Renewable and Sustainable Energy Reviews 82 (2018) 940–949

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Advances in fatigue life modeling: A review

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ARTICLE INFO

*Keywords:*
Fatigue
Critical plane
Optimization algorithm
Classical fatigue models
Hybrid models

ABSTRACT

The purpose of this paper is to examine the state-of-the-art research efforts linked with the development of fatigue life estimation models. The main objective is to identify new concepts for fatigue life estimation other than the classical models and their hybrids. Various techniques to estimate fatigue life have been identified, such as critical plane deviation, 5D deviatoric space enclosed surface, modified Wholer curve. However, the most notable one to be found is the application of evolutionary optimization algorithms for, e.g., genetic algorithms, artificial neural networking, and differential ant-stigmergy algorithms. Initially, a brief history of fatigue life estimation and modeling is presented. In subsequent sections, some familiar classical models are discussed, and then various innovative approaches to fatigue life prediction are reviewed. The survey is fairly detailed, and best efforts have been made to the net in as many new methodologies as possible. The review is organized to offer insight on how past research efforts have provided the groundwork for subsequent studies.

## 1. Introduction

The importance of fatigue is evident; although exact numbers are not available, it is expected that at least half of all mechanical failures are due to fatigue. The cost of these failures constitutes approximately 4% of the gross national product of the USA [1]. That is why it is essential to understand the physics of fatigue, to create a cause and effect relationship to reduce the probability of such failures [2]. Since the investigations by Wohler in 1860, fatigue experiments and predictions have played a major role in mechanical design [3,4], and researchers are investigating the fatigue problem have made enormous efforts to devise sound methodologies suitable for safely assessing mechanical components subjected to time-variable loadings [5–10]. It is an acknowledged fact that to estimate fatigue life accurately in real-world scenarios is a complex task in which various variables have to be taken into account to avoid unwanted and dangerous failures [11]. The reliability of a fatigue estimation technique depends on its ability to model damage due to non-zero superimposed static stresses, the degree of multiaxiality in the stress field and the effects of stress concentration phenomena [12]. For the cases of cyclic and random multiaxial loading conditions, it was difficult to estimate fatigue life as damage is dependent on all the stress components and their variations during the whole period of load application [12,13]. The fatigue assessment method should be calibrated concerning some experimental information that can be easily obtained through tests run by the relevant standard codes to predict the fatigue estimation results accurately [6,11,12,14,15]. Stress analysis is conducted to correctly estimate fatigue damage by direct post-processing simple linear elastic finite element [16] models [17–21].

In this paper, a review of fatigue estimation techniques has been presented, with the emphasis on the newly proposed models highlighting new ideas to estimate fatigue life. As the models developed by accommodating the proposed modifications to the earlier models have limited capability of estimating the fatigue life in limited loading or material conditions, no universally accepted model can estimate or predict fatigue life for a range of loadings as well as material conditions [6,22]. This review paper attempts to catalogue the novel concepts as well as methods for fatigue life estimation that may be helpful in formulating a universal model for a broad range of loadings and material conditions.

## 2. Material fatigue

Fatigue is defined as a failure under a repeated load which never reaches a level sufficient to cause failure in a single application [17]. The word fatigue originates from the Latin expression 'fatigue' which means 'to tire'. The terminology used in engineering refers to the damage and failure of materials under cyclic loads, including mechanical loads, thermal loads, and so forth [23]. Fatigue damage characterized by nucleation, coalescence and stable growth of cracks, leading ultimately to net section yielding or brittle fracture. An evaluation of fatigue of structures and materials in the 20th century raises the question

