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Shaking table test on a hybrid spatial structure with engineering application

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Abstract

Terminal building 2 in Shanghai pudong international airport is a novel hybrid spatial structure. The upper steel roof and lower reinforced concrete frame are assembled with Y-shaped steel columns. Its total length and width are 414 and 150 miters, respectively. The special architecture form leads to a complex structure.

It is significant to completely understand the overall structural behavior under moderate and strong earthquakes when designing this structure. In this regard, shaking table model test plays an important role in obtaining the overall dynamic characteristics, seismic responses and failure mechanism of targeted structure.

The seismic response and performance of this hybrid spatial structure subjected to various earthquake inputs are investigated by shaking table test. A 1:35 scaled model structure is constructed and tested. The natural frequency, seismic responses including the relative displacement and the strain are investigated based on the test results. Some features are captured and discussed. Furthermore, weak positions under seldom-occurred earthquakes of seismic design intensity 8 are found based on the visible damages on the testing model, and some corresponding suggestions were proposed and applied to the engineering design of the structure under extremely strong earthquakes. The whole project was completed in 2006 and put into operation after then.

The study attempts to provide some insights into the overall dynamic behavior of the new structural system and accumulates the experimental evidence for establishing related design guidelines for such complex hybrid spatial structures in the future.

Keywords: hybrid spatial structure, shaking table test, scaled model, seismic performance.

1. Introduction

For functional or aesthetic purposes, some public buildings are planned with a large space in the ground floor and irregularity in elevation. Their uniqueness in structure brings new challenges to engineers, since their structural behaviors are difficult to predict and analyze. Therefore, the shaking table test using scaled models is becoming a common approach in understanding the overall behavior of these buildings.

Today, the shaking table test using a scaled building model is one of the most effective tests to study complex buildings after considering the accurate, practical and economic aspects of the experiments. Through the tests, engineers can (i) study damage mechanism and failure pattern and evaluate overall seismic capacity; (ii) acquire the distribution of seismic force along the height of the structure; (iii) find out the weak points in the structure; and (iv) verify the dynamic analytical models for the new structural systems.

In China, a number of shaking table tests have been carried out to study the response of structures to earthquakes since the first shaking table was built in 1983. Many shaking table tests on model structures were conducted at the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University, including dynamic experiments on the Shanghai Oriental Pearl TV Tower, a U-shaped plan building, Shanghai financial center tower and terminal building 1 in Pudong international airport. Further information concerning these tests can be found in Lu [1-4]. Many examples show that the shaking table test has gradually become one of the most effective ways to help researchers and designers understand the seismic performance of complex structures.

The hybrid spatial structure considered in this study is terminal building 2 in Shanghai pudong international airport as shown in Figure 1. A scaled model of this hybrid building was designed and tested on the shaking table. Four signals—the El Centro earthquake record, Pasadena earthquake ground motion, Shanghai artificial accelerogram and Sim-T2 which simulated according to the construction site—were input in increasing magnitudes to the table. Model acceleration and displacement responses were measured in the test. Experimental dynamic characteristics, cracking pattern and failure mechanism were also discussed. In addition, some suggestions are given for the engineering design of the building system. The study attempts to provide some insights into the overall dynamic behavior of the new structural system and accumulates the experimental evidence for establishing related design guidelines for such complex hybrid structures in the future.

2. Description of the structure

Pudong International Airport, Shanghai, China has total floor area of 400 thousand square meters and constitutes a terminal building, a boarding hall and mass transit stations (Figure 1). Terminal building 2 consist of 25 planar frames with 18m spacing. 3 hybrid columns (in 0/1A, A and G axis) and 1 pin-pin supported steel column (in K axis) serve as horizontal resistance together with beam string system. In addition, it is a hybrid structure, in which the Upper steel roof and lower RC frame are assembled with Y-shaped hybrid columns. Terminal building 2 could be classified as a vertically irregular structure due to SRC column, Y-shaped steel column and steel roof along the height. The unique design of its RC frame and Y-shaped steel column make it become an exceptional structure. Up to now, no Chinese Design Code can be applied efficiently to this type of structure.

