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Energy-based low cycle fatigue indicator prediction of non-load-carrying cruciform welded joints

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ABSTRACT

A new uniform analytical formulation is proposed to predict the low cycle fatigue assessment indicator of non-loading cruciform welded joints under tensile cyclic loading considering the effects of plasticity and mechanical heterogeneity of the welded materials and geometry configurations. Particularly, weld toe of the joints is dealt with a notch rounding in order to avoid the notch tip singularity in accordance with generalized Neuber concept of Fictitious Notch Rounding (FNR). The relationship between elastic and plastic energy concentration factor of weld toe is firstly determined by the combination of notch stress and strain distribution with the increases of nominal loading, then the main parameters affecting the energy concentration factor are investigated by separating elastic and plastic stages. Stress and strain field intensities are finally expressed in terms of total energy values, which are linked to the nominal energy ones. The energy prediction function which takes into account the material and geometry factors is capable of providing a closed form analytical expression about the state of energy both under small and large-scale yielding for industrial facilities by the comparison against finite element analysis results.

1. Introduction

Due to cyclic loading of engineering welded structures and components such as truck cranes, pressure vessels, ships, offshore platforms, they are frequently subjected to fatigue failure. For these structures, typically, fatigue failure initiates from the vicinity of welded joints, where there are intensified stress levels due to geometrical discontinuity or weld defects. The fatigue life assessment of welded joints is commonly based on nominal, structural stress, notch stress approaches [1,2], which utilizes S-N curves to describe the fatigue strength by linear-elastic analysis for average weld geometry. However, considering the complex geometries of the weldments made by some advanced welding process (e.g. laser or laser-hybrid welding process), the fatigue life cannot be easily predicted using the traditional stress-based methods [3,4]. Especially for laser stake-welded joints of thin plates ($t \leq 5\,\text{mm}$), it needs to correct the slope of fatigue resistance curve considering crack tip plasticity and gradient stress effect under different loading conditions[5,6]. In some circumstances, Low Cycle Fatigue (LCF) may occur when cyclic applied stress locally exceeds yield strength of the material due to high stress concentration. Thus, the variation of weldment geometry and material properties needs to be considered into the models for LCF assessment. In order to exploit the potential of stress-strain evolution of welded joints under LCF, the accuracy of fatigue life predictions must be improved by considering the elastic-plastic behavior of material. This requires further understanding of the factors affecting the assessment characters, such as notch effects and elastic-plastic stress-strain relationships.

For fatigue strength assessment of welds, the geometry variation and notch sensitivity are commonly dealt by utilization of the FNR approach proposed by Radaj. Some stress concentration analytical formulations for different geometrical joint types have been widely investigated based on FNR concept in studies available in open literature [2,7,8]. Meanwhile, Radaj proposal has been recommended as a standardized design procedure within International Institute of Welding (IIW) [9]. The fictitious notch radius $\rho_f = 1$ mm is commonly suggested for normal quality welds, which is defined as effective notch approach. The corresponding fatigue class FAT 225 (Ps = 97.7%) from this recommendation is given for this specific notch rounding. Pedersen et al. [10] reanalyzed a large amount of different welded joints fatigue experiments data reported in the literature and further confirmed the validity of IIW guidance. Actually, the original fictitious notch rounding concept comes from the Neuber microstructural support theory [11]. The fictitious notch radius is given in the following form:

$$\rho_f = \rho + s\cdot\rho^* \tag{1}$$

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where the ρ is the actual radius of the notch, s is the support factor which takes multiaxial stress effects on failure into account, and ρ^* is a material dependent microstructural length. Although the introduction of FNR avoids V-shaped notch singularity effectively, the notch stress distribution around different notch rounding radii and notch opening angles is not described quantitatively. Afterward, Lazzarin proposed a generalized form of Stress Intensity Factor (SIF) considering the influence of aforementioned factors [12]. The maximum principal stress at the notch tip can be expressed linking to the generalized SIF with reference to mode I. FNR concept which has taken different notch opening angles into account is further systematically evaluated under plane stress and plane strain conditions by Berto et al. [13,14]. The generalized SIF was then used for calculation of strain energy density to predict the static failure loads and also fatigue life of notched components made of various materials in a range between ductile to brittle [15–19].

On the other hand, some recent applications [20] of FNR approach to notches with root hole under mode I loading have been proposed by employing some accurate closed analytical solutions derived for that notch configurations [21]. NSIF analytical expressions have been reported for Non-Load-Carrying fillet welded Joints (NLCJ) subjected to tension and bending loads [22]. Thus, the elastic stress concentration factors of NLCJ can be predicted from known analytical equations. Using fictitious notch rounding concept, we can evaluate the effects of geometrical characters of welded joints and mechanical heterogeneity under elastic-plastic stress-strain relationships. The notch approach is capable of calculation for local stress or strain, even plastic notch stress intensity factors and plastic strain energy density [23–26] of notch specimens in combination with material constitutive models and Neuber notch theory. It means that a LCF life assessment for notched specimens becomes possible.

