

EFFECT OF POROSITY DEFECTS ON THE FATIGUE BEHAVIOR OF WELDED JOINTS IN STEEL BRIDGE

Ying-Fang Yang¹, Zhen-Nan Peng², Ling-Zheng Wu³, Yi-Qian Zhang⁴, Qing-Hua Zhang⁴ and Chuang Cui^{4,*}

¹ Central Research Institute of Building & Construction Co., Ltd., MCC Group, Beijing 100088, China

² Shenzhen-Zhongshan Link Administration Center, Zhongshan 511462, China

³ Guangshen Expressway Expansion Project Office, Dongguan 523141, China

⁴ State Key Laboratory of Bridge Intelligent and Green Construction, Southwest Jiaotong University, Section 111 of Northbound 1, Second Ring Road, Chengdu, 610031, Sichuan, China

* (Corresponding author: E-mail: ccui@swjtu.edu.cn)

ABSTRACT

Welding technology offers high efficiency and flexibility in the bridge construction. However, weld-included defects are inevitable and significantly reduce the fatigue performance of welded joints. Porosity is one of the most common welding defects and has a considerable influence on fatigue performance. In this study, both fatigue tests and numerical simulation are used to investigate the effect of porosity defects. Test specimens of butt-welded and cruciform-welded joints were designed, with 48 specimens divided into two groups, including 24 specimens with porosity defects and 24 control specimens without pores. The results indicate that the fatigue strength of butt-welded joints and cruciform-welded joints without porosity defects with 2 million cycles was 142.0 MPa and 92.3 MPa, respectively. When the pore depth and diameter were both 2.0 mm, the fatigue strengths of butt-welded joints and cruciform-welded joints with porosity defects decreased by 27.4% and 7.3%, respectively. Numerical simulation results showed that porosity significantly increased the stress concentration factor (SCF) of the welded joints. The diameter, position, and depth of porosity had clear effects on SCF. An increase in the pore diameter significantly elevated SCF, although the rate of increase diminished when the diameter exceeded 1.6 mm; the SCF decreased when the pore was located farther from the weld toe, with cruciform joints being more sensitive to pore position; surface pores caused significantly higher SCF than internal pores, and the SCF was higher when pore depth was closer to the weld surface.

ARTICLE HISTORY

Received: 30 September 2025
Revised: 20 January 2026
Accepted: 22 January 2026

KEYWORDS

Welded joints;
Porosity defects;
Fatigue performance;
Stress concentration factor;
Numerical simulation

Copyright © 2026 by The Hong Kong Institute of Steel Construction. All rights reserved.

1. Introduction

Steel bridges have been extensively utilized in both railway and highway infrastructures, owing to their notable advantages such as high load-bearing capacity, relatively lightweight properties, and constructability [1-6]. Welding, which is an efficient and flexible joining method used in steel bridge construction, has significantly promoted the widespread use of steel bridges. But welded joints often encounter fatigue issues under cyclic stresses induced by traffic loads, primarily because of welding defects [7-13]. Investigations into several incidents of steel-bridge collapse have revealed that welding defects result in local stress concentrations [14-17]. Under repeated traffic loads, weld defects are more likely to be the main initiation sites for fatigue cracks in welded joints, significantly reducing their fatigue resistance and, in some cases, becoming a major cause of steel bridge failure [14,15].

Given the large number of welds in steel bridges, only a certain proportion are randomly inspected in accordance with the relevant standards, making it difficult to completely identify and eliminate weld defects in welded joints [16]. A typical photograph of porosity defects is shown in Fig. 1 in a welded joint of a steel bridge. Surveys of welded joints have identified a variety of welding defects, including undercutting at the weld toe, porosity, slag inclusion,

inadequate penetration and welding cracks [16-19]. Among these, porosity defects account for a relatively high proportion, according to survey results [16]. Porosity is one of the most common issues encountered during welding. It not only reduces the strength of welded joints, but also serves as a primary initiation site for fatigue cracks under cyclic loading, significantly reducing the fatigue life of welded joints.

Porosity defects are prevalent in the welded joints of steel bridges and exert a detrimental effect on their fatigue performance. Nevertheless, research dedicated to assessing the degradation of fatigue life induced by porosity remains limited, particularly in the realm of high-cycle fatigue behavior. Key characteristics of porosity, such as morphology, dimensions, and spatial distribution, govern the stress state and fatigue response of the welded joints. Consequently, a thorough investigation into the mechanisms through which porosity influences fatigue performance is imperative for enhancing the service life and structural safety of steel bridges. This study aims to elucidate the impact of porosity defects and their underlying mechanisms on the fatigue behavior of welded joints in steel bridges. By integrating experimental approaches with theoretical analysis, the effects of porosity characteristics, including morphology, size, and location, on the fatigue performance of welded joints were systematically examined.

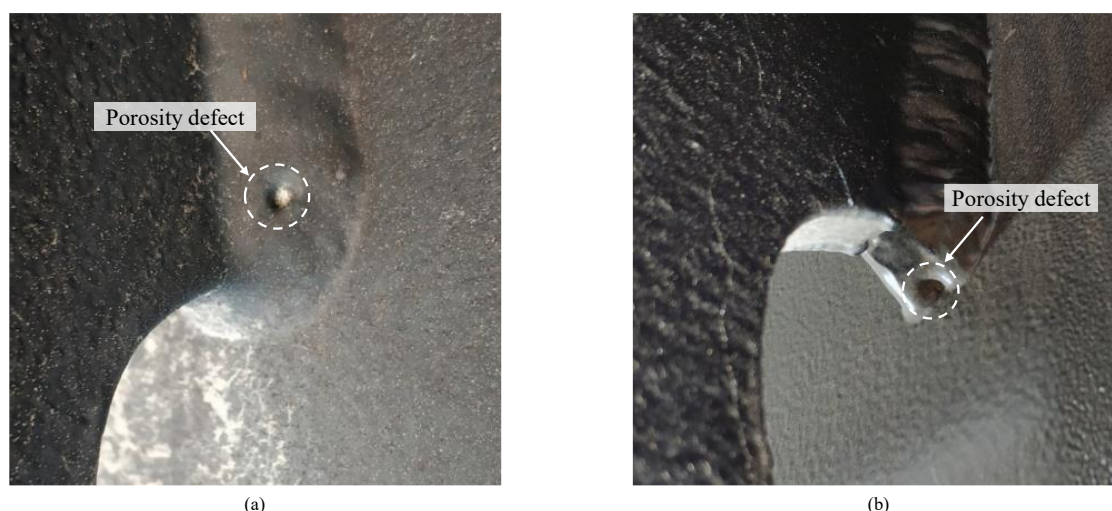


Fig. 1 The porosity in the welded joints of a steel bridge: (a) welded joint 1; and (b) welded joint 2

In recent years, the influence of porosity defects on the fatigue behavior of welded joints has been investigated by several researchers. For instance, Chen et al. [20] systematically examined the effect of porosity defects on the ultra-long fatigue life of aluminum alloy welded joints and demonstrated that such defects lead to a significant reduction in fatigue life. By combining experimental methods with finite element analysis, they further explored how porosity affects the stress concentration factor (SCF) of welded joints, revealing that the SCF at the pore location increases pronouncedly with pore diameter. Xu et al. [22] used synchrotron radiation X-ray micro-computed tomography to statistically analyze porosity defects in laser-hybrid welded aluminum alloy joints and found that the pore size and location significantly influenced the crack initiation and propagation paths. However, most of these studies focused on aluminum alloy welded joints, whereas research on welded joints of steel bridges is relatively scarce. The effect of porosity on the stress distribution in welded joints was revealed by the numerical analysis of Wu et al. [23], finding that SCF at the pore location increases significantly with increasing pore diameter. Luo et al. [24] experimentally studied the effect of porosity defects on the fatigue behavior of welded joints and observed that porosity considerably reduced the fatigue life. Nonetheless, comprehensive studies considering the combined influence of pore shape, size, and position on the fatigue performance remain limited.

To address this research gap, this study designed fatigue test models for butt- and cruciform-welded joints, including 48 specimens divided into four groups. Among these, 24 specimens contained porosity defects, whereas the remaining 24 which were without pores served as control specimens. Fatigue tests were performed under cyclic loading conditions to evaluate the impact of porosity on the fatigue life of welded joints. Furthermore, finite element analysis was employed to examine how porosity characteristics affect the stress distribution within the joints. By integrating experimental and numerical methods, this study provides a systematic evaluation of the influence of porosity defects on the fatigue performance of welded joints, thereby elucidating the underlying mechanisms through which these defects alter stress distribution.

2. Experiment

2.1. Specimen design

To delineate and quantify the detrimental influence of porosity defects, two representative welded joint types, butt joints and cruciform joints, were selected as the research objects. Four distinct categories of fatigue specimens were fabricated, each comprising 12 specimens, as detailed in Table 1. Group BW1 consisted of conventional butt-welded specimens, whereas Group BW2 consisted of butt-welded specimens with porosity defects. Group CW1 consisted of conventional cruciform-welded specimens, and Group CW2 consisted of cruciform-welded specimens having porosity defects. The butt-welded specimens were fabricated with dimensions of 300 mm (length) $\times$ 50 mm (width) $\times$ 8 mm (thickness). The cruciform-welded specimens measured 420 mm in length, 80 mm in height, with flange and web plates both 16 mm thick. Schematic diagrams and additional structural details of both specimen types are shown in Figs. 2 and 3. Specially, the width and surplus height of butt-welded seam are respectively 8 mm and 1.5 mm. The leg size of cruciform-welded seam equal to 8 mm. The tolerance of the weld size complies with the specification requirements [25].

