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A Simple Method to Predict Ultra-Low Cycle Fatigue Failure of Metal Structures

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1. Introduction

The concept of ultra-low cycle fatigue (ULCF) was recently originated with some of sudden failures of existing structures, which were characterized by large scale cyclic yielding due to occasional loadings such as earthquakes, typhoons. Generally, experimental approaches are popular for ULCF failure prediction. As for the authors view, only one theoretical study has been published in year 2007 (Kanvinde et al., 2007) and the observed failure mechanism is based on voids growth. The failure criterion is summarized as,

$$\bar{\varepsilon}_{*}^{p} > \exp(-\lambda\bar{\varepsilon}^{p}).\bar{\varepsilon}_{critical}^{p} \tag{1}$$

The $\bar{\varepsilon}_{*}^{p}$ is significant plastic strain. The λ is material damageability parameter. The $\bar{\varepsilon}^{p}$ is the effective plastic strain. The $\bar{\varepsilon}_{critical}^{p}$ is the critical effective plastic strain at ductile failure and it has been determined by monotonic load test of same structure by considering a scale of model or prototype. Even though these kinds of experimental approaches produce perfect outputs, these consume cost as well as the time too. As a result, found applications of this failure criterion are very less. Therefore, this paper describes a different theoretical approach to assess the real ULCF failure of metal structures.

2. Method to Assess ULCF Failure

The proposed method consists of four major steps.

Step 1: Determination of critical effective plastic strain

According to the monotonic ductile failure criterion (Chi et al., 2006), the critical effective plastic strain ($\bar{\varepsilon}_{critical}^{p}$) is as shown bellow.

$$\bar{\varepsilon}_{critical}^{p} = \alpha \exp\left(-1.5\frac{\sigma_m}{\sigma_e}\right) \tag{2}$$

There, it is important to consider a zone that has higher probability of failure. In finding of this zone, one can select areas where effective stresses are present and such higher effective stress area is called as "critical zone". Having found this area, critical effective plastic strain ($\bar{\varepsilon}_{critical}^{p}$) should be found for each Gauss points of this critical zone.

Step 2: Determination of critical significant plastic strain

Once the critical effective plastic strains due to monotonic loading at each sampling locations in critical zone are determined, the cyclically degraded values of the critical monotonic effective plastic strain (usually called as critical significant plastic strain) at that zone is calculated at the beginning of each tensile cycle for each sampling location using following equation,

$$\bar{\varepsilon}_{*critical}^{p} = \exp(-\lambda\bar{\varepsilon}^{p}).\bar{\varepsilon}_{critical}^{p} \tag{3}$$

For clearness of understanding the behavior, it is better to plot the critical significant plastic strain ($\bar{\varepsilon}_{*critical}^{p}$) versus locations in particular critical zone for considered loading steps. As for an example, when the critical zone becomes a nearly straight-line, plot has to be done critical significant plastic strain ($\bar{\varepsilon}_{*critical}^{p}$) versus distance along the line.

Step 3:Determination of significant plastic strain

The significant plastic strains at the critical zone can be calculated during the FE analysis simultaneously with second step using the following relations. T is triaxiality and n is the loading step number,

$$\text{When } T>0;\ (\bar{\varepsilon}_{t}^{p})_{(n+1)} = (\bar{\varepsilon}_{t}^{p})_{n} + (d\bar{\varepsilon}^{p})_{n} \tag{4}$$

$$\text{When } T<0;\ (\bar{\varepsilon}_{c}^{p})_{(n+1)} = (\bar{\varepsilon}_{c}^{p})_{n} + (d\bar{\varepsilon}^{p})_{n} \tag{5}$$

Subtracting Eq. (4) from Eq. (5) the applied significant plastic strain at sampling location in critical zone is calculated as,

$$(\bar{\varepsilon}_{*}^{p})_{n+1} = (\bar{\varepsilon}_{t}^{p})_{n+1} - (\bar{\varepsilon}_{c}^{p})_{n+1} \tag{6}$$

Step 4: The $(\bar{\varepsilon}_{*}^{p} - \bar{\varepsilon}_{*critical}^{p})$ plot and crack initiation

This $(\bar{\varepsilon}_{*}^{p} - \bar{\varepsilon}_{*critical}^{p})$ is the difference between the applied significant plastic strain ($\bar{\varepsilon}_{*}^{p}$) and the critical significant plastic strain ($\bar{\varepsilon}_{*critical}^{p}$), and it is somewhat similar to the ductile failure criteria. Failure is assumed to have occurred at a point when this quantity is greater than zero. A prediction of ULCF crack initiation is made when this quantity exceeds zero over the characteristic length (l^{*}) along the critical zone.

