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Designing efficient grid structures considering structural imperfection sensitivity

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ABSTRACT

At the initial design stage of a grid structure, shape optimisation is an effective way to find the optimal structural form. However, most of the shape optimisation methods do not take into consideration the imperfections, thus the actual buckling load capacity of the optimised structure is usually low. In this paper, an improved shape optimisation method is proposed, one that is considering the effect of structural imperfection sensitivity. In this method, the bending strain energy ratio is taken as a constraint, and when the total strain energy decreases, yet there is a certain proportion of bending strain energy in the structure. Consequently, the resulted shape is not sensitive to the initial geometry imperfection, and therefore, an efficient structure with higher buckling load capacity and low imperfection sensitivity is obtained. In order to evaluate the redundancy performance of the optimised structure, an index called structural overall redundancy, based on damage model is proposed herein. The damage model is simulated by removing a key rod of the structure. The results demonstrate that the overall redundancy of the structure obtained by the proposed method is higher than that obtained by the traditional method, thus an optimal design of a grid structure is obtained.

1. Introduction

In recent years, grid structures have become popular structural typologies thanks to their splendid visual effects and the capacity to cover large spaces with an uninterrupted span, see Fig. 1 [1]. They are widely used in a variety of building types, such as exhibition pavilions, stadiums, assembly halls and protective shelters [2]. People often marvel at the lightness of the structure and the fluidity of the lines. However, why are grid structures inherently beautiful? According to Malek and Willians [3], the aesthetics come with their superior structural efficiency since fewer materials are needed to resist such high loads. However, it is not an easy task for engineers to determinate the final optimal shape that respects architectural requirements and is structurally efficient at the same time. For this reason, the architectural aspects should always be treated together with the structural ones in the initial design phase of a grid structure.

For this reason, shape optimisation based on the structural performance is usually employed to the form-finding of grid shell structures. After years of research, many form-finding techniques have been developed such as the force density method, dynamic relaxation, updated reference strategy, and the particle-spring system method. Feng et al. [4,5] studied the shape optimisation of cable-braced free-form grid structures with the aim of reducing structural strain energy. Structural shape optimisation was realised by adjusting the generatrix and directrix rather than optimising the whole surface, as shown in Fig. 2, which improved the optimisation efficiency and resulted high engineering practical value. Winslow [6] proposed a novel algorithm to simulate the entire optimisation process of grid structures based on a traditional genetic algorithm (GA).

At a wider scope, Hawdon-Earl and Tsavdaridis [7] developed a standard and robust methodology for RC shell design for a complex site shape. The methodology uses Oasys GSA and Abaqus which allow both form-finding analysis and dimensioning to be conducted. The roof of Akrotiri, an archaeological site in Santorini island, Greece, was designed by this method and proved its applicability. Bochenek [8] studied the optimization of structures against instability, and the nonlinear behaviour of designed elements is considered. According to his research, different optimization designs can be obtained by including nonlinear structural behavior in the representation of optimization problems compared with traditional methods. Cui and Yan [9,10] proposed many advanced structural morphosis techniques, such as the extended evolutionary structural optimisation method and the height

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(a) Dalí Museum in St. Petersburg, Florida. (b) Singapore's Changi Airport

Fig. 1. Single-layer grid structures.

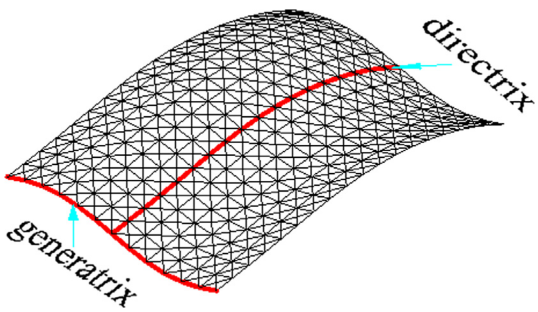

Fig. 2. Shape optimisation of free-form cable-braced grid structure.

