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The in-plane effective length of members in aluminum alloy reticulated shell with gusset joints

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ABSTRACT

This paper presents an analytical research on the in-plane stability of members in single-layer reticulated latticed shells with aluminum alloy gusset (AAG) joints. The influence of two kinds of actual boundary conditions are considered, namely, the stiffness of the AAG joint (k_1) and restraint of adjacent members (k_2). In order to explore the influence of k_1, an experimental program including 5 member specimens with AAG joints is introduced, and finite element (FE) models are established and verified. Based on the test and FE results, the effective length of the specimens are obtained. Subsequently, theoretical analysis is conducted to investigate the effect of k_2, with accounting for the stiffness reduction caused by axial compressive force. Finally, the effective length factors of members in reticulated shell with AAG joints are derived and tabulated. Numerical examples are presented to illustrate the necessity of considering the influence of k_1 and k_2, and verify the good accuracy of the given effective length factors.

1. Introduction

Stability is essential throughout the design process of a reticulated shell, where the members mainly subject compressive loads. The stability of reticulated shells includes two levels, i.e. global stability and local stability. A shell often fails with global instability, presented as large out-of-plane deflection of joints and members. Generally speaking, the global stability of a shell controls its ultimate bearing capacity. On the other hand, in-plane buckling of a single member, which is a typical type of local instability, cannot be ignored due to the further collapse it may cause [1]. Once local instability occurs, the buckling member deactivates, leading to redistribution of internal force and even the domino effect of global instability. It is fairly wasteful to let the structure fail by local instability, since the bearing capacity of most members is not utilized. As a consequence, in-plane buckling of shell members should be considered in the design of a reticulated shell.

A practical method is the effective length method, which is widely used in determining the buckling load of members. By introducing the effective length factor (hereinafter, the *K* factor), second-order analysis is avoided. For regular frames, the *K* factors of the compressive members were proposed by Kavanagh [2] and tabulated in the AISC standard [3]. As for special frames, the research findings were also abundant. The *K* factors of tapered members in steel gabled frames were investigated by Saffari [4], based on extended slope-deflection equations. Kishi [5,6] considered the non-linearity of the semi-rigid joint stiffness, and proposed the *K* factors of columns in braced and unbraced frames, by means of physical equations as well. Girgin [7] emphasized that for irregular frames, the application of *K* factors in design codes may lead to rather erroneous results, because the derivation of the K factors only considered local stiffness distributions. A simplified procedure was developed, utilizing a simple quotient based on the results of a fictitious lateral load analysis which was available for both regular and irregular frame members. Hellesland [8] highlighted that under special analysis applications, negative restraints may be involved. Approximate formulas for *K* factors were derived of compressive members with both positive and negative end constraints. From Hellesland's research results, it can be concluded that section of the member, joint stiffness and end constraint must be taken into consideration in order to determine the *K* factor of a compressive member.

In China, the *K* factors of members in common spatial structures are given in JGJ7-2010 [9]. However, for single-layer shells with gusset joints, the specified *K* value is not given. For single-layer aluminum alloy shells, the in-plane and out-of-plane *K* factors of members are recommended to be 0.9 and 1.6 respectively, by GB50429-2007 [10], but the joint types are not specified. Aluminum alloy gusset (AAG) joint is widely applied in single-layer aluminum alloy reticulated shells, and researches revealed that it is a typical semi-rigid joint system [11]. Thereby, the aforementioned values are unavailable.

The out-of-plane buckling of the member is linked to global instability involving most members, and numerous researchers have

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studied the global instability of shells with semi-rigid joints [12–15]. Therefore, this paper is mainly focused on the in-plane effective length factor of the member in reticulated shells with AAG joints. Due to the fact that the section of the shell members generally remain the same along the length, the K factor is related to the AAG joint stiffness (denoted as k_1), and end constraint (denoted as k_2). Firstly, in order to explore the influence of k_1, an experimental program is introduced. Finite element (FE) models are established to simulate the mechanical performance of the specimens, and the effective length of the specimens are obtained. Subsequently, theoretical analysis is carried out to obtain the influence of k_2. Finally, the formula of effective length factor is proposed, and validated with a FE reticulated shell model.

2. Test program

2.1. Specimens

Tests on 2 series (5 in total) of AAG shell members were conducted under axial compressive load. The overall configuration of the specimens is shown in Fig. 1. The joint zone was designed according to the research results of Ref. [16]. The diameter of the gusset plate was 240 mm, and the thickness was 5 mm. The member was connected to the gusset plate by 8 stainless steel M6 bolts hand tightened in 6.5 mm drilled holes. All of the members had the section dimension of I100 × 50 × 4 × 5, denoting that the height of the section is 100 mm, the width of the flange is 50 mm, the thickness of the web and the flange is 4 mm and 5 mm respectively, as plotted in Fig. 2. The total length of the specimen l was defined as the distance between the centers of the gusset plates, and the net length l_n was defined as the length of the member uncovered by the gusset plate, see Fig. 1. Three specimens had the total length of 1.0 m, and two specimens had the total length of 1.2 m. For convenience, the specimens were labelled with their total length. For example, specimen "1.2mB" denoted the second specimen with the length of 1.2 m. The detailed information of the specimens is tabulated in Table 1.

