Experiment and finite element analysis study on the deflection of aluminum extruded 6063-T5 hollow structural beam

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Abstract. In this study, the tensile tests were performed on samples extruded from aluminum beam to confirm the material properties of the various parts. Then, the beam was cut into lengths of 1160 mm and 680 mm to perform the bending test, and the beam loading point deformation was recorded. At the same time, the amount of beam deformation caused by three type beam fixing methods was compared. The Solidwork 3D CAD software used to build the beam model and perform finite element analysis. Among them, the analysis results of different boundary conditions were compared with the experimental results. The experimental load conditions were used to calculate the theoretical deformation formula amount through the beam theory deformation formula of material mechanics. It is to compare beam deformation data of experiments, finite element analysis, and theoretical formulas, and explore possible causes of differences.

1. Introduction

The aluminum alloy material is a kind of green metal, which can be recycled and remanufactured. Although the aluminum alloy strength is smaller than that of the steel material, the same volume is lighter than the iron metal and corrosion-resistant, so it is widely used in the aerospace and vehicle industries. Since 1950, aluminum extrusion molding technology has made significant progress in mold design and process precision due to high productivity and low-cost requirements. The development trend of aluminum alloy extrusion technology can be divided into two directions: "high strength" and "high precision." How to improve the precision of products, and thus improve their efficiency, or achieve high-quality and high-strength, has been regarded as one of the foremost research topics. High-precision aluminum alloy extrusion products, the main appeal is that the performance of the extruded product can be improved. From the beginning to the end of the extrusion, the yield of extruded products can reach more than 90%, and the dimensional accuracy and material quality of the head, middle and tail materials need to be uniform. The hollow extruded aluminum beam product has a standardized appearance, interchangeable end face dimensions, and standard cross-sectional dimensions of various lengths. The inner section of the hollow aluminum forming beam is designed with reinforcing ribs to meet the high rigidity requirement. The shape of the rib is directly related to the structural strength and the high
efficiency of material use, and the purpose is to achieve the highest rigidity with a minimum material cost.

About beam deformation and experimental research, Wang and his coworker[1] studied large deformation cantilever beam under point load at the free tip. They investigated a homotopy analytic method (HAM) to calculate the vertical and horizontal displacements of a cantilever beam with large deformation. Cruz [2] used large geometric deformations and assuming a Galerkin approach to model gas turbine fans, wind turbine blades, springboards dynamic behavior. Lee [3] had researched the elastic and buckling loads of the nonlinear elastic tapered cantilever columns subjected to an axial load at the free end. Lee [4] obtained a numerical solution by using Butcher’s fifth-order Runge–Kutta method and presented in a tabulated form. Ho [5] had analyzed of the aluminum alloy structure beam of 5086-H32, 6061-T6, 7005-T6 under cantilever loading conditions.

The purpose of the study was to understand the mechanical properties of aluminum extruded beams. Through structural experiments and finite element analysis, the effects of structural beam length and restraint fixation on deformation are studied. Moreover, find out the relationship between the deformation formula of the cantilever beam and the experimental method.

2. Methods

Material. The 6063-T5 aluminum extrusion material used in the experiment was provided by KingStone Machinery (Changshu) Co., Ltd. The length of the extruded beam was 4 m, and the beam section size was 80x80 mm. The dimensions of the extruded beam section profile are shown in Fig. 1. The 4 m beam was cut and machining in two types of beams, as shown in Fig. 2 and 3. The beam of length 1160 as model A. The beam of length 680 as model B. In Table 1, the geometric properties of the test and analysis of the two beams were listed.

