3D FINITE ELEMENT MODELLING OF A COMPOSITE PATCH REPAIR

A MAHADESH KUMAR and RIPUDAMAN SINGH
Department of Aerospace Engineering,
Indian Institute of Science, Bangalore 560012. INDIA

ABSTRACT

Composite-patching on cracked/weak metallic aircraft structures improves structural integrity. A Boron Epoxy patch employed to repair a cracked Aluminum sheet is modeled employing 3D Finite Element Method (FEM). SIFs extracted using "*displacement extrapolation*" are used to measure the repair effectiveness. Two issues viz., patch taper and symmetry have been looked into.

KEYWORDS

Repair, Composite Patch, Non-linear FEA, 3D.

INTRODUCTION

Damage during service life is a natural characteristic of any airframe. Performing repairs to damaged airframe components is virtually inevitable, for not so old airframes due to primarily economic reasons. A badly implemented repair can be more dangerous than the unrepaired configuration. Out of various class of damages, if we limit ourselves to cracks, then these can possibly be repaired either by a mechanically fastened doubler or a bonded patch. 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. Researchers in Australia have extensively employed Boron-Epoxy bonded patches to repair cracks and also to reinforce weak spots in airframes. Most of the work untill recently was based on simple analysis or experiments. With increase in computational power, full 3D finite element analysis is now possible with lot of erroneous approximation elliminated. Attempts have started in this direction so as to improve the reapir design. At IISc we have also initiated a scientific approach to the optimum design of these repair patches by full 3D FE modelling as state-of-the-art computational technology is now available with us. Although the objective is to model repairs to stiffened curved shells (representing fuselage) with longitudinal/circumferential cracks, we start with a flat thin sheet, cracked at the center and loaded biaxially.

REPAIRS – a Review

Scientific approach to designing & assessing repairs before implementing, started in early 1970s. The work was pioneered by Baker at Australian Research Laboratories (ARL) for Royal Australian Airforce (RAAF). By now there are over 6,500 flying patches at various locations on aircraft with different fleet. Adopting & following repair guidelines, given by the manufacturer, for typical minor damages is a routine activity with most airline and Defence operators. Damages not listed in such repair manuals, naturally call for intervention of the manufacturer for functional restoration.

Most of the reported work in the realm of repairs is on composite patching of metallic airframe components. A bonded overlay of high strength composite material offers an efficient method for enhancing the structural integrity. Baker (1984) has very precisely summarised a range of benefits derivable by application of selective composite reinforcement to existing metallic components. They include stiffening underdesigned regions, increasing static strength, restoring strength or stiffness, reducing stress intensity, and improving damage tolerance in safe life components. The team in Australia has very successfully employed Boron-Epoxy patch repairs to Macchi, Hercules, Mirage, Orion, F-111, B-727, B-767, B-747, Bell helicopter, and MD-82 (Baker and Chester 1993); Multi-Site-Damage problem on a test specimen representative of a fuselage lap joint in a commercial wide bodied aircraft (Jones *et al.* 1991). The key feature, in addition to functional success, is the *in-situ* repair, which leads to substantial savings in down time for the aircraft.

Most exhaustive effort for a single repair/modification has probably been with the ARL for F111C wing pivot fitting prone to cracking, where Molent *et al.* (1989) have performed extensive FEA, thermal analysis, strain gauge survey, dog bone specimen, structural detail specimen and finally the full scale static testing going in steps upto proof loading. The repair consisted of two tailored patches with upto 60 layers of BFRP, one of them having a cutout, shaping the stiffener runout and preloading the structure during curing to reduce the residual thermal stresses after the cure.

Finite element analysis of composite reinforcement by Mitchell *et al.* (1975) appears to be the first thorough attempt towards analytical understanding of this class of problems. He models the patch in 2D planform & 2D longitudinal cross-section. The predicted strains were reported to be in good agreement with the experimental observation.

