Summary of research on fatigue life assessment of welded joints

Sai Liu¹,² and Yongchen Liu²,³

¹School of Mechanical and Power Engineering, Nanjing Tech University, 211816 Nanjing, Jiangsu, China;
²Huaiyin Institute of Technology, 223003 Huai’an, Jiangsu, China.
³E-mail: liuyongchen@hyit.edu.cn

Abstract. In order to deepen the understanding of the fatigue problem of welded joints, this paper compares the research principles and limitations of four commonly used welding fatigue life prediction methods, including nominal stress method, hot spot stress method, notched stress method and fracture mechanics method. The nominal stress method is the most widely used in the four fatigue prediction methods, but it is too conservative. The hot spot stress method has high calculation accuracy, but it cannot fully reflect the fatigue behavior of the joint details. The notch stress method includes all sources of stress concentration, but the S-N curve recommended by IIW does not apply to the fatigue evaluation of butt joints. The fracture mechanics method is applicable to the crack propagation stage of joints. Through the analysis and research on the fatigue life assessment methods of four welded joints, it lays a theoretical foundation for the fatigue life prediction of welded joints.

1. Introduction

As an important technological means to connect different components and make them operate reasonably, welding plays an important role in national economic construction and industrial production. Welding technology is widely used in the manufacturing process of automobiles, airplanes, railway vehicles, and it has a great role in promoting the development of modern industry. It is important to study the fatigue life of the initial design of the welded structure. The preliminary analysis of the fatigue life of the welded joint will help the further design and development of the product.

In the 1920s, Moor HF et al. proposed a welding fatigue test method different from the general metal fatigue test. In addition to the experimental study on the fatigue properties of the metal at the welded joint, the heat state and organization of the metal on both sides of the welded joint. The influence of different structural factors on the fatigue performance of the joint should be considered [1-3]. Although the results of the test at that time were quite different from the actual conditions, it played a key role in promoting the research process of welding fatigue and laid the foundation for further research by follow-up researchers. Haixia Zhao et al. used the nominal stress method to evaluate the fatigue life of the scissor mechanism [4]. Jinxin Yao et al. used the nominal stress method to calculate the fatigue life of the rear beam structure of the wind turbine blade bolt tester bracket [5]. Wang Jianming et al. used the nominal stress method to predict the fatigue life of the welded steel tank weld under test conditions [6]. Quan Pan et al. used the nominal stress method combined with the fatigue life curve of the material to predict the fatigue life of the scissor arm structure of the scissor...
type aerial work platform [7]. In the process of estimating the fatigue life of welded joints, the nominal stress method is the most widely used method in fatigue design standards at home and abroad. The fatigue test data of typical welded joints obtained through the laboratory are included in the standard, but after all, the types of welded joints obtained in the laboratory are very limited. There are many types of joints in actual engineering, and some are more complicated, so the method has certain limitations. Yuan Liu used the hot spot stress method to evaluate the fatigue life of welded joints with consideration of vehicle speed and road roughness [8]. Ming Tang used the hot spot stress method to analyze the influence of twin-column single-span large cantilever steel-SC on the fatigue performance of steel bridge deck [9]. The hot spot stress method is different from the nominal stress method. To some extent, a common S-N curve can be used to solve the hot spot stress, and the fatigue strength of different types of joints is indicated by this curve. In today's rapid development of finite element technology, the solution of hot spot stress can make good use of finite element technology.

Xu Liu et al. conducted a multi-axial fatigue analysis of welded joints based on the notch stress method, and obtained the notched life curve of fatigue evaluation [10]. The multi-axis notched fatigue curve has a lower slope and a higher fatigue rating than the one-axis curve recommended by the IIW standard. Lin Xiao et al. used the finite element method combined with the fracture mechanics method to predict the fatigue life of the crack propagation stage of the weld hole structure, and the experimental comparison shows that the life of the fatigue crack growth stage is predicted by the finite element method combined with the fracture mechanics method [11]. The test results are in agreement. In the 1950s, with the continuous development of welding fatigue research, the theory of fracture mechanics began to be applied by researchers to the study of welding fatigue, through the theory of fracture mechanics, it is found that the formation of fatigue cracks in welded joints basically comes from the welding defects at the welded joints [12, 13]. In 1920, the British scientist Griffith proposed the concept of fracture mechanics and the energy-based method to study the fatigue fracture phenomena of various materials in the study of fatigue of glass materials. The study pointed out that when the fatigue crack growth of the material occurs, the energy released by the fatigue crack growth is consistent with the energy necessary to form a new crack of the same area [14]. In 1948, the scientist Irwin made further improvements to the Griffith theory, proposed the concept of energy release rate, and used the material constant as the criterion for the fracture to evaluate whether the fatigue crack in the material further expanded [15]. The notched stress method plays an important role in some specific welded joints. Compared with other life assessment methods, the fracture mechanics method is helpful for solving the problem of low-stress brittle fracture which is very destructive in engineering. It is one of the main methods for failure analysis today.

