A GENERALIZED LOCAL STRAIN APPROACH TO CONSIDERING THICKNESS EFFECT ON FATIGUE PERFORMANCE

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Abstract

Firstly stress concentration factors for single-edge-notch tension (SENT) specimens under different thickness-induced stress states are expressed in an explicit form by fitting the three-dimensional finite element analysis results. Then a generalized local strain approach is developed to incorporate this 'thickness effect'. Also machining technique influence factor is introduced to consider the specimen machining quality. Validation against calculation and fatigue test result for SENT specimen shows the calculation obtained by the proposed approach is in better agreement with experimental result than traditional prediction. Also the generalized local strain approach can be further applied to fatigue life prediction of other type specimens under different thickness-induced stress states.

1 Introduction

Prediction of the structural fatigue life is one of the main purposes in fatigue research community. The fatigue crack initiation life occupies a great portion of the total fatigue life[1]. In general, local strain approach is adopted to predict fatigue crack initiation life, in which calculation of local stress and strain is the prerequisite and plays an important role. Up to now, many experimental, numerical and empirical methods have been developed to improve the accuracy of local stress and strain solutions. Since experimental approach and numerical analyses are costly and time-consuming, many approximation formulae are developed by recourse to Neuber's Rule[2], Equivalent Strain Energy Density (ESED) Rule[3], etc. They improved the accuracy of local stress and strain solutions by taking into account the effects of stress redistribution induced by plasticity. However, few investigations have been attempted to address the effects of different thickness-induced stress states, especially in fatigue behaviour. The previously unsatisfactory results on fatigue life prediction may be attributed to the unreasonably simple assumption of plane stress or plane strain state when calculating the stress-strain distribution.

This paper extends the previous method to incorporate thickness effect. Then a generalized local strain approach is tentatively put forward to predict the fatigue life. Fatigue life prediction of different thickness single-edge-notch tension (SENT) specimens using the proposed approach is compared with experimental results to validate the proposed approach.

2 Finite Element Analysis for Three-dimensional Stress Concentration

Here SENT specimen is employed to analyze the three-dimensional stress concentration. SENT specimen is visualized in Fig.1 in which specimen thickness B is a varying parameter.

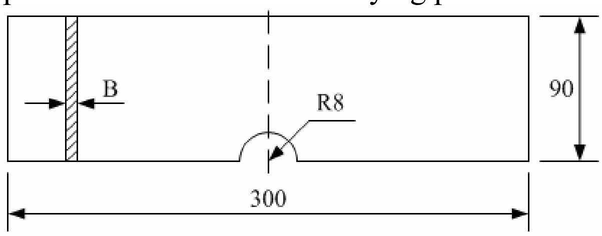


Fig.1 SENT Specimen

2.1 Geometry

According to geometry symmetry, only one quarter of specimen is applied to finite element analysis, as shown in Fig.2.

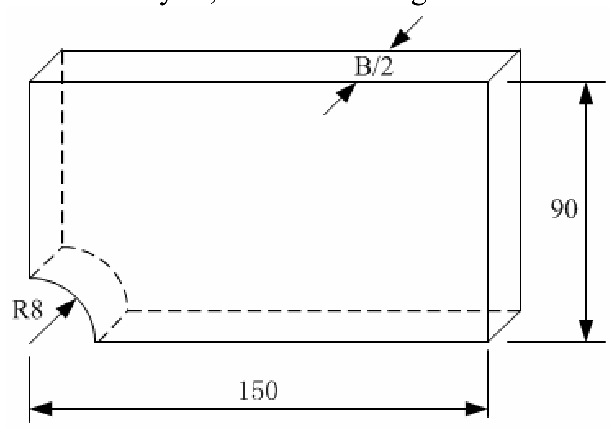


Fig.2 Geometry for Finite Element Analysis

2.2 Finite Element Meshes

Detailed three-dimensional finite element computations were performed using commercial Finite Element Method code MSC/PATRAN. Hexahedron element is used and the typical FE meshes are shown in Fig.3.

