

EARTHQUAKE ENGINEERING RESEARCH IN SHAKING TABLE TESTING LABORATORY OF TONGJI UNIVERSITY, SHANGHAI, CHINA

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Abstract: The research work in the field of earthquake engineering conducted in Shaking Table Testing Laboratory of Tongji University, Shanghai, China in recent years is reviewed briefly in this paper. It includes structural control study of high-rise buildings with application, base isolation study with application, development of new seismic energy-dissipation shear walls, study on dynamic soil-structure interaction, study on concrete-filled rectangular tubular structures, and seismic behavior of reinforced concrete high-rise buildings and towers. It can be seen that the basic research work is combined with engineering practice and most of the research accomplishments have been applied in practice successfully.

1. INTRODUCTION

Since China is an earthquake prone area, research in the field of earthquake engineering has been highlighted by the government and researchers all along, especially after the Tangshan earthquake in 1976. Quite a few research projects in this field have been carried out in Shaking Table Testing Laboratory of Tongji University, Shanghai, China, since it was founded in 1983. Up to 2003, 390 and more experiment projects including 20 and more state key projects have been conducted on the shaking table. Now, it is one of the most renowned laboratories in civil engineering in China. In this laboratory the basic research is generally combined with engineering application and can be transformed for the actual needs of engineering practice. The tradition of continuous contact and good cooperation with other institutions and companies allows it to remain abreast of the latest developments in this field. In this paper the main research work in the field of earthquake engineering completed by this laboratory in recent years are reviewed, and some topics that are being investigated now or will be investigated in the future are also presented.

2. STRUCTURAL CONTROL STUDY OF HIGH-RISE BUILDINGS WITH APPLICATION

2.1 Development of A New TMD Control System

A new TMD control system using servomotor as tuned damper shown in Figure1 was proposed to control earthquake response of buildings by Lu and Fang (1994). The system is composed of tuned mass, tuned springs, and tuned damper. The parameters of these three components can be tuned according to the dynamic characteristics of the controlled structure so as to get the optimal control

effect. The dynamic behavior and the control effect of the new system were studied through a series of free vibration tests with variant damping values. Then shaking table tests were carried out on a 3-story steel frame structure equipped with this system under various seismic inputs by Lu, Ye and Fang (2000). The test results showed that the earthquake responses of the structure with the control system were reduced significantly, compared with the structure without the control system. It was discovered that the damping value and the characteristics of frequency spectrum of the seismic input had significant effect on the control efficiency of this system. Moreover, the analytical model is developed for the tested structure as shown in Figure2, and the calculation results agree well with the test results.

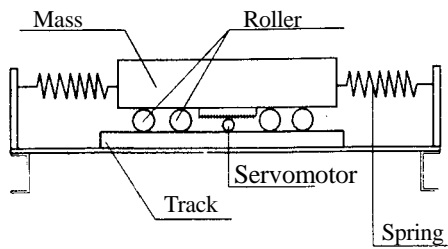


Figure1 Servomotor TMD System

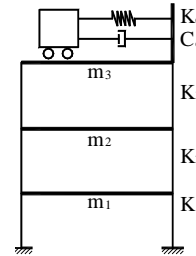


Figure2 Analytical Model for The Tested Structure

2.2 Development of A New Combined Energy-dissipation System

Although various single energy-dissipation system has been studied more extensively during the last 20 years, it still has some limitations in engineering practice. In order to meet the different requirements of structures to reduce earthquake response, a new combined energy-dissipation system was developed by Lu and Zhou (2002). It consists of lead rubber damper, oil damper, and conventional steel brace. The installation of this system in a frame is shown in Figure3. Under wind load or minor earthquake, the lead rubber damper behaves elastically and oil damper provides small damping force and stiffness. Under strong earthquake the lead rubber damper develops elasto-plastic deformation and the stiffness to the structure is decreased, and the oil damper provides larger damping force but smaller stiffness. As a result, the seismic force to the whole structure is reduced and its response decreased.

