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Elasto-plastic stability of single-layer reticulated shells with aluminium alloy gusset joints

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ABSTRACT

The single-layer reticulated shell with aluminium alloy gusset (AAG) joints is an innovative space structure system, and has been widely used in the building engineering. According to the bending behaviour of AAG joints obtained from the theoretical formulae, the finite element (FE) models of K6 AAG joint shells were established in the ANSYS program. The buckling performance of K6 shells with semi-rigid and rigid joints was discussed. It is indicated that the semi-rigid behaviour of AAG joints had a significant effect on the buckling performance of K6 shells. To develop a further understanding, parametric studies were performed, varying the span-to-thickness ratio, height-to-span ratio, ring, member section, joint bending behaviour, joint stiffness model, material property, load distribution, support condition and initial geometric imperfection. It is found that the effects of these parameters on the elasto-plastic stability of K6 shells with rigid and AAG joints were different obviously. At last, to predict the elasto-plastic buckling load of AAG joint shells, theoretical formulae were proposed on the basis of the FE results of more than 8000 shell models.

1. Introduction

From both structural and architectural points of view, single-layer reticulated shells with aluminium alloy gusset (AAG) joints which provide a good solution for small or medium span space structures have a lot of outstanding characteristics, such as attractive appearance, transparencies, material savings, corrosion prevention, rapid construction, accurate fabrication and lightness [1]. Therefore, the single-layer reticulated shells with AAG joints have a wide application prospect. Nowadays, they have been widely applied to gymnasiums, museums and auditoriums, including the Shanghai International Gymnastic Center (China), the Shanghai Science and Technology Museum (China), the Sea World of Texas (America) and the Festival South Bank Exhibition (UK). However, an available design method for the single-layer reticulated shells with AAG joints is limited, resulting in a great obstruction of their application and development. Hence, systematical studies on the elasto-plastic stability of single-layer reticulated shells with AAG joints are required.

Lots of researchers indicated that joint mechanical behaviour has a significant influence on the behaviour of steel frame structures [2–7]. Eurocode 3 [8] also recommends that the real mechanical behaviour of joints should be taken into consideration in structural analyses, and provides a component method to estimate the strength and stiffness of joints. In the conventional designs and analyses of single-layer reticulated shells, both JGJ 7-2010 [9] and JGJ 61-2003 [10] suggest that the joints can be simplified as rigid joints. However, it brings a potential safety hazard to practical engineering. Recently, more and more researchers have found that joint bending stiffness plays a key role in the global buckling behaviour of single-layer reticulated shells. Ma et al. [11] had conducted experimental and numerical studies on a single-layer cylindrical reticulated shell with semi-rigid bolt-ball joints. It is found that the buckling load of the experimental shell is smaller than that of a finite element (FE) shell with rigid joints, but larger than that of a FE shell with hinged joints. The results signify that the joint bending stiffness cannot be ignored in the designs and analyses of single-layer cylindrical reticulated shells. Hiyama et al. [12] had investigated the buckling behaviour of aluminium ball jointed single-layer reticular domes by means of experiments and FE models. Considering the influence of the joint bending stiffness, the FE results agree well with the experimental ones. Lopez et al. [13,14] had made systematical studies to estimate the buckling load of semi-rigidly jointed single-layer latticed domes and proposed a corresponding formula. It is worth noting that the innovative AAG joint belongs to a typical semi-rigid joint system. Guo and Xiong et al. [15,16] had carried out experimental investigations, numerical simulations and theoretical studies on the bending behaviour of AAG joints. Then they indicated

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that the AAG joint exhibits remarkable semi-rigid and nonlinear behaviour. Making a comparison of the FE and experimental results on the stability of a single-layer reticulated shell with AAG joints, Zeng et al. [17] found that the influence of joint semi-rigid behaviour is indispensable. Despite of that, further studies on the elasto-plastic stability of single-layer reticulated shells with AAG joints were limited.

Comprehensive and systematical researches on the elasto-plastic stability of single-layer reticulated shells with rigid joints have been carried out at an early stage. Yamada et al. [18], Luo et al. [19] and Zhang et al. [20] have studied the effects of the geometric imperfection, height-to-span ratio and loading distribution on the nonlinear buckling behaviour of single-layer lattice domes with rigid joints, respectively. Fan et al. [21] had investigated the elasto-plastic stability of seven types of commonly used single-layer reticulated shells. More than 2000 cases of geometrically and material nonlinear analyses were conducted with different initial geometrical imperfection, geometrical, structural and load parameters. Moreover, they had provided an easy design method for designers to evaluate the stability of these reticulated shells. For the time being, the stability of reticulated shells with semi-rigid joints has been a hot issue which attracts research communities' attention significantly. Fan and Ma et al. [22,23] had analyzed the stability of the spherical and the elliptical paraboloid latticed shells with semi-rigid joints respectively, considering the effect of the bending stiffness, height-to-span ratio, rotation-stiffness, ball size, load distribution, tube section, support condition and initial imperfection. Kato et al. [24] had studied the collapse of semi-rigidly jointed reticulated domes with the initial geometric imperfection, and then developed a design method based on member strength curves. The aforementioned researches are mainly focused on steel shells with circular members. Consequently, these achievements cannot be applied to aluminium alloy shells. The main reason is that the post-elastic response of aluminium alloy structures is significantly different from steel ones [25]. The material behaviour of aluminium alloy is characterized by a continuous and remarkable strain hardening and a limited ductility, while the material property of steel is tightly based on the hypothesis of perfect plasticity and unlimited ductility. In addition, it is worthy pointing out that the influence of a warp degree should be considered in the AAG joint shells due to I-shaped members, but it could be neglected in the steel shells with circular tubes. Compared with the achievements of steel shells, the state of researches in the field of reticulated shells with AAG joints is presently under development. Besides, little definitive conclusion has been achieved to date, neither in the prediction of structural behaviour, nor in the assessment of codification rules. The main reasons for this may be, on the one hand, the aluminium alloy shells are regarded as a new topic in the field of structural engineering; on the other hand, the material property of aluminium alloy is complicated, increasing the difficulty for the understanding of the behaviour of aluminium alloy structures [26–28].

