PREDICTION OF DUCTILE FRACTURE IN NOTCHED STEEL PLATES USING SMCS METHOD

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ABSTRACT

In this paper the goal is to study where, when and how the cracks in the steel connection plate between beam and column initiate and how far would the crack continue before it fails and how to detect crack initiation and prevent the same by utilizing piezoelectric sensors. In this analysis piezoelectric is placed in line of crack propagation for sensing strain and changing it to voltage. A thin plate with edge notch which is an ideal model of typical beam to column connection is assumed. The uniaxial uniform load is applied on it. With the aid of ABAQUS software, the plate is analyzed in both elastic and plastic stages. The strain-stress curve with kinematic hardening part is considered and modeled with multi-linear method. The micromechanical based model Stress Modified Critical Strain (SMCS) model are utilized for prediction of ductile crack initiation. Based on the combined effects of the triaxiality and plastic strain, the model can capture the void growth phenomenon in steel material. The triaxiality and plastic strain for several load levels are obtained. The SMCS criterion corresponding to each load is calculated and the crack status is determined.

INTRODUCTION

THE STRESS MODIFIED CRITICAL STRAIN MODEL (SMCS)

The Stress Modified Critical Strain [SMCS] criterion provides alternative approaches for modeling Ductile Crack initiation by relating the fundamental process of void initiation, growth and coalesces to macroscopic stresses and strains, obtained using detailed finite-element models. The material-specific parameters of the SMCS model are calibrated for mild A 572 Grade 50 Steel SMCS is dependent on the evolution of two key quantities: the equivalent plastic strain ε_p, and the stress triaxiality. The stress triaxiality, $T=\frac{\sigma_m}{\sigma_e}$, is a ratio of the mean or hydrostatic stress σ_m, and the effective or von Mises stress σ_e. Building on Rice and Tracey's model for void growth (Rice and Tracey, 1969), Hancock and Mackenzie (1976) suggest that ductile crack initiation depends upon the interaction of triaxiality and the equivalent plastic strain. Specifically, this implies that a larger triaxiality will hasten the onset of fracture. Consequently, fracture is predicted when the equivalent plastic strain exceeds a critical value, which can be expressed as a decreasing function of the triaxiality,i.e.

$$\varepsilon_p \geq \varepsilon_{p_{critical}} = \text{function}\left(\frac{\sigma_m}{\sigma_e}\right) = \text{function (T)} \quad (1)$$

$$\varepsilon_{p_{critical}} = \alpha \exp\left(-1.5\frac{\sigma_m}{\sigma_e}\right) \quad (2)$$

$$\text{SMCS} = \varepsilon_p - \alpha \exp\left(-1.5\frac{\sigma_m}{\sigma_e}\right) > 0 \qquad \text{for } r > l^* \quad (3)$$

The α value from the notch size which was tested in this paper is very similar suggesting that it can be assumed to be a material property indicative of toughness. ($\alpha = 1.18$).

As described earlier, the fracture criterion must be satisfied over a minimum volume of material (the characteristic length ($l^* = .01\text{inch} \sim .2\text{mm}$)to trigger ductile crack initiation (Kanvinde and Deierlein, 2006) (Fig. 1).

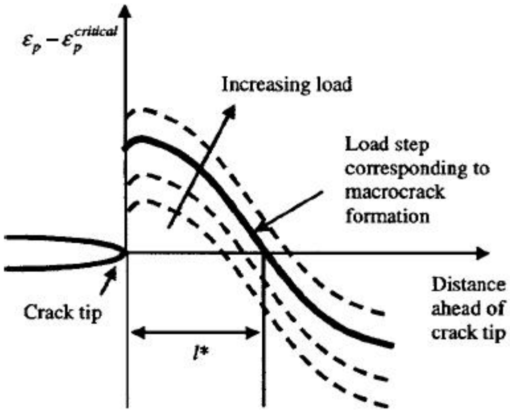

Figure 1. Schematic of the characteristic length l* in predicting ductile crack initiation

PIEZOELECTRIC PATCH

Zirconatetitanate (PZT) is one of the most effective types of piezoelectric material; however, once damage occurs in a structure, it may propagate along a certain direction and eventually lead to failure or collapse of the structure. Therefore, effective monitoring of damage propagation is an important aspect in this paper which presents a study on monitoring damage propagation in steel plates using the SMCS technique. Experiments are carried out to study the damage propagation by existing a notch in the plate. PZT admittance signatures are recorded for each damage state and compared with the signature of the pristine state. In addition, this crack propagation is analyzed qualitatively and quantitatively using a statistical method with ABAQUS software. Figure 2 shows denotation of one horizontal crack with piezoelectric transmitter and receiver in a steel plate.

