

Article

Analysis of the Geometrical Size Effect on the Fatigue Performance of Welded T-Joints

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Abstract

Fatigue fracture is the predominant failure mode in welded joints, where complex stress distributions and stress gradient effects at critical joint regions present major challenges for fatigue design. In civil engineering, the diversity of welded joint configurations, large structural spans, and complex loading conditions make it essential to investigate the influence of geometrical size effects on fatigue performance to ensure structural safety. This study focuses on welded T-joints and examines how variations in web plate thickness, weld toe size, and welding angle affect their fatigue behavior through experimental testing. The results show that fatigue life curves fitted using the Mises stress amplitude exhibit higher accuracy than those based on the normal stress amplitude used in current design codes. Pearson correlation analysis indicates that the influences of the geometrical parameters on fatigue life are mutually independent. Furthermore, analysis of the coefficient of variation reveals that welding angle has the greatest effect on fatigue life, whereas weld toe size exerts the least influence.

Keywords: welded T-joints; fatigue life; geometrical size effect; correlation analysis; coefficient of variation



Academic Editor: Mario D'Aniello

Received: 17 September 2025

Revised: 5 October 2025

Accepted: 8 October 2025

Published: 9 October 2025

Citation: Chen, Y.; Shen, P.; Li, C.; Zhou, J. Analysis of the Geometrical Size Effect on the Fatigue Performance of Welded T-Joints. *Buildings* **2025**, *15*, 3627. <https://doi.org/10.3390/buildings15193627>

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1. Introduction

Fatigue failures are the most common type of failure in welded structures, accounting for 70–90% of all welded joint failures [1–3]. The unique fabrication processes of welded steel structures lead to a higher occurrence of material defects at weld sites, which significantly reduces their fatigue strength [4–11]. Therefore, accurately determining the fatigue strength at weld sites is essential for ensuring the overall integrity and safety of welded constructions.

Extensive research has been conducted to address fatigue issues in welded connections. Fisher et al. [12–16] emphasized the importance of accurately determining stress ranges for fatigue design, particularly in steel orthotropic bridge decks. Alencar and Ban et al. [17–22] investigated the influence of joint configuration, size, and stress concentration on fatigue strength and proposed a predictive model for fatigue resistance based on *S-N* curves. Studies by Samadi, Zhao, and Malschaert et al. [23–25] and Xu et al. [26–29] further analyzed fatigue behavior under various configurations and loading conditions using finite element modeling and probabilistic approaches.

Research by Cheng et al. [30] and Akyel et al. [31] enhanced understanding of fatigue behavior under different geometrical conditions and repair processes, emphasizing the

role of weld configuration and repair techniques. Martínez et al. [32] and Bai et al. [33] examined the impact of geometrical size on fatigue life, demonstrating that variations in microstructural size and shape can significantly influence durability. Similarly, Zheng et al. [34] and Yang et al. [35] revealed that both microstructural and geometrical scales play a crucial role in fatigue behavior, while Wang et al. [36] used digital simulations to show that bridge geometry substantially affects stress distribution and fatigue responses.

Although previous studies have examined the influence of geometry on fatigue performance, most have concentrated on either microstructural size effects or single-dimensional parameters such as thickness, without addressing the combined geometric influences at welded joints. Moreover, the coupled effects of web plate thickness, weld toe size, and welding angle on the fatigue life of welded T-joints have received limited attention and remain insufficiently explored. In addition, current design standards, including those of China and the International Institute of Welding (IIW), primarily consider thickness when accounting for size effects, overlooking other geometric parameters that may significantly affect fatigue behavior [37,38].

To address these gaps, this study focuses on welded T-joints commonly used in civil engineering structures, where complex stress states and large spans exacerbate fatigue problems. Through fatigue testing and stress analysis, this paper investigates the effects of web plate thickness, weld toe size, and welding angle on the fatigue performance of T-joints. Furthermore, correlation analysis is conducted to quantify the independence and relative influence of these geometric parameters, providing a more comprehensive understanding of the geometrical size effect on fatigue life.

2. Fatigue Tests

2.1. Mechanical Properties of the Material

The test material used was Q355B steel, as specified in the Chinese steel structure standards [39]. Mechanical properties were evaluated using uniaxial tensile tests. Depending on the thickness of the plates, four standard specimens were used, loaded under displacement control at a rate of 0.5 mm/min. During the tests, elongation of the specimens was measured using an extensometer, and the tests were concluded upon specimen fracture. Results of these tests are presented in Table 1, where t is the thickness of the steel plate; f_y and f_u are the yield strength and ultimate strength of the steel, respectively; E_s is the elastic modulus of the steel.

Table 1. Mechanical properties of the steel.

Specification	t (mm)	f_y (MPa)	f_u (MPa)	E_s (MPa)
Q355B	10	375	515	2.11×10^5
Q355B	14	373	511	2.10×10^5
Q355B	18	380	520	2.14×10^5
Q355B	20	380	520	2.12×10^5

2.2. Specimen Design

The welded T-joint specimens consist of a base plate and a web plate, connected by double-sided fillet welds. The basic dimensions of the specimens are shown in Figure 1, where t represents the thickness of the web plate; h_f denotes the size of the weld toe; α indicates the welding angle.

During the fatigue tests, the web plate thickness, weld toe size, and welding angle were selected as key design parameters. The parameter ranges were 10–18 mm for web plate thickness, 8–12 mm for weld toe size, and 10–60° for welding angle. These values were chosen based on commonly used dimensions in engineering practice to ensure structural

representativeness. The specimens were divided into seven groups, and the specific parameter values for each group are summarized in Table 2.