3. Verification of Proposed Method

The pull plate specimen with bolt- holes (Fig.1) was considered for ULCF life estimation. Initially, ULCF life was estimated using the previous approach. The critical effective plastic strain ($\bar{\varepsilon}_{critical}^{p}$) was estimated from the monotonic load test (Kanvinde et al. 2007). The fractured specimen is shown in Fig. 2. Then the proposed method

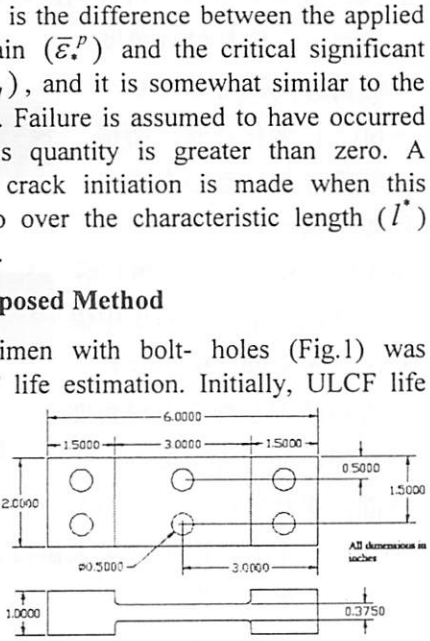

Fig 1. Geometry of pull plate specimen

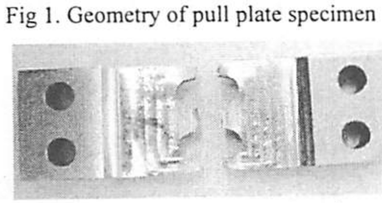

Fig 2. Fractured pull plate specimen

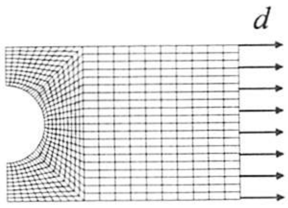

Fig 3. FEM mesh

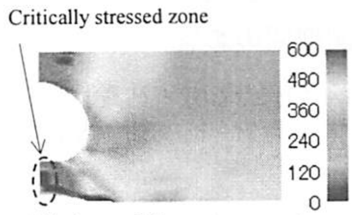

Fig 4. von Mises stress contour

was applied to assess the ULCF life of same specimen. Considering symmetri-city of the geometry, loading and boundary conditions of specimen, the one- fourth of the specimen was subjected to FE analysis. The nine- node shell element was used for FE mesh as shown in Fig 3.

As following the methodology in section 2, considered geometry is Initially subjected to the monotonic load analysis. By observing the stress distribution at ductile failure (stress contour is shown in Fig 4), it is able to conclude that critical zone lies along the transverse centerline of the specimen as shown in Fig 4. The considered material is, A572-grade 50 steel and toughness index (α) was taken as 1.18. Hence the critical effective plastic strain ($\bar{\varepsilon}^{p}_{critical}$) at monotonic loading is calculated for sampling gauss points along the transverse centerline of the specimen.

Then cyclic load FE analysis was conducted for same one-fourth part of the specimen. The applied load versus (displacement) time variation is indicated in Fig 5. The obtained displacement to the ULCF failure is compared with previous method based results as shown in Table 1 and hence, it reveals that the proposed method also produces reasonable accurate estimation to ULCF failure as previous method.

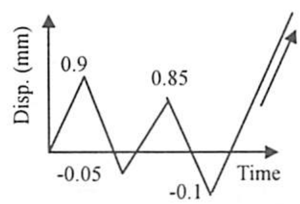

Fig 5. Loading history

Table 1: Comparison of displacement and effective stresses

Description	Previous Method	New Method	Error (%)
Failure displacement (mm)	1.129	1.098	2.7
Maximum stress (MPa)	540.57	540.47	0.02

4. Application of Proposed Method for Few Problems

The ULCF failures of two different problems were estimated using the proposed method. The geometric details and the considered FE mesh are shown in Fig. 6. The obtained ULCF results were compared with ductile failure results as shown in Table 2.

Table 2: Comparison of displacement and effective stresses

Model	ULCF Failure		Ductile Failure	
	Stress (MPa)	Disp. (mm)	Stress (MPa)	Disp. (mm)
Model 1	540.903	62.05	540.940	122.5
Model 2	540.940	213.3	540.941	486.9

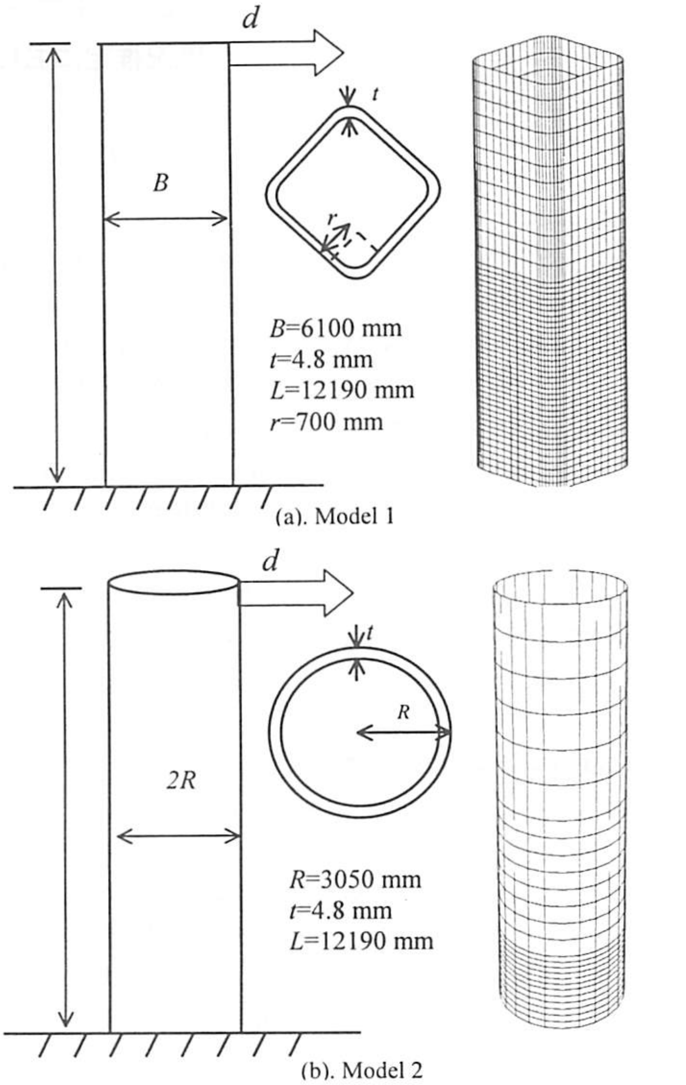

Fig 6. Geometric details and FE mesh

5. Conclusions

The verification reveals that described ULCF assessment method provides an accurate prediction to real failure of structure. Further, the Table 2 shows that all models are subjected to fail with lesser amount of displacement or effective stresses than ductile failure. Therefore, it reveals that even though the structure already designed to prevent ductile failure due to seismic loading (this is considered as the seismic design check for structural details in present day) it may fail due to the effect of ULCF failure by receiving lesser amount of applied displacement. As a result of that, it can be emphasized that the ductile failure check is not only sufficient but also ULCF failure check is required for seismic design of structural details to prevent the sudden failures.

References

Chi, W.M., Kanvinde, A.M., and Deierlein, G.G. (2006). Prediction of ductile fracture in steel connection using SMCS criterion. *Jou. of Structural Engineering*, ASCE, 132(2), 171-181.

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