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Notch effect on multiaxial low cycle fatigue

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ABSTRACT

This paper discusses the notch effect on multiaxial low cycle fatigue. Neuber's rule was firstly introduced to estimate local strains at the notch root in proportional tension and torsion loading. The Neuber's rule was applied to estimate crack initiation and propagation lives in tension–torsion low cycle fatigue. The rule conservatively estimated the crack initiation life in tension low cycle fatigue and appropriately in torsion low cycle fatigue. A simple method for estimating the local strain at the notch root was proposed in tension and torsion loading. The notch effect in nonproportional low cycle fatigue was discussed in two materials. The local strain at the notch root obtained by finite element analysis underestimated the crack initiation lives for the additional hardening material but that obtained by the Neuber's rule overestimated for the non-additional hardening material.

1. Introduction

Structures and components always have geometrical discontinuities like bolt holes, corners, non-uniform cross section, etc., that are understood as notches and numerous studies were performed to evaluate local stresses and strains around the notch [1–11]. Elastic stress concentration factors have been widely used to express the local stress and strain at the notch root. Neuber derived the stress concentration factors of many geometrical shapes and loading modes [12].

Fatigue lives are significantly reduced by notches because of higher stresses at the notched part. High cycle fatigue lives of notched components have been well studied in relation with the peak stress and stress gradient at the notch root using the fatigue strength reduction factor and the fatigue notch sensitivity factor. All components except the vicinity at the notched part deform elastically and the elastic theory is basically applicable to the high cycle fatigue strength of notched components.

In low cycle fatigue, on the other hand, most parts deform plastically and elastic theory is no longer applicable to estimate the stress and strain concentration. The Neuber's rule [13] has been widely used to estimate the stress and strain concentration at the notch root because of its simplicity but the rule overestimates the strain concentration in uniaxial tension. The reason of the overestimation results from that the rule was derived in pure shear so that the rule does not accurately estimate the stress and strain concentration in uniaxial tension [6].

The notch effect on multiaxial low cycle fatigue is especially important to estimate low cycle fatigue lives of notched components subjected to multiaxial loading but a limited number of studies have been reported [14–18]. Especially, notch study in low cycle fatigue under nonproportional loading is sparse [19–21]. This paper overviews the notch study in low cycle fatigue in proportional and nonproportional loading. This paper does not intend to make a literature survey of broad notch studies but intend to present the experimental notch studies performed under multiaxial loading. Readers are able to refer the systematic literature survey in the Refs. [1–3].

2. Notch theory

Finite element analysis is applicable to estimate local strains at notch parts (Design by Analysis) but the method has a disadvantage of high cost charged to the price of products. Designers prefer simpler a method like the Neuber's rule in practice to suppress the designing cost low (Design by Rule), so that a simple method of estimating local stresses and strains at notched part is needed.

Typical method of estimating the local stress and strain is the Neuber's rule [13] expressed by the following equation.

$$K_\sigma K_\varepsilon = K_t^2 \quad (1)$$

In the equation, K_σ and K_ε are the inelastic stress and strain concentration factors at the notch root and K_t is the elastic stress concentration factor. The Neuber's rule was derived in pure shear, so there is only a shear stress and strain components for simplicity of analysis of which stress and strain state is the same as torsion loading [22]. In tension loading, however, three stress and strain

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components exist around the notch root as shown in Fig. 1 which was obtained by elastic–plastic finite element analysis for a round bar with circumferential notch in tension. The shape of the notched bar was 12 mm in diameter with 60° circumferential V-groove of 2 mm in depth and 1.0 mm root radius. The three tensile stress components exist around the notch root but only two stress components at the notch root, plane stress state, because the notch root is a free surface. The axial strain component has a similar distribution as the axial stress component but the other two strain components are in a compressive direction. All the three strain components have the peak values at the notch root.

Fig. 2 compares the stress and strain concentration factors obtained by FEM analysis with those calculated in Eq. (1) for the same notched bar as shown in Fig. 1. The stress and strain concentration factors take constant values in the nominal stress range less than 50 MPa and there is no large difference in the stress concentration factor between the analysis and the Neuber's rule. The strain concentration factor in the FEM analysis is slightly smaller than that obtained by the Neuber's rule because of the constraint of deformation around the notch root. In the nominal stresses between 50 MPa and 100 MPa, the strain concentration factor in the FEM analysis increases but it turns to decrease at the nominal stresses larger than 100 MPa. The decrease of the strain concentration factor results from the plastic deformation in the whole notch root section. The strain concentration factor obtained from the Neuber's rule, on the other hand, increases monotonically with the nominal stress. The stress concentration factor in the FEM analysis agrees with that by the Neuber's rule, with a fair difference at large nominal stresses giving larger values than that by the Neuber's rule.

