Research Article
Constitutive Model and Fracture Criterion of Q345 Steel Welded Joints

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1.Introduction

At present, welding is the most widely used connection method of steel structure, and the welded joint is composed of weld, HAZ, and its adjacent parent metal. There are some problems in welding connection such as weld defects, welding stress, welding deformation, and thermal effect, which will significantly affect the bearing capacity and stability of steel structure, in particular, weld defects, such as unqualified weld overall size and shape, pores, slag inclusions, cracks, undercuts, and weld beading. The mechanical properties of welded joints refer to the comprehensive mechanical properties of weld and HAZ. For some materials such as low-alloy high-strength steel, HAZ is the weak link in the joint, and the joint performance often depends on the mechanical properties of HAZ. What impact this will have on the material properties of the structure is worthy of attention. At the same time, the performance of structural steel in the finite element model is generally involved in the finite element analysis of various steel structure projects, and the accurate input of material parameters is directly related to the accuracy of calculation results. Therefore, according to the characteristics of the weld joint of Q345 welded structure, the influence of BMZ and HAZ weld material stress...
triangularity is discussed, and the constitutive model and fracture criterion of each part of the material are analyzed, so as to provide material basic data for the subsequent finite element numerical analysis and practical engineering application of Q345 steel welded structure.

In the study of the constitutive model of Q345 steel materials, the traditional calculation of true stress and true strain is corrected according to the macrovolume invariance principle, which is quite different from the actual situation, especially the limit value of the maximum plastic deformation part of the sample after necking cannot be truly reflected. Aiming at solving practical problems of true strain and true strain measurement of materials, many scholars have proposed a new method based on optical measurement. For example, Wang et al. [1] established a new constitutive model, high-speed steel Daoming model, to simulate the response of high-speed steel, considering the yield platform and three-stage strength softening; Wang et al. [2] realized the direct measurement of noncontact true stress–true strain through optical measurement and established the calculation model and test system of material true stress and true strain; Yao Di et al. [3] proposed a new method called the TF (test and FEA) method to obtain the whole process’ uniaxial constitutive relationship of materials based on the tensile test of funnel samples and gave the whole process true stress-strain curves of 304 stainless steel, steam turbine blade, and rotor materials; Hoffmann and Vogl [4] measured the true stress-strain curve and normal anisotropy in the tensile test by the optical strain measurement method. It is found that the simulation with improved material characteristics shows better strain distribution than those using conventional material characteristics in high strain regions; Stadler et al. [5] studied the optical measurement of the bending curve of the strip through the camera, which shows that the experimental results of the optical measurement method based on the model are in good agreement with the measurement results of the tensile testing machine, and the test accuracy meets the limit. In view of the advantages of high observation accuracy and good observation effect of section fracture diameter, the tensile test combined with the optical measurement method is used to obtain the mechanical properties of materials.

Second, it is equally important to select a reasonable fracture criterion, especially when studying the response of structures, the failure of materials leads to the damage and fracture behavior of components and structures. A variety of failure criterion models have been embedded in the existing general commercial software, such as constant strain criterion based on engineering, J–C failure model, and so on. Among them, the three-axis strength is an important factor that affects the fracture failure process of materials. In the process of material deformation, it reflects the corresponding relationship with stress state and the degree of constraint of materials, so it is widely applied to many failure criteria. At present, many scholars have carried out failure model test research on a variety of materials with triaxial stress. Bao et al. [6, 7] designed a series of tensile shear compression tests; Brevevik et al. [8] carried out the experiment and simulation of the stress and strain rate of thick steel plate and put forward the fracture criterion and the relationship between failure strain and strain rate; Vining [9] described the type of limit state, gave the experimental results of fracture toughness characteristics, and gave examples of application of reliability theory, risk analysis, and fracture mechanics to solve various application problems. Barik et al. [10] carried out numerical and experimental study on the failure strain and fracture mode during the impact forming process of 1.5 mm thick AA 5052-H32 sheet. Akbari and Asadi [11] welded A356 aluminum pipe by friction stir welding and obtained the best FSW parameters according to the silicon particle size, hardness, and ultimate tensile strength of welded pipe. Zolghadr et al. [12] studied the formation and morphology of thermomechanical-affected zone (TMAZ) in different friction stir welding and processing materials for basic materials of copper, aluminum, and magnesium alloys. In addition, scholars such as Tang et al. [13], Liao et al. [14], Xin et al. [15], Li Z et al. [16], and Bressan et al. [17] have also researched various materials. It can be seen that many scholars have proposed failure models on the relationship between triaxial stress or strain rate and fracture strain. Among them, the J–C fracture model proposed by Johnson and Cook [18] has better integrity in general, and the measured data can better reflect the changes of model parameters, so this model is adopted in this study.

