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Experimental study on fatigue performance of high strength steel welded joints

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ABSTRACT

The welded joint of steel structure is prone to occur fatigue fracture under dynamic loads. In this paper, an experimental study on the fatigue performance of base material, butt weld, and cross fillet weld of high-strength steels were investigated. The S-N curve was fitted, and the corresponding fatigue life was predicted. Results corroborate that the base material of high-strength steel possess high fatigue resistance. AISC360 and EC3 standard design curves are applicable for the evaluation of the butt weld fatigue performance of Q460D and possess adequate safety margin, but only suitable for low-fatigue life estimation of Q690D butt weld. With respect to cross fillet weld, AISC360 design curve not only is suitable for the fatigue life analysis of Q460D and Q690D but also has enough safety margins, while EC3 and BS7608 codes possess relatively low fatigue limit. In addition, a quantitative analysis on fatigue fracture was conducted on the basis of fatigue damage theory, and the fatigue crack propagation law was disclosed on the basis of fracture morphology. The crack propagation law before instant fracture is consistent with damage development, and the fatigue striation width increases gradually with damage development. The fast crack propagation stage accounts for a small proportion in the fatigue life, thereby indicating that this stage is insufficiently developed.

1. Introduction

As a failure mode of various materials or structures, fatigue fracture occurs in many fields, such as mechanical engineering, aviation, railway, and civil engineering. Under reciprocal load, steel structural failure is mainly caused by fatigue fracture. According to incomplete statistics, approximately 80% of metal structural failures are caused by fatigue. Sudden failure commonly brings catastrophic accidents and causes tremendous economic losses because fatigue fracture exhibits no evident macroscopic plastic deformation [1].

In the fatigue development history, many theoretical and experimental studies have been reported. Researchers propose *S–N* curves and fatigue limit, linear accumulated damage criteria, and stress strength factor [2,3], laying foundations for fatigue life prediction and promoting rapid development of research on fatigue fracture. The final objective of fatigue analysis is to determine the fatigue life of structures or components. However, many influencing factors of fatigue life cannot be comprehensively considered, accurately calculating fatigue life is difficult.

Recently, high-strength steel materials were widely used in practical engineering. They exhibit a great gap with common steel materials in terms of smelting and rolling technology [4], crystalline-phase structure, chemical components, and post-processing techniques [5]. Therefore, high-strength steel materials demonstrate different mechanical properties, fracture toughness, and fatigue performances [6,7]. Chinese and foreign scholars have reported studies on the fatigue performance of high-strength steel materials and asserted that the fatigue performance of welding connection is related to welding process, welding quality, geometric parameter, and steel strength [8]. Kim et al. [9] studied the effects of welding process and quality on the fatigue performance of the butt weld of high-strength steel. They corroborated that an inadequate depth of weld penetration shortens fatigue life, but TIG post-weld treatment can prolong fatigue life. Gustafsson [10] conducted a fatigue test on the cross-welding joint of Domex550MC high-strength steels with different thicknesses and observed that the fatigue life of welding joint is negatively correlated with steel plate thickness. Chen et al. [11] estimated the fatigue life of high-performance steel ASTM A709 (HPS 485W, f_y = 485 MPa) based on stress, strain, and energy methods. They affirmed that the non-welding position of HPS 485 possesses slightly stronger fatigue resistance in a high-

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cycle fatigue zone compared with common steel materials. Pijpers et al. [12] performed a fatigue test on the transverse butt weld of high-strength steels Naxtra M70 (S690, fy = 690 MPa) and Weldox S1100E (S1100, fy = 1100 MPa). The experimental fitting *S–N* curve was compared with the EN1993-1-9 (2005) design curve, and the results verified that the fatigue strength of S690 was slightly higher than the code value, but the fatigue strength of S1100 was greatly higher than the code value. Costa et al. [13] tested the fatigue performance of the welded joint of high-strength steels with 460-690 MPa yield strength and proved that the welded joint of high strength steels exhibited better fatigue performance than common steel materials. The fatigue strength of high-strength steels was higher than the estimated value of EN1993-1-9. Zong et al. [14] tested the fatigue crack propagation rate in WNQ570 bridge steel (yield strength = 420 MPa) and corresponding butt weld and validated that the fatigue crack propagation rate in butt weld was higher than that in base material. Wang et al. [15] reported that the fatigue strength of Q500qE butt weld and cross-fillet weld was slightly higher than that of common steel, indicating that the design based on existing codes was reasonable. Song et al. [16] conducted a fatigue test on the butt weld and fillet weld of high-strength steel (yield strength = 900 MPa). They observed fracture morphology by scanning electron microscope and discovered that the fatigue life of butt weld was significantly higher than that of fillet weld. Weld toe and crack were the primary factors that influence fatigue strength. A thermal cutting technique changes the performance of cutting surface and materials, determining the fatigue performance of a cutting component. The BS7608 code provides a fatigue design curve of an oxy-fuel cutting edge but excludes plasma cutting and a laser cutting techniques. Cicero et al. [17,18] studied the effects of oxy-fuel cutting, plasma cutting, and laser cutting techniques on the fatigue performance of S355M, S460M, S690Q, and S890Q. The BS7608 code design grades of these three thermal cutting techniques were determined through the *S–N* curve and compared with abundant test data for verification. Zong [19] studied the fatigue performances of non-load-carrying fillet through tests and numerical simulation. Test results proved that the Eurocode3 design curve was generally safe and applicable but provided no adequate safety margins. Crack expansion was simulated on the basis of the four assumptions of initial cracks. The line cold lap assumption with an initial value of 0.1 mm can predict average fatigue service well in the test, whereas the I-type line crack assumption with an initial value of 0.1 mm can offer prediction that is consistent with the 95% survival probability of test results. The analysis of fatigue crack propagation by this assumption is suggested. Andrews [20] tested the influences of dislocation quantity on the fatigue strength of cross plate joint.

