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Review Paper on Analysis of Composite Patches as a Crack Arrestor

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Abstract: The present study is an attempt to take an overview of the work done in the area of bonded repair of plates with composite patches. It was found that since, last decade repair through composite patches is proven to be a very promising technique over other repair methods. This technique improves the fatigue behavior and reduces repair downtime with effective crack retardation. Most of the researchers have done both experimental as well as finite element analysis of bonded repair with composite patches. They had targeted thick plates with plain strain condition and found out stress intensity factor as a measure of fracture toughness. But looking to the large area of applications of thin sheets, it was found that there is a need to analyses bonded repair of thin sheets with composite patches. Care should to taken to minimize the out of plane loading for thin sheets.

Key words: Bonded repair, stress intensity factor, fracture toughness, care, sheets, India

INTRODUCTION

Owing to their high stiffness, high strength and light weight properties, fiber composites have found new applications in repairing cracks in components through patching. These repairs can be easily applied on-site to the structure, drastically reducing large costs associated with disassembly/assembly and downtime. To extend the service life of aging aircraft, efficient repair techniques for cracked aerospace metallic structures, some investigators have tried using polymer patches. As a result of these pioneering efforts, a repair method using composite patches to reinforce the cracked structure has been recognized as a very promising one. It offers significant advantages over the traditional repair methods like mechanical fastening, riveting or welding. It improves fatigue behavior, restores stiffness and strength, reduces corrosion and easily conforms to even complex shapes of structural components.

BACKGROUND

The technique of repairing cracked metallic structures using high strength advanced composite materials is commonly known as Crack Patching and was pioneered by the Aeronautical and Maritime Research Laboratories (AMRL) for the Royal Australian Air Force (RAAF) in early 1970's (Baker, 1991). The composite reinforcement also known as a patch can be attached to the damaged or weakened structure either by mechanical fastener or adhesive bonding. The use of adhesively bonded composite patches as a method of repair has several advantages over mechanically fastened repair method which include reduced installation cost, increased strength and fatigue life and hence, effective crack retardation, reduced repair down time, elimination of unnecessary fastener holes in an already weakened structure and stress concentrations at fasteners, corrosion resistance, high stiffness and lightweight. As a result of their excellent load transfer characteristics, bonded reinforcements or patches provide a stiff alternative load path so they can be used very effectively to repair live cracks.

In contrast, standard repairs, based on mechanically fastened metallic patches provide a relatively compliant alternative load path so they cannot effectively repair cracks and require prior removal (or some other terminating treatment) of the cracked region. Mechanical repairs also have several other disadvantages, compared to bonded repairs like: stress concentrations at fastener holes, difficult to detect cracks under repair, low patching efficiency, rapid crack growth on exit from patch and danger of corrosion under repair.

The high-performance fiber-composites boron/epoxy (b/ep) and graphite/epoxy (gr/ep) are highly suited for use as a patching or reinforcing material for defective or degraded metallic structure (Baker, 1988). Briefly, the attributes of these composites include: High Young's modulus and strength which minimizes the required patch thickness (b/ep is around three times as stiff as aluminium). Highly resistant to damage caused by cyclic loads. Immunity to corrosion forms excellent protective

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layer. High formability which allows easy formation of complex shapes. Low electrical conductivity (b/ep only) which facilitates use of eddy current NDI for monitoring the patched cracks and eliminates concerns with galvanic corrosion. The main disadvantage of composites as patching materials results from their relatively low coefficient of thermal expansion compared to the parent material which results in residual tensile mean stresses in the repaired component (Baker, 1988). Although, relatively costly, b/ep is chosen as the patch or reinforcement for most bonded composite repair applications, mainly because of its excellent mechanical properties, low conductivity and relatively high coefficient of thermal expansion. However, gr/ep because of its better formability is chosen for regions with small radii of curvature and sometimes because of its low cost and much higher availability.

