Fatigue reliability of welded joints accounting for uncertainties in weld geometry

Huiying Gao¹, Xiaoqiang Zhang², Peng Huang³, Hao Jiang² and Zhoushuo Li²

Abstract
Fatigue reliability assessment of welded joints can consider the uncertainties from various sources and can establish the design criteria and inspection plans. The present paper aims to address the uncertainties explicitly. The notch strain approach that accounts for the effects of the misalignment, local notch, and crack-like imperfection, which is referred to as secondary notch, is employed. Sensitivity analyses indicate that uncertainties in misalignment, flank angle, weld toe radius together with secondary notch are all important sources of the total uncertainty. The practical difficulty in the determination of the uncertainty models of the geometric parameters is discussed, and the acceptance limits for fabrication are used to derive the uncertainty models. And finally, the impacts of acceptance limits on the fatigue reliability of welded joints are assessed. The results indicate that the weld toe radius and secondary notch depth significantly affect the reliability index and the fatigue reliability increases with the weld quality of the welded joint becomes higher.

Keywords
Fatigue reliability, uncertainties, reliability analysis, weld geometry, notch strain approach

Date received: 18 January 2022; accepted: 19 April 2022

Handling Editor: Chenhui Liang

Introduction
Fatigue is a critical and commonly happened failure mode of engineering equipment including wind turbines¹–⁴ and marine structures⁵,⁶. Fatigue has to be controlled or avoided to exclude costly repairs and catastrophic accidents as fatigue reliability of structures will directly affect the overall performance of engineering equipment such as safety, availability, and reliability.⁷–¹⁰ Considering the significant uncertainties involved in the fatigue process of structural components, the fatigue reliability assessment is required to ensure structural safety.¹,¹¹,¹² The fatigue reliability assessment can support the establishment of design criteria¹ and inspection plans.⁶ The assessment relies on S-N curve approaches and crack propagation approaches. During the last several years, fatigue reliability assessment of welded joints has become an acceptable procedure, however, the reality is that some uncertainties associated with fatigue reliability assessment of real engineering equipment are not explicitly considered.

¹Aviation Engineering Institute, Civil Aviation Flight University of China, Deyang, China
²Institute of Electronic and Electrical Engineering, Civil Aviation Flight University of China, Deyang, China
³School of Mechanical and Electrical Engineering, Jiangxi University of Science and Technology, Ganzhou, China

Corresponding author:
Peng Huang, School of Mechanical and Electrical Engineering, Jiangxi University of Science and Technology, No. 86, Hongqi Avenue, Zhanggong District, Ganzhou 341000, China.
Email: huangpeng@jxust.edu.cn

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
Weld geometry is a notable factor influencing the fatigue strength of welded joints. Three factors of weld geometry should be accounted for, as recommended by International Institute of Welding (IIW)\textsuperscript{13}:

(i) The increase of general stress level. It is mainly induced by misalignments.\textsuperscript{7} The local stresses are increased by secondary bending under the situation that misaligned welded joints are axially loaded.

(ii) The local notch effect. It is associated with the local discontinuities that leads to stress concentrations. The weld toe radius and flank angle are geometric parameters to characterise the local notch at the weld toe.\textsuperscript{14}

(iii) The crack-like imperfections. It, like undercut, is usually observed as the initiation site of fatigue cracks.\textsuperscript{15} Extensive studies were performed to evaluate the three effects on the fatigue life of welded joints and found that these effects are significant.\textsuperscript{8,16}

Significant uncertainties are associated with the weld geometry.\textsuperscript{12,14} The variation in weld geometry is a common feature for welded joints. It occurs along with the weld line of individual joints and from joint to joint. The weld geometry hangs on the welding conditions and manufacturing processes. The welding position, work angle, travel speed, welding current, and voltage vary even adopting the same technique, causing some variation of the weld geometry. It may be the main reason for the significant scatter in fatigue lives of welded joints.

