Experimental study on fatigue performance of Q420qD high-performance steel cross joint in complex environment

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Received: 17 October 2020 / Accepted: 22 January 2021 / Published online: 4 February 2021
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Abstract

The steel structure under the action of alternating load for a long time is prone to fatigue failure and affects the safety of the engineering structure. For steel structures in complex environments such as corrosive media and fires, the remaining fatigue life is more difficult to predict theoretically. To this end, the article carried out fatigue tests on Q420qD high-performance steel cross joints under three different working conditions, established a 95% survival rate $S-N$ curves, and analyzed the effects of corrosive media and high fire temperatures on its fatigue performance. And refer to the current specifications to evaluate its fatigue performance. The results show that the fatigue performance of the cross joint connection is reduced under the influence of corrosive medium, and the fatigue performance of the cross joint connection is improved under the high temperature of fire. When the number of cycles is more than 200,000 times, the design curves of EN code, GBJ code, and GB code can better predict the fatigue life of cross joints without treatment, only corrosion treatment, and corrosion and fire treatment, and all have sufficient safety reserve.

Keywords Q420qD high-performance steel · Cross joint · Corrosive medium · High temperature of fire · Fatigue performance

Introduction

With the development of steel structure bridges in terms of light weight, high load-bearing capacity and large span in recent years, traditional bridge steel can no longer meet the demand. Q420qD high-performance steel is a new type of steel that China's independent innovation has the advantages of lower thickness, higher strength, and good ductility. It has been widely used in railway bridges across rivers and lakes and some large highway bridges (Liu et al. 2018).

These structures have been exposed to high humidity or high salt spray environment for a long time (Bhandari et al. 2015). Although the steel structure has a paint protection

layer on the surface of the steel structure in the early stage of operation, as the service time increases, it is unavoidable to suffer from the influence of corrosive media (Kim et al. 2013). According to reports, about 15% of road steel bridges and 50% of railway steel bridges in Japan are replaced by corrosion (Yamaguchi et al. (2014)). Corrosion will not only reduce the effective cross-sectional area of the steel structure, but also cause stress concentration (Tohidi and Sharifi 2016), affecting the mechanical properties of the steel structure, such as significantly reducing the ultimate stress and fatigue strength (Jia et al. 2019). As one of the most important connection methods of steel bridges, welded joints are more sensitive to defects such as corrosion pits and cracks during the service process after the strength level of the bridge steel is improved (Zhang et al. 2016).

During the service period, steel bridges may even be eroded by fire caused by traffic accidents or natural factors (Song et al. 2016; Azhari et al. 2017). Although the existing fire protection technology has been widely used in practice, the heat generated by the fire will still be transferred to the steel. Under the action of high temperature of fire, steel structure is easy to lose strength, but in most cases, steel structure exposed to the outside after the action of high

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temperature of fire can still maintain most of its bearing capacity after cooling (Radu et al. 2018,2019; Zhu and Li 2017). Welding residual stress generated during the formation of welded joints, tensile residual stress is harmful to the fatigue process, and compressive residual stress can prolong the fatigue life (Wang et al. 2018,2020a; Cui et al. 2018). Under the action of high temperature of fire, the welded joint of steel bridge is an extremely weak part, but after the high temperature of fire, part of the residual strain in the welded joint will be released due to the effect of plastic deformation, which reduces the residual welding stress and affects the fatigue performance of the structure. Make an impact (Jiang et al. 2017; Wang et al. 2020b).

In the past few decades, scholars have mostly focused their research on the effect of a single environmental factor on the fatigue performance of welded structures, such as corrosion (corrosion time (Yang et al. 2016; Garbatov et al. 2014; Liu et al. 2021), corrosive medium (Thierry et al. 2016; Kang et al. 2011; Giorgetti et al. 2019; Klinesmith et al. 2007), corrosion conditions (Zhao et al. 2018; Gkatzogiannis et al. 2019; Huang et al. 2014)); temperature (high temperature (Daryan and Yahyai 2009; Zhang et al. 2020; Langschwager et al. 2017; Azari-Dodaran and Ahmadi 2019), room temperature (Zong et al. 2017; Luo et al. 2019; Su et al. 2019), and low temperature (Li et al. 2018; Zhang et al. 2018; Walters et al. 2016)). In actual engineering, the service environment of steel bridges is extremely complex, and the influence of a single environmental factor on its structural fatigue performance can no longer meet the needs of engineering design and evaluation. Therefore, the research on the fatigue performance of welded joints after considering the coupling effect of the two environmental factors of corrosive medium and fire and high temperature is of great significance to the assessment of the remaining fatigue life of the entire steel bridge.

