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Estimation of Residual Strength and Residual Fatigue Life of Damaged Steel Plate

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Abstract: Cracks can form due to fatigue or they can exist as a consequence of manufacturing processes such as deep machining marks or voids in welds and metallurgical discontinuities such as foreign particle inclusions. Nucleation and propagation of cracks caused by repeated cyclic loading below the yield stress of a material may cause catastrophic failure. As the crack forms and grows under cyclic loading, the residual strength and residual fatigue life decreases. In the present study, relevant analytical, experimental and numerical methods are used for predicting the ultimate strength and residual fatigue life of a cracked steel plate element under axial tension, where cracking damage is treated as a parameter of influence is studied. In fatigue life estimation process of cracked steel plate element, Linear Elastic Fracture Mechanics (LEFM) is introduced to describe and predict fatigue crack growth life and fracture under the basic assumption that material conditions are predominantly linear elastic during the fatigue process. The objective of this analysis is to predict crack growth, residual strength and residual fatigue life for the given initial damage on Critical Structural Element (CSE). Information on the growth of cracks in engineering structures and the residual strength of cracked structures is necessary for prediction of service lives of structures subjected to fatigue loading and for the establishment of safe intervals.

Keywords: Residual Strength, Linear Elastic Fracture Mechanics (LEFM), Residual Life, Stress Intensity Factor (SIF), Crack Growth Analysis.

I. INTRODUCTION

Since the beginning of 17th century, the first bridge has been built near Coalbrookdale in 1777-1779 made by cast iron, after wrought steel then mild steel, nowadays high strength and weathering steel has progressively been used as a material of construction, this material has been used widely to build bridges all over the world [1] . Progressively, as the industrial forms advanced different products of structural steel became available, such as rolled sections and cold formed members. The field of application of structural steel material includes structures such as bridges, buildings and industrial plants. As the age of the steel structure increases, they are liable to different types of damages. In aging structures the two most imperative types of damages are fatigue and corrosion. In engineering components, fatigue failure is a important consideration which may lead to fatal consequences. Especially, 80 to 90% of metal failure is correlated to fatigue. In fatigue related cases, the structures which began to be tolerable later may become insignificant in life and achieve the state of catastrophic failure. In such case, it is imperative to predict the residual strength and residual fatigue life of damaged structures. Hence, it is necessary to look for acceptable standards for performance of aging structures without increase in maintenance and repair costs during the life cycle of the structure. For this purpose, a scheme for risk or reliability assessment is generally practiced. In this ultimate limit state-based scheme, estimation of residual strength and fatigue life of structural element is carried by considering the effect of damage in the structure. Residual strength is the load carrying capacity of a damaged structure or material without failing. Residual strength analysis requires an understanding state of damage in a particular structure. The cause of damage can be in-service loading. The residual strength is defined as the measure of static strength accessible at any given time during the period.

Residual Strength

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Fatigue

Fatigue is defined as a localized and progressive mechanism where damage in structure accumulates increasingly as a result of repeatedly applied external loads such as winds for high rise buildings, vehicles for steel bridges, waves for offshore structures, where this applied loads is lesser than the resistance capacity of the structure. A structural element

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that is designed to carry a static load may fail at even smaller load when applied cyclically large number of times. Fatigue defined as failure of structural element due to cyclic stress.

II. EXPERIMENTAL ANALYSIS

Experimental work was carried out using a cracked steel plate under uniaxial tension load. In experimental analysis, the residual strength for cracked steel plate element is calculated under uniaxial tension load. Initial Crack of known length (a=17 mm) is introduced at the centre edge of the steel plate element. Analysis of the cracked steel plate is done using ANSYS software. The theoretical models are studied to estimate the ultimate strength of a cracked plate subjected to tensile load. Numerical analysis of the edge cracked steel plate with initial crack of 17mm was done using FEA based software ANSYS. From this analysis the aim is to determine residual stresses at the vicinity of the crack tip for the ultimate tensile load of 71kN obtained from the experimental analysis and also to determine the residual stresses for different decrement loading and compare it against yield stress. In the present study residual strength and fatigue life analysis is made for structural steel plate element. The work can be extended for various structural steel sections. Analysis of plate element is done under uniaxial zero-tensile cyclic loading. Analysis can also be made for multi-axial loading and for various stress ratios, variable amplitude and stress range.

