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Research Progress of Long Span Steel Structures

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Abstract: The structure of the studio has the characteristics of large span, large clearance height and large hanging load. Based on the mechanical advantages of steel structure, large-span steel structure has been widely used in this kind of building. Due to the geometric characteristics of the structure and the distribution characteristics of roof load, the influence of horizontal seismic action and vertical seismic action on the mechanical properties of the structure is difficult to ignore. In this paper, the seismic performance of large-span studio steel structure is deeply studied based on the actual engineering.

Keywords: Large Span Studio Structure; Seismic Performance; Vertex Sideshift; Mid Span Vertical Deflection.

1. Introduction

With the rapid rise of China's economy and the continuous pursuit of cultural and artistic works, the film and television industry has achieved unprecedented development. In order to reduce the shooting cost and improve the level of film and television production, the demand for studios and film and television shooting bases is increasingly strong, and many large-span studios came into being. The studio is the most important production place for shooting interior scenes in film studios. In the early days, the studio was just a "big shed" with only a ceiling and scaffolding and leakage on all sides. The name of "studio" in China came from this. Because of various film and television shooting needs, the studio needs a large indoor space, and its structural form needs to adopt the structural system of large span and large space; Due to the needs of various indoor settings, the roof truss structure must have a large bearing capacity. When the structure is in normal use, it needs to bear a large hanging load. It can be seen that the studio structure is different from the ordinary long-span structure, which requires not only a larger span, but also a larger indoor clearance height and the roof has the ability to bear a larger hanging load, so the mechanical properties of this kind of structure are also different from the ordinary long-span structure.

In recent years, the large-span steel structure studio has shown outstanding social value and economic benefits due to its advantages of no shelter inside, open space, sufficient lighting, smooth ventilation, material saving and convenient construction. Therefore, this truss structure has been widely used in China and has shown a rapid development trend. The specific performance is shown in the following aspects: first of all, this kind of studio shows an obvious trend of large-scale in size. According to incomplete statistical data, many super large spatial structures with a span of more than 150 meters have been built in China, which fully reflect the excellent ability of large-span steel structures in expanding the spatial scale of buildings. Secondly, the large-span steel structure studio shows rich diversity in structural form. With the continuous innovation and progress of new material science and technology, as well as the maturing of construction technology, new spatial structures under different design concepts continue to emerge, which further widens the possibility of the shape design of this kind of studio, so that it can adapt to the diversified functional needs and aesthetic pursuit. To sum up, the large-span steel structure studio has won wide acceptance and promotion in China's construction industry by virtue of its unparalleled spatial advantages and technical adaptability, and has shown a vigorous development in both dimensions of scale expansion and form innovation, indicating that in the future, driven by new materials and new technologies, more unique large-scale spatial structures are expected to emerge.

2. Development Status of Large Span Spatial Structures Abroad

Large span spatial structures are widely used in the design of multi-functional stadiums, international top sports venues such as Olympic venues, large exhibition centers and Expo venues, as well as modern airport terminals. For example, Japan's Fukuoka gymnasium, completed in 1993, was once the world's largest open and closed steel roof gymnasium because of its unique openable steel roof design with a diameter of 222m. With the progress of new material technology and engineering technology, it has also launched innovative works. The double-layer Glulam arch is used as the support system to cover the double-layer membrane structure of the pavilion dome. Its unique oval plane size reaches 78m×157m, which effectively promotes the status of membrane structure technology as a new generation of space structure with great development potential in the world. In addition, the previous Olympic Games, world expositions and other activities have also become important milestones in the technological evolution of long-span spatial structures. For example, the main stadium of the 2012 London Olympic Games, commonly known as the "London bowl", has a construction area of more than 161800 m^2 and is still known as one of the most spectacular large-span spatial structures in the world. These magnificent buildings not only attract attention because of their large scale, but also bring together all kinds of cutting-edge technology and design concepts. Many of them have become world-renowned landmark cultural landscapes.