In conclusion, based on the BMZ and HAZ materials extracted from Q345 butt-welded steel plate, a series of round bar specimens designed with different triaxial stress were tested in this study, and the stress distribution was obtained by the optical measurement method, so as to clarify the fracture process and stress change. The constitutive model of Q345 steel, HAZ material, and the values of each parameter in the J–C fracture criterion model are obtained. The innovation of this research is as follows: aiming at the practical problem of material true stress–true strain measurement, the noncontact optical measurement method is adopted, and the whole strain distribution based on spots is measured by a digital or high-speed camera. In this study, the J–C (Johnson–Cook) fracture model based on stress triaxiality factors is applied to obtain fracture strain through experiments, which will provide theoretical guidance and technical reference for the application of steel structure weldment materials in engineering practice.

2. Theoretical Principle

In order to obtain the fracture strain under different triaxial stresses, this section introduces the theoretical calculation principles of triaxial stress $T^*$ and fracture strain $\varepsilon_f$ of notched round bar samples. According to the uniaxial tensile test of the round bar specimen at necking stage before fracture, Bridgman [19] deduced the corresponding relationship between the geometric dimension of the member and the triaxial stress:

$$T^* = \frac{1}{3} + \ln \left( \frac{a^2 + 2aR - r^2}{2aR} \right).$$

(1)
Corresponding to Figure 1, in formula (1), \(a\) is the minimum cross-sectional radius of the necking part of the round bar; \(r\) is the radius value from the center to the outermost edge at the smallest necking section; and \(R\) is the radius of curvature at the position of the smallest necking section.

According to formula (1), \(T^\sigma\) is different when \(r\) is from 0 to \(a\). It is generally considered that the corresponding triaxial stress degree of each specimen is at the radial root center of the minimum cross-section of the notched specimen, that is, when \(r = 0\), it is the maximum:

\[
T^\sigma_{\text{max}} = T^\sigma_{1/3\ln(1+a/2R)}.
\]  

(2)

And the average triaxial stress of the smallest necking cross section can be obtained by integration:

\[
T^\sigma = \frac{1}{\pi a^2} \int_0^a T^\sigma dA = \frac{1}{\pi a} \int_0^a T^\sigma d\pi r^2 = \left(1 + \frac{2R}{a}\right) \ln \left(1 + \frac{a}{2R}\right) - \frac{2}{3}.
\]  

(3)

Strain at fracture, i.e., fracture strain \(\varepsilon_f\):

\[
\varepsilon_f = 2 \ln \left(\frac{d_0}{d_f}\right),
\]  

(4)

where \(d_0\) and \(d\) are the initial diameters and the final diameter of the necking part of the specimen, respectively, representing the average fracture strain of the whole section.

Therefore, according to the design of notch size of round bar specimen, the specimen with triaxial stress range of \(T^\sigma > 1/3\) can be obtained, and the fracture strain with \(T^\sigma > 1/3\) can be obtained by measuring the minimum cross-section diameter of the specimen with the noncontact test.