Although the effects of weld geometry, as well as the uncertainties in weld geometry, are significant, the widely used S-N curve approaches and crack propagation approaches can hardly consider most of the effects explicitly. The most approaches used in practical engineering ignore the information of weld geometry. The nominal stress, hot spot stress, and effective notch stress approach can only account for the effect of misalignment. Due to the limitation of the stress intensity factor solutions,\textsuperscript{17} the crack propagation approach cannot consider the local notch effect appropriately. Recently, the effects of weld geometry has gained great attention.\textsuperscript{16–18} Extensive efforts were made to consider these effects explicitly in the frame of S-N curve approaches and crack propagation approaches. For example, Dong et al.\textsuperscript{18} proposed an updated notch strain method that accounted for the effects of misalignment, local notch, and crack-like imperfections. Although some approaches can consider the effects of weld geometry, the information of weld geometry for the fatigue strength assessment is also difficult to determine because of the random nature the weld geometry.

This paper assesses the fatigue reliability of a butt-welded joint accounting for the uncertainties in weld geometry. The notch strain approach is applied to address weld geometry’s effects. Sensitivity analyses are then performed to identify the influence of the uncertainty in each random variable on the total uncertainty. The acceptance limits for fabrication are used to derive the uncertainty models of the geometric parameters. And finally, the effects of acceptance limits on the fatigue reliability are assessed.

Notch strain approach

The notch strain approach (local strain approach)\textsuperscript{19} is employed in the fatigue reliability assessment due to its capability of dealing with the problem under consideration. The approach was originally proposed for the crack initiation life prediction of notched members. Its application was extended to welded joints.\textsuperscript{20} The approach was refined by Dong et al.\textsuperscript{18} to consider the secondary notch effect, that is the crack-like imperfection effect. The secondary notch effect was modelled in the low- and high-cycle fatigue regime, respectively. The equivalence between the Coffin-Manson law and a simple Elastic-Plastic Fracture Mechanics crack growth law in the low-cycle fatigue regime was used. The fatigue limit as a function of the crack size was employed to model the secondary notch effect in the high-cycle fatigue regime.

Notch strain estimation

In this study, the misalignment, local notch, and secondary notch for a butt welded joint are shown in Figure 1.

Two types of misalignments usually exist: angular and axial misalignment, as illustrated in Figure 1. The stress raising effect due to misalignments is described by a factor $K_m$ imposed on the nominal stress. The expressions of $K_m$ for various cases are provided in Hobbacher.\textsuperscript{13} For no restraint on the transverse member (excess weld metal in the present case), a simple formula for all cases (including both the axial and angular misalignment) are obtained by assuming symmetric lengths of the base plates and fixed ends without considering the effect of straightening\textsuperscript{21}:

$$K_m = 1 + \frac{3e}{t}$$  \hspace{1cm} (1)

where $e$ and $t$ are the magnitude and the thickness of the plate.

The local notch, that is the weld toe, is usually defined by the weld toe radius $\rho$ and flank angle $\theta$. Hence, the stress concentration factor for membrane and bending stresses can be estimated by\textsuperscript{20}:
\[ K_{mt} = 1 + 0.27(\tan \theta)^{1/4}(t/\rho)^{1/2} \]  
\[ K_{bt} = 1 + 0.165(\tan \theta)^{1/5}(t/\rho)^{1/2} \]

where \( \rho \) is the weld toe radius, \( \theta \) is the flank angle.

If the butt joint is axially loaded by nominal stress, one can determine the elastic stress response using a stress concentration factor considering both stress raising effects:

\[ K_t = K_{mt} + (K_{mt}-1)K_{bt} \]

Combined with the elastic response, the elastic-plastic material behaviour is normally described by Ramberg–Osgood equation:

\[ e_{\alpha} = \frac{\sigma_{\alpha}}{E} + \left(\frac{\sigma_{\alpha}}{K'}\right)^{1/n'} \]

where \( E \) is the Young’s modulus, \( e_{\alpha} \) and \( \sigma_{\alpha} \) are the amplitude of the cyclic strain and stress, respectively, and \( K' \) and \( n' \) are the cyclic strain hardening coefficient and exponent, respectively.