At ARL, fairly early in their venture into repairs, Jones and Callinan (1979) did analytically investigate, using FEM, the behaviour of composite patches to metallic sheets, permitting separate response of the sheet, adhesive and the patch to emerge. They emphasised patch tapering as a solution to stress reduction in the adhesive. Such an analysis can help optimise patch configuration (Jones and Callinan 1981). The Australian group appears to be the only people to have analytically investigated repairs to thick sections (Jones *et al.* 1982), the effects of expansion coefficient on residual thermal stresses (Jones and Callinan 1980) and more recently a 3D FEM of damage tolerant repairs (Chiu *et al.* 1994). Infact this report mentions about formulae for SIF in a patched cracked sheet and its assymptotic value, but does not include the bending effects. Rose (1981, 1982, 1987) has applied integral equation approach to understand 2D idealization of 3D reinforced crack problems. Double symmetry elliminates the bending effects of unbalanced patches.

Young *et al.* (1985, 1989) have investigated effects of rectangular and elliptical balanced patches on stress intensity factors at crack tips in a uniaxially loaded sheet. They present a closed form approximation for large elliptic patches. More recently, Rooke *et al.* (1992) developed BEM and investigated effect of central as well as offset patches on stress intensity factors at crack tips in stiffened & unstiffened sheets. Fatigue life times were calculated using Paris law, and were found to depend in a complex way on the crack length and patch & stiffener configurations. Central patches are found to be more useful for small cracks while offset patches are better for longer cracks. Similar observations have earlier been made by Ramesh Chandra *et al.* (1985), who used boundary collocation to solve integral equations representing patch effect on crack tip stress intensity factors.

Liu and Fan (1994), employed Green's function approach, and developed singular integral equations to evaluate stress singularities at crack tips and strip ends for partially bonded strip patch to a cracked sheet.

Arendt & Sun (1994) have quantified bending effects of unsymmetrically bonded composite repairs on cracked aluminum panels, using plate linear finite element model (using ANSYS). Stress intensity factors and strain energy release rates were obtained from the model using modified crack closure method. They report negligible variation of stress intensity factor over the thickness of the cracked plate. On the contrary, findings in this paper indicate substantial variation through the thickness of the sheet. An extensive review of reported efforts on repairs is given by Singh (1996).

PROBLEM DEFINITION

Before implementing a repair patch, there is a need for design assessment in terms of its effectiveness. The repair effectiveness can be measured in two possible ways: namely (i) enhancement in *Residual Strength* and/or (ii) increase in *Residual Life* of the component. While dealing with a composite patch repair to a cracked metallic sheet, both these boil down to a measure of reduction in crack tip Stress Intensity Factor(SIF). With an objective of eventually handling a patched crack problem in a stiffened pressurised shell structure, we have started with a simpler case of a patched central crack in an unstiffened bi-axially loaded flat sheet, primarily to understand the modelling issues. The precise problem and the scope of this paper is *Numerically model a Boron-Epoxy composite patch employed to repair a central crack in a thin aluminum sheet under bi-axial stresses.* Closed form solution for crack tip SIF for unsymmetrically repaired cracks does not exist. We need to take recourse to numerical techniques. Researchers in the last two decades have come up with various ways of extracting SIF from numerical procedures such as FEM. For simple models that we are considering, displacement extrapolation method appears to be a descent method for extracting $K_{\rm I}$. For a full 3D FE model the method is applied at various locations along the thickness. Although Modified Crack Closure Integral (MCCI) can give more accurate results, the ability to extract precise nodal forces is not available at this instant.

