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Stress Redistribution Near a Crack in Maraging Steel using Composite Patch

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ABSTRACT

The presence of a crack significantly reduces the load bearing capacity of a structure made of fracture prone material. The conventional process of repairing a defect is gouging and filling the gouged location by welding. It is not only time consuming but also constrained by the number of repairs that can be done as material properties degrade with each round of welding. In an attempt to overcome the limitation of the conventional repair process, repairing a defect using composite patch is proposed. The study is carried out on Maraging steel (M250) and the defect considered is a semi-elliptical surface crack. Stress intensity factor (SIF), being an important parameter in fracture-based design, it is evaluated using finite element analysis software Abaqus. Extended finite element method is used to model the crack in Abaqus. Fracture assessment is carried out using three parameter fracture criteria as it estimates the stress at failure from the maximum value of SIF. The stress at failure is used to predict the failure load of a surface cracked tension specimen and the same is validated with the test values reported in literature. Then, a composite patch is modelled over the crack using woven ply properties. A separate layer of adhesive is also modelled to predict the adhesive properties. Failure analysis of each of the components namely, the Maraging steel plate, the composite patch and the adhesive is carried out. It was observed that the addition of a composite patch completely nullifies the presence of a crack. The patch with thickness 1mm and woven ply properties is having minimal damage initiation and likely to survive. The adhesive properties required is also obtained from the finite element analysis. Thus, it was observed that a composite patch with woven ply properties and thickness 1mm is able to completely nullify the effect of a crack when bonded with a suitable adhesive as predicted by the analysis.

Keywords: Maraging steel; Stress intensity factor; Fracture toughness; Finite element method; Extended finite element method

1. INTRODUCTION

Maraging steel finds it application in aerospace field due to its high strength. It is regarded as fracture prone as fracture is the most prominent mode of failure for the hardware made with it[1]. The reported fracture toughness of Maraging steel (M250) is between 90 MPa√m to 95 MPa√m for a thickness of 7.8 mm. The reported 0.2% proof stress and the ultimate tensile strength is 1725 MPa and 1765 MPa respectively and the percentage elongation to failure is about 8%. The weld efficiency of M250 is about 90%. With each round of weld, both the strength and the fracture toughness decrease significantly. Presence of a crack larger the critical size can be catastrophic in Maraging steel (M250). In order to rule out the presence of defects like cracks and inclusions above a threshold size, Non-Destructive Testing (NDTs) are extensively done before and after each welding process. *Ultrasonic Testing* (UT) play an effective role in locating as well as sizing the cracks. Once a defected is reported in a UT scan, the defect location is gouged, and NDT is repeated. If the defect still persists, then gouging is repeated again to a higher depth and then NDT is carried out again. This process is repeated till no defect is reported. This process is not only time consuming but also constrained by the number of welding that can be done since the properties degrade with each round of welding. Also, each round of welding increases chances of containing weld defects. Occasionally, welding has to be repeated again and again in order to get a defect free weld. In order to overcome the above stated problems with rewelding method of crack elimination, composite patch repair on the Maraging steel structure is studied in this paper. With the addition of a composite patch at the crack location, stress redistribution at the crack will reduce the highest stress, thereby reducing the stress intensity factor.

