Hardness-Based Non-destructive Method for Developing Location Specific S-N Curves for Fatigue Life Evaluation

Chaminda S. Bandara¹, Sudath C. Siriwardane², Udaya I. Dissanayake¹ and Ranjith Dissanayake¹

1. Department of Civil Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka

2. Department of Mechanical and Structural Engineering and Material Science, Faculty of Science and Technology, University of Stavanger, Stavanger N-4036, Norway

Abstract: This paper first describes the importance of using location specific S-N curves for fatigue damage assessment of existing steel structures. It discusses the existing concepts and methods for developing S-N curves using empirical formulae and monotonic strength parameters, such as the ultimate tensile strength and hardness. It also discusses relationships among these monotonic parameters. Then it presents formulae for developing hardness-based full range S-N curves for medium strength steels. The formulae are verified using experimental data obtained from both monotonic and cyclic testing. Finally, it describes the advantages of these hardness-based formulae for developing location specific S-N curves as hardness testing is a non-destructive test which can be carried out on specific locations in structures.

Key words: Stress life curve, fatigue life, hardness, steel structures, non-destructive test.

1. Introduction

Steel plays a major role in civil engineering structures and is one of the heavily-used materials in the last several centuries. Fatigue failure is a common phenomenon in steel structures due to cyclic loading. Therefore, designing against fatigue is important. The conventional method of assessing fatigue damage of structures uses stress-life (S-N) curves in the HCF (high cycle fatigue) and GCF (gigacycle fatigue) regions while strain-life (ϵ -N) curves are used in the LCF (low cycle fatigue) region [1, 2]. Civil engineering structures are generally subjected to HCF during service loading. Therefore, S-N curves are usually employed for fatigue damage estimations.

EN 1993-1-9:2005 [3] and AASHTO LRFD: 2012 [4] are well-known codes for S-N curve based on damage evaluations of steel bridges. S-N curves given in codes take account of the effect of stress

concentrations of various detail categories; However, variation of the properties of steel is not considered sufficiently. Therefore, for precise assessment of the fatigue damage of a structural element made by particular steel, an experimentally-developed S-N curve of that particular steel (material specific S-N curve) is necessary. Further, in large structures and structures with large number of steel elements, properties of the steel used may vary from one location or element to another. The strength variation observed in centuries old wrought iron bridges due to lack of quality controlling is an instance [5]. Therefore, for a precise fatigue assessment of a specific location or element of a structure, an S-N curve which represents the material properties of that particular location (location specific S-N curve) is necessary. However, developing S-N curves by conducting fatigue testing is not easy because: (1) conducting laboratory fatigue testing is costly and time-consuming while testing for gigacycles requires sophisticated equipment [6];

Corresponding author: Chaminda S. Bandara, Ph.D., research field: structural engineering.

(2) there are limitations for obtaining large quantities of materials from critical structural elements for fatigue testing. Therefore, it is important to build up methods for developing S-N curves without conducting fatigue testing. This paper proposes a method for developing location specific S-N curves for medium strength steels using an empirical formula and non-destructive hardness testing.

1.1 Empirical Formulae and Monotonic Test-Based S-N Curves

Monotonic test-based empirical formulae are useful for developing S-N curves. Some of the well-known empirical formulae are Basquin and Manson-Coffin equation for LCF and HCF regions [7] and Murakami formulae for GCF region [8, 9]. Using these formulae saves time, money and material while producing material specific S-N curves. Basquin's equation describing the S-N behavior of metals in the HCF region (partial S-N curve for HCF region) is given in Eq. (1):

$$\sigma_a = \sigma'_f \cdot (2N)^b \quad (1)$$

where, σ_a is the cyclic stress amplitude in N/mm^2 , N is the number of cycles to failure, σ'_f is the Basquin's coefficient (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, Baume-Seeger method, Ong's method, Roessel-Fetami method and Medians method [10-13], are available for estimating σ'_f and b using monotonic material properties.

Fatigue strength prediction formula for metallic materials in the GCF region, first proposed by Murakami and Endo [9] and later modified by Wang et al. [14] for stress ratio $R = -1$, is given in Eq. (2):

$$\sigma_w = \beta \cdot \frac{H_v + 120}{(\sqrt{\text{area}})^{1/6}} \quad (2)$$

where, σ_w is the fatigue strength in N/mm^2 , H_v is the Vickers hardness in kgf/mm^2 , $\sqrt{\text{area}}$ is the effective size of the defect (inclusion or crack) that causes the failure in μm , and $\beta = 3.09 - 0.12\log N$ or $\beta = 2.79 - 0.108\log N$ for internal or external defects, respectively.

