The numerical high cycle fatigue damage model of fillet weld joint under weld-induced residual stresses

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Abstract. In this study, a development of nonlinear continuum damage mechanics (CDM) model for multiaxial high cycle fatigue is proposed in which the cyclic plasticity constitutive model has been incorporated in the finite element (FE) framework. T-joint FE simulation of fillet welding is implemented to characterize sequentially coupled three-dimensional (3-D) of thermo-mechanical FE formulation and simulate the welding residual stresses. The high cycle fatigue damage model is then taken account into the fillet weld joints under the various cyclic fatigue load types to calculate the fatigue life considering the residual stresses. The fatigue crack initiation and the propagation in the present model estimated for the total fatigue is compared with the experimental results. The FE results illustrated that the proposed high cycle fatigue damage model in this study could become a powerful tool to effectively predict the fatigue life of the welds. Parametric studies in this work are also demonstrated that the welding residual stresses cannot be ignored in the computation of the fatigue life of welded structures.

1. Introduction

Recently, welding steel structures are popularly used as productivity of bridge building, ships, aircraft, pipe line and thin walled structure, etc. The fatigue of these structures is complicated by many drawbacks to welded joint behaviours. The most important problems are the durability of welded structures under the active cyclic loading with responses of material changing at welding positions. The presence of cyclic loading and residual stresses makes the fatigue performance reduction of structures particularly in weld joints. For many defects influence to the fatigue corresponding to the structural integrity, residual stress is one of majority factors should be focused and studied. Residual stresses had significantly influence engineering properties of materials and structural component regarding to the fatigue stability, corrosion resistance [1]. Welding residual stress might lead to a dramatic reduction in fatigue strength of welded elements, therefore researching the distribution of residual stress in welded specimen and investigating the fatigue life corresponding to this effect are necessary in operating performance of materials parts and welded elements.

In practice, many studies for the residual stresses and welding deformation had been carried out both numerical and experimental manners. Deng et al [2] focused on considering the effects of thermal-mechanical welding to material properties at weld and base metals or HAZ region as well as the different response of similar or dissimilar weld zones. Kim et al. [3] had successfully developed the welding angular distortion in plate and welding local buckling. Lee and Chang [4] had carried out and investigated the residual stresses and the deformation with high accuracy computation in FEM as comparing to experimental data. This development in the computational method was significantly beneficial for taking account into calculating fatigue life and computational cost. In general, the results of residual stresses and deformation had played important role in the life cycle of welded structures due to mentioned conditions of welding defects. Moreover, residual stresses can be added to the stresses associated to applied loading, it induces the locally generated plastic strain as calculating the fatigue of welding structures. Many researchers had focused on the welding residual stresses to mechanical behaviours and fatigue life, however these have not been clearly explained until yet such as Hot spot stress method derived by Lotsberg and Sigurdsson [5], simple nominal stress method resulted by Fricke and Paetzold [7] and local strain estimation method developed by Kawin et al. [6]. They are among relatively successful methods in the recent decades and use with simple parameters obtained from the experiment results to acquire the fatigue life of materials. In addition, Teng et al [8] had developed the mathematical model to predict the effects of weld geometry parameters and residual stresses. However, the method is only calculated in 2D FE analysis to evaluate the generated residual stresses for the fatigue life of material derived through a strain life curve. Hence, the predicted results had insufficient accuracy to prove the precise residual stresses as well as the remaining fatigue of structures in only uniaxial loading cycle. Consequently, the mentioned methods were not adequately reflected the behaviours of residual stresses and internal variables such as stress, strain, elastic tensor by microstructure changes during plasticity and damage occur. Furthermore, through the experimental investigations in recent decades resulted in numerous hypotheses of high cycle fatigue, many proposals of such criteria could be found as Sine (1959), Crossland (1956) or Dang Van et al (1989) [9]. From the view point applied to numerical analysis, the convenience of first two was based on stress state invariants and the third one was based on the average value concept. These criteria were easily taken account into the FE analysis. The invariant formula always consists of quantities related to hydrostatic and octahedral stresses, then it can allow to determine the initiation point of fatigue crack when response of material reached to critical damage.