In this paper, four commonly used methods for predicting fatigue life of welded joints are compared and analyzed. Various life prediction methods have their own advantages and disadvantages. In order to improve the accuracy of fatigue life prediction of welded joints and enhance the practicability of engineering structures, life assessment is carried out. In the process, it is important to choose the appropriate life prediction methods.

2. Welding joint fatigue life assessment methods
In general, the engineering structure undergoes certain external load conditions (loading history, stress distribution, number of occurrences of specific loads, and external environment) during service. In the process of comparison with the fatigue resistance of the structure, fatigue failure occurs when the external load condition exceeds the fatigue resistance of the structure. Different fatigue life prediction methods have different effects in the process of fatigue test data processing of structures.

According to the fatigue design criteria recommended by the IIW (Fatigue Assessment Standard), there are currently four widely used fatigue life prediction methods, namely the nominal stress method, the hot spot stress method, the notched stress method, and the fracture mechanics method.
2.1. Nominal stress method

The nominal stress method uses the nominal stress range as the control parameter to predict the fatigue life of the component through the S-N curve and fatigue cumulative damage rule of a typical welded structure obtained by a large number of welded joint fatigue tests. Based on a large number of laboratory fatigue joint fatigue test data, the IIW has given the S-N curve of nearly 100 kinds of steel structure welded joints, which can be expressed by the following formula.

\[ N \cdot \Delta S^m = C \]  \hspace{1cm} (1)

Where \( N \) is the number of stress cycles, \( \Delta S \) is the nominal stress range, \( m \) and \( C \) are material constants.

The analysis method based on the nominal stress method has been widely used in the evaluation of the fatigue strength of welded structures. On the one hand, the actual welding geometry is a relatively complex structure, different geometric structures correspond to different welding standards, and life assessment must be carried out under the corresponding standards. On the other hand, the results obtained by using the finite element method to estimate the nominal stress are not very accurate. Therefore, the nominal stress method is very conservative in assessing the fatigue strength of welding. It is only applicable to some specific structures. The main influencing factor in these structures is the nominal stress. Under the above circumstances, it is only meaningful to use the nominal stress method for life estimation.

2.2. Hot spot stress method

There is always a maximum structural stress in the component structure and a stress at a dangerous point on the dangerous section, which is defined as the hot spot stress. In welded joints, the local stress calculated immediately before the weld toe front and without considering the notch effect is called structural stress, because the magnitude of the structural stress varies depending on the overall geometry and load parameters of the component and the welded joints, it is also called geometric stress. The maximum value of structural stress at the surface of the weld toe is the hot spot stress. The weld toe is often used as a hot spot in the welded structure because it is the most vulnerable part of fatigue damage.

Different from the nominal stress, the hot spot stress is considered in the stress analysis due to the geometric stress caused by the geometric discontinuity of the component and the joint. It is avoided that the nominal stress method must compare the welded joints to be evaluated with the standard structural details in the specification to select the fatigue strength S-N curve. In theory, a general hot spot stress S-N curve can be used to characterize the fatigue strength of various joint weld types. In addition, the hot spot stress is more suitable to be determined by the finite element method, and the finite element can be fully utilized in the structural stress analysis.

2.2.1. Types of hot spot stress. In the welded plate and shell structure, there are generally three types of hot spots, as shown in Figure 1, the a-type weld toe is at the root of the attached plate, the surface of the mother plate. The b-shaped weld toe is located at the edge of the end face of the attached plate. The c-shaped weld toe is located in the direction of the weld along the attachment plate and the mother plate.

![Figure 1. Hotspot Types.](image-url)
The hot spot stress of the a-type and c-type weld toe can be taken as the sum of the film stress and the bending stress distributed along the thickness direction. For the b-type hot spot, since it is located on the surface of the plate, the stress distribution at the weld toe does not depend on the thickness of the plate. Therefore, the hot spot stress cannot be determined according to the above definition, and the use of end face stress extrapolation to determine this type of hot spot stress is currently the only method used.

2.2.2. Determination of hot spot stress. In the process of applying the hot spot stress method, the most important thing is the determination of the hot spot stress value. The current finite element analysis method plus effective post-processing method is widely used. In foreign countries, many scholars use more surface extrapolation. Calculate the structural stress at these points by selecting two or three points at a distance from the weld toe surface. The surface extrapolation method performs linear or quadratic interpolation calculation on the structural stress of each point to determine the hot spot stress value at the weld toe. Different standards have slightly different provisions for the location of the interpolation nodes and the calculation method for extrapolation. The IIW recommends that the two surface feature positions of the weld toe distances of 0.4T and 1.0T are used as linear extrapolation nodes to obtain the hot spot stress of the weld toe. Different extrapolation node positions are used in other standards, such as 0.5T/1.5T. The three-point parabolic extrapolation calculation of hot spot stress is also recommended in the International Welding Association IIW standard. The hot spot stress calculation extrapolation point position given by IIW and DNV is shown in Table 1.

| Specification | Extrapolation method type | Type a / type c | Type b |
|---------------|---------------------------|-----------------|-------|
| DNV specification | Two-point linear extrapolation | 0.5t/1.5t | 5mm/10mm |
| DNV specification | Three-point quadratic extrapolation | 0.5t/1.5t/2.5t | - |
| DNV specification | Fixed point method | 0.5t | 5mm |
| IIW specification | Two-point linear extrapolation | 0.4t/1.0t | - |
| IIW specification | Three-point quadratic extrapolation | 0.4t/0.9t/1.4t | 4mm/8mm/12mm |

2.3. Notch stress method
The notch stress method is a fatigue evaluation method based on the material elasticity theory. The notch stress method includes all sources of stress concentration, including the stress concentration caused by the weld and the stress concentration caused by structural geometry changes [16].

