Research Article

Fatigue Properties Estimation and Life Prediction for Steels under Axial, Torsional, and In-Phase Loading

Ernian Zhao ¹, Qiang Zhou,² Weilian Qu ² and Wenming Wang ¹

¹School of Civil Engineering, Shandong Jianzhu University, Jinan, Shandong 250101, China

²Hubei Key Laboratory of Roadway Bridge & Structure Engineering, Wuhan University of Technology, Wuhan, Hubei 430070, China

Correspondence should be addressed to Wenming Wang; wangwenmingmr@sdjzu.edu.cn

Received 11 December 2019; Accepted 19 February 2020; Published 27 April 2020

Academic Editor: Michelina Catauro

Copyright © 2020 Ernian Zhao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In this study, several estimation methods of fatigue properties based on different monotonic mechanical parameters were first discussed. The advantages and disadvantages of the Hardness Method proposed by Roessle and Fatemi were investigated and improved through the analysis of a total of 92 fatigue test data. A new Segment Fitting Method from Brinell hardness was then proposed for the fatigue properties estimation, and a total of 96 pieces of fatigue test data under axial, torsional, and multiaxial in-phase loading were collected to verify the applicability of the new proposal. Finally, the prediction accuracy of the new proposal and three existing estimation methods was compared with the predictions based on the experimental fatigue properties. Based on the results obtained, the newly proposed estimation method has a significant improvement on the relation between fatigue ductility coefficient and Brinell hardness, which consequently improves the fatigue life prediction accuracy with the scatter band of 2, particularly for the materials with low Brinell hardness. The present study can provide a simplified analysis of the preliminary fatigue design of engineering structures.

1. Introduction

The Manson–Coffin equation combined with equivalent strain parameters or critical plane parameters has been routinely applied in the strain-life prediction for uniaxial or multiaxial fatigue. The Manson–Coffin equation is expressed as follows:

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c, \quad (1)$$

where, σ'_f , ε'_f , b , and c are fatigue strength coefficient, fatigue ductility coefficient, fatigue strength exponent, and fatigue ductility exponent, respectively, which are called fatigue properties. $\Delta \varepsilon/2$, $\Delta \varepsilon_e/2$, and $\Delta \varepsilon_p/2$ are total, elastic, and plastic strain amplitudes, respectively, and E is the modulus of elasticity and N_f is fatigue life.

When the Manson–Coffin equation is adopted to evaluate the fatigue performance, it is necessary to first determine the fatigue properties based on the uniaxial fatigue test.

In most cases, however, these parameters are not easy to obtain the basic mechanical properties of materials, so it is essential to test the fatigue properties of various materials, which needs lots of professional fatigue testing procedures and equipment. When referring to multiaxial fatigue life prediction, more parameters, such as cyclic mechanical and nonproportional additional hardening coefficient, also need to be tested [1, 2]. Considering the diversity of metal materials, many repetitive tests are required to obtain the fatigue properties by fatigue tests, which are time-consuming and expensive. In contrast, the monotonic mechanical properties of steel, such as yield strength, ultimate tensile strength, modulus of elasticity, Brinell hardness, and reduction of area, are generally used as the basic mechanical parameters of metal materials and usually available in the metal materials manual.

The fatigue properties of steel are usually quite different due to the dispersion of materials performance. In recent decades, many researchers have attempted to establish the