Table 1
Specimen categories

Group number	Group type	Porosity depth $h(\text{mm})$	Porosity radius $\rho(\text{mm})$	Number
BW1	Without porosity defects	/	/	12
BW2	With porosity defects	2.0	2.0	12
CW1	Without porosity defects	/	/	12
CW2	With porosity defects	2.0	2.0	12

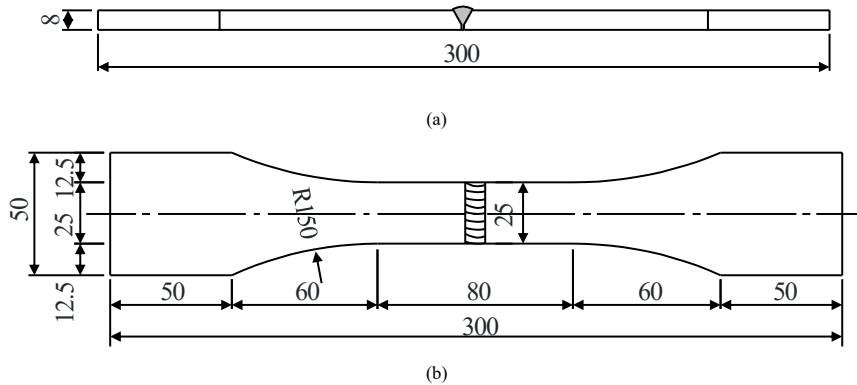


Fig. 2 Sketch of butt-welded joint specimens (unit: mm): (a) side view; (b) top view

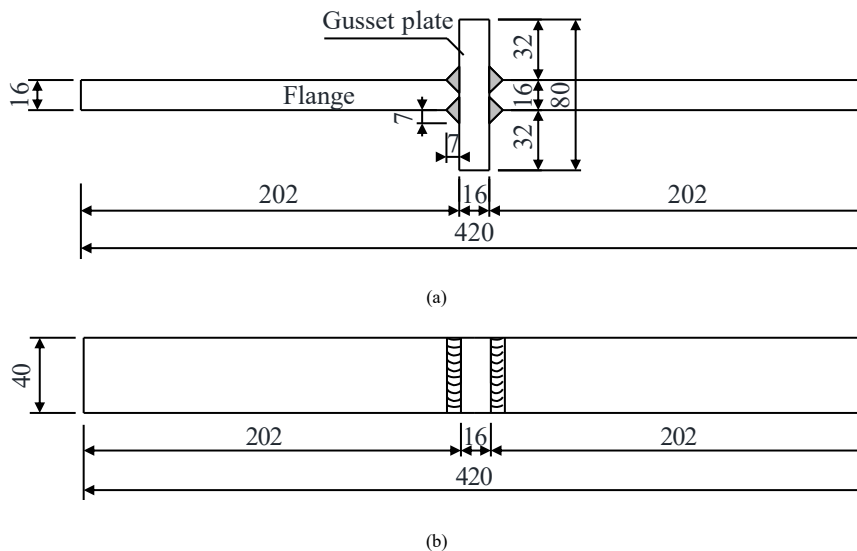


Fig. 3 Sketch of cruciform-welded joint specimens (unit: mm): (a) side view; (b) top view

Welding defects in steel bridges demonstrate marked stochasticity in their type, location, and geometry. Research on the fatigue performance of welded joints typically employs a dichotomy of defect types: natural and artificial [26–29]. A significant methodological challenge is posed by the fact that while natural defects offer superior representativeness of in-service structures, their deliberate generation under controlled laboratory conditions remains problematic. Moreover, the size and location of natural weld defects tend to be highly variable and random, complicating quantitative research. In contrast, artificial defects can be deliberately introduced and precisely positioned in critical areas of the welded joints, facilitating quantification of the effects of fatigue degradation caused by welding defects. Given the validated effectiveness of artificial defects in simulating realistic conditions [27–29], controlled artificial porosity was introduced in this study to evaluate its impact on the fatigue behavior of welded joints.

The specific requirements for the surface porosity defects according to the EN ISO 5817 standard [25] are listed in Table 2. For weld-quality level B, porosity defects are not permitted. For weld quality level C, when the plate thickness t is more than 3 mm, the pore diameter d is less than $0.2s$ ($d \leq 2\text{mm}$). For weld quality level D, the pore diameter d is less than $0.3s$ ($d \leq 3\text{mm}$) when t is more than 3 mm. When designing defect-bearing specimens, the defect dimensions were determined by combining the quality standards for weld defects from EN ISO 5817 and the findings from field investigations of steel bridge weld defects. The diameter and depth of the artificial porosity defects were set to 2.0 mm. All specimens were fabricated using welding procedures consistent with actual bridge construction. A set of 12 butt-welded specimens and 12 cruciform-welded specimens were engineered to contain artificial porosity defects within their welds. A schematic and a photograph of the porosity defects in the specimens are shown in Fig. 4, where the porosity defects were made by using the electric drill. Compared with laser or welding process manipulation, the size of artificial defects is more easily controlled. The porosities are located at the middle weld toe near to the weld zone.

2.2. Materials and fabrication

The steel materials and welding procedures used to fabricate the specimens are consistent with those used for actual bridge structures. All the specimens were made of Q345qE bridge steel with a nominal yield strength of 345 MPa. The chemical composition and mechanical properties of Q345qE steel are listed in Tables 3, respectively. CO₂ gas-shielded arc welding was employed with parameters set at 220–280 A (current), 27–33 V (voltage), and a 15–25 L/min shielding gas flow rate.

For butt-welded joints, a “V-shaped” double-sided groove was used, and a residual weld reinforcement was retained after welding. For cruciform-welded joint specimens, full-penetration welding was performed with a weld leg of size 7 mm. All the operations, including plate cutting and specimen welding, were performed indoors. Before welding, all shop primers and contaminants in the weld zones were removed. The specimens were fabricated as integrated welded plates and subsequently cut into individual specimens using wire electrical discharge machining (EDM), as shown in Fig. 5. The weld toes of the specimens were ground with sandpaper to reduce the stress concentration effect caused by surface unevenness.

Table 3
Chemical compositions of Q345qE bridge steel (%)

Thickness (mm)	C ($\times 10^{-2}$)	Si ($\times 10^{-2}$)	Mn ($\times 10^{-2}$)	P ($\times 10^{-3}$)	S ($\times 10^{-3}$)	Als ($\times 10^{-3}$)	Ni ($\times 10^{-3}$)	Ti ($\times 10^{-3}$)
8	11	24	142	10	3	38	17	2
16	10	28	146	13	2	34	10	14

Table 2
Limits for porosity defects [29]

Plate thickness	Limits for imperfections for quality levels		
	D	C	B
$t > 3.0$	$d \leq 0.3s$ and up to 3.0mm	$d \leq 0.3s$ and up to 2.0mm	Not allowed

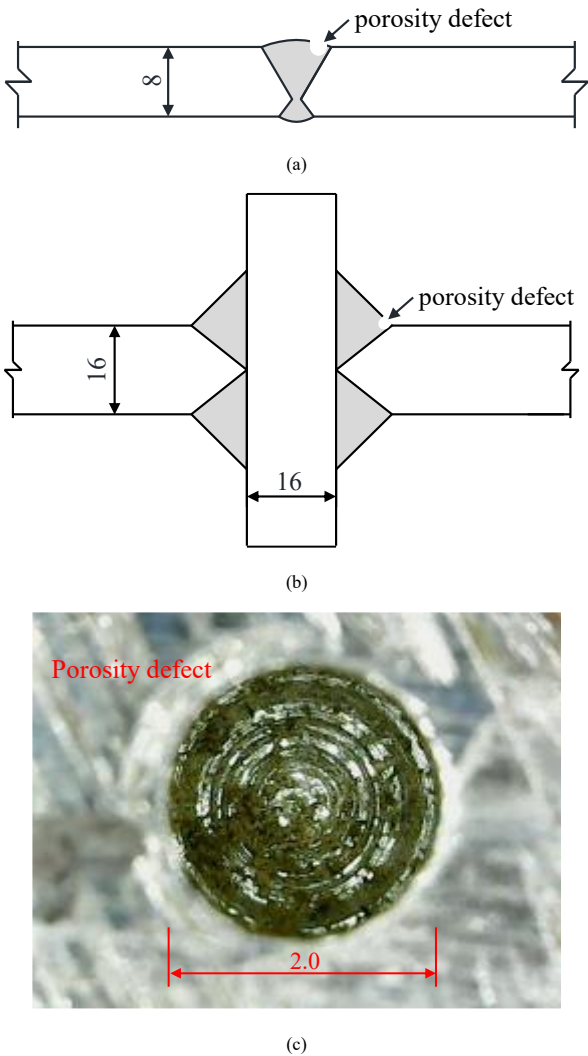


Fig. 4 Sketch of porosity (unit: mm): (a) butt-welded specimens; (b) cruciform-welded specimens; and (c) photograph of porosity defects

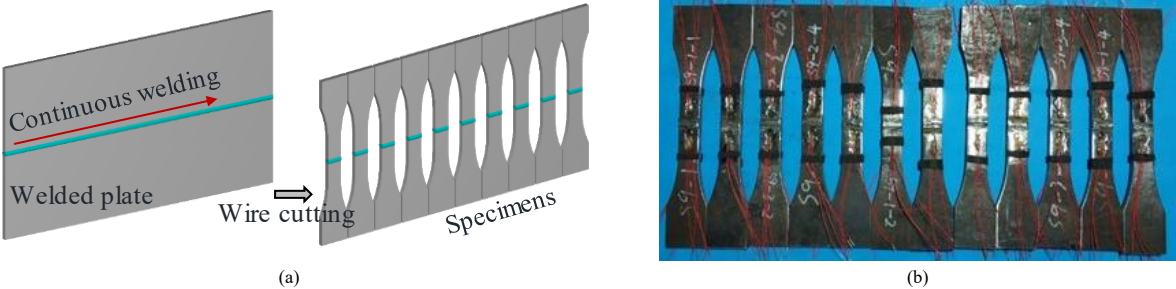


Fig. 5 Sketch of specimens manufacturing: (a) specimens manufacturing; and (b) photograph of the specimens

