CRACK NUCLEATION MODELING IN NOTCHED SPECIMEN SUBJECTED TO HIGH FATIGUE LOADING

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Abstract

The stress and strain distributions at the notch root of a small specimen for in-situ testing are analyzed by three-dimensional finite element method (FEM). From the FEM analysis results, it is found that the stress concentration factor K_t of a notched round bar and K_e of a single edge notched specimen decreases when applied stress is higher than elastic limit. Therefore the local stress concentration at the notch root under high stress level was analyzed before further investigation, such as fatigue behavior. Based on the FEM results, a sub-model for fatigue crack initiation at the notch root of the small specimen is described.

1 Introduction

Fatigue cracks preferentially nucleated in high stress concentration sites of structures, e.g. holes or notch roots. Thus a suitable configuration for investigation of fatigue crack nucleation behavior is a notched specimen. For example, a single edge notched specimen (SEN) is often selected for small crack nucleation and propagation study[1]. It should be noted that the stress concentration factor K_t is not a constant when applied stress is approaching or higher than elastic limit of material[2]. Under these conditions, the small crack behavior might be quite different from that in elastic state. But unfortunately the stress concentration factor for single edge notch is not always available in literature. Therefore the finite element method (FEM) is often used for stress concentration factor calculation[3-5]. This paper investigates the stress and strain concentrations of a small specimen with a single shallow notch in its upper side for in-situ fatigue testing when it subjected to high tensile fatigue loading. To get more accurate results, the three dimensional FEM was applied to the stress and strain field analysis. Based on the analysis results, a sub-modelto simulate crack nucleation at the notch root under high fatigue loading is proposed.

2 Stress Concentration Analysis

2.1 Material Properties

The studied material is a martensitic steel undergoing high level uniaxial fatigue stresses. The mechanical properties of the studied material are given in Table 1. The true stress-plastic strain (σ-ε_p) curve of the studied material obtained by tensile test is shown in Fig. 1.

Table 1 Mechanical properties of studied material

Elastic limit σ_y (MPa)	Young's module E (MPa)	Poisson's ratio	Tensile strength σ_b (MPa)
800	210000	0.3	1660

2.2 Finite Element Analysis of Notched Round Bar

In order to get suitable FEM simulation, a notched round bar model is analyzed.

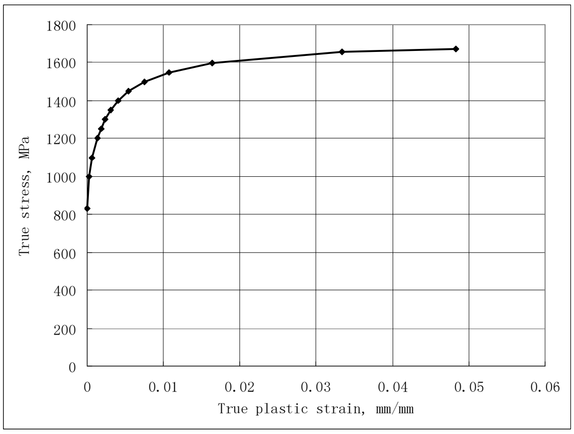

Fig. 1 True stress-plastic strain curve

The configuration and geometry dimensions of the notched round bar is shown in Fig. 2, where we noted that D is the round bar diameter, d is the notch diameter, r is the notch root radius and H is the half length of the round bar. In the FEM analysis, the aspect ratios of some key dimensions, i.e. d/D, r/D, H/D, are given. Only tensile stresses are applied on the two ends of this notched bar.

An axial symmetric analysis is chosen for the notched round bar, where a three dimensional model is suitable for FEM stress-strain analysis. Therefore three dimensional elements are used, and the meshing in the notch root is much finer than other parts of the bar, as shown in Fig. 3. From the elastic-plastic analysis (σ-ε_p curve in Fig.1 was applied), the stress distribution in the notched bar can be obtained. The stress component σ_{22}, which is along the axial direction, is given in Fig. 3. The maximum values of stress component $\sigma_{22\max}$ at the notch root varying with the applied stresses σ are obtained. The relationship of σ against the ratio of $\sigma_{22\max}/\sigma$, which is named as the stress concentration factor K_t, is shown in Fig. 4. It is found that K_t is 1.6 and is constant when applied stress level is lower than the material elastic limit σ_y (i.e. $\sigma \leqslant 800$ MPa) , but it decreases along with σ increase. When σ is approaching to the tensile strength σ_b, for example 1500 MPa, the K_t value is almost equal to 1.0.