Residual strength analysis of cracked steel plate

The experimental analysis of residual strength for cracked steel plate element under uniaxial tension load was carried out. Initial Crack of known length (a =17 mm) was introduced at the centre edge of the steel plate element as shown in the figure 1

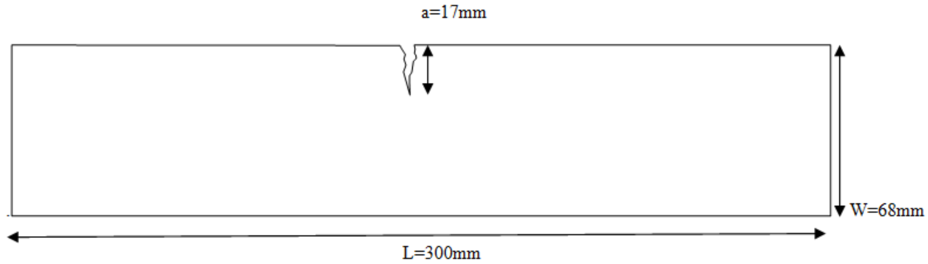

Fig 1: Single edge Cracked structural steel plate

Specification of the material:
IS 2062 Grade E250 | Fe 410WA
Structural steel plate
Length of the specimen (L) = 300 mm
Width of the specimen (W) = 68 mm
Thickness of the specimen (t) = 6 mm,
C/s Area (A) = 68×6= 408 mm^2.
An experimental study on the residual ultimate strength of Edge-cracked structural steel plate element subjected to uniaxial tensile load was carried out in Universal Testing Machine.

Fig 2 Steel plate with single edge crack

Tensile Test of theSpecimen

The test was carried out by applying axial tensile load to the specimen at a specific load increment and extension rate with known dimensions till failure. The applied tensile load and elongation are recorded during the test for the calculation of stress and strain.

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Fig 3: Experimental set up of edge cracked steel plate with uniaxial tension load


Fig 4:Enlanged view of experimental set up


Fig 5: Deformed steel plate element

Table 1: Observation and calculation of Tensile Strength

Load (P) KN	Elongation (Δl) (mm)	Stress N/mm^2	Strain	Crack length (mm)
5	0.9	19.60	0.003	17
10	1.4	39.21	0.004667	17
15	1.9	58.82	0.006333	17
20	2.3	78.43	0.007667	17
25	2.7	98.03	0.009	17
30	3.1	117.64	0.010333	17
35	3.5	137.25	0.011667	17
40	3.9	156.86	0.013	17
45	4.3	176.47	0.014333	17
50	4.7	196.07	0.015667	17
55	5.1	215.68	0.017	17
60	5.4	235.29	0.018	17
65	6.32	254.90	0.021067	17
71	6.72	294.11	0.0224	17.1
65	8.42	313.72	0.028067	19

As per IS 2062
The Ultimate strength of the steel plate =410 N/mm^2
Ultimate load carrying capacity (P_u) = (σ × t × W) = 4106×8×6 = 167280 N= 167.28 KN
Yield stress = 250 N/mm^2

From the Experiment,
The Ultimate residual strength of the cracked steel plate=331.862N/mm^2<410 N/mm^2
Ultimate load carrying capacity = 135400 N = 135.4 KN < 167.28KN.

