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Low-cycle fatigue performance of solid cylindrical steel components subjected to torsion at very large strains☆

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ABSTRACT

In this research, low-cycle fatigue performance of cylindrical specimens produced from different ductile steel grades subjected to torsion is investigated. The primary motivation behind this research is the need for data on low-cycle fatigue in solid cylindrical specimens of S355 structural steel to use in a new steel Multi-Directional Torsional Hysteretic Damper (MTHD). This steel damper is intended to be used for seismic protection of buildings and bridges. In the newly developed steel damper the energy dissipaters are in the shape of a cylinder with enlarged ends and can undergo cyclic shear strain as large as 13%. Such large strains are not encountered under service conditions in structural or mechanical components but are common in earthquake engineering in those components which are designed to plasticize and dissipate energy, e.g., plastic hinge regions, and in the case of the specific application presented in this paper, in the energy dissipaters of the steel damper. A total of 61 solid cylindrical specimens made of S355J2 + AR and C45E steel grades are tested using a special test setup capable of twisting the specimens up to ±50°. The steel specimens are tested under different levels of torsional shear strain ranging between 0.044 and 0.130 and the data is used to calibrate the Coffin-Manson model for low-cycle fatigue life prediction of specimens. Also, the impact of various other relevant factors on low-cycle fatigue behavior of specimens are looked into, including loading pattern and sequence, low temperature, surface finishing and aspect ratio (height/diameter).

1. Introduction

The term 'Fatigue' is used to broadly describe the phenomenon and process of damage due to repeated cycles of loading, leading to reduction in load capacity of a component. The subject of fatigue is of special importance in mechanical, aerospace and civil engineering, as well as materials science and engineering. Fatigue damage is best described as the nucleation and growth of cracks to final failure [1]. Fatigue is thus defined by the ANSI/AISC 360-10 [2] as the "limit state of crack initiation and growth resulting from repeated application of live loads." The origins of fatigue lie in the microstructure of a solid component and encompasses all phenomena that contribute to damage. The available literature on fatigue and fatigue-related subjects (e.g. damage and crack propagation) is immense. Fatigue, in general, whether high-cycle or low-cycle, uniaxial or multiaxial, axial or torsional, is a single phenomenon governed by common mechanisms, and a thorough review on this subject can cover many fields.

Fatigue and mechanical behavior of steel structural components with circular cross-section has been the focus of many researchers as such components are widely used as shafts in mechanical engineering [3] and as columns and braces in civil structures. Additionally, central symmetry in steel components with circular cross-section provides them with unique mechanical characteristics, which can be utilized in the experimental studies of different behavioral types. For example, thin-walled tubular specimens are used to investigate multi-axial plasticity and fatigue [4]. Also, the study of Mode III (anti-plane strain) crack propagation has been performed on circumferential notched solid cylindrical specimens [5,6,7]. Cylindrical specimens have also been used in the determination of shear plastic stress–strain relationship [8,9,10].

Many research studies on high cycle fatigue [11,12,13] as well as low cycle fatigue [14,15] performance of circular steel components subjected to torsion are available at high strain levels (1–8% shear strain) but research data at unusually high strain levels (5–13% shear strain) are lacking. Particularly, torsional low-cycle fatigue tests on solid cylindrical components of ductile steel (specifically, C45 and S355 steel) under

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unusually high levels of strains as encountered in the context of this study related to earthquake engineering applications are not available in the literature and needs to be investigated.

2. Research objective, scope and methodology

The objectives of this research study is to (i) develop a Coffin-Manson type equation [16,17] to obtain an analytical relationship between the torsional shear strain and the number of cycles to failure of solid cylindrical steel members subjected to very large levels of torsional shear strains varying between 13 and 40 times the yield strains, (ii) deduce important observations about the low cycle fatigue performance and behavior of solid cylindrical steel shafts used for earthquake energy dissipation in civil structures and subjected to large torsional shear strains expected during an earthquake, (iii) investigate the effects of several parameters such as loading pattern and sequence, low temperature, specimen size, surface finishing and aspect ratio (height/diameter) on the low cycle fatigue life of solid cylindrical specimens made of two types of ductile steel; S355J2 + AR and C45E.

The test results are then used in the design of a newly developed steel hysteretic damper for specific applications to dissipate seismic energy in civil structures. Accordingly, the problem of fatigue as encountered in this research is approached in a practice-oriented way, that is, in a way appropriate for direct application of results to the practical problem which is the basis of this research study.

In the following sections, first the newly developed steel hysteretic damper for seismic protection of buildings and bridges is briefly introduced. Then, detailed information on the test specimens and test setup is provided. This is followed by the presentation and discussion of the test results, equation development and conclusions.

