Fatigue Life Analysis of Welded Joints in Spigot-and-Socket Connections for Arch-Beam Structures

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Abstract

Using finite element numerical simulation, the influence of wind load on the fatigue life of welded joints in spigot-and-socket connections of arch-beam structures was investigated. Two methods were employed: the nominal stress method specified in the Chinese steel structure design standard GB 50017-2017, and the hot-spot stress method based on extrapolation as prescribed in the IIW (International Institute of Welding) documents XIII-1539-96/XV-845-96. The results indicate that the fatigue life predicted by the hot-spot stress method is longer than that obtained from the nominal stress method. Consequently, fatigue analysis based on the nominal stress method yields more conservative results. However, compared with the nominal stress approach, the hot-spot stress method demonstrates better integration with numerical simulation.

Keywords

Numerical Simulation; Weld Fatigue; Nominal Stress; Hot-Spot Stress.

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1. Introduction

The mechanical behavior of large-span spatial steel structures is highly complex. Joints, as intersections of multiple members, serve as critical points for internal force transfer. Failure of a joint can lead to the sequential failure of connected members, potentially resulting in progressive collapse of the entire structure. Welded joints subjected to dynamic loads are particularly vulnerable due to stress concentrations caused by geometric discontinuities, making them one of the weakest links affecting the reliability of structural systems.

Fatigue tests on beam connections composed of galvanized rectangular hollow sections and angle steel were reported in the literature [1]. Based on high-cycle fatigue test data, design curve recommendations for such beam connections were proposed. Literature [2] summarized current design and construction specifications for welded hollow section joints, discussed the softening behavior of high-strength steel and the bearing capacity of welded connections under localized softening in the heat-affected zone, and proposed a design method to address heat-affected zone failure and combined failure modes in hollow section joints. Literature [3] established a numerical model and applied the surface extrapolation method for hot-spot stress to analyze the fatigue performance of H-section steel cantilever mast column base welds under wind loading. Taking the

H-section steel cantilever mast on the Lanzhou–Xinjiang High-Speed Railway as a case study, the fatigue life of the column base welds was calculated based on the hot-spot stress versus life curve.

Currently, commonly used fatigue assessment methods for welded joints include the nominal stress method, notch stress method, hot-spot stress method, equivalent structural stress method, and experimental-based assessment methods. Among these, the notch stress method requires calculation of the local notch stress at the welded joint. However, in finite element analysis, stress singularities often arise due to the welded geometry, preventing the attainment of convergent stress values. When employing fracture mechanics methods based on crack propagation, an initial crack must be assumed at the welded joint. In engineering practice, the absence of a unified standard for defining initial crack parameters leads to considerable variability in results obtained by different designers. In contrast, the nominal stress method specified in China's current steel structure design standard GB 50017-2017 [4] and the extrapolation-based hot-spot stress method prescribed in the IIW (International Institute of Welding) documents XIII-1539-96/XV-845-96 [5] effectively circumvent issues related to stress singularity and inconsistent calculation standards, rendering fatigue analysis of welded joints practically applicable for engineering purposes. To determine the fatigue life of welded joints in spigot-and-socket connections of arch-beam structures, finite element analysis was performed using ANSYS Workbench. Fatigue life at the weld toe was evaluated using both the nominal stress method and the hot-spot stress method. The results obtained from the two methods were compared and analyzed alongside the fatigue life of the base metal, providing references for engineering design.

2. Model Analysis

Welded structures are widely used in numerous engineering fields [6]. However, due to the complex cyclic loads they experience during service, welded zones are prone to fatigue damage over time. Statistics indicate that approximately 90% of failures in welded structures are caused by fatigue failure of welded joints [7], with some such failures potentially leading to catastrophic consequences. To ensure the safe operation of arch-beam structures, it is essential to conduct fatigue life analysis on the welded connections of their spigot-and-socket joints.

2.1 Design Conditions

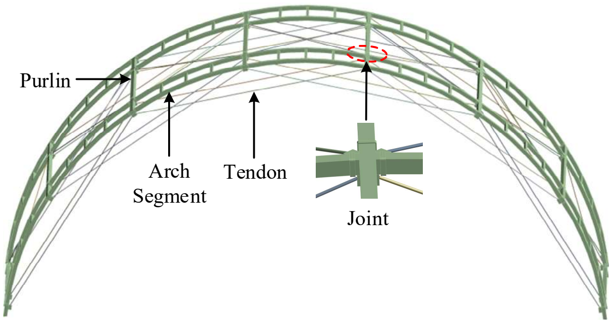

Figure 1. 3D model of a typical bay of the arch structure

Table 1. Internal forces at the joint

Load Case	Axes	X	Y	Z
Load Case 1	F (N)	459	-79	3279
	M (N·mm)	9931	-207310	7898
Load Case 2	F (N)	581	-111	4361
	M (N·mm)	10216	-508300	8275