Experiment. There are two experiment methods in this study. The first is the tensile test to understand the material properties of aluminum extruded beams. Secondly, the bending tests are performed on the beam structure to test the structural rigidity.

| Model | Length | Model weight | Actual weight | Section modulus | Cantilevered loading length | 3 points bending length |
|-------|--------|--------------|---------------|-----------------|-----------------------------|------------------------|
|       | Unit   | mm           | kg            | kg              | m²                          | mm                     |
| A     | 1160   | 7.776        | 7.640         | 2.132E-06       | 1010                        | 940                    |
| B     | 680    | 4.442        | 4.365         | 2.132E-06       | 530                         |                        |

Tensile test. The mechanical properties of the extruded beam at the axial and lateral position was studied. The tensile test specimens were sampled in the front, middle, and end positions of the 4m extrusion beam. The samples were machined, and the dimensions of the test specimens are shown in
Fig. 2. The tensile tests would follow ASTM E8M specifications. The experiments used displacement control with a speed of 6 mm/min. The data of the force and strain are recorded during the tensile process.

**Beam bending test.** The test is to let the designer understand the deformation state of the beam under the load. The experiment uses the end load bending and three-point bending experimental method. The test bench experimental architecture of the two experimental methods are shown in Fig. 3. The beam experiment would use three kinds of endpoint restraint fixation methods as shown in Fig. 4 to compare the amount of deformation at the same loading condition. The test lengths of the beam are listed in Table 1. The dial gauge is used to measure the deformation of the beam at the loading position.

**Finite element analysis.** The purpose of study by CAE is to use the finite element method to compare with the experimental results. The 3D models were built using Solidwork 2017 CAD software, and then the deformation analysis was performed.

**Model.** The analyzed 3D models were built on the section of Fig. 1. In order to match the length of the experimental specimens, two lengths of 1160 mm and 680 mm were built.

**Loading.** The counterweight of the experiment and analysis was 201 N. There are two conditions for loading as shown in Fig. 4. One is fixed at one end and loaded on the cantilever end of the beam as shown in Fig. 4(a). The other is that the ends of the beam are fixed and loaded at two intermediate positions as shown in Fig. 4(b).

**Constrains.** According to the fixed method of the experiment, there are three kinds of constraints on the analysis model. The end face fixing methods of the beam were two faces restricted by the pin with the screw fixing as shown in Fig. 5(a), the lower faces restricted by the pin with the screw fixing as shown in Fig. 5(b), and the positioning pin and the screw lock the upper and lower face as shown in Fig. 5(c). The beam length of constraining face was 110 mm.
3. Results and discussion

Material properties. The material properties of Young's modulus, yielding stress, and the ultimate stress were obtained through the stress and strain data of the tensile test. The yielding stress was obtained by the 0.2% strain offset method. The 6061-T5 aluminum extruded beam tensile stress-strain curve are shown in Fig. 6. In the axial direction, the head, middle and tail sampling positions, the tensile stress and strain curves are well superimposed in Fig. 6(a). However, in Fig. 6(b), in the lateral direction, head, middle, and tail sampling positions, the tensile stress-strain curves are different. The sample sampled at the head position has high elongation. In Table 2, it was shown that three material properties in the axial direction, in which the yield stress and the ultimate stress are higher than the lateral direction except for the Young's modulus.

It is observed from the tensile properties that the material in the axial direction of the beam during the aluminum extrusion process has enough soothing space and can be cooled slowly during the process. However, the beam has a lateral width of only 80 mm. However, the beam has a lateral width of only 80 mm. Because of the effect of the restricted mold and rapid cooling, the Young's modulus is higher, but the lodging and ultimate stress properties are slightly worse. As a whole from Table 2, although the material properties of the axial direction and the lateral direction are directional due to extrusion. However, the difference in material properties is not too significant, so aluminum extruded beams could be considered as isotropic materials. The finite element analysis will use average material properties in both directions: E = 68.5 GPA, $\sigma_y = 222$ MPa, $\sigma_u = 245.5$ MPa.

### Table 2. The material properties of 6063-T5 aluminum extrusion beam.

| Sampling Properties | Axial | Lateral |
|---------------------|-------|---------|
| $E$                 | $\sigma_y$ | $\sigma_u$ |
| $\sigma_y$          | $\sigma_u$ | $\sigma_u$ |
| $\sigma_u$          | $\sigma_u$ | $\sigma_u$ |
Deflection analysis. The deflection analysis is achieved in two ways, one using experimental methods and the other using CAE computer simulation analysis. The experiments were done on the test bench. According to the load position, it was divided into two experimental methods. One is that the cantilever beam was loaded 201 N at the end of the beam shown in Fig. 7(a), and the other end was fixed. Another experiment was loaded 201 N at the intermediate of the beam and fixed at both ends as shown in Fig. 7(b). The experimental results are shown in Table 3. The results were shown that the fixing method of the boundary condition (b) would maximize the bending deflection, followed by the boundary condition (c) and the boundary condition (a) is the smallest. This trend does not change due to the beam length and load position.