optimal fitting relationship between the fatigue properties and monotonic mechanical properties to reduce the complex fatigue test and simplify the fatigue life prediction under the condition of ensuring a certain accuracy [3]. Manson et al. [3, 4] expressed the fatigue properties as functions of ultimate tensile strength, σ_u , and reduction of area, RA , and proposed a series of simplified estimation methods, such as the Four-Point Correlation Method and Universal Slopes Method. Baumel and Seeger [5] proposed a Uniform Material Law, in which fatigue strength coefficient, σ'_f , and fatigue ductility coefficient, ϵ'_f , were represented by the ultimate tensile strength, σ_u , and the modulus of elasticity, E , while fatigue strength exponent, b , and fatigue ductility exponent, c , were expressed as statistical mean values based on a large number of test data. As mentioned in reference [3], Mitchell et al. tried to find the fitting relationship between the fatigue properties and the ultimate tensile strength, σ_u , and fracture toughness, ϵ_f . In Mitchell's method, fatigue strength coefficient, σ'_f , and fatigue strength exponent, b , were the function of ultimate tensile strength, σ_u , while fatigue ductility coefficient, ϵ'_f , was approximately taken as the fracture toughness, ϵ_f , and fatigue ductility exponent, c , was taken as the statistical mean value of test data. Muralidharan and Manson [6] and Ong [7] modified the Four-Point Correlation Method and Universal Slopes Method, respectively, and gave different simplified estimation methods of fatigue properties. In recent years, Roessle and Fatemi [8], Shamsaei and Fatemi [2, 9], and Shamsaei and McKelvey [2] studied the estimation methods of fatigue properties and nonproportional cycle mechanical parameters from Brinell hardness, and then life prediction of multiaxial fatigue by using the critical plane method was investigated.

Researchers suggested that fatigue life predictions based on the reasonably estimated fatigue properties can be guaranteed within certain scatter bands of error. The obvious advantage of the estimation method is that it can predict the fatigue life accessibly and effectively and ensure a certain accuracy. In the present paper, the existing estimation methods of fatigue properties were studied, the Hardness Method proposed by Roessle and Fatemi was discussed and improved, and also its advantages and disadvantages were analyzed by using a total of 92 pieces of fatigue test data. A new Segment Fitting Method from Brinell hardness was proposed to estimate fatigue properties, and the estimated fatigue properties were adopted for life prediction of 9 types of steel. A total of 96 pieces of fatigue test data under axial, torsional, and in-phase loading were collected to verify the applicability of the new proposal. Finally, the prediction accuracy of the new proposal and the existing estimation methods was compared with the predictions based on the experimental fatigue properties.

2. Estimation Methods of Fatigue Properties

As mentioned in the foreword, researchers have proposed several estimation methods of fatigue properties based on different monotonic mechanical parameters, and related reviews are available in [2, 3, 10]. Kim et al. [3] verify the

existing estimation methods by using uniaxial fatigue test data of eight types of steel and conclude that the Modified Universal Slopes Method, Uniform Material Law, and Hardness Method can get relatively good fatigue life prediction results. In the present study, the three estimation methods are briefly discussed below.

2.1. Modified Universal Slopes Method. Muralidharan and Manson [6] investigated the Universal Slopes Method previously proposed by Manson et al. and gave a more effective improvement as follows:

$$\sigma'_f = E \times 0.623 \left(\frac{\sigma_u}{E} \right)^{0.832}, \quad (2a)$$

$$b = -0.09, \quad (2b)$$

$$\epsilon'_f = 0.0196 \epsilon_f^{0.155} \left(\frac{\sigma_u}{E} \right)^{-0.53}, \quad (2c)$$

$$c = -0.56. \quad (2d)$$

The fracture toughness, ϵ_f , in equation (2c) can be calculated by

$$\epsilon_f = \ln \left(\frac{1}{1 - RA\%} \right), \quad (3)$$

where RA is the reduction of area.

2.2. Uniform Material Law. Baumel and Seeger [5] proposed a Uniform Material Law in which the fatigue properties are estimated according to material types. For unalloyed and low-alloy steel, the estimation equations were proposed as follows:

$$\sigma'_f = 1.5 \sigma_u, \quad (3a)$$

$$b = -0.087, \quad (3b)$$

$$\epsilon'_f = 0.59 \psi, \quad (3c)$$

$$c = -0.58, \quad (3d)$$

where $(\sigma_u/E) \leq 0.003$, $\psi = 1$, while $(\sigma_u/E) > 0.003$, $\psi = 1.375 - 125 (\sigma_u/E)$.