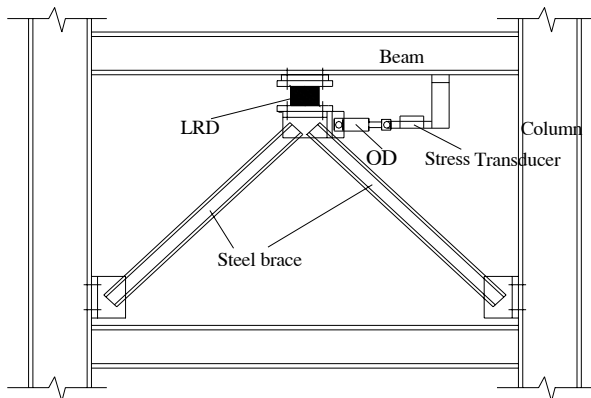


Figure3 Combined Energy-dissipation System Installed in A Frame



Figure4 Tested Model

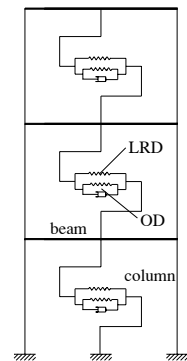


Figure5 Analytical Model

Shaking table tests were carried out on a 3-story steel frame structure equipped with the energy-dissipation system in each story, as shown in Figure4. To make comparison the structure was tested in three conditions, unbraced frame, frame braced with lead rubber damper and steel brace, frame braced with this system. The test results show that the system can increase the damping ratio and stiffness of the entire structure and so has good control effect on the earthquake response of the structure. The analytical model for this system is developed as shown in Figure5, and optimal analysis is conducted for the design parameters of the system. This new energy-dissipation system has been

applied to seismic retrofit of existing old buildings. One application example is presented here. The structural plane layout of a 9-story old building with reinforced concrete frame is shown in Figure6. After evaluation of its seismic performance, the seismic capacity of this structure is considered not able to meet the seismic demand, especially in the longitudinal direction the seismic capacity is severely insufficient. By being added six energy-dissipation devices as shown in Figure6, the earthquake responses of this structure are reduced efficiently and within the limitations specified by the seismic design code. The in-site installation of this system is shown in Figure7.

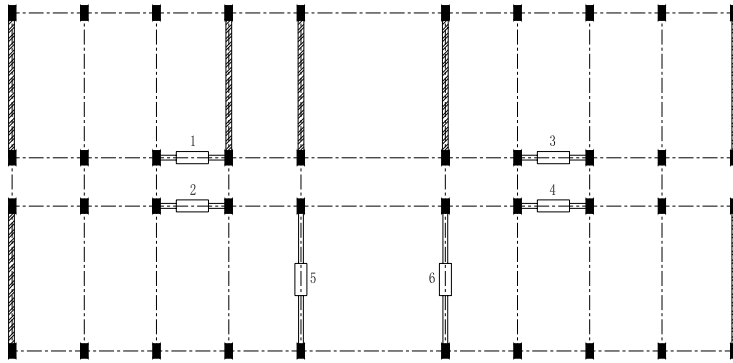


Figure6 Plane Layout of The Structure and The Energy-dissipation System

Figure7 In-site Installation of This System

2.3 Coupling-structure System Connected by Fluid Dampers

Buildings in a modern city are often built closely to each other because of limited land available and centralized services preferable. In most cases these buildings are built separately without any structural connections. Under strong earthquakes, the pounding of two adjacent buildings often occurs. In other cases, two adjacent buildings are linked together in different ways to meet the requirements of architectural function or esthetic needs. A series of theoretical and experimental studies are carried out to study the feasibility of the concept of linking adjacent buildings or connecting podium structures to a main building by fluid dampers to improve their seismic performance and to prevent the pounding between them. Shaking table tests were conducted on a 1/4-scale coupling-structure system composed of one 6-story steel frame and one 5-story steel frame by Lu, Yang and Xu (2002), as shown in Figure8. Three connection conditions between the two frames were involved: connected by rigid steel rods, connected by fluid dampers, or without any connections. In the case of being connected by fluid dampers, the influence of different connection locations, different linking forms, that is, parallel linking form and oblique linking form, were also investigated in the tests. The test results showed that the modal damping ratios of both buildings could be increased significantly and so their seismic responses could be reduced effectively if fluid dampers with appropriate parameters were installed to link the two buildings. General finite element software Ansys5.5 is used to set up the analytical model and calculate the nonlinear earthquake response of the tested structure, and good agreement is obtained between the test results and calculated results.

A standardized 3-D model of two stories, surrounded by a 3-D one-story model, as shown in Figure9, is first proposed to simulate a high tower with a podium structure based on several simplified principles. The equations of motion of the tower-damper-podium system are derived using this model. Recently, this concept has been applied to an actual 60-story ultra-tall building with 10-story large podium connected by fluid dampers to reduce their torsional seismic response. An extensive analysis on the structure and a series of experiment on the fluid dampers have been carried out to get the optional parameters for the fluid dampers, and to achieve the best structural performance under various seismic excitations. Finally 40 fluid dampers with maximum capacity of 600kN were used to connect the podium structure to the main building at different floor levels on and below the roof of podium structures, so as both the podium structure and the main building can meet the seismic design

requirements for low and higher intensity of earthquake actions. The layout of the fluid dampers is shown in Figure10, and the perspective picture of this building is shown in Figure11.



