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# Modeling the high cycle fatigue behavior of T-joint fillet welds considering weld-induced residual stresses based on continuum damage mechanics

Chin-Hyung Lee [a], Kyong-Ho Chang [b], Vuong Nguyen Van Do [c,d,*]

[a] The Graduate School of Construction Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 06974, Republic of Korea
[b] Department of Civil and Environmental & Plant Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 06974, Republic of Korea
[c] Division of Computational Mechanics, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[d] Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Viet Nam

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ABSTRACT

A nonlinear continuum damage mechanics (CDM) model for multiaxial high cycle fatigue which incorporates the cyclic plasticity constitutive equation is developed in the finite element (FE) framework. FE simulation of T-joint fillet welding is first performed to identify welding residual stresses employing sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. The high cycle fatigue damage model is then applied to the T-joint fillet welds subjected to cyclic fatigue loading to compute the fatigue life considering the residual stresses. The calculated total fatigue life which includes the fatigue crack initiation and the propagation is compared with the test result. The FE results demonstrate that the high cycle fatigue damage model proposed in this work gives a correct prediction of the fatigue life of the welds, and welding residual stresses cannot be disregarded in an estimation of the fatigue life of the welds.



## 1. Introduction

Typically, metallurgical joint made by a fusion welding process is used to fabricate steel structures. The types of welded joint can be divided into five basic classes: butt, fillet, corner, lap and edge [1]. Among the welded joints, T-joint fillet welds are extensively employed in various engineering applications such as steel bridges, shipbuilding, offshore structures, pressure vessels and pipelines. These welded structures are often exposed to dynamic service loads ranging from cyclic to completely random fluctuations. Thus, fatigue of the welded structures is one of the most important design factors. Welding process including T-joint fillet welding consists of melting and solidification of weld metal and base metal in localized fusion zone by a transient thermal heat source. Due to the intense concentration of heating in localized zone and subsequent cooling during welding, undesirable residual stresses are produced in welded structures. Residual stresses induced by welding can have a significant influence on the fatigue behavior during external cyclic loading [2–4]. Tensile residual stresses are generally harmful to the fatigue strength by increasing the susceptibility of the weld to fatigue damage and by accelerating the fatigue crack growth rate. Moreover, when combined with cyclic mechanical stresses, welding residual stresses cause welded structures to be governed by multiaxial fatigue. Accurate estimation of welding residual stresses, and understanding the service behavior of welded structures under fatigue loading are therefore very crucial for the efficient design and safety of the structures.

Validated methods for predicting welding residual stresses are desirable because of the complexity of welding process which includes localized heating, temperature dependence of material properties and moving heat source, etc. Accordingly, finite element (FE) simulation has become a popular tool for the prediction of welding residual stresses. Until now, a number of FE analyses have been performed to predict residual stresses in T-joint fillet welds by using a 2-D symmetrical generalized plane strain model [1], a full 3-D thermo-mechanical model [5–8] and the shell/3-D model to improve the computational efficiency [9]. Barsoum and Lundbäck [10] carried out 2-D and 3-D welding simulations of T-joint fillet welds to study the suitability of adopting the 2-D plane strain model to a fracture mechanics fatigue crack analysis and showed that the 2-D model yielded satisfactory results. Further-

* Corresponding author at: Division of Computational Mechanics, Ton Duc Thang University, Ho Chi Minh City, Viet Nam.
*E-mail addresses:* donguyenvanvuong@tdt.edu.vn, dovanvuong285vy@gmail.com (V.N. Van Do).

