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Tests and parametric analysis of aluminum alloy bolted joints of different material types

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HIGHLIGHTS

- A theory model was proposed to explain the mechanical mechanism of long bolted joints.
- Experimental investigation was conducted on 20 aluminum alloy bolted joints.
- A new design method considering the difference of material types was proposed.
- A more precise suggestion for the bolt hole diameter in the bolted joints was given.
- A design method for reduction factors of bolt shear force in long joints was given.

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ABSTRACT

In this paper experimental investigation was conducted on 20 aluminum alloy bolted joints. Based on the tests, three-dimensional refined finite element models were built and verified by the experimental results. By the FE model, extensive parametric analysis was carried out to clarify the influence of aluminum alloy material types (6061-T6, 6063-T5, 6082-T6 and 7A04-T6 which is a kind of ultra-high strength aluminum alloy applied in engineering structures), the diameter of bolt hole and the length of long bolted joints on the loading capacity of aluminum alloy bolted connection. The test results showed that the current design codes including EC9, AA 2010 and GB 50429-2007 underestimate the bearing strength of the joint. According to the results of parametric analysis, a new design method considering the difference of material types was proposed and fit better with the data points than the methods in current specifications; a more precise and detailed suggestion for the bolt hole diameter in aluminum alloy bolted joints was also given. The paper proposed a theoretical model to explain the mechanical mechanism of long bolted joints and gave a new design method for reduction factors of bolt shear force in long joints with different materials of plate and different materials of bolt.

1. Introduction

In recent years, the application of aluminum alloy in engineering structures is becoming more and more general because of its unique advantages, such as light weight, high strength, good corrosion resistance and gorgeous appearance. Although the research on aluminum alloy structures is much less mature than that of steel structures, a large number of researches have been conducted on aluminum alloy members including: plates [1,2], axial compression members [3–6], eccentric compression members [7], beams [8–10] and even braces [11,12]. In order to build a real complete aluminum alloy structure, joints are essential and indispensable.

The most common types of aluminum alloy joints include: gusset joint, bolt-ball joint, hub joint and cast aluminum joints which are widely applied in long-span spatial reticulated structures. The reason why designers and engineers developed these novel joint types is that they try to avoid the strength reduction by welding process in aluminum alloy. Therefore, bolted connection is the most popular and reliable type of connection in aluminum alloy structures. But the research on aluminum alloy bolted connection is still limited and immature.

Most of the existing researches focused on the material of 6061-T6 [13–15] and did not extend the study to other frequently-used aluminum alloy materials including 6082-T6, 6063-T6 and some high-strength aluminum alloy materials; and the vast majority of the researchers investigated one-bolt or two-bolt connection, neglecting the complexity of the mechanical

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behavior of multi-bolts connection or long joint which is common in practical engineering. Furthermore, many factors which affect the loading capacity of the connection haven't been investigated including: different aluminum alloy material types, the difference value between the bolt bar diameter and bolt hole diameter, distribution of shear force in long bolted connection, etc.

In order to clarify the above mentioned questions, the current paper carried out experiments on 20 aluminum alloy bolted connections and built three-dimensional refined finite element (FE) models which were used to simulate the tests. After verification, the FE models were applied to carry out large-scale parametric analysis for investigating the influence of several factors.

2. Experimental investigation

The experiments were performed in Laboratory for Structural Engineering in Tsinghua University [16] to investigate the bearing behavior of aluminum alloy plates, including two common aluminum alloy materials: 6061-T6 and 6063-T5. There were five groups of specimens for each material with two identical specimens in each group.

2.1. Tensile coupon tests

There were four tensile coupons tested for each aluminum alloy material (test setup shown in Fig. 1). 6061-T6 is a kind of weak hardening material, while 6063-T5 is strong hardening with lower strength. All of the measured mechanical properties are summarized in Table 1, where E_0 is the initial elastic modulus, $f_{0.2}$ is the nominal yield stress, f_u is the ultimate stress and n is the hardening index of Ramberg-Osgood expression [17]. It can be seen from the table that the elastic modulus of the two materials is lower than that of other aluminum alloy which is about 70,000 MPa.

Fig. 1. Test setup for tensile coupon experiments.

Table 1
Mechanical properties of aluminum alloy materials.

