SHAKING TABLE TEST AND NUMERICAL INVESTIGATION OF RC STRUCTURES WITH SPECIALLY SHAPED COLUMNS IN HIGH SEISMIC INTENSITY ZONES

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ABSTRACT :

Due to the predominance in easy of attainment for dwelling function requirement, the reinforced concrete (RC) structures with specially-shaped columns (SSC) gain acceptance in Mainland recent years. The differences between the behavior of such structure and of structure with rectangular columns focus research's attention on its seismic performance, especially on the applicable coverage in high intensity zones. Several shaking table tests and pseudo-dynamic tests of such structure have been done in recent years, but most of them were based on seismic fortification intensity 7 zones or below. In concert with the development of national Technical Specification for Concrete Structures with Specially Shaped Columns, a six-storey RC frame of 1/6 scale and a ten-story RC frame-shearwall of 1/8 scale with SSC in seismic fortification intensity 8 zone and type 3 site was designed for shaking table test, taking the requirement of elasto-plastic properties simulated by artificial mass into account. The test puts emphasis on the applicability of computational model, the global seismic performance and damage mechanism of structure. Together with the results of corresponding numerical investigation and practical application trial design of prototype structures, experimental phenomena reveals the pros and cons of this structure system, that is the easy attainment for drift control requirement and predomination of beam hinge mechanism under major shock, and more attention should be paid to joint capacity for its application in high intensity zones.

KEYWORDS: specially-shaped column, RC frame, RC frame-shearwall, high intensity zone, performance for earthquake resistance, shaking table test

1. INTRODUCTION

In recent years, reinforced concrete (RC) structures with specially-shaped columns (SSC) have gained wider application and more attention due to the following two reasons: firstly, similar to both RC frame and RC frame-shearwall structures, it has the predominance of meeting dwelling function requirement with ease, while it is especially suitable for residential buildings due to the need for maximum usable areas. Secondly, the on-going wall material reform in China has made RC structures with SSC a good replacement for clay masonry structures. Under this background, a series of research and application works have been carried out in different regions of China. Many local authorities have issued technical standards and regulations on the design and application in construction for RC structures with SSC. This has laid a good foundation for the formulation and wide application of the Technical Specification for Concrete Structures with Specially Shaped Columns.

The formulation of the Technical Specification will rely on not only the current relevant national standards, but also specially designed research work in this regard. In recent years, on the basis of static tests and pseudo-dynamic tests on structural components and simplified models, some monolithic structure model tests (seven-storey [Zhang, 2002], nine-storey [Liu, et al, 2002], twelve-storey[Wang, et al, 1999], etc.), shaking table tests in particular, have been conducted and provide basic data for the promulgation of the Technical Specification. These tests serve as a good reference in seismic fortification performance evaluation (drift indicators, damage mechanism), applicability of constructional measures of components and joints to resist earthquake, structural conceptual design, and axial pressure ratio. However, most of these tests were based on seismic fortification intensity 7 zones or below. Although shocks of seismic fortification intensity 8 were conducted for individual models in some tests, researches based on seismic fortification intensity 8 zones have not been reported. In order to better understand the applicability of RC structures with SSC in areas with high seismic intensity, Tianjin University, major editor of the Technical Specification, in collaboration with Kunming Construction Bureau, Kunming University of Science & Technology, and Tongji University, conducted a shaking table test in seismic fortification intensity 8 environment on a six-storey RC frame of 1/6 scale and a ten-storey RC frame-shearwall of 1/8 scale.

Technical Specification being formulated now divides structures with SSC into two major categories: RC frame and RC frame-shearwall structures. To a large extent, the maximum height for the application of the RC frame is restricted by the shear-bearing capacity at joints [Pan, et al., 2008]. The shaking table tests that we conducted on monolithic models of RC frame and frame-shearwall with SSC covered the application heights for the two structures listed in the National Technical Specification. Many earthquakes with large seismic impacts on urban buildings both in China and abroad show that regular frame-shearwall structures have better seismic resistance performance than frame structures. Comparison of some test results also validates the above viewpoint.