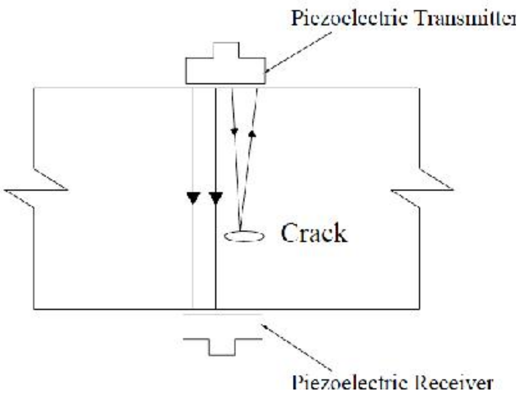

Figure 2. Denotation of one horizontal crack with piezoelectric sender and receiver

The main constants characterizing the piezoeffect are:

$$S1 = S11T_1 + d13\ E3 \quad (4)$$

With assuming short connection for piezoelectric (if one side of piezoelectric has been connected to earth) equation (5) was obtained.

$$S_1 = \frac{d_{13}}{d_{13}{}^2 - s_{11}\varepsilon_{33}} E_3 \quad (5)$$

Voltage was obtained from the equation (6):

$$V = E_3 . t_p \quad (6)$$

So curve of strain versus voltage was drawn with equation (7). This curve was illustrated that this equation is linear. And this curve is linear curve constant slope. For obtaining this constant table (1) was used, as they were come below.

$$S_1 = \frac{d_{13}}{d_{13}{}^2 - s_{11}\varepsilon_{33}} \frac{V}{t_p} \quad (7)$$

S_1: Total Strain (Y), E3: Electric Field, d13: 23 e-12, s_{11}: 365 e-12 , ε_{33}: 110 e-12

Table 1.The properties of PVDF

Symbol	Parameter	PVDF	Units
t	Thickness	52	μm(micron, 10^{-6} m)
d_{31}	Piezoelectric strain constant	23	10^{-12} m/V
d_{33}	Piezoelectric strain constant	-33	10^{-12} m/V
s_{11}	Mechanical compliance	365	pm^2/N
s_{13}	Mechanical compliance	-209	pm^2/N
k_{31}	Electromechanical coupling factor	0.12	—
k_{33}	Electromechanical coupling factor	0.14	—
C	Electric capacitance	380 for 28 mm	pF/cm^2 at 1 KHz
E	Young's modulus	2–4	GPa
ρ	Pyroelectric coefficient	30	10^{-6} C/m^2/°K
ε	Permittivity	106–113	10^{-12} F/m
$\varepsilon/\varepsilon_0$	Relative permittivity	12–13	—
ρ_m	Mass density	1780	Kg/m
ρ_e	Volume resistivity	>1013	Ω/m

Piezoelectric was placed in the direction that crack will propagate, height of the piezoelectric was placed in Y (1) direction where total strain in plate were obtained inABAQUS and curve of strain versus voltage was illustrated in figure 4. Figure 3 illustrated the place that piezoelectric was located in plate and the directions which piezoelectric placed by them.