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2. LITERATURE REVIEW

Repairing a defect in hardware with composite patch is an existing practice in the aircraft industry. The book referred in this project provides the detail of each and every step of how the concept of patch repair originated and how is it used for repair of the fighter aircrafts in the contemporary time. This is a highly cost-effective method for extending the service life of aircraft structures. Carbon–epoxy composites are considered as the patch material due to their high stiffness and strength to weight ratios. Composite patch repair has been simulated on Aluminum alloy plate and validated with experiment. A 6061–T6 aluminum alloy plate is considered and an artificial crack is made with electrical discharge machining (EDM)[2]. The stress intensity factor for a simple geometry like that of a cracked plate can be estimated by the analytical approach[3]. For complex geometry, finite element method is used to estimate the SIF accurately. The finite element a code Franc2D/L developed at Kansas University is used is one of the pioneers in the field of finite element simulation of a crack. Extended finite element method serves as an accurate and easier method to evaluate SIF. Comparison of SIF solutions obtained by XFEM and conventional FEM for cracks in complex geometries like valve body and found that XFEM is accurate in evaluating SIF[4]. The size of the mesh affects the accuracy of the SIF evaluation in commercial finite element software[5]. Evaluation of the stress intensity factors for patched cracks with bonded composite repairs in mode I and mixed mode is also carried out[6]. Some other authors have focused their attention on the optimal design of the bonded patches, by finite element models, in terms of edge taper and in-plane shape. Composite patch is the most economic option for repair on aluminum alloy[7]. The effect of adhesive on the performance of the repair efficiency of bonded aluminum alloy has also been studied. Maraging steel is considered as fracture prone since it has a low fracture toughness in spite of having a very high strength. The dominate mode of failure in Maraging steel is fracture[1]. Failure study have been carried out experimentally on Maraging steel plates with surface crack and the result available in those research papers is used for validation in this project[8]. When SIF evaluation is not possible directly, it can be evaluated from J-integral with same accuracy[9]. In this project, when a patch is modelled with orthotropic properties, direct estimation SIF was not possible in Abaqus. Thus, SIF was calculated from J-integral. Properties of composite with unidirectional as well as woven ply is studied and available in technical literature[10]. The finite element analysis is carried out for various thickness of the patch[11,12]. A parametric study was carried out to arrive at the optimum patch thickness. The damage initiation study in composites patch is carried out with two phenomenological criteria namely, Hashin's damage initiation criteria and Tsai-Wu[13] damage initiation criteria.

3. METHOD

A structure with a crack when subjected to tensile force may fail either due to brittle fracture or by ductile fracture or by plastic collapse depending upon the material with which it is made of. For fracture prone material, brittle fracture is the mode of failure. Fracture assessment of brittle material is carried out by a parameter called stress intensity factor (SIF) is developed within the purview of linear elastic fracture mechanics (LEFM). For brittle material, yield strength is less important than critical stress intensity factor (SIF). Critical stress intensity factor is also called as fracture toughness. LEFM considers the plastic zone small enough to be neglected without scarifying the accuracy of the analysis. For predicting the load bearing capacity of a brittle material, the estimated SIF is compared with the critical SIF. For material which shows a considerable plastic zone at the crack tip, the analysis based on LEFM tends to become inaccurate. For such material, Elastic-plastic fracture mechanics (EPFM) approach should be used. Within the purview of EPFM, J.C. Newman developed the two-parameter fracture criterion (TPFC)[14] to account for the effect of plastic deformation at the crack tip on the failure stress.

$$K_{Ie} = K_F\left(1 - m\left(\frac{\sigma_f}{\sigma_u}\right)\right)$$

here, K_{Ie} is the elastic stress intensity factor at failure, σ_f is the stress at failure and σ_u is the ultimate strength of the material. K_F and m are the material fracture parameter. When m=0, K_F will be same as K_{IC}. Thus, m and K_F represents the extent to which the plastic deformation at the crack tip is affecting the failure. TPFC is applicable for bigger crack size which results in failure stress lesser than the yield strength of the material. In such condition, there exists a linear relationship between σ_f and K_{Ie} as given by the TPFC. For small sizes of cracks, where yield strength<failure stress<ultimate strength, the relationship between σ_f and K_{Ie} is expected to be non-liner. Therefore, the TPFC is modified for its accurate application in case of smaller crack size. The modified criteria is called three parameter fracture criterion[15].

$$K_{\max} = K_F\left(1 - m\left(\frac{\sigma_f}{\sigma_u}\right) - (1-m)\left(\frac{\sigma_f}{\sigma_u}\right)^P\right)$$

here, $K_{\max}$ is SIF at failure

σ_f is the stress at failure

σ_u is the ultimate stress

K_F, m and p are the material constants

The value of $K_{\max}$ is estimated from the FE analysis for both the repaired as well as unrepaired case. The value of the material constants used in the 3-parameter fracture model[15] are mentioned Table 1. The above equation of the 3-parameter fracture model is solved numerically for the stress at failure (σ_f). The failure load is estimated by multiplying the cross-section area with failure stress.

Table 1. Facture parameter for failure study of Maraging steel

K_F = 235.7 MPa√m	m = 0.6
p = 20.4	Ultimate strength (σ_f) = 1720 MPa

4. MODELLING IN ABAQUS

4.1 Maraging Steel Plate

An elliptical surface used to define crack is modelled in Abaqus. The plate is modelled with solid 8 noded brick element (C3D8R) with reduced integration. Solid homogeneous section is assigned to the plate. Linear material property is used for the Maraging steel plate as mentioned in Table 2.