Label	Material	E_0 (MPa)	$f_{0.2}$ (MPa)	f_u (MPa)	n
6061-1	6061-T6	46,000	282	295	33
6061-2		46,000	280	293	32
6061-3		40,000	285	295	28
6061-4		46,000	285	297	28
Average value		44,500	283	295	30
6063-1	6063-T5	46,000	148	188	20
6063-2		50,000	145	186	20
6063-3		42,000	145	183	12
6063-4		42,000	145	181	18
Average value		45,000	146	184.5	17.5

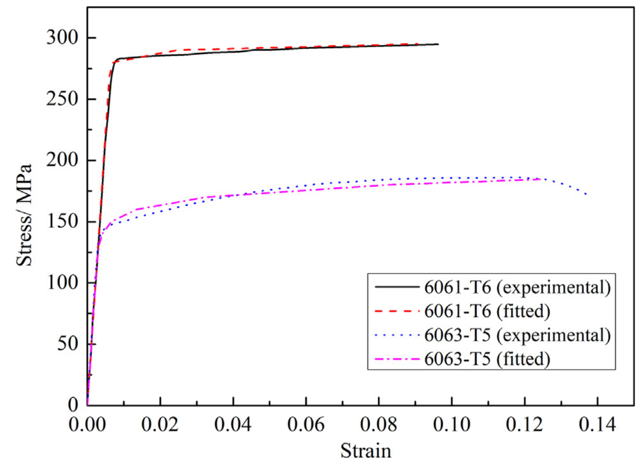

Fig. 2. Stress-strain curves of 6061-T6 and 6063-T5.

The stress-strain curves of them are shown in Fig. 2. It is clear from the figure that the fitted curves by Ramberg-Osgood model coincide well with the experimental ones, the agreement of the curves of 6063-T5 is a little inferior, though. Because 6063-T5 is a kind of strong hardening alloy with smaller value of n, it is more difficult to fit the experimental stress-strain curve with smaller n by R-O model according to the research by Kim [18].

2.2. Experimental investigation

All the specimens were tested by 100 kN tensile testing machine. 20 specimens were designed with different end distance e_1 (2 d_0, 2.5 d_0 and 3 d_0) and varied diameter of bolts d (12 mm, 16 mm and 20 mm). Edge distance e_2 for all the specimens is identical which is 50 mm. In order to ensure the reliability of the tests, there were two identical specimens for each test group. All of the bolt holes were 0.5 mm larger than the bolts, i.e., the diameter of bolt hole d_0 equals 12.5 mm, 16.5 mm and 20.5 mm for M12, M16 and M20 bolt respectively. The material of cover plates was Q345 with higher strength and larger Young's modulus than the inner aluminum alloy material to ensure far less deformation of the cover plate. Grade 10.9 high strength bolts were employed to avoid the failure on bolts and were tightened by ordinary wrench without preload.

The detailed dimensions of the specimens are shown in Table 2. In the test, the measurement of deformation of the bolt hole was of the vital importance because the loading capacity was determined not only by the peak load but also by the bolt hole elongation, however the employment of cover plates increased the difficulty of measurement. According to Hyeong J. Kim [19], deformation around the bolt holes is a design consideration and if the deformation exceeds 30%, the corresponding strength is considered as ultimate strength. The cover plate was slotted and two short bars were welded on the inner aluminum alloy plate near the bolt hole and the head of bolt to represent the deformation to be measured, as shown in Fig. 3. An electronic extensometer was applied to measure the displacement of the bolt hole.

2.3. Test results

In the initial stage of testing process, the load was withstood by friction between plates. After the friction was overtaken, the plate started to slip because the bolt hole was 0.5 mm larger than the bolt bar. When the bolt came into contact with the hole-wall, the load began to be delivered by plate bearing till the failure of the specimen. The typical failure mode of the aluminum alloy sheet is shown in Fig. 6(a). There was permanent plastic deformation of the bolt hole and the material in front of the hole bulged significantly. Large transverse deformation was observed on the right edge of the plate. Yield lines in red originated from the edge of the hole and developed to the adjacent end of the sheet. Because of the relatively large end distance, failure mode of end tearout was avoided.

All of the test results were summarized in Table 2. It can be seen from the table that with the increase of e_1/d_0, the value of $N/(f_u \cdot dt)$ increases significantly. According to the previous research [19] and current design codes [20–22], the bearing capacity is related to the ultimate strength f_u rather than the nominal yield strength $f_{0.2}$ of the aluminum alloy, so f_u was applied to normalize the N_d and N_p. N_d is ultimate loading capacity according to deformation of bolt hole (30%), while N_p is ultimate loading capacity according to the peak load. For all of the specimens, the ultimate loading capacity was dominated by deformation, although most of the N_d is close to N_p.