Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 210 (2017) 441–448

Procedia Engineering

www.elsevier.com/locate/procedia

6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading, PROTECT2017, 11-12 December 2017, Guangzhou (Canton), China

Tests Study of a 1:20 Scale Steel-concrete Hybrid Structure

Di WU [a], *Yan XIONG* [b]*

[a] *Engineering Research Center for earthquake engineering, Guangzhou University, Guangzhou 510405, China*
[b]*State Key Laboratory of Subtropical Building Science, South China University of Tech., Guangzhou 510640, China*

Abstract

The seismic resistance of a 36-storey high-rise structure with the height of 149 m is studied in this paper. The simulated earthquake shaking table tests have been performed on 1/20 scaled model of the steel-concrete hybrid structure. The steel-concrete hybrid structure is composed of the surrounding diagrid, the reinforced concrete core tube, the floor slab, the beam of floor. The dynamic properties and the seismic behaviour have been analysed by the shaking table test based on the measurement method on the natural vibration frequency and the damage of the model structure. The test results have shown that the phenomena of failure occurred in some components after undergoing the earthquakes of the different fortification levels. The buckling failures occur in the inclined column of the diagrid on the higher floors, the horizontal cracks in the core walls of the higher floors has been appeared, and also the damages occur in the connection between the concrete core tube, the inclined beam of floor and the span beam. Since these inclined column and the key joints between the concrete core tube and the beam have been damaged seriously in the shaking table test, the detailed theoretical analysis is required to avoid the local structural damage.

Peer-review under responsibility of the scientific committee of the 6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading.

Keywords: Shaking table tests, seismic analysis, hybrid structure, earthquakes;

* Corresponding author. Tel.: +86-15013257899; fax: +86-020-87114274.
E-mail address: xyan@scut.edu.cn, 11795234@qq.com

1877-7058
Peer-review under responsibility of the scientific committee of the 6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading.
10.1016/j.proeng.2017.11.099

1. Introduction

At present, most of the buildings built in the world are concentrated in economically developed areas, and have not yet experienced the crucible of earthquake disasters. In the absence of sufficient research and the lack of seismic disaster data, it is of great practical significance to carry out a systematic theoretical and experimental study on the seismic performance of the high-rise building structures.

In recent years, the steel-concrete hybrid Structures, such as steel diagrid-reinforced concrete core tube structure, (diagrid-core tube structure) have been widely used in the forms of high-rise buildings [1, 2].The geometric configuration of diagrid-core tube structure is similar to that of braced frame-tube structure, however there is no traditional "vertical column", and the vertical column in the conventional structure is replaced by the inclined column system. From the current research results of the aseismic performance of the structural system, the inclined column shows a strong spatial characteristic in the diagrid- core tube structure, and the shear lag effect is less than that of traditional tube structure. Various experimental methods are available to study the nonlinear behavior of high-rise buildings, such as quasi-static tests, forced-vibration tests, shaking table tests, and pseudodynamic tests [3]. The shaking table test is one of the most realistic and reliable experimental methods for evaluating the inelastic seismic performance of structures [4, 5].And this test method has been widely used to study the seismic behaviors of the typical hybrid tall building [6], the new shear wall model [7], the base-isolated structures [8], the High-rise building with a transfer plate [9], the reinforced concrete frames without and with passive control systems [10].

In this study, a series of experiments have been conducted on a 1/20 scaled model 36-storey steel-concrete hybrid structure through shaking table tests. The main objective is the evaluation of earthquake-resistant behaviours and strengthening of the hybrid structure.

2. Model shaking table test

2.1. Structure Model design and manufacture

A diagrid-reinforced concrete core tube hybrid structure consists of two parts: a huge steel rhombic diagonal grids frame and a reinforced concrete core tube. The total height of the structure is 162m with 4.5 m storey height. And it is in planar square configuration with the plane size is 45m * 45m. In order to transfer the structural gravity load from the slab to the outer wall, a steel oblique grid frame is set up about 1.5 meters from the exterior side of floor slab. The shear force between the surrounding diagrid and the shear wall is transmitted by the floor panel and the diagonal brace connecting the corner of the diagrid and the core tube.

In view of the complexity of the diagrid-frame reinforced concrete core tube structure system and the regulation of transfinite height of structural high-rise building [11], this building belongs to the tall buildings beyond the Code-Specification. Fig 1 is the structural plan layout of standard floor of the structure model.