The results indicate that the Neuber's rule accurately estimates the inelastic strain concentration for the pure shear deformation but overestimates the strain concentration for the tension deformation.

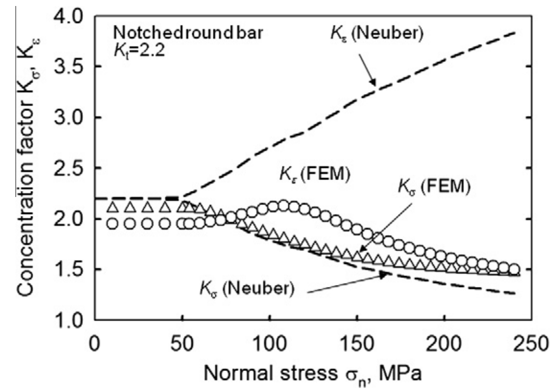

Fig. 2. Comparison of the stress and strain concentration factors between Neuber's rule and finite element analysis for a round notched bar with $K_t = 2.2$.

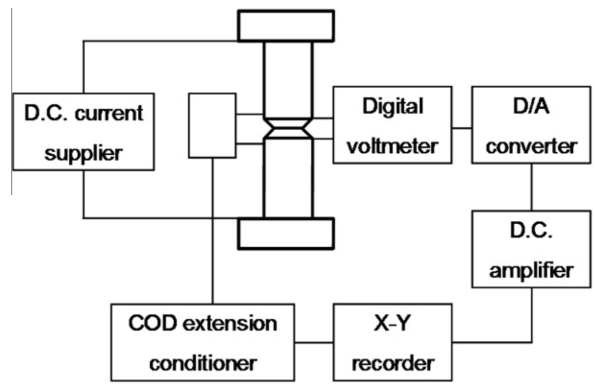

Fig. 3. Block diagram for the d.c. potential method.

3. Crack initiation detection

An accurate detection of crack initiation is a key technique when discussing the notch effect in low cycle fatigue. Visual observation is applicable for detecting the cycles to crack initiation in notched plate specimens, but is not applicable in notched round bar specimens. The authors [23] have developed a d.c. potential method for the accurate detection of the cycles to crack initiation. The schematic of the d.c. potential method is illustrated in Fig. 3 [23]. A constant direct current was sent to the specimen and the potential at the notched part was measured. A typical variation of the potential with cycles is shown in Fig. 4 [23]. The potential shows almost a constant value until the crack initiation indicated by the arrow in the figure and increased as the crack extension. The crack depth at the crack initiation detected by the method was around 0.1 mm into the specimen that was confirmed experimentally in the direct crack depth measurement.

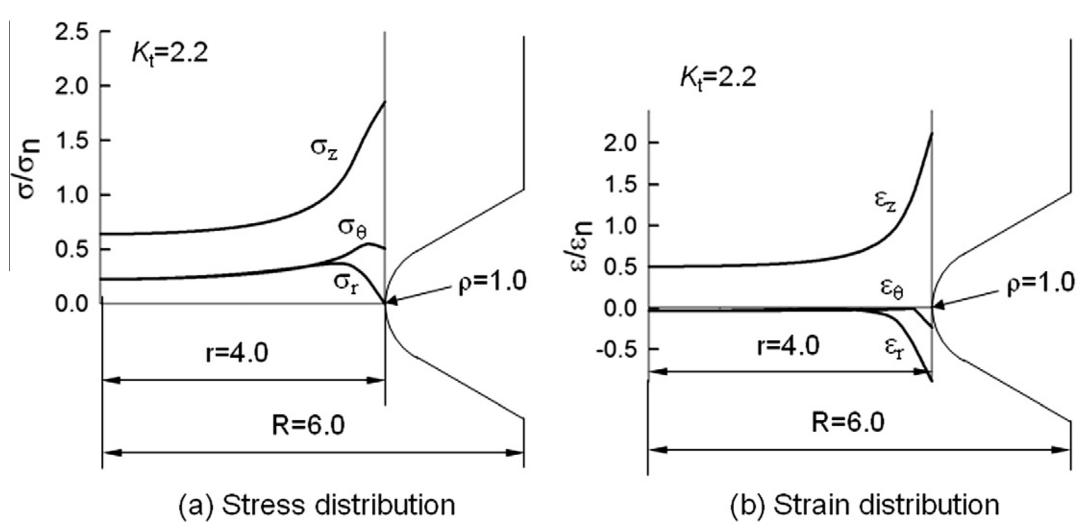

Fig. 1. Stress and strain distributions in an axially loaded circumferentially notched bar with $K_t = 2.2$.