LITERATURE REVIEW

Bonded repair reduces the stress field near the crack and leads to retardation or complete stoppage of the crack growth (Lena *et al*., 1998). In recent years, several researchers have studied different aspects of repair with bonded composite patches. It has been found that the magnitude of stresses in the cracked area after reinforcement decreases dramatically (Kam *et al*., 1998) in which the reduction in SIF (Stress Intensity Factor) in compact tension specimen of perspex material is studied by symmetrical bonding of GFRP (Glass Fiber Reinforced Plastic) patches near the crack tip. The fracture toughness of combination of glass and fiber composite was found to be greater than that of CFRP (Carbon Fiber Reinforced Plastic) and GFRP (Young *et al*., 1988). Experiments were performed to test the ability of a bonded composite reinforcement to prevent the crack from coalescing. Reinforcement for multiple-site damage was analyzed by modeling an infinite row of closely spaced cracked rivet holes (Young *et al*., 1992).

Some investigators used finite element method to analyze the behavior of the crack repaired patch by computing stress intensity factor near the crack tip in mode 1 and mixed mode (Park *et al*., 1992; Young *et al*., 1989). The effect of mechanical and geometric properties of patch on fracture parameters was highlighted. The obtained result showed that there is considerable reduction in stress intensity factor neat crack tip in case of double symmetric patch compared to single patch (Park *et al*., 1992).

The effects of the adhesive properties and the patch size on the stress intensity factor variation at the crack tip in mode 1 and mixed mode shows that the stress concentration factor at the semicircular notch root and the stress intensity factor of a crack starting from notch are reduced with the increase of the diameter and the number of the semicircular patch (Young *et al*., 1989).

Sun *et al*. (1996) presented a simple analysis method to analyze cracked aluminum plates repaired with composite patch using Midline plate theory. The adhesive layer was modeled with effective springs connecting the patch and aluminum plate. A three dimensional finite element analysis was performed using a commercial code ABAQUS and a comparison was made between stress intensity factor obtained from both cases. Umamaheswar and Singh (1999) performed finite element modeling and analysis of patch repairs to thin aluminum sheets using a commercial code NISA 6.0. They investigated an 8-noded 24 Degree of Freedom (DOF) brick element, 4-noded 24 DOF general shell elements and a 2-noded 12 DOF beam element. The results obtained were used to calculate stress intensity factor using Modified Crack Closure Integral (MCCI).

They reported that the advantages of using a three-dimensional single brick finite element for plate, patch and adhesive are minimum possible element aspect ratio and better analysis of adhesive behavior. Belason conducted two and three dimensional linear elastic FEA as well as a series of laboratory tests to evaluate the performance of bonded boron/epoxy doublers for 7075-T6 aluminum aircraft sheets. Their objective was to obtain substantiating data which will support approval for use on commercial aircraft.

They investigated stresses in adhesive, boron/epoxy patch and aluminum plate for three different loads (thermal loads, applied tensile loads and combined thermal and tensile loads) and two structural boundary conditions (doubler edge ending near to and far from an underlying stringer). They observed that the shear and peel stresses in the adhesive due to the thermal load are of about the same value but act in the opposite direction to those stresses from the application of tensile load.

They also found that peak axial stress concentrations in the aluminum and boron/epoxy were both lower for the combined load than for the tensile load. The analysis for two dimensional cases was done using ANSYS and for three dimensional cases was done using NIKE. Their tension test showed that boron/epoxy (doubler) restored the static strength of the aluminum and that failure occurred almost always in aluminum outside the patch. Their fatigue tests conducted at 0.021 (GPa (3 ksi) to 0.138 GPa (20 ksi)) at 5 Hz (sine wave) with 300,000 cycles as run out were successfully achieved with no crack re-initiation for the baseline boron/epoxy geometry. Post-fatigue ultimate tension test on the baseline configuration showed no degradation in static strength. Hu and Soutis (2000) and Soutis and Hu (1997) investigated the compressive behavior of composite patch repaired CFRP laminates subjected to compressive loading. They used a non-linear shear-lag analysis to produce gridlines for selecting patch sizes, shape and member stiffness. They also performed a three dimensional finite element analysis using FE-77 finite element package to determine the stress fields to predict compressive strength (failure load) of the repair. Only one quarter of the laminate was modeled due to symmetry.