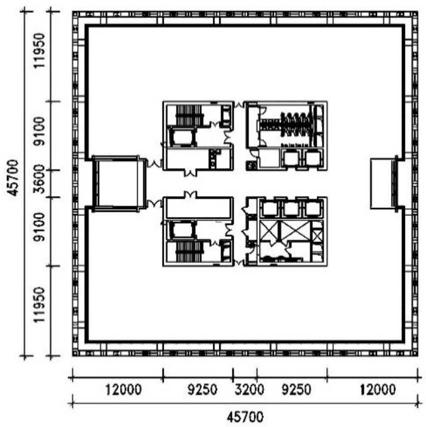


Fig.1. Structural plan layout of standard floor.

According to the π theorem proposed by Buckingham [12] and the attribute of the physical quantity, the base physical parameters, such as the dimension of length, weight and time. According to the function relation between physical quantities, the dimension of deriving physical quantity is established. At the same time, the geometrical similarity ratio of the model has been determined by considering the size of the shaking table, the bearing capacity of the table, the displacement limit and the inner height of the laboratory. The similarity coefficient of each control parameter is determined and a high-rise building model structure has been constructed in 1:20 scale. The similarity coefficient of elastic modulus, acceleration and mass of the model structure are 1/3.5, 4 and 1/5600 respectively.

The design of structural seismic dynamic test model needs to meet the requirements of similar physical conditions, similar geometrical conditions and similar boundary conditions. The experimental model has been made of microconcrete, galvanized iron wire, section steel fabrication, etc. The microconcrete has been used to simulate the concrete of the core tube, floor, beam and other concrete members in the prototype structure, the galvanized iron wire has been used to simulate the steel bar in the prototype structure, the section steel has been used to simulate the corner column of the outer frame, the inclined column of the diagrid and other structural parts of steel in the prototype structure. In the design of reinforced concrete members, the control of the bearing capacity of the positive section is based on the principle of equivalent bending ability. The control simulation of the bearing capacity of oblique section is based on the principle of equivalent shear capacity. The dimensions of steel structure members are designed according to the principle of equivalent stiffness [13]. In order to satisfy the mass density similarity, the mass block has been arranged in each floor of the model according to the mass distribution of the prototype structure [14]. After the completion of the model structure, the total height without foundation is 8.1m. The gross weight of total model, including deadweight, floor weight and additional counterweight of modal, is 16.32 *t*.

2.2. Model material test

The concrete strength grade of the prototype structural component adopts C30, C40, C50 and C60, and the strength grade of the microconcrete used in the construction of the corresponding model structure is M6, M8, M10 and M12 in turn. The strength grade of steel of the original model steel structure component adopts Q420 and Q390, and the strength grade of the corresponding model structure is Q235 steel. In the model-making process, 3 microconcrete test cubes have been poured for each group and the concrete curing of the test cube is the same as that of the model. In accordance with the requirements of the standard of test method for mechanical properties of ordinary concrete (GB/T50081-2002), Before shaking table test, 10t compression testing machine has been used to measure the cubic compressive strength, splitting tensile strength and the compression modulus of concrete prism.

2.3. Selection of seismic parameter

The seismic intensity and soil site condition were designed according to the engineering safety evaluation report of the seismic response of site soil and design ground motion and detailing provisions of 2010 Chinese code for seismic design of buildings (CCSDB). The site category of prototype structure is the fortification intensity 7 with a soil site condition of II in the 2010 CCSDB. And the design basic acceleration 0.1g, and the predominant period of site is 0.42s. According to the dynamic characteristics and the site characteristics of the prototype structure, an artificial seismic record (wave 1) and two natural seismic records (waves 4, wave 5) have been chosen as the seismic excitation of the shaking table test. The acceleration peak and duration of the seismic motion have been adjusted according to the similarity coefficient of the model, and the peak ground acceleration ratio of x, y and z is 1:0.85:0.65. The experiments on the seismic response analysis have been conducted considering 38 working conditions in x, y and z three-direction. The model experiment of shaking table on earthquake simulation have been performed in 3 stages according to the order of frequent, fortification and rare intensity level of the earthquake. Considering the damage to the model structure caused by rare earthquake, only one of rare earthquake with the largest seismic response have been executed in the test. The acceleration response spectra of the normalized seismic records at the peak acceleration of 1 g in the x direction have been shown in Fig. 2.