Figure8 Adjacent Structure Linked by Fluid Dampers

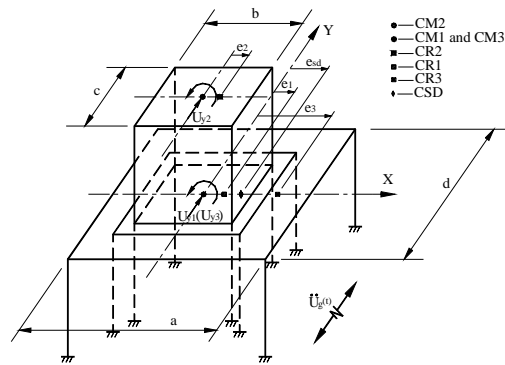


Figure9 Standardized Analytical Model

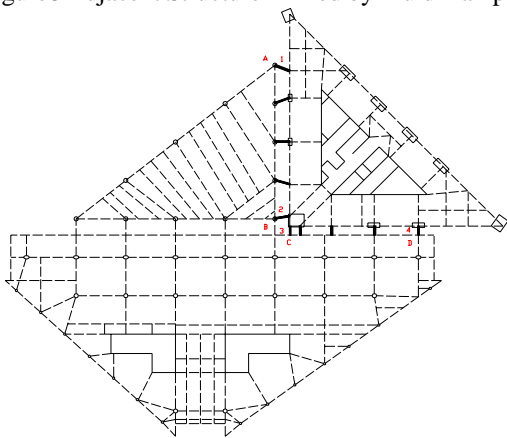


Figure10 Plane Layout of The Structure and The Fluid Dampers



Figure11 Perspective Picture of The Building

3. BASE ISOLATION STUDY WITH APPLICATION

3.1 Development of A New Type of Base Isolation System with Restrained Sliding Mechanism

In the past three decades several base isolation systems have been developed, among which sliding isolation system is one of the most attractive systems due to its effectiveness for a wide range of frequency inputs and good control of seismic force. However, the biggest disadvantage is excessive sliding and residual displacement of the isolator under strong earthquakes. A new type of base isolation system with restrained sliding mechanism was proposed by Shi and Li (1998). It consists of common friction isolator and rubber block with specified distance to friction isolator. The sliding isolator can slide freely when the maximum sliding displacement is within the control range at minor or moderate intensity earthquake excitations. The sliding lateral stiffness will increase due to the contribution of the rubber block comes into operation when the sliding displacement exceeds the pre-defined distance and the sliding isolator collides with the rubber block at high intensity earthquake excitations. The analytical model is developed for this base isolation system, as shown in Figure12. By taking the contribution of both the friction isolator and the rubber block into account, the hysteretic model of this system can be obtained, as shown in Figure13. Earthquake time history response analysis demonstrated that compared with the structure installed with common sliding isolator, the earthquake responses of the structure installed with this system were reduced considerably and the maximum sliding displacement during the earthquake as well as the residual displacement after the earthquake was more satisfactory.