In order to simplify Eq. (2), the term $\sqrt{\text{area}}$ can be replaced with the term $(14/\sigma_u^2)$. The averaged formula proposed for both internal and external defects by Bandara et al. [15] is given in Eq. (3):

$$\sigma_w = \frac{\sigma_u^{1/3}}{1,000} \cdot (H_v + 120) \cdot (155 - 7\log N) \quad (3)$$

where, σ_u is the ultimate tensile strength in N/mm^2 . It can be mentioned that Eq. (3) is a partial S-N curve that can be used to develop S-N curves in the GCF region for steels.

Combining these empirical formulae with the Palmgren function [16], the recently-proposed full range uniaxial $R = -1$ S-N curve for steels of $\sigma_u < 1,400 \text{ N/mm}^2$ [17] is given in Eq. (4) (this formula is called "the existing formula" in this paper):

$$\begin{aligned} \sigma(N) &= a \cdot (N+B)^b + c \quad (4) \\ B &= \left(\frac{\sigma_u - c}{a} \right)^{1/b} \\ a &= \left\{ \frac{\sigma_{\text{GCF}} - \sigma_k}{N_{\text{GCF}}^b - N_k^b} \right\} \\ c &= \left\{ \frac{\sigma_k \cdot N_{\text{GCF}}^b - \sigma_{\text{GCF}} \cdot N_k^b}{N_{\text{GCF}}^b - N_k^b} \right\} \end{aligned}$$

where, $\sigma(N)$ is the dependence of the stress amplitude σ_a on number of cycles N , σ_{GCF} is the fatigue strength amplitude in N/mm^2 in the GCF region for N_{GCF} cycles ($N_{\text{GCF}} > 10^9$) calculated from Eq. (3), σ_k is the stress amplitude in N/mm^2 at the knee point between the HCF and GCF regions for N_k cycles (2nd knee point) calculated from the relation $\sigma_k = 0.5\sigma_u$, slope $b = -0.19$ for steels of $300 \text{ N/mm}^2 < \sigma_u < 1,400 \text{ N/mm}^2$ and B is the indicative number of cycles at which point the S-N curve bends towards σ_u in the LCF region (the 1st knee point), as shown in Fig. 1.

1.2 Relationship between Hardness and Tensile Strength

Hardness test with portable testers is one of the

Fig. 1 Illustration of the S-N curve and related terms.

widely-used non-destructive tests in the metal industry due to the simple nature of the test and the close relationship between hardness and strength parameters of metallic materials. Murakami and Endo [9], in their study on hardness and crack geometries, mentioned that the relationship $\sigma_u = 3.53HB$ (Brinell hardness) is a reasonable approximation. After a series of experiments on fatigue properties of seven types of carbon, low alloy and stainless steels, Nishijima [18] presented values for (σ_u/H_v) , i.e., 2.91 for ferritic stainless steels, 3.12 for high temperature tempered martensitic carbon and low alloy steels, 3.44 for low carbon ferritic perlite steels and 4.00 for austenitic stainless steels. Using high, medium and plain carbon steels of the Brinell hardness range of 15 $HB \sim 700HB$, Roessel and Fetami [13] proposed a hardness-based method for estimating the parameters of the Basquin and Manson-Coffin formula while proposing a new relationship between HB and σ_u , i.e., $\sigma_u = 0.0012HB^2 + 3.3HB$. The simple relationship between σ_u and HB confirmed by Meggiolaro and Castro [12] in a statistical study on 1,924 steels is given in Eq. (5). It was mentioned that the coefficient of variation of this relationship is 3.8%:

$$\sigma_u = 3.40HB \quad (5)$$

The H_v and HB both are frequently used in fatigue-related formulae; Hence the relationship between them is important. According to ASTM

E140-2 [19], the values of HB and H_v are the same for the range 100 $HB \sim 240HB$ (i.e., $340 \text{ N/mm}^2 < \sigma_u < 816 \text{ N/mm}^2$). Murakami [8] mentioned that, for $H_v < 400$, HB can be substituted for H_v where the difference is only 20 ($400H_v = 380HB$). Accordingly, any substitution between H_v and HB for steels of $\sigma_u < 1,292 \text{ N/mm}^2$ ($\sigma_u = 3.4HB$) is acceptable.