2. DESIGN AND CONSTRUCTION OF THE TEST MODELS

2.1. Prototype Structural Design

The major objectives of the shaking table test under discussion are: First, to investigate the seismic performance of RC frame with SSC and RC-shearwall structure with SSC when they reach certain heights or certain number of stories; second, to make comparison with earlier theoretical analysis. Therefore, designs of the testing structures should not be too complex; otherwise other factors may have large impact on the test. After selecting from a number of completed construction projects and making simplifications, we adopted similar layouts for the two test models.

In general, the layout of the test models is rather regular. The structure contains columns of L shape, T shape, and cross shape and the proportion of them in the structure is basically similar to that in actual building projects. But no rectangular columns were set up in the model. The major irregularity in the structure is the occurrence of a semi-framework and a relatively low symmetry in the X direction. Design software used for the prototype are TAT, SATWE of PKPM series, and CRSC (including RCJoint) [Wang, 2000] specially used for SSC structures.

2.2. Model Similarity Relation

The model to be tested is multi-story frame and frame-shearwall structure in which vertical load has large effect. In the meantime, the axial compression of frame columns is also a major factor affecting the structural seismic performance when the different seismic impacts are combined. Therefore, the design of test models should take the impact of acceleration of gravity into consideration so that the test model can meet the requirement of elasto-plastic properties simulated by artificial mass. This can be done by adjustment of the geometric similarity factor, the mass density similarity factor, and the strength similarity factor, so that the gravity acceleration similarity factor is equal to 1. If the condition that acceleration similarity factor equal to 1 is met, the impact of vertical load has been well taken care of in the test models, so that the ratio between stress and material strength in the model structures under vertical load is consistent with that of the prototype. This helps building a dynamic model with perfect similarity and achieving the similarity of cracks in test models and the prototype.

2.3. Model Constructing

Figure 3 Finished frame model

The geometric sizes and reinforcement ratio of each structural component are calculated from similarity. Bars used in slabs are welded iron net, while longitudinal bars and hoop bars in beams and columns are iron wires. For the convenience of construction, concrete strength of beams and slabs is same as columns and walls. Similarity ratio of strength and elasticity modulus is determined as 1/6 by test blocks and additional mass is calculated according to this.

In order to make sure that the model structures can simulate the seismic resistance performance of the actual structures, great effort in construction to make the models as similar to the original as possible. Microparticle concrete is selected as the material for the main model body to simulate concrete materials of the real structure, the galvanized wire is used to simulate reinforcement bar. The construction method, pouring method, and maintenance conditions of microparticle concrete are similar to those of ordinary concrete so that it is extremely similar to it in terms of material nature. Similar to concrete used in the original structure, the microparticle concrete also has several geometric continues grading and grits of different sizes take their corresponding proportion. As a result, its mechanics functions and grading present good similarity with the original concrete. Test can be conducted on the model using microparticle concrete until it cracks or even is damaged. Therefore, test results are quite easy to observe. At the same time, because the cohesion and anchoring between galvanized wires and concrete is comparatively weaker than that between actual deformed bars and concrete, the anchor measures of wires in concrete is strengthened. For the models were constructed to a smaller scale, there is high demand for precision, which requires high-level construction. The wood is used for outside mould while the combination plate mould built up with wood and foamed plastics used for internal mould. Before the construction of models, the moulds are arranged to be a certain shape so as to form spaces required by the components, the pouring of microparticle concrete is started after the moulds were fixed reliably. In the process of pouring, the concrete was vibrated and consolidated. Concrete was poured for one storey each time and the reinforcement and moulds of the storey above are laid when it reached certain strength. The above procedures were repeated until the pouring for the whole model was completed. See Fig. 3 and 4.

