Fatigue performance of butt-welded austenitic stainless-steel joints evaluated by peak-stress method

Chunyu Pan, Zhen Dai, Jian Xue, Yang Peng and Jun Dong

1 China Construction Industrial & Energy Engineering Co., Ltd, Nanjing, Jiangsu 210023, People’s Republic of China
2 College of Civil Engineering, Nanjing Tech University, Nanjing, Jiangsu 211816, People’s Republic of China
E-mail: yang.peng@njtech.edu.cn

Keywords: stainless steel, butt-welded joints, fatigue strength, peak-stress method

Abstract
In this study, the fatigue performance of butt-welded austenitic stainless-steel joints is investigated by fatigue test, nominal-stress method and peak-stress method. Welding profiles and misalignment were analyzed, residual stresses were measured, and fatigue tests were conducted. The experimental fatigue data are regressed to the stress range versus life-to-failure (S–N) curve of the nominal stress method, and the factor affected dispersion is analyzed by using the peak-stress method. The following conclusion can be drawn: (1) The fatigue strength is 155 MPa in nominal stress method, which is higher than that of structural steel (80 MPa) in the international fatigue design standards. (2) The influence of the welding misalignment and distortion can be accurately estimated by the combing the reference S–N curve and stress magnification factor formulae from the international fatigue design standards.

Nomenclature

| Symbol | Description |
|--------|-------------|
| $K_1$  | notch-stress intensity factor |
| $\sigma_{q0}$ | the stress component |
| $2\alpha$ | opening angle of the V-shaped notch |
| $K_{FE}$ | normalised $K_1$ in the application of the peak stress method |
| $\varepsilon_1$ | parameters for the determination of the strain energy density |
| $\Delta \sigma_{eq}$ | equivalent peak stress |
| $N$ | fatigue life |
| $t$ | plate thickness |
| $l_2$ | half the length of the specimen |
| $\alpha$ | angular distortion value |
| $E$ | Young’s modulus |
| $\sigma_{\text{peak}}$ | elastic peak stress |
| $\lambda_1$ | singular index |
| $d$ | finite element size |
| $R_0$ | radius of the control area |
| $\nu$ | Poisson’s ratio |
| $f_w$ | relevant weight factor of the peak stress |
| $k_m$ | stress magnification factor |
| $l_1$ | half the length of the specimen |
| $\lambda$ | constant |
| $\sigma_m$ | stress range |
1. Introduction

Worldwide commerce, society, and science rely on bridge and road infrastructure. When it comes to stainless-steel-structural fatigue assessment, international standards [1, 2] provide the nominal stress approaches, including the hot-spot stress method, the notch-stress method, the fracture mechanics method. The nominal stress method considers the stress concentration caused by the macroscopic geometric form of the component, but it does not include the local-stress concentration caused by the specific geometric size [2]. The hot-spot method leverages the linear extrapolation of the stress distribution [2–8]. The notch-stress method considers the local regional stress state as the assessment parameter, which directly reflects the degree of local-stress concentration and is in accordance with the mechanical mechanism of fatigue failure. The fracture mechanics method [9] leverages the concept of stress intensity to describe local mechanical behaviors. The peak-stress method [10] is a local-stress method that is a rapid engineering FE-oriented tool for easily evaluating the fatigue strength with 2D or 3D coarse FE analyses.

The peak-stress method was proposed by Nisitani et al [11] and was initially used to solve the mode-I stress intensity factor. Mode I is an opening (tensile) mode where the crack surfaces move directly apart. The researchers pointed out that the ratio of the mode-I stress intensity factor to the peak stress is only related to the element size, and the peak stress can be used to rapidly calculate mode-I stress in a fixed-grid mode. Lazzarin et al [12] extended this method to the fatigue assessment of welds and determined the conversion relationship between the peak- and notch-stress intensity factors. Meneghetti et al [13] studied the fatigue performance of pipe joints using the peak-stress method, demonstrating that the peak-stress method was suitable for estimating the fatigue life of crack initiation in tubular welded joints. Campagnolo [14] applied the peak-stress method to the fatigue assessment of welded steel pipe joints under combined loads of pure axial, pure torsional, in-phase, and reverse axial torsional loads. The results showed that the position of fatigue crack initiation was correctly estimated using the peak-stress method, and the experimental results were in good agreement with the relevant design curves based on the peak-stress method. Meneghetti and Campagnolo [15] reviewed the research progress of the peak-stress method in decade. Bertini et al [16] used notch- and peak-stress methods to evaluate the fatigue life of welded joints. The results showed that the scatter band of the peak-stress method was wider than that of the notch-stress method. This may be because the peak-stress method allows all data to be compared in a single reference S–N curve, whereas the notch-stress method cannot draw conclusions from a single reference S–N curve. This could account for the slightly larger scatter band observed in the peak-stress method, which has several shortcomings. Factors such as the stress concentration caused by weld imperfections and residual stress will increase the dispersion degree between the fatigue test points and the reference S–N curve. The peak-stress method does not consider these factors. The peak stress method has been used to study fatigue strength of the welded joints of stainless-steel [17, 18]. The peak stress can accurately assess the fatigue strength of welded joints of stainless-steel, whether the fatigue crack initiates at weld toe or root. The butt-welded joints are a fatigue critical welded details for the stainless-steel bridge [19, 20]. The fatigue strength of butt-welded joints in stainless-steel is higher than that in the standards [21]. The inverse slope of the S–N curve for the butt-welded joints is shallow and the scatter band is much wider than other fatigue details. This difference can be related to the presence of beneficial compressive residual stresses [22, 23] and slight notch at weld toe [24]. The peak stress method can analyse the reason of the difference of butt-welded joints.