This paper reports the fatigue life results of Q420qD high-performance steel cross joints under three working conditions: no treatment, only corrosion treatment, and corrosion and fire treatment, and determines the effects of corrosive media and high temperature on the fatigue strength and fracture characteristics of cross joints.

Specimen design

The fatigue test object is the cross joint specimen of transverse fillet weld. The base metal is 16 mm Q420qD steel plate. The chemical composition, mechanical properties, and delivery status of the steel plate meet the relevant requirements of the Chinese high-strength low-alloy structural steels (GB/T 1591-2018), and full thickness sampling is adopted. According to the Chinese metallic materials–fatigue testing–axial force-controlled method code

(GB/T 3075-2008) and the actual test conditions, the specific size of the specimen is determined, as shown in Fig. 1. The model of welding rod is E55, and its mechanical properties are shown in Table 1. Manual arc welding is adopted. The welding voltage is 24 V, the welding current is 150 A, and the welding speed is about 5 mm/s. The weld quality meets the relevant requirements in the Chinese code for welding of steel structures (GB 50661-2011). The weld leg size is 6 mm and the calculated weld length is 50 mm. The chemical composition of steel and welding materials is shown in Table 2.

According to the Chinese metallic materials–tensile testing–Part 1: method of the test at room temperature code (GB/T 208.1–2010), three base metal specimens were made for axial tensile test (see Fig. 2 for dimensions), and the corresponding mechanical property parameters of Q420qD are measured in Table 3.

Finite-element analysis of fatigue performance of specimen

Based on ANSYS 15.0 finite-element software, a three-dimensional finite-element model of cross joints without corrosion pits and containing corrosion pits is established. SOLID45 solid elements are used, and the fillet weld area elements are all divided by 1 mm mesh. The weld zone has the same material parameters as Q420qD high-performance steel: elastic modulus E is 2.064×10^5 Mpa and Poisson's ratio ν is 0.3. Load and boundary conditions: one end is consolidated, and the other end is subjected to a tensile stress surface load of 30 MPa.

It can be seen from the stress distribution of the specimen in Fig. 3 that, when the stress distribution of the clamping part is not considered, the maximum equivalent stress of the cross joint specimens without corrosion pits and corrosion pits are located in the weld toe area. In the later fatigue test, most of the cross joint specimens were broken at the weld toe, indicating that the finite-element calculation results can be used as the basis for judging the weak position of

Fig. 1 Size of cross joint test piece (unit: mm)

Table 1 Mechanical properties of E55 electrode deposited metal

Electrode	Tensile strength R_m/MPa	Yield strength R_{el}/MPa	Elongation after fracture $A/\%$	$-30\text{ }^\circ\text{C}$ impact energy A_{KV}/J
E55	≥ 550	≥ 460	≥ 17	≥ 27

Table 2 Q420qD steel and E55 electrode chemical composition

Material category	Content of each component /%								
	C	Si	Mn	P	S	Ni	Cr	Nb	V
Q420qD	0.18	0.345	1.48	0.024	0.012	0.0085	0.022	0.005	0.07
E55	≤ 0.10	≤ 0.80	≤ 1.00	≤ 0.025	≤ 0.015	≤ 0.50	≤ 0.30	≤ 0.20	≤ 0.10

Fig. 2 Geometric dimension of cross joint specimen (unit: mm)**Table 3** Results of material property test

Specimen number	Yield strength f_y/MPa	Ultimate strength f_u/MPa	Elastic modulus E/MPa
Q420qD-1	425.803	636.446	2.069×10^5
Q420qD-2	423.535	633.281	2.058×10^5
Q420qD-3	425.172	635.567	2.064×10^5
Average value	424.837	635.098	2.064×10^5

the specimen, and the rationality of the specimen design is ensured.