2.3. Hardness Method. Roessle and Fatemi [8] studied estimation method from Brinell hardness through the least square fitting analysis of the relationship between fatigue strength coefficient, σ'_f , and Brinell hardness, HB , parameters by using 69 pieces of fatigue test data. However, the relationship between fatigue ductility coefficient ϵ'_f and Brinell hardness is established through the intermediate variable of fatigue life, N_f . To determine the fatigue strength exponent, b , and fatigue ductility exponent, c , the statistical mean values of the 69 pieces of fatigue test data were taken as the approximation of the two exponents, respectively. The Hardness Method for fatigue properties estimation method was given as follows:

$$\sigma'_f = 4.25(HB) + 225, \quad (4a)$$

$$b = -0.09, \quad (4b)$$

$$\varepsilon'_f = \frac{0.32(HB)^2 - 487(HB) + 191000}{E}, \quad (4c)$$

$$c = -0.56. \quad (4d)$$

3. A New Proposal from Hardness

The Hardness Method was adopted to fatigue life prediction by Shamsaei and McKelvey [2]. The results show that the prediction error of fatigue life using estimated fatigue properties was relatively large for the materials with small Brinell hardness and generally showed a tendency to dangerous estimation. This is mainly because the Brinell hardness range of data samples used for the estimation of fatigue properties is 150–700. Therefore, the Hardness Method may be not suitable for materials with low Brinell hardness, such as $HB < 150$, and a large amount of material data is still needed for Hardness Method to determine the optimal estimation equation.

In the present study, the collected test data have Brinell hardness and fatigue properties with a wider range. There are 92 pieces of test data of different materials, and the Brinell hardness range of the materials is about 80–660. The statistical results are shown in Table 1.

Based on the Hardness Method proposed by Roessle and Fatemi [8], a new fitting between fatigue strength coefficient, σ'_f and Brinell hardness, HB , parameter is obtained:

$$\sigma'_f = 3.98(HB) + 285. \quad (5)$$

The comparison between equation (5) and equation (4a) from Roessle and Fatemi [8] is shown in Figure 1. It can be concluded from Figure 1 that although there are some differences in the data sample, the fitting equation in the present study still has a high degree of agreement with equation (4a), which directly show the reliability for the estimation of fatigue strength coefficient based on the Brinell hardness of materials.

In contrast, it is relatively difficult to establish the approximate fitting relationship between the fatigue ductility coefficient and the basic mechanical parameters of materials. Compared with the monotonic mechanical properties, the fatigue ductility coefficient, ε'_f under fatigue load is similar to the fracture toughness, ε_f , under monotonic load. Therefore, some researchers suggested taking the fatigue ductility coefficient, ε'_f as the fracture toughness, ε_f , approximately. However, the relationship between the fatigue ductility coefficient and the monotonic fracture toughness of materials shows great discreteness. Roessle and Fatemi [8] proved the huge prediction error brought by this approximation.

In Hardness Methods, the relationship between the fatigue ductility coefficient and Brinell hardness is deduced through the intermediate variable of transition fatigue life,

TABLE 1: Statistical results of the data sample.

References	Number of data	Hardness range	Tensile strength range
Kim [3]	8	153–327	508–1100
Ong [7]	49	80–660	345–2240
Roessle [8]	20	163–536	695–2360
Shamsaei [2]	15	130–565	450–2248
Total	92	80–660	345–2360

FIGURE 1: Relationship of Brinell hardness and fatigue strength coefficient.

N_t . According to the Manson-Coffin equation, at the point of the transition fatigue life, the strain amplitudes, $\Delta\varepsilon_t$, can be expressed as

$$\Delta\varepsilon_t = \frac{\sigma'_f}{E} (2N_t)^b, \quad (6)$$

$$\Delta\varepsilon_t = \varepsilon'_f (2N_t)^c. \quad (7)$$

Substitute equation (6) into equation (7); then, fatigue ductility coefficient, ε'_f can be expressed as

$$\varepsilon'_f = \frac{\sigma'_f (2N_t)^b}{E (2N_t)^c}. \quad (8)$$

Roessle and Fatemi [8] point out that the transition fatigue life, N_t , and the nominal transition stress, $S_t = \sigma'_f (2N_t)^b$, corresponding to transition fatigue life have a good linear relationship with Brinell hardness, which can be given by

$$S_t = 0.004(HB)^2 + 1.15(HB), \quad (9)$$

$$\log(2N_t) = 5.755 - 0.0071HB. \quad (10)$$

Substitute equations (9) and (10) into equation (8); then, fatigue ductility coefficient, ε'_f can be estimated only depending on modulus of elastic, E , and Brinell hardness, HB , as follows:

$$\varepsilon'_f = \frac{0.004(HB)^2 + 1.15(HB)}{E[10^{(5.755-0.0071HB)}]^{-0.56}} \quad (11)$$

When the Brinell hardness range is $150 < HB < 700$, equation (11) can be simplified as

$$\varepsilon'_f = \frac{0.32(HB)^2 - 487(HB) + 191000}{E} \quad (12)$$

Figure 2 shows the corresponding relationship between Brinell hardness and fatigue ductility coefficient of 92 test data of different materials. The derived equation (11) and the simplified equation (12) are also plotted for comparison.