This study employs finite element numerical simulation to investigate the influence of wind load on the fatigue life of welds in spigot-and-socket joints of arch-beam structures. Accordingly, a full-scale single-layer arch-beam structure model with a height of 4 m and a span of 9 m was established based on an actual hangar structure featuring the arch-beam system, as shown in Figure 1. Both arch springings of the model were constrained using fixed hinges to simulate the actual loading and boundary conditions in engineering practice. Regarding loading conditions, two load cases were defined. The first case considers the self-weight of the structure, a dead load of 0.3 KN/m², and a cable prestress of 15 MPa. The second case incorporates the influence of wind load by applying an additional 0.5 KN/m² wind load on the basis of the first case. Contact conditions between all components were defined as frictional contact with a friction coefficient of 0.15, consistent with actual conditions. Through finite element simulation, the specific internal force distributions at the joint exhibiting the maximum stress range fluctuation under the two load cases were obtained, as presented in Table 1.

2.2 Geometric Model

To obtain the hot-spot stress at the weld toe of the joint, a three-dimensional solid model was employed in the finite element analysis. To conserve computational resources, the joint model was extracted from the global structure for detailed finite element analysis. The configuration of the joint is illustrated in Figure 2. The arch segment of the joint utilizes a 60×60×4 square steel tube, while the square tube connector adopts a 52×52×4 square steel tube. The connection between the butt joint and the components is achieved through a combined butt and fillet weld. The connection between the spigot and the arch segment is accomplished simply by socket engagement.

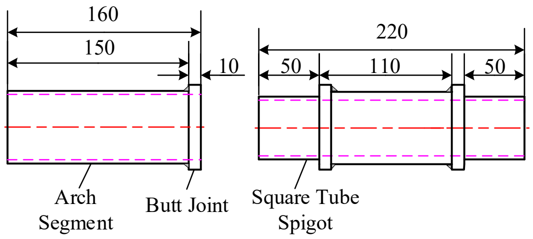

Figure 2. Joint Schematic (Unit: mm)

2.3 Material Constitutive Models

A bilinear constitutive model was adopted for the steel used in the arch-beam structure joints, with the material being Q235B. The material properties are listed in Table 2. A bilinear isotropic hardening model was employed, with the tangent modulus in the hardening stage taken as 1.5% of the elastic modulus. Both material and geometric nonlinearities were considered at the joints during the analysis.

Table 2. Material Properties

Material	Young's Modulus (×10^5Mpa)	Poisson's Ratio	Yield Strength /Map	Ultimate Strength /Map
Q235B	2.06	0.3	235	470

2.4 Mesh Generation and Boundary Condition Setup

Twenty-node three-dimensional solid elements (SOLID186) available in ANSYS Workbench were employed for meshing. The elements at the weld toe of the joint were refined to obtain more accurate results. In accordance with the quadratic extrapolation requirements specified in the IIW (International Institute of Welding) documents XIII-1539-96/XV-845-96, the mesh size on the arch segment at the weld location was set to 0.2 times the wall thickness of the arch segment, i.e., 0.8 mm. The detailed mesh configurations are shown in Figures 3. Contact between components was defined as frictional contact with a friction coefficient of 0.15, consistent with actual conditions. The end of the arch segment was designated as the loading end, while the joint connector end was fully fixed.

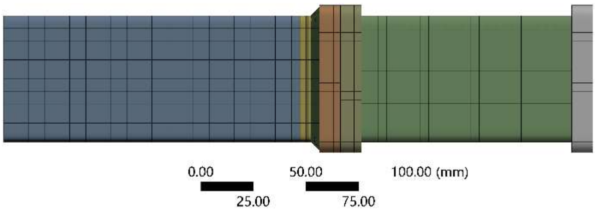

Figure 3. Mesh Generation

3. Fatigue Assessment based on the Nominal Stress Method

The nominal stress is defined as the elastic stress calculated in the relevant cross-section without considering the stress concentration effects caused by weld details, but it accounts for stress-raising effects due to macroscopic geometric discontinuities near the joint, such as pronounced notches or changes in cross-section. Both the IIW (International Institute of Welding) documents XIII-1539-96/XV-845-96 and the European fatigue design standard for steel structures, EN 1993-1-9 [8], refer to the nominal stress that considers the geometric discontinuities of welded joints as the modified nominal stress or local nominal stress.