Geometry : Consider a square elastic thin aluminum sheet $40.0'' \times 40.0'' \times 0.036''$, with a central crack of length $1.0''$. This crack is repaired by a unidirectional Boron Epoxy Patch whose volume has been chosen as 4 × 4 × crack length × sheet thickness = 0.576cubic inches. This is achieved by using a total of 6 plies $0.006''$ thick. For a symmetric case there are three plies on both sides and for an unsymmetric case, all 6 plies are on the same side. All the plies have a square planform. For the four cases the sizes would be vary so as to retain the total volume and also have a taper of '1 in 30' for the stepped configuration achieved by dropping plies at every $0.018''$ on all sides. For the four configurations considered with square planform shapes, the sides are obtained as below :

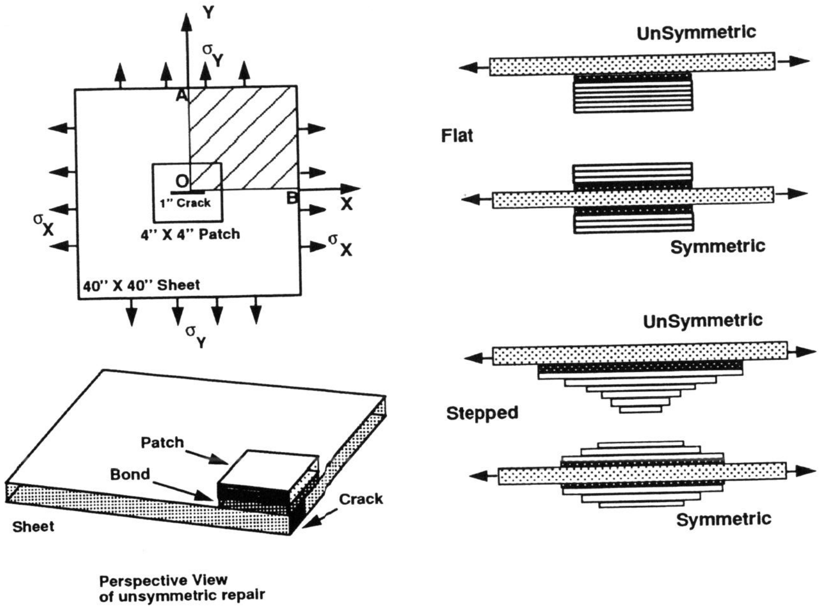

Figure 1: Geometric Model.

Sym	Flat	4.000	4.000	4.000	-	-	-
Sym	Stepped	4.348	3.988	3.628	-	-	-
Unsym	Flat	4.000	4.000	4.000	4.000	4.000	4.000
Unsym	Steeped	4.852	4.492	4.132	3.772	3.412	3.052

These are shown in figure 1 and cover the two issues under study viz., the patch taper and patch symmetry. The bonding for all situations is using a film Epoxy adhesive 0.006″ thick.

Loading & Boundary Conditions : The sheet is subjected to a biaxial stress state of $\sigma_x = 9.75$ ksi and $\sigma_y = 19.5$ ksi, to closely represent the longitudinal and hoop stresses in a typical narrow body fuselage shell. Since the geometry and boundary conditions are doubly symmetric, only one quarter needs to be analysed. In 3D model of the patch repair, the adhesive is treated as cracked along with the sheet. The crack is modeled as a face free of tractions.

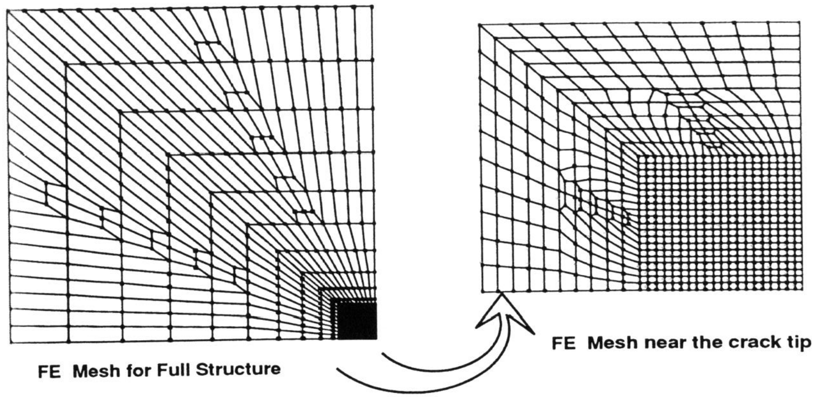

Figure 2: A typical Finite Element Mesh.