As can be seen from Figure 2, the fitting results of Brinell hardness and fatigue ductility coefficient based on equations (11) and (12) are not very accurate with the hardness range of $150 < HB < 700$. For the materials with $HB < 150$, the simplified equation (12) and derived equation (11) are obviously inconsistent with the change of Brinell hardness. It can be inferred from the founding that the prediction error based on the Hardness Method for the materials with $HB < 150$ will be large.

Another observation from the distribution of test data between Brinell hardness and fatigue ductility coefficient in Figure 2 is that the fatigue ductility coefficient increases with the increase of Brinell hardness in the low Brinell hardness zone, while the fatigue ductility coefficient decreases with the increase of Brinell hardness in the high Brinell hardness zone, or to be more exact, which is approximately a power exponential increase in the low Brinell hardness zone and decrease in the high Brinell hardness zone. Based on the observation, it is suggested to adopt the Segment Fitting Method to estimate the fatigue ductility coefficient from Brinell hardness. According to the statistical analysis of the test data in this study, the fitting range of the Brinell hardness zone is roughly divided into two segments of $HB < 350$ and $HB > 350$. The boundary value of the Brinell hardness range is determined by the intersection point of the fitting equation of the two segments.

Based on the new proposal discussed above, the optimal segment fitting equation of fatigue ductility coefficient from Brinell hardness can be given as follows:

$$\varepsilon'_f = 1.5 \times 10^{-6} (HB)^{2.35}, \quad HB < 340, \quad (13a)$$

$$\varepsilon'_f = 1.7 \times 10^{+12} (HB)^{-4.78}, \quad 340 < HB < 700. \quad (13b)$$

Figure 3 shows the fitting results of the new proposed Segment Fitting Method. The boundary Brinell hardness value of the two segments is about 340 according to the data sample used for this study. It can be seen from the figure that the Segment Fitting Method has a significant improvement in the relationship of fatigue ductility coefficient, ε'_f , and Brinell hardness, HB .

For fatigue strength exponent, b , and fatigue ductility exponent, c , there is no enough evidence to establish the

FIGURE 2: Relationship of Brinell hardness and fatigue ductility coefficient.

FIGURE 3: Segment Fitting Method of fatigue ductility coefficient from Brinell hardness.

corresponding relationship between the two exponents and the basic mechanical properties of materials. Researchers usually take the statistical mean values of the two exponents as approximate estimates. For the test data in this study, the statistical mean value of fatigue strength exponent, b , is about -0.09 , and the statistical mean value of fatigue ductility exponent, c , is about -0.56 . These values are very close to the recommended values of Baume and Seeger [5], Muralidharan and Manson [6], and Roessle and Fatemi [8].

Considering that the fatigue ductility coefficient, ε'_f , is estimated by using the Segment Fitting Method, the statistical mean value of corresponding hardness segments is also used to deal with the fatigue ductility exponent, c , in this paper. For the test data listed in Table 1, the statistical mean value of fatigue ductility exponent, c , is -0.54 for $50 < HB < 700$. Thus, the new proposal for the fatigue properties estimation from Brinell hardness can be given as follows:

TABLE 2: Mechanical parameters and the fatigue properties.