**3. Experimental Test**

3.1. Test Sample. Three 500*600*14 mm steel plates were cut from the same Q345 steel plate to complete the design and manufacture of all specimens. Butt weld specimens are designed according to the code for welding of steel structures (GB 50661–2011) [20] by FCAW, complete penetration, butt joint, V-shaped groove, and double-sided welding joint G5-BV-2. Arc welding using FCAW is a common alternative to GMAW (gas-shielded metal arc welding). Because of its higher welding efficiency, penetration, better arc stability, and relatively easy welding [21, 22], the plate thickness is 14 mm, the gap at the root of the groove is 3 mm, the blunt edge of the groove is 0 mm, the groove angle is 60°, and the welding position is flat welding. The diameter of the welding wire is 1.2 mm, and the protective gas \(CO_2\) used for welding has a purity requirement greater than 99.5%. The electrode is made of nonalloy flux cored wire CHE507, which has stable low temperature toughness, excellent plasticity, and crack resistance. It is suitable for low-alloy steel Q345. Generally, the heat-affected zone is divided into four areas: overheating zone (width of about 1–3 mm), normalizing zone, partial normalizing zone (width of about 1.2–4.0 mm), and recrystallization zone, the range of which is generally specified as 10–20 mm. In order to consider that the whole sample should have the structure of HAZ and the balance between calculation cost and accuracy should be sought during numerical simulation analysis of building structure, the HAZ material sample is considered to be extracted according to the 20 mm width of the HAZ. As shown in Figure 2, the design test pieces are taken from the corresponding positions in the butt-welding plate of two 200 * 60 * 14 mm thick steel plates and the round bar test pieces belonging to the HAZ and the BMZ, respectively. Two heat-affected zones and two base metal round bar specimens can be taken from each welded steel plate.

3.2. Specimen Design. As shown in Figure 3(a), according to the calculation principle of triaxial stress intensity of specimen in Section 2, a group of smooth round bar specimens B-6-SB (BMZ) and B-6-SH (HAZ) with standard specifications are designed and processed to obtain the constitutive relationship between BMZ and HAZ material. At the same time, different three axes should be taken into consideration to obtain the fracture strain. For this purpose, three sets of size and test pieces of round bar and notched round bar were designed, as shown in Figures 3(b), 3(c), and 3(d). In notched bar specimens, the notch opening radius \(R\) is of two types: 0.5 mm and 2 mm.

![Figure 1: Diagram of the main dimensions at the neck of a Bridgman tension specimen.](image-url)
There are 4 groups of components with specifications and sizes. Each group of materials is divided into base metal and heat affected zone, and each type of component is subject to 3 repeated tests. All sample size designs are summarized in Table 1. Due to the consideration of the comparative test of strain rate considered at the later stage, according to the conditions of high-speed test equipment, the rectangular platform surface was retained on the longer side of the specimen, and the dynamic strain gauges were pasted. The standard thread M12 was machined at both ends of the
clamping end, and the same specimen was used in the test. Figure 4 is the final processing photo of the round bar specimen.

3.3. Measurement of Specimen. In order to obtain reliable data, each type of test piece shall be tested 3 times, and the dimensions of each round bar test piece shall be measured according to the schematic diagram in Figure 3. Before the test, the actual size of each specimen was obtained by measuring, and the average value of each group is summarized in Table 2.

3.4. Test Equipment

3.4.1. Test Device. The working principle of the digital imaging strain analysis and measurement system based on the DIC method is shown in Figure 5. Before the test, spray random speckles on the surface of the sample, which will deform together with the sample during the test. At all stages of loading, a real-time image acquisition of the speckle deformation process on the specimen surface is carried out by means of video camera. In order to avoid reflection, first uniform white matte paint on the sample bottom and then randomly spread black spots on the spray. The photos of some round bar samples treated with speckle in this test are shown in Figure 6.

3.4.2. Loading Equipment. The tensile test of round bar was carried out on the CSS-44100 electronic universal testing machine with the maximum load of 100 KN, as shown in Figure 7. The loading speed of standard specimens B-6-SB and B-6-SH is 2mm/min and that of other round bar specimens is 1 mm/min. The loading strain rate of all specimens can meet the requirement of the static test.

3.4.3. Strain Measurement System. In the experimental test environment, the load is obtained by the material universal testing machine, while the real-time data such as the displacement of gauge section, the minimum cross section diameter, and the displacement changes in X and Y directions of the specimen surface are all obtained by DIC noncontact optical measurement. The VIC-3D strain measurement system is used in this test, which is based on noncontact measurement and is suitable for measuring the three-dimensional deformation and strain distribution of various materials under load, as shown in Figure 7.