Material Properties The material properties considered for this model are as follows:
Aluminum (sheet): Al 2024-T3 $E = 10,500$ ksi, $\nu = 0.33$
Boron-Epoxy unidirectional (patch): $E_1 = 29,580$ ksi, $E_2 = E_3 = 2,680$ ksi,
$\nu_{12} = \nu_{13} = 0.23$, $\nu_{23} = 1.33$, $G_{12} = G_{13} = 810$ ksi, $G_{23} = 580$ ksi.
Film Epoxy (adhesive): $E = 313$ ksi, $\nu = 0.35$

FINITE ELEMENT ANALYSIS

Finite Element Analysis is done using a commercial code NISA (on IBM Risc 6000 machine) employing 3D Brick element called NKTP 4. A problem of an unpatched cracked configuration is analysed first to ascertain the applicability of displacement extrapolation method for the chosen mesh near the crack tip. SIF is known in closed form for this situation and is equal to 24.44 $ksi\sqrt{in}$. The displacement extrapolation method gave 25.78 $ksi\sqrt{in}$ giving a percentage error of 5.5%. A typical FE Mesh is shown in figure 2. It has been confirmed earlier by Mahadesh (1995, 1996) that for unsymmetric patch configurations, large rotations and resulting out-of-plane displacements makes it imperative to perform geometrically non-linear analysis. For both the unsymmetric patch problems, the geometrically non-linear analysis is performed with equilibrium satisfied in the deformed condition, whereas for the symmetric patches linear analysis is adequate as well as appropriate.

RESULTS & OBSERVATIONS:

The SIF values across the thickness for cracked and four repaired configurations extracted from FEM results, using displacement extrapolation, are given in table below and are plotted in figure 3. (Five stations correspond to four elemnts across the thickness).

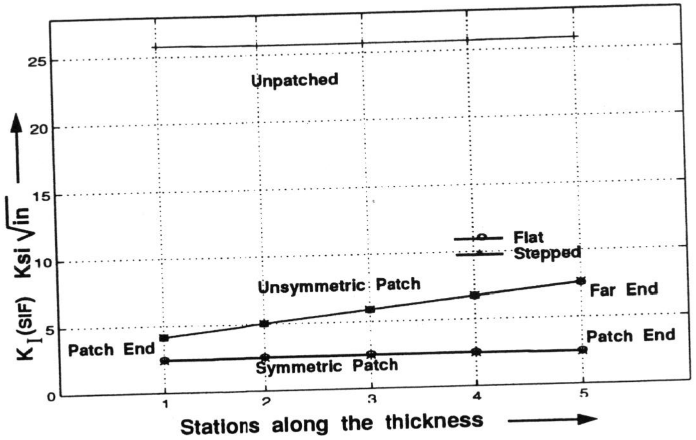

Figure 3: SIF variation across the thickness.

Location	Cracked & Unpatched	Cracked & Patched			
		Symm		Unsymm	
		Flat	Stepped	Flat	Stepped
Patch end 1	25.81	2.38	2.48	4.18	4.15
2	25.75	2.45	2.55	5.06	5.03
Mid-plane 3	25.74	2.47	2.57	5.91	5.88
4	25.75	2.45	2.55	6.76	6.72
Far end 5	25.81	2.38	2.48	7.60	7.54
$K_{I,RMS}$	25.78	2.43	2.53	6.02	5.99
da/dN $\times 10^{18}$	12121	2.52	2.91	65.4	64.3
Patch Eff.	-	10.61	10.19	4.28	4.30

In this table the patch effectiveness has been obtained as a ratio of SIF without patch and SIF with patch, and the crack growth rate is based on Paris Law with constants taken as $\frac{da}{dN} = 1.04 \times 10^{-19} \times (\Delta K_I)^{3.59}$ (Hudson 1969). Following observations can be clearly made from this set of results.