Test piece fatigue performance test

Sample preparation

Corrosion test

The cross joint specimens with corrosion pits were obtained by accelerated corrosion test (Xu 2017). Test corrosive environment: $50\text{ g/L} \pm 5\text{ g/L}$ NaCl solution was used to simulate the marine atmospheric environment, and NaOH solution was added to control the pH value of corrosion chamber in the range of 6.5–7.2. The connection and reaction principle of test equipment are shown in Fig. 4 and Table 4. Pretreatment of corrosion test: in addition to fillet weld area, other parts of the surface are coated with epoxy resin seal to prevent corrosion. In addition, due to the exothermic process and long electrolysis time in the corrosion test, the epoxy resin layer at the corner

Fig. 3 Stress distribution of specimens

(a) Schematic diagram

(b) Physical picture

Fig. 4 Equipment connection**Table 4** Reaction principle of electrified accelerated corrosion test

Classification	Chemical equation
Anode	$Fe - 2e^- = Fe^{2+}$
Cathode	$2H_2O + 2e^- = H_2 \uparrow + 2OH^-$
The total reaction of electrolysis	$Fe + 2H_2O = H_2 \uparrow + Fe(OH)_2$

Note: Given that $Fe(OH)_2$ is highly unstable, it is easily oxidized, and the final precipitate turns from white to yellowish-green and then quickly turns into reddish-brown. The reaction formula as $4Fe(OH)_2 + O_2 + 2H_2O = 4Fe(OH)_3$.

of the cross joint is easy to be hardened and damaged, resulting in corrosion, which affects the accuracy of the corrosion results. Therefore, it is considered to wrap a layer of electrical tape outside the epoxy resin anti-corrosion coating to achieve the secondary sealing effect.

Pitting corrosion is easy to occur in steel bridges under marine atmospheric environment. Corrosion depth D_a is used to evaluate pitting damage, which is expressed as:

$$D_a = \xi t^n. \quad (1)$$

In reference (Cao (2005)), the values of ocean atmospheric corrosion depth parameters of many countries in the world are given, and the mean value is taken as the parameter in the power function, i.e., $\xi = 0.062$, $n = 0.862$. According to Eq. (1), the average corrosion pit depth of welded joint in marine atmospheric environment for 10 years is 0.45 mm. Then, the relationship between current and time (see Eq. (4)) is obtained using the formula for calculating the average corrosion pit depth (see Eq. (2)) and Faraday's Law (see Eq. (3)). During the energized accelerated corrosion process, the current $I = 3A$ is always controlled. When $T = 1.92h$, the cross joint specimen with the average corrosion pit depth $D = 0.45mm$ can be obtained:

$$D = \Delta m / S_0 \rho$$

$$\Delta m = MIT / Fn$$

$$IT = DS_0 \rho Fn / M,$$

where D is the average depth of corrosion pit, mm ; m is the net loss of the test piece before and after the corrosion test, g (after the corrosion test, the corrosion product on the test piece surface is removed with baking soda and white vinegar, wiped clean with absolute ethanol, dried, and weighed); S_0 is the effective cross-sectional area of the butt weld joint, mm^2 ; ρ is the weld material density, g/cm^3 ; I is the corrosion current, A ; T is the time required for corrosion, s ; M is the mole of matter, g/mol ; F is the Faraday constant, $F = 9.62 \times 10^4 C/mol$; and n is the number of electrons. Here, given that the anode is Fe , the electrons are lost to Fe^{2+} , so $n = 2$.

Fire high-temperature test

Ten specimens are taken from the corrosion test and placed in the intelligent box-type high-temperature resistance furnace. After setting the target temperature, the temperature will be raised. In the heating section, the points are taken from the ISO-834 standard temperature rise curve (Switzerland. 2019) [see Eq. (5)] for segmented heating. Under the action of high temperature, the yield strength, elastic modulus, and other mechanical parameters of steel will be greatly reduced with the increase of temperature. When the temperature reaches 300 °C, the stress–strain curve of the steel without fireproof layer has no obvious yield step; when the temperature reaches 350 °C, the strength decreases to 2/3 of the original; when the temperature reaches 500 °C, the strength is 1/2 of the original (Li 2019), so when the temperature reaches 600 °C, continue to maintain the temperature for 1 h and then stop heating (Funderburk 1998). At this time, if the specimen is directly taken out to contact

Fig. 5 Cross joint cooling completed

Fig. 6 General system of fatigue test

with the external environment for cooling, there will be a large temperature gradient inside the specimen and new additional stress will be generated. Therefore, the cooling process is naturally reduced to room temperature with the resistance furnace. After cooling, the appearance of cross joint is shown in Fig. 5:

$$T_t = 345 \lg(8t + 1) + T_{t0},$$

where T_t is the ambient temperature at the time of fire development to t , °C; T_{t0} is the ambient temperature at the time of fire occurrence, $T_{t0} = 20^\circ\text{C}$ is taken in this test; and t is the duration of the fire, min.