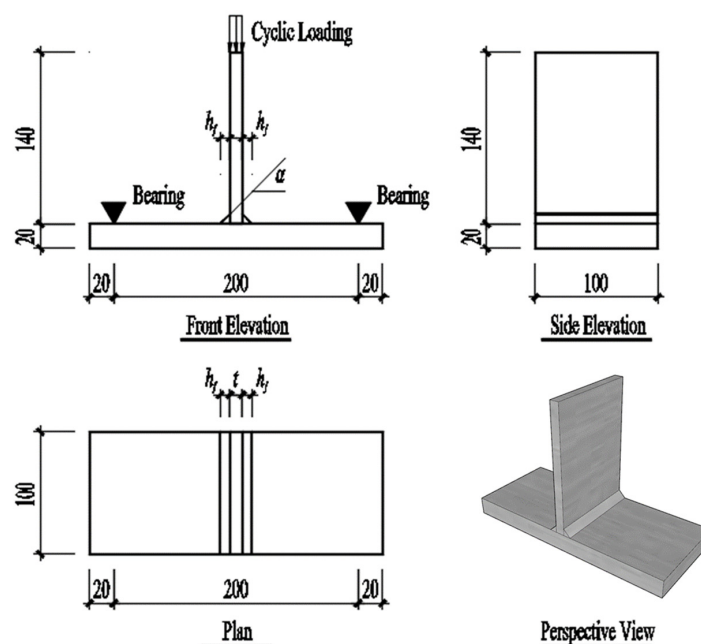


Figure 1. The dimensions of specimen.

Table 2. Specimen grouping.

Group	Base Plate Dimensions (mm)	Web Plate Dimensions (mm)	Weld Toe Size (mm)	Welding Angle (°)
T-1	240 × 100 × 20	140 × 100 × 10	8	45
T-2	240 × 100 × 20	140 × 100 × 14	8	45
T-3	240 × 100 × 20	140 × 100 × 18	8	45
T-4	240 × 100 × 20	140 × 100 × 10	10	45
T-5	240 × 100 × 20	140 × 100 × 10	12	45
T-6	240 × 100 × 20	140 × 100 × 10	8	10
T-7	240 × 100 × 20	140 × 100 × 10	8	60

Due to the different values of cyclic loads applied to the specimens, each group contains three specimens, resulting in a total of 21 specimens being manufactured and processed. The completed specimens are shown in Figure 2.

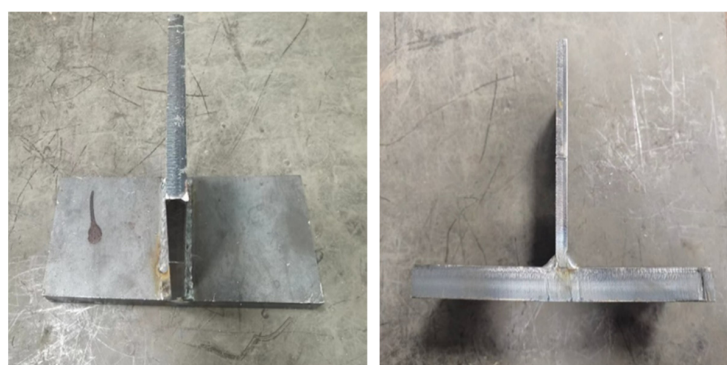


Figure 2. Specimens after fabrication.

2.3. Test Setup and Loading Protocol

Figure 3 shows the arrangement of the test setup and instruments, where cyclic loading is applied using an MTS servo-hydraulic controlled fatigue testing system.

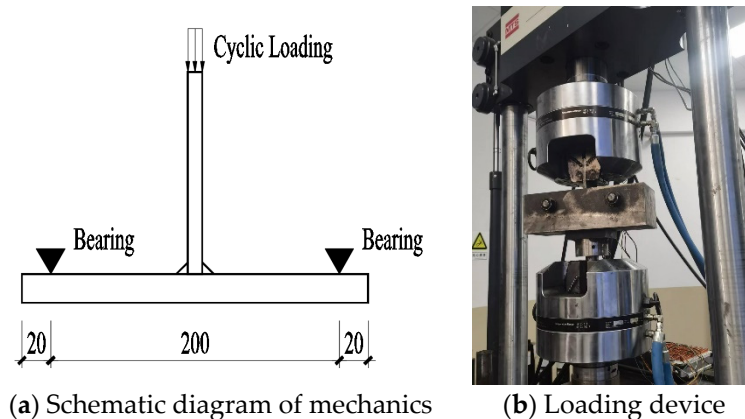


Figure 3. Test setup.

The test loading is uniaxial tension, with maximum cyclic pressures ($p_{\max}$) of 40 MPa, 50 MPa, and 60 MPa, respectively. These stress levels are representative of practical engineering applications, including orthotropic steel bridge decks, cable-stayed bridge cable joints, and suspension bridge hanger connections.

The stress ratio for the specimens is 0.1, which is defined as the ratio of the minimum stress to the maximum stress during cyclic loading. The fatigue loading frequency is 15 Hz. The loading protocol is shown in Figure 4. The figure only illustrates the cyclic loading condition within 1 s; subsequent loading is applied in the same regime. The test is terminated when the specimen exhibits fatigue cracking or fracture.