- The SIF is almost constant across the thickness for the symmetric patch repairs, both flat and stepped. This means that most of the deformation occurs as adhesive shear and there is very little shear deformation of the sheet.
- For both the unsymmetric patch repairs, there is a substantial variation of SIF across the thickness, almost a factor of 2. This contradicts the findings of Arendt & Sun (1994) and is discussed in detail in the next subsection. Here also, almost linear variation of SIF across the thickness indicates negligible shear deformation of the sheet. This can be explained due to sheet shear modulus of approx 35 times that of adhesive shear modulus.
- Symmetric patches are considerably more effective (more than twice) than the unsymmetric patches of same volume. Physically this can be explained due to the presence of more patch material closer to the cracked sheet.
- Tapering a patch by ply-drops, but retaining the volume has very little influence on SIF. In fact the curves are indistinguishable in figure 3.
- The purpose of introducing a ply drop(taper) is to relieve stresses in the system. We did observe a significant fall in stresses in the adhesive. At the corner point in the patch, the effect of taper on the peel, shear, and von-Mises stresses in the adhesive are listed below :

Configuration		Peel	Shear σ_{yz}	Shear σ_{xz}	Von-Mises
Sym	Flat	0.625	2.848	0.399	4.987
	Stepped	0.215	1.409	0.176	2.471
	% age	33 %	50 %	44 %	50 %
Unsym	Flat	1.422	3.291	1.009	6.010
	Stepped	0.438	1.242	0.339	2.246
	% age	31 %	38 %	34 %	37 %

Conflict with findings of Arendt & Sun : Significant variation of SIF for the unsymmetric patch configuration is in disagreement with results concluded by Arendt & Sun (1994). They used 2D plate elements to represent the sheet and the patch. The adhesive was modeled by shear spring elements. SIF is extracted using strain energy release rate. The model appears to be correct. They claim negligible variation of SIF across the thickness, based on negligible crack face rotation. Findings with full 3D model are different. It shows substantial crack face rotation, as at a location as close as 0.01667″ (a/30) from the crack tip. The values are:

Mid-plane crack opening = 0.3347° Patch end crack opening = 0.2299°
Crack face rotation = 0.1004° Far end crack opening = 0.4467°
Rotation / Opening = 30 % Far/patch end opening = 1.943

The magnitude of crack face rotation may appear small, but in relation to the crack opening, it is substantial (30.4%). In fact the crack opening at the patch end and far end differ by a factor of almost 2. This substantial crack face rotation causes a redistribution of strain energy within the system leading to substantial variation of SIF across the thickness, but with marginal change in total strain energy. Using 3D model we clearly see that the RMS SIF over the sheet is marginally different from the mid plane value. For our model we get : RMS SIF = 6.02 $ksi\sqrt{in}$, Mid-plane SIF = 5.91 $ksi\sqrt{in}$; Percentage difference = 2%. This difference is of the same order as felt by Arendt and attributed towards variation across the thickness.

Acknowledgement : Authors are greatful to Prof T S Ramamurthy and Prof B Dattaguru for continuous support and encouragement. It is a pleasure, being associated with them. The facilities at SERC, IISc are a big help.

REFERENCES

Arendt, C. and Sun, C. T. (1994) Bending Effects of Unsymmetric Adhesively Bonded Composite Repairs on Cracked Aluminum Panels. *NASA CP 3274*, 33-48.

Baker, A. A. (1984) Repair of Cracked or Defective Metallic Aircraft Components with Advanced Fibre Composites – An Overview of Australian Work. *Comp. Str.*, **2**, 153-181.

Baker, A. A., and Chester, R. J. (1993) Recent Advances in Bonded Composite Repair Technology for Metallic Aircraft Components. *Proc of International Conference on Advanced Composite Materials*, Ed: Chandra T. and Dhingra A. K. 45-49.