Numbers of analytical approaches for notch strain estimation are presented. For welded structures where the weld toe radius is normally smaller than the length of the weld line, it is reasonable based on the assumption of the plane strain state.\(^{22,23}\) It has been shown that the estimations by equivalent strain energy density (ESED) approach are in good agreement with experimental results\(^{24}\) and elastic-plastic finite element method (FEM) results.\(^{25}\) It is also employed in the present study.

**Secondary notch effect**

According to the estimated notch strains, the crack initiation life can be calculated by using the strain-life curve and Miner’s rule. The uniaxial strain-life curve of the material is determined by standard specimens under well-controlled experimental conditions:

\[ e_{\alpha} = \frac{\sigma_{\alpha}'}{E}(2N_i)^b + e_{\alpha}'(2N_i)^c \]

where \( \sigma_{\alpha}' \) is the fatigue strength coefficient, \( b \) is the fatigue strength exponent, \( e_{\alpha}' \) is the fatigue ductility coefficient, \( c \) is the fatigue ductility exponent. Based on the similitude concept, the notched components’ crack initiation life is equivalent to the total fatigue life of standard specimens in the case of the same strain amplitudes.

However, the notch root of welded joints cannot be as smooth as standard specimens. From Figure 1, secondary notches are usually included in welded joints, making the similitude concept questionable. To include the effect of the secondary notch, it is recommended to adopt specimens with a secondary notch when obtaining strain-life curves. These specimens must have a similar surface condition as that of welded joints, as shown in Figure 1. Thus, the similitude can be achieved. However, fatigue tests are laborious and costly. In this analysis, analytical techniques are used to estimate the degradation of the initial strain-life curve from standard specimens.

Based on the secondary notch depth \( k \), Dong et al.\(^{18}\) proposed a modified strain-life curve. The degradation of the initial strain-life curve was realised by using the \( k \)-dependent \( \sigma_{\alpha}'(k) \) and \( e_{\alpha}'(k) \) rather than \( \sigma_{\alpha} \) and \( e_{\alpha}' \):

\[ e_{\alpha}'(k) = e_{\alpha}' \left( \ln a_f - \ln a_f - \ln k \right)^c \]

\[ \sigma_{\alpha}'(k) = \sigma_{\alpha}' \left( \frac{a_0}{a_0 + k} \right)^{1/2} \]

where \( a_i \) is the half of the mean grain size of the material, \( a_i \) is the minimum radius of the cylindrical specimen, respectively, and \( a_0 \) is defined by:\(^{18}\):

\[ a_0 = \frac{1}{\pi} \left( \frac{\Delta K_{th,LC}}{D_{\sigma_w}} \right)^2 \]

where \( \Delta \sigma_w \) is the fatigue limit (stress range), \( \Delta K_{th,LC} \) is the long crack propagation threshold. To ensure consistency, their values corresponding to R-ratio of \(-1\) are used. The crack propagation threshold for any R-ratio...
can be estimated by $\Delta K_{th} = (1 - 0.73R)\Delta K_{th0}$, where $\Delta K_{th}$ is the crack propagation threshold with R-ratio of 0.26.

The modified strain-life curve of the plane strain state can be written as:

$$e_{1a} = \frac{\sigma'_1(k)}{E} (2N_i)^{\nu} + e'_c(k) \frac{1 - 0.5\mu}{\sqrt{1 - \mu + \mu^2}} (2N_i)^c$$

(10)

where $e_{1a}$ is the amplitude of the first principal strain, $\nu$ is the Poisson’s ratio, and $\mu$ is the generalised Poisson’s ratio that is gained in the notch strain estimation.