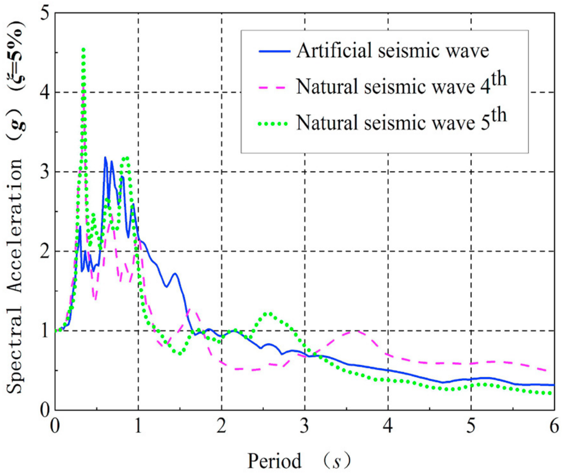


Fig.2. Acceleration response spectra of the seismic records.

3. Test result and analysis

3.1. Dynamic characteristics

In order to obtain the dynamic characteristics of the model structure after different seismic intensity levels, the dynamic characteristic parameters such as the vibration frequency, the vibration mode and the damping of the structure have been measured by the white noise excitation method [15]. The natural frequencies of the first two-order mode of the model structure in the test have been compared with those of the analysis result of the prototype structure. And the results have shown that the difference of the main frequencies of the structure is below 10%. This type of error is mainly due to the difference between the performance of the model material and the design, the difference between the number and the location of the weight of the test model and the density distribution of the calculation model, etc. [16]. The natural frequency of model structure decreases steadily after the different seismic levels of test.

According to the results of shaking table test, the natural frequencies of the model structure are reduced after rare earthquakes, which indicates that the local structure of the model has been destroyed, and the whole model structures enter elasto-plasticity condition in the strong motion earthquake.

3.2. Acceleration response

By analyzing the data obtained from the measurement of shaking table test by analyzing the shaking table test data, the acceleration responses of the model structure in the key floors along the altitude direction have been obtained.

The maximum acceleration response of each floor of the model structure in the earthquake of x and y directions is basically consistent. The peak acceleration response curve of the main model structure is in the shape of “S” along the altitude direction. The maximum acceleration of the model structure occurs on the higher story where the section size of the shear wall and the steel component have been reduced. Meanwhile, the maximum acceleration of the higher floor of the model structure increases significantly. The response of the model structure under different ground motions is obvious, which shows that the effect of different ground motions on the response of the model is remarkable. Fig. 3 shows the envelope curve of the acceleration response of the model structure under the rare earthquake in one direction at the different seismic fortification level.

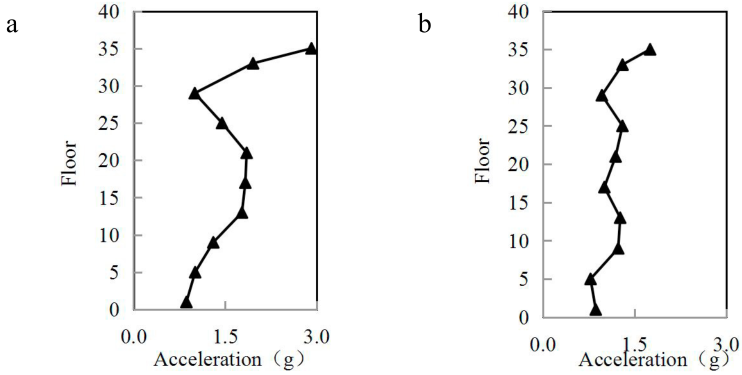


Fig.3. Envelopes of acceleration under rare earthquake: (a) in x-direction; (b) in y-direction.

3.3. Displacement response

According to the displacement response of each measuring point measured by the displacement sensor, the maximum story drift of the model structure has been obtained. The distribution trend of the maximum story drift of model structure is basically consistent under the earthquake at the different seismic fortification level, that is, the maximum story drift of each story is in the shape of inverted triangular distribution along the altitude direction. Under the seismic action, the model structure remains mainly bending deformation, and the horizontal deformation along the height direction is evenly distributed. However, the displacement mutation has been appeared in the maximum story drift of layer between 21st to 33th stories.

