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A structural strain method for low-cycle fatigue evaluation of welded components

P. Dong [a,*], X. Pei [b], S. Xing [b], M.H. Kim [c]

[a] Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48105, USA
[b] University of Michigan, USA
[c] Pusan National University, Pusan, South Korea

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ABSTRACT

In this paper, a new structural strain method is presented to extend the early structural stress based master S–N curve method to low cycle fatigue regime in which plastic deformation can be significant while an elastic core is still present. The method is formulated by taking advantage of elastically calculated mesh-insensitive structural stresses based on nodal forces available from finite element solutions. The structural strain definition is consistent with classical plate and shell theory in which a linear through-thickness deformation field is assumed a priori in both elastic or elastic–plastic regimes. With considerations of both yield and equilibrium conditions, the resulting structural strains are analytically solved if assuming elastic and perfectly plastic material behavior. The formulation can be readily extended to strain-hardening materials for which structural strains can be numerically calculated with ease. The method is shown effective in correlating low-cycle fatigue test data of various sources documented in the literature into a single narrow scatter band which is remarkable consistent with the scatter band of the existing master S–N curve adopted ASME B&PV Code since 2007.

With this new method, some of the inconsistencies of the pseudo-elastic structural stress procedure in 2007 ASME Div 2 Code can now be eliminated, such as its use of Neuber's rule in approximating structural strain beyond yield. More importantly, both low cycle and high cycle fatigue behaviors can now be treated in a unified manner. The earlier mesh-insensitive structural stress based master S–N curve method can now be viewed as an application of the structural strain method in high cycle regime, in which structural strains are linearly related to traction-based structural stresses according to Hooke's law. In low-cycle regime, the structural strain method characterizes fatigue damage directly in terms of structural strains that satisfy linear through-thickness deformation gradient assumption, material nonlinear behavior, and equilibrium conditions. The use of a pseudo-elastic structural stress definition is not fundamental, but merely a means to put low-cycle and high-cycle fatigue test data in a conventional stress-based S–N data representation which is typically preferred in engineering practice, than a strain-based representation.

1. Introduction

Since 2007, ASME Section VIII Division 2 Code has adopted an alternative fatigue evaluation method for welded joints, i.e., the mesh-insensitive structural stress based master S–N curve method [1]. A comprehensive discussion on its theoretical basis, analysis procedures, and validations using fatigue test data on this method can be found in a recent publication [2]. The master S–N curve method consists two basic elements: (a) a novel nodal force-based structural stress calculation method as a post-processing procedure to finite element structural solutions; (b) an equivalent structural stress parameter that captures a combined effect of stress concentration, plate thickness, and loading mode on fatigue behavior of welded joints [2–5]. The effectiveness of the master S–N curve method has also been validated for applications in offshore structures independently, e.g., by Healy [7] and in automotive structures by Kyuba [8].

The design master S–N curve in the 2007 ASME Div 2 [1,2] was developed by introducing an equivalent structural stress range parameter that collapses a large number of fatigue test data (about 1000 tests of large scale and full scale specimens) into a narrow

* Corresponding author.
E-mail address: dongp@umich.edu (P. Dong).

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scatter band. These tests span a wide range of joint geometries, plate or pipe wall thicknesses, and loading modes. Through a standard statistical analysis of the data in the form of equivalent structural stress range versus cycle to failure, the design master S–N curve is defined as the mean master S–N curve minus three standard derivations before an environmental effect factor is considered. For applications not governed by ASME pressure vessel codes, a design master S–N curve based on mean minus two standard derivations is typically used [6–8].

The test data on which the design master S–N curve was based have fatigue lives as low as a few hundreds of cycles to as long as nearly 10^8 cycles to failure. It should be noted that in low cycle regime, i.e., typically lower than 10^4 or 10^5, pseudo-elastic structural stress ranges [2,9] based on reported pseudo-elastic loads in displacement controlled low-cycle fatigue tests, such as those in Refs. [10,11]. In supporting the 2007 ASME Div 2 Code development effort [1], Dong et al. [9] proposed a preliminary low-cycle fatigue (LCF) treatment procedure for adapting the master S–N curve method which was mainly focused upon high-cycle fatigue to low-cycle fatigue applications in pressure vessel applications mostly subjected to load-controlled conditions. The procedure involves converting elastically calculated structural stresses under a given loading condition into a through-thickness linearly distributed structural strain according to Hooke's law, then searching for a structural strain definition that both satisfy yield conditions and through-thickness linear deformation conditions. Unsuccessful at the time, they assumed that Neuber's rule can be used to calculate approximate structural strains beyond yield using the elastically calculated structural stresses. The resulting structural strains parameter is then used to obtain pseudo-elastic structural stresses by applying Hooke's law or multiplying Young's modulus if assuming uniaxial stress state prevails. Although showing an improved fatigue life estimation over purely elastic-based assessment procedure (i.e., without any plastic deformation considerations) for some available low-cycle fatigue test data [8], there exist a number of inconsistencies or weaknesses in that approach:

(a) Although a structural strain concept was first introduced in Ref. [7], its implementation in elastic–plastic deformation regime was largely incomplete in view of the fact that a local strain definition had to be used in order to approximate structural strain according Neuber's rule that has been typically used for notch stress and strain characterization beyond elastic regime. As a result, the very structural strain definition intended to characterize linear through-thickness deformation no longer possess its original meaning;
(b) It is preferable that any low cycle fatigue correction procedure should provide an indication on extent of plastic deformation, e.g., elastic core size. The presence of an elastic core is important since it help justify that an approximate proportionality in fatigue damage accumulation so that an elastic FE stress analysis can still be used in fatigue design. To the authors' best knowledge, existing low-cycle fatigue procedures [9,11,12] for welded structures are not capable of providing any information regarding if an elastic core is still present, nor its size at a location of interest;
(c) Lastly, one advantage of the nodal force based structural stress definition is its statically equivalent decomposition of a through-thickness traction stress state in terms of membrane and bending. Once Neuber's rule is applied for estimating structural strains in elastic–plastic deformation regime, the previous method [9] is no long capable of tracking membrane and bending composition or bending ratio after calculating the pseudo elastic structural stress. As a result, elastic bending ratio must be used for calculating the equivalent pseudo-elastic structural stress range in order to use the design master S–N curve. Fortunately, under strictly load controlled conditions, fatigue lives are only weakly dependent upon bending ratio [2]. However under-displacement controlled conditions, a much stronger dependency has been shown in Ref. [2]. Therefore, an improved treatment of low-cycle fatigue is needed.

The purpose of this paper is to present a structural strain procedure that is consistent both with the mesh-insensitive structural stress method [2,3] and the original intent expressed in Ref. [9] when the terminology of structural strain was perhaps first introduced for the treatment of low cycle fatigue. The plan of this paper is as follows. We start with a brief discussion of some relevant definitions and procedures associated with the mesh-insensitive structural stress based master S–N curve method. Emphasis will be placed upon how displacement-controlled low cycle fatigue data had been interpreted in the development of the master S–N curve covering both low-cycle and high-cycle fatigue regimes [2]. The needs to develop a more general and consistent low cycle fatigue evaluation procedure are then discussed. A structural strain definition valid for both elastic and elastic–plastic deformation regimes is then presented. Analytical solutions of structural strains and resulting elastic core size are then presented by assuming elastic perfectly-plastic material response. Some existing low cycle fatigue tests both under load- and displacement-controlled conditions are analyzed to validate the effectiveness of the new structural strain method. Finally, its implementation in supporting the effective use of the master S–N method in 2007 ASME Code [1] is discussed in light of the present development.

2. Master S–N curve and LCF data

The master S–N curve method [1–3,6] embodies two key technical advances in finite element analysis based fatigue evaluation: (1) a robust stress concentration calculation procedure based on a novel nodal force method that is mesh insensitive at weld toe or weld root; (2) a single master S–N curve representation of a large amount of S–N data regardless of joint geometries, loading modes, thicknesses, etc. A brief description of the master S–N curve is provided here both for completeness and contrasting the differences between the present developments in this paper and the early master S–N curve method. Detailed discussions on the master S–N curve method, basic principles, numerical procedures as well as validation examples can be found in numerous publications, including [2–4].

2.1. The traction-based structural stress definition

As discussed in Ref. [2], a structural stress parameter can be directly formulated by representing the traction conditions on a hypothetical crack plane in the form of their respective membrane and bending components. Consider a stress state at a weld toe on the chord wall (e.g., a tubular T joint) along a through-thickness hypothetical cut shown in Fig. 1a, the corresponding stress components characterizing the traction conditions along cut plane A–A are σ_x, τ_y, and τ_z under general loading conditions. Transverse shear τ_z is often negligible. Within the context of structural mechanics, these stress components are presented in the form of membrane and bending which can be directly related to their corresponding line force and line moments if shell or plate element models are used. Such a characterization can be directly generalized to a 3D geometry, such as along the entire curved weld line shown in Fig. 1b. As such, a local coordinate system is used in Fig. 1b so that