Engineering Failure Analysis 45 (2014) 421–435

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Fatigue failure predictions for steels in the very high cycle region – A review and recommendations

Chaminda S. Bandara [a,*], Sudath C. Siriwardane [b], Udaya I. Dissanayake [c], Ranjith Dissanayake [c]

[a] National Research Council of Sri Lanka, Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka
[b] Department of Mechanical and Structural Engineering and Material Science, Faculty of Science and Technology, University of Stavanger, N-4036 Stavanger, Norway
[c] Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka

ARTICLE INFO

Article history:
Received 13 July 2014
Accepted 18 July 2014
Available online 28 July 2014

Keywords:
High cycle fatigue
Failure analysis
Structural steel
S–N curve
Fatigue failure

ABSTRACT

Very high cycle fatigue properties of various steels were studied using findings of previous research and laboratory fatigue testing. First, experimental data for more than 550 specimens covering 25 high and medium strength steels were used to investigate the relationships between the applied stress, number of failure cycles, size of defects or inclusions at fracture origins and stress intensity factors. Using the results of the investigation of these data, general conclusions were arrived at for steels as a whole. It was observed that the size of the failure origin can be predicted using strength properties of steels. Existing methods for estimating major parameters such as size of failure origins and stress intensity factors were reviewed, new methods were proposed and their accuracy was verified using experimental data. Also, the possibility of simplifying existing formulae with substitutions for the major parameters was reviewed. Employing these major parameters, new formulae for predicting fatigue strengths of both medium and high strength steels were proposed. Predictions of these proposed formulae were compared with existing well known formulae using experimental data and statistical methods highlighting the simplicity and importance of the proposed formulae. The ability of employing the proposed formulae for predicting, "fatigue strengths that are more close to the real values" as well as "fatigue strengths that are more safe and conservative" was reviewed. Secondly, fatigue properties and failure causes of medium strength – low carbon structural steels that are usually used in civil engineering structures were investigated. For this investigation, 35 smooth specimens of five steels were tested using a rotating bending fatigue tester. It was observed that fatigue failures occur up to around 10^7 cycles and that the failure originates from the surface. It was found that the formulae proposed are able to predict failures of these medium strengths steels. Slopes of stress life curves in the very high cycle fatigue regions were well predicted by these proposed formulae while the predictions were fairly aligned with values suggested in previous research. Finally, recommendations were given for employing suitable prediction methods considering safety and importance of components and structures.

---

* Corresponding author. Tel.: +94 775400273.
E-mail addresses: bandara@civil.pdn.ac.lk, chamindasbandara@yahoo.com (C.S. Bandara).

http://dx.doi.org/10.1016/j.engfailanal.2014.07.015
1350-6307/

1. Introduction

Stress life curve (*S–N* curve) that describes the relationship between cyclic stresses and number of stress cycles to failure is one of the most widely used tools for fatigue life evaluation in metals. Due to the importance of fatigue, a lot of research has been carried out since the 1850s from studies of August Wohler (1819–1914), John Goodman (1862–1935), Herbert J. Gough (1890–1965), A.A. Grifaith (1893–1963), Bernard P. Haigh (1884–1941), Heinz Neuber (1906–1989) and many other scientists and engineers [1]. One of the main observations related to *S–N* curves in the past for various steels was the fatigue limit. In the 1980s, with the development of high frequency fatigue equipment, researchers discovered that there is no fatigue limit for most steels in the long life region. Therefore, studies on very high cycle fatigue (VHCF, gigacycle) began. Existing VHCF theories are mainly based on the findings of Murakami [2], Bathias [3] in the end of the 20th century and the work of many other researchers in the 21st century. Outcomes of these fatigue research and new developments are converging towards the reality. However, to reduce uncertainties and related safety risks, more work has to be done.

