noted that the damaged zones are localized around the crack tip and more significantly at the free edges of the bonded area. The damaged zone around the crack tip for this crack length (a=5mm) is very small. This is due to the fact that the intensity of the stresses at the crack tip remains insufficient to create a significant damaged zone in the adhesive. These observations allow us to deduce that for small cracks the adhesive damage can have a negative effect on the repair durability, but its effect on the repair efficiency is not significant. Indeed, the localization of the damaged zone at the free edge may lead to a failure at this region and not at the crack tip region. Because of the small damaged area of the adhesive over the crack region, the stress transfer between the cracked plate and the composite throughout the adhesive layer remains stable.

Fig. 5. Damaged zones of the adhesive for a= 5 mm and $\sigma$ =100 MPa

In fatigue loading of aircraft structures, often yielding of the adhesive can occur at the free edge and lead to a premature adhesive failure. Our analysis of the adhesive damage is more realistic than the studies which assumed rectangular disband of the adhesive. The majority of these studies, assumed an adhesive damage over the crack region and neglect the adhesive damage at the free edge of the patch. With the model used in this study, it can be confirmed that the damaged zone of the adhesive at the free edge can propagate along the adhesive layer and can lead to the failure of the junction between the repaired structure and the composite patch. In order to make the use of the damage zone model more practical for bonded composite repair designers, it is recommended to estimate the number of cycle when the damage becomes initially detectable and when the extent of damage reaches the value of residual strength. This estimation can help the designers for the choice of optimal repair parameters. In this context, Papanikos et al [31] confirmed that when the adhesive disband initiates at the upper patch edge, it significantly reduces the patch effective area and can be catastrophic for the repair. In such cases, the disband initiation load is also the maximum load that the repair can sustain.

“Figure 6” presents the extents of the damaged zone of the adhesive for a crack length a=25mm. This length gives an asymptotic value of the stress intensity factor at the crack tip [6]. It can be noted that the variation of crack length does not affect the damaged zones at the free edges as its area remains the same compared to the case for a=5mm. However, the extent of the damaged zone of the adhesive over the crack region is more significant when the crack length increases. The ratio between the areas of the damaged zones over the crack region for $a=25$ mm and $a=5$ mm is about 10. We can thus confirm that, in the adhesive layer, there is two regions where the most load transfer take place between the patch and repaired structures (over the crack and at the free edge). In these two regions, the patch geometries (particularly the patch shape) can be modified in order to reinforce the adhesion and to reduce the adhesive damage. One of the proposed solutions is to avoid a sharp angle at the free edge of the patch and to take rounded shapes at the free edges which offer the possibility to reduce the adhesive stresses at the free edge and consequently the risk of the adhesive failure will be significantly attenuated. Between the regions of load transfer, there is a zone in the adhesive layer where the adhesive stresses are practically null. Poole [28] detected with ultrasonic inspection that, in general, the adhesive disband have an elliptical shape. This observation is in agreement with our results. Indeed, if the total structures is considered (the quarter of the structure were modeled due to the symmetry of geometry and loading), we can confirm that the adhesive damage zone ahead of the crack tip has approximately an elliptical shape. Over the crack region, the stress transfer can be significantly reduced at the crack region and theories assuming that the stress intensity factor exhibits an asymptotic behavior for patched cracks [6, 7, 10, 14 and 19] can be seriously compromised. Based on these results, designers of bonded composite repairs are recommended to take into account the adhesive damage for the patch design. The initiation of the propagation of the patch disband may be controlled by the geometry of the repair [2].

Fig. 6. Damaged zones of the adhesive for a= 25 mm and $\sigma$ =100 MPa
“Figure 7” shows the extent of the adhesive damaged zone for crack length a=45 mm. It can be seen that area of the damage zone increases significantly over the crack region and remains practically constant at the free edge of the patch. This result confirms those presented in “Figures 5 and 6”. The risk of the adhesive failure is high at the free edge of the patch for any crack length and near the crack tip it strongly depends on the crack length. It can be also noted, according to the results of “Figure 7”, that the adhesive damage or the adhesive disband propagates in parallel and perpendicularly to the crack direction. This propagation can have a very negative on the repair efficiency because the adhesive failure occurs over the crack region and the load transfer between the aluminum plate and the composite patch will be substantially reduced. The rate of reduction of the stress intensity factor by the patch will be less significant and the repair efficiency will be necessarily reduced. When the adhesive damage zone propagates perpendicularly to the crack direction, its effect on the repair efficiency is not significant because the adhesive damage will be concentrated at the region of the adhesive with minimal load transfer [19].