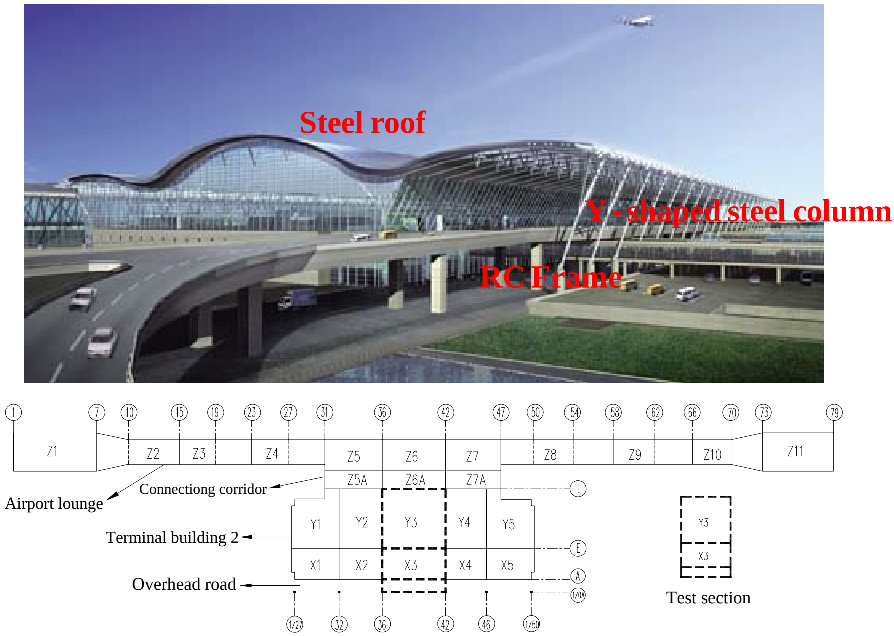

Figure 1: Panorama of Pudong international airport and illustration for test section

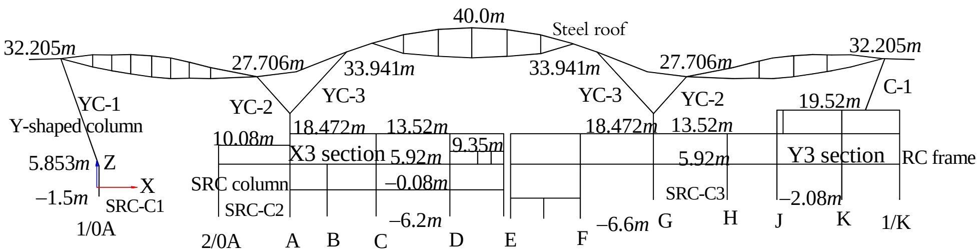

Figure 2: Panorama and elevation of terminal building 2 in Pudong international airport

Thus, it is significant to completely understand the overall structural behavior under moderate and strong earthquakes when designing this structure. It should be noted that a relatively small number of shaking table tests on this large spatial hybrid buildings are executed and published due to the difficulties in modeling scaled material properties, the cost restrictions and limitations of specimen size and capacity of available shaking tables.

Given these irregularities and complexity of the structure, the owner entrusted the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University to perform a detailed study to verify the seismic safety and rationality of the design. Generally, the detailed study includes (i) a shaking table test of the scaled building model to study its overall seismic behavior, (ii) finite element analysis of the whole building to determine its dynamic response, and (iii) a static test on joints between SRC column and Y-shaped steel column. This paper presents mainly the results of the first part.

3. Model design

3.1. Description of the shaking table

Shaking table model test is carried out using MTS shaking table facility at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. The table can input three-dimensional and six degree-of-freedom motions. The dimension of the table is 4m×4m, and the maximum payload is 25 000 kg. The shaking table can vibrate with two maximum horizontal direction accelerations of 1.2g and 0.8g, with a maximum acceleration of 0.7g vertically. Its frequency ranges from 0.1 to 50Hz and there are 96 channels available for data acquisition during testing progress.

3.2. Model similitude and materials

Due to the dimensional limitation of the shaking table, the X3 and Y3 section of the termianl building 2 as shown in Figure 1～2 is selected. The model is designed by scaling down the geometric and material properties from prototype structure. Based on past experience, steel structural elements were modeled with iron sheets in consideration of its good weldability, and those of reinforced concrete elements were modeled with fine-aggregate concrete with fine wires. The maximum aggregate size was 4 mm, and its grading was also accordingly scaled to the practically possible.

