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Analysis of the adhesive damage between composite and metallic adherends: Application to the repair of aircraft structures

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Abstract. In bonded composite repair of aircraft structures, 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 ap-plicability of the damage criteria in these models. The scope of this study is to analyze the effects of the patch thickness and the adhesive thickness on the damage damage in bonded composite repair of aircraft structures by using modified damage zone theory. The obtained results show that, when the thickness of adhesive increases the damage zone increases and the adhesive loses its rigidity, inversely when the patch is reduced the adhesive damage be-comes more significant.

Keywords: composite repair; crack; damage zone theory; cohesive failure; finite element method; dam-age ratio; stress intensity factor

1. Introduction

Recently, the use of adhesives is accepted as a process of structure repair to increase the service life of damaged components (Baker AA *et al.* (1988)-Lena MR *et al.* 1998). The metal or composite patches are stuck on a single or on both faces of the cracked structural components. The repair of the cracks by gluing composite material patches proved its efficiency in reducing the stress intensity at the crack heads. This method has been successfully used in repairing damaged plane components. Considerable work has been done to develop the technique of fitting the composite patches on aeronautical structures (Baker AA *et al.* (1993)-Jones R *et al.* 1999 Beloufa *et al.* 2016).

Oudad *et al.*(2009) 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.

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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 (Qing X.P *et al.*(2006)- Alderliesten R.C *et al.* 2009). Bachir Bouiadjra *et al.* (2008) 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 disbands 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.* (2012) 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.* (2012) 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.* (2013) used different on-line monitoring techniques, 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 (Crocombe A *et al.* (1995) - Sheppard A *et al.* 1998) 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 [Magalhães A.G *et al.* (2005)]. Sheppard *et al.*(1998) introduced a critical failure zone for composite and aluminum single-lap and double-lap joint. The critical area, where the Von 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.* (2005) 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.* (2008) introduced modifications on the damage zone model of Shepard *et al.* (1998), 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.*(2004) 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 plate's surfaces as well as inside the adhesive fillets in cases where toughened adhesives are used.

The scope of this paper is to use the modified damage zone models in order to analyze the effect of the adhesive thickness and the patch thickness on the adhesive in bonded composite repair of aircraft structures.

2. Geometrical and FE models

The basic geometry of the cracked structure considered in this study is shown in Fig. 1.

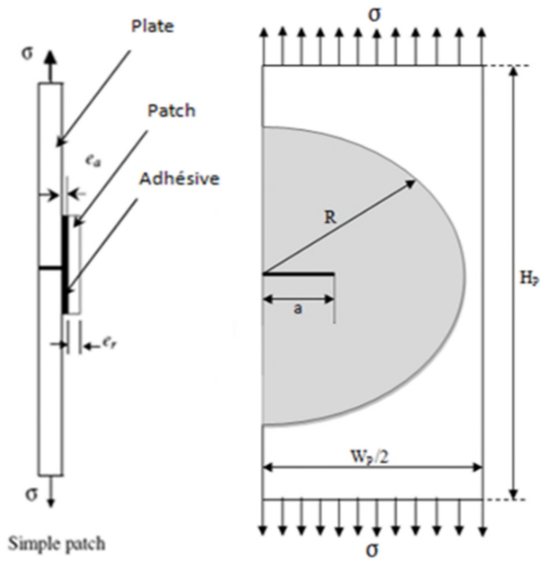


Fig. 1 Geometrical model

Table 1 Elastic properties of the different materials

Properties	Materials		
	Al alloy T3	Boron/epoxy	Adhesive(FM73)
Longitudinal Young modulus E_1(GPa)	72	200	4.2
Transversal Young modulus E_2(GPa)		19.6	
Transversal Young modulus E_3(GPa)		19.6	
Longitudinal Poisson ratio ν_{12}	0.33	0.3	0.32
Transversal Poisson ratio ν_{13}		0.28	
final stress (MPa)	507.48	509.03	685.85

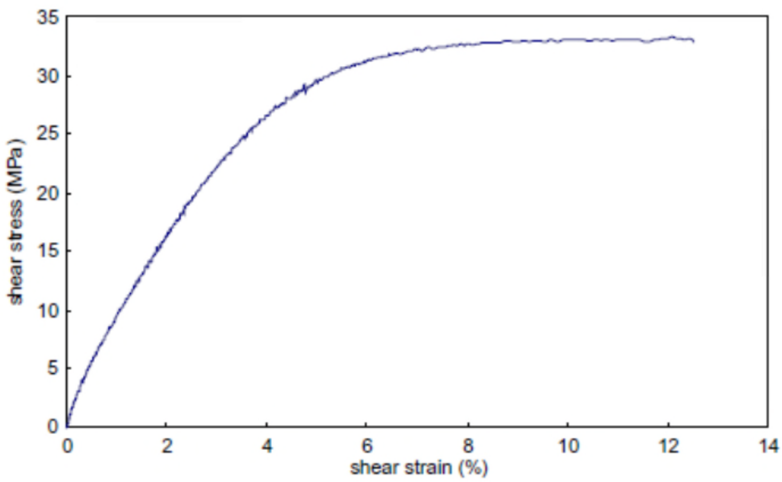
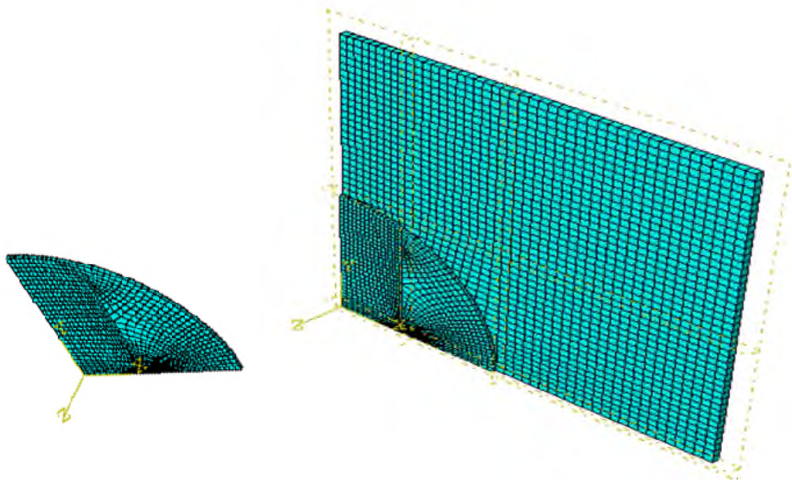


Fig. 2 Stress-strain curve of FM73M Epoxy adhesive (Oudad 2009)



Crack tip region

Fig. 3 Typical mesh model of the global structure and near the crack tip

Consider a rectangular aluminum 2024-T3 plate with the following dimensions: height Hp = 254 mm, width W_p = 254 mm, thickness e_p = 2.5 mm, with a central crack of length 2a. The plate is repaired with single circular boron–epoxy patch of dimensions: R= 75 mm, and, 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 different thick film values of FM 73 epoxy adhesive (Fig. 1).

The plate is subjected to a remote uniaxial tensile load of amplitude σ. The elastic properties of the different materials are given in Table 1, the stress-strain curves of the FM 73 epoxy adhesive is presented in Fig. 2.

The analysis involves a three-dimensional finite element method by using the commercially available finite element code ABAQUS (2007). 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 four 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 follow: the tensile stress was applied to the gripped 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 convergence test was made automatically because the analysis is non linear (Elastic plastic)

3. 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 adherend 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 adhesive layer is the equivalent Von Mises strain criterion.

$$\varepsilon_{\text{equiv}} = \frac{1}{\sqrt{2(1+\nu)}} \times \sqrt{(\varepsilon_{p1} - \varepsilon_{p2})^2 + (\varepsilon_{p2} - \varepsilon_{p3})^2 + (\varepsilon_{p3} - \varepsilon_{p1})^2} \quad (1)$$

Where $\boldsymbol{\varepsilon}_{equiv}$ is the equivalent stain, $\boldsymbol{\varepsilon}_{pi}$ are the plastic strains in the different directions and υ 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% (Ban Chang-Su *et al.* 2008). 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 (Ban Chang-Su *et al.* 2008). 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

$$D_R = \frac{\sum Ai}{l.w} \quad (2)$$

D_R is the damage zone ratio. Ai 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 σ (MPa). It was shown that he FM 73 fails when the D_R value reached 0.2474 (Ban Chang-Su *et al.* 2008).