The analysis was based on displacement formulation employing a curved A.C. Okafor composite structures 71 (2005) 258-270 259 isoparametric 20-noded elements for three-dimensional analysis. The four elements were used through the thickness of the parent laminate and the patch while the adhesive was modeled using only one element. The analysis was used to determine the stress distribution, stress concentration and stress intensity factors. Schubbe and Mall (1999) successfully modeled a cracked thick metallic structure with bonded composite patch repair using a three-layer technique.

The finite element model of the composite repair consisted of three layers of two dimensional 4-noded Midline plate elements used to model the patch, plate and adhesive separately. The significant feature of this study was modeling of the adhesive layer. The adhesive was modeled as an elastic continuum sandwiched between the plate and the patch. The displacements through the thickness were assumed linear and the constraints on the plate-adhesive interface and the adhesive-patch interface were based on the Midline plate theory. Only a quarter element was modeled due to symmetry.

The analysis also included thermal effects. Stress intensity factors obtained from the analysis were combined with the fatigue crack growth relationship for the unrepaired cracked material to obtain the analytical fatigue crack growth rates. Chue *et al.* (1996) investigated the effect of composite patch size, patch length and stacking sequence on the performance of bonded repair of cracked hole in 2024-T3 aluminum plate using 3-dimensional finite element method, linear elastic fracture energy and strain energy density theory.

They observed that increasing the composite patch size reduces the strain energy level of the crack tip and that increasing the patch length normal to the crack is a better choice. Stack sequence of the laminate was reported to have little effect on the strain energy distribution in the vicinity of the crack.

Shahani *et al.* (2010) researched on experimental and numerical investigation of thickness effect on ductile fracture toughness of steel alloy sheets. They investigated the effect of thickness on fracture toughness of plates made of steel alloy experimentally according to ASTM E813. They observed that in low thickness, critical J integral, J_c increases with the thickness increase until it reaches a maximum, however, further increase in thickness causes J_c value to decrease.

The 2D finite element analysis is done to compare it with the experimental results. Pardoen *et al.* (1999) researhed on thickness dependence of cracking resistance in thin aluminium plates wherein the experimental and numerical investigation of influence of thickness on the fracture toughness of aluminium 6082T0 thin plates of 1-6 mm thickness is done. They found that the critical J-integral, J_c, critical CTOD, $\delta CTOD_c$ and essential work of fracture, w_e increase with thickness and constitute equivalent measures of fracture toughness at small thickness. For larger thickness, J_c and $\delta CTOD_c$ increase non-linearly with thickness and reach a maximum for 5-6 mm thickness whereas w_e increases linearly with thickness.

Pardoen *et al.* (2004) researched on mode 1 fracture of sheet metal. They made a study with fracture tests performed on thin DENT plates of various thicknesses made of stainless steel, mild steel, 6082-O and NS4 aluminium alloys, brass, bronze, lead and zinc. The study emphasizes on the two parts of the work spent in the fracture process zone: the necking work and the fracture work. A model is developed in order to independently evaluate the work of necking which successfully predicts the experimental values. Experiments done show that the work of necking per unit area linearly increases with thickness. Wang *et al.* (2008) researched on size effect on the fracture toughness of metallic foil.

They explored the fracture behavior of foils and revealed the size effect of the fracture problem by a new optical experimental means that can get the deformation fields (displacement and strain) in the crack tip region and give a quantitative curve of the $J_c(t)$ (t thickness) for a kind of the copper foil material. The digital speckle correlation method is used to study the fracture behavior of foil. Displacement and strain fields around the crack tip are measured. The J integral is then calculated from the measured strain field. Fracture toughness J_c of specimens with a thickness range from 20 μ to 1 mm is evaluated.