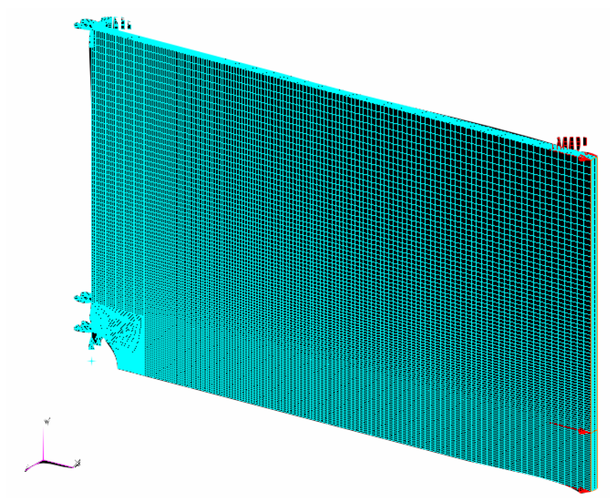


Fig.3 Typical Finite Element Meshes

2.3 Boundary Conditions

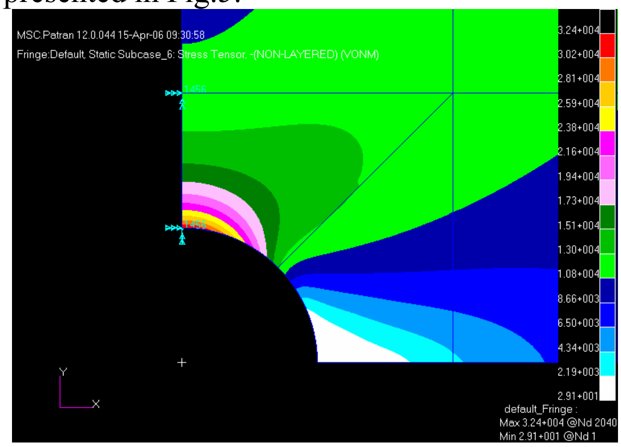
Symmetry boundary conditions are applied on the left side plane, and loading is applied to the right side plane, as shown in Fig.3.

2.4 Material Properties

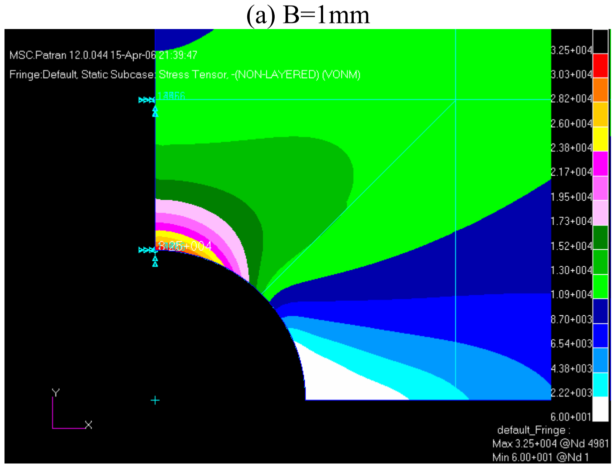
Here aluminum alloy LY12CZ is used in calculations. For LY12-CZ, Poisson's ratio υ=0.33 [4], and elastic modulus E=68GPa [5].

2.5 Finite Element Results

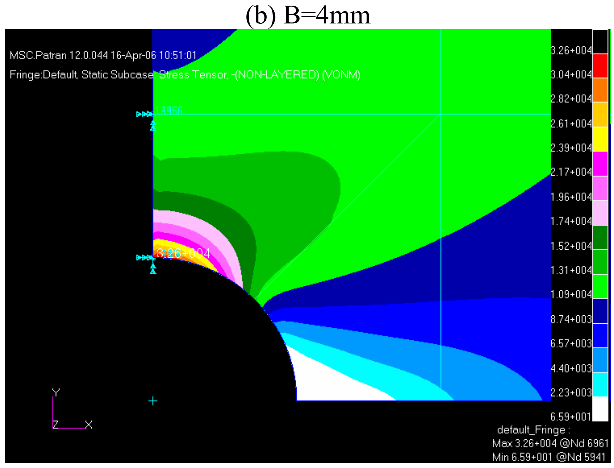
Stress contours for different thickness SENT specimens are presented in Fig.4. The corresponding stress concentration factors are presented in Fig.5.