In this study, the fatigue performance of butt-welded austenitic stainless-steel joints is investigated. Weld profiles are measured, and probabilistic analyses of measured results are performed. The residual stresses are tested, and fatigue tests are conducted. The experimental fatigue data are regressed to the stress range versus the life-to-failure (S–N) curve, and the fatigue strength is obtained. The fatigue strength is compared to fatigue classification references from common standards. The dispersion of fatigue experimental data is then analyzed using the peak-stress method. The factors affecting the degree of dispersion between the test data points, and the reference S–N curve are analyzed. The influence of stress concentration and misalignment is then corrected based on the test results of the weld profile. The reason for the large dispersion degree is discussed based on the test results of the residual stress.

2. Peak-stress method

The peak-stress engineering method is used to evaluate the notch-stress intensity factor (NSIF) via a simple finite element (FE) analysis. A fixed-element size is defined as a characterized FE grid, which is used to calculate the elastic peak stress, \( \sigma_{\text{peak}} \) at the tip of the notch. Then, the NSIF \( K_\text{I} \) can be calculated.
The Williams [25] formula for the NSIF with $K_1$ is shown in equation (1):

$$K_1 = \sqrt{2\pi} \lim_{r \to 0} [(\sigma_{00})_{0=0} \cdot r^{1-\lambda_1}]$$

(1)

where $\sigma_{00}$ is the stress component, and $\lambda_1$ is the singular index, which is related to the opening angle, $2\alpha$.

The peak stress, $\sigma_{\text{peak}}$, at the weldment includes the effects of element size and loading mode. The ratio of $K_1$ to $\sigma_{\text{peak}}$ depends only on the element size, $d$. The relationship between $\sigma_{\text{peak}}$ and $K_1$ is given by equation (2):

$$K_{FE}^* = \frac{K_1}{\sigma_{\text{peak}} \cdot d^{1-\lambda_1}}$$

(2)

In practical engineering applications, $K_1 / \sigma_{\text{peak}}$ is replaced by $K_{FE}^*$, and the average value is 1.38.

With reference to plane strain conditions, the range of the total elastic strain energy density (SED) [17, 26–28] averaged over a sector of radius, $R_0$, is shown in equation (3):

$$\Delta W = \frac{\epsilon_1}{E} \left[ \frac{\Delta K_1}{R_0^{1-\lambda_1}} \right]^2$$

(3)

where $R_0$ is the radius of the control area ($R_0 = 0.28$ mm), and the parameter, $\epsilon_1$, depends on the notch opening angle, $2\alpha$, and Poisson’s ratio, $\nu$.

Substituting equation (2) into equation (3), equation (4) can be obtained as

$$\epsilon_1 \left[ K_{FE}^* \cdot \Delta \sigma_{\text{peak}} \cdot \left( \frac{d}{R_0} \right)^{1-\lambda_1} \right]^2 = \frac{1 - \nu^2}{2E} \cdot \Delta \sigma_{eq}^2$$

(4)

where $\Delta \sigma_{eq}$ is the equivalent peak stress, which can be expressed as a function of the elastic peak-stress range, as shown in equation (5):

$$f_w \cdot \Delta \sigma_{\text{peak}} = \Delta \sigma_{eq}$$

(5)

