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Experimental investigation on the semi-rigid behaviour of aluminium alloy gusset joints

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ABSTRACT

Aluminium alloy gusset (AAG) joints are typical semi-rigid joints widely used in single-layer reticulated shells. Despite the semi-rigid behaviour of the AAG joints, structural analyses still show that dangerous situations can occur. To study the semi-rigid performance of the AAG joints, experiments on fourteen AAG joints are conducted. Initially, the failure modes of the AAG joints are summarised in terms of their collapse phenomena and the stress distributions of the plates are discussed based on the measured strain. Subsequently, the primary characteristics of the M-φ curves of the AAG joints are obtained. The bending stiffness properties of AAG joints are also investigated. The experimental results indicate the following: (1) the primary failure modes include member rupture, member buckling, block tearing of the top plates and local buckling in the bottom plates; (2) the moment-rotation relationship of the AAG joints exhibits a significant inelastic response; and (3) as the thickness of the gusset plate increases, the initial stiffness of the joint increases.

1. Introduction

Compared with traditional construction material, single-layer reticulated shells made from an aluminium alloy offer a certain attractive appearance, transparency, material savings, lightness, ease of erection and favourable durability. Therefore, these types of single-layer reticulated shells have been widely used in spatial structures recently. As a typical semi-rigid joint system, aluminium alloy gusset (AAG) joints are widely applied in single-layer reticulated shells made from an aluminium alloy. However, in the design and analysis of single-layer reticulated shells over the years, the common practice has been to regard the joints as being ideally pinned or perfectly rigid [1]. Pinned joints make it difficult for single-layer reticulated shells to achieve the required stability, whereas rigid joints greatly improve the bearing capacity of single-layer reticulated shells. Consequently, it will strongly affect the safety and economy of structures if the AAG joints are assumed as pinned or rigid joints.

Recent research has shown that the semi-rigid behaviour of joints plays a key role in the global buckling behaviour of single-layer reticulated shells [2]. A large number of investigators have explored the influence of the semi-rigid behaviour of joints on the global buckling capacity of single-layer reticulated shells using numerical simulations, experimental programs and theoretical analyses. Lopez et al. [3] developed statistical regression techniques and nonlinear structural analysis models to investigate the effect of joint stiffness on the critical buckling load of reticulated domed-shaped structures. Subsequently, based on previous results, the authors proposed a new formula, which allows designers to rapidly estimate buckling loads for single-layer latticed domes with semi-rigid joints under symmetric loading conditions [4]. Kato et al. [5] established a nonlinear elastic–plastic hinge analysis formulated for three-dimensional beam-columns with elastic-plastic hinges located at both ends and at the mid-span of each member. With the help of the proposed member model, reductions in collapse loads due to joint rigidity, geometric imperfections and member crookedness are discussed. Hiyama et al. [6,7] estimated the buckling behaviour of single-layer reticular domes made from an aluminium alloy composed of tubular truss members and ball joints via loading tests and numerical simulations on test structures scaled at a 1:5 ratio. The numerical results were in good agreement with the experimental results when the stiffness of the joints was 15.2 kN.m/rad. Fan et al. [8], Ma et al. [9] and Kitti [10] established finite element (FE) models in terms of single-layer latticed domes with semi-rigid joints and analyzed their buckling behaviour, where the bending stiffness, rise-to-span ratio, torsional stiffness, ball size, asymmetric load distribution, tube section, support condition and initial imperfections were considered. It should be noted that the geometric parameters, bending stiffness of the joint, rise-to-span ratio and tube section are the major factors that influence the critical load of these domes. The aforementioned studies showed

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that joint stiffness cannot be ignored in the analysis and design of single-layer reticulated shells, particularly for the bending stiffness of joints, which significantly affects their global buckling behavior.

Thus far, extensive experimental studies and numerical simulations have been performed to investigate the stiffness behaviour of different joint systems in spatial structures, which include bolt-ball joint system [11,12], welded hollow spherical joint system [13], tubular joint system [14–16] and so on. However, research on the semi-rigid behaviour of AAG joints is relatively limited. Comparing experimental results with FE results, Zeng et al. [17] found that to improve the accuracy of the numerical analysis in terms of single-layer reticulated shells, the stiffness of the AAG joints must be considered. To date, the behaviour of the AAG joints has primarily been investigated using the FE method. Based on the FE results of the AAG joints in practical engineering, Zou [18] highlighted that AAG joints are typical semi-rigid joints. The state of the research in the field of AAG joints is presently under development, where the primary limitations are concluded as follows: (1) research on the semi-rigid behaviour of AAG joints is currently at an early stage, and further study is required; (2) there is no specific design method to predict the bending stiffness of AAG joints; and (3) an experimental program on the semi-rigid characteristics of AAG joints must be performed. These research limitations greatly influence the widespread application of aluminium alloy single-layer reticulated shells with AAG joints.