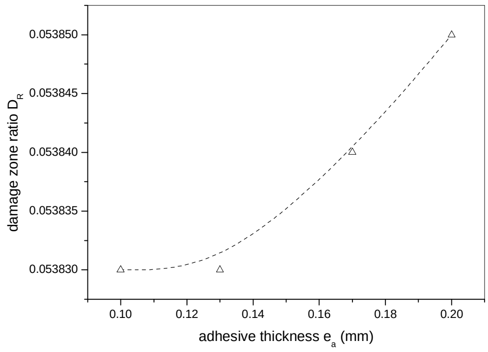
4. Results and discussion

Fig. 4 Damaged zones for circular patch shape vs adhesive thickness for: a=25 mm ; e_a=0.17mm; S=2275.00 mm^2

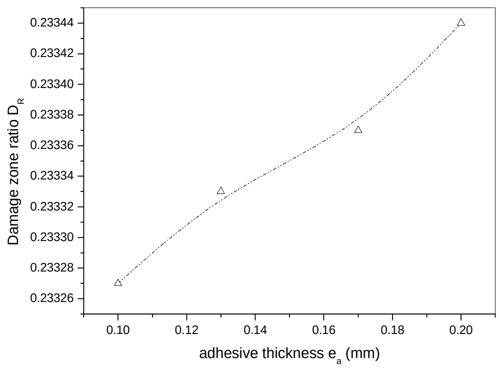
This paper was carried out in order to analyze the adhesive damage in bonded composite patch on cracked aluminum structures. The damage zone ratio was chosen as fracture criteria to achieve the analysis. Fig. 4 presents the damage zone area in the adhesive layer (In gray color) for circular patch, the crack length is equal to 25mm, the adhesive thickness 0.17 mm and the patch thickness 2 mm. It can be seen in figure 4 that the adhesive damage is located in two zones : near the free edge of the bonded surface between the composite and the aluminum and over the crack region. The adhesive damage for the crack length a=25 mm is very significant at the free edge of the bonded area, this is due to the concentration of the shear stresses in the adhesive at this zone, the risk of debonding in this is thus very important which can negatively affect the repair durability. Over the crack region, the risk of the adhesive disbond is also very significant because the adhesive damage is very sensible in this zone. The disbond over the crack region can negatively affect the repair efficiency and the repair durability because the presence of disbond over the crack region reduces considerably the stress transfer between the composite and the aluminum throughout the adhesive layer, which can reduce the fatigue life of repaired aircraft structures. It can be also note, according to the results of Fig. 4, that the damaged zone area over the crack region has an elliptical shape (If the global structures is taken into account, in Fig. 4 only the half of the structure is modeled). This is in concordance with the experimental observation of Caminero *et al.* (2013). These authors have observed with Lamb waves that the disbond in the adhesive layer has an elliptical shape.

Fig. 5 (a, b and c) present the variation of damage zone ratio (D_R) as a function of the adhesive thickness (e_a) for different crack lengths. (a=5,25 and 45 mm). From Fig. 5a, we can note that for small cracks (a=5mm), the values of the damage zone ratio are very weak whatever the adhesive thickness, this is due to the weak levels of transferred stresses from the cracked plate to the adhesive joint. On the other hand, it can observed in figure 5a that the effect of the adhesive thickness on the variation of the ratio D_R is sensible if the adhesive thickness exceeds the value of 0.13mm. If e_a is less than 0.13 mm its effect on the adhesive damage evolution is practically negligible. Beyond the value of e_a=0.13 mm, the damage zone ratio increases linearly when the adhesive thickness increases too.

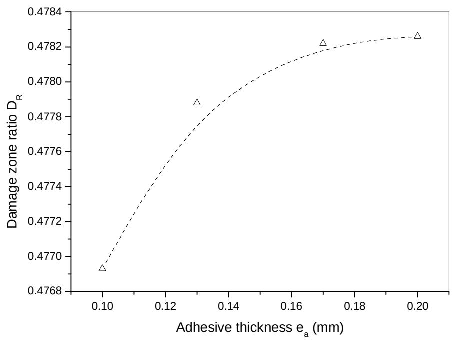
Fig. 5(b) presents the variation of the ratio D_R as a function of the adhesive thickness for crack length a=25 mm. The value of the damage zone ratio are relatively significant for this crack length but they are still less than the critical value for the FM73 epoxy adhesive (D_{Rc}=0.2474). But since