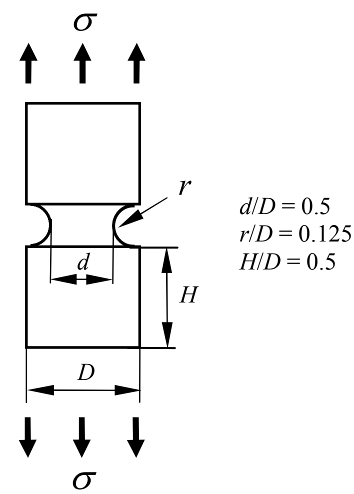

Fig. 2 The configuration of notched round bar

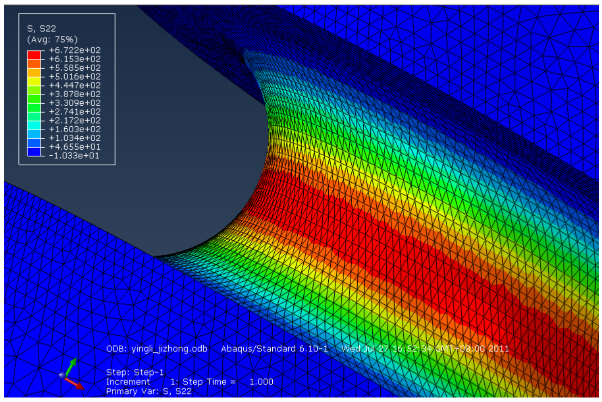

Fig. 3 Meshing and stress distribution (along axis) at notch root of the round bar

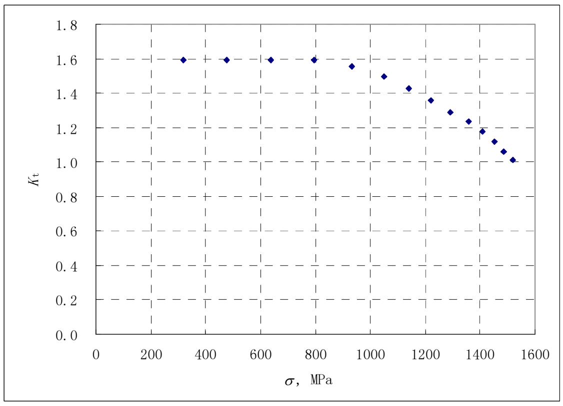

Fig. 4 Stress concentration K_t of notched bar from FEM analysis various with applied stress σ

2.3 FEM Analysis of Small Specimen for In-Situ Testing

The configuration of a small specimen for in-situ testing is shown in Fig. 5. The gauge section of the small specimen is rectangular with a shallow notch on the upper side. For the small specimen, the same elastic-plastic FEM model as for the notched round bar is used. In order to get better results, the meshing at notch root is much finer than other parts of the small specimen. Under different uniaxial tensile forces acting on the specimen ends, the stress and strain distributions at the notch root can be computed. The axial stress and strain components σ_{11}(S11) and ε_{11}(E11) are shown in Fig. 6 and Fig. 7, respectively, where the applied stress is 1337 MPa.