Note that the effect of welding-induced residual stesses27 is ignored here because the residual stress relaxation occurs due to the application of stress cycles with relatively high ranges. The residual stresses may be relaxed in a relatively short period comparing to the whole service life. Besides, the welding-induced residual stesses may not be as high as expected especially for welded joints with low constraint.28

Although the life estimated using the strain-life curve corresponds to the initiation of an easily detectable crack whose size ranges from 0.1 to 1 mm,25 it can be treated as a conservative approximation of the total fatigue life. The treatment is reasonable when the weld quality is large and fatigue loading is at a small level.

**Fatigue reliability assessment**

The fatigue reliability of the butt welded joint shown Figure 1 is estimated accounting for uncertainties. Since some reliability assessment methods are well-established, for example the first or second order reliability method (FORM/SORM), the Monte Carlo (MC) simulation method, the parameters involved in the section are considered as random variables.

**Limit state function**

The limit state function (LSF) for fatigue is written as:

$$g(X) = \Delta - D$$

(11)

where $X$ is the vector of random variables, $\Delta$ is the damage at failure, and $D$ is the cumulative damage.

The fatigue failure probability can be estimated as follows:

$$P_f = \text{Prob}_f(g(X) \leq 0) = \Phi(-\beta)$$

(12)

where $\Phi(\cdot)$ is the standard normal cumulative distribution function and $\beta$ is the reliability index.

The importance of the contribution of each variable to the uncertainty of $g(X)$ can be investigated by the sensitivity factors, which can be calculated by:

$$\alpha_i = -\frac{1}{\sqrt{\sum_{i=1}^{n} (\partial g(X^\ast)/\partial x_i)^2}}$$

(13)

In this work, the FORM29–31 is used to evaluate the reliability index and the sensitivity factor.

**Random variables**

The random variables and deterministic parameters involved in the LSF are listed in Tables 1 and 2.

The fatigue failure happens once $D$ is greater than $\Delta$, where $\Delta$ is usually set to be 1 in most deterministic studies. In fact, fatigue failure may occur when $D$ is less or larger than 1. The fatigue process can be seriously affected by many factors, like environment conditions, loading sequence, working temperature, and so forth. Note that Miner’s rule fails to present a reasonable elaboration of such a complex process. Thus, to quantify the error caused by the damage rule, $\Delta$ is treated as a random variable. As was investigated by Wirsching and Chen,5 a log-normal distribution (median of 1 and CoV of 0.3) was recommended.

**Table 1. Statistical characteristics of random variables.**

| Random variable | Distribution   | Median | CoV  |
|-----------------|----------------|--------|------|
| Damage at fatigue failure, $\Delta$ | Log-normal | (1)    | (0.3) |
| Weld toe radius, $\rho$ (mm) | Log-normal | (0.87) | (0.51) |
| Flank angle, $\theta$ (°) | Normal | 31.88  | 5.87  |
| Crack-like imperfection, $k$ (µm) | Log-normal | (59.21) | (0.31) |
| Mismatch, $e$ (mm) | Half-normal | 0      | 0.1/1.96 |
| Fatigue strength coefficient, $\sigma_f$ (MPa) | Log-normal | (1236) | (0.1)  |
| Cyclic strain hardening coefficient, $K$ | Log-normal | (1408) | (0.1)  |
| Crack propagation threshold for $R = 0$, $\Delta K_{th0}$ (MPa m$^{0.5}$) | Log-normal | (5.2)  | (0.15) |

*The values are the statistical descriptors of the corresponding normal distribution.*
The uncertainties in weld geometry are the main concern of the present study. Statistics provide powerful tools for the explanations of experimental data such as Statistical descriptors of geometric parameters were offered in many studies based on experimental measurement, and a review of the data from different sources was conducted by Schork et al.32 Jakubczak et al.37 performed experimental and statistical assessment of the weld toe radius and flank angle. The distributions fitted by the data from different units in the same factory show significant differences. The uncertainty of the misalignment was considered by Dong et al.7 in the fatigue reliability assessment. Experimental results have shown that the misalignment follows a normal distribution.38 The half-normal distribution accounting for the acceptance criteria of fabrication was proposed to represent the uncertainty of the misalignment. The acceptance criterion of 0.1 t is treated as the characteristic value under probability level of 95%. The statistical descriptors of the size of crack-like imperfections are not well documented, because there are different types of crack-like imperfections and the definition of the geometry is usually ambiguous. The roughness-based secondary notch data reported by Schork et al.32 is used in this study.