Table 1. Similitude scale factors for the test model.

Parameter	Length	Young's module	Acceleration	Frequency	Mass	Density
Model/Prototype	1/35	0.2	1.0	5.92	1.63E-04	7.0

The basic model similitude rules are established from the scaling theory. Considering the capacity and the size of the shaking table to be used at Tongji University, the dimension scaling parameter is chosen as $1/35$.Subsequently, the stress scaling parameter is chosen as 0.2, and the acceleration scaling parameter is selected as 1.0 in order to investigate the seismic response of this large span structure subjected to vertical excitations. The main scaling parameters are summarized in Table 1.

3.3. Test set-up and procedure

To ensure an effective transmission of the table motion to the base of the test structure, the model base plate was firmly mounted on the shaking table through bolt connections as shown in Figure 3. The building model was placed approximately at the center of the shaking table in the test. It is should be noted that due to the dimensional limitation of the shaking table, a part of the model is hanged in the air in its longitudinal direction. To ensure firm of the foundation and accuracy of the test, two rigid beams are constructed specially in these positions.

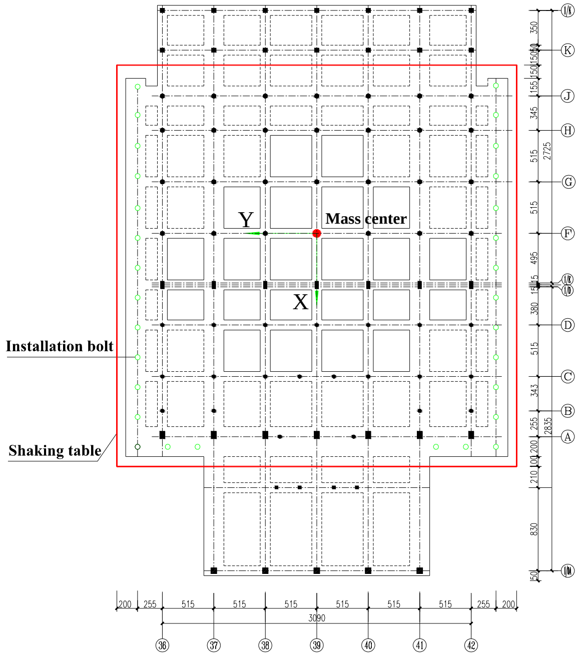

Figure 3: Model installation

Figure 4 demonstrates an overview of the model constuction and full model structure after the test set-up. The sensor instrumentation is organized so that both overall and local responses of interest could be measured, including accelerations measured by accelerometers, displacements measured by LVDTs and strains measured by strain gauges. Total of 33 accelerometers and 12 LVDTs are placed at reinforced concrete frame, Y-shaped steel column and steel roof, respectively. In addition, total of 20 electric strain gauges were distributed on key members of the model such as Y-shaped column and curved steel beam in steel roof. All the test data are collected by a computer-controlled data acquisition system and can be transferred to other PC computers for further analysis.

Condition of site soil is one of the important factors to determine the earthquake inputs for dynamic test. Considering the spectral density properties of Type-IV site soil, El Centro wave, Pasadena wave and SHW2 wave were selected. Moreover, Sim-T2 wave which simulated according to the construction site was also inputed during the test. Except that SHW2 is 1-D wave, the other three waves are all 3-D wave.

Figure 4: Model panorama

According to China code, frequent, basic and seldom occurrences represent three peak levels of ground motions with intensity less than, equal to and higher than the design intensity, respectively. Three different requirements related to the three levels, are set to evaluate the overall capacity of structure under corresponding intensity. Since the design intensity in Shanghai is specified as 7, the test is carried out in four phases representing frequent, basic and seldom occurrences of design intensity 7, and seldom occurrence of design intensity 8, respectively. The last phase is utilized for further investigation of dynamic responses of the targeted structure under extremely strong earthquakes. During the test, the gradually increasing amplitudes of base excitation are inputted successively in a manner of time-scaled earthquake waves. After different series of ground acceleration are inputted, white noise is scanned to determine the natural frequencies and the damping ratios of the model structure.