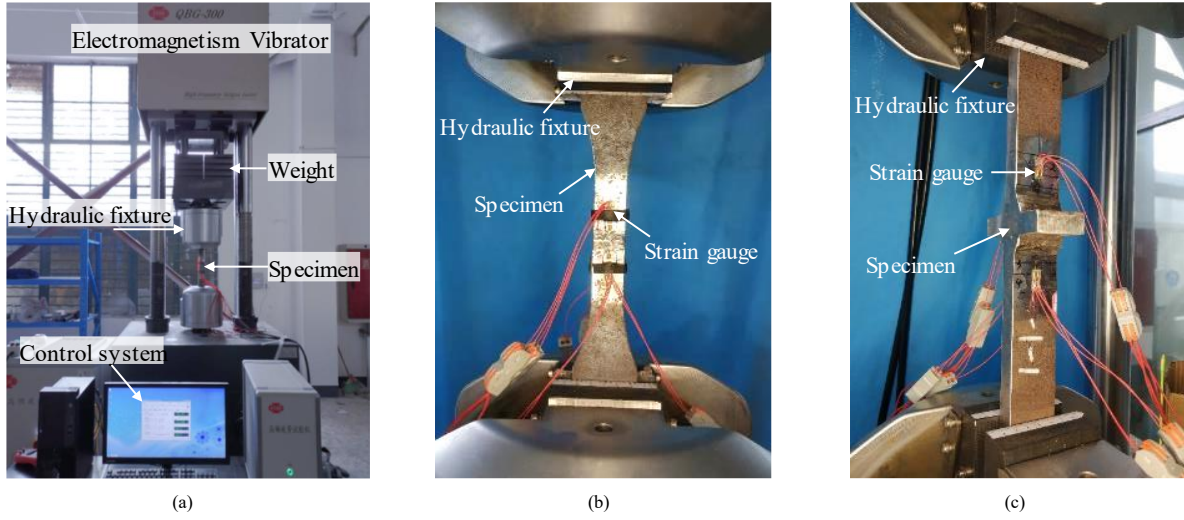


Fig. 6 Test setup: (a) Layout; (b) butt-welded joint; and (c) cruciform-welded joint

2.3. Test setup, loading scheme, and instruments

A QBG-300 electromagnetic resonance fatigue testing machine, operating under force control with a sinusoidal waveform (68–120 Hz, Fig. 6), was used to apply constant amplitude cyclic loading. The specific stress range and loading frequency for each specimen are provided in Section 3.2. The maximum loading cycle limit for each specimen was set to 5×10^6 cycles. If a specimen did not fracture after exceeding 5×10^6 cycles, a new specimen was tested with increased stress to continue the experiment. A Vernier caliper and an electronic microscope were used to measure the width, plate thickness, weld dimensions, and pore sizes of the specimens.

The experimental loading scheme is presented in Fig. 7. Prior to fatigue testing, static load tests were conducted to verify the functionality of all equipment and to determine the appropriate stress range for each specimen. Strain gauges were strategically positioned at locations susceptible to crack initiation, with eight gauges in total affixed to the top and bottom surfaces to measure hot-spot stresses at distances of $0.4t$ and $1.0t$ from the weld toe (where t denotes the plate thickness). The specific locations and designations (B1–B4) for these four measurement zones are illustrated in Fig. 8. The strain gauges located at $0.4t$ and $1.0t$ from the weld toe were denoted by “04” and “10,” respectively. For example, “B1-04” refers to the strain gauge positioned at $0.4t$ from the weld toe in the measurement zone B1.

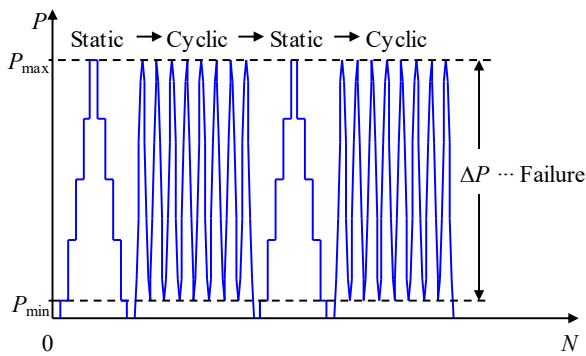


Fig. 7 Fatigue loading procedure

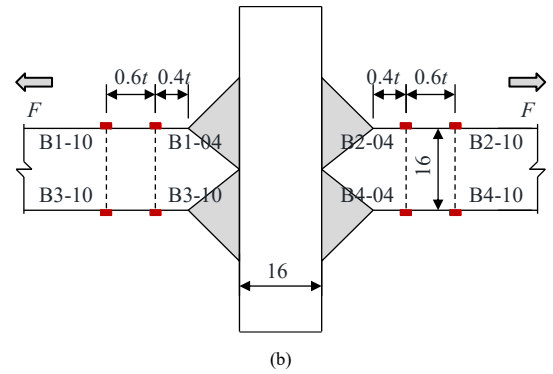
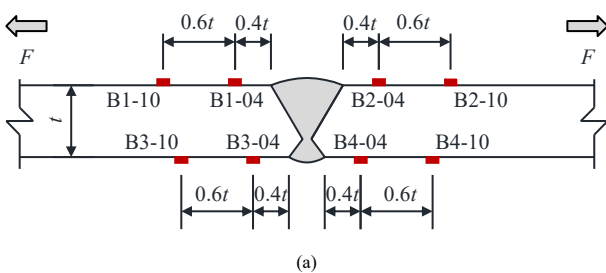


Fig. 8 Location of strain gauges (unit: mm): (a) BW groups; and (b) CW groups

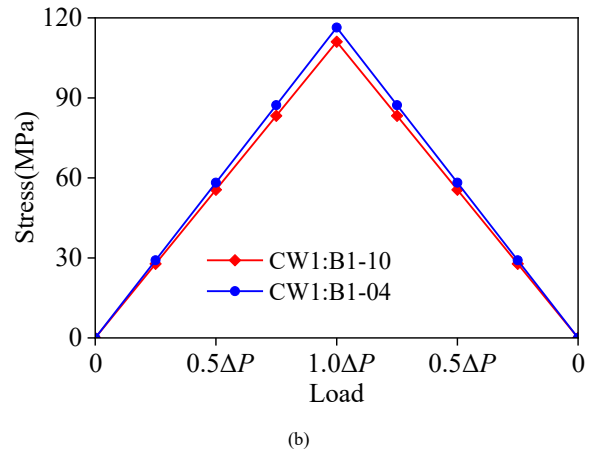
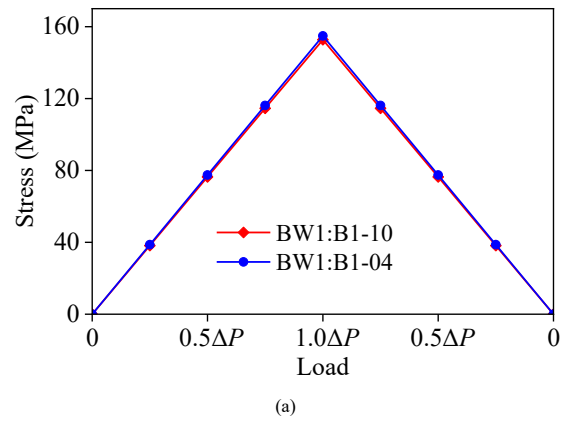


Fig. 9 Stresses of the specimens: (a) butt-welded specimen; and (b) cruciform-welded specimen

3. Experimental results and discussion

3.1. Initial static test results

The static tests validated the experimental system's reliability, as evidenced by the linear and symmetric stress-load responses shown in Fig. 9 (tension positive). Moreover, the measured stresses at points B1-04 and B1-10 were nearly identical for both joint configurations, implying a minimal stress gradient in the critical weld toe area.

3.2. Fatigue test results

3.2.1. *S-N curve fitting method*

A standard methodology for evaluating fatigue life involves the construction of an *S-N* curve. This study derived the *S-N* curve for the butt-welded joints by subjecting the experimental data to linear regression analysis on a log-log plot, consistent with the typical power-function representation for welded details:

$$\Delta\sigma^m N = C \quad (1)$$

where N represents the number of cycles to failure, $\Delta\sigma$ is the applied stress range, C is a material constant related to fatigue strength, and m is the slope of the *S-N* curve plotted on a log-log scale.

Taking the logarithm of both sides of Eq. (1) yields the logarithmic form expressed in Eq. (2).

$$\lg N = \lg C - m \lg \Delta\sigma \quad (2)$$

The *S-N* curves were evaluated through regression analysis. The slope m was set to 3, as stipulated by the governing standards [29-32]. It is imperative to clarify that the failure cycle represents the critical point of structural failure under cyclic loading. Conversely, the total failure life accounts for the entire

fatigue process, comprising both the initiation and subsequent propagation of a crack to a critical size.

3.2.2. Test results

Summary of the fatigue test data from 19 specimens (17 valid) is presented in Table 4. Despite a common stress ratio, individual specimens were subjected to different stress ranges and loading frequencies. The *S-N* relationship was established by applying a linear regression to the log-log plot of nominal stress range $\Delta\sigma$ against failure cycles (N), as shown in Fig. 10. The corresponding *S-N* curves for the BW1 and BW2 groups are defined by Eqs. (3) and (4).

$$\lg N = 12.758 - 3.000 \lg \Delta\sigma \quad (3)$$

$$\lg N = 12.341 - 3.000 \lg \Delta\sigma \quad (4)$$

Fatigue assessment according to Eurocode 3 assigns a detail category of 90 to the tested butt-welded joints, indicating a reference stress range of 90 MPa at 2 million cycles. The experimental *S-N* curves for groups BW1 and BW2, determined from the data in Table 4 using the nominal stress method (Fig. 10), provide a basis for comparison with this standard. The run-out values are conservatively regarded as the failure cycle. The fatigue test results for the BW1 group showed a fatigue resistance of 142.0 MPa after 2 million cycles, which was 57.8% higher than the standard value of 90.0 MPa specified in Eurocode 3. This indicates that the standard value is relatively conservative when estimating the fatigue resistance of butt-welded joints.

Evaluation using the fixed-slope fitting equation yielded an equivalent nominal stress fatigue strength of 103.1 MPa at 2 million cycles for the BW2 group. The primary failure mode initiated at porosity defects, with crack propagation through the plate thickness leading to fracture. This resulted in a 27.4% decrease in fatigue strength relative to defect-free specimens, indicating that porosity substantially compromises the fatigue strengths of butt-welded joints.

