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Mechanism of coupled instability of single-layer reticulated domes

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ABSTRACT

Single-layer reticulated domes are typical structures with high degree of static indeterminacy. The stability of the reticulated dome structures is complicated and closely related to both the member buckling and the overall buckling of the structure. However, little theoretical research work deals with this very complex phenomenon. Meanwhile, for the statically indeterminate structures, it is a common belief that the local failure would occur first and result in the change of internal force paths, while the structure could support load continually before the overall collapse of the structure. In this paper, the interaction between the member buckling and the overall buckling of the structure was investigated, and this common belief was explored. The geometrically and materially nonlinear analyses (GMNA) were carried out for the reticulated domes with eight types of different grid forms, and the examination of member buckling for each dome was conducted based on the examination method of the P–δ_{end} curve or the P–δ_{mid} curve of the member. The relationship between the member buckling and the global instability of the structure was obtained by evaluation results of member buckling. Consequently, for the common reticulated domes, two instability patterns were identified, i.e. progressive instability and synchronous instability. In the case of progressive instability, the member buckling occurs in advance of the overall buckling of the structure. Then the number of the instable member increases, and finally the overall buckling of the structure occurs. In the case of synchronous instability, the member buckling and the overall buckling of the structure happen simultaneously. The interaction mechanism between the member buckling and the global instability of the structure was analyzed for both instability patterns.

1. Introduction

In 1961, the brittle failure of the Bucharest dome in Romania, and in 1978, the sudden collapse of the Hartford Coliseum roof had dramatically drawn much attention on the collapse behavior and instability mechanism of the long span spatial structure. As a typical spatial structure, the single-layer reticulated dome has a relatively high strength-to-weight ratio and can cover large space without intermediate supports. Stability is crucial to the safety and serviceability of single-layer reticulated domes. Since 1960s, the stability of reticulated shell structures has been a hot research topic which has been attracting the attention of researchers [1,2]. The research work mainly focuses on the following three basic issues: the first issue is the stability theory and analysis method of reticulated shell structures, which is to answer the question of how to conduct the stability analysis of reticulated shell structures; the second issue is the investigation of the elastic stability and elasto-plastic stability of reticulated shell structures, which is to answer the question of what is the stability performance of reticulated shell structures; the third issue is the study on the instability mechanism of reticulated shell structures, which is to answer the question of why reticulated shell structures would lose stability bearing capacity.

For the first and second issue, fruitful results have been achieved through extensive research on the stability theory, analytical method, elastic stability and elasto-plastic stability of reticulated shell structures [1,2]. The continuum shell analogy theory, the finite element method and the experiment method have been adopted successfully in the stability analysis of reticulated shell structures [1]. With the rapid development of the computer technology and the availability of advanced finite element software, the nonlinear finite element analysis can be adopted to conduct the geometrically nonlinear elastic analysis (GNA) and the geometrically and materially nonlinear analysis (GMNA) for reticulated

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Nomenclature

L	span of a reticulated dome	f	rise of a reticulated dome
σ_s	yield strength of the material	E	Young's modulus of the material
P	axial compression of a member	$\vec{d}$	deflection vector of a node
δ_{end}	relative deflection between the two ends of a member	δ_{mid}	relative flexural deflection of the mid-point of a member
δ	initial curvature of members	l	length of a member
P_m	load when the member buckling occurs	P_s	load when the overall buckling of the structure occurs
R_b	ratio of P_m to P_s		

shell structures, to better understand the elastic and elasto-plastic stability performance of the structure. The nonlinear finite element analysis can consider the influence of multiple structural parameters on the structure stability, such as geometry of structure, type of loading and deviation of nodes [3–17].

For the third issue, the instability mechanism of reticulated shell structures is closely related to the stability performance of the structure. The instability mechanism is the essence of the complicated instability phenomenon of reticulated shell structures. The load applied on reticulated shell structures is mainly transferred in the form of the axial force of members. The members are under considerable axial compression, and member buckling is prone to occur in reticulated shell structures. The mutual interaction between the member buckling and the overall buckling of the structure is a major factor affecting the stability of reticulated shell structures, and provides an essential access to understand the instability mechanism of reticulated shell structures.