The weld joint of steel structures easily suffers fatigue fracture under dynamic loads. Studying the fatigue performance of welding structure is extremely important for the safety evaluation of steel structures. In this study, the fatigue performances of base materials, butt weld, and cross fillet weld of Q460D and Q690D were tested, and the *S–N* curves were fitted. The fatigue performances of base materials and welded specimens were compared. The qualitative analysis of fatigue fracture was carried out on the basis of the damage quantity. The crack propagation law was investigated by combining fracture morphology. Moreover, the fatigue characteristics and fatigue life of Q460D and Q690D were evaluated on the basis of the existing codes.

2. Testing arrangement and specimen details

2.1. Specimen design

In this experiment, the 8 mm-thick high-strength steel materials Q460D and Q690D were used as test materials. Three groups of 84 specimens, namely, base material, butt-welded joint, and cross-fillet-welded joint (Table 1), were designed. The full plate thickness sampling method was used. The butt weld adopted “V-shaped” bilateral groove welding, and the surplus seam height was retained after the welding process. A fillet weld are used for the cross joint specimens, and the weld leg size was 5 mm. The specimen dimensions are shown in Fig. 1. The welding rod models of Q460D and Q690D were CHE557RH and CHE857Cr, respectively. Table 2 lists the chemical compositions of steel materials and welding rods. Manual arc welding was accomplished by strictly following specified environmental conditions and the butt weld quality was evaluated as level 1. Tables 3, 4 exhibit the welding parameters and mechanical properties of welding rods.

2.2. Material properties

Material parameters of Q460D and Q690D low-alloy rolling steels were tested according to “Tensile Test of Metal Materials Part I: Experimental Method under Room Temperature” (GB/T 228.1-2010). The stress–strain curves of high-strength steels were tested (Fig. 2). Table 5 lists the corresponding mechanical properties.

2.3. Test setup and loading procedure

This experiment was accomplished on the MTS322 electro-hydraulic servo fatigue tester. Force-controlled loading was adopted, and the loading waveform was a constant amplitude sinusoid. PVC compensation was used, and the loading frequency fluctuated at a range of 20–45 Hz. The stress ratio was set as $R = S_{min}/S_{max} = 0.1$, and the maximum stress level of the fatigue test was determined by the yield strength of specimens(Table 6). Specimens were maintained at an elastic state throughout the experiment, so the maximum stress, S_{max}, was set at $K{\cdot}f_y$, with the initial loading coefficient, K, was 0.6–0.8. The fatigue limit was determined according to the small sample up-and-down method and gradually approached by adjusting the loading coefficient. The experiment was ended upon the presence of anomalies and fractures or upon reaching 2 million times cycle numbers.

3. Theoretical analysis

The *S–N* curve is the basic formula used to describe the fatigue performance of materials or components, as shown in the following:

$$S^m N = C, \tag{1}$$

where S is the nominal stress amplitude of the specimen section, C and m are fatigue parameters that are related to a component type.

By calculating the logarithm at the two sides of Eq. (1), we can obtain the following:

$$\lg N = \lg C - m \lg S. \tag{2}$$

The 95% survival probability can be expressed as follows:

$$\lg N = \lg C - 1.645\sigma - m \lg S. \tag{3}$$

3.1. BS7608

On the bases of linear damage accumulation theory, BS7608 [21] provides a certain amount of fatigue test data of weld joint and is applicable to materials with 200–960 MPa yield strength. The BS7608 standard considers the influences of local stress concentration, weld size, and loading direction on the fatigue strength of weldment. This standard summarizes abundant fatigue test data, provides the fatigue calculation data of multiple welded joint, and effectively supports the fatigue life prediction of different welding structures.

The BS7608 standard divided the welded joint into 13 design classes of B, C, D, E, F, F2, G, G2, W1, X, S_1, S_2, and TJ according to the geometrical shape, possible failure position, welding form, and loading direction of joint. For different design levels, the relationship between stress amplitude (S) and the number of fatigue failures (N) is as follows:

$$\lg N = \lg C_0 - d\sigma - m \lg S, \tag{4}$$

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