Daniel [1] and others conducted in-depth research on a large-span steel frame structure, and discussed the effect of vertical seismic load on this kind of structure. The research shows that when subjected to vertical seismic force, the vertical deflection response and acceleration response of the structure in the middle of the span are significantly enhanced compared with the horizontal seismic action, especially in the long-span structure, the component is the most sensitive to the vertical seismic effect, and the impact is more prominent. Chopra[2] refined and summarized a calculation method that can fully consider the contribution of multiple vibration modes and accurately evaluate the stability of arch structure by implementing the elasto-plastic dynamic analysis of spatial arch structure. Goel [3] selected the long-span cantilever steel truss structure as the research object, established the corresponding steel truss structure model by using a variety of finite element software, and compared and analyzed the natural vibration frequency, dynamic performance characteristics of the structure, as well as the dynamic response performance under different seismic waves. Shama et al. [4] conducted in-depth research on four different types of stadium roof structures, and analyzed the dynamic characteristics of these four types of roof structures one by one by combining the vibration experimental data with finite element simulation.

Kim et al. [5] took the steel frame structure as the research object, conducted in-depth research on its seismic performance under earthquake, and compared its seismic performance with the results obtained by several static analysis methods. The results show that if the inclined support system is configured in the cantilever part, the continuity and integrity of the whole structure can be effectively improved, and then the lateral displacement of the structure can be reduced, and the seismic capacity of the structure can be enhanced. Moehle [6] explored the seismic performance of a specific truss structure. The research shows that the overall seismic performance of the truss structure is good, and the influence of the performance of each component unit on the seismic performance of the overall structure cannot be ignored. Therefore, when designing similar structures, we must pay attention to strengthening measures for weak areas. Bozorgnia et al. [7,8] and their team conducted in-depth research on the vertical vibration characteristics and the relationship between them and the horizontal vibration components based on the acceleration records of the free site, and finally successfully designed a simplified model based on the vertical response spectrum. Japanese scholars [9-11] based on the restoring force model of the actual axial compression members, used the elasto-plastic time history analysis method to conduct a detailed research and Analysis on the seismic response of the grid structure under the vertical seismic action, and scientifically evaluated the influence of the global buckling phenomenon and the local buckling of the members on the seismic performance of the structure.

Charney et al. [12,13] used the dynamic analysis method to deeply explore the internal relationship between the whole grid structure and its constituent units. The research results showed that there was a close interdependence between the overall stress state of the structure and the state of each independent unit. If the individual unit in the grid structure loses its function for various reasons, it will significantly affect the stability of the overall structure. Specifically, once one or a group of members bearing important loads lose their original bearing capacity, it will trigger the reconfiguration of the internal force of the structure, and then trigger the dynamic response of other surrounding members. In this case, even under normal load conditions, the structure may lose stability instantly, and then collapse [14-16]. Kennedy et al. [17] noted that although many steel structures are built in accordance with seismic design standards, the problem of insufficient protection may still occur under the action of actual earthquakes. Therefore, the seismic action is deeply studied. The final research results show that through the time history analysis of the specific corner column of the steel structure, it is found that the stress of the column changes greatly under the vertical seismic action; The conclusion of nonlinear time history analysis also confirms this phenomenon. Based on this result, he believes that the impact of vertical seismic action on steel structure frames must be fully considered in the seismic design code. Xuesuduo et al. [18] reviewed the theoretical methods and application research results of large-span spatial structure cooperative work, and summarized the research and development process of large-span spatial structure cooperative work. On this basis, the applicability of the current soil structure interaction calculation model in solving the problem of long-span spatial structure cooperative work is analyzed. At the same time, the selection strategy of damping ratio of long-span spatial structures under cooperative working state is systematically summarized. Yin Yue et al. [19] introduced the concept of generalized mode participation mass to quantify the dominant motion direction of each mode in the vibration process of long-span spatial structures. By setting a certain proportion threshold of the sum of the generalized mode participation mass to the total mass of the structure, the number of effective modes that should be included in the combined analysis in the mode decomposition response spectrum method of long-span spatial structures is reasonably determined.

