SHAKING TABLE MODEL TEST ANALYSIS OF GYMNASIUM BUILDING WITH LARGE SPAN

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ABSTRACT

This paper summarized the structure characteristics of gymnasium building with large span and the key points of shaking table test for this kind of structures. Take a shaking table test of a 1/20 scale model of the Jinan Olympic Center for example, the pre-test preparations, test process and test results had been detailed introduced. The model's dynamic properties, damp ratio and responses of acceleration and deformation on the different level earthquake are studied. It's dynamic behavior, cracking pattern and failure mechanism are discussed. The seismic effects on large span spatial structure with high supports are amplified over 10 times especially in the vertical direction.

Key words: hybrid structure; gymnasium building; large span; shaking table test; seismic performance

1 SUMMARY

Along with the development of the society, people hold higher and higher requirements to the sports facilities, so gymnasium buildings with large span appear more and more often in people's sights. It is necessary to do seismic analysis on these structures as they are usually big in size, unique in shape, and complicated in loading. Shaking table model test is frequently used in the engineering world domestic and abroad as a well-developed testing method to learn the structure dynamic properties and the structure reaction under an earthquake. But because of the particularity of gymnasium buildings with large span, making a shaking table test for it differs from other structural forms. This article summarizes the characteristics of this kind of buildings firstly, then points out the difficulty and key point of making such test to them and finally introduces preparations, process and relevant results of the test in detail, taking the shaking table model test for Jinan Olympic Center as background, hoping to be useful to the shaking table tests for other gymnasium buildings with large span.

2 STRUCTURAL FEATURES OF GYMNASIUM BUILDINGS WITH LARGE SPAN

The structure of gymnasium buildings with large span has three main features as below:
(1) It usually uses mixed structural form. The concrete parts are for working areas and spectator stands, and the metal parts are for roof, side direction parts of the main body or the maintenance parts. In the mixed structure, concrete parts are mostly used as the supports of the metal parts. There is non-proportional damping problem in its seismic analysis.
(2) Its spatial size is huge but the component size is relatively small. Huge spatial size requires

consideration of horizontal and vertical earthquake influences in seismic analysis, while it's rather difficult to make test models as the component size is small.

(3) It has two failure mode: intensity destruction and dynamic instability. The former mainly appears on component nodes and bars, and the latter appears on bars. The shaking table model test can hardly simulate the destruction on nodes. It mainly observes the component destruction in macroscopic perspective.

3 THE DIFFICULTIES IN SHAKING TABLE MODEL TEST FOR GYMNASIUM BUILDINGS WITH LARGE SPAN

Shaking table test for gymnasium buildings with large span is not widely used presently. There are many reasons:

(1) There are not so many gymnasium buildings with large span. They are usually the symbol buildings of a city or even a province. And the amount of those which need to do shaking table test is smaller.

(2) People are not familiar to the shaking table test. We usually use small scale model in the shaking table test, which could only observe the seismic reaction of the structure in macroscopic perspective and can not see the destruction on nodes.

(3) Shaking table test for gymnasium buildings with large span still has technical problems in the similarity relation designing part and the model making part, which still need to be solved.

Gymnasium buildings with large span are usually composed of special structures and complicated in loading, so it is necessary to do shaking table test for it. The reduced scale proportion of the test model should not be too small while its making will be very difficult because the test components are usually small in size and made of metal. It's best to choose the reduced scale proportion according to the existing metal material size, and materials in special size could be specially made according to the model component size but this will increase the cost.

The problems below are some major to be solved problems in the similarity relation designing of shaking table test.

(1) The integrative designing problem of structural dynamic similarity with different materials.

As the model of the gymnasium buildings with large span uses relatively big reduced scale proportion, and the modulus of elasticity of the materials is relatively close as the prototype (for example the modulus of elasticity ratio is 1/1 while using steel, and 1/2 to 1/2.5 while using copper to make the model). In this case, if the concrete part is too big, according to the traditional similarity relation, the model needs to be very heavy, which the shaking table could not afford even the gravity distortion effect is not considered. So we may concentrate on the spatial structure part chiefly to do the model similarity relation designing because the designers of this kind of structures pay more attention to the upper spatial structure part's reaction and the concrete part's seismic reaction is smaller.