Test equipment and method

Fatigue test was carried out on MTS Landmark electro-hydraulic servo universal testing machine (see Fig. 6). The load was controlled by force, and the loading waveform was sine wave (China Standard Press 2006) with PVC compensation. The loading frequency varied in the range of 10–15 Hz. The stress ratio $R = 0.1$ is the ratio of the minimum stress $S_{\min}$ to the maximum stress $S_{\max}$ in a cycle, i.e., $R = S_{\min}/S_{\max}$. During the test, the system will automatically record the number of loading cycles and the fatigue displacement value at the end of each loading. If there is any abnormality, fracture or the number of cycles reaches 2 million, the test will be stopped. The effective data obtained from the fatigue test of the cross joint are summarized in Table 5.

Table 5 Fatigue life test data of cross joints under different processing conditions

Specimen number	ΔS /MPa	F_a /kN	F_m /kN	N /cycle	Forms of destruction	Specimen number	ΔS /MPa	F_a /kN	F_m /kN	N /cycle	Forms of destruction
SJ1-1	96	24.89	20.36	1,491,575	Weld toe fracture	SJ8-2	143	33.14	27.12	261,473	Weld toe fracture
SJ1-2	96	24.89	20.36	1,472,863	Weld toe fracture	SJ9-1	167	38.71	31.67	151,277	Weld toe fracture
SJ2-1	119	30.85	25.24	866,294	Weld toe fracture	SJ9-2	167	38.71	31.67	110,013	Weld toe fracture
SJ2-2	119	30.85	25.24	882,499	Weld toe fracture	SJ10-1	191	44.27	36.22	75,179	Weld toe fracture
SJ3-1	143	37.08	30.33	529,826	Weld toe fracture	SJ10-2	191	44.27	36.22	81,278	Weld toe fracture
SJ3-2	143	37.08	30.33	545,400	Weld toe fracture	SJ11-1	96	22.25	18.20	886,604	Weld toe fracture
SJ4-1	167	43.30	35.43	316,157	Weld toe fracture	SJ11-2	96	22.25	18.20	860,041	Weld toe fracture
SJ4-2	167	43.30	35.43	291,409	Weld toe fracture	SJ12-1	119	27.58	22.57	508,322	Weld toe fracture
SJ5-1	191	49.52	40.52	203,963	Weld toe fracture	SJ12-2	119	27.58	22.57	499,182	Weld toe fracture
SJ5-2	191	49.52	40.52	167,907	Weld root fracture	SJ13-1	143	33.14	27.12	289,932	Weld toe fracture
SJ6-1	96	22.25	18.20	629,946	Weld toe fracture	SJ13-2	143	33.14	27.12	287,118	Weld toe fracture
SJ6-2	96	22.25	18.20	534,395	Weld toe fracture	SJ14-1	167	38.71	31.67	195,033	Weld toe fracture
SJ7-1	119	27.58	22.57	335,833	Weld toe fracture	SJ14-2	167	38.71	31.67	149,899	Weld toe fracture
SJ7-2	119	27.58	22.57	271,230	Weld toe fracture	SJ15-1	191	44.27	36.22	119,715	Weld toe fracture
SJ8-1	143	33.14	27.12	177,625	Weld root fracture	SJ15-2	191	44.27	36.22	101,769	Weld toe fracture

SJ1–SJ5 are untreated specimens, SJ6–SJ10 are all corrosion-only specimens, SJ11–SJ15 are corrosion and fire treatment specimens. After that, the untreated specimen, the corrosion treated specimen, and the corroded and fire-treated specimen were simplified to specimen #1, specimen #2, and specimen #3, respectively

Test results and analysis

S–N curve

S–N curve is commonly used in engineering in the form of power function, namely:

$$C = S^m N. \quad (6)$$

Take the logarithm of both sides to get : $m \lg S + \lg N = \lg C$. (7)

After finishing, the deformation is as follows : $\lg N = a - m \lg S$. (8)

where a and m are parameters to be determined by the fitting.