Table 4
Fatigue test parameter and results of specimens

Specimens	Weld size	Stress range (MPa)	Failure cycle ($\times 10^4$ cycles)	Defect/ Location	Fracture mode
BW1-1	Butt	120.0	>500.00	No	Run-out
BW1-2	Butt	130.0	416.91	No	Weld toe
BW1-3	Butt	140.0	278.00	No	Weld toe
BW1-4	Butt	150.0	211.17	No	Weld toe
BW1-5	Butt	160.0	166.11	No	Weld toe
BW1-6	Butt	170.0	64.78	No	Weld toe
BW1-7	Butt	180.0	89.10	No	Weld toe
BW1-8	Butt	190.0	117.14	No	Weld toe
BW1-9	Butt	200.0	32.14	No	Weld toe
BW2-1	Butt	120.0	102.91	Porosity	Porosity
BW2-2	Butt	130.0	124.52	Porosity	Porosity
BW2-3	Butt	140.0	115.39	Porosity	Porosity
BW2-4	Butt	150.0	58.18	Porosity	Porosity
BW2-5	Butt	160.0	37.12	Porosity	Porosity
BW2-6	Butt	170.0	43.83	Porosity	Porosity
BW2-7	Butt	180.0	69.19	Porosity	Weld toe
BW2-8	Butt	180.0	37.95	Porosity	Porosity
BW2-9	Butt	190.0	31.87	Porosity	Porosity
BW2-10	Butt	180.0	30.65	Porosity	Porosity
CW1-1	Cruciform	90.0	368.52	No	Weld toe
CW1-2	Cruciform	100.0	202.84	No	Weld toe
CW1-3	Cruciform	110.0	90.65	No	Weld toe
CW1-4	Cruciform	120.0	119.06	No	Weld toe
CW1-5	Cruciform	130.0	53.06	No	Weld toe
CW1-6	Cruciform	140.0	52.96	No	Weld toe

CW1-7	Cruciform	150.0	35.63	No	Weld toe
CW1-8	Cruciform	190.0	19.89	No	Weld toe
CW2-1	Cruciform	100.0	160.52	Porosity	Porosity
CW2-2	Cruciform	110.0	181.28	Porosity	Weld toe
CW2-3	Cruciform	120.0	97.97	Porosity	Weld toe
CW2-4	Cruciform	130.0	83.91	Porosity	Weld toe
CW2-5	Cruciform	140.0	41.55	Porosity	Weld toe
CW2-6	Cruciform	150.0	36.60	Porosity	Weld toe
CW2-7	Cruciform	160.0	31.97	Porosity	Porosity
CW2-8	Cruciform	160.0	21.07	Porosity	Weld toe
CW2-9	Cruciform	170.0	18.49	Porosity	Porosity

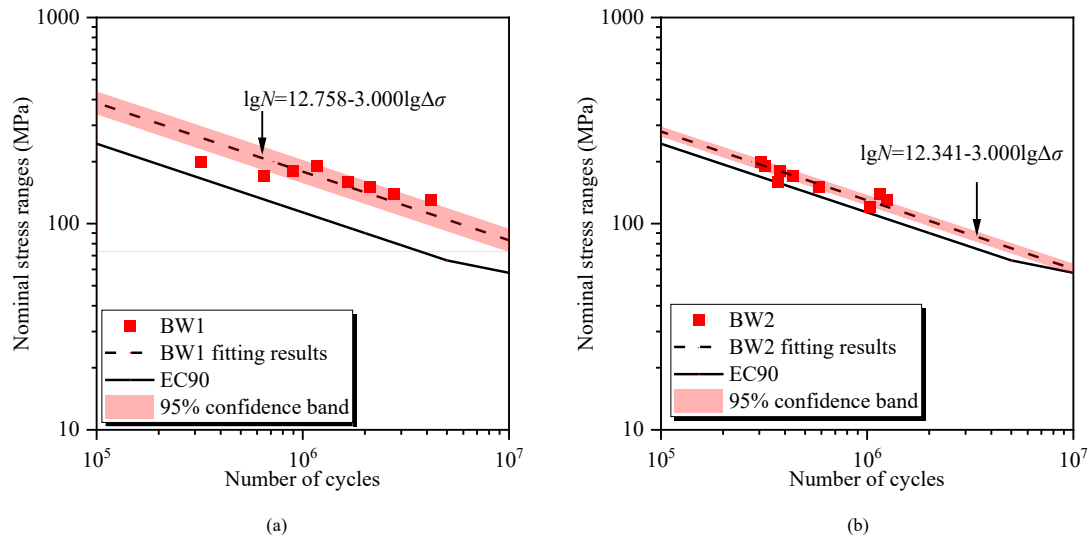


Fig. 10 Fatigue test data and the S - N curves: (a) BW1 group; (b) BW2 group

Through fatigue testing of cruciform-welded joint specimens, 11 valid fatigue test data points were obtained a total of 9 fatigue tests were conducted on cruciform joints with porosity defects, among which 6 specimens exhibited crack initiation and propagation from the weld toe. Only 3 specimens showed crack initiation at the porosity defect and propagation through the plate thickness. A summary of failure cycles and fracture locations is provided in Table 4, and the S - N data are plotted in Fig. 11. To obtain the S - N curves, a linear fit was performed on the nominal stress range $\Delta\sigma$ and the number of failure cycles N for each specimen. The nominal stress S - N curves for the CW1 group, CW2 group initiating at the weld toe and initiating at the porosity are

expressed by Eqs (5), (6) and (7), respectively.

$$\lg N = 12.197 - 3.000 \lg \Delta\sigma \quad (5)$$

$$\lg N = 12.161 - 3.000 \lg \Delta\sigma \quad (6)$$

$$\lg N = 12.094 - 3.000 \lg \Delta\sigma \quad (7)$$

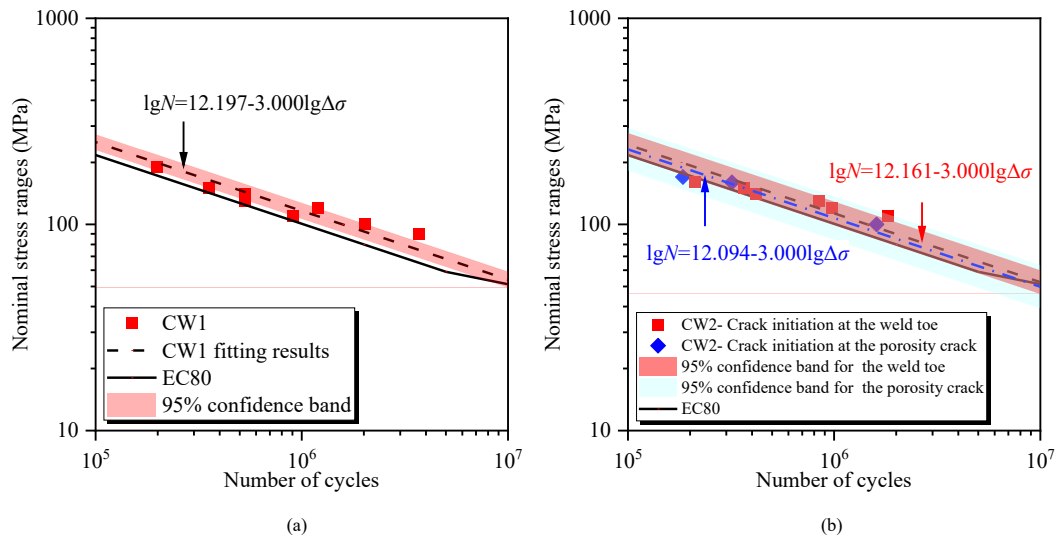


Fig. 11 Fatigue test data and S - N curves: (a) CW1 group; (b) CW2 group

On the basis of the fatigue test results (Table 4), the S-N relationships for the CW1 and CW2 specimen groups were constructed via the nominal stress method, with the results depicted in Fig. 11. According to the standard, EC 80 corresponds to a nominal stress range of 80 MPa for 2 million cycles. The fatigue test results for the CW1 group were all higher than the standard value of 80 MPa, with a fatigue resistance of 92.3 MPa at 2 million cycles, which was 15.4% higher than the value specified in Eurocode 3.

For the CW2 group specimens, the average nominal stress fatigue strength at 2 million cycles for specimens where cracks initiated at the porosity defect was 85.5 MPa, representing a 7.3% reduction compared to the CW1 group comprising conventional cruciform joint specimens. For specimens where

cracks were initiated at the weld toe, the average nominal stress fatigue strength at 2 million cycles was 90.3 MPa, which is close to the average value of 92.3 MPa observed in the CW1 group.

The fatigue failure of BW1 specimens, characterized by a loss of load-bearing capacity, is attributed to crack initiation and growth. As shown in Fig. 12, cracks predominantly initiate at the weld toe. The resulting fracture surface morphology correlates with the initiation location: semi-elliptical cracks correspond to mid-section initiation (Fig. 12b, d), while quarter-elliptical cracks correspond to weld-end initiation (Fig. 12c). The observation of multiple initiation zones (Fig. 12d) and varied initiation sites among specimens underscores the inherent randomness in the crack nucleation phase.