Figure 4 Finished frame-shearwall model

Three seismic waves were selected as the shaking table input, including: El Centro record (Imperial Valley Earthquake in the U.S., May 18, 1940), Taft record (California Earthquake in the U.S. on July 21, 1952), and synthesized record.

3. SHAKING TABLE TEST ON SIX-STORY RC FRAME STRUCTURE

3.1. Test Procedures

In the order of frequent intensity 8, rare intensity 8, a simulated earthquake test was conducted on the model structure in two stages. Inputs for frequent earthquake are in the following order: synthesized (X direction, Y direction), El Centro (XY bi-direction, YX bi-direction) and Taft (XY, YX). Inputs for rare earthquake are the following in succession: synthesized (X, Y), El Centro (X, Y), Taft (X, Y), El Centro (XY, YX) and Taft (XY, YX). Frequency scan with white noise was conducted before and after each input in order to measure the free vibration frequency, the vibration mode, and the damping ratio. Duration of the input on shaking table was scaled to 1/2.45 of the original record according to similarity relationship, and peak ground (table) acceleration (PGA) of frequent and rare earthquakes corresponding to seismic fortification intensity 8 were determined also by this relationship.

3.2. Brief Description of Test

(a) After the input of synthesized, El Centro and Taft record with PGA of 0.07g and frequency scan, there were several small cracks at the beam end appearing on the surface of the model. The width of the cracks were very small, all of them were below 0.05 mm and almost invisible. The free vibration frequency decreased slightly. In general, the model structure was still in the elastic working situation in this test stage.

(b) After the input of two synthesized records with PGA 0.4g (one in X direction and another in Y direction), the number of cracks near beam-columns joints of the 2nd and the 3rd story increased and the distribution of cracks expanded. Some cracks expanded further to the middle span of beams and some even developed across the section of beams or columns. Cracks are rather obvious at the top of the outer columns in third-story at axis C and 1, ends of beams of the 2nd story as well as beams at the forth-story joints at the axis C and 1. Number of cracks occurring at the inner side of beam joints rose sharply and the cracks became wider. At the base of the cross-shaped column in the middle of the model, concrete begins to be crisped.

Figure 5 Concrete spall near joints

After the input of El Centro with PGA 0.4g (one in X and another in Y), cracks on the outside of the model continued to develop. The number and length of the cracks continued to grow. Circular or semi-circular peeling off of the concrete cover occurred on the outside surface below some beam and column joints (see Fig. 5). This is particularly obvious on the top of the 2nd and the 3rd stories. Visible cracks appeared in some beam and column joints corner and concrete peeled off there. At some individual joints, the concrete cover protruded out. Cracks also appeared in the core area of the top beam-column joints on the 3rd story (Fig. 6).

Figure 6 Cracks cross the core of joints in floor 3

After the input of Taft with PGA 0.4g (one in X and another in Y), many cracks connected to each other expanded, circular or semi-circular peeling off increased remarkably. Some has even fallen off from the model. At the base of cross-shaped columns in the middle of the model, serious collapse occurred. Similar situation also found at the base of L-shaped columns and the cross-shaped middle columns on the 2nd and the 3rd stories. On the floor surface, cracks appeared along the beam side, which was particularly obvious at the top surface of the 3rd story. Similar cracks were also found on the 2nd and the 4th stories. The number of cracks at the beam-column joints of the 5th story increased.

In the final stage, bi-direction input of El Centro and Taft was conducted. Cracks in some joint core areas are obvious and the concrete was compressed to be crisped and peeling. At the column bottom on the outside of the model, semi-circular peeling off of the concrete cover became obvious. Falling off has worsened and sounds of fragmented pieces falling on the ground were heard. Plastic hinges was produced at the columns. Since the concrete cover is too thick, the relatively big plastic rotation concentrated in such a narrow area forced the cover protrude out. The stress in the flange of T-shaped and L-shaped columns is comparatively large only in a small area corresponding to the web. While away from the web, the stress at the sides of the T-shaped column flange and at one side of the L-shaped column flange was rather small. As the result, the concentration of stress in a certain area forces the concrete here to be broken and protrude out. When approaching the outside surface of the model, the concrete protection layer became circular or close to circular.

