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Experimental study and parametric analysis on the stability behavior of 7A04 high-strength aluminum alloy angle columns under axial compression

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ABSTRACT

An experimental program including study has been conducted to investigate buckling behavior of 7A04 high-strength (HS) aluminum alloy columns under axial compression, in which 42 L-shaped extruded specimens were designed and tested. The specimens involved two sections and seven slenderness ratios varying from 15 to 100. The test results were compared with design results in accordance with American Aluminum Design Manual, GB 50429-2007 and Eurocode 9. A finite element (FE) model of the tested specimens under axial compression has been developed by using general finite element software ANSYS, and was verified by using the test results reported herein and other experimental results presented in the literature. By using this FE model, an extensive body of parametric analyses were conducted to clarify the effects of width-to-thickness ratio of angle legs, initial imperfections and material strengths on the buckling resistance of the 7A04 angle columns. Based on the test and FE analyses results, a modified design method was proposed for predicting the buckling resistance of 7A04 high-strength aluminum alloy columns more accurately.

1. Introduction

There has been a wider application of aluminum alloy in engineering structures due to its light weight, high strength, good corrosion resistance and visual effect, especially in the area of bridges, large span grid structures and reticulated shell structures. It is shown by Eurocode 9 [1] that the ultimate strength of all types of aluminum alloy is no more than 350 MPa, close to 235 MPa steel. However, with the rapid development of high-rise buildings, large-span structures and special structures, the 5000 series aluminum alloy and 6000 series aluminum alloy, commonly used in engineering structures, cannot meet the demand of strength gradually, and the improvement of the structural material strength is becoming an urgent need.

7A04 (7075 in American codes) aluminum alloy is Al-Zn-Mg-Cu series HS ultra-hard aluminum alloy, which can be hardened by heat treatment and has been widely used in aerospace engineering and automobile industry. The nominal yield strength of 7A04 aluminum alloy is about 530 MPa, close to 460 MPa HS steel. According to the research [2], the density of it is 2.85 g/cm^3, about 1/3 of the steel's.

The research of 7A04 aluminum alloy is quite mature in the aspect of material, like its mechanical property and smelting technology, yet is still quite immature in terms of its structure or members in structure engineering. It seems that the only research of HS aluminum alloy structures and members was on 6082-T6 aluminum alloy [3–5], whose ultimate strength is 330 MPa, far from that of 7A04 aluminum alloy.

The lacking in the research on the constitutive relation of 7A04 aluminum alloy and its stability behavior, has greatly restricted the application and development of HS aluminum. The Young's modulus of HS aluminum is 70,000 MPa, which is 1/3 of the steel's, which leads to prominent stability problem. Therefore, through 42 extruded specimens, this paper conducted a series of experiments on the stability behavior of 7A04 HS aluminum alloy angle columns under axial compression, and developed a corresponding FE model. The FE model was verified against the corresponding experimental results and those available in the literature. By the FE model, a comprehensive parametric analysis was carried out to investigate the effects of width-to-thickness ratio of angle legs, material strength and initial geometric imperfection on the loading capacity of the angle columns. The test results and the FE results are compared with design results in accordance with American Aluminum Design Manual, China's national standard and Eurocode 9 for design of aluminum structures.

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2. Test program

2.1. Test specimens

In total, 42 7A04 HS aluminum alloy angle columns, including 2 different sections (L110 × 8 and L90 × 8) and 7 different slenderness ratios ($\lambda_{y0\text{-}y0}$ = 15, 30, 40, 50, 60, 80 and 100) were tested under axial compression. There are three identical specimens of each slenderness ratio. Fig. 1 is the schematic diagram of the angle section. All of the test specimens were extruded and the heat treatment condition is T6.

The measured dimensions of the specimens are summarized in Table 1. *L* is the longitudinal length of the column, which is the average length of three edges; *w* is the width of the section, which is the average width of the midspan section and two end sections; *t* is the thickness of the section, which is the average thickness of the midspan section and two end sections. The specimens were labeled by the dimensions. For example, the label L110-80-2 defines a column of L-shaped section with nominal section width of 110 mm and nominal slenderness ratio of 80, “2” is the serial number of the same specimens. Two end sections of the column were polished through finish machining in order to attach closely to the loading bearing plates.

2.2. Initial geometric imperfections

The extrusion forming could reduce the initial geometric imperfections of the aluminum specimens [6], however, the angle column wasn't ideal. The initial geometric imperfections of the column have an influence on the stability resistance of the specimens. In order to analyze the influence of the imperfection, the paper measured the initial geometric imperfection of the 42 specimens.

Method proposed in our patent [7] was taken to measure the imperfections, using optical theodolite and vernier caliper. Fig. 2 is the schematic diagram of measuring initial geometrical imperfections. In the Fig., “1” is 7A04 HS aluminum angle column, “2” is optical theodolite, “3” is vernier caliper and “4” is the intersection point of the cross hair. Fig. 3 is the measuring site.