Here, $f_w$ is the relevant weight factor of the peak stress, and $f_w \cdot \Delta \sigma_{\text{peak}}$ is the weighted peak stress, which can more reasonably be used to assess the fatigue strength of the weld at the toe and root. The formula for the relevant weight factor, $f_w$, is shown in equation (6):

$$f_w = K_{FE}^* \cdot \sqrt{\frac{2\epsilon_1}{1 - \nu^2} \cdot \left( \frac{d}{R_0} \right)^{1-\lambda_1}}$$

(6)

where $K_{FE}^* = 1.38$, $\lambda_1$ is the intersection value between the functions of equation (7) and the positive semi-axis of the X-axis. The calculation formula of parameter $\epsilon_1$ [12] is shown in (8):

$$\sin (\lambda q \pi) + \lambda \cdot \sin (q \pi) = 0$$

(7)

$$\epsilon_1 = -5.373 \times 10^{-6}(2\alpha)^2 + 6.151 \times 10^{-4}(2\alpha) + 0.1330$$

(8)

The relevant weight factor of peak stress $f_w$ and the weighted peak stress, $f_w \cdot \Delta \sigma_{\text{peak}}$, can be calculated, and the $S$–$N$ curves of the nominal stress versus fatigue life can be converted into the $S$–$N$ curves of peak stress versus fatigue life.

3. Experimental details and results

3.1. Specimens configurations

The thickness of the plate was 10 mm. To avoid fracture of the width change part of the specimen, the radius was set to 285 mm. The length of the entire parallel specimen was 490 mm, which meets the requirement that the length of the specimens be not less than 420 mm. The geometrical sizes of the specimens are shown in figure 1.

3.2. Material properties

Austenitic stainless steel S30403 (022Cr19Ni10) is widely used, owing to its good corrosion resistance, heat resistance, low temperature strength, and good mechanical properties. The mechanical properties and chemical compositions of the austenitic stainless steel are listed in tables 1 and 2.

3.3. Specimen preparation

TIG was selected as the welding process for the test specimens. Double-sided V-groove welds lacking backing plates were used for the butt-weld specimens. The welding reinforcements were between 1.5 and 2 mm, and the welding reinforcement was not polished. The welding conditions are presented in table 3.

The number of fatigue test data greater than or equal to 10 is mentioned in the International Institute of Welding (IIW) recommendations [2], which meets the requirements of the free-slope regression $S$–$N$ curve.
specimens were tested in this study, as shown in table 3. The specimens were obtained via water-jet cutting of the welded stainless-steel plates.

3.4. Test setup
Fatigue tests were carried out on an MTS fatigue testing machine with a capacity of 1,000 kN, and the frequency range was 0–100 Hz. The constant stress-range fatigue tests were conducted at a frequency of 20 Hz and stress ratio of 0.1. To avoid the influence of eccentricity on test results, the axes of the specimen and the upper and lower fixtures should coincide. The specific loading system of the constant stress range fatigue test is presented in table 4.

3.5. Residual stress test and results
Considering the influence of residual stress on fatigue performance, a specimen (BW–11) was selected from the same batch of specimens for the residual stress test. The residual stress test was performed on the PROTO IXRD residual stress machine. The oxide layers on the weld surface were removed prior to the residual stress test. The position of the residual stress test was 6–7 μm below the surface. Four points in the middle of each weld toe were tested, as shown in figure 2. The results of the residual stress tests are shown in table 5.

3.6. Weld-profile measurement and results
To assess the quality of welds and the influence of the weld profile on fatigue strength, it is necessary to measure the weld profile. The silica gel measurement method were used to measure the weld profile, as shown in figure 3, respectively. The measurement positions and test parameters are shown in figure 4.

To investigate the real weld profile of the butt weld from-measured data obtained by the silica-gel measurement method, a probability statistical analysis of each parameter was carried out. The probability statistics for each parameter of the butt weld are shown in figure 5.

The measurement parameters of the butt-weld specimens included the test section width, plate thickness, and plate length, as well as axial and angular distortions. The results show that there was no axial misalignment in the specimen, the angular distortion was in the range of 2–4°, and no undercut phenomenon was found.