To better understand the effect of the adhesive damage on the repair efficiency, the modified damage zone theory was used in this study. This theory introduces the damage zone ratio DR defined in equation 2. Su Ban et al [29] have shown that the FM 73 adhesive joint fails if the damage ratio reaches the value of 0.2474. “Figure 8” presents the variation of the ratio DR as a function of the crack length for two applied stresses $\sigma$=100 and 250 MPa. It can be noted that the ratio DR increases approximately linearly with the crack growth.

The applied stress has a very significant effect on the damage ratio variation. The relative variation of the damage ratio between $\sigma$=100 and 250 MPa is about 54% and it is greater than the ratio between the two applied loads which is equal to 40%. For $\sigma$=100 MPa, the results of “Figure 8” show that whatever the crack length, the risk of the adhesive failure does not exist since the damage ratio DR is lower than the critical value of 0.2474. On the other hand, for $\sigma$=250 MPa, the adhesive failure occurs when the crack length exceeds the value of 35 mm. These results can be explained by the fact that the increases of the applied load leads to a more significant plasticization of the adhesive. The adhesive absorbs the stresses in the form plastic energy and consequently the adhesive failure occurs with the increase of the applied load. It can be also noted, according to the results of “figure 8”, that the effect of the crack length on the damage zone ration is more significant for $\sigma$=250 MPa. For higher applied load, the stress intensity around the crack tip increases significantly and the stress transfer throughout the adhesive layer will be more important, this transfer may be the cause of the damage initiation and propagation in the adhesive layer. Xu and Wei [29] showed that, in single lap joint subjected to tensile load, improving the adhesive fracture energy can significantly enhance the load-bearing capability of the joints. It was also demonstrated that the load-bearing capability can be significantly enhanced not only by increasing the overlap length under the condition of larger adhesive fracture energy, but also by increasing the thickness of the adhesive layer [9].
The effect of the adhesive damage on the repair efficiency is illustrated in figure 9. This last figure presents the variation of the stress intensity factor at the crack tip according to the damage ratio DR. It can be noted that, if the damage ratio is less than 0.2, its effect on the stress intensity factor is not significant and this effect becomes sensible when the ratio DR exceeds the value of 0.22. One can conclude the adhesive damage can have a significant effect on the repair efficiency when the damage zone ratio tends toward the critical value (DR≥0.2474). It was shown by several studies [6, 7, 10, and 19] that for repaired cracks with bonded composite patch, the stress intensity factor at the crack tip exhibits an asymptotic behavior as the crack length increases. This behavior was established regardless the adhesive damage or failure. According to the results of “figure 9”, we can confirm that the stress intensity factor has an asymptotic behavior if the damage ratio of the adhesive is less than 0.22. Beyond this value of the damage ratio, the variation stress intensity factor at the tip of repaired cracks becomes very sensitive to the variation of the adhesive damage ratio DR. In order to reduce the risk of the adhesive failure, the increases of the adhesive ductility can have a positive effect.

Fig. 9. Stress intensity factor vs. Damage zone ratio

V. CONCLUSIONS

In this study, a simple and efficient theory was used to analyze the effect of the adhesive damage on the performances of bonded composite repairs of aircraft structures. It was shown that there are two zones of the adhesive in which the adhesive damage can initiate and propagate. It was also shown that the adhesive damage over the crack region has approximately an elliptical shape and this damage propagates with the crack growth. The damage zone area is highly affected by the variation of applied load because the stress transfer toward the adhesive is more accentuated when the applied load increases.

It was highlighted, in this study, that the repair efficiency is affected by the adhesive damage if the damage zone ratio exceeds the values of 0.22 (DR>0.22). In this case, the variation of the stress intensity factor at the crack tip is very sensitive to the variation of damage zone ratio. In future work, the study will be completed by fatigue tests in order to predict the fatigue life of repaired structures with taking into account the adhesive damage.

REFERENCES