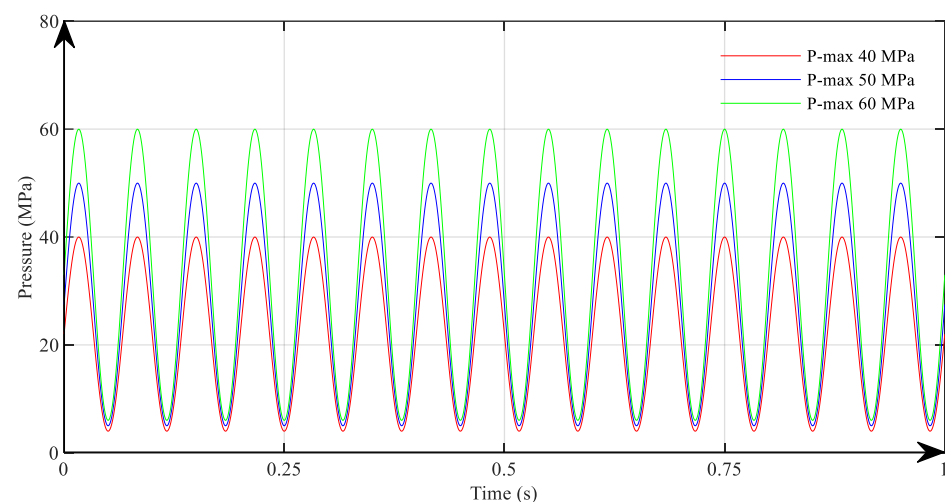


Figure 4. Loading protocol.

2.4. Measurement Scheme

The force and displacement at the cyclic loading point were automatically recorded by the fatigue testing machine. Because the stress distribution at the weld toe of the T-joint is complex, strain gauges and strain rosettes were symmetrically arranged on both sides of the joint to measure the Mises stress. Strain gauges were installed on both the top and bottom surfaces of the base plate at identical planar positions. The strain gauges on the top are labeled as SF-*, and those on the bottom as SB-*. The strain measurement setup is illustrated in Figure 5.

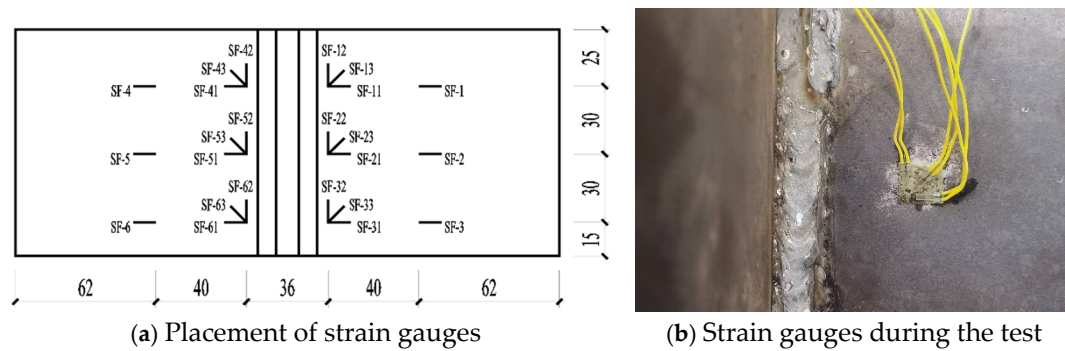


Figure 5. Strain gauge layout.

3. Test Results

3.1. Test Phenomenon

During the fatigue tests, all T-joint specimens exhibited fracture failure characterized by distinct features of fatigue damage. The fractures consistently occurred at the weld toe region, and specimens subjected to higher load levels were more likely to experience cracking at both weld toes. Once initiated, cracks gradually propagated within the weld zone and eventually penetrated the weld and base material, leading to the fracture of the base plate. The fracture surfaces were inclined relative to the direction of cyclic loading, which can be attributed to the uniform and dense weld formation that transferred loads along the fillet welds of the T-joint to the weld toes.

To further verify the experimental results, finite element models of the same joints under identical conditions were developed using ABAQUS 6.14. Both the steel plates and welds were modeled with C3D8R solid elements, and the material properties and cyclic loading conditions were consistent with those used in the experiments. The mesh size ranged from 1 to 5 mm, and displacement constraints were applied at locations corresponding to the experimental boundary conditions. The welds were connected to the web plate and base plate using surface-to-surface contact. The simulation results showed good agreement with the experimental observations, confirming the validity of the test findings. The appearance of the specimens at failure is shown in Figure 6.

