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THE BEHAVIOR OF SOME STEELS AT FATIGUE UNDER MULTIAXIAL STRESSES

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Abstract: This study deals with simulations for cyclic stress/strain evolutions and redistributions, and evaluations of fatigue parameters suitable for estimating fatigue lives under proportional or non-proportional multiaxial loadings. The local cyclic elastic-plastic stress-strain responses were analysed using finite element program for both smooth and notched specimens made of three materials: a medium carbon steel in the normalized condition, an alloy steel quenched and tempered and a stainless steel, respectively.

1. INTRODUCTION

Fatigue failure of mechanical components is a process of cyclic stress/strain evolutions and redistributions in the critical stressed volume. It may be imagined that due to stress concentration (notches, material defects or surface roughness) the local material yields firstly to redistribute the loading to the surrounding material, then follows with cyclic plastic deformation and finally crack initiates and the resistance is lost. Therefore, the simulations for cyclic stress/strain evolutions and redistributions are critical for predicting fatigue failure of mechanical components.

In this study, both numerical and experimental methods are applied to study the cyclic stress/strain evolutions under biaxial loading conditions. The local cyclic elastic-plastic stress-strain responses are analysed using Ansys finite element program for the notched specimens made of three materials: medium carbon steel in the normalized condition, an alloy steel quenched and tempered and a stainless steel, respectively.

Elastic-plastic FEM is used to predict the stabilized cyclic stress/strain state. The predicted stress relaxations are then compared with experimental observations. For experimental verifications, a series of tests of biaxial low-cycle fatigue composed of tension/compression with static or cyclic torsion were carried out on a biaxial servo-hydraulic testing machine (8800 Instron). Different loading paths were carried out, including proportional and non-proportional loading paths in order to verify the effects of these loading paths in the additional cyclic hardening [2, 3].

The FEM simulations allow better understanding on the evolutions of the local cyclic stress-strain. Based on the local cyclic elastic-plastic stress-strain responses, the energy-based multiaxial fatigue damage parameters are applied to correlating the experimentally obtained lives. A non-proportional parameter, based on the Minimum Circumscribed Ellipse to the shear stress path is proposed, which when applied to the ASME methodology for multiaxial loading improves correlation between the predicted and the experimental results.

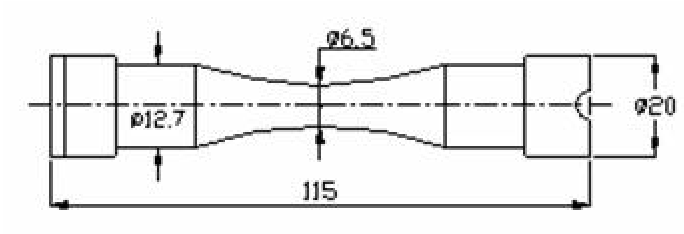
2. EXPERIMENTS

In order to compare the sensitivity of materials to non-proportional loadings, three materials are studied in this research. The materials studied are: CK45 steel normalized, high strength steel 42CrMo4 and the stainless steel AISI 303. Some of the monotonic and cyclic mechanical properties of studied materials are shown in table 1.

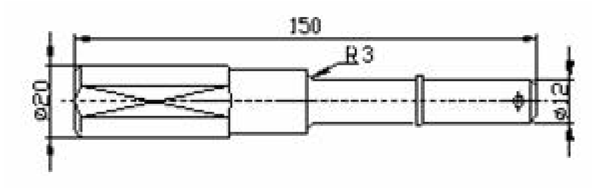
Table 1: Mechanical properties of studied materials

Mechanical properties	CK45	42CrMo4	AISI 303
Tensile strength s_R (MPa)	660	1100	625
Yield $Rp_{0.2}$, (MPa)	410	980	330
Young`s modulus E (GPa)	206	206	178
Elongation A (%)	23	16	58

The geometries and dimensions of the specimens are shown in Fig. 1. To compare the cyclic stress/strain evolutions and redistributions in the critical stressed volume, both smooth specimen, Fig. 1(a), and notched specimen, Fig. 1(b), were used in experiments. Table 2 shows the biaxial loading paths applied in experiments carried out using a biaxial servo-hydraulic machine 8800 Instron (fig.2).