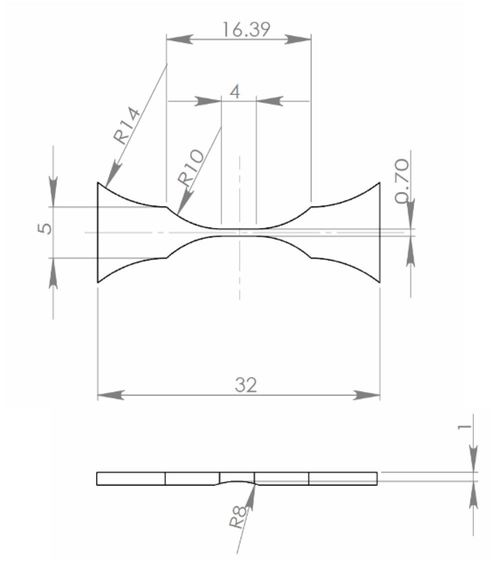

Fig. 5 Configuration of a small specimen

The relationship of σ against the ratio of $\sigma_{11\max}/\sigma$, which is named as K_σ, is shown in Fig. 8. It is found that K_σ is 1.5 and is constant when applied stress level is lower than elastic limit σ_y (i.e. $\sigma \leqslant$ 800 MPa) , but it decreases along with σ increases. When σ is approaching to the tensile strength σ_b, the K_σ value is almost equal to 1.0. This is quite similar to the results in Fig. 5 for the notched round bar. The relationship of σ against the ratio of $\varepsilon_{11\max}/\varepsilon$, which is named as K_e, is shown also in Fig. 8, where $\varepsilon = \sigma/E$. The $\varepsilon_{11\max}$ is the strain component in the area marked by a black curve in Fig. 8. Because of the high strain gradient, the average value of lowest and highest strain component in the area is calculated. The average is employed to represent the strain $\varepsilon_{11\max}$. It is obvious that the tendency of σ-K_e is totally different with σ-K_σ. K_e is increasing along with σ increases. The results of $K_t = (K_\sigma \cdot K_e)^{1/2}$ is 1.5, which is a constant along with different σ. This is coincidence with the results in paper [2] and the consequence of Neuber's theory.

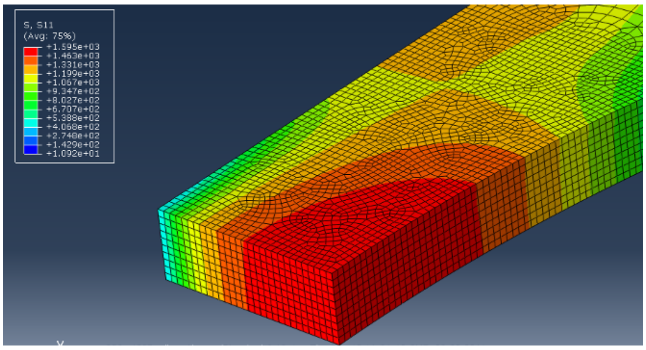

Fig. 6 Stress distribution (along specimen axis) of the notch root of small specimen

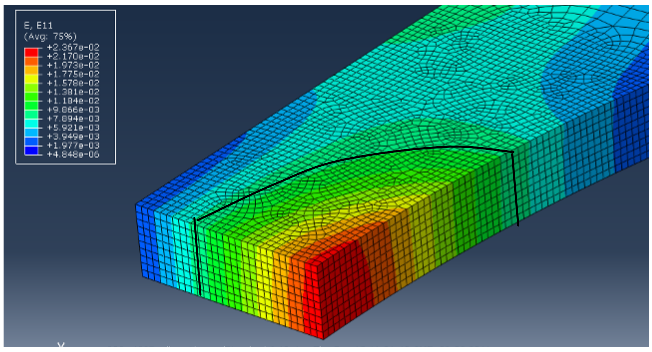

Fig. 7 Strain distribution (along specimen axis) of notch root of small specimen

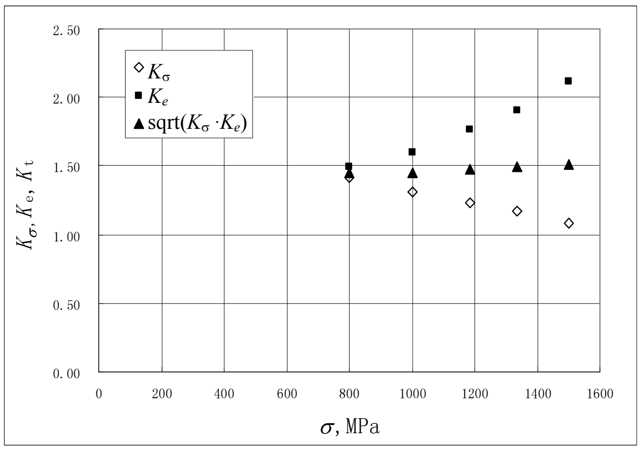

Fig. 8 Stress concentration K_t of small specimen from FEM analysis various with applied stress σ

3 Stress Distribution in Sub-Model

During in-situ fatigue tests, it is found that the cracks were initiated in the notch root of the small specimen, as expected. To simulate the crack initiation process more close to the reality, a sub-model was created. The sub-model is extracted from the central part of the notch root, as shown in Fig. 9. The boundary conditions were computed from the FEM analysis of the small specimen, as mentioned in Section 2.3.

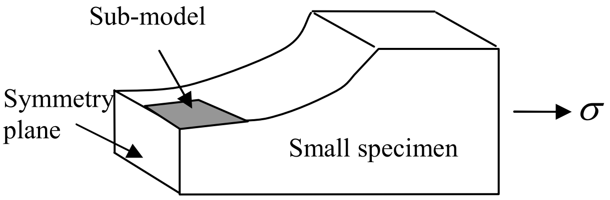

Fig. 9 Schematic illustration of sub-model

The sub-model is an aggregation of 400 grains orientated randomly. The material stress-strain response of each grain is supposed to be anisotropic for the elastic portion and is isotropic for the plastic portion, which is shown in Fig. 1. From FEM analysis, it is found that the local stress field is inhomogeneous caused by the orientation misfit between grains. As an example, the distribution of shear stress component S12 in local coordinate *xyz* is shown in Fig. 10, where the applied loading is 1337 MPa.

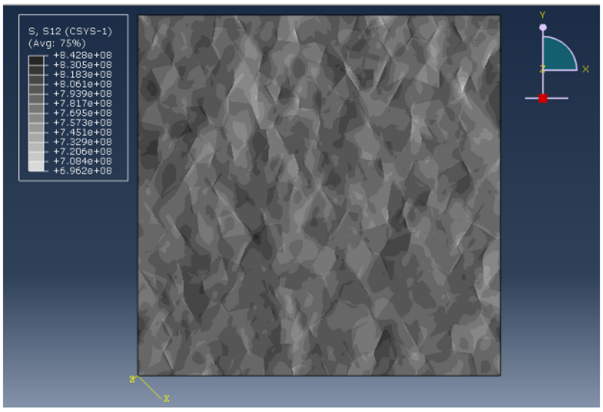

Fig. 10 Shear stress distribution in sub-model

Cracks are assumed nucleating at high stress areas. One sub-model under 1000 MPa stress and with 4 nucleated cracks is shown in Fig. 11.

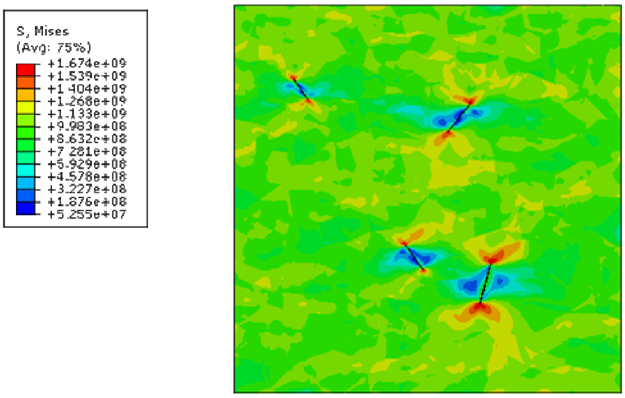

Fig. 11 Stress distribution in simulated aggregation with 4 nucleated cracks

4 Conclusions

This paper presents the FEM results of stress concentration for notched round bar and single edge notched small specimen under high applied stress loading. The results show that the stress concentration factor decreases along with increasing applied stress σ when σ is higher than elastic limit. This is important for the research of fatigue crack behavior since notched specimens are often used in experimental testing. This paper also gives an example to simulate crack nucleation in small specimen. But the further study is still going.

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