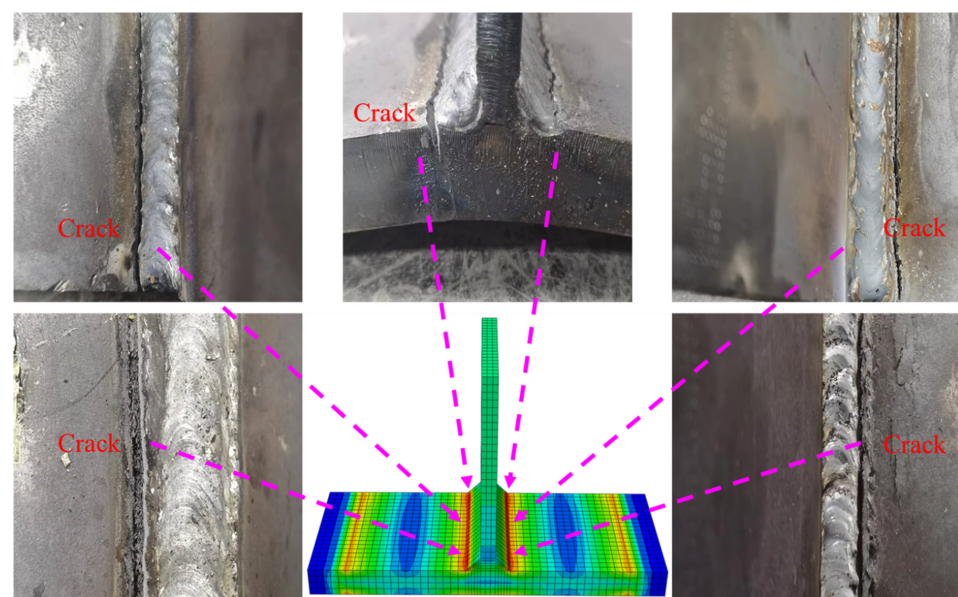


Figure 6. Test phenomenon of the specimens.

3.2. Fatigue Life

Based on data automatically collected and recorded by the fatigue testing system, the number of load cycles at the time of specimen failure, which represents the fatigue life of the specimens, was obtained and is shown in Table 3.

Table 3. Load cycles of the specimens.

$p_{\max}$ (MPa)	T-1	T-2	T-3	T-4	T-5	T-6	T-7
60	36,785	35,362	33,692	37,608	38,532	28,622	39,748
50	108,653	95,702	88,685	112,496	115,682	81,561	129,406
40	222,493	207,635	197,812	232,642	243,951	185,237	266,234

3.3. Displacement Curve

During the test, the maximum displacement per cycle for each group of specimens was recorded and plotted as a function of the number of cycles, as shown in Figure 7. These curves effectively demonstrate the three typical stages of fatigue failure: crack initiation, crack propagation, and fracture.

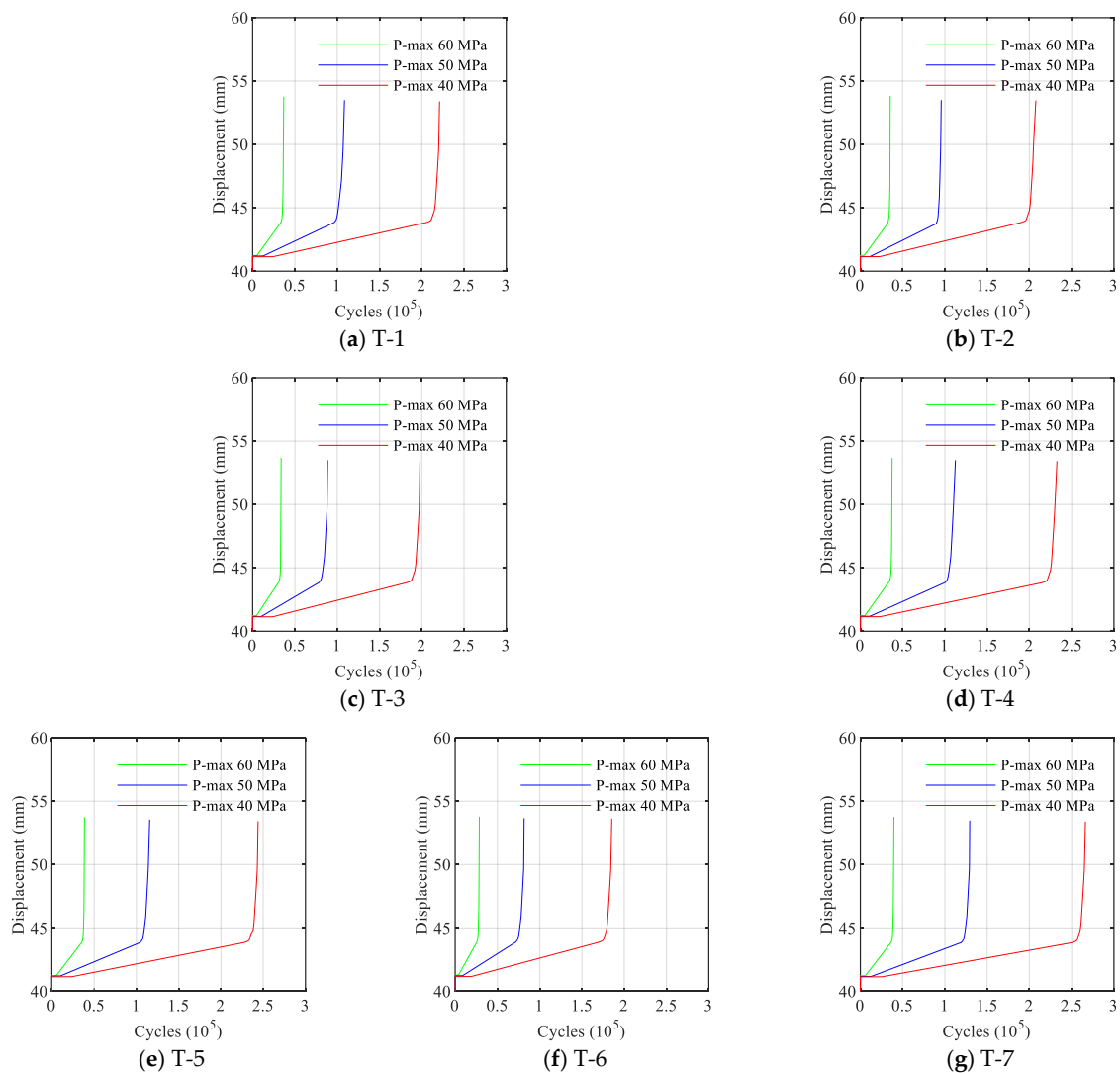


Figure 7. Displacement curves.

