Experimental and Numerical Investigation on Global Buckling of Q690 High Strength Steel Tubes under Axial Compression

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Abstract. Due to the excellent bearing capacity, high-strength steel (yield stress ≥ 460 MPa) is gradually utilized in the design of super high-rise buildings, long-span bridges and other important structures to reduce section size and self-weight. In the present study, the axial compression test and numerical simulation were carried out to investigate the global buckling of high strength steel tubes. Eighteen specimens of Q690 high strength circular steel welded tubes were tested under axial compression to obtain the ultimate bearing capacity and buckling mode. An effective finite element numerical model incorporating the residual stress and geometric imperfection was established to analyse the influence of slenderness ratio, diameter thickness ratio and residual stress on the global stability coefficient. According to the calculation results, the column curve of Q690 circular steel tube was obtained and compared with three different codes. Finally, a formula to calculate the global stability coefficient of Q690 welded circular steel tubes was suggested.

1. Introduction

High-strength steel, as its name implies, has higher yield stress and bearing capacity per unit area section than ordinary steel. The application of high strength steel in engineering not only reduces the section size of components and the weight of structures, but also decreases the size of weld seams, providing the excellent anti-fatigue performance for engineering life of structures. Correspondingly, the demand of welding materials and welding manpower is lessened. At the same time, it can reduce workloads of coating, processing, installation, and transportation, bringing both high efficiency and considerable economic benefits to the engineering [1-2].

However, the reduction of section of members due to the employment of high-strength steel may inevitably have adverse effects on the stability of the structure, and the members under compression are more likely to suffer from buckling damage [3-4]. Therefore, it is crucial to investigate the buckling failure mode and stability performance of high strength steel. At present, some scholars have studied this aspect [5-8]. According to the different slenderness ratio of components, the stability failure can be divided into global instability and local instability. This paper mainly focuses on the global instability of Q690 welded circular steel tubes, conducting both experimental study and numerical simulation to study observe the failure modes of members under axial compression and analyse the influence of key factors.
2. Experimental Study

2.1. Material Properties
In order to determine the basic mechanical properties of materials, including yield strength, Poisson’s ratio, tensile strength and modulus of elasticity, a coupon tension test was conducted following the guidelines of GB/T 228-2010 and GB/T 22315-2008. A total of 6 specimens were processed and the geometric dimensions of the specimens are shown in figure 1. To measure strain, the CML-1H strain-force tester was used and bidirectional strain gauges were mounted on the middle part of each specimen. The tests were operated in the M-4100 electronic universal testing machine with a load capacity of 100 kN applying constant grip displacement rate of 1.0 mm/min. The average mechanical properties of the 6 specimens are presented in table 1. The yield strength is determined by the stress corresponding to the residual strain of 0.2% after unloading.

![Figure 1. Tensile specimen dimensions.](image)

Table 1. Average measured mechanical properties of material.

| Mechanical properties       | Value  |
|-----------------------------|--------|
| Modulus of elasticity       | 196.1 GPa |
| Yield strength              | 740 MPa |
| Ultimate strength           | 880 MPa |
| Poisson’s ratio             | 0.2350 |

2.2. Global Buckling Axial Compression Test of Q690 Steel
For researching the global stability bearing capacity of Q690 steel tubes, the global buckling axial compression test was conducted and six groups of specimens (eighteen Q690 steel tubes) were tested.

2.2.1. Preparation. The cross-section specification of specimens was 140*6, i.e., the outer diameter was 140 mm and the wall thickness was 6 mm. The slenderness ratios were designed to be 30, 35, 40, 45, 50 and there were 3 same specimens in each group. The machine used in the axial compression test was YAW-5000F electro-hydraulic servo pressure testing machine with a load capacity of 5000kN. Two knife-hinged supports were set to simulate the constraints, which were hinged at both ends of the specimens. Arranging strain gauges linked to the SDY2206 static resistance strain indicator on specimens to measure strain. Displacement meters were used to measure both transverse and radial deformations. Before the test, a theodolite was used to center the specimens.

