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Computation of the SIF for repaired semi-circular surface cracks in finite-thickness plates with bonded composite patch

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Abstract- In this paper, the analysis of the behavior of surface cracks in finite-thickness plates repaired with bonded composite patch subjected to traction effect is performed using three-dimensional finite element methods. The stress intensity factor at the crack-front was used as the fracture criteria. The stress intensities at the internal and external positions of repaired surface crack were compared. The effects of the mechanical and geometrical properties of the adhesive layer and the composite patch on the variation of the stress intensity factor at the crack-front were analyzed. The obtained results show that the presence of the bonded composite repair reduces significantly the stress intensity factor, which can improve the life span of the structure.

Keywords: Bonded composite repairs, Patch, Surface cracks, Stress intensity factorI.

I.Introduction

Externally bonded composite patches have proved to be an effective method of repairing cracks or defects in aircraft structures. Considerable researches have been performed to develop the technology of bonded composite repairs in aircraft structures. Alan Baker pioneered these researches at the aeronautical and maritime research laboratory for the Royal Australian Air force [1–7]. However, the most of these studies has been based on simple analysis, experiment or experiences and are limited to the case of mode I opening of the crack. With increase in computational power, attempts have started in the direction of numerical modelling for better understanding of repair effectiveness and improved repair design.

The bonded patch offers many advantages over a mechanically fastened doubler, which include improved fatigue behaviour, reduced corrosion and easy conformance to complex aerodynamic contours [1,2]

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The determination of the stress intensity factors at the crack tip is one of the possible means to analyse the performance of the bonded composite repairs. It is known that the finite element method gives, with a great accuracy, the stress intensity factors at the crack tip. Among the authors whom used this method for computing the SIF in the case of 2 repaired cracks, we can quote Ouinas et al. [8], Albedah et al. [9], Oudad [10] and Mhamdia et al [11]. The scope of this paper covers studying of the behaviour of repaired surface cracks in finite-thickness plates in aluminum alloy, by the finite element method. Various authors [12-14] showed that in practice the parameters influencing the performances of the bonded composite repairs are the patch and the adhesive properties. For that, the effects of adhesive thickness, patch thickness, patch area and mechanical properties of the patch on the variations of the stress intensity factor, at the internal and external positions, of repaired semi-circular surface cracks were examined.

II. Numerical Calculation of Stress Intensity Factors

The relevant parameters in Linear Elastic Fracture Mechanics are the Stress Intensify Factors (SIFs) which can be calculated by using either a J integral based equivalent domain integral (EDI) [15], a virtual crack closure method (VCCM) [16], a virtual crack extension method [17] or a displacement extrapolation method [18]. For a comparison of these methods see [19]. In this paper, the displacement extrapolation method is used to calculate the stress intensity factors as follows [20-22]:

$$K_I = \frac{E}{3(1+\nu)(1+k)}\sqrt{\frac{2\pi}{L}}\left[4(v_b - v_d) - \frac{(v_c - v_e)}{2}\right], \qquad (1)$$

$$K_{II} = \frac{E}{3(1+\nu)(1+k)}\sqrt{\frac{2\pi}{L}}\left[4(u_b - u_d) - \frac{(u_c - u_e)}{2}\right], \qquad (2)$$

Where E is modulus of elasticity, ν is Poisson's ratio, k is elastic parameter defined by:

$$k = \begin{cases} \dfrac{3-\nu}{1+\nu} & \text{stress plane} \\ 3-4\nu & \text{strain plane} \end{cases}$$

and L is the quarter-point element length. u and v are the displacement components in the x and y directions, respectively; the subscripts indicate their position as shown in Fig. 1.

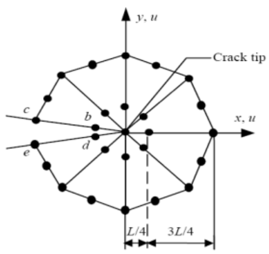

Fig. 1 Quarter-point singular elements around the crack tip

II.1 Geometrical and finite element models

The basic geometry of a semi-circular surface crack in a plate under uniform tension is considered with (t/W)=0.5 and W=H=10c (Fig. 2).