By using image processing technology on the Atlas collected by the camera in the experiment, the deformation process of speckle on the sample is analyzed and calculated by computer vision algorithm. As shown in Figure 7, by reconstructing the three-dimensional shape from the 2D images under the two cameras, the three-dimensional coordinate values of scattered points can be accurately calculated. By tracking the three-dimensional reconstruction points, the change of each measurement point of the cross-section can be tracked at any time, so as to accurately calculate the real-time deformation position and displacement value of the sample surface, the local strain change, and the propagation of the whole field strain distribution. Furthermore, this method has been widely used in the research of many scholars, such as Sato et al. [23], Deng et al. [24], Mehrabian and Boukhili [25], Luis et al. [26], and Al-Kamaki [27].

4. Test Results and Analysis

4.1. Strain Distribution Nephogram. The nephogram of stress distribution in axial and transverse direction of each group of specimens during the static tensile test is shown in Figure 8 and Figure 9. Six representative images of each specimen are selected from each deformation stage. Themise stress value with continuous color changes represents the maximum principal stress in the image analysis based on the printed mesh size. Compare the smooth round bar test pieces of the BMZ and the heat-affected zone test pieces, such as the standard round bar test pieces shown in Figure 8(a) and Figure 9(a). The position of the fracture distance closest to the gauge end point can be judged in the posttreatment process, and the actual gauge shift can be carried out according to whether it is greater than $1/3L_g$, so as to accurately measure the gauge distance $L_g$ after fracture.

It can be seen from Figure 8(b) and Figure 9(b) that the fracture position of the base metal member is located at the center of the parallel section, which is different from the
fracture surface position of the heat-affected zone member. From the stress nephogram of the whole process shown in Figures 8 and 9, it can be seen that since the maximum triaxial stress of all notched round bar tensile specimens is at the central root of the minimum diameter; the sudden change of notch edge will lead to stress concentration, the stress change of notch section is the most significant, expanding from near the notch, and finally the maximum strain is at the root of the notch, and the fracture location occurs at the minimum section of the notch.

In summary, the cloud map of the stress distribution change of each group of specimens during the static tensile test process can observe the cross-sectional change of the whole process of loading and judge the final fracture position.

4.2. Stress-Strain Relationship Curve. The engineering stress-strain curves and real stress-strain curves of BMZ and HAZ materials are obtained by tensile tests of standard members B-6-SB and B-6-SH, as shown in Figure 10. Comparing the engineering stress-strain curve with the real stress-strain curve, the former has a yield platform and a descending section, while the latter has no yield platform and shows a monotonic upward trend, and the elongation is significantly greater than the former.

Table 2: Measurement data of round bar specimens.

| No. | Section diameter of specimen, \( D \) (mm) | Diameter of necking section, \( 2a \) (mm) | Average necking section triaxial stress degree |
|-----|---------------------------------|---------------------------------|-------------------------------------------|
| B-6-SB | 5.972 | — | 0.333 |
| B-6-B | 5.964 | — | 0.333 |
| B0.5-6-B | 6.972 | 5.904 | 1.173 |
| B2-6-B | 7.065 | 6.016 | 0.640 |
| B-6-SH | 5.945 | — | 0.333 |
| B-6-H | 5.956 | — | 0.333 |
| B0.5-6-H | 7.117 | 5.953 | 1.178 |
| B2-6-H | 7.094 | 6.036 | 0.641 |

Figure 4: Processing diagram of round bar specimen. (a) B-6-SB. (b) B-6-SH. (c) B-6-B. (d) B-6-H. (e) B2-6-B. (f) B2-6-H. (g) B0.5-6-B. (h) B0.5-6-H.
Through the design of three groups of round bar specimens, the true stress-strain curves with triaxial stress ranging from 0.33 to 1.18 are obtained, as shown in Figure 11. It can be seen from the figure that with the increase of triaxial stress, the yield stress and ultimate stress of BMZ and HAZ material increase and the elongation decreases. The strain and stress at the moment of fracture can be judged from the development trend of the curve, and the strain corresponding to the maximum stress position is the fracture strain.