2.2.2. Test Results. The global instability of all eighteen specimens was obvious and the failure bending occurred almost in the middle part for each specimen. The typical failure form is shown in figure 2. The load-displacement curves of specimens with different slenderness ratios are drawn on one graph for comparison, as shown in figure 3.

According to the results, the ultimate bearing capacity decreases with the increase of slenderness ratio. To compare with design codes, the ultimate bearing capacities given by both Chinese and American codes (GB50017-2017 and ASCE/SEI 48-05) are calculated. According to the results, the
ultimate bearing capacity of specimens with different slenderness ratios is higher than that calculated by GB50017-2017, which indicates that to design Q690 steel members under axial compression according to GB50017-2017 is conservative. While the test results are very close to the calculated values of ASCE/SEI 48-05.

Figure 2. The typical failure form for different slenderness ratio (30, 35, 40, 45, 50, 60).

Figure 3. The load-displacement curves of specimens with different slenderness ratios.

3. Numerical Analysis of Global Buckling of Q690 Welded Circular Steel Tubes

3.1. Simulation Approach

3.1.1. Basic Finite Element Model and Boundary Conditions. In order to facilitate verification, a finite element model corresponding to the test specimens was established in the ANSYS finite element software. In this model, 8-node SOLIDE45 solid element was used which is suitable for inputting initial residual stress and has the ability of plasticity, large deformation and large strain. In the global buckling axial compression test, both ends of the specimens were hinged by knife hinge supports, while in ANSYS finite element software the hinged connection was achieved by setting the coupling nodes. First, two reference notes were set at the center of the section at both ends of the model. Then all 6 degrees of freedom of all nodes on sections at the upper and lower ends were coupled to their respective reference nodes using the connection element MPC184. At this time, the relative displacements of each node on the both end sections were restrained. Finally, the hinged connection was achieved by constraining the displacement in the x and y directions and the rotation about the Z axis at the top section, and the displacement in three directions and the rotation about the Z axis at the bottom one.

3.1.2. Initial Imperfections. Since the steel will inevitably produce more or less initial bending in processing and transportation, the model took 1/1000 of the length of the specimen as the initial bending amplitude. In addition, there are residual stresses in the butt weld of steel tubes, both longitudinal and lateral. The residual stress has an adverse effect on the stiffness of members, thus affecting the ultimate bearing capacity. In this paper, the residual stress distribution model was adopted according to W. F. Chen and D. A. Ross’s model [9] and applied at the Gauss integral points of the specimens in the finite element model.

3.1.3. Verification of Finite Element Model. The calculation results of the finite element model considering initial bending and residual stress were compared with the experimental specimens in
terms of failure form and ultimate bearing capacity. The contrasts are shown in figure 4 and table 2. Comparisons show that the calculated results of the model are in good agreement with the experimental results, which proves that the finite element model has considerable accuracy and reliability.

![Figure 4. Comparison of failure form between test and model.](image)

**Table 2.** Comparison of ultimate bearing capacity between test and model.

| Specimen  | Experimental average value (kN) | Model calculated value (kN) | Error  |
|-----------|--------------------------------|-----------------------------|--------|
| 140×6-λ30 | 1749                           | 1769                        | 1.15%  |
| 140×6-λ35 | 1690                           | 1722                        | 1.88%  |
| 140×6-λ40 | 1647                           | 1672                        | 1.14%  |
| 140×6-λ45 | 1437                           | 1584                        | 1.03%  |
| 140×6-λ50 | 1428                           | 1460                        | 2.25%  |
| 140×6-λ60 | 1264                           | 1160                        | -8.24% |

### 3.2. Analysis of Factors Affecting the Global Instability and Ultimate Bearing Capacity

This subsection is based on the ANSYS finite element model in the previous subsection. By modifying the parameters, twenty different finite element calculations were carried out for the circular steel tubes of different slenderness ratios and section sizes, considering residual stress and no residual stress, to study the effects of residual stress, slenderness ratio and diameter thickness ratio of the global stability of high strength steel. To put it clearly, all specimens were divided into the following three groups, as shown in table 3.