Table 2. Properties of Maraging steel plate used

Young's modulus = 190000 MPa	Plate dimension
Poisson's ratio = 0.3	Length 80 mm, width 30 mm, thickness 7.5 mm
0.2% Proof stress = 1650 MPa	
Ultimate strength = 1720 MPa	

4.2 Crack

Tight surface crack of elliptical shape is modelled in Abaqus software as shown in Fig. 1. Extended finite element method (XFEM) is used to model the crack owing to the simplicity. In XFEM, a crack is modelled as a planar elliptical surface with no thickness whereas, no section is assigned to the crack. The length (2c) is 5.6 mm and depth (a) is 2.5 mm.

4.3 Composite Patch

The composite patch is also modelled with solid 8 noded brick element (C3D8R) with reduced integration. Solid homogeneous section is assigned to the patch. The patch dimensions are length = 30 mm, width = 15 mm and thickness = 1 mm. Woven ply property is used for the composite patch as mentioned in Table 3.

4.4 Adhesive

The adhesive is also modelled with solid 8 noded brick element (C3D8R) with reduced integration. The thickness of adhesive modelled is 0.2 mm. The property of the epoxy resin which was used as adhesive between the plate and the patch are mentioned in Table 4.

Table 4. Properties of the adhesive used to bond the patch

Young's Modulus	3780	MPa
Poisson's Ratio	0.35	
Tensile Yield Strength	54.6	MPa

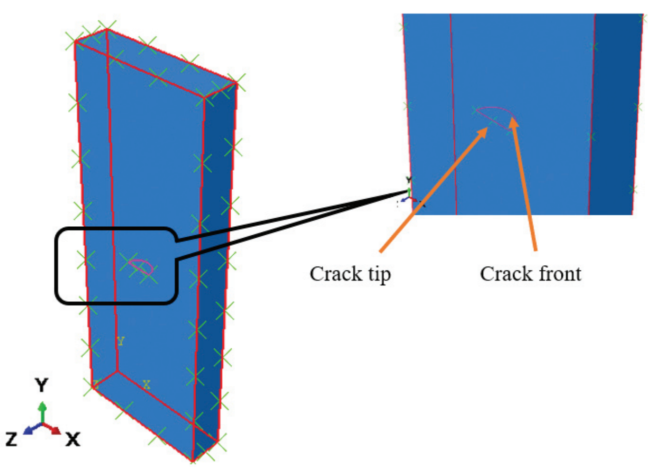

Figure 1. A tight elliptical crack is defined using XFEM.

4.5 Interaction

It is assumed that there is no debonding either between the plate and the adhesive or the adhesive and the patch. The reason for this assumption is that the stress distribution on the adhesive can be studied and required property of the adhesive can be evaluated when the there is a complete bonding between these parts. Cohesive behaviour with finite sliding is specified between these parts.

4.6 Boundary Condition

The bottom end surface of the plate is fixed (U1=0, U2=0, U3=0) and the top end surface is applied with a tensile load of 1600 MPa. The boundary conditions used to model the surface cracked plate tension is given in Fig. 2.

4.7 Details of the Finite Element Analysis

3D solid elements are used to mesh all the components involved in the finite element analysis. Mesh convergence study was carried out and it was observed that the results converged when the mesh size for the plate is equal to or smaller than 1 mm. Since the thickness of the patch is also 1mm and adhesive is only 0.2 mm, a finer mesh was opted for these components. The size of the mesh is different for different components i.e, plate, adhesive and patch as shown in Fig. 3. The various parameters to show the size of the finite element analysis is shown in Table 5.

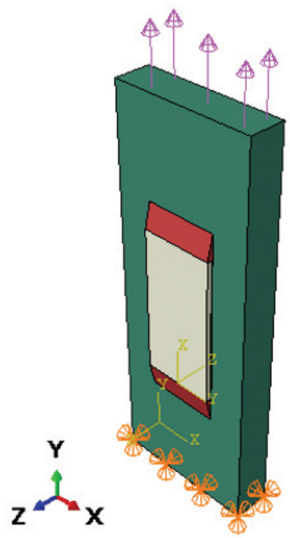

Figure 2. Boundary conditions for finite element model.