According to the fatigue test data in Table 5, the least square method is used to fit the fatigue life N and stress amplitude S of fillet weld under different treatment conditions. According to IIW specification (Hobbacher 2016), when $N < 10^7$, the negative inverse slope of S–N curve is taken as $m = 3$. Therefore, taking the fitting curve $m = 3$, the logarithmic linear expression of cross joint S–N curve under different treatment conditions is obtained. In addition, the S–N curve with 50% survival rate is obtained from the experimental data, and the logarithmic linear expression of corresponding S–N curve with the 95% survival rate can be obtained by subtracting 2 times of standard deviation of $\lg N$ (0.339, 0.321, and 0.340) (Fricke 2012), see Table 6.

The S–N reference curve of welded joint in air is available in steel structure codes of various countries, but the S–N reference curve of welded joint under sea water corrosion or fire high temperature is not included. Although the S–N reference curve of free corrosion of welded joints in air or sea water is provided in the rules of classification societies of various countries, the S–N reference curve of welded

joints after high-temperature fire is not specified. Therefore, the S–N curves of welded joints after corrosion and fire treatment are evaluated based on the steel structure design codes of various countries and classification societies. See Table 7 for S–N reference curve of cross joint in various specifications under different treatment types.

For the convenience of comparison, the S–N curve of specimen #1, specimen #2, and specimen #3, the fitting curve under the 95% survival rate, and the S–N fatigue curve of national codes are plotted in Fig. 7, and the 2 million cycle fatigue limit value of fillet weld under corresponding conditions is calculated, as shown in Table 8.

It can be seen from Fig. 7 and Table 8 that:

1. The test fatigue limit values of specimen #2 and specimen #3 are 26.83% and 17.21% lower than that of specimen #1, respectively. Corrosion will increase the stress concentration on the surface of the test piece, resulting in a decrease in the fatigue performance of the cross joint; when the fire temperature is about 600 °C, the high temperature of the fire will increase the fatigue performance of the cross joint (Wang et al. 2020c).
2. For specimen #1, the fatigue limit value under the 95% survival rate is 53.09 MPa, which is 11.38% lower than that calculated by ABS code and 6.18% higher than that calculated by DNV code. The fatigue limit value of specimen #1 is 25.47%, 11.58%, and 41.68% higher than the theoretical design value of GB code, EN code, and IIW code, which is equivalent to the theoretical design value of ANSI code. Comparatively speaking, IIW code obviously underestimates the fatigue of cross joint Working life. Compared with ANSI code, EN code design curve can better predict its fatigue life and has enough safety reserve. However, when the number of cycles is less than 200,000, more fatigue test data are needed.
3. For specimen #2, the fatigue limit value is higher than the theoretical value calculated by the classification societies of various countries. The main reason is that the corrosion time of the welded joint in the environment is not considered in the calculation formula of the national codes. The fatigue limit value of specimen #2 is 11.35%

Table 6 Logarithmic linear expression of S–N curve

Type	Regression of test data	The 95% survival rate
Specimen #1	$\lg N = 12.153 - 3 \lg \Delta S$	$\lg N = 11.476 - 3 \lg \Delta S$
Specimen #2	$\lg N = 11.746 - 3 \lg \Delta S$	$\lg N = 11.104 - 3 \lg \Delta S$
Specimen #3	$\lg N = 11.907 - 3 \lg \Delta S$	$\lg N = 11.227 - 3 \lg \Delta S$

Table 7 S–N reference curve of cross joint in national codes under different treatment types