Fig. 4 describes the envelope curve of the interstory displacement angle of the model structure under different fortification levels. The maximum interlayer displacement angle appears on the 29th to 33rd story under frequent earthquakes of fortification intensity 7 in X direction, and the maximum interlayer displacement angle appears on the 25th to 29th story in Y direction. Secondly, the maximum interlayer displacement angle appears on the 29th to 33rd story under the fortification intensity earthquakes in X and Y direction. Also, the maximum interlayer displacement angle appears on the 21st to 25th story under rare earthquakes in X direction, and the maximum interlayer displacement angle appears on the 29th to 33rd story in Y direction.

Under frequent earthquakes, according to the clause on "Technical specification for concrete structures of tall building" (JGJ 3-2010), the allowable interlayer displacement angle is selected by linear interpolation between 1/800 and 1/500 for the tall building with a height between 150-250 meters. Therefore, the interlayer displacement angle limit of the structure according the clause are 1/765 and 1/100 under the frequent and rare earthquake, respectively. The interlayer displacement angles of the structure are less than the limit in the specification in X and Y directions, respectively.

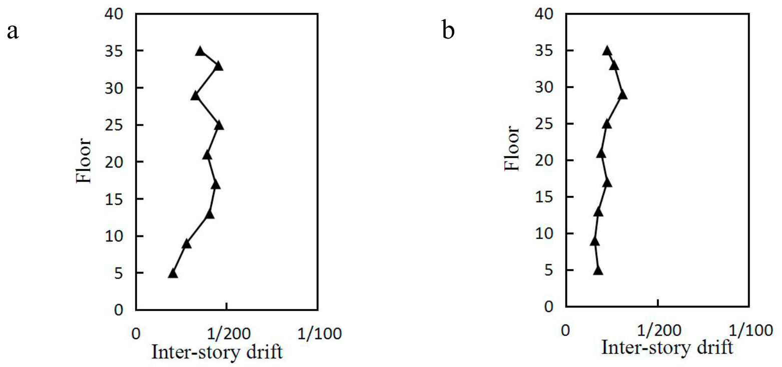


Fig.4. Envelopes of inter-story drift under 7 degree unidirectional earthquake: (a) in *x*-direction; (b) in *y*-direction.

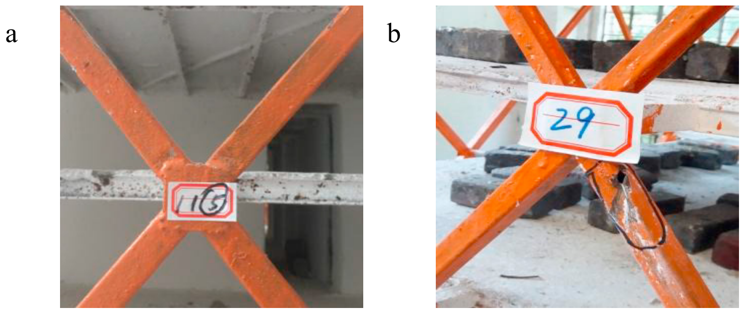
3.4. Test phenomenon and damage conditions

During the simulating seismic shaking table test, the displacement response of the model structure under different fortification levels is mainly translational, and the torsional effect of the whole structure is not obvious.

After all the test conditions has been completed, the observations have been made of the whole and local damage of the model structure. The cracks appears in the local parts of the shear wall of the model structure core tube, and the serious damage occurs in the main members of the steel structure, such as the inclined column of the diagrid, on the story where the cross section of the members of the diagrid changed. The details have been shown in Fig. 5 The story 11th (Fig. 5 (a)), 28th (Fig. 5 (a)), 30th of the model structure is the position where the section size of the members changed. And the compressive buckling occurs in some inclined columns in these stories.

The failure of concrete core tube as shown in Fig. 5 (c), there occurs a large number of the cracks in the bottom of shear wall on the 25-35th story. The connection of the concrete core tube, the inclined beam of floor and the span beam and the connection of overhang short beam of floor, the inclined beam of floor and the corner column or the inclined column of diagrid belong to the joint of force transfer between the vertical and horizontal forces of the inner and external tubes. These joints that are in the multi direction force state have been damaged seriously in the test, as shown in Fig. 5 (d).