![Deflection analysis](image)

Table 3. Beam deflection analysis.

| Method          | Experiment test | CAE nonlinear analysis |
|-----------------|-----------------|------------------------|
| Loading position|                 |                        |
| Beam length (mm)| 1010            | 1010                   |
| Boundary conditions | 530 | 530          | 940 | 940 |
| Deflection (μm) | 1482 234 10 565| 530 84 7.43 |
| a                | 2335 466 18 770| 139 13.74 |
| b                | 1965 365 16 639| 104 12.54 |
| c                |                 |                        |

The finite element model with three type boundary conditions were shown in Fig. 8. The deflection is in Y axis direction.

![Finite element analysis models](image)
Fixed the beam both ends and with an intermediate load, the experimental method is similar to the condition of 3-point bending. In the meantime, the experimental and CAE analysis data Compared to the experimental results of the cantilever method, the deformation data is relatively small, and the experiment is similar to the CAE analysis data. From the experimental and analytical results data, it is close to the elastic analysis, not the phenomenon of large deformation.

Under the experiment of cantilever beam loading, the deflection of the beam is the largest. This experimental model is already in a state of large deformation. The three-point bending experimental method with fixed ends has the smallest deflection. Experimental data is near linear elastic deformation state. This state is because the structural rigidity of the beam will be better under the constraints of both sides.

From the experimental results of the cantilever beam load, the beam deflection formula Equ. 1 is applied. Among them, the index $x$ of the beam length is used to compare the indices of different restraint conditions. The formula index from the known beam endpoint when fully fixed is $x = 3$.

$$v_{\text{max}} = \frac{PL^2}{3EI}$$ (1)

In Equ. 1, The values are known: $P = 201$ N, $E = 68.5$ GPa, $I = 2.132 \times 10^{-6}$ m$^4$, $L = 1010$ mm, and $530$ mm. Since in equation (1), the independent variable is the beam length $L$, and the dependent variable is $v_{\text{max}}$, other parameters are known. By introducing the deformation values obtained for the two experimental lengths into equation (1), the index $x$ value can be obtained. The experimental data of Table 3 are calculated to obtain the index $x$ of Table 4. The index $x$ represents the degree of restraint in the boundary conditions. The closer the index $x$ is to 3, the closer it is to the ideal full restraint condition. The beam boundary condition (a) is close to complete restraint. The coefficient of CAE analysis in condition (a) is close to 3; this indicated that the model's boundary condition is nearly wholly constrained. Boundary condition (b) in test and analysis is fixed in one surface; the beam is slightly constrained. The index $x$ at boundary condition (b) is the minimum value. Boundary condition (c) is fixed by the positioning pin at the upper and lower holes of the beam surface. The degree of restraint is between the boundary conditions (a) and (b).

| Boundary conditions | Test  | CAE  |
|---------------------|-------|------|
| a                   | 2.863 | 2.956|
| b                   | 2.499 | 2.655|
| c                   | 2.611 | 2.815|

4. Conclusion
1. The material properties of the aluminum extruded beam are not much different from the tensile test results in the axial direction, and the lateral direction and can be regarded as an isotropic material.
2. The experiment of 3 point bending of the beam and the CAE analysis results show the elastic deformation phenomenon of small displacement, and the two deformation results are very close.
3. The large deformation analysis of the beam is analyzed by CAE nonlinear method, and the result is quite different from the experiment. Some factors are not included in the analytical model, which may be caused by assembly gaps, deformation of the fixture.
4. The index of the test length in the cantilever beam deformation formula can be used to check the degree of restraint of the experimental and analytical models. The model of the CAE boundary condition (a) is closest to the ideal constraint condition.

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