2. Developing Formulae for Hardness-Test-Based Full Range S-N Curve

Keeping the existing formula for the full range S-N curve given in Eq. (4) unchanged, the formulae for estimating parameters σ_{GCF} , σ_k , N_k and B are derived with substitutions. Accordingly, substituting for σ_u from Eq. (5) and replacing HB for H_v , σ_{GCF} is given in Eq. (6):

$$\sigma_{GCF} = 0.0015HB^{1/3} \cdot (HB+120) \cdot (155 - 7 \cdot \log N_{GCF}) \quad (6)$$

where, $N_{GCF} \geq 10^9$ cycles.

Substituting from Eq. (5) for $0.5\sigma_u$, σ_k is given in Eq. (7):

$$\sigma_k = 1.7HB \quad (7)$$

Substituting from Eq. (5) for σ_u and replacing HB for H_v , N_k is given in Eq. (8):

$$N_k = 10^{\left(22.14 - \frac{162HB^{2/3}}{HB+120}\right)} \quad (8)$$

Then, B is calculated by using Eq. (4).

The value of b is significant as it describes the slope, as well as the 1st knee point of the S-N curve.

Therefore, b is determined substituting the coordinates of the 1st knee point (σ_j , N_j) in Eq. (4) and doing iteration. The 1st knee point N_j for steels is generally considered as 1,000 cycles while the fatigue strength at the 1st knee point σ_j varies with σ_u in the range $0.76\sigma_u - 0.9\sigma_u$ where $0.9\sigma_u$ is applicable for wrought steels [20]. According to Meggiolaro and Castro [12], the average fatigue strength of 754 medium and high strength steels at 1,000 cycles under uniaxial fatigue is $0.76\sigma_u$. Accordingly, using $0.9\sigma_u$ for steels with $\sigma_u < 400 \text{ N/mm}^2$ and $0.76\sigma_u$ steels with $400 \text{ N/mm}^2 < \sigma_u < 1,400 \text{ N/mm}^2$, a global value for b ($b = -0.21$) is estimated. The main reason for the change of b from the previous value (i.e., -0.19 in Eq. (4)) is the use of Eq. (5) throughout the proposed method.

3. Experimental Work

QST (quenched and self-tempered) steel and CTD (cold twisted deformed) steel tested in our laboratory and experimental data of three other steels from Refs. [18, 21-23] are used for verifying the hardness-based proposed formulae. Table 1 shows the chemical compositions of QST and CTD steels.

3.1 Tensile and Hardness Testing

Tensile testing for specimens prepared from QST and CTD steels was carried out in accordance with ASTM E 8-01 [24] using three tensile specimens of diameter of 4.0 mm for each steel. A Hounsfield tensile tester was used together with gauges for measuring the

reduction in area and elongation.

The hardness testing for QST and CTD steels were carried out in accordance with ASTM A 833-84 [25] and ASTM E 18-02 [19]. A hammer hitting type portable Brinell hardness tester with a diameter of 10 mm ball indenter, as well as a Rockwell hardness tester, were used to obtain the hardness values. Rockwell hardness values were converted to Brinell hardness as per ASTM E 140-7 [26]. Comparing the hardness values obtained from the two tests, the accuracy of the hardness measurements obtained from the portable hardness tester was verified. Mean values of tensile strengths, tensile properties and Brinell hardness of steels are given in Table 2.

3.2 Fatigue Testing

Fatigue testing for QST and CTD steels was carried out in accordance with BS 3518-2:1962 [27] by using a rotating bending ($R = -1$) fatigue testing facility at frequency of 50 Hz. Specimen dimensions are shown in Fig. 2. From each steel, 18 specimens were tested up to failure or stopped at 5×10^7 cycles, otherwise. The factor 0.85 was used for converting the rotating bending fatigue strengths into uniaxial fatigue strengths [1]. The resulting S-N curves of the two steels are shown in Section 4.

Strength properties of three kinds of steels (42CrMo4, D38MSV5S and S25C) obtained from literature for this study are given in Table 3. Fatigue testing of these steels has been done using axial tension-compression testers with stress ratio $R = -1$.

Table 1 Chemical compositions of QST and CTD steels.

Steel	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V	B
QST	0.191	0.152	0.880	0.025	0.029	0.132	0.055	0.077	0.010	0.354	0.010	0.005
CTD	0.174	0.165	0.812	0.054	0.039	0.108	0.021	0.020	0.010	0.223	0.010	0.005

Table 2 Strength properties of QST and CTD steels.