This crack is repaired with unidirectional Boron/Epoxy, Glass/Epoxy and Graphite/Epoxy composite patches of rectangular shape. The ply orientation is parallel to the loading axis. The dimensions of the patch are: (hr/wr) =2, (hr/H) =1 and (er/t) =0.02, where hr, wr and er represents the height, width, and thickness of composite patch, respectively. The adhesive used to bond the patch on cracked finite-thickness plate is FM73, epoxy 3 adhesive with (ea/t) =0.0026, Where ea represent the adhesive thickness. The elastic of the plate, the patch, and the adhesive are given in Table1.

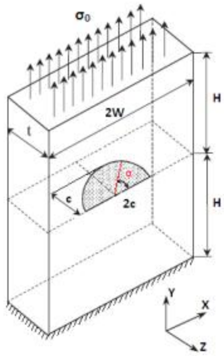

Fig. 2 Semi-circular surface crack in a finite-thickness with Boundary conditions and loading applied

Table 1 Materials properties (plate, patch and adhesive)

	Aluminum Alloy	Boron/Epoxy	Glass/Epoxy	Graphite/Epoxy	Adhesive FM73
$_1$(GPa)	72.4	200	50	134	
E_2(GPa)		19.6	14.5	10.3	
E_3(GPa)		19.6	14.5	10.3	
G_{12}(GPa)		7.2	2.56	5.5	0.42
G_{13}(GPa)		5.5	2.56	5.5	
G_{23}(GPa)		5.5	2.24	3.2	
ν_{12}	0.33	0.3	0.33	0.33	0.3
ν_{13}		0.28	0.33	0.33	
ν_{23}		0.28	0.33	0.53	

The analysis involved a three-dimensional finite element method using a commercially available finite element code ANSYS 11.0. The finite element model consists of three subsections to model the cracked plate, the adhesive, and the composite patch. Due to symmetry, only one half of the repaired plate was considered (Fig.3).

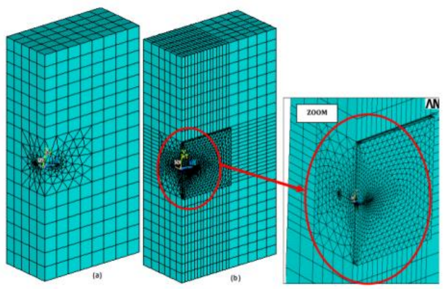

Fig. 3. FE model of the semi-circular surface cracks in finite-thickness plates: a) without patch, b) with patch

A typical FE model between the external position crack (α=0), adhesive layer and composite patch layer is shown in Fig. 4a. The special quarter point singular elements proposed by Barsoum [23] are used for modeling the singular field near the crack-tip (Fig. 4b) and (Fig. 4c). This mesh will serve to calculate the stress intensity factors using the displacement extrapolation method implemented in finite element code ANSYS 11.0.

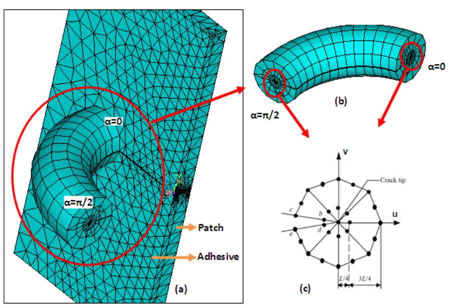

Fig. 4. Typical mesh model: (a) between the external position crack tip, adhesive layer and composite patch layer; (b) around the crack-front; (c) special elements used for displacement extrapolation method.