adjusting method. With these methods, different architectural forms were obtained by changing different kinds of design parameters such as constraints or space conditions according to the designer's needs. All of the architectural form achieved by the above two methods can keep the structure in a mostly uniform axial-stress state and with the bending moment controlled. The shortcoming of the methods is that they did not consider the effect of the geometry imperfection on structural mechanical performance. Maggie et al. [11,12] proposed a two-stage optimisation algorithm based on GA. Then, Kociecki and Adeli [13] extended the algorithm to shape optimization of the structures, which was performed simultaneously with size and topology optimization, and a free-form surface grid roof (Ottawa Railway Station) was studied by using the algorithm that resulted in a lightweight structure. Ding et al. [14] presented a node-shifting method for shape optimisation of reticulated spatial structures to enhance their stiffness. With the constraint of volume, jagged surfaces were automatically smoothed during the volume adjustment process, thus no extra smoothing procedure is required. The method was suitable for many types of single-layer grid structures including those with cantilevered parts. Liu et al. [15] proposed a modified double-control form-finding (MDFF) method for suspendomes considering the construction process and the friction of cable–strut joints. The incremental equilibrium equation is built to include geometric nonlinearity based on the total Lagrangian increment formulation. The results showed that the proposed method can provide more accurate nodal coordinates and cable forces of the initial geometry state. The nonlinear analysis and the optimum design of cable domes are studied by Yuan et al [16]. They considered two optimal variables, including prestress level and cross stress, respectively. The numerical results showed the accuracy and validity of the nonlinear analysis model and the optimum algorithms, which also indicated that their work is very useful for understanding the behaviour of cable domes.

It is well known that geometrical imperfection may cause a significant reduction in the buckling load capacity of shell structures. The optimisation for the buckling load capacity of shell structures has been investigated by Rritinger [17], Ohsaki [18], and Ohuchi [19]. Ohsaki [20] summarized the existing methods of design sensitivity analysis and optimization of elastic conservative finite-dimensional systems with respect to nonlinear buckling behavior and presented a new optimization results of flexible truss. It is worth to note that the buckling load capacity of the single-layer grid structure is also greatly influenced by the initial geometric imperfection. Sometimes even a small geometric imperfection can lead to a significant reduction in buckling load capacity.

In general, during shape optimisation of a single-layer grid structure, the structural total strain energy is usually set as the objective function. Rational structural shapes with high buckling load capacity are obtained by minimising the total strain energy. After the optimisation, the axial strain energy is dominated and there is little bending strain energy in the structure. Since the structure is dominated by axial compression, the imperfection sensitivity is gradually enhanced. However, if the structure is dominated by bending strain energy, the structure will be insensitive to geometric imperfection. In this case, the total strain energy will be large and the buckling load capacity of the structure will not be too high. Consequently, it is important to understand how to determine the relationship between the total strain energy and the bending strain energy. In the method proposed in this paper, while reducing the total strain energy, a certain proportion of bending strain energy in the structure is ensured. With this way, a rational shape with higher buckling load capacity and lower imperfection sensitivity can be obtained.

In the literature, researchers have tried to minimise the influence of the geometrical imperfection on the buckling load of the single-layer grid structure. However, the subject of the presented work is to demonstrate how to find a better shape of a single-layer grid structure which has both higher buckling load capacity and lower imperfection sensitivity. This can be achieved by adding the ratio of bending strain energy as another constraint based on the traditional shape optimisation method, in order to control the bending strain energy of a grid structure and reduce the structural imperfection sensitivity. In addition, with respect to the obtained shape based on the improved optimisation scheme, the structural redundancy performance is investigated.

2. Method of shape optimisation

2.1. Definition of imperfection sensitivity

The imperfection sensitivity is expressed as follows.

$$\varphi = \left|\frac{P_d - P_i}{P_i}\right| \times 100\% \tag{1}$$

where P_d is the buckling load of the structure considering initial geometric imperfection; P_i is the buckling load of intact structure; the larger φ the greater influence of initial geometric imperfection on the buckling load of the structure and the more sensitive the structure is. In this paper, the imperfection was implemented according to the first-order eigenvalue buckling mode and the maximum value is 1/300 of the structural span, which meets the requirements of technical specification for space frame structures [21].