(a)



(b)

Fig.1: Specimens: (a) smooth, (b) notched

Axial stress s and shear stress t were calculated from load and torque measured by a load cell. Equivalent stress s_{eq} and equivalent plastic strain e^p_{eq} were defined by von Mises equivalence for tension/torsion loading as:

$$s_{eq} = \sqrt{s^2 + 3t^2} \qquad (1)$$

$$e^p_{eq} = \sqrt{e^{p^2} + \frac{g^{p^2}}{3}} \qquad (2)$$

Fig.2: Biaxial testing machine 8800 Instron

Equivalent total strain s_{eq} was defined by analogy [6] as:

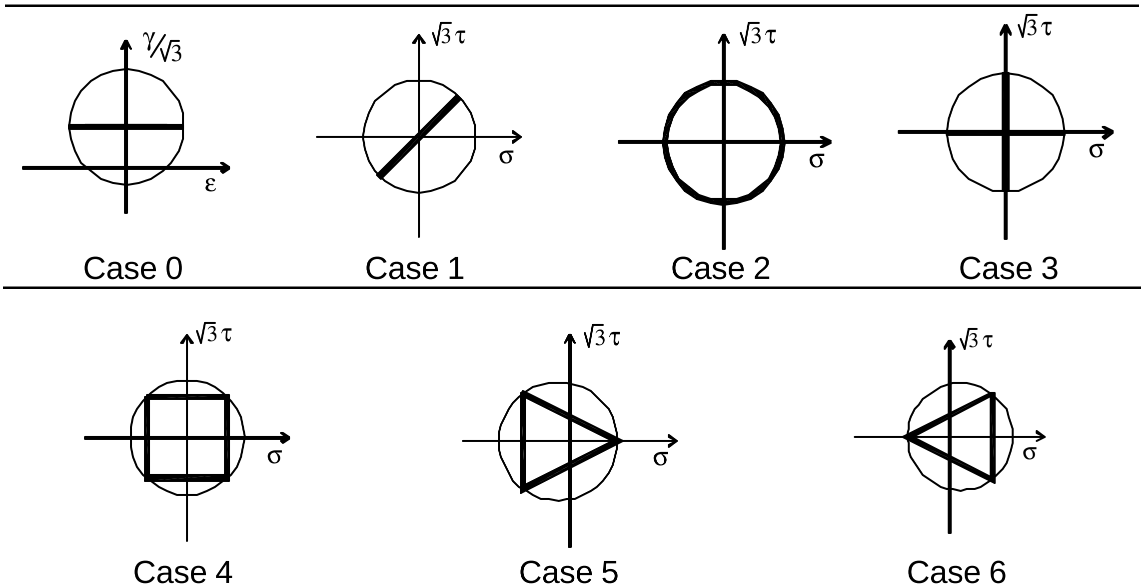
$$e_{eq} = \sqrt{e^2 + \frac{g^2}{3}} \tag{3}$$

The factor of non-proportionality of the loading paths can be characterized by the MCE (Minimum Circumscribed Ellipse) approach [5]:

$$F_{NP} = \frac{R_b}{R_a} \tag{4}$$

Where R_b and R_a are the minor and major radius of the Minimum Circumscribed Ellipse involving the loading path, as will be explained at the section of the MCE approach.

Table 2: Biaxial fatigue loading paths



3. NUMERICAL SIMULATIONS

The local cyclic elastic-plastic stress/strain responses are evaluated using Ansys finite element code. Isoparametric solid element C3D20R with 20 nodes and reduced integration points was used. Kinematic hardening model with von Mises yield criterion and associative flow rule was used for elastic-plastic FEA.

Fig. 3 shows the FE models for smooth specimen (a) and notched specimen (b), full models were used due to the combined axial/torsion loadings.

a) *b)*

Fig.3 FE meshes for smooth specimen (a) and notched specimen (b)

The FEM analyses showed that the cyclic stress-strain responses are different under different loading paths. The images of stress/strain distributions at different instant of the loading cycle are helpful to study the evolutions and redistributions of the cyclic stress/strain fields. Fig. 4 shows some cutting-view images of the notched specimen and Fig. 5 shows some cutting-view images of the smooth specimen under non-proportional loading.

Fig. 4: Some cutting-view images of the notched specimen

Fig. 5: Some cutting-view images of the smooth specimen

Fig. 6 shows the evolution histories of some local cyclic stress-strain responses, where it shows that the stabilized cycle differs from the initial cycle and the stress-strain ranges of the stabilized cycle are appropriate for life predictions.