III. Results and Discussions

III.1 Comparison between repaired and unrepaired surface cracks for internal and external positions

In this study, the SIF calculations were conducted for repaired and unrepaired cracks in finite-thickness plates under traction in order to estimate the repair performances. Figure 5 presents the variation of the SIF for repaired and unrepaired cracks at external position of the crack-front for different ratio c/W. One notes a major reduction in the SIF. For example, for c/W=0.15, the reduction rate of the SIF is about 20% and one notices an asymptotic behavior of the SIF variation for repaired crack at the external position which proves that the good efficiency of the repair by composite patch for finite-thickness plates under traction loading. It can also be noted, according to Figure 5, that for repaired crack with Boron/Epoxy composite, the SIF exhibits an asymptotic behavior as the crack length increases. This is due to the fact that there is a stress transfer between the repaired plate and the composite patch throughout the adhesive layer.

The variation in the SIF along the internal crack front (unpatched front) is analyzed in Figure 6. It is noticed that repair reduces even the concentration of the stresses for internal crack position.

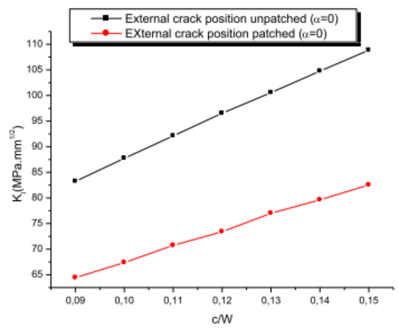

Fig. 5. Variation of the SIF K_I according to the ratio c/W for external position of crack-front patched and unpatched (α=0).

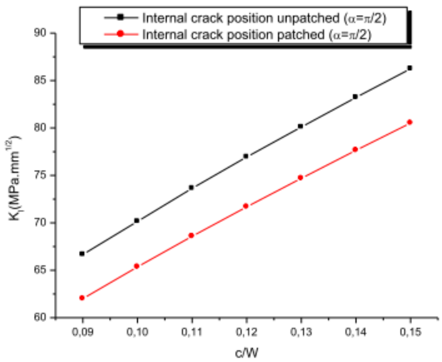

Fig. 6. Variation of the SIF KI according to the ratio c/W for internal position of crack-front patched and unpatched (α=π/2).

The Figure 7. presents a comparison of the variation in the SIF between cracks in internal and external positions of the rectangular block model repaired with Boron/Epoxy composite. It is noticed that the difference between the SIFs of the repaired cracks in internal and external position is slightly weak for all interval of variation in the ratio c/W.

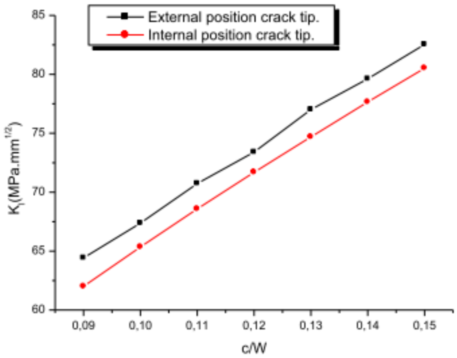

Fig.7. Stress intensity factor (SIF) vs. ratio c/W for internal and external position of crack-front

III.2 Effect of the adhesive thickness (ea)

The adhesive layer is the bridge which allows the transfer of stress from the stress concentration region toward the composite patch. Figure 8 described the variation in SIF according to the ratio (ea/t) for internal position of repaired semi-circular surface cracks, for various ratio c/W. It can be noted that the increase in the adhesive thickness leads to the growth of the SIF, especially for external positions of crack-front (α=0).

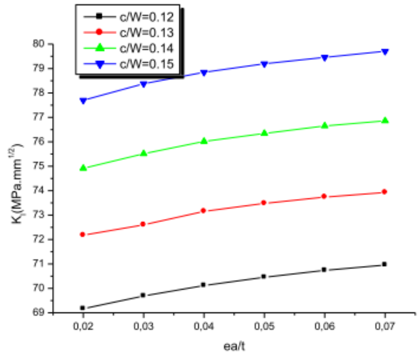

Fig. 8. Stress intensity factor (SIF) vs. ratio (ea/t) for internal position of crack-front

III.3 Effects of the geometrical properties of the patch

III.3.1 Effect of the patch thickness

Several authors [24-27] showed the importance of the effect of the patch thickness on the repair performance in damaged structures. This effect is illustrated in Figs. 9 and 10 by the plot of the SIF variation for external and internal position crack-front according to the ratio (er/t), for various ratio (c/W). It can be seen that the increase of the patch thickness reduces the stress intensity factor at the crack tip in a proportional way. These results can confirm that the choice of thicker patches makes it possible to increase their performances. For a better distribution of the stresses, it is preferable to use a multiple layers of bonded composite patches for repairing surface cracks.