(2) The dynamic similarity relation designing problem of the spatial structure with large span.
The geometry comparability ratio coefficient is generally determined at first according to the size of the structure and the table and the manufacture situation of the model component. Steel or copper is usually chose to be the model material, then the material intensity or the modulus of elasticity comparability ratio coefficient is determined too. Compared with steel, copper holds the advantage of smaller intensity and modulus of elasticity, and the mass of the model is relatively smaller. So it is easier to meet the capability requirement of the shaking table test. But the yield strength of copper is not so notable as steel. So we should use steel material to make models as possible as we can as long as the capability of the shaking table test allows.

(3) The simulation problem of the additional load
As there is generally additional dead load and additional live load on the surface of the prototype, which are turned into gravitational representative value to calculate the seismic response of the structure. Therefore, most shaking table test models are made of not enough mass nowadays. Because of it, the seismic affection become smaller in the shaking table simulated seismic affection. The right way to solve this problem is to change the model proportion and add additional mass on the model.

There are many ways to add additional mass, such as laying iron or lead directly, colligating reinforcing rod directly or colligating double-deck canvas with sand in it, etc. It is worth paying attention to the question of how to choose rational additional mass form not only to suit the mass similarity relation, but also to prevent extra structural change (for example irrational colligating canvas will enlarge the rigidity of the structure).

4 EXAMPLES

4.1 Project Overview

The Jinan Olympic Sports Center is complicated huge sports architecture. The upper part is steel construction canopy, and the lower part is the concrete stands and functional houses. Its horizontal shape is near ellipse. The long axis is 360m and the short axis is 310m. The structure's width is 88m. Fig.1 is its whole structural effect drawing. There are four permanent slots in the lower concrete structure which divide the whole structure into four units. The east and the west canopy are supported on two independent concrete structural units. Fig.2 is the sketch map of the slots.
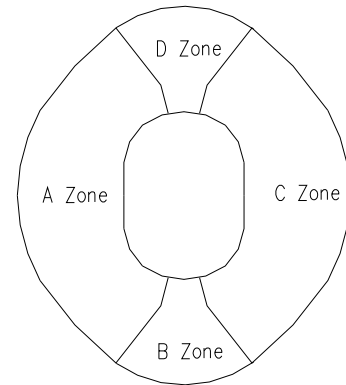
Fig. 1   Photo of Jinan Olympic Center

Fig. 2   Subareas of understructure

The upper steel construction canopy is made up of radial main truss and circumferential minor truss. It's higher in the middle and lower at the both sides while the difference of elevation is 14m. Its highest point is 52m above the ground. The biggest cantilever span of the main truss is about 53m, and the biggest height of the truss base is 7m. The smallest cantilever span is 28m, and the base height is 5m. The cantilever end height is 1.5m. The main truss uses diamond and circle combined section. Six pre-stressed steel stick which diameter is 50mm are set on the bottom plane of the main truss for horizontal cross-braced.

The upper steel canopy is supported on the inside and outside supports of the lower concrete structure. The outside support is linked to the steel reinforced concrete column by the triangular support made up of the steel tube column with reinforced concrete core; and the inside supports connect to the lower steel reinforced concrete column by four circle steel tubes.

4.2 Design and Manufacture of the Test Model
4.2.1 Model Test Range

According to the shaking table size, if using the whole prototype structure to do the shaking table test, the reduced scale proportion will be 1/60. Then the size effect will be very serious. In order to achieve the goal of test better, according to the characteristic of the prototype structure, we take the structure ranged in A zone 9th axis to 72nd axis to do the model test. The plane size in this range is about 120m×88m, including 20 main truss. Fig.3 shows the range of the testing part. Fig.4 shows the sections.
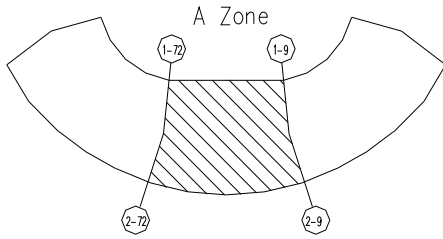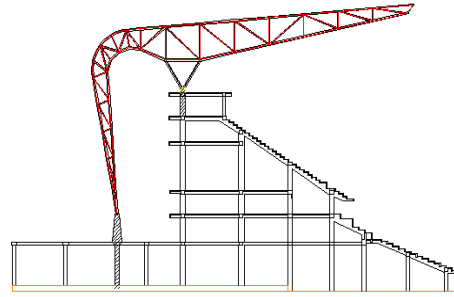
Fig. 3   Range of the testing part   Fig. 4   Sectional view of the stand

The test structural prototype in this report refers to the structure in the testing part (A zone 1-72nd axis to 1-9th axis to 2-72nd axis to 2-9th axis). The real prototype structure refers to the A zone structure of Jinan Olympic Center.