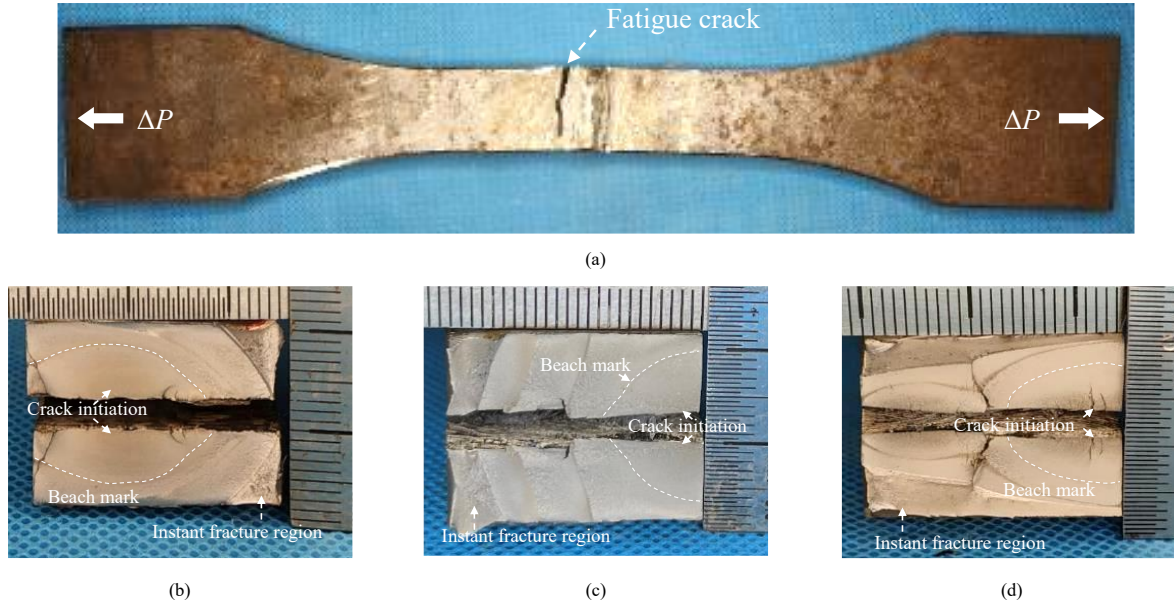
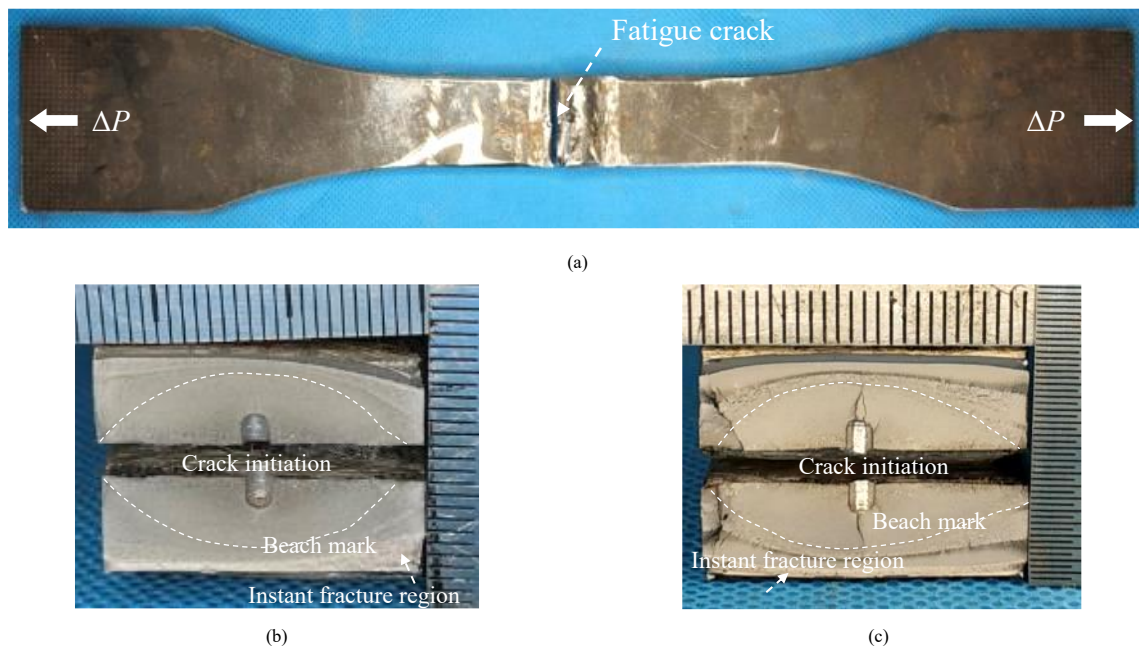


Fig. 12 Fatigue crack of the BW1 group: (a) failed welded joint; (b) failure section 1; (c) failure section 2; (d) failure section 3

A key distinction observed in the fracture morphology of the BW2 specimens (Fig. 13) is that fatigue crack initiation was primarily associated with porosity defects, a contrast to the behavior observed in the BW1 group. The fracture surfaces predominantly exhibited elliptical cracks, all showing typical fatigue fracture features. The fatigue crack propagation zones were smooth and flat, while the final fracture zones were rough and exhibited tearing patterns. Fatigue cracks initiated at the fusion line between the defect and weld metal and propagated through the plate thickness, with radial striations observed on the fracture surfaces. The macroscopic fracture sections of the specimens are shown in Fig. 13(b), (c) and (d). The fatigue crack propagation zones appeared darker,

with clear striations on the fracture surface, and obvious tearing secondary cracks were present. The fatigue fracture morphology of specimen observed under a Scanning Electron Microscope (SEM) was shown in Fig. 13(e). Fatigue cracks originate at the fusion line between the porosity defect and the weldment in the specimen, and extend towards the plate thickness direction. There are outward radiating streaks on the fracture surface. The crack extension area is darker in color, and the bands on the fracture surface are more distinct, with obvious tear-like secondary cracks present. Overall, the failure process is similar to that of actual pores causing crack initiation and propagation. The results are therefore representative to a certain extent.



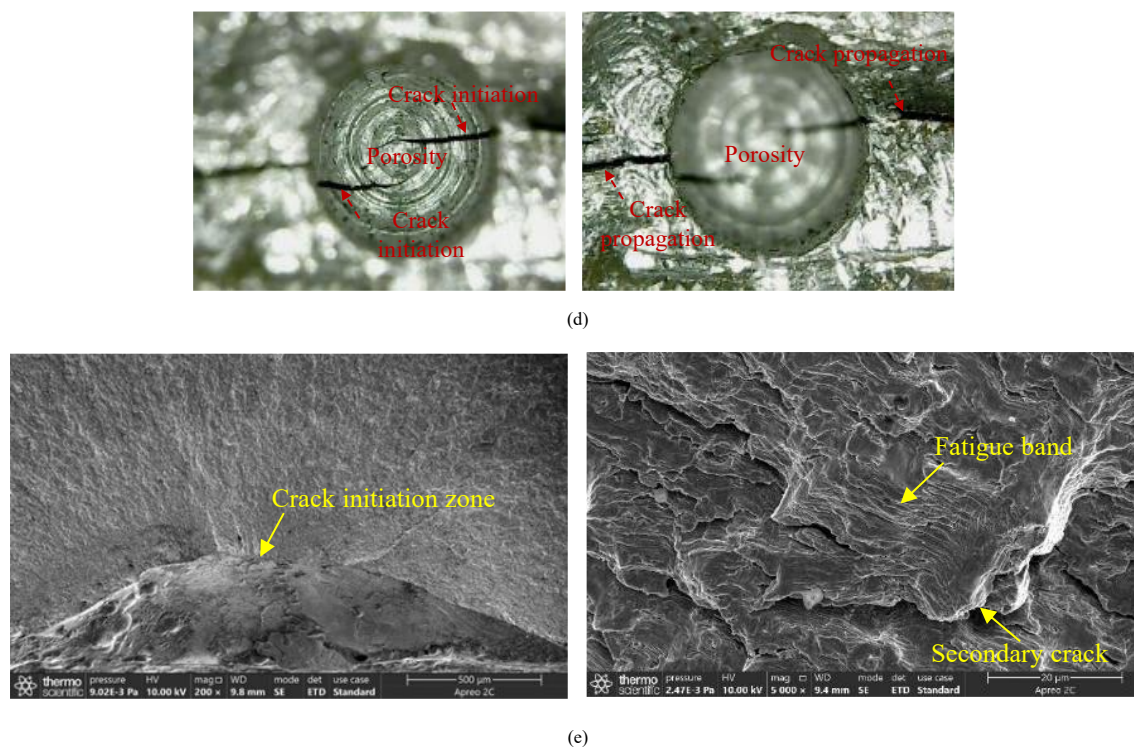


Fig. 13 Fatigue crack of the BW2 group: (a) failed welded joint; (b) failure section 1; (c) failure section 2; (d) location of crack initiation; (e) SEM morphology of crack initiation and propagation zone

Figs. 14 and 15 show the typical morphology of the fatigue failure in the CW1 and CW2 groups, respectively. Fatigue cracks were generally initiated at the weld toe where the stress was concentrated. The fatigue tests on CW1 specimens indicated crack initiation at the weld toe and subsequent through-thickness propagation, leading to elliptical fracture surfaces and, notably, multiple initiation zones as shown in Fig. 14(c). For the CW2 group specimens, when there was no overlap between the porosity defect and the weld toe line,

fatigue cracks initiated from the weld toe. However, when the porosity defect intersected the weld toe line, cracks initiated at the location of the porosity defect. After initiation, the cracks propagated primarily through the plate thickness with predominantly elliptical crack patterns. All fracture surfaces displayed typical fatigue fracture features, where the fatigue crack propagation zones were smooth and flat, whereas the final fracture zones were rough with tearing characteristics, as shown in Fig. 15.

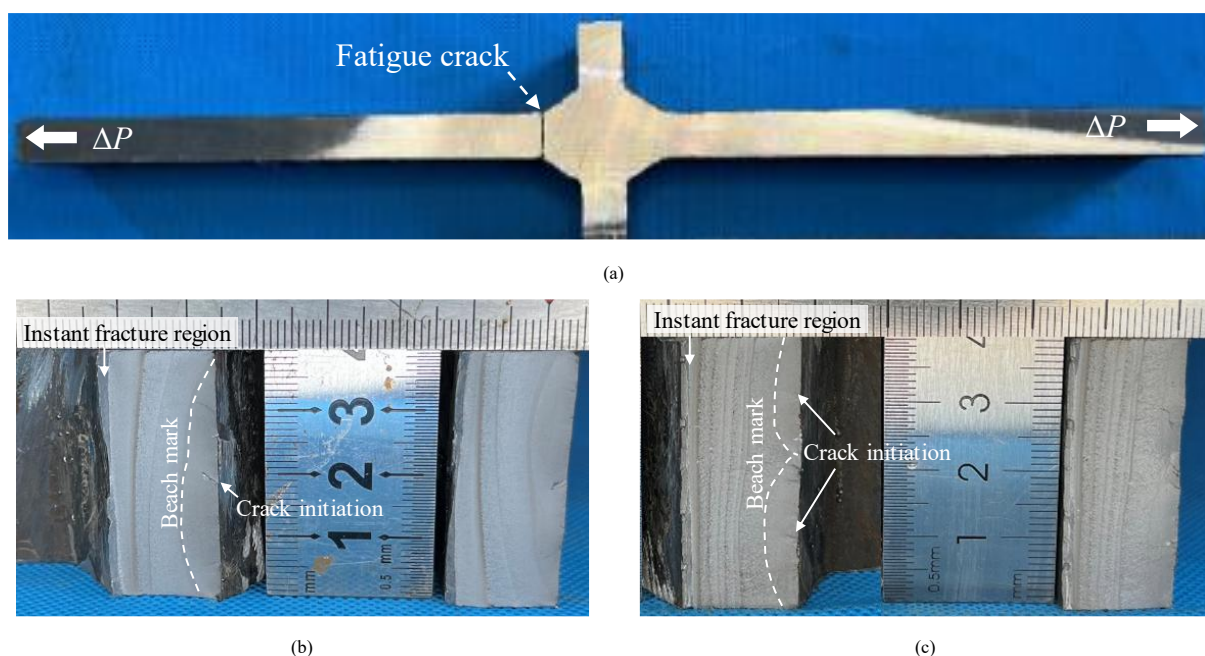


Fig. 14 Fatigue failure of the CW1 group: (a) failed welded joint; (b) failure section 1; (c) failure section 2