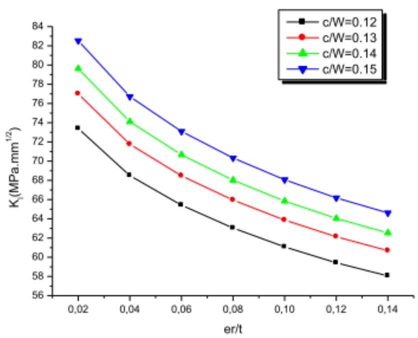

Fig. 9. Effect of the patch thickness on the variation of the SIF for external position of crack-front

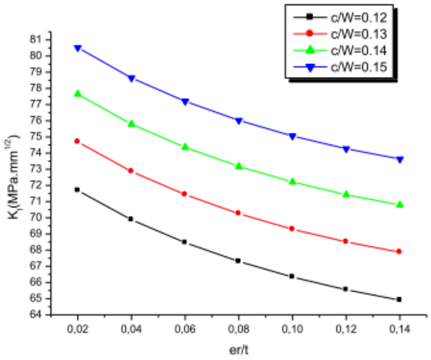

Fig. 10. Effect of the patch thickness on the variation of the SIF for internal position of crack-front

III.3.2 Effect of the patch area

To analyze the effect of the rectangular area of patch (hr x wr, with hr/wr=2) on the SIF variations, three configurations were considered: hr/W=0.4, 0.6 and 1. Fig. 11 illustrates the effect of this geometrical parameter on the SIF variation, for external position of crack-front. It can be seen that the increase of the 5 rectangular area of patch increases the SIF in a proportional way. This shows that the choice of the smallest surface of patch improves the repair performances.

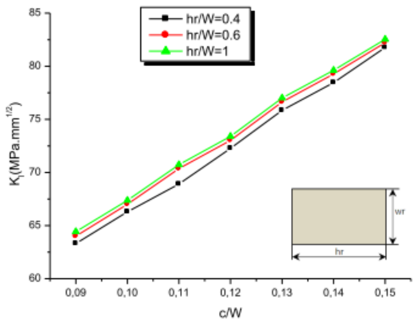

Fig. 11. Effect of the patch area on the variation of the SIF for external position of crack-front

III.3.2 Effect of the mechanical properties of the patch

Figures 12 and 13 present the variation of the SIF according to the ratio c/W, for two positions of crack-front and for different composites (boron/epoxy, glass/epoxy,and graphite/epoxy). The results on these figures show that the boron/epoxy composites give the lowest values of the SIF especially for external position of crack-front. This behavior can be explains by the fact why the composites boron/ epoxy have the higher values of Young modulus E_2 (E_y) that those of glass/epoxy and graphite/epoxy, i.e. boron/ epoxy composite is harder according to the direction of the loading applied (mode I). For this purpose, several authors [28-31] studied the behavior of the cracks repaired with this composite patch.

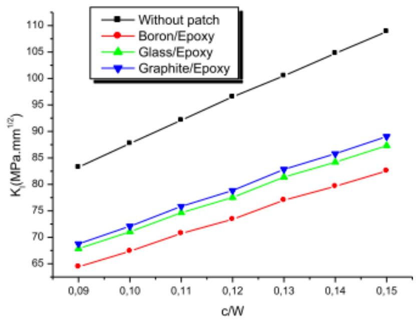

Fig.12. Stress intensity factor (SIF) vs. ratio c/W for external position of crack-front, for different composites.