A summary of the inputs in this test is listed in Table 2. There are four types of inputs: 3D synthesized white noise, and 1D, 2D and 3D earthquake inputs. The model was designed to be subjected to earthquake simulations with frequent, basic and rare earthquake events, respectively. Before the inputs of each event, a 3D white noise was first input to acquire the model dynamic behavior at that moment. Accelerogram were then input to the model in turn. Each ground motion simulation was input triple: in the principal horizontal direction X and Y, and vertical direction Z. The peak acceleration ratio of the principal direction to the other horizontal direction and vertical direction are designed to be 1 to 0·85 and 1 to 0.65, respectively.

Table 2. Test program

Test cases	Case name	Earthquake Occurrence Frequency	Input signal	Peak value of input acceleration (g)				Note
				Principal Direction	Direction X	Direction Y	Direction Z	
1	W1				0.04	0.04	0.04	
2	F7EXY	Frequent 7	ElCentro	X	0.035	0.03	--	2D
3	F7EYX			Y	0.03	0.035	--	2D
4	F7EZ			Z	--	--	0.23	1D
5	F7PXY		Pasadena	X	0.035	0.03	--	2D
6	F7PYX			Y	0.03	0.035	--	2D
7	F7PZ			Z	--	--	0.23	1D
8	F7SHX		SHW2	X	0.035			1D
9	F7SHY			Y		0.035		1D
10	F7SHZ			Z			0.023	1D
11	F7SMXY		Sim-T2	X	0.035	0.03	--	2D
12	F7SMYX			Y	0.03	0.035	--	2D
13	F7SMZ			Z	--	--	0.23	1D
……..								
14	W2				0.04	0.04	0.04	
15	B7EXY	Basic 7	ElCentro	X	0.1	0.085	--	2D
16	B7EYX			Y	0.085	0.1	--	2D
17	B7EZ			Z	--	--	0.065	1D
……..								
27	W3				0.04	0.04	0.04	
28	R7EXY	Rare 7	ElCentro	X	0.2	0.17	--	2D
29	R7EYX			Y	0.17	0.2	--	2D
30	R7EZ			Z	--	--	0.13	1D
……..								
41	W4				0.04	0.04	0.04	
42	R8EXY	Rare 8	ElCentro	X	0.36	0.31	0.23	3D
43	R8EYX			Y	0.31	0.36	0.23	3D
……..								
50	W5				0.04	0.04	0.04	

4. Test results

4.1. Cracking and failure pattern

For earthquake simulations with a high rate of occurrence (test cases 02–26) no visible cracks were observed on exterior faces of the model. After the third white noise test, it was found that the frequency of the model in both *X* and *Y* directions decreased slightly.

Although this result indicated that micro-cracks of the model structure had developed inside, the building model still behaved elastically during these tests. under earthquakes of moderate level concrete cracking became visible and natural frequencies were significantly reduced. Small horizontal cracks could be seen in columns at the joint between the SRC column and Y-shaped steel columns. The deformation of the model became obvious and the rigidity of the model was greatly decreased. Under the rarely occurring earthquakes (test cases 42–49) previously observed cracks became wider and new cracks had developed in the model. More significant damage was observed although no failure of structural components had occurred.

Distribution of major cracks is shown in Figure 5. There are typically five crack-concentrated zones on the model structure. They are: (1) SRC columns; (2) Joint between the SRC column and Y-shaped steel column; (3) Curved steel beam on the steel roof; (4) RC columns and beams. These positions are the weak points in the structure and special attention needs to be paid to them in the design.

Figure 5: Cracking and failure pattern of test model

4.2. Dynamic characteristics

The natural frequencies of the structure are obtained from white noise scan tests. The variations of frequencies at the end of each occurrence phase are presented in Table 3. The first three order vibration mode and the trend of natural frequency are given in Figure 6～7. It should be noted that, owing to the big difference between the RC frame and steel roof, the first four vibration mode is mainly the steel roof deformation. The frequencies remained constant during the first series of tests, which revealed that almost no damage occurred in the structure. The first natural frequency decreased slightly after the model withstood the second series of tests referring to basic intensity 7, which suggested that the structure was still behaving in elastic state. In the third stage, the structure was subjected to the stronger earthquake inputs resulting in 14.29% and 16.67% decrease of the X and Y direction natural frequencies, which demonstrated that the intrinsic damage occurred even though no visible crack was observed on the model surface. After the input of seldom-occurred earthquake intensity 8, the natural frequencies dropped faster, which indicated that the model structure is now severely damaged.