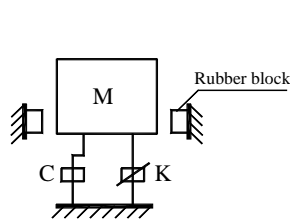


Figure12 Analytical Model

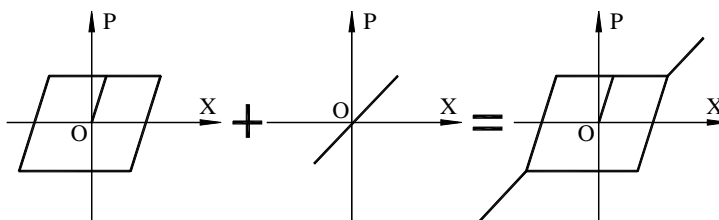


Figure13 Hysteretic Model for The Developed Base Isolation System

3.2 Research on A Hybrid Isolation System

A hybrid isolation system, composed of frictional slider isolation system and rubber bearing re-centering the isolation system, was studied by Lu, Zhu et al. (2002). To verify the effectiveness of this system, a 1/12-scale and three-story steel frame model was tested on the shaking table with base fixed (FIX) and isolated (SLD) separately for comparison. The isolation system was composed of four rubber bearings and two frictional sliding bearings. The layouts of the isolation system and the superstructure are illustrated in Figure14 and Figure15. Compared with FIX, the responses of SLD were reduced significantly. In addition, the isolation system was of good re-centering capability with a small residual displacement. For each piece of ground motion input, the total input energy and the constitutive energy components were calculated by integration, which showed that in FIX most of the total input energy was dissipated by the superstructure itself while in SLD, by the sliding isolators. A new simplified analytical model for the tested model is developed. The superstructure and the rubber bearing are supposed to be elastic, the frictional force in the slider is simulated by the Coulomb-friction characteristics, and the damping of the rubber bearing and slider is taken as viscous damping. By using this analytical model, the earthquake responses of the tested model are calculated through finite element program Ansys5.5.

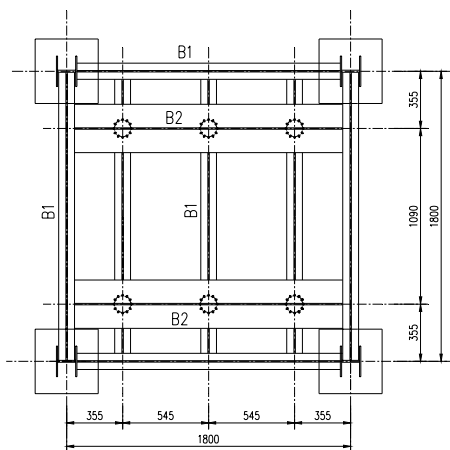


Figure14 Layout of Base Isolators



Figure15 Base Isolated Structural Model on The Shaking Table

3.3 Inter-story Seismic Isolation

The new method of inter-story seismic isolation was developed to improve the seismic performance of the existing old buildings, especially in the case of adding story to original buildings by Shi and Zhu (1994). The principle of inter-story isolation is to add an additional energy-dissipation system, composed of the top mass block and rubber bearings installed between the top mass block and original roof, at the top of the building. After being installed this system, the damping ratio of the building can be increased significantly, and so the earthquake responses are decreased considerably. In practice, there are three forms of this system, as shown in Figure16. Shaking table tests were carried out on one 1/7-scale 6-story flying-ash concrete block masonry structure model and one 1/6-scale

3-story reinforced concrete frame structure model with inter-story isolation system as shown in Figure17. The test results showed that compared with common structures without this system, the earthquake responses of the structures with this system were reduced by 20%~40%. The calculation and design method has been developed to analyze and design the inter-story isolation system. This new method has been applied to strengthen twenty and more old buildings in China.

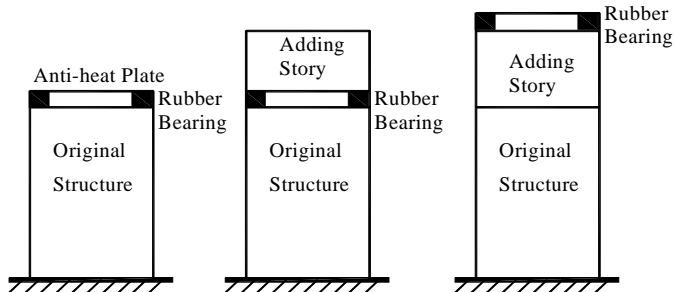


Figure16 Inter-story Isolation System



Figure17 Comparing Shaking Table Tests on Frame Structure Model

4. DEVELOPMENT OF NEW SEISMIC ENERGY-DISSIPATION SHEAR WALLS

4.1 Reversed Cyclic Tests on Interfaces between Concrete and Rubber

To prevent R. C. shear walls suffering damage concentrating at the base and to improve the seismic performance, a new type of energy-dissipation shear wall was proposed by Lu and Wu (2000). It is one with vertical slit purposely cast within the wall, and the rubber belt penetrated by a part of web shear reinforcement as seismic energy-dissipation device was filled in the slit. A series of experimental and theoretical studies were carried out. As the first stage of investigation, reversed cyclic tests on the energy-dissipation device were carried out to study its energy-dissipation mechanism and analytical model. Each specimen was divided into three parts, four steel bars passed through the middle rubber belts. The testing setup is shown in Figure18. The tests proved that the device had large capacity of dissipating energy and good ductility.