For specimen T-1, at the initial stage of loading, the maximum displacement under a single cycle load was 41.2 mm. As the number of cycles increased, the maximum displacement remained approximately constant, depicted by a horizontal line on the displacement curve, representing the first phase, the crack initiation stage. As the number of cycles continued to increase, the maximum displacement steadily increased, showing a roughly proportional relationship between the two. The slope of the curve was steeper for higher cyclic loads, indicating that the fatigue crack was slowly expanding at a constant rate. This phase, the crack propagation stage, lasted for a considerable duration, occupying about 80% of the entire loading process. With continued loading, as the fatigue crack continued to expand and the crack width increased, the rate of expansion accelerated until the material reached unstable fracture, marking the third stage, which lasted for a shorter duration, about 10% of the total loading process. The pattern of change was consistent across all specimen groups and is not repeated here for brevity.

4. Test Analysis

Based on the measured strain data, the Mises stress at the weld toe was calculated, as shown in Table 4, where the listed stress values correspond to the stress at the moment of fatigue failure. The fatigue life curve was fitted using the least squares method [40,41], resulting in Equation (1):

$$\lg S = k - m \cdot \lg N \quad (1)$$

where k and m are parameters to be determined by the curve fitting process, and their values are related to the material properties and the stress ratio used during the tests. For this analysis, the amplitude of the Mises stress at the weld toe, denoted as S , was used.

Table 4. Mises stress of the specimens (MPa).

$p_{\max}$	T-1	T-2	T-3	T-4	T-5	T-6	T-7
60	340.43	338.06	336.49	342.77	345.93	345.14	349.08
50	234.41	236.59	233.57	235.50	235.53	234.96	236.06
40	185.39	186.32	184.38	185.79	182.76	184.94	185.77

The study investigates the impact of web plate thickness, weld toe size, and welding angle on the fatigue life of T-joint specimens.

4.1. Impact of Web Plate Thickness on Fatigue Life

Specimens T-1, T-2, and T-3 have web plate thicknesses of 10 mm, 14 mm, and 18 mm, respectively, with all three groups having a weld toe size of 8 mm and a welding angle of 45°. A comparative analysis of these three groups produced fatigue life curves as shown in Figure 8.

Based on the curves, parameter values were fitted as shown in Table 5.

Table 5. Parameter values varying with web plate thickness.

Group	Web Plate Thickness (mm)	k	m
T-1	10	4.083	0.340
T-2	14	4.079	0.342
T-3	18	4.065	0.342

The results show that the slopes of the fatigue life curves for all three groups are approximately consistent at 0.34. However, variations in web plate thickness cause a horizontal shift in the curves within the coordinate system. For a given fatigue life, specimens

with thinner web plates require higher stress amplitudes to reach failure, indicating greater resistance to fatigue damage. Thus, fatigue life increases as web plate thickness decreases, demonstrating an inverse relationship between the two. This behavior can be attributed to the reduction in stress concentration factor associated with thinner web plates, which enhances the fatigue resistance of the T-joint.

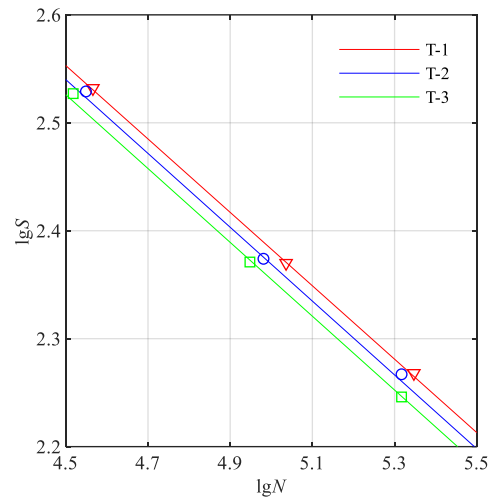


Figure 8. Fatigue life curves with varying web plate thickness.

4.2. Impact of Weld Toe Size on Fatigue Life

Specimens T-1, T-4, and T-5 have weld toe sizes of 8 mm, 10 mm, and 12 mm, respectively, all with a web plate thickness of 10 mm and a welding angle of 45°. Comparative analysis of these groups produced fatigue life curves as shown in Figure 9.

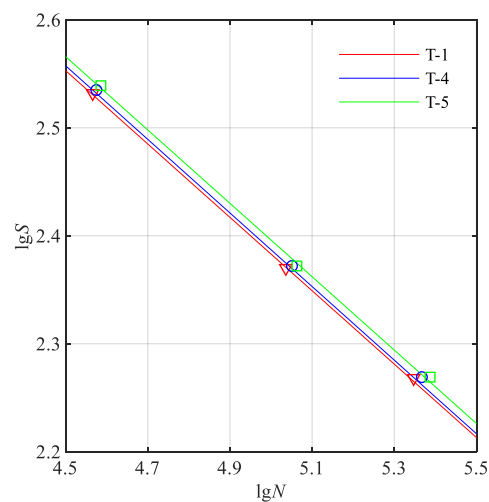


Figure 9. Fatigue life curves with varying weld toe size.