Type	Standard	Formula	Standard	Formula
Atmospheric corrosion	GB code (2017)	$[\Delta\sigma] = \left(\frac{0.72 \times 10^{12}}{N} \right)^{1/3}$	ANSI code (2010)	$F_{SR} = \left(\frac{14.4 \times 10^{11}}{n_{SR}} \right)^{0.333}$
	EN code (2005)	$\lg N = 12.010 - 3 \lg \Delta\sigma$	ABS code (2013)	$N = 4.30 \times 10^{11} \times S^{-3}$
	IIW code (2016)	$\lg N = 11.699 - 3 \lg \Delta\sigma$	DNV code (2014)	$\lg N = 11.398 - 3 \lg \Delta\sigma$
Seawater corrosion	ABS code	$N = 1.43 \times 10^{11} \times S^{-3}$	DNV code	$\lg N = 10.921 - 3 \lg \Delta\sigma$
	CCS code (2013)	$\lg N = 11.155 - 3 \lg \Delta\sigma$	GJB code (1999)	$\lg N = 11.261 - 3 \lg \Delta\sigma$

lower than the theoretical design value of GJB code and 15.09% higher than the theoretical design value of DNV code under the 95% survival rate, which is equivalent to the theoretical calculation value of ABS code and CCS code.

4. For specimen #3, the fatigue limit value is 73.90 MPa, which is not different from the theoretical calculation value of GB code, and the fatigue life of specimen #3 is predicted by the design curve of GB code, which has sufficient safety reserve. The fitting curve of specimen

#3 under the 95% survival rate is in good agreement with the design curve of GJB code.

Fatigue fracture analysis

Macro analysis

It can be seen from Fig. 8 that the fracture morphology has typical fatigue fracture characteristics, and the instantaneous section is rough and tear like. Before instantaneous break, the section is smooth and flat. The fatigue fracture

Fig. 7 S – N curve comparison

Table 8 Comparison of fatigue limit values

Type	Test fitting/specification	Fatigue limit	Test fitting/specification	Fatigue limit
Specimen #1	Experimental fitting	89.26 MPa	The 95% survival rate	53.09 MPa
	GB code	71.14 MPa	ANSI code	89.63 MPa
	EN code	80.00 MPa	ABS code	59.91 MPa
	IIW code	63.00 MPa	DNV code	50.00 MPa
Specimen #2	Experimental fitting	65.31 MPa	The 95% survival rate	39.90 MPa
	ABS code	41.51 MPa	DNV code	34.67 MPa
	CCS code	41.51 MPa	GJB code	45.01 MPa
Specimen #3	Experimental fitting	73.90 MPa	The 95% survival rate	43.85 MPa

(a) Weld toe fracture

(b) Weld root fracture

Fig. 8 Macroscopic morphology of fatigue fracture surface of cross joint

is divided into three parts: crack source area, crack growth area, and fracture area. As the initial point of fatigue failure, the crack source area is smooth and fan-shaped, and radiates slowly to the surrounding area, which is relatively smooth. The fracture surface of crack propagation zone is smooth and smooth with convex wavy lines. According to the spacing of corrugated lines, it is obvious that the crack growth velocity near the crack source is faster than that far away from the crack source. The surface of the crack instantaneous fracture zone is rough and uneven, and there is a certain inclination angle with the main section. With the crack propagation, the effective section of the

member is weakened. When the stress reaches the ultimate strength, the cross joint will break instantaneously.

Micro analysis

To observe the micro-failure mode of the fatigue fracture, the fracture surface was scanned by HITACHI SU8010 cold field-emission scanning electron microscope. The micro-fracture morphology is shown in Fig. 9. After high magnification, it is found that the cross-section of the crack source area is relatively flat and smooth, and the crack extends from the core to the surrounding, and there may be multiple crack sources at the same time. There are many arc fatigue bands

Fig. 9 Fatigue fracture morphology of cross joint

protruding forward in the crack growth zone. Due to different crack sources or different crack growth rates, secondary cracks can be observed in some fractures, and the spacing of fatigue bands at the same fracture increases with the increase of crack growth rate. There are many round or ellipse dimples with different sizes in the instantaneous fracture zone, and some dimples also contain inclusions or particles, which indicates that the material fracture is ductile fracture. Moreover, the existence of dimples indicates that the material is not easy to slip in the process of growth, and the rapid growth stage is not enough, which accounts for a small proportion of the fatigue life. Affected by corrosion, the fracture of the specimen contains multiple crack sources (Liu et al. 2021). After the high temperature of the fire, secondary cracks at a certain angle to the fracture can be seen at the fracture of the specimen. The number of dimples is reduced, but the size of the dimples is relatively larger (Zhang et al. 2020).