Materials	E (GPa)	σ_u (MPa)	HB	σ'_f (MPa)	b	ϵ'_f	c
Haynes188 [11]	170	490	130	823	-0.105	0.327	-0.546
304SS [12]	195	585	160	1287	-0.145	0.122	-0.394
1Cr18Ni19Ti [13]	193	605	160	1124	-0.091	0.807	-0.665
1045HR [14]	204	620	189	1027	-0.107	0.322	-0.487
1050N [15]	206	709	198	1109	-0.100	0.292	-0.456
SNCM630 [16]	196	1103	348	1272	-0.073	1.540	-0.823
1050QT [15]	203	1164	360	1346	-0.062	2.010	-0.725
Inconel718 [17]	209	1850	370	1640	-0.060	2.670	-0.820
1050IH [15]	198	2248	565	4974	-0.152	0.529	-0.910

FIGURE 4: Fatigue loading paths.

$$\begin{cases} \sigma'_f = 3.98(HB) + 285 \\ b = -0.09, \\ \epsilon'_f = 1.5 \times 10^{-6}(HB)^{2.35}, \\ c = -0.54, \\ 50 < HB \leq 340. \end{cases} \quad (14a)$$

$$\begin{cases} \sigma'_f = 3.98(HB) + 285, \\ b = -0.09, \\ \epsilon'_f = 1.7 \times 10^{+12}(HB)^{-4.78}, \\ c = -0.69, \\ 340 < HB < 700. \end{cases} \quad (14b)$$

4. Results and Discussion

In this section, 96 pieces of fatigue test data of 9 types of steel are used to verify the new estimation methods of fatigue properties, and Brinell hardness range of the types of steel is about 130–600. Some basic mechanical properties and the fatigue properties determined by the fatigue test are listed in Table 2. The fatigue test data include uniaxial, torsion, and in-phase loading paths, as shown in Figure 4. The fatigue test results such as applied strain amplitude and fatigue test life can be found in [11–17].

For the life prediction under axial, torsional, and multiaxial in-phase loading, the von Mises equivalent strain parameters combined with the Manson–Coffin equation can obtain good prediction results, which were verified by a large

amount of fatigue test data [18, 19]. The equivalent strain model used for the fatigue life prediction in this investigation is given as

$$\frac{\Delta\epsilon_{eq}}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \epsilon'_f(2N_f)^c, \quad (15)$$

where $\Delta\epsilon_{eq}/2$ is the von Mises equivalent strain amplitude. σ'_f , ϵ'_f , b , and c are the estimated or experimental fatigue properties. For the Modified Universal Slopes Method, the modulus of elastic, E , tensile strength, σ_u , and fracture toughness, ϵ_f , are used to estimate the fatigue properties. Due to the unavailability of the reduction of area, RA , in [11–17], RA is approximately 50 in the calculation of fracture toughness by equation (3). For the Uniform Material Law, only the two parameters of modulus of elastic, E , and tensile strength, σ_u , are required; while for the Hardness Method, modulus of elastic, E , and Brinell hardness, HB , are needed for the fatigue properties estimation.

Figures 5–7 show the predicted fatigue life given by three equivalent strain parameters, that is, Modified Universal Slopes Method, Uniform Material Law, and Hardness Method, respectively.

It can be found from the figures that approximately 95%, 92%, and 90% of all the data are within scatter bands of 5 based on the three estimation methods, respectively, which indicates a well agreement of the predictions within scatter bands of 5, while the prediction accuracy of fatigue life is relatively poor within the scatter band of 2, which is about 64%, 45%, and 58%, respectively. It is noteworthy in Figure 7 that only 40% of prediction results for the Haynes 188 steel

FIGURE 5: Prediction results of the Modified Universal Slopes Method.

FIGURE 7: Prediction results of the Hardness Method.

FIGURE 6: Prediction results of the Uniform Material Law.

FIGURE 8: Prediction results of the Segment Fitting Method.

with the Brinell hardness of $HB = 130$ fall within the scatter band of 5. This is mainly because the Hardness Method may be most suitable for the materials with a Brinell hardness range of $150 < HB < 700$, as shown in Figure 2. For the materials with low Brinell hardness, such as Haynes 188 steel used in the present study, the life prediction based on Hardness Method leads to the decrease of the prediction accuracy, as shown in Figure 7.

Figure 8 shows the prediction results of fatigue life based on the Segment Fitting Method. It can be found from the figure that the prediction accuracy of the scatter band of 2 and 5 is 73% and 97%, respectively. It should be pointed out that, for Haynes 188 steel with low Brinell hardness, all the life prediction results fall in the scatter band of 3. This

indicates that the predicted results under axial, torsional, and in-phase loading are significantly improved by using the fatigue properties estimated from the newly proposed method.