Due to more similar specimens and strictly controlled experimental conditions, the uncertainty in the strain-life data is not as significant as that in the S-N data of welded joints. Some studies investigated the uncertainties of the strain-life curve parameters.37,39 The uncertainty of $\varepsilon_f$ is ignored because the fatigue loading mainly causes elastic responses. The CoV of $\sigma_f$ is assumed to be 0.1 according to.39 Note that the cyclic strain hardening coefficient $K'$ can be estimated by $\sigma_f^{1-b/c}$. Therefore, the CoV of $K'$ is equal to that of $\sigma_f$. Another material property subjected to significant uncertainty is the crack propagation threshold. It has been shown that the R-ratio, material microstructure, and experimental method can affect the experimental results of the crack propagation threshold.40

Note that engineering structures are generally exposed to environmental loading or operation loading. Due to their random nature, the fatigue loading during a relatively long period is also subjected to significant uncertainties. The fatigue loading specified by design codes deviates from the real ones. In this work, the primary focus is the uncertainties in weld geometry, and thus the modelling error of the fatigue loading is not considered to simplify the analysis. Assuming that the nominal stress range acting on the butt welded joint follows a Weibull distribution:

$$F(\Delta \sigma_n) = 1 - \exp\left(-\left(\frac{\Delta \sigma_n}{q}\right)^h\right)$$

where $h$ and $q$ are the shape and scale parameters. The shape parameter is set to be 1 and various scale parameters are assumed. The total number of stress cycles is $10^8$.

**Results**

**Sensitivity analyses**

The sensitivity factor $\alpha$ is the directional cosine of the design point with respect to the origin in standard normal space. For a random variable, the square of its sensitivity factor is the fraction of the total uncertainty of LSF. It has been shown in the present study that changing the fatigue loading, that is value of $q$, can only slightly affect the value of $\alpha$ for each random variable. Figure 2 shows the results of $\alpha$ for $q = 14$.

It can be seen that the uncertainties of the four parameters defining the weld geometry, are all important

---

**Table 2. Values of deterministic parameters.**

| Deterministic parameter | Value $^{18}$ |
|-------------------------|---------------|
| Young's modulus, $E$ (MPa) | 206,000 |
| Poisson's ratio, $\nu$ | 0.3 |
| Cyclic strain hardening exponent, $n'$ | 0.161 |
| Fatigue strength exponent, $b$ | $-0.09$ |
| Fatigue ductility coefficient, $\varepsilon_f$ | 0.444 |
| Fatigue ductility exponent, $c$ | $-0.56$ |
| Half of average grain size, $a_0$ (mm) | 0.005 |
| Radius of cylindrical specimen, $a_f$ (mm) | 4 |
| Plate thickness, $t$ (mm) | 25 |
| Fatigue limit (stress amplitude) at $R = -1$, $\sigma_w$ (MPa) | 369 |

---

**Figure 2. Sensitivities of random variables (values of $\alpha$).**
sources of uncertainties of the LSF. Even though the uncertainty of the flank angle is the smallest contributor, it is as important as the uncertainty of the fatigue damage at failure. Among the three random variables describing the uncertainty of material properties, that is $\sigma_f$, $K'$, and $\Delta K_{th0}$, the influence of $K'$ on the uncertainty of LSF is negligible. The reason may be that the assumed fatigue loading mainly results in elastic responses at the local notch. The other two random variables have similar importance.