(a) a=5 mm



(b) a= 25 mm

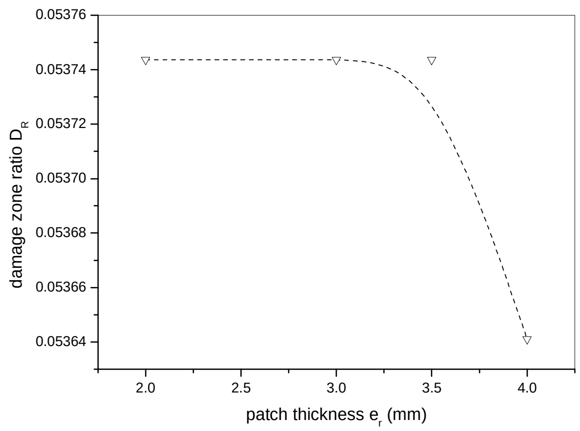


(c) a= 45 mm

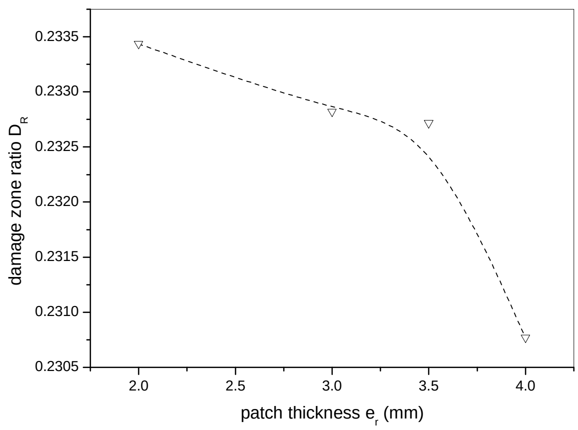
Fig. 5 Damage zone ratio vs adhesive thickness e_a (mm)

the aircraft structure are subjected to fatigue loading, the values of the ratio D_R a=5 mm presents a very high risk of adhesive failure. We can also observe in Fig. 5(b) that the variation of the damage zone ratio as a function of the adhesive thickness is approximately linear.

Fig. 5(c) presents the variation of the damage zone ratio for a=45 mm. It can be noted that,



(a) a=5mm



(b) a=25 mm

Fig. 6 Damage zone ratio vs patch thickness e_r (mm)

whatever the adhesive thickness the damage zone ratio exceeds its critical value for this crack length, which that for an applied stress of 70 MPa the adhesive layer may fail completely when the crack length exceeds the value of 35 mm. It can be noted that the ratio D_R increases exponentially for a=5 mm and it have an asymptotic behavior for a= 45 mm, this is because for a= 45 mm, we have the total failure of the adhesion and the ratio D_R will be stable.

In order to analyze the effect of the patch thickness on the adhesive damage, Fig. 6(a) and 6(b) present the variation of the ratio D_R a function of the patch thickness for a=5mm and a=25 mm respectively. From Fig. 6(a), it can be seen for a= 5mm , the patch thickness has no effect on the adhesive damage when this thickness is less 3.5mm, the damage zone ratio remains practically constant. Beyond this value of the patch thickness, the damage zone ratio decreases significantly. This is due to the fact that for higher patch thicknesses, the composite absorbs more stress, which relaxes the stress levels in the adhesive layer.

Fig. 6(b) presents the variation of the damage zone ratio D_R as a function of the patch thickness for a=25 mm. The results of this last figure show that the reduction of the patch thickness leads to higher value of the damage zone ratio of the adhesive, this is because the stresses in the adhesive increase when the patch thickness decreases and consequently the adhesive damage more significant when the patch thickness is reduced.

5. Conclusions

This study is carried out in order to analyze the adhesive damage between bonded composite patch and aluminum plate for repairing cracked aircraft structures. The obtained results showed that the adhesive damage can be initiated on the free edge of the bonded area and over the crack region. This damage strongly depends on the length of the repaired cracks. The adhesive damage is affected by the thickness of the patch and the adhesive thickness. A good choice of the patch and the adhesive thicknesses offers high safety because it can reduce considerably the risk of the adhesive failure.

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References

ABAQUS/CAE Ver 6.9 (2007), *User's Manual*, Hibbitt, Karlsson &Sorensen, Inc.

Alderliesten, R.C. (2009), "Damage tolerance of bonded aircraft structures", *Int. J. Fatigue*, **31**(6)**,** 1024-1030.

Apalak, M.K., Apalak, Z.G. and Gunes, R. (2004), "Thermal and geometrically nonlinear stress analyses of an adhesively bonded composite tee joint with double support", *J. Therm. Compos. Mater.*, **17**(2), 103-136.

Atluri, S.N. (1997), *Structural integrity and durability*, Forsyth, Georgia, USA, Tech Science Press.

Baker, A.A. and Chester, R.J. (1993), "Recent advances in bonded composite repair technology for metallic aircraft components", *Proceeding of the International Conference on Ad Comp Materials*, 45-9.

Baker, A.A. and Jones, R. (1988), *Bonded repair of aircraft structures*, Dordrecht: Martinus Nijhoff.

Ban, C.S., Lee, Y.H., Choi, J.H. and Kweon, J.H. (2008), "Strength prediction of adhesive joints using the modified damage zone theory", *Compos. Struct.*, **86**(1), 96-100.