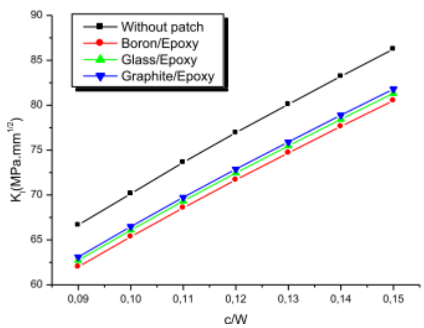

Fig. 13. Stress intensity factor (SIF) vs. ratio c/W for internal position of crack-front, for different composites

I.V Conclusions

This study demonstrates that the reduction in the stress intensity by the composite patch repair of semi-circular surface cracks in finite-thickness plates subjected to the traction effect is significant, which can improve the lifespan of repaired plates. The optimization of the mechanical properties of the adhesive and the composite patch can improve the repair and reinforcement performances and durability significantly. This optimization must equilibrate between the reduction in the stress intensity at the repaired defect and the reduction in the risk of adhesive layer failure.

References

[1] AA. Baker, RJ. Callinan, MJ. Davis, R. Jones, JG. Williams. Repair of mirage iii aircraft using BFRP crack patching technology. Theor Appl Fracture Mech, 2(1984); 1-16.

[2] AA. Baker. Repair of cracked or defective metallic components with advanced fibre composites an overview of Australian work. Compos Struct,2 (1984); 153-81.

[3] AA. Baker, R. Jones, editors. Bonded repair of aircraft structures. Dordrecht: Martinus Nijhoff Publishers; 1988.

[4] AA. Baker, RJ. Chester. Recent advances in bonded composite repair technology for metallic aircraft components. In: Proceeding of the International Conference on Advanced composite Materials, (1993) 45–9.

[5] AA. Baker. Fatigue studies related to the certification of composite crack patching for primary metallic aircraft structure. Presented at FAA-NASA Symposium on Continued Airworthiness of Aircraft Structures, Atlanta, 28-30 August 1996.

[6] AA. Baker. On the certification of bonded composite repairs primary aircraft structures. In: Proceeding of the Eleventh International of composite Materials (ICCM-11). Gold Coast, Australia, 1997.

[7] AA. Baker. Joining and repair of aircraft composite structures. In: Mallick PK, editor. Part 14, composite engineering handbook. New York: Marcel Decker Inc 1997.

[8] D. Ouinas, M. Sahnoune, N. Benderdouche, B. Bachir Bouiadjra, Stress intensity factor analysis for notched cracked structure repaired by composite patching, Materials & Design, 30(7) (2009); 2302-2308.

[9] A. Albedah, B. Bachir Bouiadjra, R. Mhamdia, F. Benyahia, M. Es-Saheb, Comparison between double and single sided bonded composite repair with circular shape, Materials & Design (2011); 3(2): 996-1000.

[10] W. Oudad, K. Madani, B. Bachir Bouiadjra, M. Belhouari, S. Cohendoz, S. Touzain, X. Feaugas, Effect of humidity absorption by the adhesive on the performances of bonded composite repairs in aircraft structures, Composites Part B: Engineering, In Press, Corrected Proof, Available online 9 January (2012).

[11] Mhamdia Rachid, B. Serier, B. Bachir Bouiadjra, M. Belhouari, Numerical analysis of the patch shape effects on the performances of bonded composite repair in aircraft structures, Composites Part B: Engineering, 4(2) (2012); 391-397.

[12] R. Mhamdia , B. Bachir Bouadjra, B. Serier, W. Ouddad, X. Feaugas, and S. Touzain, Stress intensity factor for repaired crack with bonded composite patch under thermo-mechanical loading, Journal of Reinforced Plastics and Composites 30(5) (2011); 416-424.

[13] B. Bachir Bouiadjra, W. Oudad, A. Albedah, F. Benyahia, M. Belhouari, Effects of the adhesive disband on the performances of bonded composite repairs in aircraft structures, Materials & Design, 37 (2012); 89-95.