To compare the prediction accuracy of the estimated fatigue properties with experimental ones, the fatigue life prediction results based on experimental fatigue properties are also shown in Figure 9.

It can be seen from Figure 9 that the prediction accuracy of the scatter band of 2 and 5 is 74% and 94%, respectively, which is in good agreement with the prediction accuracy of the proposed estimation method. The prediction accuracy based on experimental fatigue properties and the four estimation methods is listed in Table 3. Compared with the

FIGURE 9: Prediction results based on the experimental fatigue properties.

TABLE 3: Prediction accuracy based on various fatigue properties.

Error criterion EC (s)	Experimental fatigue properties	Modified Universal Slopes Method	Uniform Material Law	Hardness Method	Segment Fitting Method
$EC(2)$	0.74	0.64	0.45	0.58	0.73
$EC(3)$	0.89	0.89	0.72	0.83	0.90
$EC(5)$	0.94	0.95	0.92	0.90	0.97

fatigue life prediction results in Figures 5–8 and Table 3, it can be concluded that the prediction accuracy of the fatigue life under axial, torsional, and in-phase loading has little difference within the scatter band of 5. However, the difference in prediction accuracy is mainly happened in the small scatter band, such as the scatter band of 2.

It should be noted that the experimental fatigue data may be quite scattered, which leads to relatively poor prediction accuracy based on experimental fatigue properties, while for the life prediction by using the estimation method, because a large amount of fatigue test data of various materials is adopted for fitting, to some extent, it can mitigate the negative influence caused by individual scattered data of a certain material and consequently provide satisfactory fatigue life prediction.

In conclusion, the proposed Segment Fitting Method modified the Hardness Method, previously proposed by Roessle and Fatemi, based on the observation of statistic distribution of 92 pieces of test data, which consequently improves the fatigue life prediction results, particularly for the materials with low Brinell hardness, which illustrated the feasibility of the new proposal based on the thought of segment fitting of fatigue properties from Brinell hardness. However, what should be noted is that the optimal Segment Fitting Method is also limited by the size of the data sample, the Brinell hardness range included in the data sample, and the discreteness of fatigue test data and cannot fully cover all cases. The proposed segment fitting equation still needs a

wider range of test data to correct the form and parameters in the equations.

5. Conclusions

An improved estimation method of fatigue properties from Brinell hardness is proposed, and the fatigue life prediction based on the estimated fatigue properties is studied. The new method and three estimation methods of fatigue properties are verified based on 96 pieces of fatigue test data in the existing literature. The following conclusions can be made from the analyses performed in the present study:

- (1) The fatigue strength confident, σ_f' , has a fine linear relationship with Brinell hardness. The Segment Fitting Method combined with the power exponential form is adopted to estimate fatigue ductility confident, ϵ_f' , from Brinell hardness in the present study, which improves the prediction accuracy. However, it is difficult to estimate fatigue strength exponent, b , and fatigue ductility exponent, c , directly from the monotonic mechanical properties, and the statistical mean values of numerous test data are usually taken as the approximation of these two exponents.
- (2) The fatigue life predictions have a good agreement with the experimental ones within scatter bands of 5 based on the estimation method of fatigue

properties, such as Modified Universal Slopes Method, Uniform Material Law, and Hardness Method, while the prediction accuracy of fatigue life is relatively poor with the scatter band of 2 based on the three exciting methods.

- (3) The new proposed Segment Fitting Method from Brinell hardness modified the Hardness Method and has a significant improvement of the relation of fatigue ductility coefficient and Brinell hardness, which consequently improves the fatigue life prediction accuracy, particularly for the materials with low Brinell hardness and within the scatter band of 2. The prediction results illustrate the feasibility of the new proposal based on the thought of segment fitting of fatigue properties from Brinell hardness.
- (4) The obvious advantage of life predictions based on the estimation methods is that it can predict the fatigue life accessibly and effectively and ensure a certain accuracy comparing with the predictions based on the experimental fatigue properties. The present study can provide a simplified analysis of the preliminary fatigue design of engineering structures.

Data Availability

The fatigue test data used to support the findings of this study are available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors gratefully acknowledge the financial support for this work from the National Natural Science Foundation of China (nos. 51438002 and 51908340).