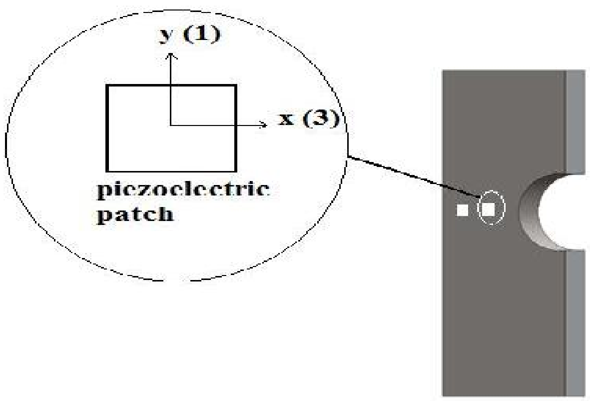

Figure 3. location of piezoelectric patch in the plate

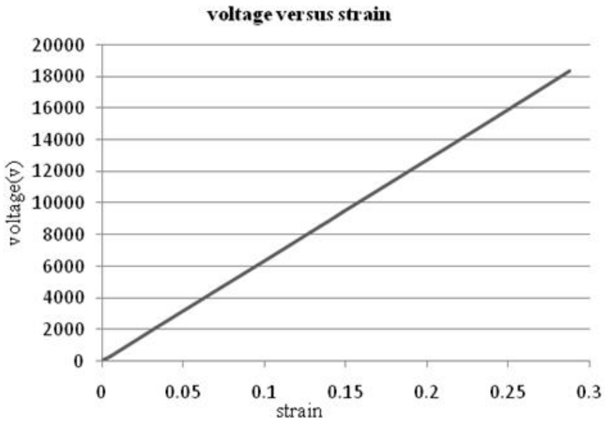

Figure 4.Voltage versus strain

NUMERICAL MODELING AND VERIFICATION

FINITE-ELEMENT SIMULATION

Finite element simulations are used to analyze the steel connection plate data. Elastic–plastic finite element analyses with incremental plasticity are conducted using ABAQUS6.11. The finite element solutions employ nonlinear, large deformation material constitutive models and geometric nonlinearity of the system. The plasticity behavior is modeled using the von Misses yield criterion and isotropic strain hardening. The steel kind used for this test is A572 Grade 50 steel is a piecewise linear fit to the measured true stress-strain curve obtained from the smooth tensile tests (Kanvinde and Deierlein 2004). Taking advantage of symmetry, two-dimensional ax symmetric finite element analyses are performed for the specimens. The element sizes in the notch area are about 0.1 mm, which is sufficient to capture the SMCS gradients in the notch. True Stress_Strain Curve for Steel AP50 with kinematic hardening part is considered and modeled with multi-linear method. Kanvinde and Deierlein (2004) illustrated this curve in (ksi) unit instead of (Mpa) for stress quantity. This curve illustrated as figure 5.

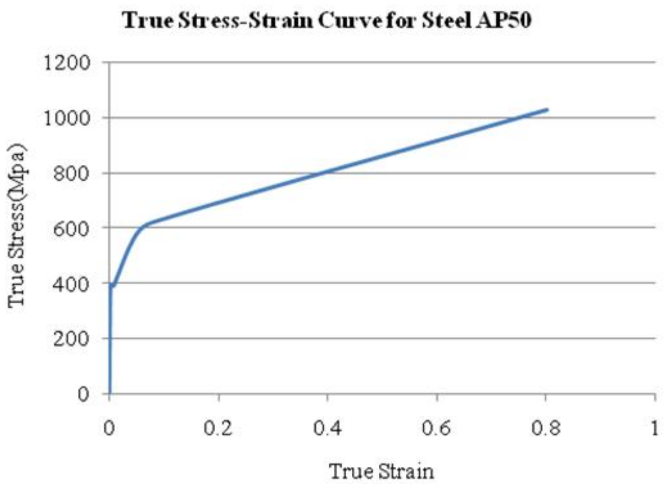

Figure 5.True Stress- Strain Curve for Steel AP50

PROBLEM STATEMENT& RESULTS

PROBLEM STATEMENT

Owing to the symmetry of the problem, only one quarter of the plate with dimensions 20×100×6 mm including an 8mm-diameter notch at its center is modeled utilizing the ABAQUS software. The material-dependentα, and l^* parameters of the SMCS criterion are 1.18 and 0.20 mm, respectively. Figure 6 shows the plate dimensions.

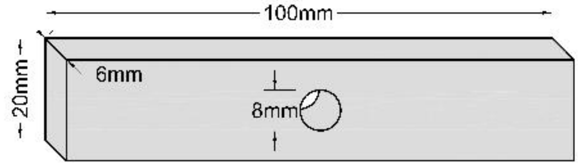

Figure 6. Plate Geometry

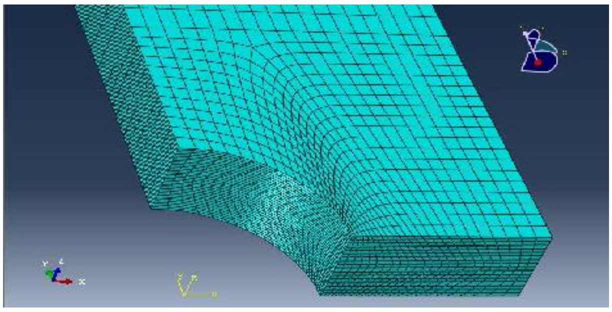

Figure 7. Quarter of the plate (assumed plate for our model)