Chiu, W. K., Rees, D., Chalkley, P. and Jones, R. (1994) Designing for Damage Tolerant Composite Repairs. *Comp. Str.*, **28**, 19-37.

Hudson, M. (1969) Effect of Stress Ratio on Fatigue Crack Growth in 7075-T6 and 2024-T3 Aluminum Alloy Specimens. *NASA TN-D 5390.*

Jones, R., Bridgford, N., Wallace, G. and Molent, L. (1991) Bonded Repair of Multi-Site Damage. *Structural Integrity of Aging Airplanes*, Ed: Atluri, S. N., Sampath, S. G. and Tong, P., Springer Verlag, 199-212.

Jones, R. and Callinan, R. J. (1979) Finite Element Analysis of Patched Cracks, *J. Struct. Mech.*, **7**, 107-130.

Jones, R. and Callinan, R. J., (1980) Thermal Considerations in the Patching of Metal Sheets with Composite overlays. *J. of Struct. Mech.*, **8**, 143-149.

Jones, R. and Callinan, R. J. (1981) A Design Study in Crack Patching. *Fibre Sc. & Tech.*, **14**, 99-111.

Jones, R., Davis, M., Callinan, R. J. Mallinson, G. D. (1982) Crack Patching: Analysis and Design. *J. of Struct. Mech.*, **10**, 177-190.

Liu, T. and Fan, W. (1994) Analysis for an Adhesively Bonded Finite Strip Repair to a Cracked Plate. *Engg. frac. Mech.*, **47**, 629-637.

Mahadesh Kumar, A. (1996) Finite Element Modelling of Patch Repairs to Cracked Sheets. *Masters Dissertation*, Aerospace Engg, Indian Institute of Science, Bangalore.

Mahadesh Kumar, A. and Ripudaman Singh (1995) Modelling of Composite Patch Repairs to Cracked Metallic Sheet. *NISA Users Conference*, Bangalore.

Mitchell, R. A., Woolley, R. M. and Chwirut, D. J. (1975) Analysis of Composite Reinforced Cut-outs and Cracks, *AIAA J.*, **13**, 744-749.

Molent, L., callinan, R. J. and Jones, R. (1989) Design of an all Boron/Epoxy Doubler Reinforcement for F111C Wing Pivot Fitting: Structural Aspects. *Comp. Str.*, **11**, 57-83.

Ramesh Chandra, Murthy, M. V. V., Ramamurthy, T. S. and Rao, A. K. (1985) Analytical Estimation of Stress Intensity Factors in Patched Cracked Plates. *Engg. Frac. Mech.*, **21**, 479-494.

Ripudaman Singh (1996) Repairs to Damage Tolerant Structures: Issues and a Viewpoint. *J. Aero. Soc. India*, In press.

Rooke, D. P., Young, A. and Courtney, T. J. (1992) Effect of Repair Patches on Fatigue Lifetimes. *Durability of Metal Aircraft Structures*, Ed: Atluri, S. N., Harris, C. E., Hoggard, A., Miller, N. and Sampath, S. G., Atlanta Technology Publications, 132-145.

Rose, L. R. F. (1981) An Application of Inclusion Analogy for Bonded Reinforcements. *Int. J. of Solids Struct.*, **17** 827-838.

Rose, L. R. F. (1982) A Cracked Plate Repaired by Bonded Reinforcements. *Int. J. Frac.*, **18** 135-144.

Rose, L. R. F. (1987) Crack Reinforcement by Distributed Springs. *J. Mech. Phys. Solids.*, **35** 383-40.

Young, A., Cartwright, D. J. and Rooke, D. P. (1985) Model Studies of Repair Patches. *Proc of Int. Conf. on Fatigue, Corrosion, Cracking, Fracture Mechanics and Failure Analysis*, Salt Lake City, 339-346.

Young, A., Rooke, D. P. and Cartwright, D. J. (1989) Numerical Study of Balanced Patch Repairs to Cracked Sheet. *Aero. J.*, 327-334.