On the shortcomings of the present approaches to access the high cycle fatigue of weld structures, the investigation in the high cycle fatigue damage model is necessary. The fatigue damage model based on the continuum damage mechanics introduced the macroscopic damage phenomena and considered the localized at the microscopic scale to evaluate the fatigue life of steel specimen derived by Lemaitre et al [10]. This model presented quite well prediction physical phenomena related to high cycle fatigue in full reversed cycle loading, the effect of mean stress for high cycle fatigue was difficult to investigate. Shang and Yao had proposed the fatigue damage model for a nonlinear damage cumulative model [11], however these models only utilized for uniaxial fatigue, then they may not adequately determined much of behaviours of fatigue steel structures.

In this study, the three dimensional finite element simulation of computational fatigue damage model for welding structures is developed based on the continuum damage mechanics. The damage framework produced into elasto-plastic analysis is indispensable to illustrate the material degradation response as well as remaining fatigue life. On the basis of aforementioned criteria, the multi-axial high cycle fatigue formula are also derived. The residual stress and welding deformation are also determined by the studies in thermal-elasto-plastic analysis [4-12]. Three dimensional couple damage-elasto-plastic finite is implemented into a FEM code to derive the results. Update Lagrangian finite element formulation and a co-rotational system for the stress update algorithm were considered. Particularly, the proposed method has been the effective tool for analysis the fatigue and residual stresses of weld steel structures.

2. 3D couple thermal welding induced.

In order to consider the effect of welding-induced residual stresses and welding deformation which are determined by stress relaxation method, the computed residual stresses and deformation in welding process are used as initial data taken into fatigue damage FE model. The effective program should be developed to solve the couple elasto-plastic and damage mechanics for numerical evaluation of fatigue crack by FE simulation and damage evolution. Generally, there are two kinds of simulation methodologies: one is couple elasto-plastic damage analysis while another is uncouple between FEA and damage as considered a weak condition in fracture model. It is well recognized that the first with couple one is the high accuracy method, which means that full combination of damage process during the FEA [13]. The damage level and stress field of all representative volume element (RVE) are variable can be taken into account from the beginning to the end of the fatigue damage process. In detail, the initial Young's modulus should be updated and altered by effective Young's modulus at each computation step in FE analysis.

During the high cycle fatigue life computation of analysis FEM, the residual stress and welding deflection results will be considered into calculation due to the high residual stress concentration generating at the welding line position. This consideration is affected from the welding temperature and thermal-mechanical process. The material properties of specimen are also considered with different features of weld and base metals. From the view point of thermal mechanical simulation, the temperature is taken account as volumetric or surface energy distribution and thermal flow effect could be simplified by increasing thermal conductivity over the fusion temperature. Welding procedure is thermal mechanical process in which the temperature field has large effect and induces to residual stress field. On the other hand, these stresses have also weakly affected on thermal fields. Therefore, in order to simplify on this study, un-coupled analysis works of three-dimensional FE model are developed in consisting of two parts: a thermal model followed by a mechanical model.

2.1. Thermal model

The balance of energy equation for thermal simulation is given following as

$$\nabla(k\nabla T) + \dot{q} - \rho c \dot{T} = 0 \quad (1)$$

where T is the temperature, $\dot{T}$ is the rate change of temperature, k is the thermal conductivity, c is the specific heat, ρ is the density, $\dot{q}$ is the rate of moving heat generation and ∇ is the spatial gradient operator. As for the boundary conditions applied to the thermal model, convection and radiation are both taken into the consideration and their combined effects are presented via following equation for the total temperature-dependent heat transfer coefficient, h [14]

$$h = \frac{\sigma\varepsilon((T+273)^4 - (T_0+273)^4)}{T - T_0} + h_c \quad (2)$$

2.2. Mechanical model

The second step of the current analysis involves the use of temperature histories predicted by the previous thermal model as an input for mechanical model. During the welding process, the solid state phase transformation does not occur in the base and weld metals. Therefore, total strain can be expressed to the differential form of the total strain into three components as follows:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} \quad (3)$$

where $d\varepsilon_{ij}^{e}$ is the elastic strain increment and $d\varepsilon_{ij}^{p}$ is the plastic strain increment, $d\varepsilon_{ij}^{th}$ is the thermal strain increment. The elastic strain increment is calculated by using the isotropic hook's law with temperature-dependent Young's modulus and Poisson's ratio. The thermal strain increment is computed using the coefficient of thermal expansion. For the plastic strain increment, a rate independent elastic-plastic constitutive equation is considered with the Von-Mises criterion, temperature dependent mechanical properties and linear kinematic hardening rule. Kinematic hardening rule is considered as an important feature as material point typically undergo both loading and unloading in the course of welding process.