The notch stress method uses the true stress at the dangerous position obtained in the finite element calculation process as the reference stress. It uses this stress to establish the fatigue life S-N curve. However, in the finite element analysis phase, the local geometry of the weld toe and root is irregular and can be said to be highly irregular, so this irregularity is unpredictable during the finite element design of the joint. In order to solve such a problem, when applying the notch stress method, it is ideal to assume that there is a relatively regular transition arc at the root and the weld toe. Under such assumptions, the local stress can be calculated numerically. Nominal stress, hot spot stress, and notch stress are shown in the Figure 2.
2.4. Fracture mechanics method
From the point of view of fracture mechanics, there are always cracks of different sizes inside the engineering components, that is to say, the existence of cracks is certain. During the normal use period of the component, the presence of cracks can be allowed as long as measures to prevent crack propagation are provided. Scholars at home and abroad continue to deepen the understanding and research on the mechanism and law of crack propagation, and find the closure effect of crack propagation, the crack propagation requires certain conditions, and will not expand until fully expanded. The difference between the maximum stress and the open stress is an important factor in judging whether the crack propagates. On the other hand, the crack growth rate is affected by the effective stress intensity factor. In 1970, Elber developed an Elber model of the crack growth rate and the effective stress intensity factor based on the test results of the crack closure effect [17].

The key problem of the fracture mechanics method is to correctly estimate the crack propagation life. Fracture mechanics provides a theoretical basis for solving the crack propagation problem and estimating the crack life reasonably. Common crack propagation rate formulas are Paris formula and Forman formula.

\[ \frac{da}{dN} = C(\Delta K)^m \]  
\[ \frac{da}{dN} = C(\Delta K)^m / [(1 - r)K_{IC} - \Delta K] \]

Where \( \Delta K \) is stress intensity factor, \( \Delta K = K_{max} - K_{min} = Y\Delta\sigma\sqrt{\pi a} \), \( C \) and \( m \) are material constant, \( K_{IC} \) is fracture toughness of materials, \( r \) is stress ratio, \( Y \) is correction factor, coefficient related to crack shape and position, loading mode and geometrical factors of the sample. The Paris formula is more widely used, but the cycle that can be applied is limited. When solving the crack growth rate and considering the influence of the average stress, it is convenient to use the Forman formula.

3. Conclusions
Nominal stress method, hot spot stress method, notched stress method and fracture mechanics method are the main methods for fatigue life evaluation of welded joints. These methods have certain advantages and limitations. The nominal stress method is the most widely used, but it is too conservative. The hot spot stress method has high precision, but the scope of use is limited. The notch stress method considers the source of all stress concentrations, but it is not suitable for welded butt joints. The fracture mechanics method has a good effect in the crack propagation stage. Through the comparative analysis of four fatigue life prediction methods, it is helpful to further develop the fatigue life prediction method of welded joints.
Acknowledgement
This research was financially supported by project of National Natural Science Foundation of Youth Foundation (grant number 51505172), and project of “533” talent engineering of Huai’an (grant number HAA201736).

References
[1] Liangchen W 2008 Tianjin University
[2] Gurney T R, Maddox S J 1973 Welding Research Int 3(4) 1-54
[3] Claudio B, Saad K, José O P and Alain N 2017 International Journal of Fatigue 96 127-141
[4] Haixia Z, Yumin W and Xiao Z 2018 Lifting and Transport Machinery 7 104-107
[5] Jinwei Y, Xuemei H and Lei’an Z 2018 Machinery Design & Manufacture 6 41-44
[6] Jianming W, Wei L 2019 Journal of Zhengzhou University 40(1) 72-76
[7] Quan P, Zhe Z et al. 2017 Food & Machinery 33(5) 119-124
[8] Yuan L 2018 Highway Engineering 43(5) 260-265
[9] Ming T 2018 Highway 7 216-220
[10] Xu L, Kailin Z, Bin L and Yuan Y 2017 Journal of Chongqing University 40(04) 9-17
[11] Lin X, Lifang L et al. 2018 Journal of the China Railway Society 40(4) 113-119
[12] Zhentong G, Junjiang X 1995 Mechanical Strength 17(3) 61-80
[13] Fengwu Z 2011 Wuhan University of Technology
[14] Shouwen Y 2015 Proceedings of the 7th National Conference on Mechanics History and Methodology 390-394
[15] Tao Y 2014 Harbin Engineering University
[16] Renjun Y, Feng H and Wei Y 2017 Journal of Wuhan University of Technology (Transportation Science and Engineering) 41(05) 766-769+775
[17] Elber W 1971 American Society for Testing and Material 230-242