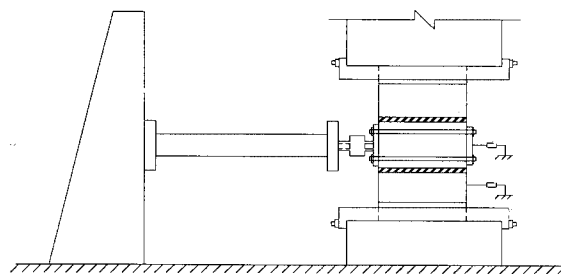


Figure18 Testing Setup for The Energy-dissipation Device

4.2 Reversed Cyclic Tests on Low-rise Shear Wall and High-rise Shear Wall Models

To compare the different seismic performance between the solid wall and the new shear wall, low-rise wall models and high-rise wall models were tested under reversed cyclic loads respectively by Jiang and Lu (2003). The vertical compressive load was applied on the top loading beam in advance of the application of the horizontal cyclic load. At the beginning of loading the behavior of solid wall models was similar to that of the solid wall models, and then different failure process took place in two different types of wall models. In solid wall models damage concentrated at the base while in slit wall models the damage at the base was much lightened and damage dispersed along the slit. The final failure modes of these models are shown in Figure19. Compared with solid wall models, the ductility and energy-dissipation capacity of slit wall models was enhanced significantly.



(a)



(b)



(c)



(d)

Figure 19 Failure Modes of The Shear Wall Models: (a) Solid Low-rise Shear Wall, (b) Slit Low-rise Shear Wall, (c) Solid High-rise Shear Wall, and (d) Slit High-rise Shear Wall

4.3 Shaking Table Tests on Slit Shear Wall Models

In order to further verify this concept of slit wall, shaking table tests were carried out on a 10-story 1/5-scale shear wall model. The model consisted of two pieces of 40 mm thick walls connected by floor slabs and four foundation beams. Under minor earthquake ground motions, the model was in elastic stage, and its responses were very much like those of solid wall model. Under moderate earthquake ground motions, the relative sliding along the slits between the rubber belts and wall piers took place to dissipate the input seismic energy, and damage appeared along the slits. Under severe earthquake ground motions, slight flexural failure occurred at the base of the wall. The good seismic performance of slit wall was proved once again by the tests.

4.4 Finite Element Analysis on Slit Shear Walls

The slit shear walls are analyzed by finite element method. To reflect the seismic energy-dissipation mechanism on the sliding friction interfaces between concrete and rubber, a contact element is derived from the joint element that is conventionally used in the rock mechanics. The contact element is composed of two sliding surfaces. The analytical model is shown in Figure 20. Cyclic shear-sliding relationships for the interface is shown in Figure 21. The steel reinforcement is treated as a uniaxially stressed material and smeared among the concrete element. Nonlinear time history analysis is conducted by the finite element models for the slit shear wall model tested on the shaking table. The numerical results are in good agreement with test results. This new slit shear wall was applied in two actual tall buildings in Shanghai in 1997.

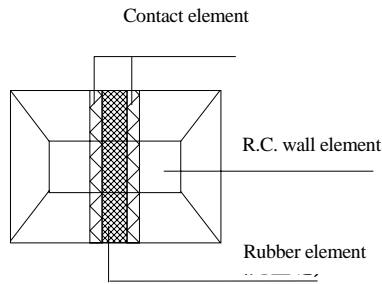


Figure20 Analytical Model

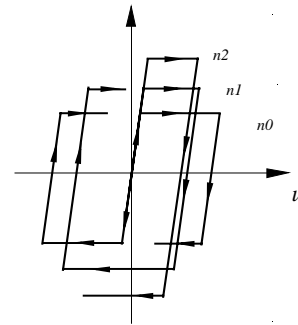


Figure21 Shear-sliding Relationships for The Interface

5. STUDY ON DYNAMIC SOIL-STRUCTURE INTERACTION

5.1 Shaking Table Tests on Interaction System Including Soil-pile-structure

In order to reduce the box effect, a flexible container and the proper construction details were designed by Lu, Chen et al (2002). The ratio of ground plane diameter D to structure plane size was taken as 5. The cylindrical container was 3000 mm in diameter and its lateral rubber membrane was 5 mm in thickness. The reinforcement of $4@60$ along the outside perimeter of the container was used to strengthen the container. The foundation of the model consisted of 3X3 group piles capped by a slab. Shanghai soft soil was used as model soil. From top to bottom, three kinds of model soil, silty clay, sandy silt, and medium sand, were stacked. Two 12-story R.C. frame structure models, with the scale of 1/10 and 1/20 respectively, were tested. Accelerometers and strain gauges were installed on the models to measure the earthquake responses of the superstructure, foundation, and soil. Soil pressure gauges were also installed to measure the contact pressure between the piles and soil. The tested model is illustrated in Figure22.