3.1 Calculation Results

A combined approach of traditional formulas and finite element simulation was adopted in this study. The internal forces at the joint extracted from Table 1 were applied as loads. After finite element simulation, the normal stress contours at the joint were obtained, as shown in Figures 4 and 5. It can be observed that stress concentration occurs at the welded connection, and the stresses are compressive.

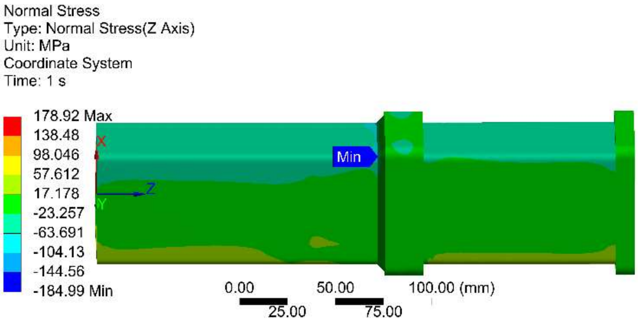

Figure 4. Stress contour for Load Case 1

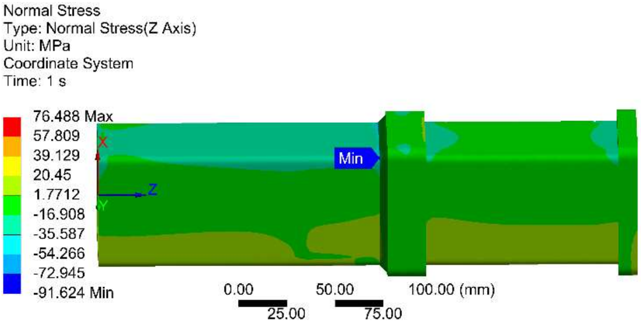

Figure 5. Stress contour for Load Case 2

The calculation formula for the nominal stress method is as follows:

$$\sigma_{nom} = \frac{N}{A} + \frac{M}{W} \tag{1}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{2}$$

Where σ_{nom} is the nominal stress; N is the axial force at the evaluated section; A is the cross-sectional area at the evaluated section; M is the bending moment at the evaluated section; W is the section modulus at the evaluated section; $\Delta\sigma$ is the nominal stress range at the welded detail; $\sigma_{\max}$ is the maximum tensile or compressive stress in the stress cycle at the evaluated section; $\sigma_{\min}$ is the minimum tensile or compressive stress in the stress cycle at the evaluated section, with tensile stresses taken as positive and compressive stresses as negative.

The internal forces at the weld toe were extracted and are presented in Table 2.Based on the internal forces extracted at the weld toe of the joint under the two load cases, the nominal stresses at this location were calculated using Equations (1) and (2). Under Load Case 1, the nominal stress was determined to be -23.5 MPa; under Load Case 2, it was -46.8 MPa. The corresponding nominal stress range was 23.3 MPa.

Table 3. Internal forces at the joint weld toe

Load Case	Axes	X	Y	Z
Load Case 1	F (N)	611.6	-63.3	3279
	M (N·mm)	1174.5	-285420	4208.2
Load Case 2	F (N)	659.66	--71	4361
	M (N·mm)	3759	-604780	4285.6

3.2 Fatigue Life Calculation

Referring to the classification table for members and connections of steel tubular sections in the steel structure design standard GB 50017-2017, the corresponding welded joint type was identified. The fatigue curve for this welded connection is classified as Class 45.

Based on the S-N curve and the steel structure design code, the fatigue life of the welded joint can be calculated using the following formula:

$$N = \frac{c}{(\frac{\Delta\sigma}{\gamma_t})^m} \tag{3}$$

where c and m are constants. According to the code, c = 2.0 × 10^{14} and m = 5; γ_t is the thickness correction factor, which is taken as 1.0 when the wall thickness is less than 25 mm.

Therefore, based on the nominal stress method specified in GB 50017-2017, the fatigue life of this welded structure is calculated to be 29,123,957 cycles.

4. Fatigue Assessment based on the Hot-Spot Stress Method

The extrapolation-based hot-spot stress method has been applied to tubular joints in offshore structures since the 1970s and gradually extended to fields such as shipbuilding and vehicle engineering in the 1990s [7]. Subsequently, this method was incorporated into the IIW (International Institute of Welding) standard-Fatigue Design of Welded Joints and Components. In the IIW standard, the structural or geometric stress at the hot spot includes all stress-raising effects of the structural detail, excluding the influence of the local weld profile itself. Consequently, the nonlinear peak stress caused by local notches (i.e., the weld toe) must be excluded from the structural stress.