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**Nomenclature**

| | |
|---|---|
| $b_c$ | modification coefficient |
| $c_h$ | specific heat |
| $h$ | temperature-dependent heat transfer coefficient |
| $h_c$ | convection coefficient |
| $k$ | thermal conductivity |
| $p$ | effective accumulated plastic strain |
| $\dot{p}$ | rate of effective accumulated plastic strain |
| $\dot{q}$ | rate of moving heat generation |
| $\dot{r}$ | isotropic hardening rate |
| $A_{II}$ | 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 |
| $N$ | 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 |
| $Q$ | saturated value of isotropic hardening |
| $R$ | isotropic hardening stress |
| $R(p)$ | isotropic hardening stress function |
| $R_s$ | stress ratio |
| $T$ | temperature |
| $\dot{T}$ | rate of change of temperature |
| $T_0$ | room temperature |
| $X_{ij}$ | back stress tensor of nonlinear kinematic hardening for cyclic loading |
| $X_{ij}^D$ | deviatoric part of back stress tensor |
| $X_\infty$ | saturated value of back stress |
| $\dot{X}_{ij}^D$ | rate of deviatoric part of back stress tensor |
| $Y$ | damage strain energy release rate |
| $\dot{Y}$ | rate of damage strain energy release rate |
| $\delta_{ij}$ | Kronecker delta |
| $\varepsilon$ | emissivity |
| $\dot{\varepsilon}_{ij}^t$ | rate of total strain tensor |
| $\dot{\varepsilon}_{ij}^e$ | rate of elastic strain tensor |
| $\dot{\varepsilon}_{ij}^p$ | rate of plastic strain tensor |
| $\dot{\varepsilon}_{ij}^{th}$ | rate of thermal 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 |
| $\dot{\sigma}_{kk}$ | rate of hydrostatic stress tensor |
| $\sigma_{ij}^D$ | 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 |
| $\sigma_y$ | initial yield stress |
| $\sigma_{-1}$ | fatigue limit of symmetrical loading |
| $\bar{\sigma}$ | effective stress |
| $\bar{\sigma}_m$ | 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 |
| $\Delta D$ | damage increment corresponding to $\Delta N$ |
| $\Delta N$ | increment of number of cycles |
| $\nabla$ | spatial gradient operator |

more, a significant volume of research works has been devoted to investigating the fatigue behavior of welded structures. Itoh et al. [11] calculated the fatigue crack growth rate in welding residual stress field based on the experimental measurements and the linear elastic fracture mechanics (LEFM). Barsoum and his coworker [12,13] and Lee and Chang [14] developed FE models for the analysis of fatigue crack growth in welds incorporating the residual stresses from the welding simulation based on the LEFM. Servetti and Zhang [15] compared the fatigue crack growth rates in welding residual stress field calculated from the different empirical fatigue crack growth laws using the FE analysis method. Huang et al. [16] evaluated the fatigue reliability of a complex web-frame welded structure subjected to multiple cracks by developing a probabilistic crack growth model based on the fracture mechanics. Wang and Wang [17] proposed an analytical model for the fatigue life assessment of welds joining corrugated plates to flange plates based on the LEFM. The residual stresses which were postulated to exist with the magnitude of the yield stress in the vicinity of welds were considered in the form of the combined stress intensity factor. However, these research activities have focused on the fatigue crack growth behavior based on the existing cracks. Fracture mechanics based model used to estimate fatigue crack propagation life can provide a lower bound to the total fatigue life. Nevertheless, neglecting fatigue crack initiation life causes serious underestimation of the total life particularly in high cycle fatigue life regime, where crack initiation dominates the total life [18]. The study of fatigue crack initiation in welds has been limited to very few works, which is attributed to the lack of adequate methodologies for describing internal damages that should be considered prior to crack occurrence. Actually, Teng et al. [19] developed a FE model to predict the fatigue crack initiation life of steel welded-joints based on the strain-life estimation method. However, they could not simulate the fatigue crack propagation in the welds. Consequently, it is crucial to develop a new approach for predicting the total fatigue life in welds.

Recently, continuum damage mechanics (CDM), which is able to describe microcracks initiation, growth and coalescence through the material damage state, has been adopted for modeling creep damage, ductile plastic damage, brittle damage and fatigue damage. A number of high cycle fatigue damage models based on CDM have been proposed, i.e. Xiao et al. [20] developed a CDM model for high cycle fatigue on the basis of a brittle damage mechanism, Lemaitre et al. [21] proposed a microscopic-mesoscopic two scale brittle damage model for high cycle fatigue, Shang and Yao [22] suggested a nonlinear fatigue damage cumulative model which considered the fatigue limit, the mean stress, the inseparable characteristic for the damage variables and the loading parameter, Dattoma et al. [23] presented a nonlinear high cycle fatigue damage model by proposing a new damage evolution model and Zhang et al. [24] devised a nonlinear CDM model which took into