Based on the curves, parameter values were fitted as shown in Table 6.

Table 6. Parameter values varying with weld toe size.

Group	Weld Toe Size (mm)	k	m
T-1	8	4.083	0.340
T-4	10	4.092	0.341
T-5	12	4.096	0.340

The results indicate that the slope of the fatigue life curves for all three groups remains roughly consistent at about 0.34. However, with increasing weld toe size, the fatigue curves shift within the coordinate system. At a given fatigue life, larger weld toe sizes require higher stress amplitudes to fail, indicating greater resistance to fatigue damage. The fatigue life increases with increasing weld toe size, showing a direct proportional relationship between weld toe size and fatigue life. The increase in weld toe size enhances the load-bearing capacity of the fillet weld, thereby increasing fatigue life.

4.3. Impact of Welding Angle on Fatigue Life

Specimens T-1, T-6, and T-7 have welding angles of 45°, 10°, and 60°, respectively, all with a web plate thickness of 10 mm and a weld toe size of 8 mm. Comparative analysis of these groups produced fatigue life curves as shown in Figure 10.

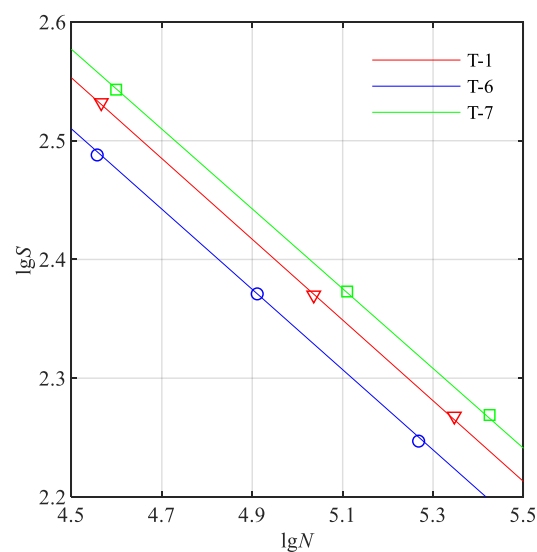


Figure 10. Fatigue life curves with varying welding angle.

Based on the curves, parameter values were fitted as shown in Table 7.

Table 7. Parameter values varying with welding angle.

Group	Weld Toe Size (mm)	k	m
T-1	45	4.083	0.340
T-6	10	4.031	0.338
T-7	60	4.089	0.336

The results indicate that the slope of the fatigue life curves for all three groups remains roughly consistent at about 0.34. However, with changes in welding angle, the fatigue curves shift within the coordinate system. At a given fatigue life, larger welding angles require higher stress amplitudes to fail, indicating greater resistance to fatigue damage. The fatigue life increases with increasing welding angle, showing a direct proportional relationship between welding angle and fatigue life. The increase in welding angle enhances the load-bearing capacity of the fillet weld, thereby increasing fatigue life.

4.4. Comparison of Experimental Data with Standards

The current Chinese standards for fatigue verification use the stress amplitude at the corresponding part of the specimen, considering only normal stress amplitude, and provide corrections related to plate thickness only for normal stress amplitude calculations. The

T-joint studied in this paper corresponds to category Z8 in the standards, and the derived fatigue S - N curves are as Equation (2):

$$\lg S = 3.952 - 0.333 \lg N \quad (2)$$

Equation (3) is fitted from experimental data for normal stress amplitude:

$$\lg S = 3.955 - 0.330 \lg N \quad (3)$$

Equation (4) is fitted from experimental data for Mises stress amplitude:

$$\lg S = 4.076 - 0.340 \lg N \quad (4)$$

Figure 11 below shows the fatigue life curves under different stress amplitudes along with the standard curve plotted on the same coordinate system.

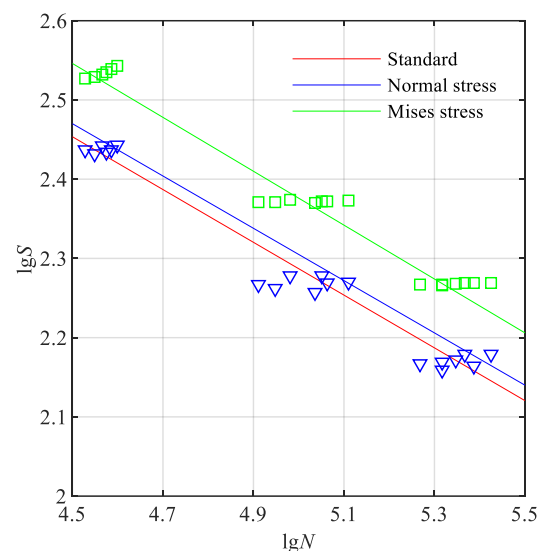


Figure 11. Comparison of fatigue life curves under different stress amplitudes.

The results show that the standard fatigue curve closely aligns with the normal stress amplitude fatigue life curve and is positioned slightly to its lower left, indicating that the standard curve is conservative. In contrast, the Mises stress amplitude fatigue life curve is located toward the upper right, farther from both the normal stress amplitude curve and the standard curve. The complex stress state in the loaded region is more accurately represented by the Mises stress. Although further verification is needed to confirm whether Mises stress better reflects fatigue life than normal stress, the comparison of goodness-of-fit values supports this assumption. The R -squared value for the normal stress amplitude fatigue life curve is 0.53, while that for the Mises stress amplitude curve is 0.78, indicating a significantly better fit for the latter [42–44]. These results demonstrate that the normal stress amplitude curve exhibits greater data scatter than the Mises stress amplitude curve. Therefore, employing Mises stress amplitude provides a more reliable basis for predicting the fatigue life of welded T-joints.