The hot-spot stress can be obtained through extrapolation. Based on finite element analysis, stress reference points (with specified locations) are used to extrapolate (using a defined extrapolation method) the stress at the weld toe, which is referred to as the hot-spot stress of the weld. The hot spot is defined as the point where initial cracking is likely to occur; in welded structures, the hot spot is typically located at the weld toe or weld root. EN 13445-3 introduces the same hot-spot stress method as that in the IIW documents, where it is termed the structural equivalent stress and must be obtained through extrapolation.

4.1 Stress Results

To assess the fatigue life of the welded joint using the hot-spot stress method specified in the IIW standard, this study employed the quadratic surface stress extrapolation method. The locations of the three extrapolation reference points are illustrated in Figure 6. This method requires that the gauge length in the vicinity of the extrapolation points should not exceed 0.2t, where t is the wall thickness of the shell. In finite element analysis, the gauge length corresponds to the element edge length.

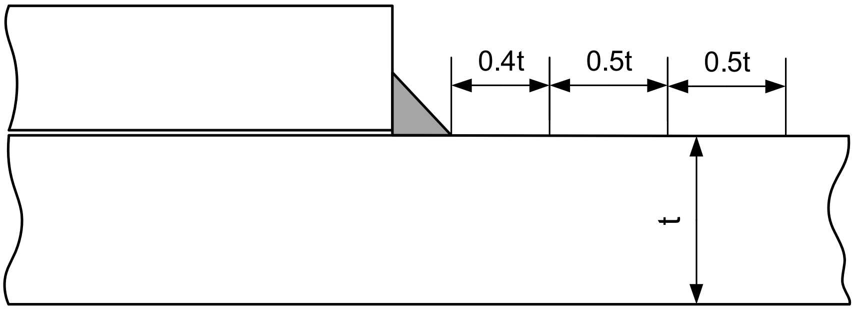

Figure 6. Schematic of extrapolation reference points for quadratic extrapolation of hot-spot stress

After calculation and post-processing of the model, the equivalent stress contours were obtained, as shown in Figures 7 and 8. The equivalent stresses at the three extrapolation reference points were extracted. As can be seen in Figure 7, under Load Case 1, the equivalent stresses at the three extrapolation reference points were -43.633 MPa, -33.516 MPa, and -24.43 MPa, respectively. Figure 8 shows that under Load Case 2, the equivalent stresses at the three extrapolation reference points were -87.92 MPa, -67.159 MPa, and -58.765 MPa, respectively.