3. Proposed high cycle fatigue damage model

For high cycle fatigue damage is called quasi-brittle when the loading is a large number of repeated cycles and it is at low level below the conventional yield stress which subjected to quasi-brittle materials. The damage is localized in such the way that the damaged material occupies a small volume in comparison with the macro-scale of the structural component and even with the mesoscale of the RVE [15]. For the sake of the welded fatigue fracture, the fatigue fractures in welded structure had been known as the complicated phenomenon due to the accumulated damage evolution not be regarding to the plastic deformation at the macro-level while the damage growth and plasticity occurred at the micro-scale. The structural calculation is fully elastic even in the stress concentration zones. The brittle damage evolution obtained by micro-mechanics for particular mechanisms. In the brittle model of Kintzel et al [16] which novel damage indicator function was derived from Kuhn-Tucker complementation condition for low cycle fatigue calculation, the damage evolution as well as damage rate is evident as

$$\dot{D} = BY^{q-1}\dot{Y} \quad (4)$$

$$B = \frac{N^2}{S_2^2\left(B_\Gamma \dfrac{sign(Y^N - \Gamma)}{S_2}(\Gamma_\infty - \Gamma) + B_d(Q_{d\infty} - Q_d)\right)} \text{ and } q - 1 = 2(N-1) \quad (5)$$

where Γ_∞ and $Q_{d\infty}$ are defined the implicit thresholds at which the damage rate accelerates, B_Γ and B_d are material parameters which have a similar meaning as the saturation constant materials. From above Eq.(5), the evolution of 1D fatigue damage model rewritten and introduced as following

$$\delta D = \left[1-(1-D)^{\beta+1}\right]^{\alpha(\sigma_M,\bar{\sigma})}\left[\frac{\sigma_{Max} - \sigma_m}{M(\sigma_m)(1-D)}\right]^{\beta}\delta N \quad (6)$$

with

$$M(\sigma_m) = M_0(1 - b_2\,\sigma_m/\sigma_u)$$

$$\alpha(\sigma_{Max},\sigma_m) = 1 - a\left\langle\frac{\sigma_{Max} - \sigma_l(\sigma_m)}{\sigma_u - \sigma_{Max}}\right\rangle;\ \sigma_l(\sigma_m) = \sigma_{-1}(1 - b_1\,\sigma_m/\sigma_u) \quad (7)$$

Under a cyclic loading, the fatigue laws for a 1D problem depend on the mean stress value (σ_m) and the maximum stress (σ_{Max}). σ_{-1} is the fatigue limit which denoted as fully reversed loading and N is the number of cycles. For fatigue life prediction, the integration of Eq.(6) is performed with a number of cycles until crack initiation appears (D=1). The integration between $D=0$ and $D=1$ could achieve the number of cycle under the constant amplitude loading, the number of high cycle fatigue life is as following

$$N_f = \frac{1}{(1+\beta)aM_0^{-\beta}}\frac{\langle\sigma_u - \sigma_{\max}\rangle}{\langle\sigma_a - \sigma_{af}(\sigma_m)\rangle}\left(\frac{\sigma_a}{1 - b_2\,\sigma_m/\sigma_u}\right)^{-\beta} \quad (8)$$

In this study, the process of welding was simulated using 3-D thermo-mechanical FE formulation and the fatigue damage model based on the in-house FE code, which has been extensively verified against numerical results found in the literature and experiments.