Fatigue testing is usually expensive and time consuming; both factors are much higher for gigacycle testing [4]. Therefore, empirical formulae and various approximate methods have been used for predicting *S–N* curves. One of the well-known formulae that describes the *S–N* relationship in the high cycle fatigue (HCF) region for stress ratio $R = -1$ is Basquin's formula given in Eq. (1),

$$\sigma_a = \sigma'_f \cdot (2N)^b \tag{1}$$

where, σ_a is the cyclic stress amplitude in N/mm^2, N is the number of cycles to failure, σ'_f is the fatigue strength coefficient and b is the fatigue strength exponent. Several empirical methods such as Morrow method, Manson's universal slope method, Manson's four-point method, Mitchell's method, Muralidharan–Manson method, Baumel–Seeger method, Ong's method, Roessel–Fetami method and Medians method [5–8] are available for estimating σ'_f and b using monotonic material properties. When the stress ratio $R \neq -1$, a mean stress correction should be applied to fatigue strength predictions of Eq. (1). Goodman, Morrow, Gerber, Soderberg and modified Goodman are some of the well known methods used for mean stress correction. Smith–Watson–Topper (SWT) and Walker proposed simplified formulae that include mean stress corrections within those formulae. Many studies have been done and improvements have been suggested to these mean stress correction methods [1,9–11].

It is known by experiments that Basquin's formula is valid for failure predictions in the VHCF region. However, σ'_f and b should be estimated using a different set of formulae than those used in the HCF region [12]. VHCF failures are generally caused by internal inclusions and defects that exist in metallic materials. After extensive research on inclusions and defects, the fatigue strength prediction formula for metallic materials in the VHCF region, proposed by Murakami and Endo [2,13] for any stress ratio R is given in Eq. (2),

$$\sigma_w = \beta \cdot \frac{(Hv + 120)}{\sqrt{area}^{1/6}} \left(\frac{1-R}{2}\right)^{\alpha} \tag{2}$$

where, σ_w is the fatigue strength amplitude in N/mm^2, H_V is the Vickers hardness in kgf/mm^2, $\sqrt{area}$ is the effective size of the failure origin (defects, inclusions and cracks) that causes the failure in µm, $\alpha = 0.226 + Hv \times 10^{-4}$ and, β is 1.43 for surface inclusions or defects and 1.56 for internal inclusions or defects. Various alterations have been proposed for Murakami formulae by many researchers [4,12,14–16]. However, there are still contradictions and unsolved problems. Therefore, in this study, a comprehensive analysis of past research was carried out together with experimental investigations thereby providing solutions for at least some of the problems. Further, addressing deficiencies of existing fatigue prediction formulae, simplified formulae are investigated and proposed.

Fatigue is a well known cause of failure of civil engineering steel structures such as railway bridges, offshore platforms, jetties, towers, factory buildings and various other structures that are subjected to cyclic loading. Iron (i.e. cast iron and wrought iron) has been used in civil engineering structures since the 18th century [17]. From the 19th century, steel (mild steel) became common due to its improved strength properties and workability. Most of the structural steels used in civil engineering structures are medium and low carbon steels (Carbon < 0.3%) that are in the category of low and medium strength (ultimate tensile strength $\sigma_u < 1200$ N/mm^2). Structural steel is the major metallic material used in the world. However, research work available on VHCF properties of low and medium strength steels is few. Therefore, this study on fatigue properties of medium strength structural steels was carried out and applicability of usual VHCF *S–N* relationship for these structural steels was investigated.

2. *S–N* relationship

S–N relationship is the link between the applied stress (*S*) versus the applied number of stress cycles until failure (*N*) of specimens. *S–N* relationship is usually presented as a graph where *N* is on the *X* axis on the log scale and *S* is on the *Y* axis on the log scale. The shape of *S–N* curves of metallic materials varies with material properties. Fatigue limit (constant fatigue strength for low stresses) for *S–N* curves of most steels used before the 1980s is now referred to as the HCF limit beyond which the VHCF region exists. The HCF limit is empirically estimated by $0.5\sigma_u$ of the material that starts around 5×10^5 to 10^7 cycles. A study carried out by Yamaguchi et al. [18] for rotating bending fatigue testing of steels (quenched and