Figure22 Shaking Table Tests on SSI model



Figure23 Analytical Model

5.2 Computer Simulation on Soil-pile-structure Interaction Considering Soil Liquefaction

Analytical model was developed by finite element program Ansys5.5 for numerical analysis by Chen and Lu (2002), as shown in Figure23. The lateral rubber membrane of the container is meshed by shell element. The bottom of soil is considered as fixed. Soil is meshed by three-dimensional solid element, and the equivalent linearization model is adopted. The effect of effective confining pressure of soil on initial shear modulus is considered when the initial shear modulus of each layer soil is chosen. The equivalent linearity model is realized in Ansys program by using the APDL, so the calculation of material nonlinearity is realized automatically. In Ansys program contact analysis is

realized by overlaying a thin layer of elements upon the contact interface of analysis model to reflect sliding and splitting phenomena on the soil-structure interface. The soil surface is taken as contact surface, and the structure (foundation) surface due to its larger rigidity, as target surface. A material-damping input method is used, and different damping ratio can be input for different materials.

The effect of the material nonlinearity of soil and the changing-status nonlinearity of soil-structure interface on the computational results is studied. The computational analysis is carried out under three conditions, not considering material nonlinearity, considering material nonlinearity, and considering both material nonlinearity and changing-status nonlinearity. By using the above analytical model, the calculation results agree with the test results approximately. Along the height of the piles in different location in the group piles the distribution of the strain amplitude, contact pressure amplitude on soil-pile interface, and sliding amplitude between soil and pile are studied. Along the height of the pile, the strain amplitude at the top is larger than in the middle, and that at the tip, smaller. The contact pressure amplitude at both ends is larger than in the middle. The strain amplitude of corner pile is larger than that in other location; the sliding amplitude of the pile in the side row is larger than that in the middle row.

6. STUDY ON CONCRETE-FILLED RECTANGULAR TUBULAR (CFRT) STRUCTURES

6.1 Ultimate Strength and Confinement Mechanism of Axially Compressed CFRT Stubs

Six CFRT columns and two square steel tubes without infilled concrete were tested for comparison. The width-to-thickness ratio of steel plate and the concrete grade were variant parameters. In steel tubular columns local buckling failure of the plate panels occurred before the yielding stress was reached. Compared with the steel tubular columns, the CFRT columns had better ductility because the infilled concrete increased the stability and slowed down the development of the local buckling. A constitutive model for concrete subjected to triaxial compressive stresses is developed, which is based on hypoelastic orthotropic approach. The criterion proposed by Ottosen is adopted herein and the equivalent uniaxial strain concept of Darwin and Pecknold is incorporated further into the nonlinear three-dimensional incremental stress-strain relationship. A 3D nonlinear F.E.M. analytical model was developed to analyze the steel-concrete composite structures and corresponding computer program was completed by Lu and Yu (2000). The concrete material model, where Sargin's stress-strain expression and corresponding tension and compression failure surfaces are adopted, is based on a hypo-elastic orthotropic approach. Von Mises elasto-plastic isotropic hardening model is employed for steel element. Smeared crack approach is applied. In order to trace pre- and post-collapse response of structure, the arc-length method is used to solve nonlinear equations. The calculation results agree well with the test result

6.2 Seismic Behavior of CFRT Columns

Eleven CFRT columns were subjected to cyclic lateral loads, while one subjected to monotonic load for comparison, as shown in the work by Lu and Lu (2000). The width-to-thickness ratio of plate, concrete grade, and axial force ratio are variant parameters. The analysis method is based on finite slices model. In analysis, Bernoulli-Euler hypothesis and planar assumption are adopted, and the slippage between the infilled concrete and steel tube and the buckling of the steel plate are ignored.

6.3 Connections between CFRT Columns and Beams

The Seismic behavior of connections between CFRT columns and beams was studied through sub-assembly loading tests by Lu, Yu et al. (2000). Cruciform tensile tests for modeling connections of column-to-tension part of beam on CFRT connection was conducted, and then the transfer mechanism was investigated by Li and Lu (2002). Simple stress transfer mechanism is assumed to

compute yielding and ultimate tension strength of the joint, which is based on yielding line theory and takes the contribution of the inner diaphragm and flange of CFRT columns into account. The computational and experimental results are in good agreement. Secondly, tests on CFRT column and steel beam sub-assemblages were conducted. The tests showed that the infilled concrete and inner diaphragm improved the behavior of connections, i.e., reducing the deformation of joint panel and enhancing the strength and rigidity.