When the magnitude of the applied loading is large enough that make local stress exceed material yield strength, localized plastic deformation needs to be accounted for notch components and structures. Over the years, various approximated methods have been proposed to calculate the elastic-plastic strain at notch root. As most popular local stress strain evaluated method for notch specimens, Neuber rule has been widely used to estimate the notch stress and strain under monotonic or cycle, axial or multiaxial, proportional or non-proportional loadings in different fracture and fatigue researches [27–32]. Although this rule or its extensive formations can illustrate the notch elastic-plastic behaviors by correcting related functions, the notch stress predictions are still overestimated compared to the real notch stresses. Another widely used method to analyze notch stress is the Equivalent Strain Energy Density (ESED) method proposed by Molski and Glinka [33]. The origin version is defined in terms of the assumption that the plasticity zone of notch deformation is controlled by surrounding elastic stress field and energy density distribution. The notch stress results based on the ESED method are slightly underestimated than the experimental data. Lately, Ye et al. [34] established the physical relationship between Neuber's rule and ESED method by analyzing the elastic-plastic body and introducing dissipated heat energy into plastic energy density under monotonic and uniaxial cyclic loading. The modified version further improved the precision of local stress prediction in contrast to the original ESED method. Additionally, Li et al. [35] extended the Ye's ESED model by correcting the dissipated heat energy taking the effect of Poisson's ratio into account. The results demonstrated good agreement with measured data under both axial and multiaxial cycle loadings. These researches are focused on fatigue behaviors of local stress and strain for small-scale notch specimens, however, very limited literature is related to low cycle fatigue of notch welded components or structures under large scale yield conditions. Not like materials low cycle fatigue assessment, low cycle fatigue life of welded structures is significantly affected by the welds inherent defects and material mechanical heterogeneity. Since geometric parameters, loading conditions and material properties impose strong influences on the fatigue life of structural components [36]. It is necessary to clarify the relationship between these factors under high and low cycle fatigue behaviors. To the best of the authors' knowledge, limited literature is related to elastic-plastic behavior, or energy evolution of components or structures critical area, such as joints weld toe or root.

On the other hand, although non-linear finite element analysis (FEA) techniques are capable of calculating highly accurate local stress-strain solutions under arbitrary loading conditions, the process is computationally expensive and highly impractical in cases involving complex component geometries and/or long loading histories. Due to the presence of plastic strain deformation in low cycle fatigue, strain-based or energy-based approaches can better account for this behavior. The analytical formulations for fatigue assessment based on the deviatoric form of Neuber rule can estimate elastic-plastic strains or energy at weld toe in NCLJ. From this perspective, some researchers have established some analytical solutions for different joints. Saiprasertkit et al. conducted low cycle fatigue experiments and numerical simulations to examine the low and high cycle fatigue for load-carrying cruciform joints considering different strength matching conditions and weldments geometries [37]. An effective notch strain analytical model based on the effective notch concept was established to predict the notch strain according to numerical simulations. The model was used successfully to assess the fatigue strength with a narrow scatter band. Recently, an energy-based close-form analytical formulation of NCLJ based on modified Neuber's rule was proposed to assess the low cycle fatigue behaviors [38]. The material plastic properties and geometric effects on this new indicator have been considered into prediction formulation. The energy-based approach for fatigue assessment can provide more integral and accurate estimation around crack tip in different yielding states. Especially, it can efficiently characterize the LCF behavior. According to above available literature, the combination effects between welded joint geometric configurations and mechanical heterogeneity on the LCF indicator have not been systematically evaluated.

The current study is concerned with the fatigue behavior of NCLJ in the as-welded condition and cyclic tensile loading. Taking effects of material elastic-plastic properties and mechanical heterogeneity of welded joint and geometrical configurations on low cycle fatigue performance of NCLJ into account, a new energy-based fatigue assessment indicator is proposed, which employs cycle Ramberg-Osgood stress-strain relationship and generalized Neuber fictitious notch rounding concept for notch elastic-plastic estimation. The primary goal is to develop an analytical formulation using the new energy indicator which can be used in fatigue assessment. The paper is composed of three parts. The first part illustrates the theoretical background for notch fatigue assessment, such as generalized Neuber concept of fictitious, elastic-plastic notch estimation theory, and elastic-plastic stress-strain constitutive models. The subsequent section examines the evolution of weld toe stress and strain concentration factor in cruciform joints based on the effective notch approach and illustrates the availability of the new energy-based fatigue indicator. Further discussions on the relationship between the new elastic and plastic energy magnitude for a large strain loading by non-dimension analysis are demonstrated. Then the key factors affecting the energy characters in non-load-carrying cruciform joints, such as material yield stress, hardening exponent, welded joints strength mismatch, joints geometrical configurations are systematically investigated by numerical simulation. Combining the fictitious notch rounding concept, an analytical formulation is proposed to estimate the new energy indicator for engineering application. In order to verify the rationality of the proposed formulation, the numerical simulation results of various material and geometric integrated models are compared with analytical solutions. Finally, the proposed model is used to predict the energy indicator for low cycle fatigue life assessment by taking new parameters into accounts.