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Table 1. Mechanical properties of austenitic stainless-steel.

| Material | Yield strength $f_{0.2}$ (MPa) | Tensile strength $f_u$ (MPa) | Elastic modulus $E$ (MPa) | Elongation (%) | Hardness (HV) |
|----------|--------------------------------|-----------------------------|---------------------------|----------------|--------------|
| S30403   | 251.7                          | 777.2                       | $2.02 \times 10^3$       | 53.9           | 204          |

Table 2. Chemical composition of austenitic stainless-steel.

| Material | C    | Si   | Mn   | P    | S    | Cr   | Ni   |
|----------|------|------|------|------|------|------|------|
| S30403   | 0.023| 0.48 | 0.89 | 0.033| 0.008| 18.12| 8.11 |
| Layer | Pass            | Current type              | Welding current I/(A) | Welding voltage U/(V) | Welding speed v/(cm min⁻¹) | Heat input HI/(kJ/cm) | Gas flow rate(L min⁻¹) |
|-------|-----------------|---------------------------|-----------------------|------------------------|-----------------------------|------------------------|------------------------|
| 3     | One-scar backing welding | Straight polarity direct current | 100–130               | 11–14                  | 8–10                        | 8.3–13.7              | 8–10                   |
|       | Two-scar filling welding |                                           | 100–130               | 12–16                  | 13–16                       | 4.5–9.6               | 13–16                  |
|       | Three-scar cover welding |                                           | 100–130               | 12–16                  | 13–16                       | 4.5–9.6               | 13–16                  |

Table 3. Welding conditions for butt-welded joints.
The failure modes of the 10 specimens obey a specific rule. The fatigue cracks were all initiated at the weld toe and propagated along the direction perpendicular to the base metal, penetrating through the entire base metal surface until the specimens broke, as shown in figure 6. The fracture surfaces were analyzed. The initiation of fatigue cracks had the morphological characteristics of ratchet marks. In the stable fatigue-crack propagation stage, the fracture surfaces were smooth and bright. In the final stage of the unstable fracture, the fracture surface was rough.

The fatigue-test results and the $S-N$ curves obtained by regression of the test data are shown in figure 7. The correlation coefficient of the regression curve was 0.335, which is less than the critical value of $R = 0.532$ [29]. The inverse slope of the curve was significant and did not meet the general curve inverse slope requirements.

Atzori and Lazzarin [30] conducted a fatigue test, and the test results showed that the inverse slope of the $S-N$ curve varied in the range of 3–20, which did not follow the general rule that the slope should be less than 10. Similarly, Gallo et al [31] studied the inverse slope of the $S-N$ curve obtained under axial, shear, and multi-axial load fatigue tests, and they showed significant differences, varying between 3 and 22. Maddox [32] mentioned that the excessive inverse slope of the $S-N$ curve is caused by the influence of residual stress. The results of these
residual stress tests show that the residual stresses of the four test points are all compressive stresses. The maximum compressive residual stress was $-268.25$ MPa. Obviously, there was a large compressive residual stress in the specimens, which is the main reason the inverse slope of the $S$–$N$ curve does not meet the general requirements.

The butt-weld test data in this study and reference [33–37] are shown in figure 8. The above reasons were considered, and the $S$–$N$ curve of the test data should be regressed with the collected test data. The fatigue strength obtained by regression of the test data and the collected test data was 155 MPa, which was 94% higher than the fatigue strength of 80 MPa of structural steel according to IIW recommendations [2].

5. Fatigue strength analyzed by peak-stress method

5.1. FE model

A 1/4-axisymmetric model with a two-dimensional shell element of butt-weld specimens was established using ABAQUS FE analysis software [38]. In the present analysis, the Young’s modulus was $E = 202$ GPa, and Poisson’s ratio was $\nu = 0.3$. The boundary condition of the $Y$ direction was fixed, and a tensile stress of 1 MPa was set in the $X$-direction. The element type was four-node bilinear plane strain quadrilateral incompatible mode. The grid-control attribute included quadrilateral-free progression algorithms, and mapped meshing was not used. The grid was distributed globally, and the unit size, $d$, was 1 mm, as shown in figure 9. The peak-stress concentration factor of the butt weld at the weld toe was 1.045 MPa.

According to the profile measurement data of the butt weld (as shown in figure 5), FE modeling analysis was carried out to obtain the peak-stress concentration factor at the four weld toes. The results of the peak-stress concentration factor for all specimens are listed in Table 6. The fatigue-crack initiation positions were compared between the peak-stress and fatigue tests. The fatigue-crack initiation positions of the fatigue test and the maximum peak-stress obtained by the FE calculation were consistent.

Conversion of the side angle measured by the specimen into the form of $2\alpha$. According to equation (7) and equation (8), parameters $\varepsilon$ and $\lambda$ of the butt-weld specimens at different positions in the weld can be calculated. Thus $f_{u0} \cdot \Delta \sigma_{peak}$ value can be obtained by equations (1–6).