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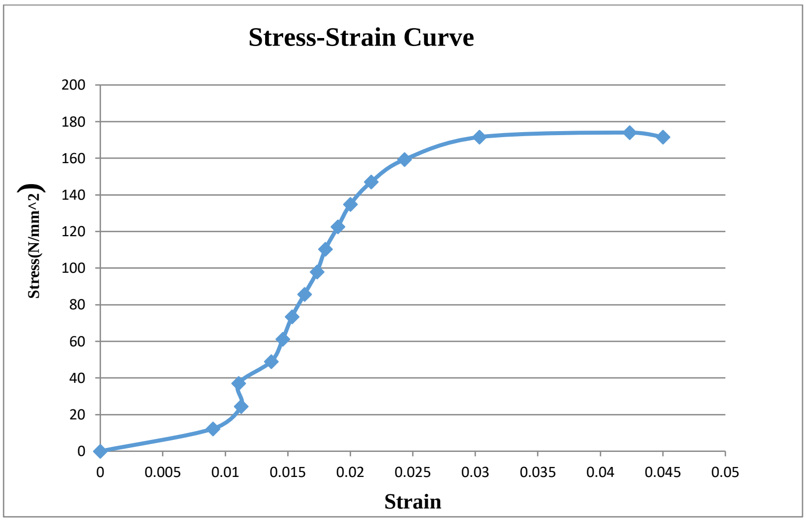

Fig 6 Stress-Strain Curve

III. NUMERICAL ANALYSIS

Numerical analysis of the edge cracked steel plate with initial crack of 17mm was done using FEA based software ANSYS. From this analysis the aim is to determine residual stresses at the vicinity of the crack tip for the ultimate tensile load of 71kN obtained from the experimental analysis and also to determine the residual stresses for different decrement loading and compare it against yield stress.

Finite element model Development

The finite element model was developed using Iso-parametric curved plane elements (PLANE183) in ANSYS. The material used for the present case study is Steel. The Modulus of Elasticity and Poisson's ratio are to be defined for the analysis. The Modulus of Elasticity for steel is 210000MPa. The Poisson's ratio for steel is 0.3. The boundary condition and load is applied as per the experimental analysis.

The crack tip is characterized by a set of special elements known as the singular elements. A total of 64 singularity elements are generated around each crack tip, thus maintaining the singularity element angle of 5.6250 as shown in figure. The crack propagates at this tip.

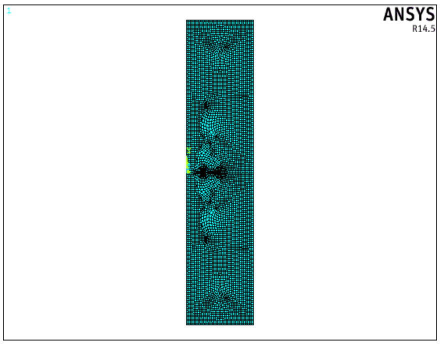

Fig 7 Finite element model of structural steel plate with cracking damage

Solution using Ansys

After the pre processing with assigned loads and boundary condition it is solved for the results. The following are the results obtained.

The deformed model is shown in the figure below

Residual stresses for cracked plate element under different load condition

Ultimate load of 71KN

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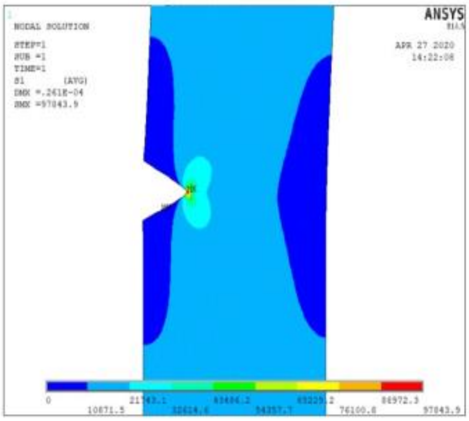