#### 3.2.1. Effect of Residual Stress

In order to study the effect of residual stress on global stability, the results of the first and third groups were compared. By comparing the displacements, it is found that the deformation degree of the specimens without residual stress is almost the same as that of the specimens with residual stress. In the aspect of ultimate bearing capacity, although the residual stress reduces the ultimate bearing capacity of Q690 circular steel tube members, the maximum reduction percentage is 0.79%, which is almost negligible. Therefore, the residual stress has little effect on the global stability of Q690 high strength circular steel tubes.

#### 3.2.2. Effect of Section Size (Diameter-thickness Ratio)

In order to study the influence of section size (diameter-thickness ratio) on global instability and ultimate bearing capacity, the second group of specimens were calculated. The load-displacement curves of the specimens were drawn together as shown in figure 5. The results show that the maximum axial displacement of 120×6-sdr20-N is 5.7
mm, while the maximum axial displacement of the other three specimens is 11.8 mm, 11.6 mm and 11.8 mm, which is about 6 mm larger than that of 120*6-sdr20-N. According to the load-displacement curve, unstable bifurcation buckling occurred in all 4 specimens. The bearing capacity of 120*6-sdr20-N is lower than that of 240*6-sdr40-N, which indicates that as the outer diameter get larger, the bearing capacity get larger. The bearing capacity of the last three specimens decreases in turn, which indicates that the smaller the diameter thickness is, the smaller the bearing capacity is. Although 240*4-sdr60-N and 140*6-sdr40-N (in Group 3) have the same diameter-thickness ratio, their bearing capacity is quite different (1791.52kN and 1678.09, see table 3). From the above conclusions, it can be inferred that the ultimate bearing capacity is affected by the size of outer diameter and thickness of diameter, rather than only by the ratio of diameter to thickness. In order to study the influence of diameter-thickness ratio on the stability coefficient, the global stability coefficients of the 4 specimens were calculated by using the formula \( \phi = \frac{N}{f_A} \). It is found that there is almost no difference among the calculated values. Therefore, it is concluded that the ratio of diameter to thickness has little effect on the global stability coefficient of high strength circular steel tubes.

Table 3. All specimens with different parameters in 5 groups.

| Specimen     | Group | Section size | Diameter thickness ratio | Slenderness ratio | Residual stress | Ultimate bearing capacity (kN) |
|--------------|-------|--------------|--------------------------|-------------------|----------------|-------------------------------|
| 140x6-l30-A  | 1     | 140*6 60    | 30                       | Applied           | 1826.0         |
| 140x6-l35-A  | 1     | 140*6 60    | 35                       | Applied           | 1817.0         |
| 140x6-l40-A  | 1     | 140*6 60    | 40                       | Applied           | 1813.0         |
| 140x6-l45-A  | 1     | 140*6 60    | 45                       | Applied           | 1802.7         |
| 140x6-l50-A  | 1     | 140*6 60    | 50                       | Applied           | 1792.8         |
| 140x6-l60-A  | 1     | 140*6 60    | 60                       | Applied           | 1768.8         |
| 120x6-sdr20-N| 2     | 120*6 20    | 40                       | Not applied       | 1426.95        |
| 240x6-sdr40-N| 2     | 240*6 40    | 40                       | Not applied       | 2922.02        |
| 240x4-sdr60-N| 2     | 240*4 60    | 40                       | Not applied       | 1971.52        |
| 240x3-sdr80-N| 2     | 240*3 80    | 40                       | Not applied       | 1481.71        |
| 140x6-l30-N  | 3     | 140*6 60    | 30                       | Not applied       | 1776.10        |
| 140x6-l35-N  | 3     | 140*6 60    | 35                       | Not applied       | 1735.58        |
| 140x6-l40-N  | 3     | 140*6 60    | 40                       | Not applied       | 1678.09        |
| 140x6-l45-N  | 3     | 140*6 60    | 45                       | Not applied       | 1586.73        |
| 140x6-l50-N  | 3     | 140*6 60    | 50                       | Not applied       | 1465.80        |
| 140x6-l60-N  | 3     | 140*6 60    | 60                       | Not applied       | 1157.47        |
| 140x6-l80-N  | 3     | 140*6 60    | 80                       | Not applied       | 705.821        |
| 140x6-l100-N | 3     | 140*6 60    | 100                      | Not applied       | 462.472        |
| 140x6-l120-N | 3     | 140*6 60    | 120                      | Not applied       | 323.193        |
| 140x6-l140-N | 3     | 140*6 60    | 140                      | Not applied       | 240.347        |