Fatigue damage analysis

Figure 10 shows the fatigue displacement curve of the specimen SJ4-2, where δ is the displacement variation of the specimen, and n and N represent the number of cycles and fatigue life of the specimen, respectively. It can be seen that the displacement change of the specimen can be divided into two stages. The first stage is the steady-state crack growth stage, and the overall displacement change is small in this stage, which is basically in a stable state, accounting for about 90% of the whole fatigue life. The second stage is the stage of unstable crack growth, and the displacement growth rate is obviously accelerated. With the gradual propagation of the crack, the effective bearing section of the specimen decreases rapidly. Finally, the cross-section stress under the

external cyclic load is greater than the ultimate strength of the material, resulting in instantaneous fracture. The proportion of the instantaneous fracture stage in the fatigue life is very small, indicating that the unstable propagation stage of the crack is not sufficient.

In damage mechanics, as an internal variable, damage is used to represent the deterioration of metal materials. The constitutive equation and evolution equation of metal materials are constituted by the internal variable and load parameters to describe the deterioration process of metal materials (Li 1992). Therefore, the damage can be used to predict the residual life of metal materials, and to replace or dismantle the metal structure with low life, so as to ensure that the metal structure can be used safely during the operation period. For high cycle fatigue, assuming that the damage variable remains constant in a stress cycle, i.e., incremental linear, the cumulative fatigue damage D_f caused by fatigue fringes of fatigue fringes of dimple secondary cracks in a stress cycle is (Lou 1991):

$$D_f = 1 - \left(1 - \frac{N}{N_f}\right)^{1/(\beta+2)} \quad (9)$$

$$N_f = \frac{(\beta + 1)(S_{\max}^{\beta+1} - S_{\min}^{\beta+1})^{-1}}{2B(\beta + 2)}, \quad (10)$$

where B and β are material constants, which can be determined by the fatigue test results; N_f is the fatigue life.

The fitting result of fatigue test shows that $\beta = 2$. According to Eq. (9), the change curve of cumulative damage with cycle ratio is drawn, as shown in Fig. 11. It can be seen that with the increase of N/N_f , the degree of fatigue damage

Fig. 10 Fracture morphology of cross joint

Fig. 11 Fatigue displacement curve

is also increasing, and the increase rate of damage is also increasing continuously, which is consistent with the phenomenon that the fatigue band spacing of micro-fracture increases gradually under high-power microscope. When $0 < N/N_f < 0.9$ is the stage of crack propagation, the D value before fracture of cross joint is about 0.45, and the cumulative damage is large. When $0.9 \leq N/N_f < 1.0$, the increasing rate of D value of cross joint is obviously accelerated, which is the instantaneous breaking stage. This is consistent with the displacement change characteristics of fatigue displacement curve in Fig. 10 at the second stage, which shows that the theoretical results are consistent with the experimental results.

Conclusion

This paper conducted fatigue test research under three working conditions, deeply studied the influence of corrosive media and high temperature of fire on the fatigue performance of Q420qD high-performance steel cross joints, and reached the following conclusions:

1. The fatigue limit value of the cross joint is reduced after being affected by corrosion, and its fatigue limit value is increased after being subjected to the 600 °C high temperature of fire.
2. For the cross joint specimen, the fatigue life without treatment can be well predicted using the design curve of EN code, and there is enough safety reserve; The fitting curve of 95% survival rate in corrosion treatment is not different from that in ABS code and CCS code; The fatigue life of corrosion and fire treatment can be estimated by the design curves of GB code safely, and the fitting curve under 95% survival rate is in good agreement with the design curves of GJB code.
3. Corrosion will increase the source of fatigue cracks. After the 600 °C high temperature of fire, the relative size and number of dimples in the instantaneous failure zone are larger. The fatigue damage analysis results are basically consistent with the change law of the fatigue displacement curve, and conform to the microscopic morphology characteristics of the fatigue fracture.

Acknowledgements The authors are incredibly grateful to the Mechanics Laboratory of East China Jiaotong University for providing a fatigue testing machine.

Author contributions Conceptualization, HGC; investigation and stress test, CH; methodology, CH; data curation, YJ; writing-original draft preparation, CH; writing-review and editing, CH, HGC, and YJ.

Funding This research was funded by the National Natural Science Foundation of China (Grant No. 51368018, 51968024).

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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