To sum up, foreign scholars' research on space truss structure started relatively early. Scholars from various countries have done a lot of research on the bearing capacity of truss intersecting joints, structural dynamic performance, structural static and dynamic yield, and achieved corresponding results [20-22]. However, the seismic design theory of large-span space structures under earthquake is still immature and needs to be constantly improved. According to the actual project, the seismic performance of different types of structures is analyzed, and the failure mechanism of weak area components of various structures under different earthquakes is summarized, so as to design reasonable seismic mitigation measures. In addition, the seismic research methods of spatial structures should be further improved to ensure the accuracy of the calculation results while improving the calculation efficiency.

3. Development Status of Large Span Steel Structure Space Structure at Home

The terminal building of Guangzhou New Baiyun International Airport, as a large-scale hollow tube structure representative work in China at that time, its main structure was completed in 2004, achieving a 76.9m long-span design. The roof steel structure system of the terminal uses circular and square steel tubes as the main building materials to build a streamlined curved roof. In particular, the innovative inverted triangular three-dimensional truss section design was adopted in the interior of the roof, which was the first time that the triangular tapered section herringbone column technology was applied in engineering practice in China. Combined with the large-span roof box profiled steel plate project, it showed advanced engineering and technical strength at that time [23]. The Nanchang International Sports Center Stadium, which was completed in June 2011, adopts the roof system of space pipe truss steel structure. The roof plane layout of the stadium is a ring structure, the diameter of the outer ring is 287.7m, the length of the inner ring in the long axis direction is 212m, and the width in the short axis direction is 141.7m. There are 96 main trusses as radial supports in the whole structure, and 5 ring trusses are configured to enhance stability. The support part includes "V" shaped support, unidirectional diagonal support, and some edge trusses. A total of 192 cast steel joints are used to realize the stable connection and stress transfer of the overall structure [24].

The steel roof system of Hengyang gymnasium [25] built at the end of 2014 integrates radial and plane circumferential truss structures, with an overall peripheral diameter of 96m. The structure has a total of 36 bearings. The inner bearings are distributed in the circular arc section with a diameter of 71m, while the outer bearings are located in the circular arc position with a diameter of 86m. In order to effectively deal with the problem of concentrated stress on the truss, the design team added a pressure ring truss at 22m in the center of the structure, which not only strengthens the structural stability, but also meets the needs of the appearance modeling of architectural design. In January 2016, the expanded T3 terminal building [26] of Wuhan Tianhe International Airport was completed. The maximum cantilever length of the structure is 37.5m. The roof bridge structure adopts a three-dimensional space pipe truss structure with a span of 122m. Some joints adopt cast steel joints. The column top adopts a combination of rigid connection and hinged connection. The rigid connection area adopts intersecting welded joints, and the hinged area adopts spherical steel joint bearings. In September 2020, the construction of Lu'an Sports Center Stadium [27] was completed. The overall structure adopted the design scheme of combining cantilever truss and V-shaped steel column. Among them, the maximum extension distance of cantilever section reached 31m, and the main truss adopted spatial triangle truss structure. In order to enhance the structural stability, a plane truss is added between the radial main trusses; Two sets of inverted triangle space trusses and three plane trusses are set for the circumferential secondary truss, and horizontal supports are set at the upper chord.

In China, the research on seismic performance of long-span space truss structure is still in the initial and development stage, especially in the specific seismic performance of long-span space truss, the literature and practical experience are relatively limited. The main direction of research work is at the macro level of mechanical performance, stability characteristics and integrity of the overall structure. However, the construction of standardized system for seismic design criteria and seismic mitigation technology of long-span space pipe truss structures is not yet mature and perfect. At present, the research on the dynamic characteristics and seismic performance of such long-span spatial structures in China mainly relies on the practice of actual engineering projects, resulting in insufficient in-depth analysis of the overall seismic performance of the structure, which is difficult to fully meet the needs of structural optimization design and new construction in areas with different seismic fortification intensities.