3.2.3. Effect of Slenderness Ratio. In order to study the influence of slenderness ratio on global stability, the third group of specimens were calculated. The axial displacement of the specimens with slenderness ratio of 30 to 140 increases from 5.27 mm to 218 mm, which means that the global instability becomes more and more obvious. The load-displacement curves of the specimens were drawn together as shown in figure 6. The ultimate bearing capacity of the specimens was listed and compared in table 3. It is obvious that the ultimate bearing capacity decreases with the increase of slenderness ratio. The global stability coefficients were also calculated. The larger the slenderness ratio is (from 30 to 140), the smaller the global stability coefficient is (from 0.951 to 0.129
correspondingly). Therefore, it can be clearly concluded that the slenderness ratio has a significant impact on the global stability of Q690 circular steel tube.

4. Design Method

4.1. Contrast of Codes of Different Countries for Global Stability Coefficient of Q690 Welded Circular Steel Tube

After regularization of slenderness ratio, the column curves of Q690 circular steel tube were fitted from the data calculated before. The overall stability coefficients of 10 members with slenderness ratio of 30, 35, 40, 45, 50, 60, 80, 100, 120 and 140 were calculated respectively by using Chinese code (GB50017-2017), American code (ANSI/AISC 360-16) and European code (Eurocode3). The column curves were fitted from the result and compared in figure 7.

![Figure 5. The effect of diameter-thickness ratio.](image)

![Figure 6. The effect of slenderness ratio.](image)

From the comparison of figure 7, it can be clearly seen that the column curves obtained in this paper are all above the column curves of different codes. The stability coefficient obtained in this paper is 13.40% higher than that calculated by GB50017-2017, 11.68% higher than that calculated by ANSI/AISC 360-16, and 28.16% higher than that calculated by Eurocode3. This means that the design of global stability of Q690 welded circular steel tube is conservative.

![Figure 7. The column curves obtained in this paper and calculated by 3 different Codes.](image)

4.2. A New Calculation Formula

According to the column curve of Q690 welded circular steel tube in figure 7, a new formula for calculating the global stability coefficient of Q690 welded circular steel tube was fitted and proposed:
\[ \varphi = \alpha_1 + \frac{2}{\pi} \alpha_2 \left[ \frac{\alpha_3}{4(\lambda_n - \alpha_2)^2} + \frac{\alpha_4}{4(\lambda_n - \alpha_2)^2} \right] \] (when \( \lambda_n \geq 0.587 \))

In the formula, \( \alpha_1 = 0.02406 \); \( \alpha_2 = 2.18977 \); \( \alpha_3 = 1.51336 \); \( \alpha_4 = 0.61814 \).

5. Conclusions
Eighteen Q690 welded circular steel tubes with slenderness ratio from 30 to 60 were tested under axial compression in the global stability test. The failure bending occurred in the middle of the members which is the typical failure of global bulkling. The ultimate bearing capacity and load-displacement curve were obtained. An effective finite element numerical model was established in ANSYS and well verified. 26 specimens of Q690 circular steel tube with different parameters were calculated by the model. The effects of residual stress, section size and slenderness ratio on the global stability of Q690 circular steel tube were analyzed. According to the results, it is found that residual stress has little effect on the global stability; diameter-thickness ratio can influence ultimate bearing capacity but has little effect on global stability coefficient of Q690 circular steel tube under axial compression; the slenderness ratio has a significant impact on global stability: as the slenderness ratio gets larger, the global stability coefficient gets smaller. The column curve of Q690 circular steel tube was obtained and compared with three different codes. The comparison indicated that GB50017-2017, ANSI/AISC 360-16 and Eurocode3 are all conservative in the design of Q690 welded circular steel tube. Finally, a new formula for calculating the global stability coefficient of Q690 welded circular steel tube was suggested.

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