4.2.2 Test Materials Choosing

The prototype structure of this test is mainly made up of upper and lower parts. The upper part is the steel canopy and the lower part is the concrete stand. In the model we use red copper to simulate the upper steel construction part, and use micro concrete and galvanized iron wire and net to make the lower concrete part while micro concrete simulates prototype concrete and galvanized iron wire simulates prototype reinforcing bars.

4.2.3 Test Similarity Ratio

Synthetically considering the factors such as the main performance indicators of the shaking table, prototype structural characteristic, model materials and the making technique[1], we confirm several main dynamic similarity relation of this model test on the basis of equal strain law, showed in Table 1.

Table 1   Primary similarity ratio of the model

Physical parameters	Symbol	Similarity ratio
Reduced scale proportion, Displacement	S_L	1/20
Modulus of elasticity	S_E	1/2
Acceleration	S_a	1
Deformation	S_ε	1
Stress	S_σ	1/2
Mass	S_m	1/800
Time, Cycle	S_T	1/4.47
Force	S_F	1/800

4.2.4 Model Making

Use copper to simulate the section steel of the steel reinforced concrete and the members of steel canopy. The size of the section steel component and the steel members of the canopy and the wall thickness reduce strictly according to the reduced scale proportion. The component of the section copper is welded by copper plate and the red copper pipe is customized by the manufacturer. All the copper materials are finished in the factory to reduce the weld workload on site as possible as we can, in order to meet the quality and the schedule requirement of the model making. The radial main truss of the canopy is welded in the factory, and the circumferential minor truss is assembled on site.

Micro concrete is used to simulate prototype concrete, and galvanized iron wire is used to similate prototype reinforcing steel bar. Polystyrene board is used as pattern plate to make micro concrete components. Fig.5 showed the test model.
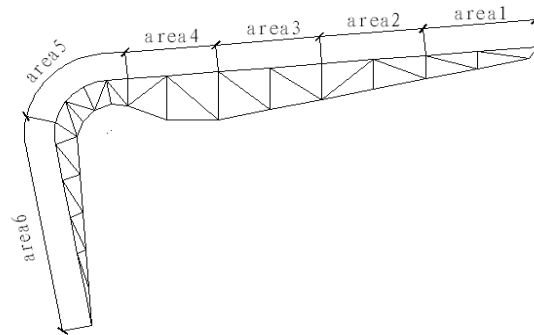

| Fig. 5   General view of the model | Fig. 6   Distribution of additional weight |

4.2.5 Model Additional Weight Lay Out

The model additional weight should be calculated separately due to the big difference between the gravitational representative value of the steel canopy of the prototype structure and the concrete stand. Because the plane area of the canopy is relatively big, but the distribution of the steel members are not symmetrical, so we divide the canopy into 6 areas to simulate the weight distribution of the prototype structure more exactly, and then calculate the additional weight need to be added in each area. Fig.6 shows the division.

4.3 Earthquake Simulating Shaking Table Test
4.3.1 Seismic Wave Chose

Choose two groups of natural seismic wave (El Centro wave and Tarzana wave) and one group of artificial wave which are used in the structural seismic analysis[2]. According to the model similitude principle, all groups of wave are compressed on the basis of S_t in time axis, and the amplitude is changed according to the acceleration peak value needed in each load level.

4.3.2 Description of the Test Process And Phenomenon

(1) Frequent earthquake affection input

The natural vibration frequency of the model doesn't change after experiencing frequent earthquake condition. The model stands intact and is in elastic state. The peak value of the acceleration is between the frequent earthquake and the fortifying earthquake and the structure is still in elastic state.

(2) Fortifying earthquake affection input

The natural vibration frequency of the model decreases after experiencing fortifying earthquake condition. Some major truss and the web members of the minor truss which connecting the canopy and the upper support yield (showed in Fig.7) and the concrete components cracks (showed in Fig.8). The model calculating result shows that in this condition, the biggest stress ratio value of the web members of the main trusses connected to the upper support is nearly to 1.0. The calculating result is in good agreement with the test phenomenon.
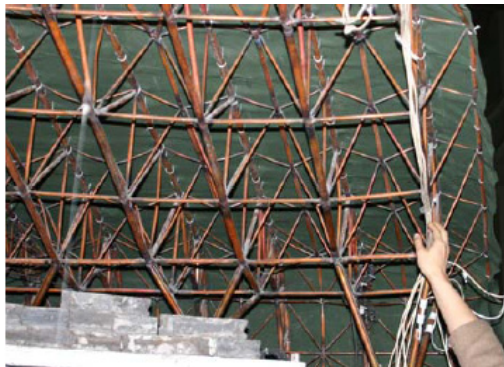