Present types of CFRT joints are concerned on the connection between CFRT columns and steel beams. But in China, the floors of high-rise buildings are mostly composed of R.C. beams and R.C. slabs. In order to accomplish the connection between CFRT columns and reinforced concrete floors, two new types of joint, the one that reinforcements are put through the CFRT column; and the other one that the beam reinforcements are located outside the column and connected by R.C. ring beams around the column, are developed, shown in Figure24.

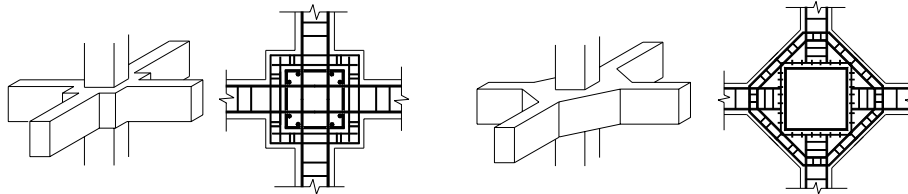


Figure24 New Types of Connections

7. SEISMIC BEHAVIOR OF R.C. HIGH-RISE BUILDINGS AND TOWERS

7.1 R. C. Coupled Shear Walls

Three 1/4-scale 5-story R.C. coupled shear wall models shown in Figure25 were tested under cyclic loading. The only difference between the models was the height of coupling beams, which brought forward different stiffness ratio of coupling beams to wall piers. After constant vertical loads were applied on the top beam, the horizontal cyclic loads were applied through two points, with the ratio of 2, to simulate the reversed triangular load. The failure process and mechanism were studied.

A nonlinear macro model is proposed to simulate coupled shear walls, as shown in Figure26. This model consists of multi-vertical-element model for wall piers and a combined model for coupling beams. In the model for wall piers, some key characters, such as shifting of neutral axis within wall section, interaction among flexure, shear and axial forces, can be taken into account. In the model for coupling beams, the deformation of flexure and shear, and the interface bond-slip action are considered by using different elements. The analytical results agree well with the test results.

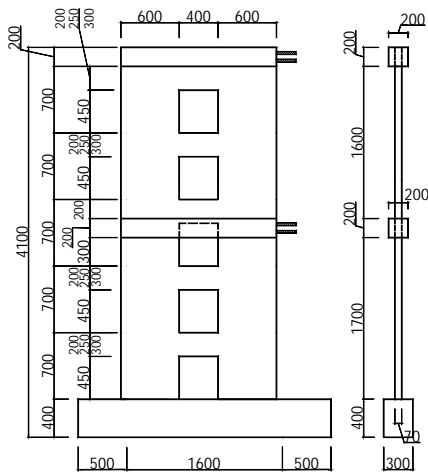


Figure25 Profile of The Tested Models

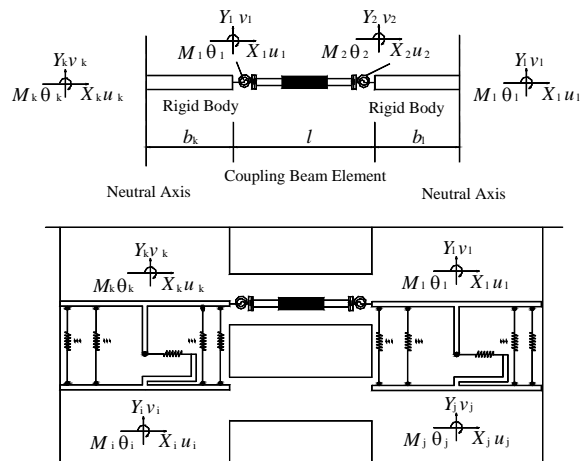


Figure26 Analytical Model

7.2 R. C. Core Walls

Three 1/5-scale 3-story core wall models (the first group) and two 1/6-scale 5-story core wall models (the second group) were tested under cyclic loading, as shown in the work by Li and Lu (2003). For the first group, the vertical loads were exerted by hydraulic jacks, and the horizontal loads acted on the top floor level. For the second group, the vertical loads were applied by prestressed strands, and the horizontal loads acted on the top floor level and second floor level simultaneously. The testing setups for the two groups are shown in Figure27 and Figure28. The failure process and mechanism were studied. The phenomenon of shear lag of the core wall was observed distinctly.