Overall, the model structure has entered the elastoplastic stage and has been damaged in some local parts of the structure. However the structure has not reached the collapse state. The model structure has not been severely damaged in the whole, which shows that the aseismic capability of the model structure is in the satisfactory performance.



c

d

Fig.5. Damages of test model: (a) inclined column of story 11th; (b) inclined column of story 28th; (c) concrete core tube; (d) joint.

4. Conclusion

These experimental results contain of course much more information than included in this paper, the information that is thoroughly published in Reference [17]. Based on the analysis of the simulation seismic shaking table test of the scale model, the following conclusions can be drawn. After undergoing the earthquakes of the different fortification levels, the plastic development and failure of the inclined column appear firstly in the structural component on the floor where the cross-section size of the shear wall and the steel component have been reduced. Meanwhile, the connection of the concrete core tube, the inclined beam of floor and the span beam and the connection of overhang short beam of floor, the inclined beam of floor and the corner column or the inclined column of diagrid have been damaged seriously. The main reason of these joints damages is that the joints are in the multi direction force state. The maximum story drift of each story is in the shape of the inverted triangular distribution along the altitude direction. In general, the model structure mainly remains bending deformation in the different seismic action according to the damages in the model structure.

Reference

[1] Ali M M, Moon K S. Structural developments in tall buildings: current trends and future prospects [J]. Architectural science review, 2007, 50(3): 205-223.
[2] JOHN S, LESLIE R. IBM Building[R]. USA:RIGIDIZED METALS,2015:1-3.
[3] Shing P B, Mahin S A. Pseudodynamic test method for seismic performance evaluation: theory and implementation [J]. EERC Report. UBC/EERC-84, 1984, 1.
[4] Chung W J, Yun C B, Kim N S, et al. Shaking table and pseudo dynamic tests for the evaluation of the seismic performance of base-isolated structures[J]. Engineering Structures, 1999, 21(4): 365-379.
[5] Li Guoqiang, Zhou Xiangming, Ding Xiang. Shaking table study on a model of steel-concrete hybrid structure tall buildings [J]. Journal of Building Structures, 2001, 22(2):2-7.
[6] Li G, Zhou X, Ding X. Shaking Table Study on a Model of Steel-Concrete Hybrid Structure Tall Buildings [J]. Journal of Building Structures, 2001, 2(22): 2-7.
[7] Lu X, Wu X. Study on a new shear wall system with shaking table test and finite element analysis [J]. Earthquake engineering & structural dynamics, 2000, 29(10): 1425-1440.
[8] Chung W J, Yun C B, Kim N S, et al. Shaking table and pseudodynamic tests for the evaluation of the seismic performance of base-isolated structures [J]. Engineering Structures, 1999, 21(4): 365-379.
[9] Li C S, Lam S S, Zhang M Z, et al. Shaking table test of a 1: 20 scale high-rise building with a transfer plate system [J]. Journal of structural engineering, 2006, 132(11): 1732-1744.
[10] Dolce M, Cardone D, Ponzo F C, et al. Shaking table tests on reinforced concrete frames without and with passive control systems[J]. Earthquake engineering & structural dynamics, 2005, 34(14): 1687-1717.
[11] Krawinkler H, Moncarz P D. Similitude requirements for dynamic models[J]. Special Publication, 1982, 73(1): 1-22.
[12] Huang Xiangyun, Zhou Fulin, Jin Jianmin, et al. Shaking table test of Guangzhou new TV tower [J]. China Civil Engineering Journal, 2010, 43(8): 21-29.
[13] Zhou Ying, Lu Xilin. Method and technology for shaking table model test of building structure [M]. Science Press, 2012.
[14] Zhang Minzheng. Study on similitude laws for shaking table tests [J]. Journal of Earthquake Engineering and Engineering Vibration,1997, 17(2):52－58.
[15] Zhang Jin, Lu Zhitao. Earthquake simulation test of short-leg shear wall-tube model [J]. Journal of southeast university: Natural science edition, 2001, 31(6) :4－8.

[16] Huang Xiangyun, Cao Jingyun, Ma Yuhong, et al. Experimental study on seismic behavior of a steel-concrete composite structure for a high-rise building [J]. Journal of Earthquake Engineering and Engineering Vibration, 2011.31(2):68-74.

[17] Di WU. Seismic Simulated Earthquake Test Research Reporton Structure Model of XinTong Finance Building in ShenZhen [R]. China: Guangzhou University, 2016.