Table 3 Natural frequencies, damping ratios and vibration modes

Excitation	Frequency (Hz)	Period (s)	Damping ratio	Vibration mode
Initial	3.517	0.284	0.038	Translation of X
	5.275	0.190	0.036	Torsion & Warp
	6.029	0.166	0.032	Translation of Y
Frequent 7	3.517	0.284	0.035	Translation of X
	5.275	0.190	0.029	Torsion & Warp
	6.029	0.166	0.029	Translation of Y
Basic 7	3.517	0.284	0.040	Translation of X
	5.275	0.190	0.029	Torsion & Warp
	5.778	0.173	0.030	Translation of Y
Rare 7	3.014	0.332	0.059	Translation of X
	4.773	0.201	0.054	Torsion & Warp
	5.024	0.199	0.048	Translation of Y
Rare 8	2.512	0.398	0.066	Translation of X
	2.763	0.362	0.086	Torsion
	3.768	0.265	0.071	Translation of Y

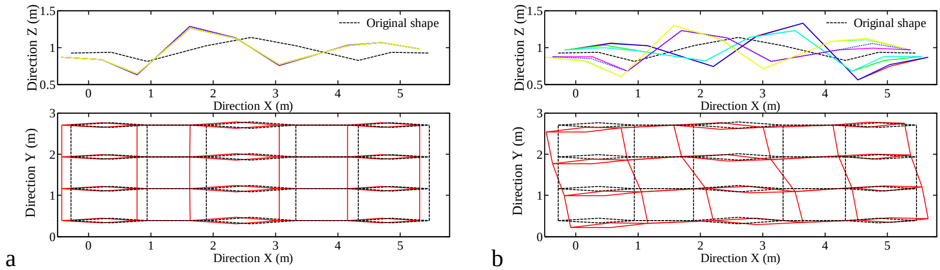

Figure 6: The fist four order vibration modes (a) First vibration mode (translation in X); (b) Second vibration mode (warp and torsion)

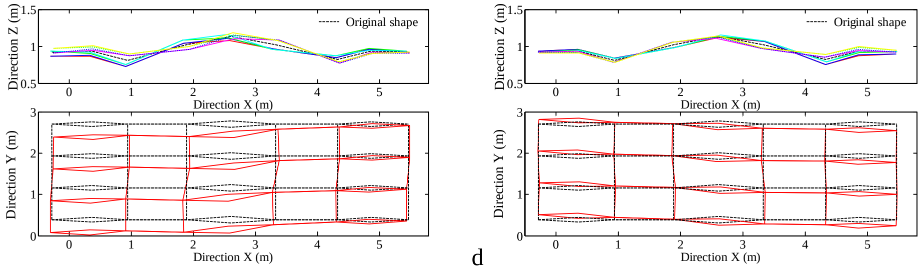

Figure 6: The fist four order vibration modes(continue) (c) Third vibration mode (translation in Y); (d) fourth vibration mode (torsion)