Beloufa, H., Ouinas, D., Tarfaoui, M. and Benderdouche, N. (2016), "Effect of stacking sequence of the bonded composite patch on repair performance", *Struct. Eng. Mech.*, **57**(2), 295-313.

Bouiadjra, B.B., Oudad, W., Albedah, A., Benyahia, F. and Belhouari, M. (2012), "Effects of the adhesive disband on the performances of bonded composite repairs in aircraft structures", *Mater. Des.*, **37**, 89-95.

Bouiadjra, B.B., Ouinas, D., Serier, B. and Benderdouche, N. (2008), "Disbond effects on bonded boron/epoxy composite repair to aluminium plates", *Comput. Mater. Sci.*, **42**(2), 220-227.

Callinan, R.J., Sanderson, S. and Keeley, D. (1997), *Finite element analysis of an F-111 lower wing skin fatigue crack repair*, DSTO, Melbourne, DSTO-TN-0067.

Caminero, M.A., Pavlopoulou, S., Lopez-Pedrosa, M., Nicolaisson, B.G., Pinna, C. and Soutis, C. (2013), "Analysis of adhesively bonded repairs in composites: damage detection and prognosis", *Compos. Struct.*, **95**, 500-517.

Chow, W. and Atluri, S. (1997), "Composite patch repairs of metal structures: adhesive nonlinearity, thermal cycling, and debonding", *AIAA J.*, **35**(9), 1528-1535.

Crocombe, A.D., Richardson, G. and Smith, P.A. (1995), "A unified approach for predicting the strength of cracked and non-cracked adhesive joints", *J. Adhesion*, **49**(3-4), 211-244.

Hart-Smith, L.J. (1985), *The design of repairable advanced composite structures*, Douglas Paper 7550, McDonnell Douglas, Douglas Aircraft Company.

Jones, R. and Chiu, W.K. (1999), "Composite repairs to cracks in thick metallic components", *Compos. Struct.*, **44**(1), 17-29.

Lena, M.R., Klug, J.C. and Sun, C.T. (1998), "Composite patches as reinforcements and crack arrestors in aircraft structures", *J. Aircraft*, **35**(2), 318-323.

Magalhães, A.G., De Moura, M.F.S.F. and Gonçalves, J.P.M. (2005), "Evaluation of stress concentration effects in single-lap bonded joints of laminate composite materials", *Int. J. Adhes. Adhes.*, **25**(4), 313-319.

Oudad, W., Bouiadjra, B.B., Belhouari, M., Touzain, S. and Feaugas, X. (2009), "Analysis of the plastic zone size ahead of repaired cracks with bonded composite patch of metallic aircraft structures", *Comput. Mater. Sci.*, **46**(4), 950-954.

Ouinas, D., Bouiadjra, B.B. and Serier, B. (2007), "The effects of disbonds on the stress intensity factor of aluminium panels repaired using composite materials", *Compos. Struct.*, **78**(2), 278-284.

Ouinas, D., Bouiadjra, B.B., Achour, T. and Benderdouche, N. (2010), "Influence of disbond on notch crack behaviour in single bonded lap joints", *Mater. Des.*, **31**(9), 4356-4362.

Ouinas, D., Bouiadjra, B.B., Himouri, S. and Benderdouche, N. (2012), "Progressive edge cracked aluminium plate repaired with adhesively bonded composite patch under full width disbond", *Compos. Part B: Eng.*, **43**(2), 805-811.

Papanikos, P., Tserpes, K.I. and Pantelakis, S. (2007), "Initiation and progression of composite patch debonding in adhesively repaired cracked metallic sheets", *Compos. Struct.*, **81**(2), 303-311.

Poole, P. (2002), "Graphite/epoxy patching efficiency studies", *Adv. Bond. Compos. Repair. Metal. Aircraft Struct.*, **1**, 415-41.

Qing, X.P., Beard, S.J., Kumar, A. and Hannum, R. (2006), "A real-time active smart patch system for monitoring the integrity of bonded repair on an aircraft structure", *Smart Mater. Struct.*, **15**(3), N66.

Rose, L.R.F. (1982), "A cracked plate repaired by bonded reinforcements", *Int. J. Fract.*, **18**(2), 135-144.

Sheppard, A., Kelly, D. and Tong, L. (1998), "A damage zone model for the failure analysis of adhesively bonded joints", *Int. J. Adhes. Adhes.*, **18**(6), 385-400.

Xu, W. and Wei, Y. (2012), "Strength and interface failure mechanism of adhesive joints", *Int. J. Adhes. Adhes.*, **34**, 80-92.

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