5. Correlation Analysis of Factors Affecting Fatigue Life

5.1. Correlation Among Geometrical Dimension Parameters

Pearson correlation analysis is an effective method for assessing the degree of association between two variables [45]. Therefore, the Pearson correlation coefficient can be used to calculate the degree of association between two variables. A higher Pearson coefficient

indicates a stronger association, while a lower value suggests a weaker association, with the coefficient ranging from 0 to 1 [46,47]. Through Pearson correlation analysis, the degree of correlation (or coupling) among factors affecting fatigue life can be determined. The Pearson correlation coefficient is calculated using Formulas (5)–(8).

$$r = \frac{S_{xy}}{S_x S_y} \quad (5)$$

$$S_{xy} = \sum_{i=1}^n [X_i - E(X)][Y_i - E(Y)] / (n - 1) \quad (6)$$

$$S_x = \sqrt{\sum_{i=1}^n [X_i - E(X)]^2 / (n - 1)} \quad (7)$$

$$S_y = \sqrt{\sum_{i=1}^n [Y_i - E(Y)]^2 / (n - 1)} \quad (8)$$

where r represents the Pearson correlation coefficient, X and Y represent two different sets of variables, n is the number of data samples, S_{xy} is the covariance between variables X and Y , S_x is the variance of variable X , and S_y is the variance of variable Y .

By performing these calculations, a Pearson correlation coefficient matrix can be created for the factors influencing fatigue life, as shown in Figure 12.

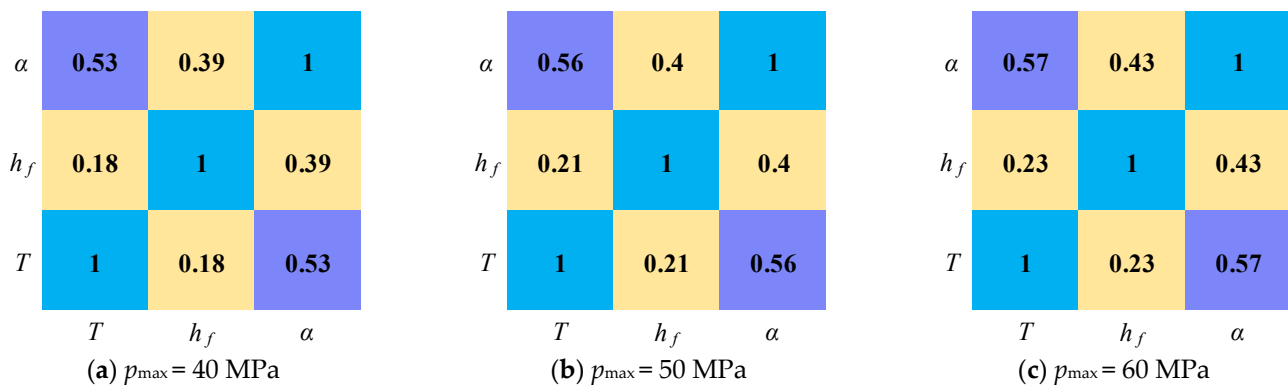


Figure 12. Pearson matrix for geometrical parameters.

The calculated results indicate that the Pearson correlation coefficients between different geometrical dimension parameters are all less than 0.6, suggesting that there is a low correlation between these parameters [47]. According to the experimental research results, each geometrical dimension parameter affects the fatigue life of T-joint specimens. Section 5.3 will further investigate the extent of the impact of these three geometrical dimension parameters on the fatigue life of welded T-joints.

5.2. Correlation Between Geometrical Dimension Parameters and Stress Concentration Factor

In the field of structural fatigue research, the elastic stress concentration factor (K_t) is often used to reflect the impact of stress concentration on fatigue life [48–51]. The formula for calculating K_t is as follows:

$$K_t = \frac{\sigma_{\max}}{\sigma_{\text{nom}}} \quad (9)$$

where $\sigma_{\max}$ is the maximum stress at the joint of the specimen, and σ_{nom} is the average stress at the joint.

Using the Pearson correlation analysis method, the correlation between the elastic stress concentration factor and geometrical dimension parameters was calculated based on experimental data. The Pearson correlation coefficient matrix is shown in Figure 13.

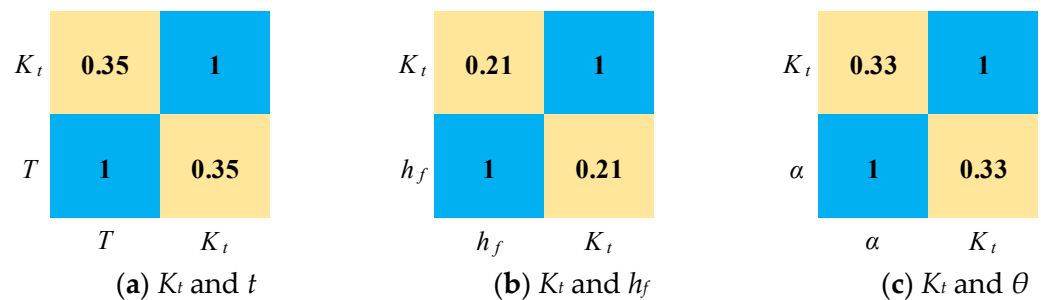


Figure 13. Pearson matrix between stress concentration factor and geometrical parameters.