References

- [1] A. Fatemi and N. Shamsaei, "Multiaxial fatigue: an overview and some approximation models for life estimation," *International Journal of Fatigue*, vol. 33, no. 8, pp. 948–958, 2011.
- [2] N. Shamsaei and S. A. Mckelvey, "Multiaxial life predictions in absence of any fatigue properties," *International Journal of Fatigue*, vol. 67, no. 10, pp. 62–72, 2014.
- [3] K. Kim, X. Chen, C. Han et al., "Estimation methods for fatigue properties of steels under axial and torsional loading," *International Journal of Fatigue*, vol. 24, no. 7, pp. 783–793, 2002.
- [4] S. S. Manson, "Fatigue: a complex subject—some simple approximations," *Experimental Mechanics*, vol. 5, no. 7, pp. 193–226, 1965.
- [5] A. Baumeister Jr. and T. Seeger, *Materials Data for Cyclic Loading*, Elsevier Science Publishers, Amsterdam, Netherlands, 1990.
- [6] U. Muralidharan and S. S. Manson, "A modified universal Slopes equation for estimation of fatigue characteristics of metals," *Journal of Engineering Materials & Technology*, vol. 110, no. 1, pp. 3595–3601, 1988.
- [7] J. Ong, "An evaluation of existing methods for the prediction of axial fatigue life from tensile data," *International Journal of Fatigue*, vol. 15, no. 1, pp. 13–19, 1993.
- [8] M. Roessle and A. Fatemi, "Strain-controlled fatigue properties of steels and some simple approximations," *International Journal of Fatigue*, vol. 22, no. 6, pp. 495–511, 2000.
- [9] N. Shamsaei and A. Fatemi, "Fatigue life predictions under general multiaxial loading based on simple material properties," *SAE International Journal of Materials and Manufacturing*, vol. 4, no. 1, pp. 651–658, 2011.
- [10] K. Lee and J. Song, "Estimation methods for strain-life fatigue properties from hardness," *International Journal of Fatigue*, vol. 28, no. 4, pp. 386–400, 2006.
- [11] S. Kalluri and P. J. Bonacuse, "In-phase and out-of-phase axial-torsional fatigue behavior of Haynes 188 at 760 C," NASA Sti/recon, Technical Report N, 1991.
- [12] N. Shamsaei, *Multiaxial Fatigue and Deformation Including Non-proportional Hardening and Variable Amplitude Loading Effects*, The University of Toledo Dissertations, Toledo, OH, USA, 2010.
- [13] X. Chen, K. An, and K. S. Kim, "Low-cycle fatigue of 1Cr-18Ni-9Ti stainless steel and related weld metal under axial, torsional and 90° out-of-phase loading," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 27, no. 6, pp. 439–448, 2004.
- [14] A. Fatemi and D. F. Socie, "A critical plane approach to multiaxial fatigue damage including out-of-phase loading," *Fatigue & Fracture of Engineering Materials and Structures*, vol. 11, no. 3, pp. 149–165, 1988.
- [15] N. Shamsaei and A. Fatemi, "Effect of hardness on multiaxial fatigue behaviour and some simple approximations for steels," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 32, no. 8, pp. 631–646, 2009.
- [16] C. Han, X. Chen, and K. Kim, "Evaluation of multiaxial fatigue criteria under irregular loading," *International Journal of Fatigue*, vol. 24, no. 9, pp. 913–922, 2002.
- [17] D. F. Socie, L. A. Waill, and D. F. Dittmer, "Biaxial fatigue of Inconel 718 including mean stress effects," in *Multiaxial Fatigue*, ASTM, Philadelphia, PA, USA, 1985.
- [18] W. L. Qu, E. N. Zhao, Q. Zhou, and Y.-L. Pi, "Multiaxial low-cycle fatigue life evaluation under different non-proportional loading paths," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 41, no. 5, pp. 1064–1076, 2018.
- [19] W. Qu, E. Zhao, and Q. Zhou, "Refined analysis of fatigue crack initiation life of beam-to-column welded connections of steel frame under strong earthquake," *Shock and Vibration*, vol. 2017, pp. 1–13, 2017.