Table 3. Properties of the composite lamina used in the patch

Young's Modulus X direction	91820 MPa	Tensile Strength X direction	829 MPa
Young's Modulus Y direction	91820 MPa	Tensile Strength Y direction	829 MPa
Young's Modulus Z direction	9000 MPa	Tensile Strength Z direction	50 MPa
Poisson's Ratio XY	0.05	Compressive Strength X direction	-439 MPa
Poisson's Ratio YZ	0.3	Compressive Strength Y direction	-439 MPa
Poisson's Ratio XZ	0.3	Compressive Strength Z direction	-140 MPa
Shear Modulus XY	3600 MPa	Shear Strength XY	120 MPa
Shear Modulus YZ	3000 MPa	Shear Strength YZ	50 MPa
Shear Modulus XZ	3000 MPa	Shear Strength XZ	50 MPa

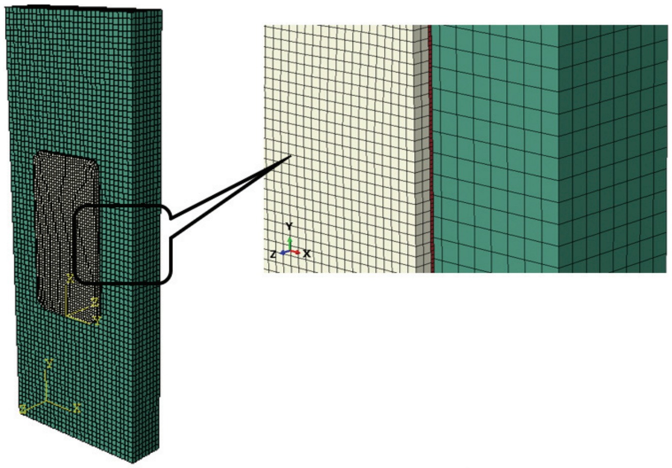

Figure 3. Finite element model showing different mesh sizes.

Table 5. Various parameters to show the size of the finite element analysis

Mesh size for Maraging steel plate	1 mm
Mesh size for epoxy adhesive	0.2 mm
Mesh size for composite patch	0.5 mm
Number of elements is	53364
Number of nodes is	114591
Time integration scheme	Direct time integration

5. RESULTS

5.1 Observation on the Maraging Steel Plate

The product of the far field stress and the cross-sectional area of the plate matched closely with the applied tensile load. SIF was obtained for the cracked and patched model are plotted in the graph shown in Fig. 4. The graph suggests that the SIF in the cracked plate is highest at the end. This is in line with the fact that crack tip opening displacement is also highest at the crack opening surface. The end points of the crack tip coincide with the nodes on the surface.

The graph suggests that the SIF of the patched plate is considerably lower than the cracked plate. This implies that the failure load for the patched plate should be higher than the cracked plate. The estimated failure stress from the analysis for the cracked plate (unrepaired) is 1551.64 MPa. The failure stress as found from a tensile test of the cracked plate (unrepaired)[8] is 1668 MPa and the same is fairly close to the failure stress evaluated from the finite element analysis. This validates the FE model and the analysis performed. The estimated failure stress from the analysis for the plate with a composite patch repair is 1828.66 MPa. The Ultimate strength of maraging steel (M250) is about 1765MPa. It means that the addition of a composite plate to a cracked plate is able to completely nullify the presence of a crack. when such plate will be subjected to a high load, it will fail at the ultimate strength of Maraging steel and the location of failure initiation will be away from the crack.

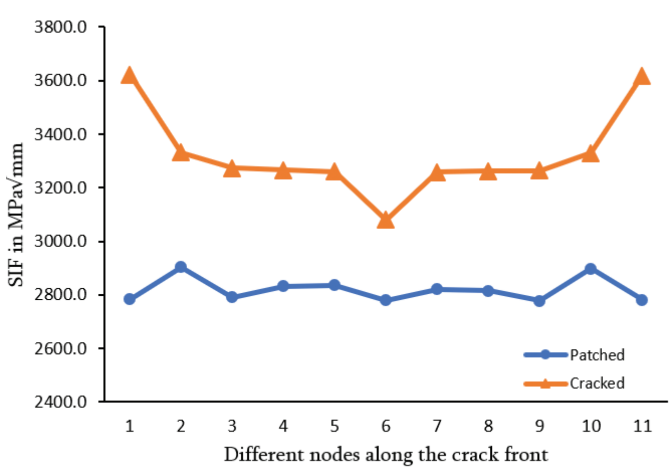

Figure 4. SIF at different nodes along the crack front.