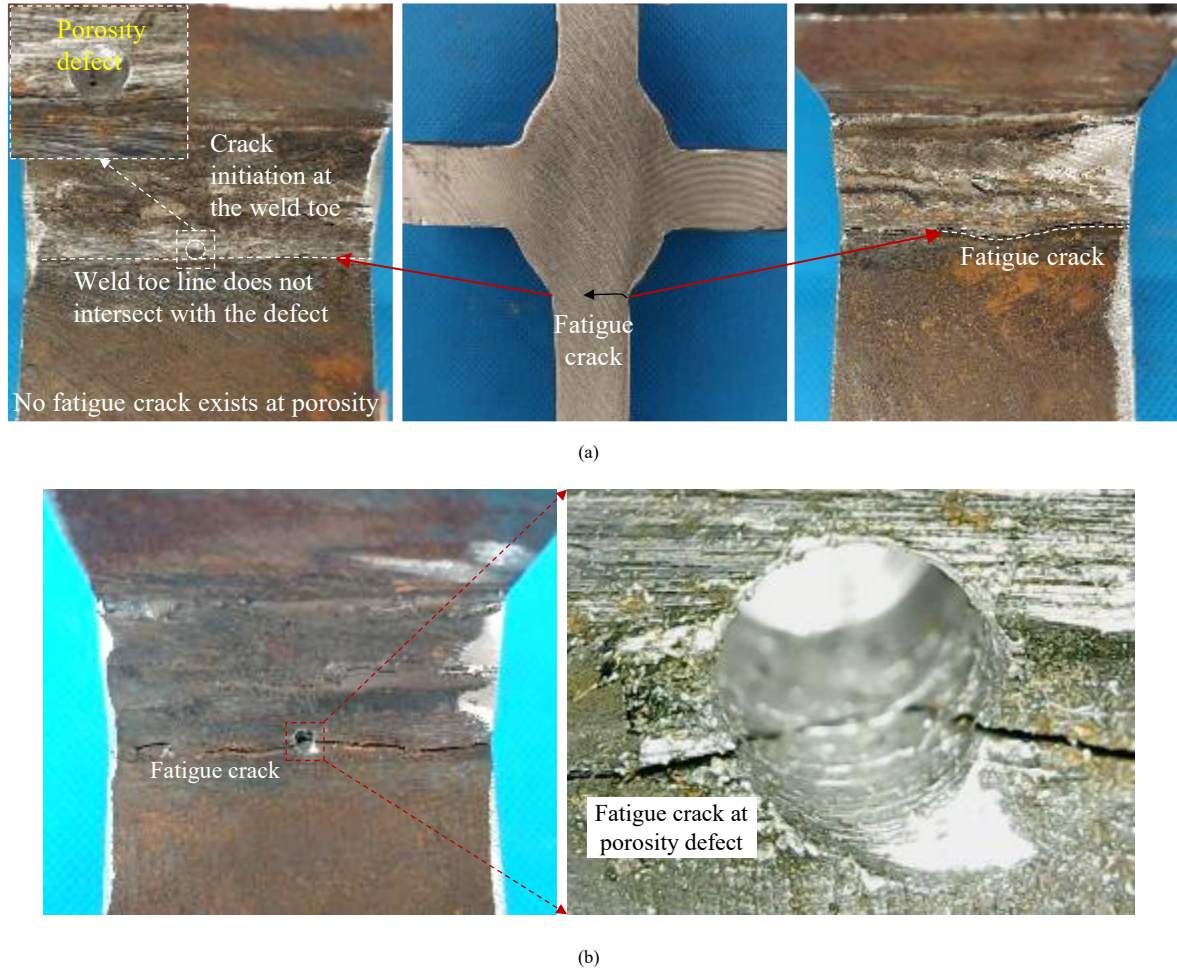


Fig. 15 Fatigue failure of the CW2 group: (a) initiation at the weld toe; (b) initiation at the porosity defect

3.2.3. Fatigue strength analysis

Butt-welded joints demonstrated superior fatigue strength under nominal stress compared to cruciform-welded joints in the absence of defects (Table 5). Nevertheless, under the condition of 2 mm pore defects, their fatigue resistance decreased significantly by 27.4%, a reduction substantially greater than the 7.3% observed for cruciform-welded joints, highlighting the critical influence of joint geometry on defect sensitivity. These findings indicate that porosity defects significantly affect the fatigue performance of welded joints.

Table 5
Comparison of fatigue strength

Group number	Group types	Fatigue resistance at 2 million cycles (MPa)	Failure locations
BW1	without porosity defects	142.0	Weld toe
BW2	with porosity defects	103.1	Porosity
CW1	without porosity defects	92.3	Weld toe
CW2	with porosity defects	90.3	Weld toe
CW2	with porosity defects	85.5	Porosity

4. Numerical study

4.1. Finite element model

A series of finite element models were developed within the ABAQUS environment to analyze stress distributions in the welded joints (Fig. 16). The geometry was meshed with C3D8 solid elements. Subsequently, a high level of mesh refinement, achieving an element size of 0.2 mm near the weld toe, was refined to enhance the accuracy of the finite element analysis. The butt-welded model consisted of approximately 65,700 elements, whereas the cruciform-welded model contained approximately 235,500 elements. The boundary conditions were consistent with those used in the fatigue tests. The translational degrees of freedom at one clamped end of the specimen were fully restrained, and cyclic loads were applied to the clamped region at the opposite end,

following the loading values defined in the experimental scheme, to simulate the fatigue loading.

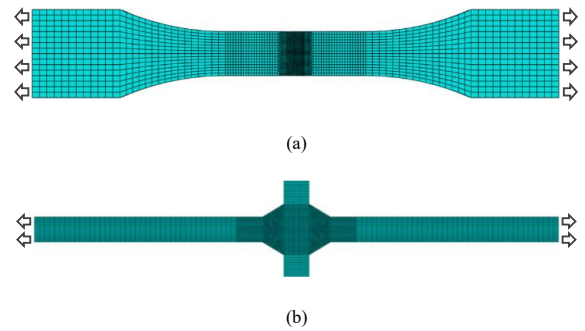


Fig. 16 The finite element model of the welded joints: (a) butt-welded joints; and (b) cruciform-welded joints

4.2. Model validation

The accuracy of the finite element model was validated through a comparison with static load test results. Two representative measurement points (B1-04 and B1-10) within the B1 strain measurement zone were selected, and their experimental data were compared with the results of the finite element analysis, as shown in Fig. 17. The results showed that for the butt-welded joint, the average deviation between the experimentally measured stress amplitudes and the finite element results at the two representative points was 1.4%. For the cruciform-welded joint, the average deviation in the strain amplitude between the experimental measurements and results of the finite element analysis at the two points was 3.1%. The close correlation observed between the finite element predictions and the experimental measurements serves to affirm the reliability and accuracy of the computational model.

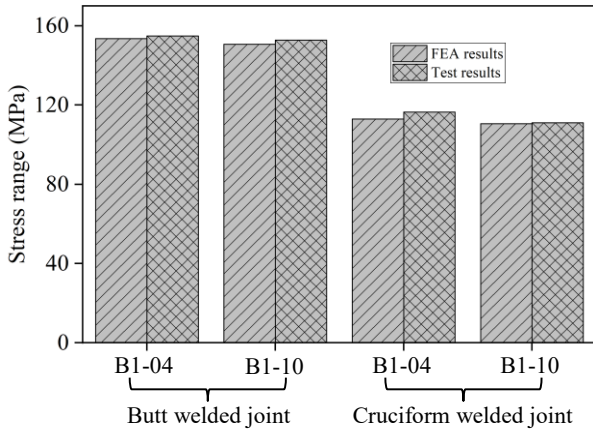


Fig. 17 Comparison of test results and numerical results

4.3. Parametric study and results

The influence of porosity defects on the stress state of welded joints was investigated through a parametric study using finite element modeling, focusing on key defect characteristics, such as pore diameter, pore depth, and pore position, on the stress state of the welded details. First, refined finite-element models were established based on the design drawings of the two types of welded joints used in the fatigue tests. During modeling, the welded joints were assumed to be homogeneous and continuous, whereas the porosity defect was modeled as a hollow sphere. The dimensions of the finite element model were consistent with those of the actual specimens. The modeling procedure and parameter settings were the same as those described in Section 4.1 and are therefore not repeated here. A far-field load was applied with nominal stress $\sigma_{nom}=100$ MPa as the control parameter. The effect of porosity defects on stress concentration was evaluated using the stress concentration factor, k_t , which is the ratio of the local maximum tensile stress at the pore to the nominal stress.

According to EN ISO 5817, the diameter d of the porosity defects should be limited to 3 mm. Therefore, the pore diameter parameter was selected accordingly, with a minimum pore diameter of 0.4 mm and a maximum of 3.0 mm. The center of the pore was aligned with the weld surface in the depth direction, and the pores were located on the weld near the weld toe. For consistency, the same pore diameter parameters were applied to both the butt-welded and cruciform-welded joints. To eliminate interference from other factors, only the pore diameter was varied during the study, whereas the other parameters remained unchanged. Plotted in Fig. 18 are the stress concentration factors corresponding to various porosity diameters for the butt- and cruciform-welded joints.

The results indicate that both joint types exhibit similar trends in the variation of k_t with the pore diameter. As the pore diameter increased, the stress concentration factor initially increased significantly and then gradually leveled off. Once the pore diameter reached 1.6 mm, the rate of increase in k_t began to decrease and eventually stabilized. The stress concentration factors for the butt- and cruciform-welded joints were 1.13 and 1.40 at a 0.4 mm pore diameter, with corresponding increases of 39.7% and 24.6% observed when the diameter was raised to 3.0 mm.