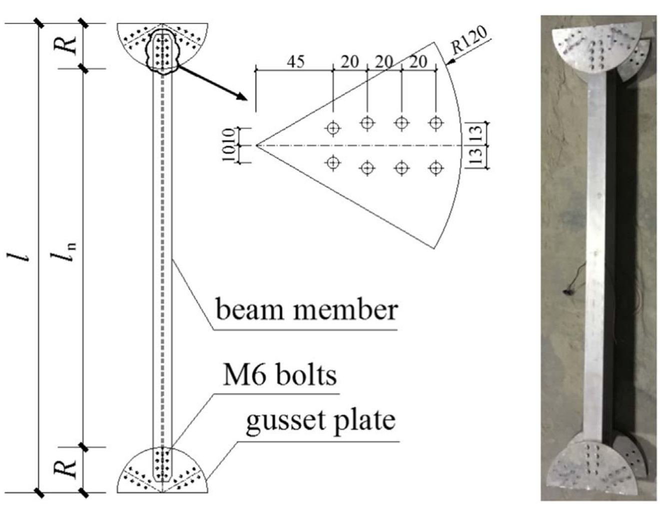

Fig. 1. Overall configuration of AAG shell member specimens.

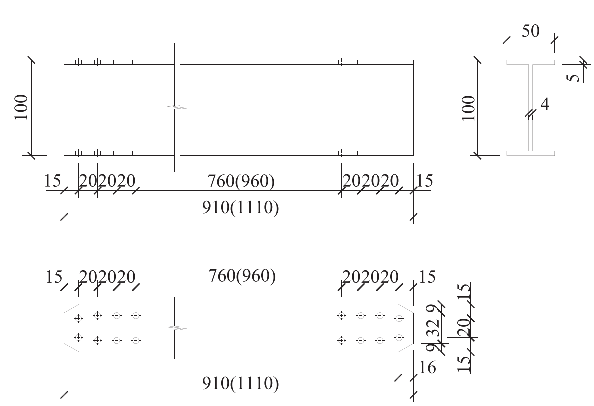

Fig. 2. Configurations of the members.

Table 1
Information of specimens.

Specimen	Plate thickness (mm)	Beam section	Total length (mm)	Net length (mm)
1mA	5	I100 × 50 × 4 × 5	1000	760
1mB	5	I100 × 50 × 4 × 5	1000	760
1mC	5	I100 × 50 × 4 × 5	1000	760
1.2mA	5	I100 × 50 × 4 × 5	1200	960
1.2mB	5	I100 × 50 × 4 × 5	1200	960

2.2. Materials

Aluminum alloy 6061-T4 [17] was adopted to be the material of the gusset plates and the extruded members. The material of the bolts was austenitic stainless steel A2-70 [18]. Tensile tests were conducted to obtain the mechanical properties of the material, according to the Chinese mechanical testing standard [19]. The tensile specimens were cut directly from the gusset plates and the members, as shown in Fig. 3. Tensile tests on the stainless bolts were performed in Ref. [11]. All of the test results are given in Table 2.

2.3. Test arrangement

The elevation view of the test device is shown in Fig. 4. Both of the ends of the specimens were connected to the steel clamp using several stainless steel bolts, see Fig. 5(a). In order to simulate the fixed-end boundary condition, a steel sleeve (shown in Fig. 5(b)) was covered on the end of the hydraulic jack.

To monitor the response of the specimens, three types of measuring points (demonstrated in Fig. 4) were arranged:

(1) 4 strain gauges SG1–SG4 were placed on the edges of the flange, at the mid-section of the specimen. The axial load and eccentricity could be calculated using the readings of the strain gauges.

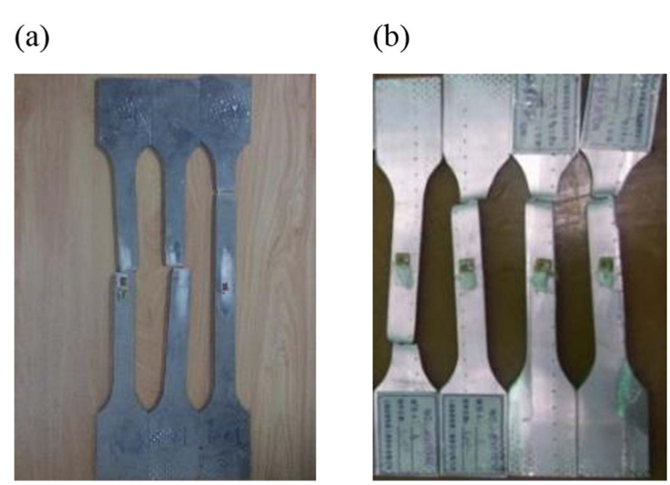

Fig. 3. Tensile specimens. (a) Specimens cut from the plate. (b) Specimens cut from the beam member.