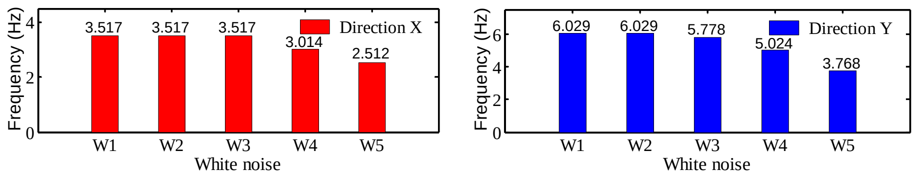

Figure 7: The trend of natural frequency during the whole test

4.3. Displacement

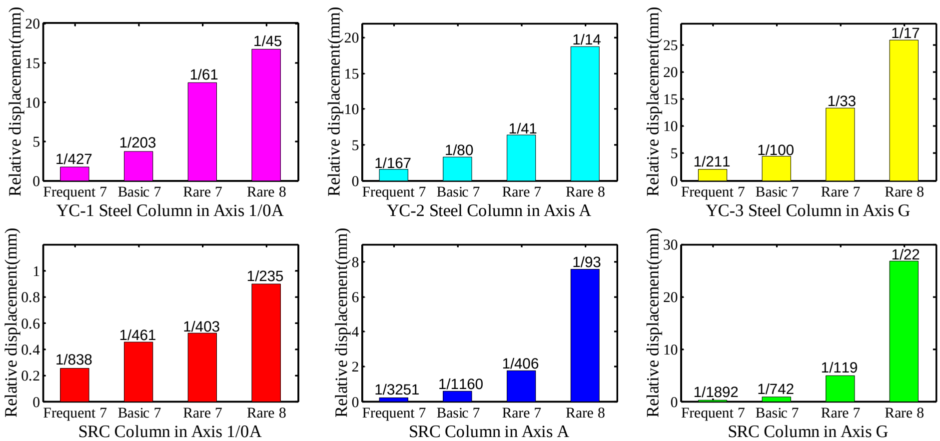

Figure 8: The distribution of the displacement in each major structural element

For each recorded displacement time history, the maximum values can be found, however, these maximum values at different locations do not necessarily occur at the same point in the same time. In order to investigate the structural displacement responses under different earthquake levels, the maximum displacement obtained from four series of waves were compared to get the final maximum values. Figure 8 demonstrates the maximum relative displacement distributions along the height under four earthquake levels. It was shown that, among the three SRC columns, the SRC columns located at the axis 1/0A and G may undergo the maximum and minimum displacement response, respectively. This phenomenon coincide with the obvious crack appear in the top of SRC column located at axis A and G compared to the axis 1/0A. For the Y-shaped steel column, the YC2 located in axis A may experience the largest displacement compared to the other two steel columns. Moreover, compared to the SRC columns, the Y-shaped steel columns may undergo the larger displacement response.

4.4. Strain

Table 4 Summary of maximum and minimum strain value

Structural element	YC-1	YC-2 in Axis A	YC-3 in Axis A	YC-3 in Axis G	C1	Beam in Roof
Maximum value ($\mu\varepsilon$)	500	1500	1200	1200	320	800
Minimum value ($\mu\varepsilon$)	-500	-1500	-1200	-1200	-70	-1200

Similar to the dynamic response of displacement, the maximum and minimum values of the strain in different structural element (especially for steel columns and beams) were extracted and summarized in Table 4. The results shown that the YC2 located in the axis A may experience the largest strain response compared to the other steel columns, which coincide the result obtained from the displacement. The C1 column may experience the smallest strain during the whole test. In addition, due to the hinge connection, the column C1 mainly subjected to tension and compression.

5. Conclusions and suggestions

Set the terminal building 2 in Shanghai Pudong international airport as a target structre, the seismic behavior of large hybrid spatial structure has been experimentally investigated. A 1/35 scaled model, which consists of RC frame structure, Y-shaped steel column and steel roof, is designed and tested on a shaking table by subjecting it to a serie of ground motions with increased intensity. The following conclusions can be drawn from the test

(1) The model test results indicate that the structure is able to withstand frequent occurred, basic intensity and seldom-occurred earthquakes of intensity 7 without sever damage. And it can resist frequent earthquakes without damage, resist basic earthquakes with some structural cracking, and resist rare earthquakes without collapse, but with some severe structural as well as non-structural damages. The structural system in this building demonstrates good quality in resisting earthquakes.

(2) The big dynamic response difference exists between the upper steel roof and under RC frames due to the irregular distribution of the stiffness.

(3) Under seldom occurrence of intensity 8, curved steel beam ruptures or buckles in steel roof, and fine crack spread in the joint between SRC column and Y-shaped steel column. These damages indicate that the curved beam and the joint is a weak position. Design measures are suggested to increase the ductility to avoid extensive deformations. In detail:

(a) For SRC columns of the ground floor: Control the axial-compressive ratio; increase the reinforcement; configure the small-spacing stirrups along the column; prolong the encased steel column up to the SRC columns.

(b) For the joints of SRC column and Y-shaped steel column: Regulate the stiffness and ductility of the joints.

(c) For elements of curved steel beam: Increase the steel support beam and strut bar.

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