Construction and Building Materials 171 (2018) 96–108

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Improving the progressive collapse resistance of long-span single-layer spatial grid structures

Jian-peng Wei, Li-min Tian *, Ji-ping Hao

School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, PR China

HIGHLIGHTS

- Four specimens were tested on a spatial loading system for simulation calibration.
- Multi-scale technology was adopted to save resources and increase accuracy.
- A novel method including two aspects is proposed to resist progressive collapse.
- Strength and stability failure are prevented by the novel method.

ARTICLE INFO

Article history:
Received 6 December 2017
Received in revised form 12 March 2018
Accepted 16 March 2018

Keywords:
Single-layer spatial grid structure
Progressive collapse
Substructure
Multi-scale
Reinforcement

ABSTRACT

The progressive collapse of long-span single-layer spatial grid structures, which are widely applied in public buildings, is a hot research topic in structural engineering. Four substructure experiments were conducted, and two types of failure were observed: strength and stability. Based on the experimental results, a numerical simulation using multi-scale technology was calibrated. A novel method including kinked steel pipe reinforcement and extra member reinforcement was proposed and validated by numerical simulation. Kinked steel pipe reinforcement is a local reinforcement method that prevents strength failure. The shape of the kinked steel pipe was determined through single-member analysis. Simulation results showed that the bearing capacity and deformation were improved simultaneously. The increase in the potential energy induced by member removal was absorbed into the strain energy. Extra member reinforcement is a global reinforcement method that prevents stability failure. Eigenvalue and nonlinear buckling analyses were adopted to locate the extra members. The extra member reinforcement was applied in the anti-collapse analysis of two typical domes. The results validated that extra member reinforcement is a powerful technique for resisting progressive collapse.

1. Introduction

Thanks to continuous socioeconomic and cultural development, a large number of public buildings continue to be built. However, local failure in accidents can lead to the partial or entire collapse of a structure, which causes huge economic losses and heavy casualties [1,2].

Long-span single-layer spatial grid structures possess a graceful shape and excellent mechanical properties and thus are widely applied in public buildings. Therefore, research on its progressive collapse resistance has gained increasing interest. Zhao et al. [3] tested two identical single-layer latticed domes under different load conditions and revealed the anti-collapse mechanisms for the member-loss scenario. Han et al. [4] conducted a progressive collapse experiment on different single-layer latticed domes and proposed three evolution methods. Yan et al. [5] analysed the stability of reticulated domes with eight different grid forms and identified progressive and synchronous instability patterns. Tian et al. [6] presented an evaluation method of important members and a novel dynamic analysis method for long-span spatial grid structures.

The above studies provided experimental or analysis methods for single-layer spatial grid structures but all of the methods are limited to conventional structures. The aim of this study was to improve the progressive collapse resistance of a single-layer spatial grid structure by developing a novel method to optimise conventional structures. This type of study commonly considers frame structures [7]. Previous studies have presented two kinds of methods: local reinforcement and global reinforcement. With local reinforcement, a new configuration of reinforcing members is applied in a local region to increase the deflection of beams [8–10] and

---

* Corresponding author.
E-mail address: tianlimin701@163.com (L.-m. Tian).

https://doi.org/10.1016/j.conbuildmat.2018.03.126
0950-0618/

cause the catenary mechanism to develop more fully. Additional steel plates can be utilised in reinforced concrete frames [11,12] and steel frames [13–15] to prevent or mitigate the initial fracture of beams. Global reinforcement methods commonly arrange extra reinforcing members at the mid-height of the concrete section [9,16–18]. Note that the post-tensioned steel frame has been demonstrated to be a favourable structural form for resisting progressive collapse [19]. Another effective technique is using auxiliary members, and their layout is critical for the retrofitting effect [20,21]. An advanced method to prevent collapse is using composite materials [22,23].

Based on the above reinforcement methods for frame structures, the proposed method includes two aspects to improve the resistance of single-layer spatial grid structures. First, a kinked steel pipe is welded to the interface between a member and joint. Second, extra members are added based on buckling analysis. Four substructure experiments were performed to obtain the two types of failure corresponding to the two aspects of the proposed method: strength and stability. The experimental results were employed to calibrate a numerical simulation for validating the proposed method. Multi-scale technology [24,25] was utilised in the simulation to save resources and increase the calculation accuracy.

2. Experimental study

2.1. Test specimens

The triangle grid is frequently applied in single-layer spatial grid structures because of its good stability. Considering the different mechanical properties of members, two substructures with triangle grids were selected, as shown in Fig. 1. When a member is in a horizontal state, the internal forces consist of the bending moment and tensile force. If there is a certain amount of inclination, the axial pressure dominates the internal force. Consequently, these substructures can be used to comprehensively reveal the typical failure patterns of a single-layer spatial grid structure, which was a part of experimental study for anti-progressive collapse mechanism of long-span single-layer spatial grid structures [26]. In addition, it is a superb benchmark to calibrate the numerical simulation.

Fig. 2 presents axonometric drawings of four specimens that were derived from the above substructures. Inclinations of 0° and 30° were chosen, and the member-loss scenario was considered. The nomenclature I-0 (30) and D-0 (30) was applied: I indicates an intact substructure, while D indicates a damaged substructure with a single member removed; 0 and 30 indicate the member inclination in degrees. Double inner steel pipes (Φ94 mm × 3.5 mm) were installed at the end of the members to ensure the welding quality. Fig. 3 presents the specimen details. In order to simplify the test apparatus, a fixed boundary was adopted for peripheral connections, and the specimens were inverted to sustain an upward load. Grade Q235 steel was used for all components, except for the hollow spherical joint (Grade Q345 steel). Because of the importance of the circular steel pipe (dimensions: Φ102 mm × 3.9 mm), its mean material properties were derived in six coupon tests and are presented in Table 1.

Fig. 1. Substructures of a single-layer spatial grid structure.

2.2. Test setup

For the test, a self-balancing spatial support system was adopted, as shown in Fig. 4. A cooperating vertical reaction frame was used to apply an upward load. A 1000 kN actuator was utilised, and its loading end was connected to a hollow spherical joint with no restraint on the rotation. Note that this was a quasi-static test, so the loading speed needed to be limited within an appropriate range for different member inclinations.

2.3. Test results

Fig. 5 shows the load–displacement curves of four specimens to illustrate two types of failure for a single-layer spatial grid structure: strength and stability. For specimens I-0 and D-0, the members deformed from bending to stretching before reaching the peak load, and the centre joints experienced a vertical displacement over 250 mm. Favourable deformability was observed in the two specimens. As the material reached the ultimate strength, some of the members fractured, and strength failure occurred, as shown in Fig. 6. However, there was no obvious test phenomenon before the stability failure of specimens I-30 and D-30, while the bearing capacity increased rapidly. After the sudden buckling of the first member, the bearing capacity decreased sharply, and two specimens rotated counter-clockwise, as shown in Fig. 7.

Although members in compression can bring superior bearing capacity, the stability failure occurred rapidly and without obvious warning compared to the strength failure. In the design process, the redundancy of the compression structure should be increased to avoid stability failure.

3. Calibration of the numerical simulation

3.1. Multi-scale technology

The key to multi-scale technology is establishing a connection between two elements of different scales. Ideally, three equations should be satisfied at the connection interface: the force equilibrium equation, compatibility equation of deformation, and material constitutive equation (Eq. (3)). These are given in order below:

$$\sigma_{ij,j} + f_i = 0 \tag{1}$$

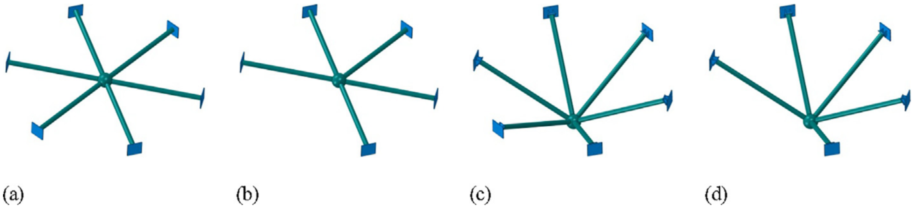

Fig. 2. Axonometric drawings for specimens (a) I-0, (b) D-0, (c) I-30, and (d) D-30.