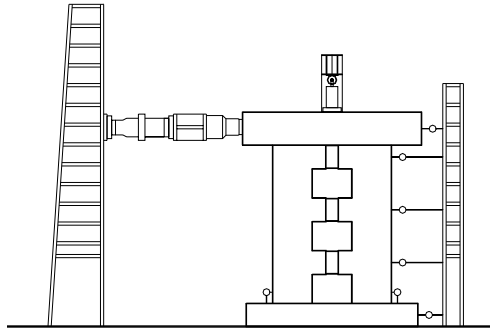


Figure27 Testing Setup for The First Group



Figure28 Testing Setup for The Second Group

A nonlinear finite element analytical model is developed using eight-joint plane-stress elements, as shown in Figure29. A simple and reliable constitutive model of reinforced concrete under cyclic loading as shown in Figure30, and the concept of a smeared crack approach with orthogonal cracks are utilized. Using this analysis model, the behavior of reinforced concrete core walls under cyclic loading with different axial load ratio, different height-width ratio and different coupled-beam stiffness is studied. The comparison of the experimental and computational results shows that the analytical model is reasonable and reliable.

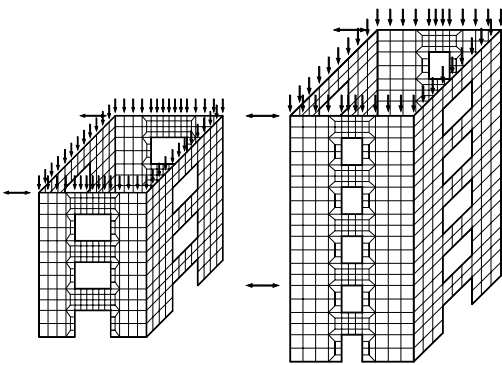


Figure29 Analytical Model for Core Wall Models

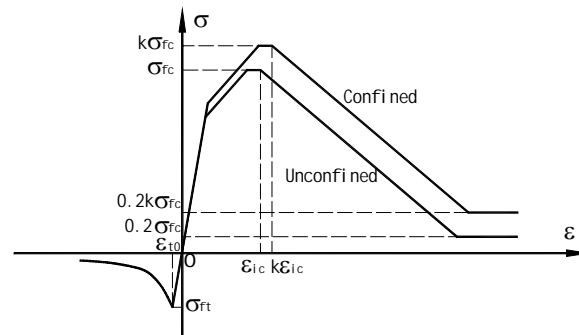


Figure30 Cyclic Stress-strain Relationships for Concrete

7.3 Shaking Table Tests on Models for Various Complicated Buildings and Towers to Guide The Engineering Design

Physical testing is important to structural engineering because it helps establish fundamental understanding about the behavior and failure mechanism of structures. Structural model testing is often used to help structural engineers to directly acquire the knowledge about the prototype, especially in the case of complicated buildings for which the numerical simulations are considered unreliable. Shaking table model tests has been considered an economic, accuracy, and practical way to evaluate the seismic performance of structures. To ensure that the model behaves in a similar manner

as the prototype, the model designed should meet the requirements of dynamic similitude theory. It is no doubt that dynamic similitude theory is the most important basis in shaking table model test. To verify the validity of dynamic similitude theory in shaking table model test, two 6-story R C. frame models, one with 1/4 scale and the other with 1/8 scale, designed according to the same prototype, were tested on the shaking table. The test results demonstrated that there existed good consistency with the similarity on natural frequency, failure mechanism, and restoring force model between the two scale models.

On the basis of the above research, more than twenty structural models of complicated tall buildings and TV towers, such as Shanghai TV tower, Tianwang Tower, China Southern Airline Tower and so forth, have been tested on shaking table in the past two decades. Two tested structural models are shown in Figure31 and Figure32. The model design and construction method, testing and analysis procedures, and measure techniques have been developed maturely. By these shaking table tests, the earthquake responses and dynamic characteristics were derived, the failure process, failure mechanism, and structural weak points were discovered, and then the overall seismic performance of the prototype was evaluated accordingly. Advices or suggestions were proposed as references for structural design to improve the seismic performance of structures. Some test results were also verified by in-site testing on completed actual structures.



Figure31 Shanghai Join-by Department Store



Figure32 Shanghai Jinghua Garden Apartment

8. FURTHER RESEARCH

Based on the previous research work, the following topics are being investigated now or will be investigated in the future in this laboratory:

1. Performance-based seismic design of building structures
2. Smart material and smart structural system
3. Seismic behavior of composite ultra-tall buildings and nonlinear earthquake response analysis
4. Development of new structural control devices and engineering application
5. Development of new evaluation and strengthening methodology for old buildings
6. Development of computer software for nonlinear seismic analysis of tall building and ultra-tall building structures

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