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Collapse optimization for domes under earthquake using a genetic simulated annealing algorithm

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ABSTRACT

There are two primary collapse scenarios for single-layer latticed shells subjected to severe earthquake action: dynamic instability and strength failure. Of these, dynamic instability is the collapse scenario that must be avoided. First, taking the minimization of the standard deviation of the well-formedness as the optimization objective and the member sections as the optimization variables, an optimization model representing collapse scenarios for single-layer spherical shells is established. This optimization model also accounts for the displacement and stress constraints. Second, a genetic simulated annealing algorithm (GASA) is proposed by combining a genetic algorithm (GA) and a simulated annealing algorithm (SA). Finally, partial and overall optimizations are performed for a single-layer spherical shell that collapses due to instability under earthquake action. The results show that the optimized structure is subject to ideal strength failure under earthquake action with clear warning signs prior to collapse. In addition, the GASA performs better than the GA for optimization. Therefore, it is concluded that the optimization model and method presented in this paper can be used to perform collapse scenario optimization for single-layer spherical shells subjected to earthquake action.

1. Introduction

Reticulated shells are widely used in public buildings, such as stadiums and exhibition centers, because they have an elegant shape, can withstand reasonable loading, can provide long spans and are cost effective. These shells have achieved great popularity and have become the most widely used spatial structures in the last half-century (Fig. 1). In earthquake zones, reticulated shells that collapse suddenly under unexpected earthquake action can endanger lives and cause major losses to the economy. Therefore, it is necessary to control and optimize the collapse of reticulated shells subjected to earthquake action. Reticulated shells belong to a class of highly statically indeterminate structures and have completely different dynamic characteristics than high-rise buildings. Meanwhile, earthquakes are uncontrollable and unpredictable. Consequently, the failure mechanism of reticulated shells is complicated, and engineers face major difficulties in the control and optimization of collapse scenarios for this type of structure [1].

Recent in-depth research on the optimization of latticed shells under static loads has been widely performed, and optimization methods have developed significantly. Early approaches to optimization consisted primarily of the optimality criteria method and mathematical programming. However, these two approaches are difficult to apply to the optimization of actual structures [2]. Intelligent algorithms have gradually been applied to structural optimization, as they are not limited by the continuity or differentiability of objective functions and constraint equations. The commonly applied intelligent algorithms include the genetic algorithm [3], the simulated annealing algorithm [4], the bee colony algorithm [5], the ant colony algorithm [6], the harmony search method [7], the big bang-big crunch algorithm [8] and the mine blast algorithm [9]. Nonetheless, actual structures inevitably bear some dynamic loading or action. Therefore, some researchers have conducted studies on the optimization of structures under dynamic action. Structural dynamic optimization primarily includes dynamic characteristic optimization and dynamic response optimization. Structural dynamic characteristic optimization takes the inherent frequency as the objective function or constraint equation and pushes it far from the range of the dynamic loads to prevent the structure from resonating [10–15]. Structural dynamic response optimization is a procedure that takes the response of a structure, such as velocity, displacement and strain, as the objective function or constraint equation [16–24]. Structural dynamic response optimizations can be visualized. However, the calculations are extensive. In addition, single-layer reticulated shells are prone to collapse due to instability under earthquake action. Therefore, it is necessary to consider collapse scenario optimization problems for this type of structure subject to earthquake action.

This paper first introduces the two collapse scenarios for reticulated shells subjected to severe earthquake action. Next, based on the failure mechanism of reticulated shells described in the literature [25], an optimization model for collapse scenarios for single-layer latticed shells is

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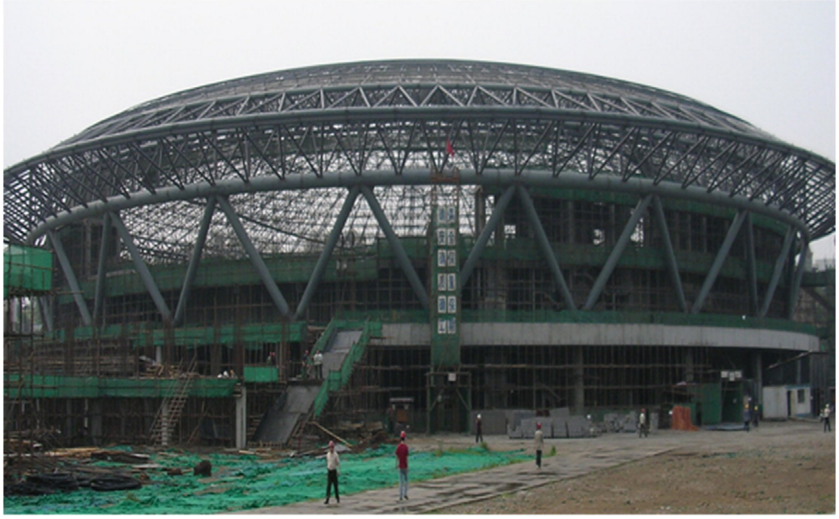


