Thin-Walled Structures 122 (2018) 124–136

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Experimental investigation on bending and shear performance of two-way aluminum alloy gusset joints

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ARTICLE INFO

Keywords:
Aluminum alloy gusset joint
Semi-rigid behavior
Failure modes
Experimental study

ABSTRACT

Two-way aluminum alloy gusset joints (AAGJs) are considered to be employed in cable-stiffened aluminum alloy single-layer reticulated shell structures meshed with quadrilateral grids. In this study, a series of experiments on six AAGJs with and without shear connectors were conducted to investigate their semi-rigid behavior. Two joints were subjected to pure bending moments and others to shear loads, then their corresponding failure modes were investigated which were mainly beam rupture, beam web buckling, and bolt failure. The moment-rotation curves, shear load-rotation curves, and strain-load curves were also obtained, indicating that AAGJs are typical semi-rigid joints. Shear connectors can optimize the load transferring path and improve ductility under bending moment while enhancing shear performance significantly. A simplified theoretical AAGJ model was also established and parameterized according to the experimental results.

1. Introduction

Single-layer reticulated shell structures provide a highly efficient method for building large-span structures. Introducing a tensioning system into a reticulated shell structure can improve the stability of such buildings. There currently exist two kinds of single-layer reticulated shells with tensioning systems: Suspen-domes [1–3] and cable-stiffened shells [4,5]. Both systems can effectively improve the stability of reticulated shells. Suspen-domes are only applicable to domes, however, while cable-stiffened shells can suit almost any curved shape.

A cable-stiffened reticulated shell (CSRS) structure is typically comprised of a single-layer quadrilateral-mesh reticulated shell with X-shaped pre-tensioned cables disposed within the grids. The cable can be arranged within the curved surface to improve the in-plane stiffness (Type A) or work with posts externally (Type B) to improve the out-of-plane stiffness of the shell [6]. The Neckarsulm dome (Fig. 1) [7] is a practical application that adopted the Type A cable arrangement; the Kumagaya dome (Fig. 2) [8] adopted the Type B.

There have been many studies on the stability of cable-stiffened single-layer reticulated shells. Wu et al. [9] analyzed the introducing process of pre-stress tensile units of a CSRS. Zhang and Fujimoto [10] conducted a numerical study on a series of CSRSs to explore the effect of cable arrangement on linear and nonlinear stability. Feng et al. [11] derived the formula for the linear buckling load of an elliptic paraboloid CSRS with imperfections based on continuum analogy. Li et al. [4,6] performed a series of parametric analysis on the stability behavior of cylindrical and elliptic paraboloidal CSRSs with different cable arrangements. Li et al. [12] conducted experimental investigations on two-way single-layer shells with and without cables under different load distributions.

Many studies have shown that joint stiffness cannot be ignored in the analysis and design of single-layer reticulated shells, as it significantly affects the global stability behavior [13–17]. There have been extensive numerical and experimental investigations on the semi-rigid behavior of joints in different systems. Feng et al. [18] conducted experiments and numerical analyses including on in-plane and out-of-plane stiffness for bolted joints that are used to constructing CSRSs. Fan et al. [19] and Ma et al. [17] carried out a series of studies on socket joints and bolt-ball joint systems subjected to bending moment, shear force, and axial force to investigate semi-rigid behavior. Han and Liu [20] conducted experiments on twelve welded hollow ball joints subjected to tensile and compress loads.

Previous studies and practical engineering projects typically center around steel as the primary material. Aluminum alloy has many notable advantages compared to steel; it is light-weight, cheap to maintain, and has excellent cryogenic properties, among others [21]. It also has some disadvantages, however. Its thermal expansion coefficient is twice as steels, and it has a relatively poorer high temperature material performance than steel. Researches regarding aluminum alloys thermal behavior is fairly limited, however. Chen [22] performed experimental investigation on 114 aluminum alloy coupons to study the influences of temperature, material grade and cooling method on the post-fire mechanical properties. Maljaars [23] carried out investigations on local

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http://dx.doi.org/10.1016/j.tws.2017.10.002
Received 27 June 2017; Received in revised form 13 September 2017; Accepted 2 October 2017

Fig. 1. The Neckarsulm dome.

Fig. 2. The Kumagaya dome.

buckling of aluminum alloy members at elevated temperatures. Maljaars [24] conducted a parametric study on fire exposed aluminum structural members, and proposed a verified model for designing aluminum alloy members at elevated temperatures. Liu [25] measured the solar radiation absorption coefficient of aluminum alloy, and analyzed the temperature distribution and thermal response of aluminum alloy space structures.