Comparing the BMZ and HAZ material under the same triaxial stress, it can be seen that the B-6-H ($T^\sigma = 0.33$) and B2-6-H ($T^\sigma = 0.64$) of HAZ material correspond to the base metal B-6-B and B2-6-B, respectively, and the elongation of base metal is higher than that of HAZ material; while, the elongation of HAZ material is higher when $T^\sigma = 1.18$ (B0.5-6-B and B0.5-6-H). In addition, the ultimate stress of the two materials is more sensitive than the yield stress. When the triaxial stress is different, the ultimate stress of the two materials shows obvious differences. The yield stress of the two materials is close to the yield stress when $T^\sigma$ is 0.64 and 1.18, except that the yield stress of the HAZ material increases when $T^\sigma = 0.33$.

In summary, the true stress-strain curve is obviously different from the engineering stress-strain curve, and the true stress-strain curve can capture the strain value when the material is fractured.

4.3. Constitutive Model. An ideal constitutive model can relate a series of real state variables in materials with continuous response. At present, many scholars have put forward some typical and widely used constitutive models, such as the B–P (Bodner and Partom) model [28], J–C (Johnson and Cook) model [29], and Z–A (Zerilli and Armstrong) model [30, 31]. In this study, the J–C constitutive model is an empirical constitutive model established by Johnson and Cook in 1983. It is simple in form and takes account of the factors, such as strain, temperature, and strain rate. The expressions (without considering strain rate effect and temperature softening effect) are as follows:

$$\sigma_s = A + B\varepsilon_{eq}^n$$  \hspace{1cm} (5)

where $\sigma_s$ is the static stress at room temperature; $\varepsilon_{eq}$ is the equivalent strain; $A$ is the yield strength; and $B, n$ are the strain hardening coefficients.

There are three undetermined empirical parameters $A, B, n$ in the model, which can be obtained by experiments.
Figure 8: Continued.
Figure 8: The stress nephogram distribution of BMZ specimens. (a) B-6-SB. (b) B-6-B. (c) B2-6-B. (d) B0.5-6-B.

Figure 9: Continued.
It is easy to obtain and is widely used. In this study, the J–C constitutive model will be used to determine the parameters of Q345 steel BMZ and HAZ material. The true stress-strain curves of standard tensile members of BMZ and HAZ material and the J–C material model curve fitted by the least square method are shown in Figure 12.

The fitting formula (6) is obtained for the B-6-SB base metal bar specimen. When the constitutive parameters $A$, $B$, and $n$ are 379.80, 452.89, and 0.37, respectively, the fitting curves are in good agreement with the experimental results. Similarly, the fitting curves of the B-6-SH heat-affected zone round bar specimen when the constitutive parameters $A$, $B$, ...
and $n$ are 392.90, 540.61, and 0.49 are in good agreement with the experimental results. The fitting formula (7) shows that the goodness of fit is 0.991 and 0.998, respectively.

$$
\sigma_{sB} = 379.8 + 452.89 \varepsilon_{eq}^{0.37},
$$

$$
\sigma_{sH} = 392.9 + 540.61 \varepsilon_{eq}^{0.49}.
$$

In summary, based on the test results of the material's true stress and strain, the J–C constitutive model was used to determine the constitutive parameters of the Q345 BMZ and HAZ material.

4.4. Fracture Criterion. For the failure criterion of materials, many scholars have proposed the model of the relationship between triaxial stress or strain rate and fracture strain. Among these failure models, the J–C fracture model has better integrity on the whole, and the corresponding parameters can be obtained only through experimental measurement, so it is widely used. The expression is as follows:

$$
\varepsilon_f = D_1 + D_2 \exp(D_3 T^n).
$$

The influence of strain rate and temperature effect is not considered in formula (8), and the three parameters $D_1$, $D_2$, and $D_3$.
and $D_3$ can be quantified by the experimental test. According to the same triaxial stress component, three repeated tests were carried out, and the actually measured triaxial stresses of these three components were averaged. According to the three real stress-strain curves obtained from the tests, the real fracture strains were also averaged. Finally, the fracture strains under different triaxial stresses were obtained and are summarized in Table 3.