Fig 8: 1stPrincipal Stress

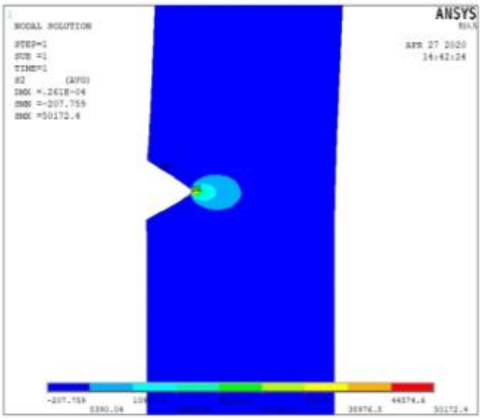

Fig 9: 2ndPrincipal Stress

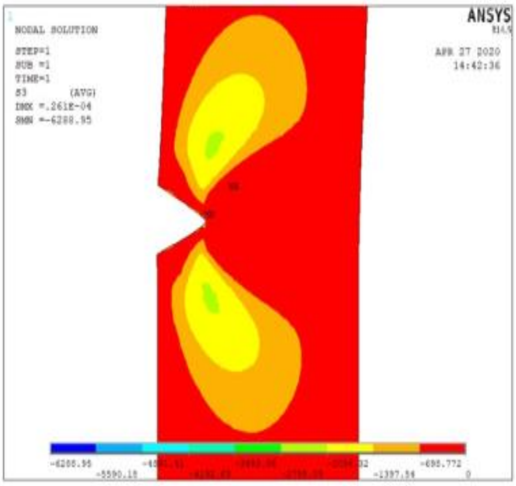

Fig 10: 3rdPrincipal Stress

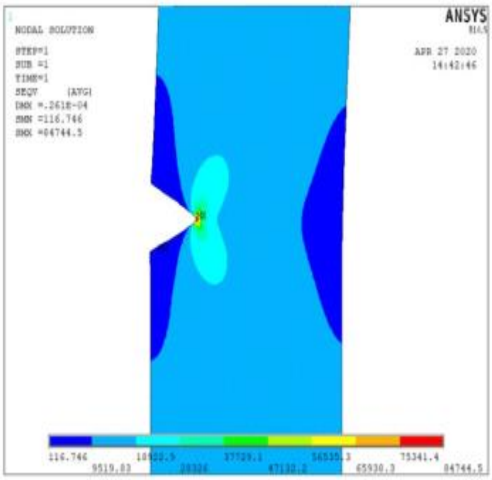

Fig 11:Von Misesstres

Table 2 Comparison of Von-Mises stress at Different Regions for ultimate load of 71kN

Region	Ultimate Stress (N/mm^2)		VonMises Stress (N/mm^2)		Yield Stress (N/mm^2)
Red	410	<	84744.5	>	250
Orange	410	<	75341.4	>	250
Yellow	410	<	65938.3	>	250
Green 1	410	<	56535.3	>	250
Green 2	410	<	47132.2	>	250
Green 3	410	<	37729.1	>	250
Blue1	410	<	28326	>	250
Blue 2	410	<	18922.9	>	250
Blue 3	410	<	9519.83	>	250

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IV. THEORITICAL ANALYSIS

Residual fatigue life analysis of cracked steel plate element.
In this chapter Theoretical analysis of Residual fatigue life for a edge-cracked structural steel plate element
(IS 2062 Grade E250 | Fe 410WA Structural steel plate)
Under zero -tension cyclic loading (constant amplitude) as shown in fig 12 was carried out. The dimension of the cracked plate is same as the cracked plate used for experimental analysis with initial crack length of 17mm (a_o=17mm), Length(L) =300mm, width (W)= 68mm and thickness(t)=6mm.