It should be noted that the sensitivities of random variables can be changed if other distribution types and statistical descriptors are employed. In the present study, the statistical descriptors of $r$, $u$, and $k$ are adopted from measurements of specimens representing most recent welding quality, while, the statistical descriptors of other random variables are mainly from assumptions or from experiences that may be out of date. Therefore, the comparison between the three random variables is more credible.

**Fatigue reliability assessment**

It has been shown that the uncertainties of weld geometry play a significant role in the uncertainty of LSF, and thus on the fatigue reliability. A reasonable fatigue reliability assessment requires an accurate description of the uncertainties of weld geometry. In practice, it is difficult to gain such detailed information because of the ambiguous definition of the weld geometry parameter and the difficulty in the measurements. Besides, the statistical descriptors are different from joint to joint hanging on the welding process.

Some studies suggested that the acceptance limits for fabrication can be used to derive the statistical descriptors. The acceptance limits are usually specified in manufacturing guidelines. For example, the weld toe radius $\rho$ should be larger than 0.25 mm for normal weld quality; misalignment $e$ should be smaller than 0.1 t for normal weld quality. In this study, the acceptance limits are considered as the characteristic values under the 95% or 5% probability level. Assuming that $\rho$ and $k$ obey log-normal distribution with a COV of 0.51 and 0.31, and $e$ follows the half-normal distribution. Various characteristic values are assumed to study the effect of the acceptance limit on the fatigue reliability.

The reliability index as a function of the scale parameter of the fatigue loading for various acceptance limits is shown in Figure 4. It can be found from Figure 4(a) that if the acceptance limit of weld toe radius is increased...
from 0.25 to 0.55 mm, the reliability index is significantly improved by approximately 1 at an arbitrary value of the scale parameter. The variation in reliability index is more important when the acceptance limit of $r$ is low. The results indicate that the effect of the acceptance limit of the weld toe radius on the reliability is great. Hence, enlarging $r$ can be an efficient method when aiming to enhance the fatigue performance.

The effect of the acceptance limit of the secondary notch depth on the fatigue reliability is also crucial, as shown in Figure 4(b). The acceptance limit of $k$ by 30 $\mu$m decreases with the increasing of reliability index by 0.5. Some post-weld improvement techniques can enlarge the weld toe radius and reduce the secondary notch depth simultaneously. These techniques may be adopted to efficiently improve the fatigue reliability of welded joints.

The decrease of the acceptance limit of the misalignment from 0.1 to 0.05 $t$ can increase the fatigue reliability slightly, as shown in Figure 4(c). It indicates that the three uncertainty models of the misalignment lead to slightly different reliability indices. The results do not imply the effect of misalignment is not important. Two deterministic misalignments, $e = 1.25$ and 2.5 mm, and two uniformly distributed misalignments, $U(0, 1.25)$ and $U(1.25, 2.5)$, are assumed. The statistical descriptors of other random parameters and values of the deterministic parameters are listed Tables 1 and 2, respectively. The resulting reliability indices are presented in Figure 5.

It can be seen that the fatigue reliability index is improved by approximately 0.5 due to the increase of the deterministic misalignment from 1.25 to 2.5 mm. If the misalignment is uniformly distributed, the shift of the distribution from $U(0, 1.25)$ to $U(1.25, 2.5)$ can reduce the fatigue reliability index by approximately 0.5.

Conclusions

A new fatigue reliability analysis methodology of welded joints has been proposed in this paper to reflect the impact of uncertainties in weld geometry. Two A
sensitivity analyses in carried out and which indicates that the uncertainties in misalignment, weld toe radius, flank angle, and secondary notch are important sources of the total uncertainty. Moreover, the acceptance limits for fabrication are used to derive the uncertainty model and concluded that the fatigue reliability increases with the weld quality of the welded joint becomes higher.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by Sichuan Science and Technology Program (No. 2021YJ03519), the General Program of Civil Aviation Flight University of China (Nos. J2021-032 and J2021-034), and the Doctoral Scientific Research Foundation of Jiangxi University of Science and Technology (No. 20520010056).