Pardoen *et al.* (2009) researched on essential work of fracture compared to fracture mechanics towards thickness independent plane stress toughness. In this study, the Essential Work of Fracture (EWF) and the J-integral methods are applied in a study of the effect of the thickness on the cracking resistance of thin plate. The relationship between the two methods or concepts is explained. Cracked aluminium 6082O thin plates of 1-6 mm thickness are tested in tension until final separation. They found that EWF, w_e and the J integral at cracking initiation, J_i, increase identically with thickness except at larger thickness for which the increase of J_i levels off. J_i reached a maximum for 5-6 mm thickness whereas, w_e kept increasing linearly with thickness. Chandra and Guruprasad (1987) researched on numerical estimation of stress intensity factors in patched cracked plates. In this investigation, a finite element technique to compute the SIF through the J integral for patched cracked plates is done. TRIM6 and TRUMPL elements of ASKA are employed to model cracked sheet and cracked sheet-adhesives-patch regions, respectively. Data used were aluminium sheet (thickness = 1 mm), carbon-epoxy as patch and epoxy as adhesive.

DISCUSSION

In recent years, several investigators have studied the effect of bonded repair on fracture parameters of various materials. It was found that magnitude of stresses around the crack tip zone was drastically reduced after reinforcement of composite patch around the crack tip. Most of the work has been done by bonding polymer composite patches to metal sheets of large thickness, 2 mm or more. However, many structural parts use thinner plates. It is difficult to experimentally determine, the toughness of thin plates of the order of 1 mm thickness because the material close to the crack faces tends to buckle out of the plane.

As most of the work was targeted for thick plates in which plain strain conditions exists, hence the stress intensity factor was analysed as the fracture toughness parameter. The experimental methods for evaluation of plane strain toughness are simple, available as ASME codes. As the thickness reduces, there is transitional behavior observed from plane strain to plane stress wherein the fracture toughness increases with reduction in thickness of the plate. In case of thin plates, the fracture toughness is still found to be geometry dependent if the thickness is reduced.

The behavior in plane stress conditions is still not well known. Experimental determination of fracture toughness is difficult because of the practical problem that the plate tries to buckle close to cracked surfaces and so the condition of mode 1 no longer exists.

A new technique should be developed in which the buckling problems should be minimized. Furthermore, in case of thick plates, the reinforcement is not very effective because the patch thickness will have to be very large to match its stiffness (modulus) and the strength with those of the structural plates. The patch with its high thickness will not look compatible with the rest of the structural sheets. On the other hand, composite patches in thin plates are more effective as the strength and the stiffness of composite patches can be easily matched with those of the plates being reinforced. The Linear Elastic Fracture Mechanics (LEFM) ignores the existence of plastic zone at the crack-tip following only linear elastic relations. In thin plates, the plastic zone size is comparable to the plate thickness.

So, it becomes imperative to account for such large plastic zone by considering elastic-plastic behavior of the material, i.e., Elastic-plastic Fracture Mechanics (EPFM). J Integral is a parameter that characterizes a crack in linear and nonlinear elastic materials free of body forces and subjected to a two dimensional deformation field exhibiting elastic-plastic behavior near the crack tip. Hence for thin plates J integral should be analysed as a measure of fracture toughness.

CONCLUSION

The purpose of this study was to do an overview of analysis of composite patches as a crack arrestor. Most of the investigators have proved that composite patches are very effective as bonded repair for most of the applications. The area of interest by most of the investigators was thick plates with plain strain condition and hence, stress intensity factor was analysed as a parameter to measure fracture toughness. Finite element analysis of the bonded repair was also analyzed by most of the researchers to compare the results with experimental method. It was found that there is a need to analyses bonded repair with composite patches for thin sheets.

RECOMMENDATIONS

For thin sheets analysis should be done with plane stress condition taking either energy release rate or J integral as a measure of fracture toughness. For thin sheets care should be taken to design the experimental technique with buckle free specimen. Hence, it was realized with this study that instead of so much work done in this area still there is a scope to analyses the thin sheet specimen repaired with bonded composite patches.