With the aim of resolving the aforementioned research limitations, this article is primarily focused on the semi-rigid behaviour of AAG joints. Tests on fourteen AAG joints are conducted to study their out-of-plane flexural capacity. Firstly, the experimental program is introduced. Secondly, the failure modes of the AAG joint specimens are summarised in terms of their collapse phenomena. Finally, the experimental results are discussed. In addition, both the stress distributions of the plates and the out-of-plane bending stiffness of the AAG joint specimens are evaluated.

2. Experimental program

2.1. Specimens

A series of tests on fourteen AAG joint specimens was performed to investigate their semi-rigid behaviour. The AAG joint system is commonly composed of six beam members tightly attached to top and bottom circular plates by means of bolted connections, as shown in Fig. 1(a). All the beam members have an I-shaped cross-section, and the angle between adjacent members is 60 degrees. The identification numbers of I-shaped members range from L1 to L6, as shown in Fig. 1(b). Hand tightened stainless steel M6 bolts in 6.5 mm drilled holes were used in all the specimens, as shown in Fig. 1(c). In addition, ten bolts were used to connect one side of the flanges to the gusset plate. In the AAG joint system, the force acting on the members can be transmitted to each other through the bolts and circular plates. It is worth noting that in practice, six I-shape beams meet at each joint. Therefore, the specimens designed in this article are similar to practical scenarios.

All the I-shaped members have the same cross-sectional dimensions of $100 \times 50 \times 4 \times 5$ mm, which represents that the height of cross-section is 100 mm, the width of cross-section is 50 mm, the thickness of web is 4 mm and the thickness of each flange is 5 mm. The length of each I-shaped member is 890 mm, and the diameter of each circular plate is 280 mm. Detailed configurations of the test specimens are plotted in Fig. 2.

Three primary parameters were varied. The first parameter was the plate thickness. Four specimens were classified as a thick plate joint system (plate thickness $t \geq 5$ mm), and ten specimens were classified as a thin plate joint system (plate thickness $t \leq 3$ mm). The second parameter was the shear connector. The A series corresponded to a joint specimen without a shear connector, whereas the B series corresponded to a joint specimen with a type B shear connector, and the C series corresponded to a joint specimen with a type C shear connector, as illustrated in Fig. 3. The final parameter was the loading scheme. Three loading schemes, which include six loaded members, three loaded members and two loaded members, were applied to the specimens, as shown in Fig. 12. Detailed information of these specimens is presented in Table 1.

2.2. Materials

Aluminium alloy 6063-T5 [19] was selected as the material for the extruded beam members and extruded plates. Austenitic stainless steel was the material chosen for the bolts (material grade of A2-70) [20]. Tensile tests were performed to investigate the actual mechanical properties of these components according to the Chinese mechanical testing standard [21]. Four tensile coupons were cut directly from the flange and the web of the I-shaped beam members, as shown in Fig. 4(a). Six tensile coupons were cut directly from the extruded plates, as shown in Fig. 4(b). In addition, the six tensile coupons, which had diameters of 6 mm, were the same material as that of the bolts, as shown in Fig. 4(c). All the aluminium alloy tensile coupons had the same dimensions described in Fig. 5. The mechanical properties of these components obtained from the tensile tests are listed in Table 2, where E is the elastic modulus, $f_{0.2}$ is the nominal yield strength and f_u is the ultimate tensile strength.

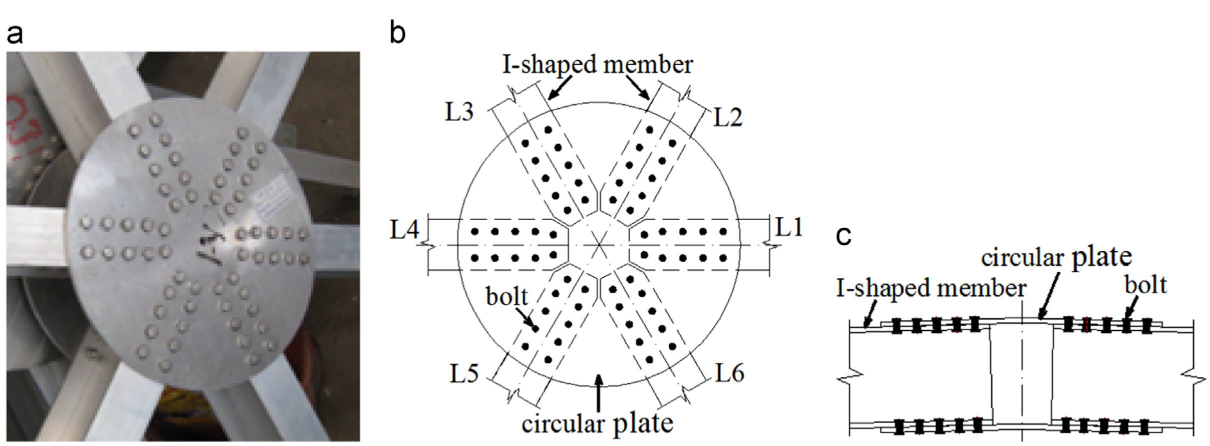

Fig. 1. AAG joint. (a) AAG joint specimen (b) Planar graph of the AAG joint (c) Cross-section of the AAG joint.