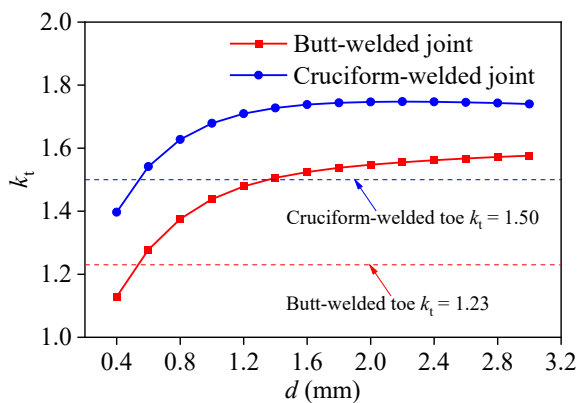


Fig. 18 Curve of stress concentration factor of welding details vs. pore diameter parameter

To accurately describe the location of the porosity defect in the finite element model, the pore center was assumed to be located on the weld surface, with the distance from the pore center to the weld toe defined as L . This distance parameter L was used to characterize the pore location, as illustrated in Fig. 19. The pore diameter d was set to 2 mm and all other model parameters were the same as those previously described.

The influence of porosity location L on the stress concentration factor is shown in Fig. 20. For both joint types, the stress concentration factor decreased significantly with increasing L , implying a weaker effect with greater distance from the weld toe. The cruciform-welded joint was considerably more sensitive to this parameter. As L increased from 1.75 mm to 8.50 mm, the stress concentration factor decreased by 19.9% (1.64 to 1.31) for the butt-welded joint, in contrast to a 51.3% decrease (1.96 to 0.96) for the cruciform-welded joint.

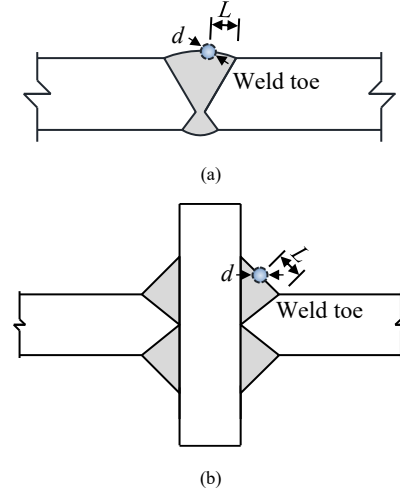


Fig. 19 Positional relationship between pores and weld toes

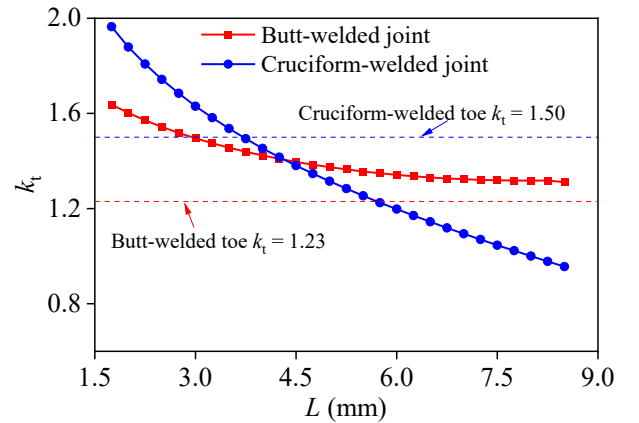


Fig. 20 Curve of stress concentration factor of welding details vs. pore location

To investigate the stress distribution characteristics of the welded details at different pore depths, a butt-welded joint was selected as an example, and the stress distributions at various pore depths were analyzed. The distance between the pore center and weld surface is defined as s , and the pore diameter is defined as d . The ratio s/d was used to describe the pore depth. A schematic diagram of the pore depth within the weld is shown in Fig. 21.

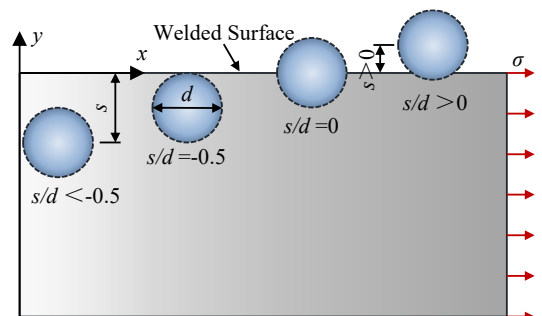


Fig. 21 Positional relationship between pores and the weld surface

In this context, $s/d = -0.5$ indicates that the pore is tangential to the weld surface; when $s/d < -0.5$, the pore is considered an internal pore; and when $s/d > -0.5$ it is defined as a surface pore. In the finite element model, the pore diameter d was set to 2 mm, and all other modeling parameters were kept consistent with those previously described.

Fig. 22 shows the contour plots of the first principal stress σ_1 at the pore defect location in the butt-welded joint specimen under tensile loading conditions. Figs. 22(a) to 22(d) correspond to the stress fields on a plane

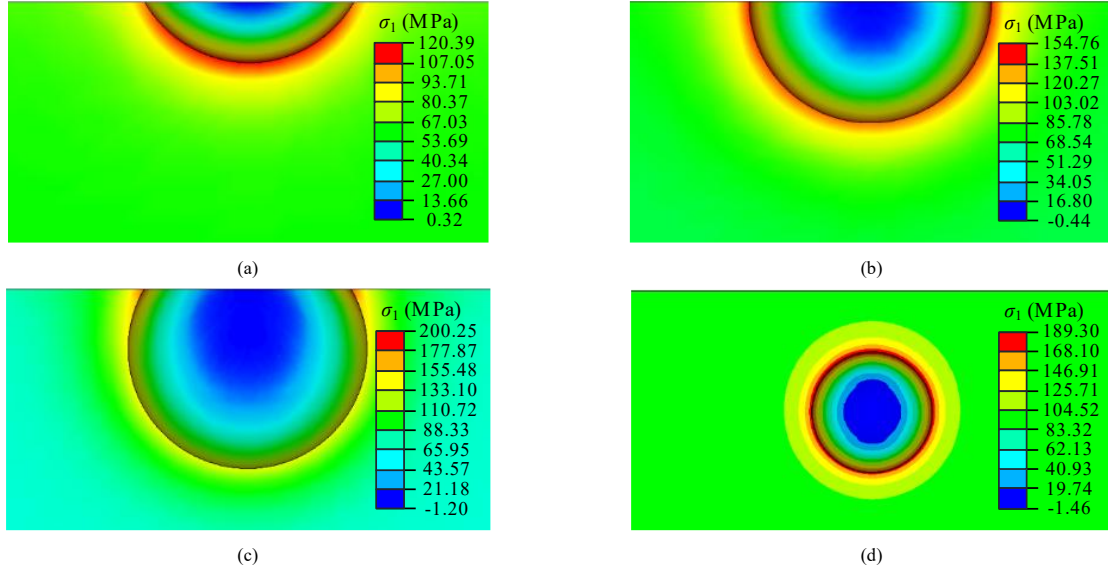


Fig. 22 Stress nephogram of the position of porosity defects in butt joints: (a) $s/d = 0.25$; (b) $s/d = 0.00$; (c) $s/d = -0.25$; and (d) $s/d = -1.00$

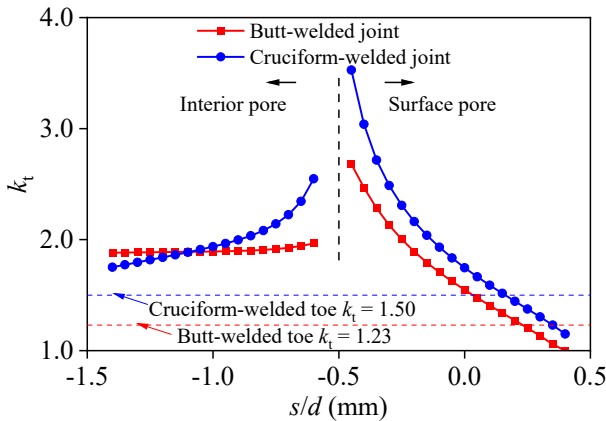


Fig. 23 Curve of stress concentration factor of welding details vs. pore depth

To further apply k_t to the structural design, a quantitative study on the parameters of porosity and the stress concentration effect was carried out. According to the standard EN ISO 5817[29], the diameter d of porosity defects is limited to within 3mm. Therefore, when determining the influence of porosity diameter on the stress state of welding details, the porosity diameter parameters were selected in accordance with this regulation, with the minimum pore diameter set at 0.2 mm and the maximum at 3.0 mm. Additionally, the location of porosity has a significant impact on their stress concentration coefficient. However, when the porosity does not overlap with the weld toe line, although their stress concentration coefficient is relatively large, the fatigue test results show that it does not affect their fatigue performance. Therefore, only the condition where the location coincides with the weld toe line is considered in the following analysis. The previous research results indicate that the porosity diameter has a varying degree of deteriorating effect on the fatigue resistance of welding details. When the porosity diameter is greater than 0.4 mm, the relationship between the porosity diameter parameter and the defect deterioration coefficient conforms to the polynomial function rule. Therefore,

perpendicular to the tensile load and passing through the pore center when s/d equals 0.25, 0.00, -0.25, and -1.00, respectively. The relationship between the stress concentration factor and porosity depth s/d is presented in Fig. 23. A critical observation is the pronounced decrease in the stress concentration factor for the cruciform joint when $s/d < -0.5$, exemplified by a value of 1.75 at $s/d = -1.4$. In contrast, the butt-welded joint showed minimal impact from pore depth changes, with the stress concentration factor remaining high at the $s/d = -0.50$ threshold.

the evaluation equation for the deteriorating effect of porosity defects on fatigue resistance can be determined through fitting. The least square method is used to fit the relationship between the porosity diameter and the defect deterioration coefficient according to the cubic function shown in Eq. (7):

$$k_t = a_1 + a_2 d + a_3 d^2 + a_4 d^3 \quad (8)$$

where d is the diameter of the porosity defect. Coefficient a_i ($i=1, 2, 3, 4$) of the equation can be determined by fitting the results of parameter analysis, as shown in Table 6.

Table 6
The fitted coefficient of k_t

Coefficient	Butt-welded joint	Cruciform-welded joint
a_1	1.1810	1.0745
a_2	-0.5787	-0.3000
a_3	0.2244	0.0954
a_4	-0.0312	-0.0110

Fig. 24 shows the correlation coefficient between the calculated values of the stress concentration equation for porosity defects and the calculated values from the finite element model. The correlation coefficients for butt- and cruciform-welded joint are above 0.9991, indicating that the proposed effect evaluation equation can well reflect the stress concentration effect.

It should be noted that the parameters of the equation are determined through data fitting based on a range of 0.4 to 3.0 mm for the porosity diameter. Therefore, this equation is mainly applicable to situations where the porosity diameter is within the range of 0.4 to 3.0 mm. For cases where the porosity diameter is less than 0.4 mm, a more conservative approach can be taken by assuming a porosity diameter of 0.4 mm and determining the defect-induced stress concentration coefficient accordingly.