5.2 Observation on the Composite Patch

A local coordinate system was defined aligned with the material axis and stress values were extracted in that coordinated system. The variation of S11 is shown in the Fig. 5. It represents the normal stress in the vertical direction.

The maximum stress in the vertical direction (same as the direction of loading) is 914.6 MPa. It is same as the maximum principal stress. Maximum shear stress is 91.06 MPa. Failure analysis has been carried out as per Hashin's criteria[13] and it was observed from Table 6 that there is no fiber damage and only 2.2% of the total 3700 elements in the patch are likely to have damage initiation. The mode of damage initiation is likely to be matrix damage.

Table 6. Failure analysis of the composite patch using Hashin's criteria

Fibre damage		Matrix damage	
Tensile	Compressive	Tensile	Compressive
0.0%	0.0%	0.6%	1.6%

5.3 Observations on Adhesive

Resin is a isotropic material and can be choosen to act as an adhesive. The properties of a typical resin used in our finite element analysis is mentioned in section 1.1.4. The maximum principal stress in the adhesive as per Fig. 6 is 165 MPa. The maximum effective stress (von mises stress)

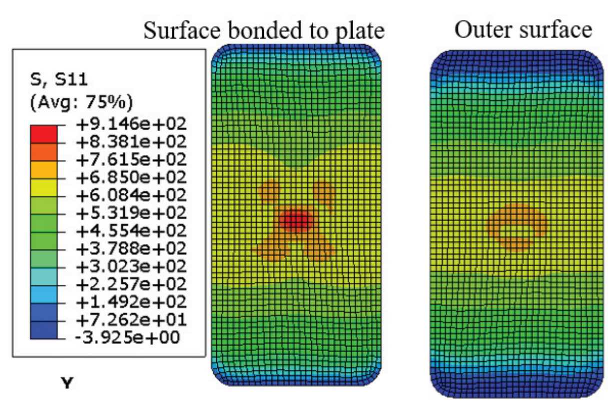

Figure 5. Tensile stress distribution in MPa on the composite patch on both sides.

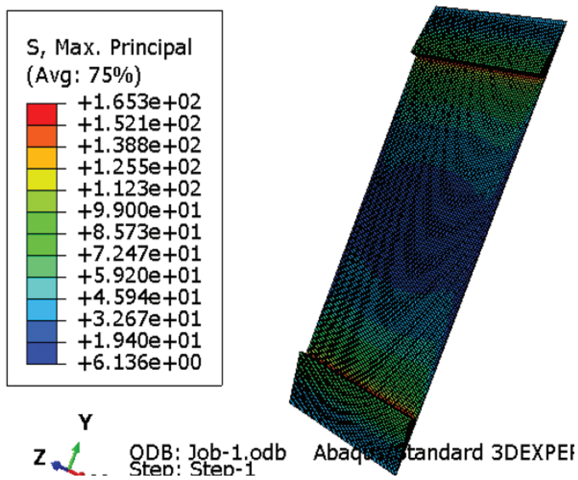

Figure 6. Maximum principal stress distribution in MPa on the epoxy.

observed is 198.1 MPa and the maximum shear stress observed is 110 MPa. The minimum bond strength requied is expected to be 200 MPa. It is implied that with the properties that the simulation is carried out, the adhesive is not likely to withstand the load. But with the selection of a suitable adhesive with the minimum strength of 200 MPa, the patch repair is likely to withstand the load without any failure in any of its components.

6. CONCLUSION

A detailed FE analysis of a Maraging steel plate with surface crack is carried out with and without a composite patch. It is observed that a composite patch made of woven fibers can serve as an effective way to repair a structure with a defect when bonded with a suitable adhesive. The shape and size of the patch will depend upon the magnitude and direction of loading. In this paper, unidirectional tensile load has been applied on Maraging steel plate of thickness 7.5mm and the results suggests that the effect of the crack is completely nullified due to the addition of a composite patch. Failure analysis of the patch shows that damage initiation is there only 2.2% of the total elements and the same is less likely to grow. As per the adhesive property used, it is likely that the adhesive will be locally debonded as the strength of most of the commercially available the resin is about 100 MPa whereas the maximum principal stress observed is 200 MPa. But this local debond is not likely to result in complete failure of the composite patch. Experimental verification is suggested to verify the results of this paper. Thus, bonding composite patch on the crack with a suitable adhesive can serve as a cost effective and efficient means of repairing a crack.

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In this paper, he guided the author and reviewed the manuscript.