(a) B=1mm

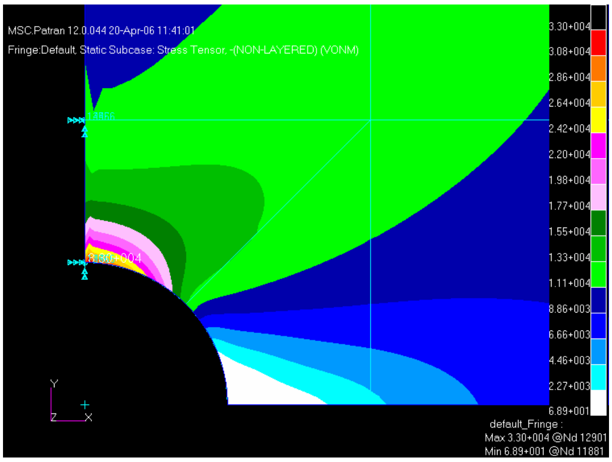


(b) B=4mm



(c) B=6mm

Fig.4 Stress Contours at the Neighbourhood of Notch



(d) B=12mm

Fig.4 Stress Contours at the Neighbourhood of Notch

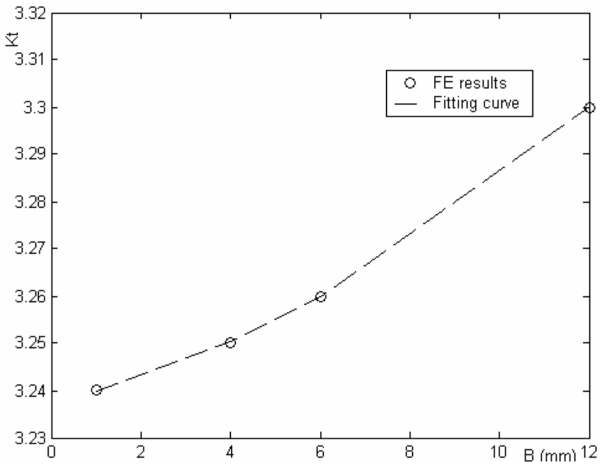


Fig.5 Stress Concentration Factors v.s. Specimen Thickness

The relation between these stress concentration factors and specimen thickness can be fitted by

$$K_t = 0.0002\mathrm{B}^2 + 0.0022\mathrm{B} + 3.2374\,. \qquad (1)$$

Here the length unit for specimen thickness is milimeter and $1 \le B \le 12$.

3 Generalized Local Strain Approach

The nominal stress history in components is converted into local stress-strain history at dangerous position of components by virtue of cyclic stress-strain properties of materials in traditional local strain approach, and then fatigue life is predicted. For local stress and strain, they can be obtained by the modified Neuber's formula[6]

$$\Delta\sigma \cdot \Delta\varepsilon = \frac{K_f^2 \cdot \Delta S^2}{E} = C\,, \qquad (2)$$

where ΔS, $\Delta\sigma$ and $\Delta\varepsilon$ are the nominal stress amplitude, local stress amplitude and local strain amplitude respectively, C is Neuber constant, K_f is fatigue notch factor, and E is the Young's modulus of the material. The fatigue notch factor can be derived from stress concentration factor, K_t, by the following equation

$$K_f = 1 + \frac{K_t - 1}{1 + A/R}\,, \qquad (3)$$

where A is materials' constant, and R is the notch root-radius.