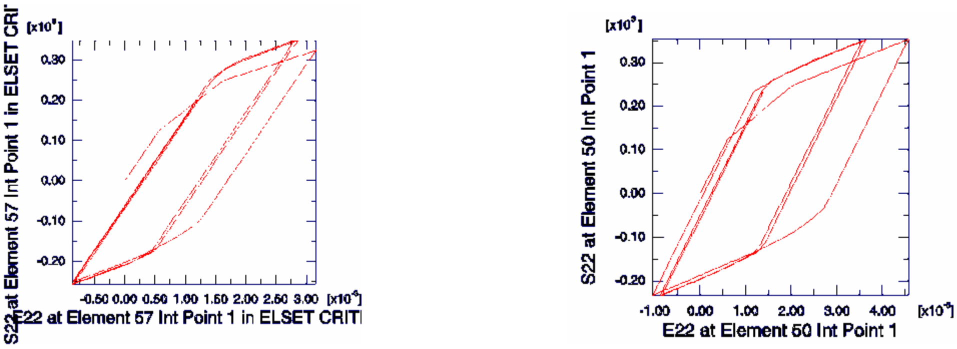
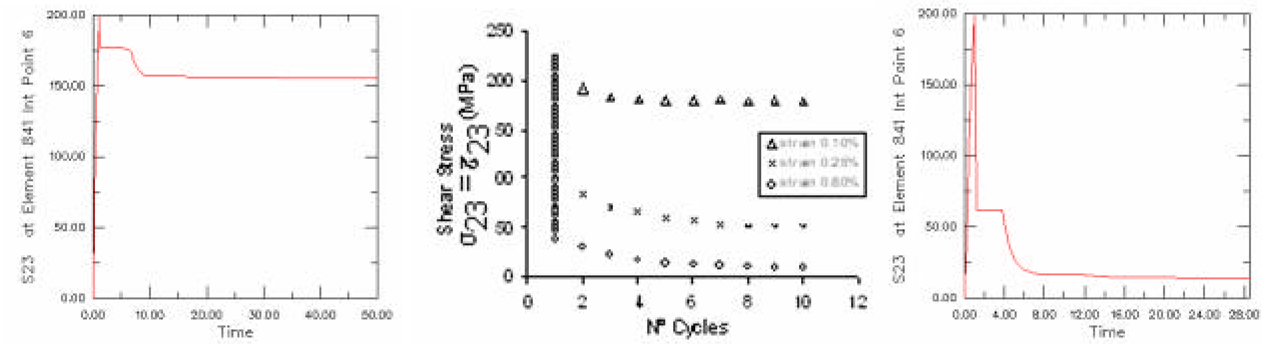


Fig. 6: Evolution histories of some local cyclic stress-strain responses

Fig. 7 shows the comparison between the shear stress relaxation during the first ten cycles for different levels of strain loading with loading path case 0, initial condition (see table 2). It is very interesting to note the similar way of the behaviour obtained.

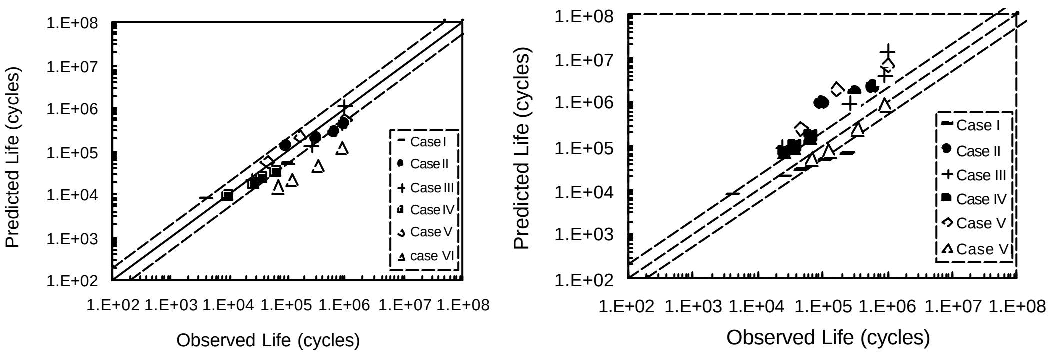


Strain=0.10% *Strain=0.60%*

Fig. 7: Comparison between FEA simulation and experimental evolution of the shear stress (CK45 steel)

5. RESULTS AND DISCUSSIONS

Fig. 8 shows the comparisons of the experimental fatigue life against the predicted results without and with modification for non-proportional effects, respectively. It can be seen that the predictions with the modified equivalent strain range of the ASME code (Fig. 8(b)) are more accurate when compared to the experimental results.



a) *b)*

Fig. 8: Comparison between andurance experimental fatigue life of 42CrMo4 with predicted results by: (a) equivalent strain range of the ASME code, (b) modified equivalent strain range of the ASME code.

6. CONCLUSIONS

The local cyclic stress-strain states are influenced by the multiaxial loading paths, due to the interactions between the normal stress and shear stress during cyclic plastic deformation. The numerical simulations are very helpful to understand the evolutions and redistributions of the cyclic stress/strain field under multiaxial loading conditions.

The simple and easy of use approaches, such as the equivalent strain range of ASME code approach based on the distortion energy (1), can provide good predictions of fatigue life by taking into account some modifications for non-proportional effects.

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