4. Numerical results and discussion

4.1. Verification for the numerical residual stress results

This section is concerned with parameters be determined by analyzing residual stresses and fatigue damage model for SM490 carbon steel. On the calibration, the basic parameters of SM490 steel are obtained by tensile and cyclic tests according to ASTM standard E8-96 and E606-92, respectively with smooth round bar specimen under displacement control. The material constants on the elastic-damage plastic model are investigated by utilizing the experimental tests as shown in Table 1 and Table 2

Table 1. Mechanical properties of SM490 steel

Material	E (GPa)	ν	σ_y (MPa)	σ_u (MPa)	Elongation (%)	ε_{st}

SM490	206	0.3	365	560.	30.6	0.0133

Table 2. Fatigue damage model parameters for the damage evolution

β	a	M_0	b_1	b_2
1.196	0.8362	2.082E+05	0.002085	0.000371

In order to confirm the accuracy of welding FE analysis for this calculation, the experiment work was carried out by Kim et al. [3] with the geometry and dimension of the fillet weld plate which is made of carbon steel is considered with the length, width and thickness of L=500mm,W=300mm, t=6mm, respectively. The temperature histories were recorded by thermo-couples and residual stress measurements were carried out on the two axis strain gauges with layering technique. Measuring stresses by strain gauges can obtain the residual stresses on the surface of the specimens to be evaluated. The development of 3-D thermo-mechanical analysis by using finite element method is implemented to verify the experimental test with the welding parameters as obtained in fabrication of specimen. It seen that the trend of FE simulation as shown in Figure 1 and experiment data agrees very well. Therefore, the welding formulation of Eq.(3) is considered as an appropriated method for analyzing and introducing the residual stresses into fatigue damage model.

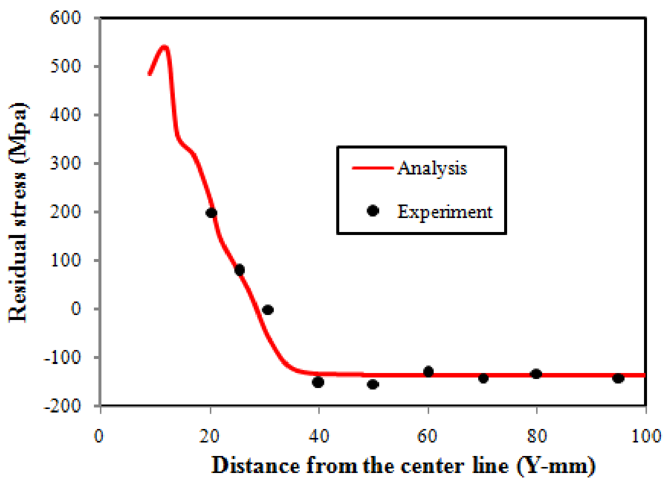

Figure 1. Verification of residual stresses for the numerical results with testing data

4.2. Fatigue damage study

Based on thermal residual stresses obtained from the welding process, the damage evolution was also determined through the damage growth rate Eq.(6). The fully coupled elastic-plastic damage is considered in analyzing structural damage interaction with effective stiffness degradation. Under the number of cycles the stress-plastic-strain upgrade, the damage variable was accumulated until reaching to critical value D_c at which the crack initiation will occur in the structure. The FE analysis was continuously repeated until the crack propagation processes and through the entire length at cross-section of the welded length. In addition, all variables in FE model were simultaneously updated for every cycle in calculation. The fatigue life of welded specimen subjected to the cyclic load is determined by the number cycles of repetition until the termination of the calculation.

A crack is described in the damage model by a region of totally damaged material. It is important to recognize that the local loss of stiffness in this region implies that the stresses drop to zero in deformation field. The material in the crack is given with a small residual stiffness, herein the damage variable is limited to a value which is slightly small than one, it makes to avoid the discrete equilibrium equations become singular. The increment led to the critical damage is then recomputed starting from the converged state in the previous increment, so that the damage accumulation is consistent with the current configuration under cyclic loading. The distribution of longitudinal residual stress profiles at the weld toe along the weld length indicated that the middle part high tensile residual stress appears meanwhile lower one exists in the edges. In spite of the relaxation occurring, the tensile stress in middle part is still high therefore the crack initiation will begin at mid position as displayed in Figure 2.