Table 2. Properties of steel plate which was tasted

Kind of steel	A572 Grade 50(AP50)
α	1.18
l^*	0.2mm
Dimensions of Plate	15*50mm^2
Radius of notch	6.2mm
Δ_f	1.2446mm

RESULTS

Curves of equivalent plastic strain and triaxiality stress along distance from the notch tip for increasing load were obtained. This distance is 4.2 millimeter. Since $l^*$for this type of steel is 0.2 mm and initiation of crack goes around this quantity and crack initiated ahead of notch, so 0.2 millimeter from ahead of notch was assumed for drawing SMCS curve to finding when crack will propagate over criteria equation (3).

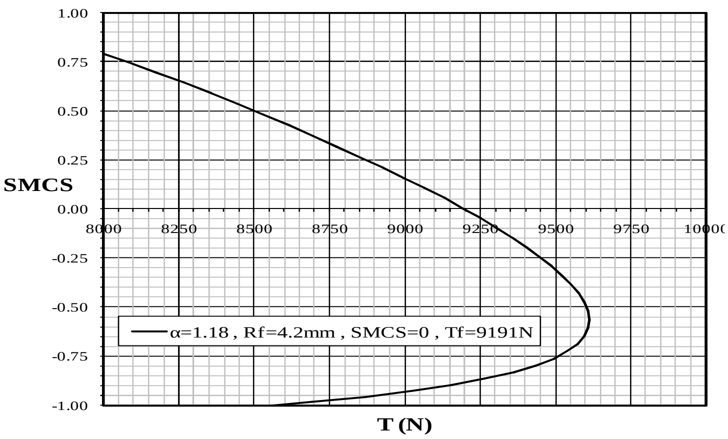

Figure 8. SMCS versus T

Figure 8 shows SMCS versus T in r=4.2 mm but in different times. It has been seen when load increases, the SMCS criterion goes from positive value to 0 values and after that goes to negative value. Softening is happening in this curve cause of displacement loading. It means as you can see in this figure the value of SMCS criterion goes lessened after it enters in negative value area. If Force loading applied on plate, the happening of softening in section would be disappeared and this event happens in reality and correct one. SMCS criterion is equal to zero when the applied load is 919 N.

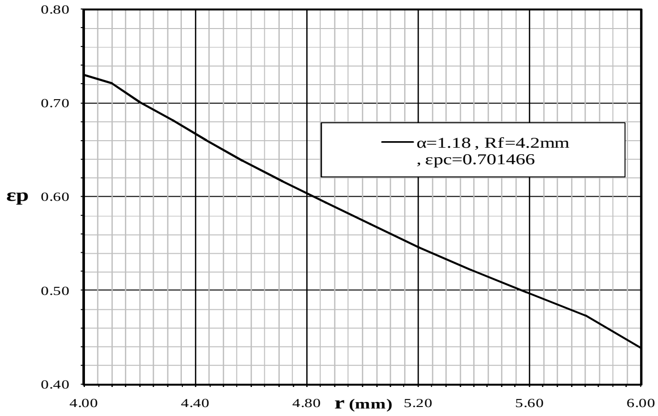

Figure 9. Plastic strain along distance from a notch tip

Figure 9 shows plastic strain along the distance from the notch tip (quadrant of circle hole) to end edge of plate. This curve shows plastic strain has decreasing behavior along this distance.

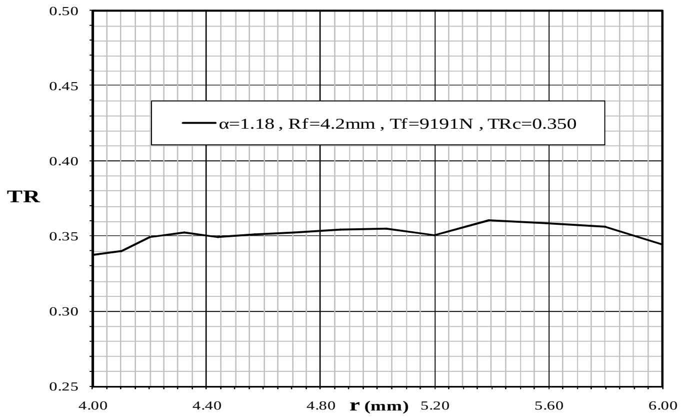

Figure 10. Traxiality stress along distance from a notch tip

Figure 10 shows Triaxiality stress along the distance from the notch tip (quadrant of circle hole) to end edge of the plate. It shows that Triaxiality stress is relatively constant along (r) .

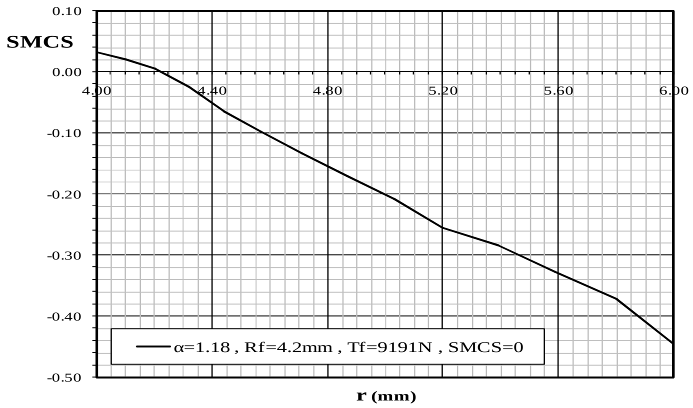

Figure 11. SMCS along distance from a notch tip

Figure 11 shows SMCS criterion along the distance from the notch tip (quadrant of circle hole) to end edge of plate. It describes SMCS at failure time but in different (r). SMCS criterion is positive during 0.1 millimeters ahead of notch (from r=4mm to r=4.1mm).because this distance (r) is smaller than l^* so plate didnot have any failure. SMCS is positive during 0.2 millimeter when load is 919 N on the plate .this distance is equal to l^*.it means crack initiated and goes to propagate. SMCS criterion is positive during r=4.2mm ahead of notch to the end edge of the plate. Because this distance is bigger than l^*, so plate starts to fail.

SMCS CONDITIONS FOR CRACK INITIATION

In this section plastic analysis of plate have been done, assume 5 loads, which were gained from applied displacements on the plate, and then obtain plastic strain, triaxiality stress and SMCS criterion for each loading point. When SMCS is negative (SMCS< 0), its mean there isnot any crack initiation in plate but when is equal to zero (SMCS$= 0$), its mean that crack will initiate .and when is bigger than zero (SMCS> 0) crack initiate and propagate.When load=9250 N, then SMCS=0 at notch tip but it does not mean that failure starts. Failure starts when distance from notch tip is equal tol^*.

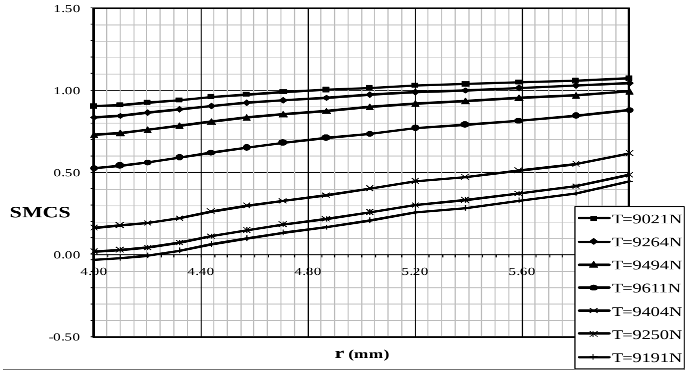

Figure 12. SMCS along distance from the notch tip for seven load levels

Conclusion

A thin plate with edge notch was assumed. The displacement loading was applied on it. With the aid of ABAQUS software, the plate is analyzed in both elastic and plastic stages. The strain-stress curve with kinematic hardening part is considered and modeled with multi-linear method. Required parameters for SMCS model were obtained that was described insection 1.Cause of the void growth to be the defining step for ductile Crack initiation, models that aim to predict ductile fracture need to capture the combined effects of the triaxiality and plastic strain. Figures that related to SMCS analysis were shown insection 3 for each load separately and in comparison with each other in one chart in continue.Until the crack initiates and the response fields of piezoelectric detector are recorded during loading process. The recorded data are analyzed and the relation between the applied load and crack properties is depicted for different locations of piezoelectric sensor. With the aid of the obtained results, the inverse analysis of a cracked medium can be performed.

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