However, as an important access to study the instability mechanism of the structure, the interaction between the member buckling and the overall buckling of the structure has not been explored systematically. For reticulated shell structures, the coupled instability between members and the whole structure is ubiquitous and is of great significance for research on the instability mechanism.

In addition, reticulated shell structures are typical statically indeterminate structures. The collapse mechanism of reticulated shell structures has raised much discussion. A widely accepted belief is that, the local failure would take place first, which results in the redistribution of the internal force paths, and then the structure could support the load till the overall collapse of the structure. This belief mainly relates to the interaction mechanism between the local part of the structure and the whole structure. The study on the interaction between the member buckling and the overall buckling of the structure would be an approach to discuss this belief.

The research of Lenza [18] showed the collapse of the structure was initiated by member buckling, resulting in a coupled instability of the whole structure. Through the introduction of the member imperfection to a reticulated barrel vault, Gioncu et al. [19] observed a significant reduction of the stability bearing capacity of the structure due to member buckling. Butterworth [20] showed that, in practice, the buckling of the compression member was a brittle-type buckling, while the stress dropped suddenly after the member buckled. Supple and Collins [21] proposed a double-layer grid model to demonstrate the importance of choosing a correct member characteristic in the structure. The model reflected the influence of member buckling on the propagation of member buckling and the overall buckling of the structure. The experimental dome model of Marinescu [22] was made with steel wire of ϕ 2.6 mm. The buckling of the dome was due to the buckling of the majority of compressed members, and a sudden overall buckling of the structure occurred. Similar result was obtained in the experiment carried out by Lenza [23], which showed that the occurrence and propagation of member buckling resulted in the overall buckling of the structure.

Given that the buckling of the member is brittle and will cause internal force redistribution in the structure, member buckling is emphasized as the starting point of the study in this paper, to explain the coupled instability mechanism of reticulated domes, and to explore the interaction mechanism between local regions and the whole structure. Using the finite element package ANSYS [24], the geometrically and materially nonlinear analyses (GMNA) were carried out for the reticulated domes with eight different types of grid forms, and the member buckling for each dome was evaluated. According to the analyses of the relationship between the member buckling and the overall buckling of the structure, two instability patterns were identified, i.e. progressive instability and synchronous instability. For each instability pattern, the interaction mechanism between the member buckling and the overall buckling of the structure was critically examined.

2. Analytical models and method

2.1. Analytical models

The analytical models of single-layer reticulated domes shown in Fig. 1 are employed in this study, including Kiewitt-8 dome, Kiewitt-6 dome, Geodesic dome, Schwedler monoclinal dome, Schwedler bidirectional dome, Sunflower dome, Lamella dome and Radial rib dome [7]. The analytical parameters are span (L) and rise-to-span ratio (f/L), as listed in Table 1. For each span value, four groups of members are selected. For each group, two types of cross-sections are used for different members, as shown in Table A1 of the Appendix A.

2.2. Analytical method

The member model in this paper is similar to that in Refs. [25,26]. The members with cross sections of steel circular tubes are assumed rigidly connected at each joint. Modeling of reticulated domes is conducted by using the finite element package ANSYS 10.0. The members in the model are simulated by BEAM188 elements. Based on Timoshenko beam theory and taking shear-deformation effects into consideration, the BEAM188 element is suitable for analyzing slender to moderately stubby/thick beam structures [24]. Along the length direction, each member is simulated with 4 BEAM188 elements, and along the perimeter of the cross-section of the member, the cross-section of each member is divided into 8 parts (Fig. 2). The definition of different plasticity development degree on the cross-section of BEAM188 element is shown in Fig. 3.

The elasto-plastic constitutive model is used for the steel. The yield strength and Young's modulus of the steel is 235 MPa and 2.1×10^5 MPa, respectively. The uniformly distributed vertical load is applied over the whole span of the structure. For each analytical model of the dome, the geometrically and materially nonlinear