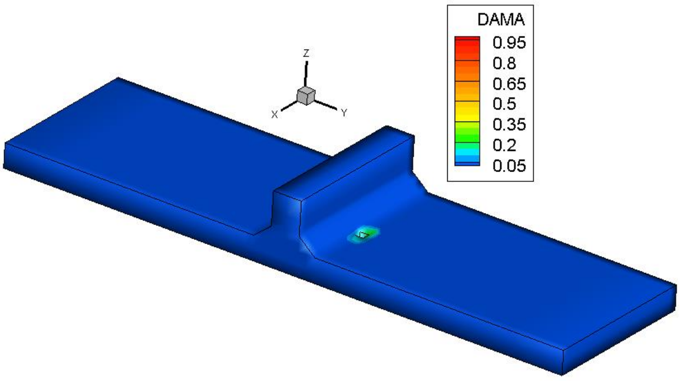

Figure 2. Failure analysis of fillet welding specimen as crack initiation and total crack processing

Initial imperfections such as initial defections and residual stress are explicitly considered since the reversed loading applied in the top of specimen. For most materials, compressive loadings are less critical than tensile ones, the damage evolution rate in compression case is lower than damage rate in tension as long as the structural instability is not taken placed, therefore crack takes place faster in tension case [15]. This is due to the phenomenon of micro-defects or micro-cracks closure when the material compressed. In fatigue, the existing of mean stress has plays role to reduce the fatigue life for a given stress amplitude. In this study, initial residual stress incorporating to high tensile part at the weld toe leads to increase mean stress effects as well as stress range. It is observed that the residual stress on FE model significantly speeds up both of crack initiation and propagation. As a result that the fatigue life of specimen is shown in Figure 3 has shorter life than base specimen and illustrates the high accuracy between analysis FEM and testing data with stress ratio R=0.1.

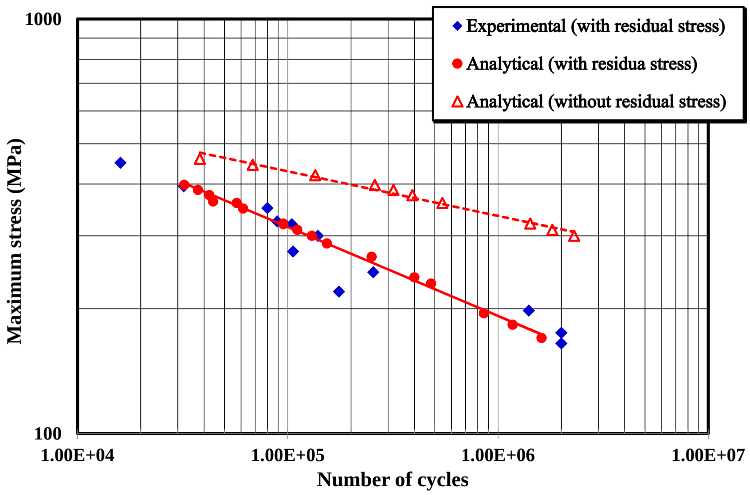

Figure 3. Fatigue damage analysis of fillet welding specimen as comparing to experimental data with/without residual stresses

5. Conclusion

This work aims to provide basic insight into the numerical simulation of multiaxial fatigue damage within considering the residual stresses on fillet welding structures. Material parameters included are used to describe high cycle damage evolution which are obtained from uniaxial experiments. The fatigue numerical simulation in which the residual stresses are incorporated into the fatigue damage model provides a simple step by step derivation of the consistent elasto-plastic modulus corresponding to FE algorithm and accesses the total fatigue life of undamaged welded structures. It can be drawn as following

a) The multiaxial high cycle fatigue damage model considered the effects of welding residual stresses be able to predict the total fatigue life of fillet welded joints under various cyclic load types with no initial cracks until to complete damage failure.

b) The temperature distribution and generating residual stresses in proposed damage model have been successfully developed in the welding process to indicate the highest intensity values at the welding joints.

c) The development of this fatigue damage model in accurately predicting the total high cycle fatigue life of welded structures can used as an effective method to reduce the cost and consuming time of fatigue test.

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