ORCID iD
Peng Huang https://orcid.org/0000-0003-0620-0911

References
1. Márquez-Domínguez S and Sorensen JD. Fatigue reliability and calibration of fatigue design factors for offshore wind turbines. Energies 2012; 5: 1816–1834.
2. Li H, Diaz H and Guedes Soares C. A developed failure mode and effect analysis for floating offshore wind turbine support structures. Renew Energy 2021; 164: 133–145.
3. Li H, Diaz H and Guedes Soares C. A failure analysis of floating offshore wind turbines using AHP-FMEA methodology. Ocean Eng 2021; 234: 109261.
4. Li H, Teixeira AP and Guedes Soares C. A two-stage failure mode and effect analysis of offshore wind turbines. Renew Energy 2020; 162: 1438–1461.
5. Wirsching PH and Chen YN. Considerations of probability-based fatigue design for marine structures. Mar Struct 1988; 1: 23–45.
6. Lotsberg I, Sigurdsson G, Fjeldstad A, et al. Probabilistic methods for planning of inspection for fatigue cracks in offshore structures. Mar Struct 2016; 46: 167–192.
7. Dong Y, Teixeira AP and Guedes Soares C. Fatigue reliability analysis of butt welded joints with misalignments based on hotspot stress approach. Mar Struct 2019; 65: 215–228.
8. Yuan R, Tang M, Wang H, et al. A reliability analysis method of accelerated performance degradation based on Bayesian strategy. IEEE Access 2019; 7: 169047–169054.
9. Yuan R, Li H, Gong Z, et al. An enhanced Monte Carlo simulation–based design and optimization method and its application in the speed reducer design. Adv Mech Eng 2017; 9: 168781401772S648.
10. Yuan R, Li H and Wang Q. An enhanced genetic algorithm-based multi-objective design optimization strategy. Adv Mech Eng 2018; 10: 1687814018S4836.
11. Li H, Huang HZ, Li YF, et al. Physics of failure-based reliability prediction of turbine blades using multi-source information fusion. Appl Soft Comput 2018; 72: 624–635.
12. Yuan R, Li H and Wang Q. Simulation-based design and optimization and fatigue characteristics for high-speed backplane connector. Adv Mech Eng 2019; 11: 1687814019S6752.
13. Hobbacher A. Recommendations for fatigue design of welded joints and components. Cham: Springer International Publishing, 2016.
14. Lee CH, Chang KH, Jang GC, et al. Effect of weld geometry on the fatigue life of non-load-carrying fillet welded cruciform joints. Eng Fail Anal 2009; 16: 849–855.
15. Otegui JL, Kerr HW, Burns DJ, et al. Fatigue crack initiation from defects at weld toes in steel. Int J Press Vessel Piping 1989; 38: 385–417.
16. Dong Y, Garbatov Y and Guedes Soares C. Improved effective notch strain approach for fatigue reliability assessment of load-carrying fillet welded cruciform joints in low and high cycle fatigue. Mar Struct 2021; 75: 102849.
17. Dong Y and Guedes Soares C. Stress distribution and fatigue crack propagation analyses in welded joints. Fatigue Fract Eng Mater Struct 2019; 42: 69–83.
18. Dong Y, Garbatov Y and Guedes Soares C. Strain-based fatigue reliability assessment of welded joints in ship structures. Mar Struct 2021; 75: 102878.
19. Radaj D, Sonsino CM and Fricke W. Fatigue assessment of welded joints by local approaches. Cambridge: Woodhead Publishing, 2006.
20. Lawrence FV, Ho NJ and Mazumdar PK. Predicting the fatigue resistance of welds. Annu Rev Mater Sci 1981; 11: 401–425.
21. Jonsson B, Samuelsson J and Marquis GB. Development of weld quality criteria based on fatigue performance. Weld World 2011; 55: 79–88.
22. Dowling NE. Mechanical behavior of materials: engineering methods for deformation, fracture, and fatigue. Harlow: Pearson, 2013.
23. Dong Y, Garbatov Y and Guedes Soares C. Fatigue strength assessment of an annealed butt welded joint accounting for material inhomogeneity. In: Guedes Soares C and Garbatov Y (eds) Progress in the analysis and design of marine structures. London: Taylor & Francis Group, 2017, pp.337–348.
24. Sharpe WN, Yang CH and Tregoning RL. An evaluation of the Neuber and Glinka relations for monotonic loading. Int J Appl Mech 1992; 59: S50–S56.
25. Dong Y, Garbatov Y and Guedes Soares C. A two-phase approach to estimate fatigue crack initiation and propagation lives of notched structural components. Int J Fatigue 2018; 116: 523–534.
26. Garwood SJ. Fatigue crack growth threshold determination. Weld Inst Res Bul 1979; 20: 262–265.
27. Dong Y, Garbatov Y and Guedes Soares C. Fatigue crack initiation assessment of welded joints accounting.
for residual stress. *Fatigue Fract Eng Mater Struct* 2018; 41: 1823–1837.

