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# High cycle fatigue analysis in presence of residual stresses by using a continuum damage mechanics model

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ABSTRACT

This study attempts to predict the high cycle fatigue life of steel butt welds by numerical method. At first, FE simulation of plate butt welding is carried out to obtain the weld-induced residual stresses employing sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. Then, a nonlinear damage cumulative model for multiaxial high cycle fatigue based on continuum damage mechanics (CDM), which can incorporate the effect of welding residual stresses, is derived using FE technique. The high cycle fatigue damage model is applied to the butt welds subjected to cyclic fatigue loading to calculate the fatigue life considering the residual stresses, and the computed total fatigue life which takes into account the fatigue crack initiation and the propagation is compared with the test result. In addition, the fatigue life prediction of the welds without considering the residual stresses is implemented to investigate the influence of welding residual stresses on the fatigue performance. The FE results show that the high cycle fatigue damage model proposed in this work can predict the fatigue life of steel butt welds with high accuracy, and welding residual stresses should be taken into account in assessing the fatigue life of the welds.

## 1. Introduction

Most of steel structures in engineering practice such as pipelines, steel bridges, shipbuilding, offshore structures and pressure vessels are fabricated by welding. These welded structures are often subject to variable loading ranging from cyclic to completely random fluctuations. Thus, fatigue of the welded structures is an important design consideration. Welding is a reliable and efficient metal joining process whose advantage includes high joint efficiency, simple set up and low fabrication cost. However, due to the intense concentration of heating in localized zone and subsequent cooling during welding, highly non-uniform temperature distributions occur across weld metal and base metal; thus they finally result in inevitable residual stresses there. The presence of residual stresses in welded structures can significantly affect the fatigue behavior during external cyclic loading [1,2]. Tensile residual stresses are generally detrimental to the fatigue life by increasing the susceptibility of welds to fatigue damage and by accelerating the rate of fatigue crack growth. Moreover, the combination of welding residual stresses and cyclic mechanical stresses causes welded structures to be governed by multiaxial fatigue. Accurate and reliable prediction of welding residual stresses and precise knowledge of the behavior of welded structures under fatigue loading are then needed for the efficient design and safety of the structures.

Nowadays, numerical modeling based on finite element (FE) method is used to predict weld-induced residual stresses due to the expense and impracticalities of generating comprehensive structural performance data through experiments [3]. Numerical techniques have become an important part of most structural research communities, since they can be employed as a useful tool for analyzing the behavior of structures provided that suitable care is taken to ensure that the modeling is appropriate for the analysis [4]. Until now, a significant number of FE models have been proposed and employed to predict welding residual stresses in steel welds [5–12]. Thus, welding residual stresses in welded components for structural applications have been thoroughly investigated.

During the past decades, there have been numerous research activities on the fatigue behavior of structural components containing weld-induced residual stresses [13–17]. However, they have been confined to the stage of fatigue crack growth based on the existing cracks. Fatigue life prediction based on fracture