A considerable number of aluminum alloy single-layer reticulated shells have been constructed since 1950; such structures are widely considered to have attractive appearance and favorable structural features such as easy erection and high durability in moist environments [26]. Building a CSRS using aluminum alloy forms an efficient, economical and elegant structure.

Research on the semi-rigid behavior of joint systems of aluminum alloy reticulated shells is fairly limited, however. Sugizaki et al. [27,28] carried out a series of experimental and numerical studies on aluminum insertion joints, and Hiyama et al. [29] performed experimental studies on six aluminum ball joints. Shi et al. [30] investigated the semi-rigid behavior of a novel cast aluminum joint under different loading conditions, and Guo et al. [31–33] derived and experimentally verified a formula for bending stiffness of aluminum alloy gusset joints (AAGJs). Shi et al. [34] investigated the bending and shear stiffness of an AAGJ using FE simulations.

This paper also focuses on the AAGJ system, which is one of the most commonly used joint systems in building aluminum alloy reticulated shells, as shown in Fig. 3. There has been very little research to date on combining AAGJ with CSRS, however, leaving the following problems to be solved:

(1) As opposed to traditional aluminum alloy reticulated shells, CSRSs usually have quadrilateral meshes rather than triangular meshes; this means that four beam members are connected to a joint instead of six. The semi-rigid behavior of this kind of AAGJ may differ from the traditional joint, but this has yet to be fully confirmed.

(2) Many free-form reticulated shell structures have been built in recent years [35], among which aluminum alloy reticulated shells have been especially popular. Unfortunately, the AAGJ does not readily transfer shear force across the joint due to the lack of connection between beam webs (Fig. 3(a)). Previous research has also indicated that joint shear stiffness affects reticulated shell structures to some extent [34]; the shear stiffness of AAGJ has yet to be fully understood, however.

In this study, tests on six full-scale AAGJs were conducted to explore the bending and shear stiffness with and without shear connectors, respectively. The experimental program is introduced below, followed by the results obtained for the failure modes of the joints. Response curves of the joints are then presented and discussed. Finally, the corresponding theoretical AAGJ model is proposed and concluding remarks are provided.

2. Experimental program

2.1. Materials

The material for the beam members and gusset plates used in this study was aluminum alloy 6061-T6 [36]. The bolts were made of austenitic stainless steel and the shear connectors of steel. Though the same raw material was used for the beam members and gusset plates, their mechanical properties may have varied due to differences in processing techniques. Two sets of tension coupon tests were performed to investigate the mechanical properties of the materials: One set contained three coupons cut directly from the unprocessed gusset plates, and the other contained two pairs of coupons cut from the flange and the webs of the I-shaped beam members, respectively. All the seven coupons had the same dimensions except for the thickness, as shown in Fig. 4(a). The chemical composition of the aluminum alloy coupons is in accordance with GB/T 3190-2008 [37] and the shapes and sizes are designed in accordance with GB/T 228.1–2010 [38]. The material properties of the steel components, including the stainless steel bolts type A (connecting beams with plates), stainless steel bolts type B (connecting shear connectors with beams), and steel shear connectors, were provided by the manufacturers.

The surface of the aluminum alloy was initially smooth, but became coarse as plastic deformation progressed during the tensile tests (Fig. 4(b)). This phenomenon (plastic texture) can be used to identify regions with high strain concentration among the aluminum alloy components.

The stress-strain curves of aluminum alloy coupons are shown in Fig. 5, the results of the tensile coupon tests meet requirements of GB/T 6892-2006 [39]. The mechanical properties of all the materials mentioned above are summarized in Table 1, including the elastic modulus, E, the nominal yield strength, σ_y, and the ultimate tensile strength, σ_u.

2.2. Specimens

A series of tests on six specimens were conducted to study the semi-rigid behavior of AAGJs. A standard AAGJ in a reticulated shell with quadrilateral meshes contains two circular plates and four I-shaped beam members connected by bolts, as shown in Fig. 3. The diameter of the circular plates was 515 mm and the thickness was 12 mm. All the I-shaped beam members had the same cross-sectional dimensions of $350 \times 200 \times 8 \times 12$ mm, as shown in Fig. 4(a). The detailed configuration of the beam member is shown in Fig. 6. Each specimen had two long beams and two short ones (Fig. 6(a)). This study focuses on the semi-rigid behavior along principal axis of joints, so the X-direction beams were kept short and with the same length of 300 mm. Each I-shaped beam member was tightly attached to top and bottom plates by 36 stainless steel bolts 10 mm in diameter. The bolts were numbered as shown in Fig. 6(b).

As shown in Table 2, two sets of joint specimens were investigated: