Study on progressive collapse resistance of single-layer reticulated shells

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Abstract: In order to analyze the progressive collapse resistance of single-layer reticulated shells, the finite element model of single-layer reticulated shell structure was established by ABAQUS software, and the method of removing key component constraints was used to simulate the progressive collapse resistance of the single-layer reticulated shell structure. The results show that the removal of the key components can cause the continuous failure of the upper members of the reticulated shell, and then lead to the progressive collapse of the whole structure.

1. Introduction

The single layer reticulated shell structure with orthogonal and oblique combination is a kind of space truss structure. It is based on the struts, forms a grid according to certain rules, and arranges the space truss according to the shell structure. So it has the properties of the struts and shells and the advantages of large span, small deformation, reasonable stress and large stiffness. It is mainly used in some buildings with large span and large space requirements, such as some factories, the construction of sports venues. Due to the large span of the single-layer reticulated shell structure, the space utilization ratio is relatively sufficient and it is easy for the central reticulated shell structure to collapse continuously due to the destruction of columns which leading to the destruction of the whole structure. This kind of damage to the single-layer reticulated shell structure is very large.

At present, many researchers in China have studied the continuous collapse performance of different structures. The method of extraction column simulation was carried out on a steel frame structure collapse in reference [1]. They mainly analyze the continuous collapse resistance of steel frame structure from two perspectives of different failure locations and different failure times, the influence of vertical cycle was obtained in 1/10 can be well characterized the structure failure under the dynamic response of the state. By comparing the resistance increase coefficient, the short failure time should be given priority to with dynamic analysis research of the structure of the collapsed ability continuously. And for the long failure time, the dynamic analysis and static analysis results are basically identical, the static analysis is able to replace the dynamic analysis for the characterization of structural dynamic response. Reference 3 took the steel truss of Hubei Olympic Sports Center as an example, analyzed the mechanism of internal force redistribution against continuous collapse, and concluded that attention should be paid to the internal force redistribution process of the main truss and suspended structure of the steel truss in order to ensure the anti-collapse function of the structure. In the case of continuous collapse resistance, it is necessary to analyze the function of the whole structural components to determine the key
components of the whole structure, improve the redundancy of the structure, and ensure the multi-load transfer path. Reference 4 discussed the design of support resistance against continuous collapse of truss structures from the aspects of system stress and support joint design, through bearing structure optimization to improve the safety of the whole structure. In Reference 5, the static linear elastic method based on GSA code is used to study the collapse resistance of 5 span and 6 storey plane steel frame structure, that is, the DCR (the ratio of internal force and bearing capacity of the remaining structural members) is used to judge whether the remaining structure has the ability to resist continuous collapse. It is concluded that the static linear elastic method is more conservative than the static nonlinear method and the dynamic nonlinear method, and the latter two methods can be used to accurately study the anti-collapse performance of the structure. In reference 7, progressive collapse analysis of seismically designed, special moment resisting steel frame buildings is presented. The analysis model and the assumptions needed to create it are described and the results of a simulation in which a critical structural member is removed are shown.

There are few research on the collapse performance of single-layer reticulated shell structures in China. Therefore, in order to understand the collapse performance of single-layer reticulated shell structures, this paper will use the method of removing the bottom constraint of columns to simulate the collapse of single-layer reticulated shell structures under sudden loads. In this paper, the impact of the removal of different column bottom constraints on the collapse displacement of the whole structure is compared mainly with the removal of the column bottom constraints at the maximum displacement. Finally, the key columns of the single-layer lattice shell structure are determined.

2. Finite element model

2.1. The geometric model
The span of the single-layer reticulated shell structure is 72 m and the length is 336 m. The middle part of the shell is composed of orthogonal and oblique beam elements, and the two sides are composed of truss elements.

2.2. Model materials and element types
Q345 steel, with young's modulus of 2.06×10^5 MPa, poisson's ratio of 0.3, density of 7860kg/m^3, yield strength of 310MPa, and coefficient of linear expansion of 12×10^{-6} °C, was used for the material of this single-layer reticulated shell structure. Flexible damage model is added to the structure in order to simulate the performance of continuous collapse. The middle shell is mainly truss beam element and the left and right sides are truss elements.

2.3. Constraints and load conditions
The load condition of the upper part of the single-layer reticulated shell structure is simulated precisely by increasing the dead weight load.

2.4. Analysis method
ABAQUS was used to analyze the single-layer reticulated shell structure, and the part with the maximum displacement and deformation was determined by adding dead weight load. Then the bottom constraint of this part of column was removed. In order to increase the reliability of the results, the left and right columns at the maximum displacement were also taken into account. Therefore, there were 6 columns at the maximum displacement, which were divided into three rows at the left, middle and right, and each row was divided into two columns at the top and bottom, as shown in Figure 1:
3. Results and analysis

3.1. Unconstraint
In order to verify the accuracy of the column with the maximum displacement, the six selected columns should be removed from the bottom constraint firstly to see whether the single-layer reticulated shell structure will collapse. Its collapse diagram is shown in Figure 3, and the load-displacement curve is shown in Figure 4:
As can be seen from Figure 3, after all the bottom constraints on the six columns were removed, the structure collapsed because the grid structure on the columns was not supported. All of the six columns were deformed to different degrees. The left and right columns were inverted to the two sides respectively, and the middle column moved downward with the collapse of the grid structure and had an angle with the normal position before.

It can be seen from Figure 4 that the displacement at the maximum node is close to 90cm, it has satisfied the maximum displacement caused by the burst load, and it thus proves that the selected six columns at the maximum displacement selected are more accurate.

As for the columns on the left and right sides that have not been removed, the stress has a sudden change at 0.9 seconds, and it indicates that the single-layer reticulated shell structure is under the simulated situation of sudden load. The stress diagram is shown in Figure 5:
Next, in order to determine which column or several columns are the key component of the single-layer reticulated shell structure, different combinations of these six columns were carried out.

3.2. Structural responses under different combinations of lateral restraints

The four columns on the left (No. 1, 2) and the middle (No. 3, 4) were combined and their bottom constraints were removed. Their collapse and displacement curves were shown in Figure 6 and Figure 7:

![Figure 6. Collapse diagram.](image)

As can be seen from Figure 6, under this combination of constraints, the structure collapsed. The columns that remove the constraint at the bottom collapse to the two sides respectively because of the collapse of the net frame above them. In addition, according to Figure 7, the stress still shows a small mutation at 0.9 seconds, and the displacement of the largest part of the collapsed structure is about 30cm. Although the change in stress was less than in the previous case, the results are reasonable as only four columns were removed. It can be inferred that the left and middle columns have an impact on the stability of the structure.

After that, the bottom constraints of the four columns in the middle (No. 3, 4) and on the right (No. 5, 6) were removed, and their deformation and displacement diagrams were shown in Figure 8 and Figure 9:

![Figure 8. Collapse diagram.](image)
As can be seen from Figure 8, under this constraint combination, the structure also collapsed, and its collapse displacement of about 50cm is very close to that of the previous combination. The stress at the bottom of adjacent columns also has a sudden change at 0.9 seconds. Thus, the combination between the middle columns and the right columns can also lead the structure to collapse continuously.

The four columns on the left (No. 1,2) and the right (No. 5,6) are combined, and the result is shown in Figure 10:

As can be seen from Figure 10, when these four columns were combined to remove their bottom constraints, the structure did not collapse. The network frame above these four columns was slightly deformed, and the positions of these four pillars were not greatly affected. Therefore, it is inferred that the combination of left and right columns has little influence on the stability of the single-layer reticulated shell structure. In order to obtain clearer comparison results, the left column (No. 1,2), the middle column (No. 3,4), and the right column (No. 5,6) were removed in order. In the case of these constraint combinations, the structure did not collapse, but only slightly deformed. The typical results are shown in Figure 11:
As can be seen from Figure 11, when the bottom constraints of left, middle and right columns are removed separately, the influence on the stability of the structure is relatively weak. It can be seen that only under the combination of left-center-right, left-center-left or right-center, can lead the structure to continuous collapse. It is impossible to remove the sole constraint of the column in these three areas alone to make the structure collapse continuously. In other words, the bottom constraint of two columns in the middle and any other area on both sides should be removed.

3.3. Structural responses under different combinations of longitudinal restraints
According to the previous combination, the combination of the middle column and any other columns on both sides can cause continuous collapse of the structure. Because there are two columns in each of the three areas on the left, the middle and the right. In order to get more accurate results, the columns in the three areas on the left, the middle and the right are divided into two rows on the top and the bottom according to the distance from the middle shell. The columns numbered 1, 3, and 5 are defined as upper column and the columns numbered 2, 4, and 6 as lower column. Next, the bottom constraints of the upper and lower columns should be removed to check their influence on the stability of the structure. The collapse results are shown in Figures 12-14:

![Figure 12. Collapse diagram.](image)

![Figure 13. Displacement and stress curve.](image)

The comparison between Figure 12 and Figure 14 shows that the removal of bottom constraints on the upper row of columns results in a large collapse displacement of the whole single-layer reticulated shell structure, while the removal of bottom constraints on the lower row of columns does not lead to continuous collapse at the structure of dismantled columns, and only slight deformation occurs. In addition, it can be seen from Figure 13 that, the bottom stress of the adjacent columns without the column bottom constraint removed also changed suddenly at 0.9 seconds, and the collapse displacement at the maximum displacement of this combination was close to 60cm, which was similar to the displacement at the maximum displacement of the combination with all six columns removed. It can be seen that the columns in the previous row (No 1, 3, 5) have a great influence on the stability of the single-layer reticulated shell structure. Therefore, it can be inferred that the columns in the upper row are the key columns of this structure.
3.4. Precise analysis based on longitudinal constraints

According to the previous results, the influence of the three columns (No.1,3,5) on the single-layer reticulated shell structure is the largest. In order to accurately understand the impact of the three columns in this structure, the three columns can be divided into the following three combination, namely the right column and intermediate column (No. 1 and 3), on the right side of the column, and the left column (No. 1 to 5) and intermediate columns (No. 3 and 5) on the left. The column bottom constraint was removed for these three combinations, and the specific results were shown in Figure 15:

Figure 15. Collapse diagram.

Figure 15 shows that the right column (No. 1) combined with the left column (No. 5), the single-layer reticulated shell structure of continuous collapse does not occur. The right side columns and the pole and the left column and the pole this two kinds of combination can make the structure collapsed in a row, and maximize the collapse of the displacement close to 50 cm, it is very close to the collapse of the previous section. And this also illustrates the conclusion of the second section, namely the right column (No. 1) and intermediate column (No. 3), the left column (No. 5) and intermediate column (No. 3), the combination of the two kinds of column bottom constraint demolished to make this single-layer reticulated shell structure collapsed. And the right column (No. 1) combined with the left column (No. 5) of the column bottom constraints removed does not make the structure collapsed. Therefore, combined with all the previous analyses, it can be seen that the three columns No. 1, 3 and 5 have the greatest impact on the stability of the single-layer reticulated shell structure, namely the key columns of this structure.
4. Conclusion

(1) It is reasonable and feasible to analyze the progressive collapse resistance of single-layer reticulated shells by removing the constraints of key components.

(2) The progressive collapse performance of the whole single-layer reticulated shell structure is affected by a single column, which is the result of the joint action of the columns at the maximum deformation of the structure under the static load.

(3) It is concluded that the combination failure of key components is the main factor affecting the progressive collapse resistance of single-layer reticulated shells.

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References

[1] Zheng W H 2012 Progressive Collapse Analysis of Steel Frame Structures under Floor Slab Influence Special Structures 37(03) 116-22

[2] Li W R 2018 Structural Stressing State Analysis of Plane Steel Frame Under Progressive Collapse Scenario (Heilongjiang: Harbin Institute of Technology)

[3] Zheng Z F 2020 Analysis and Mechanical Research on continuous Collapse Prevention of Body Building Steel Truss Science and Technology Innovation (14) 115-6

[4] Chen D P 2019 Research on the Design of Resistance to Continuous Collapse of Long-span Steel Truss Bracket Fujian Architecture 000(011) 52-56

[5] Xie F Z, Gu B and Lei I H 2019 Analysis and Evaluation methods for continuous collapse of Steel frame Structures Journal of Building Science 035(001)14-19

[6] Chen T P, Lv T, Tang W F and Li G 2019 Numerical simulation of the influence of columns on the progressive collapse resistance of frame structures based on ABAQUS Jiangsu architecture (4) 66-70

[7] Khandelwal K and El-Tawil S 2005 Progressive collapse of moment resisting steel frame buildings Conference Information Structures Congress 2005(New York) 2005 (Virginia: ASCE) 171220.

[8] El-Tawil S, Khandelwal K, Kunnath S and Lew H S 2007 Macro models for progressive collapse analysis of steel moment frame buildings Research Frontiers at Structures Congress 2007 (California) 2007 (Virginia: ASCE) 10.1061/40944(249)66.