Since stress concentration factor is related to the thickness-induced stress state, the above equation can be rewritten as

$$K_f(B) = 1 + \frac{K_t(B) - 1}{1 + A/R}\,, \qquad (4)$$

where $K_t(B)$ can be obtained by fitting finite element results.

Based on $K_t(B)$, a generalized local strain approach is presented here to consider thickness effect on fatigue life prediction. When calculating the fatigue life of SENT specimens under different thickness-induced stress states, it contains the following steps[6]:

a. Calculation of Neuber constant

Stress concentration factors for different thickness SENT specimens can be obtained by three-dimensional finite element analyses and the fitting equation, Eq.1. Then fatigue notch factor is calculated by Eq.4. As $K_f(B)$ is based on net cross section area, the nominal stress should be in accordance with $K_f(B)$ and can be expressed in the form

$$\Delta S_n = \Delta S \frac{W}{W - R}\,. \qquad (5)$$

Therefore Neuber constant can be obtained by

$$C = \frac{K_f^2(B) \cdot \Delta S_n^2}{E}. \tag{6}$$

b. Determination of $\Delta\sigma$ - $\Delta\varepsilon$ curve

The $\Delta\sigma$ - $\Delta\varepsilon$ curve can be obtained by recourse to cyclic stress-strain curve and usable factor.

c. Determination of P($\Delta\sigma$, $\Delta\varepsilon$)

This step is to determine the intersection point of hyperbola $\Delta\sigma \cdot \Delta\varepsilon = C$ and $\Delta\sigma$ - $\Delta\varepsilon$ curve $\Delta\sigma = f(\Delta\varepsilon)$, as shown in Fig.6.

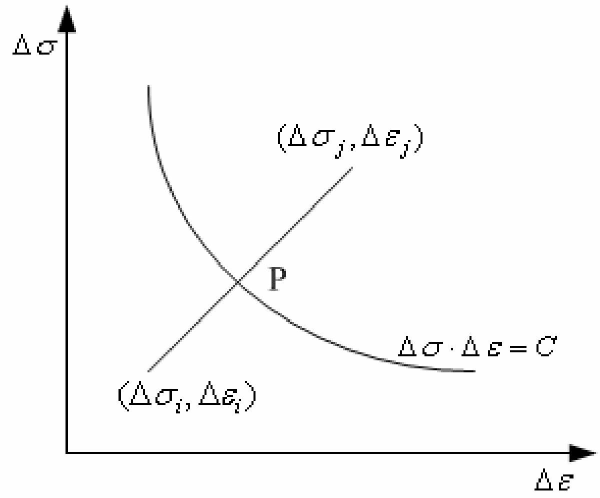


Fig.6 Intersection Point

By solving the following equations

$$\begin{cases} \dfrac{\Delta\sigma - \Delta\sigma_i}{\Delta\sigma_j - \Delta\sigma_i} = \dfrac{\Delta\varepsilon - \Delta\varepsilon_i}{\Delta\varepsilon_j - \Delta\varepsilon_i}, \\ \Delta\sigma \cdot \Delta\varepsilon = C \end{cases} \tag{7}$$

we can get

$$\Delta\varepsilon = \frac{-q + \sqrt{q^2 + 4pC}}{2p}, \tag{8}$$

$$\Delta\sigma = C / \Delta\varepsilon. \tag{9}$$

Here p and q are determined by

$$p = \frac{\Delta\sigma_j - \Delta\sigma_i}{\Delta\varepsilon_j - \Delta\varepsilon_i}, \tag{10}$$

$$q = \Delta\sigma_i - p \cdot \Delta\varepsilon_i. \tag{11}$$

d. Calculation of local stress and strain values

The local stress and strain values corresponding to the peak or valley of nominal stress history can be obtained by

$$\sigma = \sigma_0 + sign(\Delta S) \cdot \Delta\sigma, \tag{12}$$

$$\varepsilon = \varepsilon_0 + sign(\Delta S) \cdot \Delta\varepsilon. \tag{13}$$

e. Prediction of fatigue life

The fatigue life and corresponding fatigue damage for a kind of loading level can be obtained by means of Manson-Coffin equation, and then fatigue life under variable amplitude loading can be predicted by using Miner's fatigue damage cumulative rule. To consider the influence of mean stress, the modified Manson-Coffin equation given by Morrow is used here,

$$\varepsilon_a = \frac{\sigma_f' - \sigma_m}{E}(2N)^b + \varepsilon_f'(2N)^c. \tag{14}$$

Therefore fatigue life can be obtained by using iterative algorithm

$$\frac{2N}{\alpha} = \left[\frac{\dfrac{\sigma_f' - \sigma_m}{E}\left(\dfrac{2N}{\alpha}\right)^{b-c} + \varepsilon_f'}{\varepsilon_a} \right]^{-\frac{1}{c}}. \tag{15}$$

Here a factor α is introduced to consider influence of machining technique,

$$\alpha = \frac{N_T}{N_{Cl}}. \tag{16}$$

Here N_T is experimental result, and N_{Cl} is calculated fatigue life not considering influence of machining technique. According to its definition, the machining technique influence factor α can be obtained by fatigue experiments of specimens under one certain thickness. That is to say, substituting the experimental result into Eq.15, then α can be obtained.

Therefore the generalized local strain approach can be verified by comparing experimental result with the calculated fatigue life for different thickness SENT specimen machined by the same technique once the corresponding machining technique influence factor is determined.

4 Verification of the Proposed Approach

4.1 Determination of Machining Technique Influence Factor

Aluminum alloy LY12CZ SENT specimen is used in the fatigue experiments, in which contains 3 pieces of SENT specimens and its dimensions are shown in Fig.1 and B=1mm.

The fatigue experiments were carried out in air and at room temperature by MTS810.13 fatigue machine, whose loading error is less than 1 percent and loading frequency f=15Hz. Experiments were carried out under constant amplitude loading, in which stress ratio R=0 and σ_{max}=110MPa. Fatigue crack was observed by microscope, and fatigue initiation life N_T was recorded when the fatigue crack length a=0.5mm[7]. And the average fatigue life is 82514 cycles.

For LY12CZ, $\sigma_f' = 768MPa$, b=-0.0882, $\varepsilon_f' = 0.361$, and c=-0.6393[5]. The cyclic stress-strain curve of LY12CZ is presented in Table 1.

Table 1 Cyclic Stress-strain Curve of LY12CZ[6]

ε_a /%	σ_a /MPa
4.419	616
3.343	613
2.762	601
1.936	572
1.484	539
0.822	500
0.626	467
0.459	336

For B=1mm SENT specimen, $K_t = 3.24$. Following the steps in the generalized local strain approach, solution can be derived for the machining technique influence factor α =0.2173.

4.2 Validation of the Generalized Local Strain Approach

Fatigue tests were carried out for B=6mm SENT specimen under the same conditions. The experimental results were given in Table 2. Also the fatigue life N_{CI}^{T1}, N_{CI}^{T2} and N_{CI}^{G} calculated by the traditional local strain approach without and with considering influence of machining technique, and generalized local strain approach respectively were listed for comparing.

Table 2 Experimental Results v.s. Calculated Life

Specimen	Average tested life $\overline{N}_T$	Calculated life and error		
		N_{CI}^{T1}	N_{CI}^{T2}	N_{CI}^{G}
6-*d*1 6-*d*2 6-*d*3	68867	776450	168722	76379
		1027.5%	145.0%	10.9%

The above table shows that the calculation obtained by the proposed approach is in better agreement with the fatigue result than traditional prediction. Even when introducing the machining technique influence factor, the fatigue life calculated by traditional local strain approach cannot match with the experimental result well because of inadequate consideration of thickness effect.

5 Summary

A generalized local strain approach is presented to calculate thickness influence in fatigue life assessment of structural components. Prediction accuracy is improved by using the proposed approach.

The generalized local strain approach can be further applied to fatigue life prediction of other type specimens under different thickness-induced stress states.

Acknowledgement

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