According to the test results in Table 3, the test points of fracture strain and triaxial stress of Q345 BMZ and HAZ material are shown in Figure 13, and the J–C fracture model is fitted by the least square method. For Q345 BMZ material, when $D_1 = 1.025$, $D_2 = -0.008$, and $D_3 = 3.617$, the fitting curve is in good agreement with the experimental results, and the fitting formula is shown in equation (9); for HAZ materials, when $D_1 = 0.678$, $D_2 = -2.689E - 5$, and $D_3 = 7.683$, the fitting formula is shown in equation (10).

$$\varepsilon_{fB} = 1.025 - 0.008 \exp\left(3.671T^\sigma\right), \quad (9)$$

$$\varepsilon_{fH} = 0.678 - 2.689E - 5 \exp(7.683T^\sigma). \quad (10)$$

In summary, based on the actual fracture strain at each triaxial stress degree in the experimental results, the J–C fracture model was used to determine the fracture model parameters of the Q345 BMZ and HAZ material.

### Table 3: Fracture strain of base metal and heat-affected zone specimens.

| No.     | $T^\sigma$ | $\varepsilon_f$ | BMZ          | No.     | $T^\sigma$ | $\varepsilon_f$ | HAZ          |
|---------|------------|-----------------|--------------|---------|------------|-----------------|--------------|
| B-6-B   | 0.333      | 0.998           | B-6-H        | 0.333   | 0.678      |                 |              |
| B2-6-B  | 0.64       | 0.937           | B2-6-H       | 0.641   | 0.673      |                 |              |
| B0.5-6-B| 1.173      | 0.442           | B0.5-6-H     | 1.178   | 0.449      |                 |              |

5. Conclusion

In this study, a series of static loading experiments on Q345 steel butt weldment materials are carried out by DIC technology, and the whole process of three-dimensional deformation and strain distribution of the two materials under load is obtained. The conclusions of this study can be summarized as follows [15, 24, 29]:

1. The maximum three-axis strength is located at the center root of the minimum diameter of the notched circular bar tensile specimen. The stress change of the notch edge will appear as stress concentration. The stress change of notched section is most significant. It begins to expand near the notch. The maximum strain is located at the root of the notch, and the fracture position appears at the smallest section of the notch.

2. The true stress-strain relationship curves of base metal and HAZ material in Q345 steel butt weldment are obtained, and the parameters fitting the J–C constitutive model are obtained. For the base metal, the constitutive model parameters A, B, and $n$ are 379.80, 452.89, and 0.37, respectively. For heat-affected zone materials, the constitutive model parameters A, B, and $n$ are 392.90, 540.61, and 0.49, respectively.
(3) The fracture failure strains of Q345 base metal and HAZ material under different triaxial stresses were measured, and the failure criterion parameters fitting the J–C fracture model were obtained. For Q345 base metal, J–C fracture model parameter values are $D_1 = 1.025$, $D_2 = -0.008$, and $D_3 = 3.617$; for heat-affected zone materials, J–C fracture model parameter values are $D_1 = 0.678$, $D_2 = -2.689E-5$, and $D_3 = 7.683$.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Additional Points**

Safety reserve is usually considered in the design of bearing capacity of building structures, so the ductile fracture of steel structure materials is often not considered as a key consideration. However, for engineering problems characterized by fracture, such as the essence of structural continuous collapse, it is often the further expansion and spread of local failure caused by the failure of key component materials. In steel structure engineering, the structural load transfer path and collapse failure mechanism caused by building structural steel fracture will change. Therefore, the research on the ductile fracture of building steel is very important. At present, scholars have proposed a large number of fracture models from different theoretical basis and application background. Whether these models can be applied to building structural steel and how to select the appropriate fracture model in practice is a problem to be solved. Determine the fracture model and model parameters used for building structural steel Q345, provide a refined finite element model considering material failure for structural numerical analysis, and provide basic data for evaluating and designing the continuous collapse resistance of building structures.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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