The measurement procedure is as follows: **1)** Fix the optical theodolite on the tripod and then levelling. **2)** Fix the vertical axis of the optical theodolite and rotate the horizontal axis. **3)** Move the vernier caliper until the measure-hand coincide with the intersection point of the cross hair, take the scale as the distance (d^*) between the edge of column and the line of sight. **4)** Take 3 points (two end sections and middle section) on the edge as the measure points, and derive the distance (d^*) of each measure point. **5)** Calculate the distance (d_1, d_2, d_3 and d_4) between the measure point of the middle section and the line of two measure points in the end sections by geometric relationship. The distance (d_1, d_2, d_3 and d_4) is the initial geometric imperfection. Fig. 4 is the distribution of imperfection in the angle section and in the column. The measured imperfection is listed in Table 2. It can be found from the table that, the imperfection includes two kinds: bow imperfection and eccentric imperfection. The research [8,9] showed that, the residual stress in aluminum alloy extruded members could be neglected. So the residual stress wasn't measured in the tests.

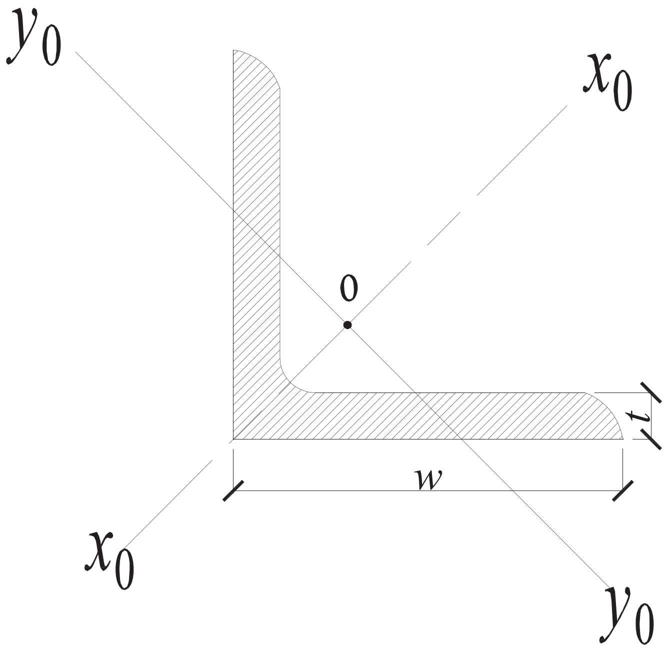

Fig. 1. Schematic diagram of angle column.

2.3. Material properties

The material properties of 7A04 HS aluminum alloy are determined by static uniaxial tension experiment. Eight material specimens taken from columns with two different sections (L110 × 8 and L90 × 8) along its length divided into two groups and each group had four specimens. The dimension of the material specimens is shown in Fig. 5. The static uniaxial tension experiment was conducted by hydraulic universal testing machine (Fig. 6).

During the tests, material specimens tension hardly caused necking, the specimens' failure process was very sudden with a loud sound. The fracture surface was very rough and the material specimens after tensile failure is shown in Fig. 7. All of the material properties is summarized in Table 3 in which f_u is the ultimate strength, $f_{0.2}$ is the nominal yield strength, E is the elastic modulus and ε_u is the ultimate strain. Eight stress-strain curves are plotted in Fig. 8.

2.4. Test configuration

All of the angle columns, except the column with the slenderness ratio of 15, were tested between pinned end bearing by YES-500 hydraulic compression testing machine with a maximum load of 5000 kN. There were two spherical hinges on both ends of the testing machines. In order to check the flexibility of the spherical hinges, two specimens (L110-100-1 and L110-80-1) were tested with the spherical hinges first. However, the spherical hinges almost didn't rotate during the process until the failure of the angle columns occurred and the stability resistance of the angle columns was much higher than prediction. So these spherical hinges couldn't meet the ideal hinged condition. Therefore, a pair of single knife-edge bearing was placed between the spherical hinges and loading bearing plates. According to the previous research [10], although the angle section is monosymmetrical, the single knife-edge bearing can achieve the same effect as the double knife-edge bearing to provide ideal hinged condition. Fig. 9a is the test set-up.

In order to ensure the effective constraint of the end sections and avoid local buckling in the end sections, two end plates were placed. Usually, we connect ear plates with steel plate by spot welding to make end plates in the research [11]. However, this kind of end plate should be replaced after each test, wasting time and material. To optimize the end plates, we invented a patent “an adjustable device fixing equal leg angle column precisely in structural experiment” [12] which was used in the tests. Fig. 10 is the picture of the end plate. The end plate consisted of bottom