3. Brief introduction of the newly developed steel hysteretic damper

The Multi-Directional Torsional Hysteretic Damper (MTHD) [18,19] is a recently-patented invention composed of a rail system and an energy dissipating unit which holds eight symmetrically arranged identical energy dissipaters in the shape of a cylinder with enlarged ends, as shown in Fig. 1. The rail system is attached to the superstructure and the energy dissipating unit is attached to the substructure. The energy dissipaters are designed and configured to yield and develop large plastic shear strains under torsion and dissipate energy, as a result of any planar displacement imposed on the damper (as a result of relative displacement between the superstructure and substructure). Torque is generated in these steel energy dissipaters via arms undergoing a rotational motion via sliding within the steel rail system as shown in Fig. 1(d). Bending of the steel energy dissipaters is prevented by transferring the horizontal force imposed on the arms directly to the attachment point at the base of the MTHD via a steel diaphragm and a central column (Fig. 1(c)). Thus, the energy dissipaters are subjected to nearly pure torsion. Detailed information about this steel damper including its conceptual, theoretical and experimental development are presented in [18,19]. Fig. 1(e) shows a torsion-based hysteretic damper with a mechanism similar to that of MTHD, which is developed for application to chevron braced steel frames. A single energy dissipation unit of this steel damper is shown in Fig. 1(f), which is composed of a cylindrical energy dissipater with enlarged ends, similar to those in MTHD.

4. The approach towards low-cycle fatigue

The classical approach towards low-cycle fatigue in engineering applications, is based on using the number of cycles to failure at a constant amplitude strain, as the measure of total fatigue life. Accordingly, an exponential law proposed by Coffin [16] and Manson [17], known as the Coffin-Manson Equation, is generally used to predict the low-cycle fatigue life:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f (2N_f)^c \tag{1}$$

where, $\Delta\varepsilon_p$ denotes the range of plastic strain (between the maximum and minimum, with consideration of the sign), N_f is the number of load reversals to failure ($2N_f$ being the number of fully-reversed cycles), ε'_f and c stand for ductility coefficient and ductility exponent. ε'_f is approximately equal to the true fracture ductility and c is in the range of -0.5 to -0.7 for most metals [20]. Years of experience with this model have proved its validity for low cycle fatigue life prediction of engineering components subjected to constant-amplitude cyclic loading. An analogous equation can be written in terms of shear strain:

$$\frac{\Delta\gamma_p}{2} = \gamma'_f (2N_f)^{c'} \tag{2}$$

where parameters $\Delta\gamma_p$, γ'_f and c' are analogous to $\Delta\varepsilon_p$, ε'_f and c. The above model is used in this research to develop a model for torsional low-cycle fatigue life prediction of cylindrical specimens. The fact that the above relationship is specific to constant-amplitude loading means that it cannot be used directly in earthquake engineering applications, where the loading history is composed of cycles of different amplitudes and even asymmetric cycles. The common method to tackle non-uniform strain histories is based on the concept of damage accumulation, as proposed by Palmgren [21] and cast in mathematical form by Miner [22]. Palmgren-Miner rule defines a damage variable, D, ranging between 0 and 1.0, indicating undamaged and failure conditions, respectively. The damage variable is then assumed to be a linear combination of contributions from cycles with different strain levels each calculated independent of others. It is assumed that the contribution to damage from cycles experienced at each strain level is proportional to the number of cycles, n_i, at that specific strain level, where the subscript i indicates the strain level. Thus:

$$D = \sum \frac{n_i}{N_{fi}} \tag{3}$$

where $N_{f\,i}$ indicates the number of fully-reversed cycles to failure at the strain amplitude indicated by i. It has been shown that simple cumulative damage models such as the one above can be utilized to assess deterioration and failure in steel structural components [23].

5. The test specimens

Following the development of the new steel damper, with the aim of gaining insight into the phenomenon of torsional fatigue in solid cylindrical steel specimens and to acquire data for the design of the new damper, a series of torsional low-cycle fatigue tests on cylindrical specimens of S355J2 + AR and C45E steels are performed using a specially-designed test setup, capable of twisting the specimens up to ± 50°. The specimens are tested under different levels of torsional shear strain (engineering shear strain at most-strained fibers) ranging between 0.044 and 0.130 (about 13 to 40 times the yield strain) and the data was used to calibrate the Coffin-Manson model for the prediction of the low-cycle fatigue life of the steel specimens for use as energy dissipaters in earthquake engineering applications. Also, The impact of various other relevant factors on low-cycle fatigue behavior of specimens are looked into, including loading pattern and sequence, low temperature, specimen size, surface finishing and aspect ratio (H_0/D_0).

A total of 67 specimens were produced out of C45E and S355J2 + AR steels. The specimens are basically cylinders with enlarged ends, with both ends machined into a semi-rectangular-shaped section to provide a plug-type attachment. The specimens are shown in Fig. 2(a). The