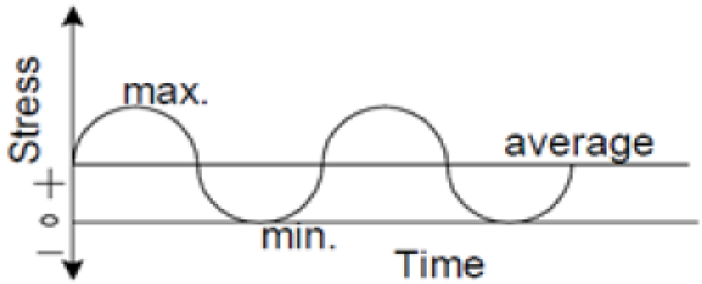

Fig 12 Zero tension cyclic loading

Procedure for calculation of residual fatigue life

1. Determine critical crack length corresponding to $K_{max} = K_{Ic}$

$$a_c = \frac{1}{\pi}\left(\frac{KIC}{F*\sigma}\right)$$

2. Determine stress intensity factor (SIF) for the current geometry.

$$\Delta K = F * \Delta\sigma * \sqrt{\pi . a}$$

where, $\alpha = ai/W$

$$F=f(\alpha) = 1.12 - 0.23\alpha = 10.55\alpha - 21.72\alpha + 30.39\alpha$$

3. Using the Paris law, the applied stress intensity factor range can be related to the crack propagation rate as follows:

$$\frac{da}{dN} = C. \Delta Km$$

where, Cis the constant of the Paris law =6.87×10−12 for Mild steel. *m* is the exponent of the Paris law =3 for Mild steel.

4. Integrate Paris' law

$$N = \int_{a0}^{ac} \frac{da}{C.\Delta Km}$$

5. Solve for the number of stress cycles corresponding to failure to calculate residual fatigue life.

$$N = \frac{ac-ao}{C.\Delta Km}$$

The same procedure was carried out for different load conditions and different crack lengths and compared by plotting.

Residual fatigue life of the element under different Zero-Tension cyclic load conditions

For , initial crack length of 17 mm , α = ai/W = 0.25

F=f(α)= 1.12-0.23(0.25)+10.55(0.25)2-21.72(0.25)3+30.39(0.25)4 = 1.501211.

For Steel, Fatigue limit is 30% of ultimate strength

From experiment, residual ultimate strength = 71 KN

Plate subjected to cyclic load of 71KN

$$Stress = \frac{load}{area} = \frac{71\times103}{68\times6} = 174.01\ N/mm2$$

Stress range (Δσ) = σmax - σmin = 174.01 - 0 = 174.01N/mm2.

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Step 1: **Critical crack length**

$$a_c = \frac{1}{\pi}\left(\frac{KIC}{F*\sigma}\right) = \frac{1}{\pi}\left(\frac{1075.36}{1.501211*174.01}\right)^2$$

ac = 16.94mm>$widthofplate$

Step 2: **SIF for critical crack length ac= 68mm.**

$$\Delta K = F * \Delta\sigma * \sqrt{\pi.a}$$

$$\Delta K = 1.501211*174.01*\sqrt{\pi.68} = 3818 \text{ Mpa}\sqrt{mm}$$

Step 3: **Crack growth rate**

$$\frac{da}{dN} = C.\Delta Km \qquad \frac{da}{dN} = 6.87 \times 10{-}12 \times (3818)^3$$

$$\frac{da}{dN} = 0.3823\frac{mm}{\text{cycle}}$$

Step 4: **Residual fatigue life**

$$N = \frac{ac - ao}{C.\Delta Km}$$

$$N = \frac{64-17}{6.87 \times 10{-}12 \times (1075.36)3} \qquad N = 835\ cycle$$

V. CONCLUSION

From experiment and analytical models, the residual ultimate strength of the cracked steel plate is 174.01N/mm2 and 147.05 N/mm2 which is less than the ultimate strength of the un-cracked steel plate i.e., 410N/mm2.The percentage error between the analytical and experimental model is 5.6% and 1.8%.From Paris Law the number of cycles for 71KN is 835.From the numerical analysis using ANSYS software, it can be seen that the stresses at the crack tip are high compared to ultimate and yield stress .The stresses at the crack tip increases with increase in loads. The stresses at crack tip exceeds ultimate stress, the crack initiates and propagates. High stresses increases the crack propagation rate which results in catastrophic failure of the element.

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