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http://dx.doi.org/10.1016/j.rser.2017.09.047
Received 13 August 2015; Received in revised form 27 July 2017; Accepted 14 September 2017
1364-0321/ 

what may have happened in the 19th century. The fatigue of structures became evident as a by-product of the industrial revolution in the 19th century. Fatigue failures frequently associated with steam engines, locomotives, and pumps. Systematic fatigue tests were done in a few laboratories, notably by August Wohler. It recognized that small radii in the geometry of the structure would be avoided. A fundamental step regarding fatigue as a material problem made at the beginning of the 20th century by Ewing and Humfrey [24]. The author investigated that the fatigue crack nuclei start as microcracks in slip bands [25]. When components stressed in the high-cycle fatigue (HCF) or very high-cycle fatigue (VHCF) regime, most load cycles in realistic in-service loading sequences are at stress amplitudes that are too low to cause failure under constant amplitude loading conditions. Constant amplitude cycling below the endurance limit does not lead to fracture, but it can cause fatigue damage. Several investigations show that short fatigue cracks could be initiated by cycling carbon steels below the endurance limit [26,27].

In the real-world scenarios, loading conditions are variable and complex, and the resulting stress states are also multiaxial. Multiaxial loads, which can be in-phase (proportional) or out-of-phase (non-proportional), are common for many components and structures. Even under uniaxial loads, multiaxial stresses often exist, although typically in-phase, for example, due to geometric constraints at notches. Such multiaxial loads and stress states are frequently encountered in many industries, including automotive, aerospace, and power generation, among others [28]. Non-proportional multiaxial fatigue damage occurs if the principal stress directions vary during the loading induced by out-of-phase bending and torsion moments [29]. The methodologies for the more complex case of multiaxial variable amplitude loading are not yet well established, particularly when the loads are non-proportional [30].

## 3. Reported researches on fatigue life estimation methods

### 3.1. Classical models

#### 3.1.1. Stress-based models

Sines [31], Sines [32] proposed that octahedral (von Mises) shear stress is used as a fatigue damage criterion as expressed in Eq. (1), but this model is incapable of handling non-proportional loading.

$$\frac{\Delta\tau_{oct}}{2} + \alpha(3\sigma_h) = \beta \tag{1}$$

where $\Delta\tau_{oct}$ = octahedral stress (von Mises) range, $\sigma_h$ = hydrostatic stress, $\alpha$, and $\beta$ are material parameters.

Crossland [33] proposed a similar parameter to that of Sines but used maximum hydrostatic stress ($\sigma_{hmax}$) instead of mean, as expressed in Eq. (2) to face problems in dealing with out-of-phase multiaxial loading [22].

$$\frac{\Delta\tau_{oct}}{2} + \alpha(3\sigma_{h\,\max}) = \beta \tag{2}$$

Findley [34] proposed a fatigue life parameter, as expressed in Eq. (3) based on the combination of shear stress range and normal stress on the plane having the maximum value of the parameter.

$$\left(\frac{\Delta\tau}{2} + k\sigma_n\right)_{\max} = f \tag{3}$$

where $\Delta\tau$ = shear stress range, $\sigma_n$ = normal stress, $k$ = material constant.

McDiarmid [35,36] proposed a model similar to Findley's, as expressed in Eq. (4), in which the critical plane is identified as the plane with the maximum shear stress range, but has a large scatter in results.

$$\frac{\Delta\tau_{\max}}{2t_{A,B}} + \frac{\sigma_{n,\max}}{2\sigma_{uts}} = 1 \tag{4}$$

where $\Delta\tau_{max}$ = maximum shear stress range, $t_{A,B}$ = shear fatigue strength, $\sigma_{uts}$ = ultimate tensile strength.

Van [37] proposed an endurance limit criterion, also known as the Dang Van model, based on the concept of micro-stresses within a critical volume of material, expressed in Eq. (5). Hofmann and Bertolino [38] and Charkaluk and Constantinescu [39] revisited Dang Van model and suggested a finer qualitative analysis to understand the ability of the model better.

$$\tau(t) + a\sigma_h(t) = b \tag{5}$$

where $\tau(t)$ = instantaneous shear stress, $\sigma_h(t)$ = instantaneous hydrostatic stress, $a$ and $b$ = material constants.