The calculation results were placed into the reference scatter bands of the butt weld [18]. The inverse slope of the scatter bands is three, as shown in figure 10. Most butt-weld data points deviated from the scatter bands. The influence of stress concentration caused by weld geometry on fatigue strength was considered, and the dispersion degree between test data points and reference $S$–$N$ curve was large.
Figure 5. Probability statistics of geometrical parameters of the butt weld.
5.2. Misalignment and residual stress influence on fatigue strength

In FE analysis, the influence of misalignment was not directly considered. In actual situations, axial misalignment and angular distortion in axially loaded joints lead to an increase in stress in the welded joint, owing to the occurrence of secondary-bending stresses. The regression $\Delta \sigma_{\text{peak}}$-N curve in the code considers the influence of misalignment. Hence, the influence of misalignment was studied in this study.

Misalignment is divided into axial and angular distortions. The stress magnification factors, $k_m$, caused by axial misalignment and angular distortion are given in the IIW recommendations [2], which are shown in equations (9) and (10).

The axial misalignment of butt-weld joints is

$$k_m = 1 + \lambda \cdot \frac{e \cdot l_1}{t (l_1 + l_2)}$$

where $\lambda = 6$, $e$ is the axial misalignment value, $t$ is the plate thickness, and $l_1$ and $l_2$ are half the length of the specimen.
The angular distortion of butt-weld joints is

\[ k_m = 1 + \frac{3\alpha}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2} \left( \beta = \frac{2l}{t} \sqrt{\frac{3\sigma_m}{E}} \right) \]  

(10)

where \( \alpha \) is the angular distortion value, \( t \) is the plate thickness, \( l_1 \) and \( l_2 \) are half the length of the specimen, \( \sigma_m \) is the stress range, and \( E \) is the Young’s modulus.

The stress magnification factors, \( k_m \), caused by axial misalignment and angular distortion were calculated as shown in table 7, and the weighted peak-stress range was modified. The modified weighted peak stress of the butt weld is plotted on the scatter bands, as shown in figure 11. The data of the butt weld were partly in the scatter band.
bands and partly exceeding the upper characteristic S–N curve. The influence of misalignment caused by the welding deformation was modified. It can be seen that the dispersion degree between the test data points and the S–N curve is reduced. Therefore, misalignment is an important factor that affects the degree of dispersion.

Table 7. Stress magnification factor $k_m$.

| Specimen | Axial misalignment (mm) | Angular distortion (°) | $k_m$ axial misalignment | $k_m$ angular distortion | $k_m$ |
|----------|-------------------------|-------------------------|--------------------------|--------------------------|-------|
| BW-1     | 0                       | 4                       | 1.000                    | 2.575                    | 2.575 |
| BW-2     | 0                       | 3.5                     | 1.000                    | 2.575                    | 2.575 |
| BW-3     | 0                       | 2.5                     | 1.000                    | 2.622                    | 2.622 |
| BW-4     | 0                       | 3.5                     | 1.000                    | 2.622                    | 2.622 |
| BW-5     | 0                       | 2.5                     | 1.000                    | 2.673                    | 2.673 |
| BW-6     | 0                       | 2                       | 1.000                    | 2.673                    | 2.673 |
| BW-7     | 0                       | 3                       | 1.000                    | 2.700                    | 2.700 |
| BW-8     | 0                       | 4                       | 1.000                    | 2.700                    | 2.700 |
| BW-9     | 0                       | 3                       | 1.000                    | 2.670                    | 2.670 |
| BW-10    | 0                       | 3.5                     | 1.000                    | 2.686                    | 2.686 |
According to the residual stress test results, there was a large residual compressive stress in the specimens. It is well known that residual compressive stress can improve the fatigue life of the specimens, and the large residual compressive stress is related to the data point exceeding the upper characteristic S–N curve. Therefore, the residual stress has a greater impact on the dispersion degree between the test data point and the S–N curve.

6. Conclusions

In this study, the fatigue performance of butt-welded austenitic stainless-steel joints was investigated experimentally and theoretically. The detailed conclusions are as follows:

- The fatigue strength of the butt-weld joints of austenitic stainless-steel was 155 MPa, which was 94% higher than the fatigue strength of 80 MPa according to the IIW recommendations.
- The fatigue strength of butt-welded austenitic stainless-steel joints can be reasonably predicted by the reference S–N curve of the peak-stress method combined with stress magnification factor formulae for welding misalignment and distortion.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Author contributions

C P, Z D, J X, Y P and J D prepared the figures and drafted the manuscript. All authors critically revised and approved the final manuscript version.

Funding

This research was funded by the Project of National Natural Science Foundation of China grant number [51408307].

Conflicts of interest

The authors declare no conflicts of interest.

ORCID iDs

Chunyu Pan https://orcid.org/0000-0003-0498-7212

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