Fig. 1. Laoshan Velodrome built for the Beijing Olympic Games.

established. Next, a genetic simulated annealing algorithm (GASA) is proposed by combining a genetic algorithm with a simulated annealing algorithm. This combined algorithm uses the genetic algorithm as its primary process and integrates it with the simulated annealing mechanism. Finally, taking a single-layer spherical shell as an example, partial and overall optimizations are performed using the GA and the GASA, respectively. It is concluded that the GASA performs better than the GA for complex structural optimization problems with multiple variables. Therefore, the optimization model and method presented in this paper can be used to perform collapse scenario optimization for single-layer spherical shells subjected to earthquake action.

2. Collapse scenarios for single-layer latticed shells

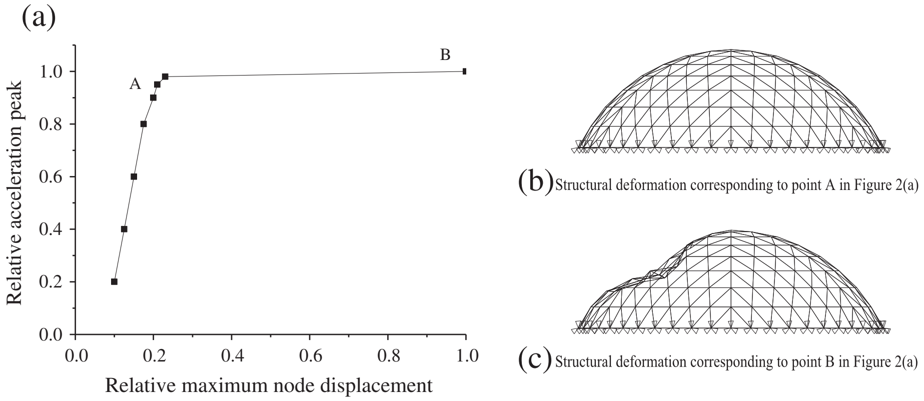
Many theoretical calculations and testing results indicate that there are two main collapse scenarios for single-layer latticed shells subjected to severe earthquake action: dynamic instability and strength failure [26]. Geometrical nonlinearity plays a more important role in the dynamic instability collapse scenario. Fig. 2(a) shows the relative load peak–relative maximum nodal displacement curve of a typical dynamic instability collapse scenario. It can be concluded that with an increase in the intensity of dynamic loads, the increase in nodal displacement is relatively small, and there are no clear excursions from the balance position of the structural vibration; neither is there a clear reduction in structural rigidity (Fig. 2(b)). When the excitation reaches a critical peak, the nodal displacements suddenly increase, and partial or total structural collapse occurs (Fig. 2(c)). In the dynamic instability scenario, the ductility and energy dissipation of the reticulated shell are relatively poor, and its destruction is typically sudden.

Fig. 3(b) shows the relative load peak–relative maximum nodal displacement curve of a typical strength failure scenario. The nodal displacement gradually increases as the intensity of the dynamic load increases. Meanwhile, structural stiffness degenerates gradually. The structure collapses when it cannot maintain a stable vibration state (Fig. 3(b)–(c)). There is large deformation before structural failure. In the strength failure scenario, the ductility and energy dissipation of the reticulated shell are high, and the structure shows clear signs of damage prior to collapse. In this collapse scenario, this damage can attract attention after the structure is subjected to small earthquakes that are more frequent, allowing for timely repair of the damaged structure so that collapse caused by a larger future earthquake can be avoided. Therefore, strength failure is the ideal structural collapse scenario for preservation and safety.

3. Optimization model of collapse scenarios for single-layer latticed shells

3.1. Optimization objective

The structure vulnerability represents the susceptibility of a structure to any external actions. It reflects the tolerance of the structure to accidental damage. A structure is vulnerable if any damage produces



(b) Structural deformation corresponding to point A in Figure 2(a)

(c) Structural deformation corresponding to point B in Figure 2(a)

Fig. 2. Dynamic instability of a single-layer latticed shell. (Note: In panel (a), the vertical axis is the ratio between the acceleration peak and the limit acceleration peak, and the horizontal axis is the ratio between the maximum nodal displacement and the maximum nodal displacement corresponding to structural failure that occurred.)