[14] D. Ouinas, B. Bachir Bouiadjra, S. Himouri, N. Benderdouche, Progressive edge cracked aluminium plate repaired with adhesively bonded composite patch under full width disbond, Composites Part B: Engineering, 43(2) (2012), 805-81.

[15] CF. Shih, RJ. Asaro. Elastic–plastic analysis of cracks on bimaterial interfaces: part I - small scale yielding. J Appl,55 (1988); 299-316.

[16] EF. Rybicki, MF. Kanninen. Finite element calculation of stress intensity factors by a modified crack closure integral. Eng Fract,9 (1977)

[17] DM. Parks. A stiffness derivative finite element technique for determination of crack tip stress intensity factors. Int J Fract,10 (1974); 487-502.

[18] SK. Chan, IS. Tuba, WK. Wilson. On the finite element method in linear fracture mechanics. Eng Fract Mech,2 (1970); 1-17.

[19] TN. Bittencourt, PA. Wawrzynek, AR. Ingraffea. Quasi-automatic simulation of crack propagation for 2D LEFM problems. Eng Fract Mech (1966); 55:321-334.

[20] M. Souiyah. A. Alshoaibi, A. Muchtar ., A.K. Ariffin, Finite element model for linear-elastic mixed mode loading using adaptive

mesh strategy, J Zhejiang Univ Sci A 9,(2008);32-37.

[21] AM. Alshoaibi, AK. Ariffin . Finite element simulation of stress intensity factors in elastic-plastic crack growth. J Zhejiang Univ Sci A,7 (2006); 1336-1342.

[22] AM. Alshoaibi, MSA. Hadi, AK. Ariffin. An adaptive finite element procedure for crack propagation analysis. J Zhejiang Univ Sci A,2 (2007); 228-236.

[23] RS. Barsoum. On the use of isoparametric finite element in linear fracture mechanics. Int J Num Meth Engng,10 (1974); 25-37.

[24] B. Bachir Bouiadjra, M. Belhouari and B. Serier. Computation of the stress intensity factor for repaired crack with bonded composite patch in mode I and mixed mode. Compos Struct, 56 (2002); 401-406.

[25] B. Bachir Bouiadjra, H. Fekirini, B. Serier and Benguediab M. Numerical analysis of the beneficial effect of the double symmetric patch repair compared to single one in aircraft structures. Comput Mater Sci, 38 (2007); 824-829.

[26] T. Achour, B. Bachir Bouiadjra and B. Serier. Numerical analysis of the performances of the bonded composite patch for reducing stress concentration and repairing cracks at notch. Comput Mater Sci, 28 (2003); 41-48.

[27] A. Megueni, B. Bachir Bouiadjra, M. Belhouari, Disbands effect on the stress intensity factor for repairing cracks with bonded composite patch, Comput Mater Sci, 29 (4) (2004);407-413.

[28] B. Bachir Bouiadjra, T. Achour, M. Berrahou, D. Ouinas, X. Feaugas, Numerical estimation of the mass gain between double symmetric and single bonded composite repairs in aircraft structures, Materials & Design, 31 (2010); 3073-3077

[29] B. Bachir Bouiadjra, D. Ouinas, B. Serier, N. Benderdouche, Disbond effects on bonded boron/epoxy composite repair to aluminium plates, Comput Mater Sci, 42 (2008); 220-227.

[30] D. Ouinas, B. Bachir Bouiadjra, S. Himouri, N. Benderdouche, Progressive edge cracked aluminium plate repaired with adhesively bonded composite patch under full width disband, Composites: Part B, 43 (2012); 805-811.

[31] B. Bachir Bouiadjra, M. Fari Bouanani, A. Albedah, F. Benyahia, M. Es-Saheb, Comparison between rectangular and trapezoidal bonded composite repairs in aircraft structures: A numerical analysis, Composite Structures, 32 (2011); 3161-3166.