Due to the limited state of researches in the field of single-layer reticulated shells with AAG joints, this paper was focused on their elasto-plastic stability. Based on the powerful FE software package ANSYS, reliable and effective FE models were established to simulate the elasto-plastic stability of single-layer reticulated shells with AAG joints. These FE models were compared and validated with experimental results. The buckling modes and process of Kiewitt-6 (K6) single-layer reticulated shells with semi-rigid and rigid joints were reported and discussed by means of the FE models. To develop a further understanding, parametric studies were performed. The effect of the span-to-thickness ratio, height-to-span ratio, ring, member section, joint bending behaviour, joint stiffness model, material property, load distribution, support condition and initial geometric imperfection on the buckling behaviour of AAG joint shells was investigated in the parameter studies. In addition, to predict the elasto-plastic buckling behaviour of AAG joint shells, theoretical formulae were proposed on the basis of the FE results of more than 8000 shell models.

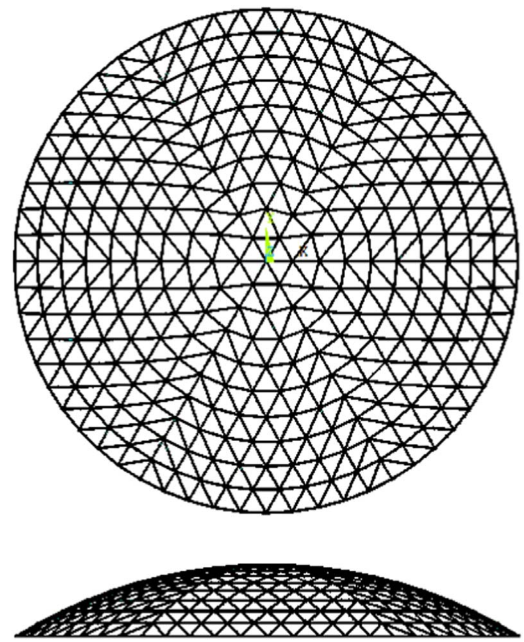

Fig. 1. K6 single-layer reticulated shell.

2. Structural configuration and parametric analysis plan

The K6 single-layer reticulated shell with AAG joints is shown in Fig. 1. The primary parameters taken into account herein included the span, height-to-span ratio, ring, member section, joint bending behaviour, joint stiffness model, material property, load distribution, support condition and initial geometric imperfection. According to the code recommendations and practical engineering structures [9,10,29], the decisions of the shell parameters are shown as follows:

(1) The span, 40 m, 50 m, 60 m and 70 m.
(2) The height-to-span ratio, 1/4, 1/5, 1/6 and 1/7.
(3) The ring, 16 rings, 18 rings, 20 rings and 22 rings.
(4) The member section, M1, M2, M3 and M4.
(5) The joint bending behaviour, J1, J2, J3 and J4 (corresponding to member M1–M4, respectively).
(6) The joint stiffness model, linear models and non-linear models.
(7) The material property, elastic behaviour and elasto-plastic behaviour.
(8) The load distribution, $p/g = 0$, 1/4, 1/2 and 1/1 (p represents live load uniformly distributed over the half span, g represents dead load uniformly distributed over the whole span and the value of g is 1 N/m^2).
(9) The support condition, pinned supports and fixed supports.
(10) The initial geometric imperfection, adopting the first eigenvalue buckling mode of AAG shells, the magnitude of the initial geometrical imperfections is 0, S/1000, S/500, S/300, S/200 and S/100 (S is the span).

The detailed dimension of AAG joints is shown in Fig. 2. The member section was just only varied in height, as listed in Table 1. It is worthy pointing out that according to the four-linear model (Fig. 3) proposed in reference [16], the corresponding joint bending behaviour was obtained, as also listed in Table 1. In addition, aluminium alloy 6063-T6 with the elastic modulus $E = 70000$ MPa, the Poisson's coefficient $\nu = 0.3$, the yield strength $f_{0.2} = 240$ MPa and the ultimate tensile strength $f_u = 260$ MPa, was selected as the material for the components of shell models [30].