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**Nomenclature**

| | |
|---|---|
| $b$ | modification coefficient |
| $b_i$ | body force |
| $h$ | temperature-dependent heat transfer coefficient |
| $h_c$ | convection coefficient |
| $p$ | effective accumulated plastic strain |
| $\dot{p}$ | rate of effective accumulated plastic strain |
| $\dot{r}$ | isotropic hardening rate |
| $A_D$ | damaged surface area |
| $A_T$ | total cross-section area of the undamaged surface |
| $A_{II}$ | amplitude of octahedral shear stress |
| $D$ | damage variable |
| $\dot{D}$ | damage evolution rate |
| $D_c$ | critical damage at which rupture occurs |
| $D_N$ | damage value at the $N$th cycle |
| $E$ | Young's modulus |
| $E_{ijkl}$ | tangential stress–strain matrix |
| $N$ | number of cycles |
| $N_f$ | number of cycles to failure |
| $N_f(0)$ | number of cycles to failure corresponding to the fatigue limit for symmetrical loading |
| $N_f(\sigma_m)$ | number of cycles to failure corresponding to the fatigue limit for an arbitrary mean stress |
| $R$ | stress ratio |
| $R(p)$ | isotropic hardening stress function |
| $T$ | temperature |
| $T_0$ | room temperature |
| $X_{ij}$ | back stress tensor of nonlinear kinematic hardening for cyclic loading |
| $X_{ij}^D$ | deviatoric part of the back stress tensor |
| $X_\infty$ | saturated value of the back stress |
| $\dot{X}_{ij}^D$ | rate of deviatoric part of the back stress tensor |
| $Y$ | damage strain energy release rate |
| $\dot{Y}$ | rate of damage strain energy release rate |
| $\delta_{ij}$ | Kronecker delta |
| $\varepsilon$ | emissivity |
| $d\varepsilon_{ij}$ | total strain increment |
| $d\varepsilon_{ij}^e$ | elastic strain increment |
| $d\varepsilon_{ij}^p$ | plastic strain increment |
| $d\varepsilon_{ij}^{th}$ | thermal strain increment |
| $\dot{\varepsilon}_{ij}^e$ | rate of elastic strain tensor |
| $\dot{\varepsilon}_{ij}^p$ | rate of plastic strain tensor |
| $\dot{\varepsilon}_{ij}^t$ | rate of total strain tensor |
| $\sigma$ | Stefan–Boltzmann constant |
| $\sigma_a$ | stress amplitude |
| $\sigma_{af}$ | fatigue limit |
| $\sigma_{eq}$ | equivalent von Mises stress |
| $\dot{\sigma}_{eq}$ | rate of equivalent von Mises stress |
| $\sigma_{ij}$ | stress tensor |
| $\sigma_m$ | mean stress |
| $\sigma_H$ | hydrostatic stress |
| $\dot{\sigma}_H$ | rate of hydrostatic stress |
| $\sigma_y$ | initial yield stress |
| $\sigma_{ij}^D$ | deviatoric part of stress tensor |
| $\dot{\sigma}_{ij}^D$ | rate of deviatoric part of stress tensor |
| $\dot{\sigma}_{ij}$ | rate of stress tensor |
| $\sigma_{\max}$ | maximum stress |
| $\sigma_{\min}$ | minimum stress |
| $\sigma_r$ | residual stress |
| $\sigma_u$ | ultimate stress |
| $\sigma_{-1}$ | fatigue limit of symmetrical loading |
| $\bar{\sigma}_{ij}$ | effective stress tensor |
| $\bar{\sigma}_{ij}^D$ | deviatoric part of effective stress tensor |
| $\bar{\sigma}_m$ | effective mean stress |
| $\bar{\sigma}_H$ | mean hydrostatic stress |
| $\underline{\sigma}^{dev}$ | deviatoric stress tensor |
| $\underline{\sigma}_{\max}^{dev}$ | deviatoric tensor of maximum stress in a loading cycle |
| $\underline{\sigma}_{\min}^{dev}$ | deviatoric tensor of minimum stress in a loading cycle |
| $\rho$ | density |
| $\dot{\lambda}$ | plastic multiplier |
| $\nu$ | Poison's ratio |
| $\phi^*$ | damage dissipation potential |
| $\Delta D$ | damage increment corresponding to $\Delta N$ |
| $\Delta N$ | increment of number of cycles |

mechanics can provide a lower bound to the total fatigue life which consists of crack initiation and subsequent crack propagation causing structural failure. Nevertheless, neglecting fatigue crack initiation leads to serious underestimation of the total life particularly in high cycle fatigue life regime, where crack initiation dominates the total life. Actually, the phase of fatigue crack initiation occupies even 80% or more of the total fatigue strength for many structural components [18]. Therefore, it is of critical importance to develop a new approach for predicting the total fatigue life in welds. Teng et al. [19] proposed a procedure for predicting the fatigue crack initiation life of steel butt welds with the strain–life estimation method. But, they could not consider the fatigue crack propagation life in the estimation of the total fatigue life. The strain–life method requires the exact location of critical area where fatigue crack originates, which is difficult to identify. Moreover, it assumes the linear damage accumulation based on the Miner's rule, which may lead to inaccurate calculation of the fatigue life. The residual stress relaxation by cyclic loading [20] cannot also be incorporated into the approach.

Recently, continuum damage mechanics (CDM) has emerged as a viable framework capable of describing microcracks initiation, growth and coalescence. The damage mechanics has been applied to model creep damage, ductile plastic damage, brittle damage and fatigue damage. Several high cycle fatigue damage models based on CDM have been proposed [21–26] since the development of classical fatigue damage models [27,28]. These models have predicted quite well physical phenomena related to high cycle fatigue. However, they have been generally limited to uniaxial fatigue of virgin materials, i.e. multiaxial high cycle fatigue of welded components could not be assessed by the fatigue damage models. On the available multiaxial high cycle fatigue damage model, limited models have been proposed [29–35] and there has been a lack of experimental verification. More efforts should therefore be taken to enhance the prediction accuracy of the fatigue damage model. Furthermore, as for the fatigue analysis of welds based on the high cycle fatigue damage model, very few works have been reported to date due to the truly complex analysis procedure involved in welding and subsequent cyclic mechanical loading problems, and thus the high cycle fatigue analysis deserves special attention. Actually, Lee et al. [36] developed a computational procedure for high cycle fatigue life prediction of welded structures incorporating welding residual stresses, which were obtained from the inherent strain scheme [37], based on the Lemaitre two-scale damage model [22]. Nevertheless, the method employed uniaxial fatigue damage model in the computation of fatigue life and it could not reflect the mean stress effect.