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Stress-based fatigue failure models for uniaxial ratchetting–fatigue interaction

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Abstract

Based on the experimental results of uniaxial ratchetting–fatigue interaction obtained at room temperature for the materials presenting different cyclic softening/hardening features [Kang GZ, Liu YJ, Li Z. Experimental study on ratchetting–fatigue interaction of SS304 stainless steel in uniaxial cyclic stressing. Mater Sci Eng A 2006;435–436:396; Kang GZ, Liu YJ. Uniaxial ratchetting and low-cycle fatigue failure of the steel with cyclic stabilizing or softening feature. Mater Sci Eng A, in press], two kinds of stress-based fatigue failure models were proposed to predict the fatigue life of the materials by addressing the ratchetting–fatigue interaction occurred. In the primary stress-based failure model (namely, SBF model), the effect of ratchetting strain produced in the asymmetrical cyclic stressing on fatigue life was reflected by an item dependent upon the stress ratio *R*. Comparison with the experimental results shows that the SBF model provides a good prediction for the cyclic stable material, annealed 42CrMo steel, but over-estimation for the materials presenting cyclic softening feature, i.e., SS304 stainless steel and tempered 42CrMo steel, since the effect of cyclic softening/hardening feature on the ratchetting–fatigue interaction is not concluded in the primary model. To overcome such shortcoming, the primary model was then extended by introducing a new variable FP to address the effect of cyclic softening feature. In the modified stress-based failure model (namely, MSBF model), the variable FP was determined by applied maximum stress and stress ratio as well as the cyclic softening feature of the material. It is shown that the MSBF model gives fairly good predictions for both SS304 stainless steel and tempered 42CrMo steel by addressing the effect of cyclic softening feature on the fatigue life reasonably.

Keywords: Ratchetting; Low-cycle fatigue; Uniaxial cyclic stressing; Failure model; Cyclic softening

1. Introduction

Ratchetting, a cyclic accumulation of inelastic deformation, will occur in the components subjected to asymmetrical cyclic stressing within plastic deformation regime (see Fig. 1). The ratchetting strain shall increase with the number of applied cycles until the failure occurs in the most of loading cases. Therefore, when the low-cycle fatigue behaviour of the materials presented in the asymmetrical cyclic stressing with apparent plastic deformation is addressed, it is extremely necessary to discuss the effect of ratchetting behaviour on the fatigue life, i.e., ratchetting–fatigue interaction. Since the ratchetting is important in the design of such components, in the last two decades, it was studied by many researchers, as reviewed by Ohno [1], Bari and Hassan [2] and Abdel-Karim [3] and recently done by Chen et al. [4,5], Kang [6], and Kang et al. [7–12], Vincent et al. [13], Abdel-Karim [14,15], Johansson et al. [16], Khoei and Jamali [17], Yaguchi and Takahashi [18,19] and so on. However, the above-referred literature focused only on the ratchetting deformation and its constitutive modeling. Since the number of applied cycles was relatively small (less than 1000 cycles), and the ratchetting–fatigue interaction was not addressed in the above-referred literature.

For its significance in the design and assessment of structure components, the ratchetting–fatigue interaction has been investigated recently by some researchers. The

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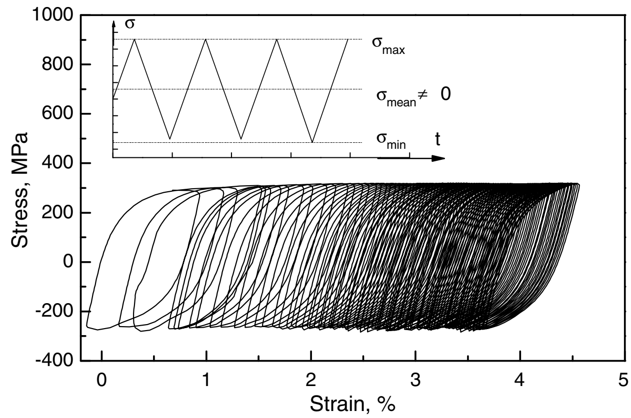

Fig. 1. Stress–strain curve in asymmetrical cyclic stressing, where ratchetting occurs.