#### 3.1.2. Strain-based models

Brown and Miller [40,41] and Kandil and Brown [42] proposed a parameter based on the maximum shear strain range and normal strain range on the plane experiencing the maximum shear strain range, as expressed in Eq. (6).

$$\frac{\Delta\gamma_{\max}}{2} + S\Delta\varepsilon_n = A\frac{\sigma_f^{'} - 2\sigma_{n,mean}}{E}(2N_f)^b + B\varepsilon_f^{'}(2N_f)^c \tag{6}$$

where $\Delta\gamma_{max}$ = maximum shear strain range, $\Delta\varepsilon_n$ = normal strain range, $\sigma_{n,mean}$ = mean normal stress, $S$, $A$ and $B$ = material constants.

Wang and Brown [43] proposed a modification of the model proposed by [41], adding the capability to handle the strain path effect. The model is expressed in Eq. (7).

$$\begin{aligned}\frac{\Delta\hat{\gamma}}{2} = \frac{\Delta\gamma_{\max}}{2} + S\varepsilon_n^* \; &= \; (1+\nu_e+(1-\nu_e)S)\sigma_f'(2N_f)^b \\ &+ (1+\nu_p+(1-\nu_p)S)\varepsilon_f'(2N_f)^c\end{aligned} \tag{7}$$

where $\Delta\hat{\gamma}$ = equivalent shear strain connection, $\Delta\gamma_{max}$ = maximum shear strain range, $\varepsilon_n^*$ = normal strain excursion between two turning points of $\gamma_{max}$, $\nu_e$ and $\nu_p$ = elastic and plastic Poisson ratio, $S$ = material parameter representing the influence of normal strain on fatigue crack growth.

#### 3.1.3. Strain energy-based models

Smith, Watson [44] proposed a damage model also known as the Smith Watson Topper (SWT) model, including the cyclic normal strain range and maximum normal stress, as expressed in Eq. (8); the critical plane is identified as the plane of maximum normal stress. This model was originally developed, and it is still used for mean stress correction.

$$\sigma_{n,\max}\frac{\Delta\varepsilon_1}{2} = \frac{\sigma_f^{'2}}{E}(2N_f)^{2b} + \sigma_f^{'}\varepsilon_f'(2N_f)^{b+c} \tag{8}$$

where $\sigma_{n,max}$ = maximum normal stress, $\Delta\varepsilon_1$ = principal strain range, $\sigma_f^{'}$ = fatigue strength coefficient, $\varepsilon_f^{'}$ = fatigue ductility coefficient, $E$ = elastic modulus, $N_f$ = fatigue life, $b$ = fatigue strength coefficient, $c$ = fatigue ductility exponent.

Fatemi and Socie [45] suggested a modification to the Brown and Miller model by replacing the normal strain term with normal stress. Eq. (9) represents the Fatemi–Socie model when shear fatigue properties are used [1] and also in the form of uniaxial fatigue properties [45,46]. Additional cyclic hardening developed during out-of-phase loading included in the normal stress term. Mean stress accounted for by adding the normal mean stress across the maximum shear plane to the alternating normal stress across the same plane.

$$\begin{aligned}\frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,\max}}{\sigma_y}\right) &= \frac{\tau_f^{'}}{G}(2N_f)^{b\gamma} + \gamma_f^{'}(2N_f)^{c\gamma} \\ &= \left[(1+\nu_e)\frac{\sigma_f'}{E}(2N_f)^b + (1+\nu_p)\varepsilon_f'(2N_f)^c\right]\Bigg[1 \\ &\quad + k\left(\frac{\sigma_f'}{2\sigma_y}(2N_f)^b\right)\Bigg]\end{aligned} \tag{9}$$

where $\Delta\gamma$ = shear strain range, $\sigma_y$ = yield stress, $\tau_f^{'}$ = shear fatigue