Luoyongfeng et al. [28] studied the distribution law of the internal force coefficient of structural members when analyzing the seismic performance of the roof of Qingdao Grand Theater. The effect of vertical earthquake on the internal force of the roof structure is relatively small, while the safety performance of the supporting members around the roof is relatively low under the horizontal earthquake. Chenmeng et al. [29] conducted an elasto-plastic time history analysis on the building structure of Pudong Cadre College, and deeply explored the member bearing capacity and deformation distribution characteristics of the structure under the influence of seismic load. Yangfugang et al. [30] conducted a detailed seismic response study on a specific long-span spatial latticed shell structure, and the results showed that the response performance of the structure during the earthquake was not only closely related to its own inherent vibration characteristics, but also significantly related to the type of seismic load. Wangfangli [31] conducted in-depth research on a stadium building with a span of 290m, compared the different influence degrees of single earthquake action and combined earthquake action on the building structure, and further discussed the regular changes of structural node displacement response under the action of earthquakes in different directions. At the same time, how the difference of traveling wave propagation velocity leads to the change of structural response characteristics is also analyzed in detail. Yu Jinghai [32] conducted in-depth discussion and Analysis on the hinge sequence and failure principle of the structure under the rare earthquake action for a specific space steel truss viewing platform.

Li Lu [33] took the pipe truss roof structure of Suzhou railway station as the research object, and used the response spectrum method to conduct an in-depth analysis of the maximum displacement difference of long-span and short-span partial nodes under the influence of a variety of seismic combinations, aiming to find out the vulnerable links in the whole structure and determine the performance of the structure under extremely adverse conditions. Sun Changqing [34] selected the building cover structure of the main station of Qingdao north railway station as a research case, and systematically explored the seismic response law of the structure under different seismic combined loads with the help of finite element analysis software. Through the implementation of static analysis and time history dynamic analysis, he successfully revealed some key dynamic characteristics of this kind of structure. Tang Lichun [35] took a specific gymnasium roof steel truss project as the research background, and carried out the elasto-plastic dynamic time history analysis for the structure, so as to explore the response characteristics of its joints under dynamic action and the possible damage conditions of each component. Zhangchuancheng [36] took a special plane irregular T-shaped structure as the research object and carried out in-depth research on seismic performance with the help of SAP2000 finite element software. Through the comparative analysis of eight kinds of openings located in different floors, the seismic performance of the structure under the action of earthquakes in different directions is systematically studied. On this basis, the weak floors in the structure are accurately judged, and the overall seismic performance is scientifically evaluated. Combined with the analysis results, the targeted design improvement suggestions of the structure are put forward.

Shi Xuyang [37] took CRRC science and technology culture exhibition center as a research case, built bowl and barrel models on the original model based on the finite element analysis software, and made a comparative analysis of the elastic-plastic time history of the two models. In addition, he also explored the failure mechanism of strong earthquake action especially for the components in the weak area in the model. Niuxiaolin [38] took a long-span exhibition hall roof structure as the research carrier, and with the help of SAP2000 finite element analysis software, carried out an in-depth study on the vertical seismic performance of the whole structure. Through the analysis, it revealed the response law of the structure system and its members under the vertical seismic action, and effectively evaluated the overall seismic performance of the roof structure. Wang Ying [39] selected a science and technology museum building as the research subject, conducted response spectrum analysis and dynamic time history analysis on the structure, compared the differences between Ritz method and eigenvector method in modal analysis, further summarized the seismic performance characteristics of the structure under various working conditions, and extracted the response laws of the overall structure and several key member nodes under dynamic action.

4. Summary

At present, the research on the seismic performance of spatial structures is mainly focused on the response spectrum method and time history analysis method. Although domestic researchers have carried out a lot of exploration and Analysis on such buildings, due to the diversity of site conditions and the unique properties of the building itself, it is difficult to build a universal and comprehensive reference framework for the research results, especially for complex structures such as long-span spatial truss, the conventional response spectrum method is often difficult to fully capture all the key influencing factors, and its analysis results are easily restricted by the frequency characteristics and mode complexity of the structure, resulting in the actual dynamic response under the action of earthquake showing more complex multimodal interaction. Therefore, for the in-depth understanding of the seismic performance of long-span spatial structures, only it is not enough to rely on the response spectrum method, It is necessary to combine time history analysis method to supplement and improve the cognition of structural seismic response. Time history analysis can provide the dynamic response details of the structure in the process of earthquake, which is very important for accurately evaluating and analyzing the specific seismic performance of this kind of complex structure under earthquake disasters.

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