3.3. Primary Test Data

Frequencies of first three modes of model are 3.95, 4.67, and 5.39Hz, respectively. Calculated accordingly with similarity relation, periods of the prototype are 0.620, 0.525 and 0.455s, respectively. It is similar to the results of design calculation. Vibration modes of lower order are horizontal movement and torsion as a whole. The frequency of the model decreased with the increase of the input, while the damping ratio increased with the structural damage. After the rare earthquake inputs were finished, the frequencies of first three modes decreased to 1.44, 1.80 and 2.15Hz respectively.

The displacement responses of the model were obtained from LVDT wide range sensor and twice integration of recorded acceleration. Data obtained from the two methods are then compared and they are in consistence with each other. Drift data shows the model is of typical shearing deformation, from the top to the bottom, increment in the maximum drift increases by each story.

Under the effect of frequent earthquake of intensity 8, inferred from the data of model response, the ratio of top displacements to structural height of the prototype are: 1/895 in X direction and 1/923 in Y direction, the maximum floor drifts are: 1/543 in X direction which occurred on the 2nd story and 1/526 in Y direction on the 3rd story. Under the effect of rare earthquake of intensity 8, cracks of various degrees occurred in the majority beam-column joint areas from 2nd to 5th story. In some individual parts with severe cracks, concrete were compressed to be crisped or collapse. The frequency further decreased and the rigidity also decreased to a large degree. From the start of rare earthquake inputs (two synthesized) to the 7th rare earthquake case (bi-direction El Centro), floor drifts of the model still satisfied the requirement of being less than 1/50. Only in the last case (bi-direction Taft) did the floor drifts surpass this limit. After all test inputs, the ratios of top displacements to structural height of the prototype are: 1/54 in X direction and 1/93 in Y, the maximum floor drifts are: 1/29 in X direction which occurred on the 2nd story and 1/53 in Y on the 2nd story too.

4. SHAKING TABLE TEST ON TEN-STORY FRAME-SHEARWALL STRUCTURE

4.1. Test Procedure

In the order of frequent, fortification, rare and strong rare intensity 8, the test was conducted in four stages. Inputs for frequent earthquake are in the following order: synthesized (X, Y), El Centro (XY, YX) and Taft (XY, YX). Inputs order for fortification intensity is: synthesized, El Centro and Taft (all are X, Y). Inputs order for rare intensity is the same as the frequent. After all above preconcerted inputs were finished, according to the damage status of the model, it was decided on site to add four inputs of El Centro and Taft (XY, YX for each) under the circumstances of strong rare quake intensity 8. Frequency scan was conducted before and after each input. Duration of the input was shortened to 1/2.83 of the original record.

4.2. Brief Description of Test

(a) Frequent intensity: After the input of synthesized, El Centro and Taft record with PGA of 0.07g and frequency scan, there was no visible crack on the surface of the model. Frequency scan found that the frequency of the model decreased slightly by about 9%, this suggests that invisible small cracks has already occurred in the structure. In general, the model structure was still in the elastic working situation in this test stage.

(b) Fortification intensity: In the order mentioned above, records with PGA of 0.20g were input. Frequency scan after two one-direction synthesized records showed that the frequency decreased again by 18%, while after two one-direction El Centro and Taft, the frequency decreased at a slower rate, 3.4% and 7.5%. At this point, the model was checked carefully and several small diagonal cracks with a length of around 5 to 15mm and minor width were found at the top of the shearwall columns between the 2nd and the 5th story.

(c) Rare intensity: After the input of two synthesized records with PGA 0.4g (one in X direction and one in Y direction), a large number of cracks appeared, but did not expand yet, crack width was around 0.5mm. Most of them was oblique cracks occurred near conjugation of beam and column (Fig.7a), or beam and wall (Fig. 7b), a few occurred on shearwalls (Fig.7c). In addition, some vertical cracks appeared in beam ends and few in column and shearwall. Skew shearing cracks also occurred in some beams in the inner side of the model. At this time, plastic hinge at the end of the beam has been formed.