experimental results conducted by Rider et al. [20] showed that cyclic plastic strain vs. fatigue life curves did not fit Manson–Coffin relationship [21,22] for En3 steel in the cyclic stressing with axial mean stress; however for En19 steel, the curves fitted Manson–Coffin relationship well in the cyclic stressing with lower axial mean stress. The effects of mean stress and ratchetting strain on fatigue life were separated by two different preloading procedures in [23]. It is shown that both ratchetting strain and mean stress can cause additional damage and then result in a monotonically decreasing of fatigue life when the applied mean stress increases. The effect of mean stress on low-cycle fatigue in cyclic stressing was discussed for copper was discussed in [24]. The results showed that fatigue life increased with mean stress till a critical mean stress was reached, after then the further increase of mean stress would shorten the fatigue life. However, for SS304 stainless steel, Kang et al. [25] found that the fatigue life did not decrease monotonically with the increase of tensile mean stress. Variation of mean stress slightly influenced the fatigue life, and the shortest fatigue life occurred in the cyclic stressing with small mean nominal stress (such as 5 and 10 MPa). Kang and Liu [26] also found that for 42CrMo steels with different heat-treatment, the fatigue life monotonically decreased with the increases of applied mean stress and stress amplitude, similar to that in [23]. For tempered carbon steel 45, Yang [27] found that the failure mode in cyclic stressing depended on the applied stress amplitude and mean stress: the failure was mainly caused by large ratchetting strain and characterized by apparent necking if the stress amplitude and mean stress were relatively higher; however, the failure was mainly caused by the low-cycle fatigue and featured by brittle fracture if the applied stress level was relatively lower. To sum up, it is shown that the ratchetting–fatigue interaction differs for various materials and loading cases.

In last decades, many failure approaches were constructed to correlate and predict the fatigue life of the materials. For high-cycle fatigue, most of failure models were established in the framework of stress-based approach, such as Basquin relation [28], Goodman's diagram [29], Soderberg's diagram [30] and so on, where fatigue life was mainly related to stress amplitude and the effect of mean stress was also included. However, for low-cycle fatigue, the experimental results were mainly obtained in cyclic straining and most of life prediction models were established in the framework of strain-based approach, such as Manson–Coffin relationship [21,22], Morrow model [31], SWT model [32] and so on. Although the effect of mean stress on low-cycle fatigue life was considered in some traditional models [31,32], the ratchetting–fatigue interaction in asymmetrically cyclic stressing was not addressed there. Recently, Rider et al. [20], Xia et al. [23] provided some newly developed failure models to provide more accurate prediction for the low-cycle fatigue life in cyclic stressing by addressing the effect of ratchetting strain. For some cyclic hardening/softening materials, since their stress–strain responses are always varied during the cyclic stressing, it is difficult to obtain steady responded strain amplitude. Therefore, a stress-based approach is more suitable when the cyclic stressing is specified. Traditionally, the application of stress-life approach is limited to high-cycle fatigue; however, recent researches show that the stress-based approach is also capable of correlating the data of low-cycle fatigue [24,33]. Although the ratchetting–fatigue interaction was considered in [33] by the established stress-based failure model, the effect of cyclic softening/hardening feature of the material was not addressed in such model, and then the prediction was not so good for the materials presented cyclic softening feature.

In this paper, based on the experimental results obtained by Kang et al. [25,26] for SS304 stainless steel, annealed and tempered 42CrMo steels, a stress-based fatigue failure model (SBF model) is constructed to predict the fatigue life of the materials presented in uniaxial cyclic stressing with the ratchetting effect concerned. In the SBF model, applied maximum stress and stress ratio R are addressed, and an item dependent upon stress ratio R is introduced into the SBF model to describe the effect of ratchetting strain on the fatigue life. To consider the effect of cyclic softening feature on the ratchetting–fatigue interaction of the materials, the SBF model is then extended by a newly defined variable FP, which is dependent upon maximum stress, stress ratio and cyclic softening effect. Comparison with the experimental results shows that the modified SBF model (i.e., MSBF model) provides a fairly good prediction to the fatigue life of the materials with cyclic softening feature.

2. Experimental results and discussion

To keep the integrity of this work, some experimental results necessary to construct failure model are outlined in the next paragraphs and the detailed discussion of the ratchetting–fatigue interaction for the materials in question can be found in [25,26]. It should be noted that some predicted results are also plotted in the figures to be compared with the results obtained by tests.