Steel	σ_u (N/mm ²)	Yield strength σ_Y (N/mm ²)	Breaking strength σ_f (N/mm ²)	Brinell hardness number (HB)	Elongation at break (EB%)
QST	595	402	390	178	33
CTD	562	403	469	169	33

Fig. 2 Fatigue specimen dimensions (units in mm).

Table 3 Strength properties of steels obtained from literature.

Material	Reference	σ_u (N/mm ²)	H_v (kgf/mm ²)	HB (converted from H_v)
42CrMo4 steel	Pyttel et al. [23]	1,350	405	384
D38MSV5S steel	Garcia et al. [21]	878	246	251
Carbon steel (S25C)	Nishijima [18] and NRIIM (National Research Institute for Metals) [22]	489	142	142

(a)

(b)

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(c)

(d)

(e)

Fig. 3 S-N curves for: (a) S25C steel; (b) CTD steel; (c) QST steel; (d) D38MSV5S steel; (e) 42CrMo4 steel. P_s is the probability of survival.

4. Verification of the Proposed Formulae

The proposed formulae are based on the relationship between σ_u and HB . Therefore, this relationship is first investigated by comparing Eq. (5) with the experimental results. The coefficient of variation between Eq. (5) and experimental results is 2.7%.

Then, the predicted S-N curves using the proposed formula with Eqs. (6)-(8) are compared with the experimental S-N curves (Figs. 3a-3e). The S-N curves predicted by employing the existing formulae that used σ_u and H_v are also plotted in the same figure.

Due to large scatter of experimental fatigue data, probability-based approaches are usually used for determining the safe design S-N curve. The probability of survival P_s for metals is determined by Eq. (9) :

$$T_\sigma = 1: [\sigma_a (P_s = 10\%) / \sigma_a (P_s = 90\%)] \quad (9)$$

where, T_σ for structural steels (medium strength steels) is 1:20 [6]. Accordingly, $P_s = 90\%$ curves are also plotted in Figs. 3a-3e in order to confirm the validity of the proposed formula.

It is observed that the difference between the proposed formula and the existing formula is negligible for medium strength steels of the range ($489 \text{ N/mm}^2 < \sigma_u < 1,350 \text{ N/mm}^2$) used in this study. A good agreement between the experimental data and predicted S-N curves was also observed. These observations verify that the proposed formula is capable of predicting S-N curves of medium strength steels only using Brinell hardness.

5. Discussions

Fatigue, high stresses, corrosion, wear and tear, fretting, temperature etc. cause changes to materials in existing structures. Therefore, damage assessment of existing structures is not easy. For accurate fatigue damage assessments, material and location (or element) specific S-N curve are very important. However, obtaining material samples from existing structures is difficult. Therefore, onsite non-destructive testing is preferred. Hardness testing is one of the

non-destructive methods used for estimating properties of steels. The described method and formula proposed in this paper can effectively be used to obtain fatigue S-N curves using hardness measurements for medium strength steels.

The formula proposed in this paper is a full-range S-N curve. Full-range S-N curve of a material is important for assessing cumulative fatigue damage of structures subject to varying stress ranges. Hence the main advantage of this formula is that it can be used to estimate the cumulative damage with loading sequence effects (with the sequential law or similar damage accumulation methods). Further, the formula may be an effective tool for fatigue based designing of new steel structures as well.

6. Conclusions

Monotonic testing and empirical formulae-based methods are widely used for developing S-N curves for metallic materials. Such S-N curves are more appropriate than code provided general S-N curves for fatigue damage assessment and life evaluation. Accordingly, a simplified formula of full range S-N curves for medium strength steels was proposed by combining existing empirical formulae and a mathematical function. The monotonic test-based material parameter needed for the formula is only the Brinell hardness. Major conclusions of the study are as follows:

- Existing empirical formulae and methods can be used with hardness measurements of steels for assessing fatigue damage of existing structures effectively. This study shows that the S-N curves developed using hardness measurements are very close to the S-N curves developed using fatigue testing;
- The proposed formula is able to predict S-N curves of medium strength steels from the first cycle to gigacycles. The accuracy of predictions was verified using experimental data. Therefore, the formula can be used for assessing cumulative damage caused by various stress ranges;

• Recent researches show that there is no fatigue limit for most of steels. Therefore, assuming a fatigue limit is not safe. The formula proposed in the present paper predicts a reasonable slope in the HCF-GCF region that represents the true S-N behavior.

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