(a) Oblique crack in beam-column joint | (b) oblique crack in beam-wall joint | (c) oblique crack in shearwall

Figure 7 Crack after the input of first two one-way synthesized record of rare intensity

At the point, the structural frequency decreased remarkably. In order to obtain relative accurate test results and to avoid the accumulation of structural damage caused by several single-direction major shocks, the single-direction inputs of El Centro and Taft were skipped, bi-direction input was conducted instead. After two bi-direction inputs (0.4g in primary direction and 0.34g in secondary direction) of El Centro, new visible cracks on structure surface were observed and the previous cracks also expanded. See Fig. 8.

Figure 8 Crack after input of two bi-direction El Centro records of rare intensity

Frequency scan after these two bi-direction inputs found that structure frequency did not decrease with a high rate (around 10%). However, after the following two bi-direction inputs of Taft, cracks in different places further developed. Damages due to compression were observed in some columns and corners of the shearwall. See Fig. 9.

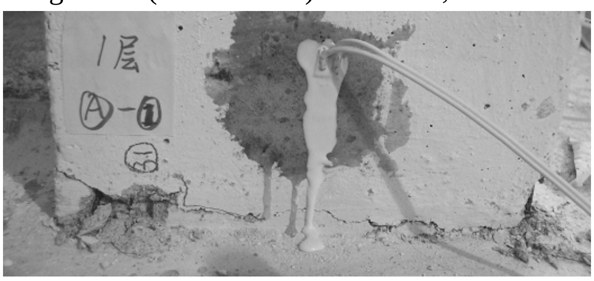

Figure 9 Crack after the input of two bi-direction Taft records of rare intensity

(d) Strong rare intensity: When the rare intensity tests finished, cracks appeared in a large number and the rigidity decreased remarkably. But in general, no severe destruction occurred in the structure. Therefore, we decided to add test case. First, two bi-direction inputs of El Centro (0.6g in primary direction and 0.51g in secondary direction) were conducted to simulate rare earthquakes stronger than intensity 8, but weaker than intensity 9. The PGA in primary direction actually measured to be 0.677g in one input. Then two bi-direction inputs of Taft (0.51g in primary direction and 0.43g in secondary direction) were conducted. In this stage, structural destruction was severe. A large number of places near the conjugation of shearwalls and beams became broken and the cracks cut through. During the vibration, cracking sounds could be heard. In the process, two frequency scans showed that the structural frequency stopped decreasing. This suggests that structural destruction was severe and cracks were basically completed.

After all inputs, most kinds of typical damage of frame-shearwall structures under major shocks were observed. For example, at bottom story, column and shearwall base suffered from severe destruction partially or wholly, concrete was compressed to be crisped and drum-shape curving occurred with wires in individual places. Many cracks expanded to cut through beam ends. Slight cracks also appeared at some beam-column joints in the upper part of the structure (above 5th story, including top story). Diagonal cracks also occurred in beams with comparatively short span. In some of them, horizontal cracks parallel to the floor also appeared.

4.3. Primary Test Data

Frequencies of first three modes of model are respectively 5.13Hz (X-direction horizontal movement), 5.27Hz (Y-direction horizontal movement) and 5.41Hz (torsion). Calculated accordingly with similarity relation, periods of the prototype are respectively 0.551, 0.537 and 0.523s. It is smaller than the results of design calculation, which may be due to the following facts: concrete of higher strength grade was adopted for model construction, the Young's module of micro-particle concrete is comparatively higher, and strengthening measures have been taken for floors, etc. After the rare earthquake test, the frequencies of first three modes decreased to 2.36, 2.36 and 2.91Hz respectively.