The calculated results show that the Pearson correlation coefficients between the three types of geometrical dimension parameters of T-joints and the stress concentration factor are all less than 0.4. Therefore, the dimensional effects influencing the fatigue life of T-joints and the stress concentration can be considered approximately independent of each other. This is because the impact of size effects on fatigue life is primarily related to the stress gradient, and the elastic stress concentration factor is insufficient to reflect this fully.

5.3. Impact of Geometrical Dimension Parameters on Fatigue Life

To assess the variance in the impact of different geometrical dimension parameters on the fatigue life of T-joints, the coefficient of variation (μ) is used, which compares the relative variability among these parameters [52,53]. Equation (10) for calculating the coefficient of variation in fatigue life is as follows:

$$\mu = \frac{S_N}{m_N} \quad (10)$$

where S_N is the standard deviation of the fatigue life samples, and m_N is the arithmetic mean of the fatigue life.

Figure 14 shows the coefficients of variation for T-joints under three different stress levels, with variations in web plate thickness, weld toe size, and welding angle.

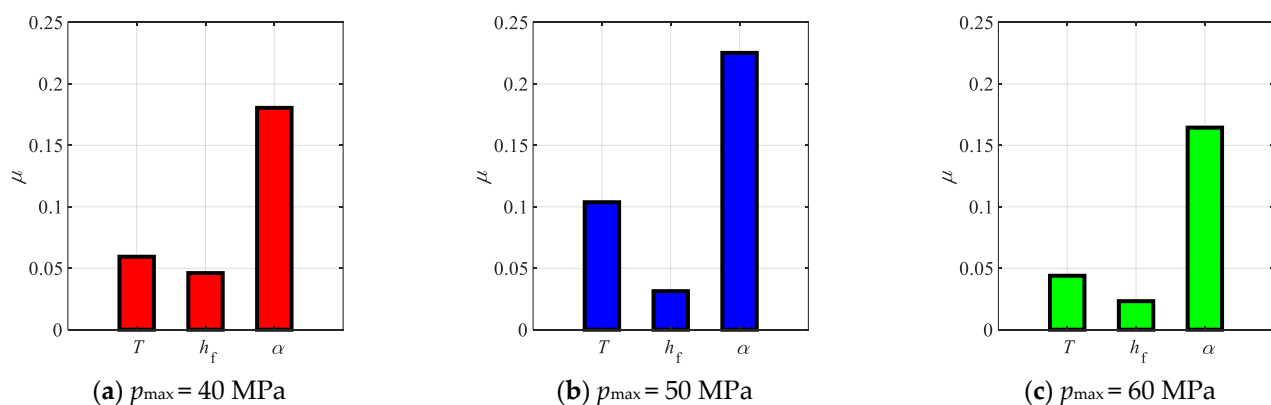


Figure 14. The μ of fatigue life under different stress levels.

The results indicate that the μ value is smallest when the weld toe size varies, and higher for variations in web plate thickness and welding angle than for weld toe size. This suggests that changes in the weld toe size of T-joints have a minor impact on fatigue

life, whereas changes in the web plate thickness and welding angle significantly affect the fatigue life of the joints, with the welding angle having the greatest impact on fatigue life.

6. Conclusions

Considering the complex stress characteristics of T-joint regions, particularly under cyclic loading where stress gradients often induce size effect phenomena, this study conducted fatigue tests on seven sets of specimens with three key geometrical parameters. The influence of web plate thickness, weld toe size, and welding angle on the fatigue life of T-joints was examined. The main conclusions are summarized as follows:

- (1) The maximum displacement evolution curve of welded T-joints under cyclic tensile loading exhibits three distinct stages—crack initiation, propagation, and final fracture—confirming the typical fatigue damage process. The real-time maximum displacement of T-joints can thus serve as an effective indicator for studying fatigue failure mechanisms and monitoring fatigue damage.
- (2) Compared with fatigue life curves fitted using normal stress amplitude, those based on Mises stress amplitude show a higher degree of fit, indicating that Mises stress amplitude provides a more accurate representation of the fatigue performance of T-joints.
- (3) Web plate thickness, weld toe size, and welding angle are critical geometrical design parameters that significantly affect the fatigue life of T-joints. The web plate thickness shows an inverse relationship with fatigue life, while both weld toe size and welding angle are directly proportional to fatigue life.
- (4) Pearson correlation analysis revealed weak correlations among the geometrical parameters, indicating that the dimensional effects and stress concentration influencing fatigue life can be considered approximately independent.
- (5) Analysis based on the coefficient of variation shows that variations in weld toe size exert the smallest effect on fatigue life, whereas web plate thickness and welding angle have more pronounced effects, with welding angle being the most influential factor.

Author Contributions: Conceptualization, Y.C.; Methodology, Y.C.; Investigation, Y.C.; Resources, P.S.; writing—review and editing, P.S. and C.L.; Data curation, C.L.; Supervision, J.Z.; Funding acquisition, P.S. and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: The financial support from the Natural Science Foundation of Chongqing with Grant No. CSTB2023NSCQ-MSX0654, and the Natural Science Foundation of Chongqing with Grant No. cstc2019jcyj-msxmX0556.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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