Fig. 7   Yield of web members

Fig. 8   Cracks on the 4th floor column

(3) Rare earthquake affection input

The natural vibration frequency of the model changes after experiencing rare earthquake condition. The number of the yielded major and minor web members increases, and the yielding spreads to the top of the canopy (showed in Fig.9), and the number of the cracks on the concrete component increases.
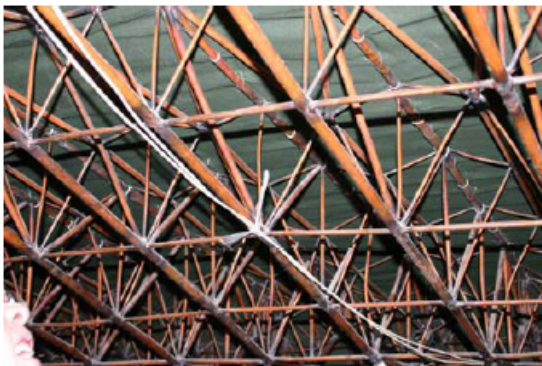

Fig. 9   Web members yielding progress

Fig. 10   Cracks on the boundary beam

(4) Above rare earthquake affection input

The number of the yielded web members has further increases after experiencing fortifying earthquake and rare earthquake of 8 degree(0.30g) and the deforming gets bigger (showed in Fig.11). Deformation and pits appear on the components connected to the lower support (showed in Fig.12). More cracks appear in the concrete parts. The shear wall in the elevator tube and the component connected to it are tensile splitted. Especially, cracks appear generally on the column in the 4th floor which floor height is relatively big and the top of the column connected to the stand (showed in Fig.13). Plastic hinge is formed on the top of the concrete column in the end of the stand's bottom floor. The concrete flakes off (showed in Fig.14). Learnt from the destroy phenomenon of the concrete column, the main reason of the column crack is the thrust of the oblique stand.

Fig. 11   Yielding degree deepened compare with Fig.9

Fig. 12   Pits on the support members

Fig. 13   Cracks on the 4th floor column

Fig. 14   Concrete flaking off on the bottom floor column

4.4 Test Results and Analysis
4.4.1 Model Dynamic Characteristic

The measured first vibration mode of the model structure is y translation, and the natural frequency is 3.38hz. So according to the model similar principle, the first natural frequency of

the test structural prototype (y translation) is 0.756Hz and the test structural calculating result is 0.710Hz. The test result meets well with the calculating analysis result. The measured natural vibration character of the model and its change after each condition are showed in Table 2.

The test result shows that the basic frequency in all directions doesn't change before the model experienced the fortifying earthquake and the model is wholly in elastic state. After experiencing the fortifying earthquake, the model damage starts and strengthens gradually. The natural vibration frequency decreases and the law is obvious.

Table 2　Model natural parameter

Test stages	First order cycle (s)			First order damp ratio (%)		
	X	Y	Z	X	Y	Z
Before seismic wave input	0.215	0.296	0.131	2.8	5.1	1.4
After frequent earthquake	0.218	0.296	0.131	3.8	6.1	1.5
After fortifying earthquake	0.227	0.305	0.132	5.9	5.7	1.5
After rare earthquake	0.230	0.310	0.134	3.2	6.2	1.4
8 （0.30g） fortifying earthquake	0.246	0.318	0.134	4.3	6.8	1.7
8 （0.30g） rare earthquake	0.265	0.337	0.138	3.9	5.6	1.4

Annotation: X is the radial, Y is the circumferential and Z is the vertical.

The damp ratio on X direction of the model is between pure steel structure and pure concrete structure, which means the vibration on X direction is caused by the steel canopy and the concrete stand coordinately, and the damp ratio is provided by these two together. Not like it on X direction, the damp ratio on Y direction is mainly provided by the concrete stand, because on Y direction the concrete stand gives relatively less restriction to the steel canopy and the vibration on Y direction is mainly the whole steel canopy vibration relative to the concrete stand. The measured damp ratios on Y direction are all above 5%. Vibration on Z direction is mainly of the steel construction canopy and the measured ones are all below 2%.

The model's cycle and the damp ratio on Z direction stay relatively stable, which means although some web members of the steel canopy yield after a moderate intensity earthquake, the whole canopy is basically in elastic state.