28. Hensel J, Nitschke-Pagel T, Tchoffo Ngoula D, et al. Welding residual stresses as needed for the prediction of fatigue crack propagation and fatigue strength. *Eng Fract Mech* 2018; 198: 123–141.

29. Hasofer AM. An exact and invariant first order reliability format. *J Eng Mech* 1974; 100: 111–121.

30. Huang P, Huang H, Li Y, et al. An efficient and robust structural reliability analysis method with mixed variables based on hybrid conjugate gradient direction. *Int J Numer Methods Eng* 2021; 122: 1990–2004.

31. Huang P, Huang HZ, Li YF, et al. Positioning accuracy reliability analysis of industrial robots based on differential kinematics and saddlepoint approximation. *Mech Mach Theory* 2021; 162: 104367.

32. Schork B, Kucharczyk P, Madia M, et al. The effect of the local and global weld geometry as well as material defects on crack initiation and fatigue strength. *Eng Fract Mech* 2018; 198: 103–122.

33. Yuan R, Meng D and Li H. Multidisciplinary reliability design optimization using an enhanced saddlepoint approximation in the framework of sequential optimization and reliability analysis. *Proc IMechE, Part O: J Risk and Reliability* 2016; 230: 570–578.

34. Yuan R and Li H. A multidisciplinary coupling relationship coordination algorithm using the hierarchical control methods of complex systems and its application in multidisciplinary design optimization. *Adv Mech Eng* 2017; 9: 1687814016685222.

35. Li H, Guedes Soares C and Huang HZ. Reliability analysis of a floating offshore wind turbine using Bayesian Networks. *Ocean Eng* 2020; 217: 107827.

36. Li H, Deng ZM, Golilarz NA, et al. Reliability Analysis of the main drive system of a CNC machine tool including early failures. *Reliab Eng Syst Saf* 2021; 215: 107846.

37. Jakubczak H, Glinka G and El-Zein M. Fatigue and reliability of welded structures. SAE paper 2007-01-1657, 2007.

38. Lillemäe I, Lammi H, Molter L, et al. Fatigue strength of welded butt joints in thin and slender specimens. *Int J Fatigue* 2012; 44: 98–106.

39. Socie D and Downing S. Statistical strain-life fatigue analysis. SAE paper 960566, 1996.

40. Kucharczyk P, Madia M, Zerbst U, et al. Fracture-mechanics based prediction of the fatigue strength of weldments. Material aspects. *Eng Fract Mech* 2018; 198: 79–102.

41. Schubnell J, Jung M, Le CH, et al. Influence of the optical measurement technique and evaluation approach on the determination of local weld geometry parameters for different weld types. *Weld World* 2020; 64: 301–316.

42. Shiozaki T, Yamaguchi N, Tamai Y, et al. Effect of weld toe geometry on fatigue life of lap fillet welded ultra-high strength steel joints. *Int J Fatigue* 2018; 116: 409–420.