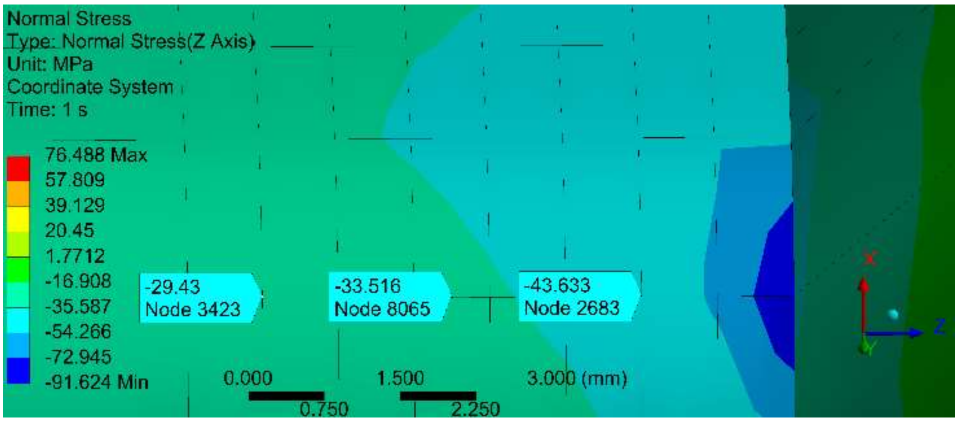

Figure 7. Stresses at extrapolation points for Load Case 1

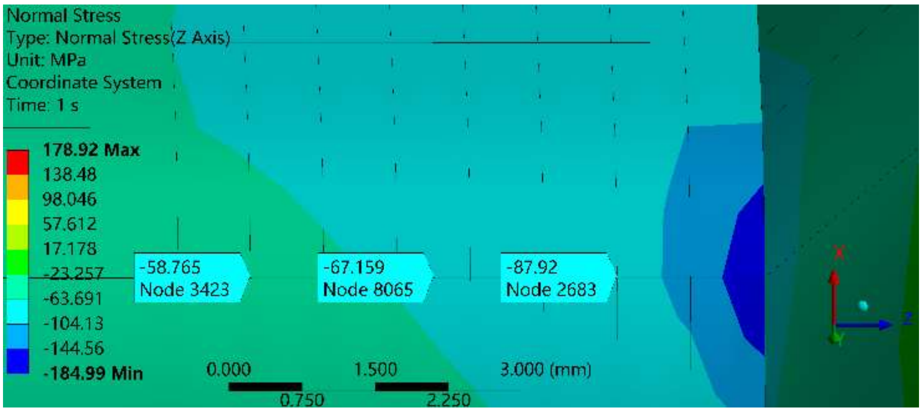

Figure 8. Stresses at extrapolation points for Load Case 2

The quadratic extrapolation formula for the hot-spot stress is given by:

$$\sigma_{hs} = 2.52 \cdot \sigma_{0.4t} - 2.24 \cdot \sigma_{0.9t} + 0.72\sigma_{1.4t} \tag{4}$$

Substituting the equivalent stresses at the three extrapolation reference points into Equation (4), the hot-spot stresses were calculated as -56.1 MPa under Load Case 1 and -113.4 MPa under Load Case 2. Accordingly, the hot-spot stress range was determined to be $\Delta\sigma$ = 57.3 MPa. Meanwhile, the hot-spot stress concentration factor was calculated as Ks = 2.42 using the formula $K_s = \sigma_{hs}/\sigma_{nom}$.

4.2 Fatigue Life Calculation

Since the welded joint of the spigot-and-socket connection in the arch-beam structure is a square hollow section, reference was made to the international design standard for welded hollow section joints, AS ISO 14347:2008 [9]. According to this standard, for the hot-spot stress method, square or rectangular hollow sections with wall thicknesses between 4 mm and 16 mm have corresponding fatigue curves (S-N curves). For a square hollow section with a wall thickness of 4 mm, the cut-off limit for the hot-spot stress range at 10^8 cycles is 81 MPa. When the fatigue curve reaches this cut-off limit, the slope becomes zero, indicating that if the calculated hot-spot stress range of the welded structure is below this cut-off limit, the welded structure exhibits infinite fatigue life. Based on the calculation results, the hot-spot stress range of this welded structure is 57.3 MPa, which is lower than the cut-off limit. Therefore, according to the standard, the fatigue life of this welded structure is determined to be infinite.

4.3 Comparison of the Two Fatigue Life Calculation Methods

The nominal stress is defined as the elastic stress calculated in the relevant cross-section without considering the stress concentration caused by the welded joint itself. In contrast, the structural or geometric stress at the hot spot includes all stress-raising effects of the structural detail while excluding the influence of the local weld profile. Currently, these two methods are widely adopted in various structural fatigue design codes. In this study, both methods were employed to analyze the fatigue life of the welded joint in the spigot-and-socket connection of the arch-beam structure. The results indicate that the fatigue life calculated using the nominal stress method specified in GB 50017-2017 is 29,123,957 cycles, whereas the fatigue life obtained from the hot-spot stress method prescribed in the IIW standard exceeds 10^8 cycles. According to the standard, fatigue lives exceeding 10^8 cycles are considered infinite. Consequently, the fatigue life predicted by the hot-spot stress method is greater than that obtained from the nominal stress method.

5. Conclusion

(1) Stress concentrations at welds, along with micro-porosity, slag inclusions, and micro-cracks that are difficult to completely avoid during the welding process, render welded zones the most vulnerable locations in a structure. Therefore, fatigue analysis should prioritize these areas. Even if the static strength of a weld fully meets requirements, the absence of fatigue analysis may lead to sudden, unanticipated fracture under long-term cyclic loading due to accumulated damage, potentially resulting in serious safety incidents.

(2) The fatigue life of welded joints obtained from the nominal stress method for weld fatigue analysis of spigot-and-socket connections in arch-beam structures is lower than that obtained from the hot-spot stress method. Fatigue analysis based on the nominal stress method yields more conservative results; however, it requires extracting internal forces at the weld toe and performing calculations using the corresponding formulas. In contrast, the hot-spot stress method is more convenient to apply in conjunction with finite element simulation.

(3) Despite conducting detailed fatigue analysis on welded joints, design requirements such as full penetration welding, smooth grinding transitions, and surface magnetic particle (MT) inspection should still be specified to improve the fatigue performance of the welded joint. Additionally, other fabrication and inspection requirements that align with the fatigue design approach in relevant standards must be satisfied. When necessary, techniques such as TIG dressing, hammer peening, or needle peening may be employed to extend fatigue life.

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