Maximum total drifts (ratio of top displacement to building height) of the prototype structure calculated with model response data are the following: 1/1399 in X-direction and 1/1283 in Y-direction under the circumstance of frequent earthquake intensity, 1/457 under shocks of fortification intensity, 1/124 under rare intensity, and 1/108 under strong rare intensity.

Maximum floor drifts of the prototype structure are the following: 1/813 in X-direction occurring on the 8th story and 1/1283 in Y-direction occurring on 4th story under the frequent intensity, 1/314 in X-direction occurring on 3rd story and 1/253 in Y-direction occurring on 4th story under fortification intensity. Among the three input records of rare intensity, the structure had the strongest response in X-direction to bi-direction El Centro with the maximum floor drift, 1/82. This is higher than one-direction input of the synthesized record and the follow-up bi-direction input of Taft record, none of the floor drifts in four inputs of these two records exceeded 1/100. This, to some extent, suggests the random nature of earthquakes.

5. CONCLUSIONS

5.1. RC Frame Structure with SSC

- Drift of the prototype structure inferred from model test data suggest that this structure can meet the seismic fortification criteria required in the current seismic code of China, which is "undamaged under a minor shock, no collapse under a major shock".
- From the final damage status of the model, it is observed that the beam plastic hinge mechanism can take shape at most joints. The requirement for strong column and weak beam can be met.
- Although partial collapse due to compression occurred at the flange end of the central column foot, the majority of concrete at the column section keep intact. Because the axial compression ratio limit of SSC is rather strict, the structure presents good vertical loading bearing capacity.
- Partial concrete collapse and peeling-off at some joints on the 2nd and 3rd story suggest that

damage of the joints of structures with SSC has its own characteristics. When previous joint tests and analytic reports are also taken into consideration, it is concluded that special attention should go to calculations of the shear bearing capacity of joints under high intensity.

5.2. RC Frame-shearwall Structure SSC

- The destruction process of the frame-shearwall structure can be summarized as: Under minor shocks, invisible minor cracks occurred but in general the structure was still in the elastic stage. Under moderate shocks, vertical and oblique cracks with small width occurred at the beam end at each story of the lower and middle part of the structure. Under major shocks, the existed cracks expanded in length and width, some of them could cut through the section and some develop to be X-shape cracks at conjugation of beam and column or beam and wall. At upper stories of the structure, a few cracks also appeared. Oblique and horizontal cracks appeared on the shearwall but they have not formed X-shape intersections yet. Partial collapse at the flange end of SSC only occurred at the T-shape column foot of the shearwall. Vertical cracks were found at the foot of the cross-shaped columns. Partial collapse was also found in corners of shearwall.
- From this test, it could be concluded that the prototype structure meets the following criteria: Under frequent quakes with an intensity lower than the fortification intensity (frequent intensity 8), the structure will keep intact or maintain function without repair. When struck by quakes with fortification intensity 8, the structure may be slightly damaged but can be occupied with or without ordinary repair. When suffered from rare earthquake with intensity 8, the structure should not collapse or no severe destruction which may endanger lives occurs. In shaking table test, after the input stronger than rare intensity, the structure did not collapse.
- The drift indicators show that, only in one of the three earthquake input situations, the structure failed to meet the drift control requirement (1/82) under rare intensity. Final results also suggest that the structure has good anti-collapse capacity.
- Judged from the damage process and the final damage status of the model, large amount of cracks occurred firstly in beams, then appeared in shearwalls and columns. In the end, foot of shearwalls and columns at the first story was compressed to collapse. The beam hinge mechanism was formed at majority joints, thus meeting the requirement of strong columns and weak beams.
- Different from frame structure, almost no damage occurred at the joints of beam-columns and beam-walls, and partial collapse at the flange end of SSC foot was also less severe in frame-shearwall structure. Shearwalls have effectively alleviated the impact of earthquake.
- Priority choice should be given to frame-shearwall system if structures with SSC were to be used in zones with high seismic intensity.

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