REFERENCES

Baker, A.A., 1988. Crack Patching. In: Bonded Repair of Aircraft Structures, Baker, A.A. and R. Jones (Eds.). Martinus Nijhoff, Dordrecht, pp: 107-173.

Baker, A.A., 1991. Fatigue crack propagation studies on aluminum panels patched with boron/epoxy composites. Proceeding of the International Conference on Aircraft Damage Assessment and Repair, August 1991, Barton, ACT, pp: 209-215.

Chandra, R. and K. Guruprasad, 1987. Numerical estimation of stress intensity factors in patched cracked plates. Eng. Fracture Mech., 27: 559-569.

Chue, C.H., W.C. Chou and T.J.C. Liu, 1996. The effects of size and stacking of composite laminated patch on bonded repair for cracked hole. Applied Compos. Mater., 3: 355-367.

Hu, F.Z. and C. Soutis, 2000. Strength prediction of patch repaired CFRP laminates loaded in compression. Compos. Sci. Technol., 60: 1103-1114.

Kam, T.Y., K.H. Chu and Y.C. Tsai, 1998. Fatigue of cracked plates repaired with single-sided composite patches. AIAA J., 36: 645-650.

Lena, M.R., J.C. Klug and C.T. Sun, 1998. Composite patches as reinforcements and crack arrestors in aircraft structures. J. Aircraft, 35: 2-14.

Pardoen, T., F. Hacheza, B. Marchionia, P.H. Blythb and A.G. Atkinsb, 2004. Mode I fracture of sheet metal. J. Mech. Phys. Solids, 52: 423-452.

Pardoen, T., Y. Marchal and F. Delannay, 1999. Thickness dependence of cracking resistance in thin aluminium plate. J. Mech. Phys. Solids, 47: 2093-2123.

Pardoen, T., Y. Marchal and F. Delannay, 2009. Essential work of fracture compared to fracture Mechanics-towards a thickness independent plane stress toughness. Eng. Fracture Mech., 69: 617-631.

Park, J.H., T. Ogiso and S.N. Atluri, 1992. Analysis of crack in aging aircraft structures with and without composite-patch repairs. Computational Mech., 10: 169-201.

Schubbe, J.J. and S. Mall, 1999. Modeling of cracked thick metallic structure with bonded composite patch repair using three-layer technique. Compos. Struc., 45: 185-193.

Shahani, A.R., M. Rastegar, M.B. Dehkordi and H.M. Kashani, 2010. Experimental and numerical investigation of thickness effect on ductile fracture toughness of steel alloy sheets. Eng. Fracture Mech., 77: 646-659.

Soutis, C. and F.Z. Hu, 1997. Design and performance of bonded patch repairs of composite structures. Proc. Inst. Mech. Eng., 211: 263-271.

Sun, C.T., J.A. Klug and C. Arendt, 1996. Analysis of cracked aluminum plates repaired with bonded composite patches. AIAA J., 34: 369-374.

Umamaheswar, T.V.R.S. and R. Singh, 1999. Modeling of patch repair to a thin cracked sheet. Eng. Fracture Mech., 62: 267-289.

Wang, H.W., Y.l. kang, Z.F. Zhang and Q.H. Qin, 2008. Size effect on the fracture toughness of metallic foil. Int. J. Fracture, 123: 177-185.

Young, A., D.J. Cartwright and D.P. Rooke, 1988. The boundary element method for analyzing repair patches on cracked finite sheets. Aeronautical J. Royal Aeronautical Soc., 92: 416-421.

Young, A., D.P. Rooke and D.J. Cartwright, 1992. Analysis of patched and stiffened cracked panels using the boundary element method. Intl. J. Solid Struct., 29: 2201-2216.

Young, A., D.P. Rooke and D.J. Cartwright, 1989. Numerical study of balanced patch repairs to cracked sheets. Aeronautical J. Royal Aeronautical Soc., 93: 327-334.