4.4.2 Model Seismic Reaction

(1) Floor acceleration reaction
Table 3 to Table 5 show the amplification factor of the acceleration of the model structure under different earthquake conditions.

Table 3   Amplification factor of the acceleration under frequent earthquake

wave	X		Y		Z
	6th floor	canopy	6th floor	canopy	canopy
El Centro	4.07	5.70	1.59	7.92	10.74
Tar Tarzana	3.44	4.79	1.73	3.49	13.05
Artificial	1.94	3.18	1.16	3.68	7.72

Table 4   Amplification factor of the acceleration under fortifying earthquake

wave	X		Y		Z
	6th floor	canopy	6th floor	canopy	canopy
El Centro	2.59	3.92	1.57	6.26	24.80
Tar Tarzana	2.91	4.35	0.83	2.47	11.61
Artificial	2.14	2.77	0.96	3.85	10.01

Table 5   Amplification factor of the acceleration under rare earthquake

wave	X		Y		Z
	6th floor	canopy	6th floor	canopy	canopy
Rare earthquake	3.14	3.49	1.66	4.57	16.04
8 (0.30g) fortifying earthquake	2.10	2.93	1.86	3.63	7.72
8 (0.30g) rare earthquake	2.45	2.30	2.00	3.74	5.60

We could know from the tables above that the floor amplification factor of the acceleration differs under different seismic wave input, which means the spectral properties of the input wave highly affects the structure reaction, and the structural dynamic reaction is relatively big under El Centro wave.

The test result shows in elastic state, the horizontal dynamic amplification factor of the stand and the canopy and the vertical dynamic amplification factor of the canopy are relatively big. As the acceleration peak value of the input seismic wave increases and the test model gets some damage, the structure turns into elasto- plasticity state, and the structural dynamic amplification factor decreases slowly.

The canopy is supported by the concrete stand which rigidity is relatively big. The rigidity sudden change is showed as the structural dynamic amplification factor suddenly increases in the canopy. The canopy is long cantilever structure and the measured biggest vertical amplification factor of the acceleration on the canopy end is 24.80.

(2) Floor displacement reaction

We could get each measure point's displacement time history by doing a quadratic integral to measured acceleration time history. Statistic shows the test model's displacement reaction in the biggest one while input El Centro wave. Under different seismic wave, the biggest inter-story drift ratio of the lower concrete structure of the model appears in the 4th floor. The biggest inter-story drift ratio on X and Y directions under frequent earthquake is 1/2285 and 1/2747, and those under the same condition concluded by finite element analysis is 1/2873 and 1/2085, which shows good agreement. The biggest inter-story drift ratio on X and Y directions under fortifying earthquake is 1/1038 and 1/1378, and those under rare earthquake is 1/1031 and 1/712, which all meets the seismic code requirements on the biggest inter-story drift ratio.

4.5 Test Conclusions

(1) The measured first vibration mode of the test model structure is y translation. The natural period is 0.296s. According to the model similitude principle, the natural first frequency of the test prototype structure is 1.323s, while the theoretical calculation result is 1.408s, which agrees well. So the designing calculation and analysis model is correct and reliable.

(2) The upper canopy of the sports center is steel construction, and the lower stand is reinforced concrete structure. The measured damp ratio on X direction of the model is between it of pure steel structure and pure concrete structure, which means the vibration on X direction is caused by the steel canopy and the concrete stand coordinately, and the damp ratio is provided by these two together. The damp ratio on Y direction is mainly provided by the concrete stand, because on Y direction the concrete stand gives relatively less restriction to the steel canopy and the vibration on Y direction is mainly the whole steel construction canopy vibration relative to the concrete stand. The measured damp ratios on Y direction are all above 5%. Vibration on Z direction is mainly of the steel construction canopy and the measured ones are all below 2%.

(3) Under fortifying earthquake condition, the model structure is in elasto-plasticity state. Some major truss and the web members of the minor truss which connecting the canopy and the upper support yield. The testing part structural elastic calculating result shows the biggest stress ratio value of this web members of the main trusses connected to the upper support has been larger than 1.0. The calculating result is in good agreement with the test phenomenon.

(4) After rare earthquake effects, the canopy upper and lower support components of the model structure are not damaged. So the fortifying aim of the large earthquake elasticity of the prototype canopy upper and lower support according to the code could be achieved.

(5) Learnt from the destroy phenomenon of the concrete column, the main reason of the column crack is the thrust of the oblique stand.

ACKNOWLEDGEMENT

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