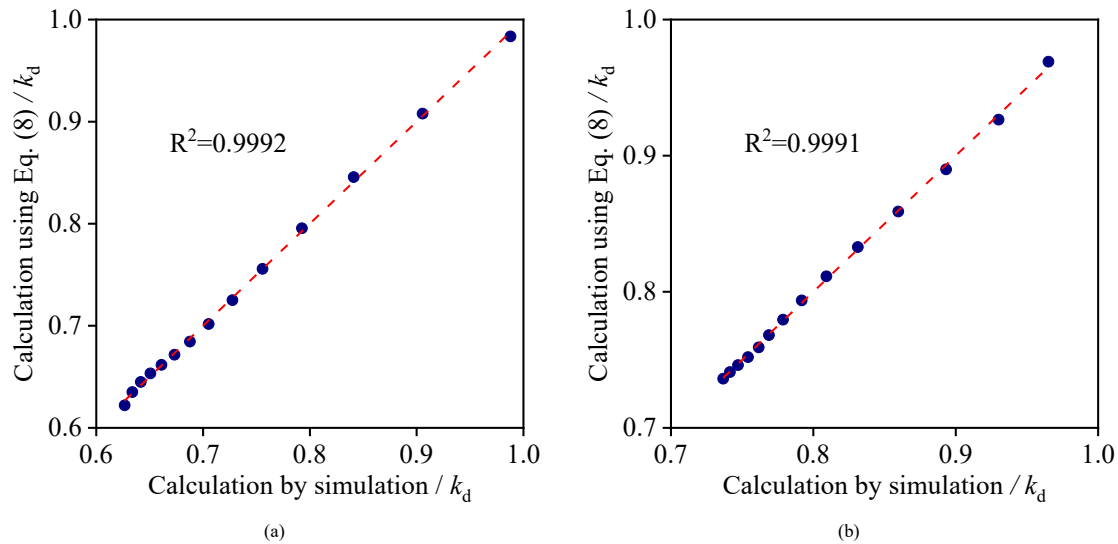


Fig. 24 Correlation coefficients of fitted equation: (a) butt-welded joint; cruciform-welded joint

5. Conclusions

This investigation centers on two prevalent types of welded joints found in steel bridge structures. Utilizing an integrated methodology of fatigue tests and numerical simulations, the study analyzes how porosity defects influence the fatigue performance and stress behavior of these joints. The main conclusions are as follows:

(1) The fatigue strengths at 2 million cycles for the conventional butt-welded and cruciform-welded joints without porosity were 142.0 MPa and 92.3 MPa, respectively. This failure mode was associated with cracks initiating at the weld toe, which then propagated through the plate thickness. The fracture surfaces were primarily elliptical, and the presence of multiple initiation zones in some specimens suggested stochastic crack nucleation behavior.

(2) For joints with porosity defects (2.0 mm depth/diameter), fatigue cracking originated at the porosity-weld toe intersection. This led to a fatigue strength of 103.1 MPa for butt-welded and 85.5 MPa for cruciform-welded joints, representing reductions of 27.4% and 7.4% compared to defect-free specimens, respectively, indicating a markedly higher defect sensitivity for the butt-welded geometry.

(3) Porosity defects induced a localized stress concentration in the weld region, significantly increasing the stress concentration factor of the welded joints. As the pore diameter increased, the stress concentration factor for both the butt-welded and cruciform-welded joints increased significantly, although the rate of increase slowed when the pore diameter exceeded 1.6 mm. The farther the pore was from the weld toe, the lower was the stress concentration factor, with cruciform joints being more sensitive to pore location. In addition, the surface pores exhibited significantly higher stress concentration factors than internal pores. When the pore was close to the weld surface, the stress concentration factor was high. As the pore depth increased, the stress concentration factor in cruciform joints decreased significantly, whereas the butt-welded joints were relatively less affected by the pore depth.

Acknowledgments

This study was funded by the National Key Research and Development Program of China [Grant Numbers: 2022YFB3706400] and the National Natural Science Foundation of China [Grant Numbers: 52278318, 52108176, and 52378316].

References

- [1] Cheng B, Ye X, Cao X, Mbako DD, Cao Y. Experimental study on fatigue failure of rib-to-deck welded connections in orthotropic steel bridge decks. *International Journal of Fatigue* 2017; 103: 157-167.
- [2] Liao X, Wei H, Pan H, Li HT, Sun B, Xin H. Fatigue resistance of rib-to-bimetallic steel deck welded joints in orthotropic steel bridge decks. *Thin-Walled Structures* 2024; 194: 111318.
- [3] Li D, Cheng B, Shi L, Xiang S, Zhao Q. An automated measurement method for the fatigue crack propagation based on decorrelated digital image correlation. *International Journal of Fatigue* 2024; 183: 108265.
- [4] Zhao Q, Du Y, Peng Y, Xu C. Shear performance of short channel connectors in a Steel-UHPC composite deck. *International Journal of Steel Structures* 2020; 20(1): 300-310.
- [5] Cui C, Xu Y L, Zhang Q H, Wang F Y. Vehicle-induced dynamic stress analysis of orthotropic steel decks of cable-stayed bridges. *Structure and Infrastructure Engineering* 2020; 16(8): 1067-1081.
- [6] Da L T, Zhang Q H, Yuan D Y, Ma Y, Cui C. A new orthotropic steel deck system incorporating two novel structural details. *Journal of Constructional Steel Research* 2022; 199: 107633.
- [7] Fisher JW, Barsom JM. Evaluation of cracking in the rib-to-deck welds of the Bronx-Whitestone Bridge. *Journal of Bridge Engineering* 2016; 21(3): 04015065.
- [8] Fisher JW, Roy S. Fatigue of steel bridge infrastructure. *Structure and Infrastructure Engineering* 2011; 7(7-8): 457-475.
- [9] Leander J, Andersson A, Karoumi R. Monitoring and enhanced fatigue evaluation of a steel railway bridge. *Engineering Structures* 2010; 32(3): 854-863.
- [10] Murakami Y, Endo M. Effects of defects, inclusions and inhomogeneities on fatigue strength. *International Journal of Fatigue* 1994; 16(3): 163-82.
- [11] Cui C, Xu Y L, Zhang Q H. Multiscale fatigue damage evolution in orthotropic steel deck of cable-stayed bridges. *Engineering Structures* 2021; 237(3): 112144.
- [12] Cheng Z, Zhang Q, Bao Y, Deng P, Wei C, Li M. Flexural behavior of corrugated steel-UHPC composite bridge decks. *Engineering Structures* 2021; 246: 113066.
- [13] Wang C, Xu Y, Chen A, Chen W. System fatigue damage reliability assessment of railway riveted bridges. *Key Engineering Materials* 2007; 347: 173-178.
- [14] Fisher JW. *Fatigue and fracture in steel bridge: case studies*. New York: Wiley-Interscience Publication; 1984.
- [15] Lee SB. Fatigue failure of welded vertical members of a steel truss bridge. *Engineering Failure Analysis* 1996; 3(2): 103-108.
- [16] Yuan D. *Welding defect-induced fatigue resistance degradation mechanism and evaluation method of typical welded joint in steel bridge*. Chengdu: Southwest Jiaotong University; 2023.
- [17] Shi Y, Yang Y, Chen Z. Examples of fatigue damage to railway steel bridges in China. *Bridge Construction* 1981; 4: 22-34.
- [18] Luo P, Zhang Q, Bao Y, Bu Y. Fatigue performance of welded joint between thickened-edge U-rib and deck in orthotropic steel deck. *Engineering Structures* 2018; 181: 699-710.
- [19] Li J. *Research on formation mechanism and performance evaluation of dominant fatigue failure modes of orthotropic steel deck*. Chengdu: Southwest Jiaotong University; 2021.
- [20] Chen L, Fang K, Fu S. Effect of porosity defects on the ultra-long fatigue life of aluminum alloy welded joints. *Journal of Constructional Steel Research* 2015; 107: 123-130.
- [21] He M, Li X, Zhang Y. Study on the effect of porosity defects on the stress concentration factor of welded joints by experiment and finite element analysis. *Journal of Constructional Steel Research* 2016; 121: 234-242.
- [22] Xu L, Lei B, Liu M. Statistical analysis of porosity defects in laser hybrid welded aluminum alloy joints using synchrotron radiation X-ray microcomputed tomography. *Journal of Constructional Steel Research* 2017; 132: 456-464.
- [23] Wu W, Zhang Q, Li X. Finite element analysis of the effect of porosity defects on the stress distribution of steel bridge welded joints. *Journal of Constructional Steel Research* 2018; 143: 123-131.
- [24] Luo Y, Wang Z, Zhao X. Experimental study on the effect of porosity defects on the fatigue life of steel bridge welded joints. *Journal of Constructional Steel Research* 2019; 152: 234-241.
- [25] European Committee for Standardization. EN ISO 5817: 2014 Welding-Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded)-Quality levels for imperfections[S]. Brussels: European Committee for Standardization; 2014.
- [26] Yu Y, Li X, Li Q, Zhao S. Quantitative evaluation of fatigue life for welded traction and bolster structures with undercut defects. *Transactions of the China Welding Institution* 2017; 38(9): 33-37, 130.
- [27] Wei A, You Y, Lu Y, Gao G, Wang L. Initiation life of weld undercuts fatigue crack in pressure vessel. *Chinese Journal of Mechanical Engineering* 2006; 42(9): 214-218.
- [28] Aman M, Wada K, Matsunaga H, Remes H, Marquis G. The influence of interacting small defects on the fatigue limits of a pure iron and a bearing steel. *International Journal of Fatigue* 2020; 135: 105560.
- [29] Murakami Y, Takagi T, Wada K, Matsunaga H. Essential structure of S-N curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter. *International Journal of Fatigue* 2021; 146: 106138.
- [30] CEN. EN 1993-1-9:2005, Eurocode3: Design of Steel Structures - Part 1-9: Fatigue. Brussels, Belgium: European Committee for Standardization; 2005.
- [31] Hobbacher AF. IIW document IIW-2259-15, Recommendations for fatigue design of welded joints and components. 2nd ed. Switzerland: Springer International Publishing; 2016.
- [32] AASHTO. LRFD Bridge Design Specifications. 6th ed. Washington, DC: American Association of State Highway and Transportation Officials; 2012.