REVIEW OF SEISMIC RESEARCH AND APPLICATION OF CONCRETE CORE WALLS IN HIGH-RISE BUILDINGS

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ABSTRACT :

Concrete core walls are widely used to be the main lateral force resisting units of hybrid structure in high-rise buildings in China due to its larger lateral space stiffness and lateral force resistance. But the seismic behavior of this structural system is still under dispute in the field of engineering especially abroad because of few researches on its performance. Therefore, the research for the mechanic behavior and failure characteristic of this structural system has a significant influence on the engineering design. At first, this paper reviewed the application and development of concrete core walls in high-rise buildings home and abroad, based on the analysis of the mechanic behavior, it is pointed that the earthquake resistant performance of the frame-concrete core walls hybrid structure depends on the concrete core walls from the point view of the whole structural system. Then, it is summarized that the experimental studies and the theoretical analysis models adopted in the research of the seismic performance of concrete core walls are far from sufficient for the extensive use of this kind of structural system in high-rise buildings in China. At last, the existing main problems now and the further research for the future on the seismic behavior of concrete core walls are discussed in particular.

KEYWORDS: concrete core walls, seismic performance, high-rise buildings

1. INTRODUCTION

There are many types of structural systems for high-rise buildings, and this structural system is composed of plenty of structural elements or units which could be classified into three basic forms called linear elements, area elements and space elements respectively (Liu, D.H., 1993). The mechanic behavior and earthquake resistant performance of the linear elements (such as beams, columns, braces, trusses and so on) and area elements (such as floors, shear walls) are understood clearly, because a large number of theoretical analyses and experimental investigations have been carried out in the home and abroad. On the contrary, researches on mechanic behavior and seismic performance of space elements are very scare, such as staircase or elevator hoistway in high-rise buildings, inner core of tube-in-tube structures and concrete core walls of hybrid structures. Thus it is obvious that concrete core walls are widely used in high-rise buildings because of their larger lateral stiffness and space stiffness. In this paper, application and seismic research of concrete core walls are systematically generalized and discussed, and the main existing problems on seismic research for concrete core walls and how to make further researches on them in the future are pointed out.

2. APPLICATION OF CONCRETE CORE WALLS IN HIGH-RISE BUILDINGS

During recent years, the frame-concrete core wall hybrid structure has been rapidly developed and highly concerned by owners with its performance and economic advantages. The steel frame or steel reinforced concrete frame with higher strength materials mainly bears the vertical load, and the former could also be used as floor structure with lager span because of its lightness. At present, the frame-concrete core wall hybrid structures have been used in 19 high-rise buildings taller than 150m in our country, including in the non-seismic region, seismic region, and even in earthquake fortification zone of 7 degree or above. For example, the frame-concrete core wall hybrid structure with RC core walls, SRC columns and steel columns has been used in

Jinmao Tower (88 floors, 420.5m) and International Financial Center (95floors, 460m, in built) in Shanghai. Additionally, the concrete core walls structures are also adopted in the high-rise buildings such as Diwang Tower (81 floors, 325m), Development Center (48 floors, 165m) in Shenzhen, Yunshan Tower (52floors, 208m) and so on. The concrete solid web tube is widely used in tube-in-tube structures, with the external frame-tube and internal core-tube which are connected by the floor with large stiffness. For example, the steel reinforced concrete tube-in-tube structure has been used in Information Tower (52 floors, 189m) in Shaanxi and Baodu Tower (48 floors, 179m) in Nanning whose external and internal systems are respectively the concrete frame-tube and SRC core-tube. Thus it can be seen that the concrete core walls and the solid web tube are widely used in high-rise buildings as the main lateral force resisting systems in our country.

Although the frame-concrete core wall hybrid structure has been widely used in our country, it is seldom applied in earthquake zone at aboard. It is pointed out that seismic performance of this structure mainly depends on the concrete core walls according to some American design standards (Bahram, M., 2001). This hybrid structure system had been destroyed before (a 14-floor hotel building collapsed completely during the Alaska Earthquake in 1994, and it was caused by failure of RC core walls), so its seismic behavior hasn't been studied systematically, and some people think it isn't suitable to be used for earthquake zone and buildings taller than 150m. In Japan, the steel frame-concrete core wall hybrid structure is only used in two tall buildings whose height are 78m and 107m respectively, and seismic behavior of this structural system is still under dispute in the field of engineering although some researches on its seismic design methods and the experiments have been made.

3. LOADING FEATURES AND SEISMIC PERFORMANCE OF CONCRETE CORE WALLS

The working principle of frame-concrete core wall hybrid structure is similar to that of frame-shear wall structure. The frame and concrete core walls are double resistance to lateral force system and they could work cooperatively to resist earthquake action. The concrete core wall which has larger lateral stiffness resist most horizontal loads, and the outer frame mainly suffers from vertical loads, so seismic performance of concrete core walls in this structure is very important. The concrete core wall is in elastic state and bears most earthquake shear as the first seismic resistant system under frequent earthquake, and the core walls could effectively transfer earthquake action to the second seismic resistant system to make the structure keep stability. Therefore, seismic performance of the frame-concrete core wall hybrid structure is mainly determined by concrete core walls (Fang, E.H., 1999). For concrete core walls with larger height-width ratio (10~12) and more bending deformation, the external frame is used to work cooperatively to decrease displacement, but what the effect will be has never endured test of moderate or large earthquake.

4. RESEARCH STATUS ON SEISMIC PERFORMANCE OF CONCRETE CORE WALLS

4.1. Experimental Researches on Seismic Performance

The concrete core wall structure is mostly used in seismic fortified areas, and its seismic performance under earthquake action becomes a problem highly concerned by civil engineers. In china, the researches on seismic performance of concrete core walls lag behind their developing speed, and this could not satisfy the need of seismic design at all. The pseudo-static test of reinforced concrete core walls were conducted by professor Lv Xilin in Tongji university and a low-cyclic reversed loading experiment of five specimens was finally finished(Lv, X.L.,2002), in which the failure mechanism, carrying capacity, failure mode, energy dissipation capability and transfer rule of story shear for core walls with different axial compression ratio and shear span ratio were studied. The test results indicated that the cracking load has unique relation with corresponding displacement, and their ratio will not increase with the larger axial compression ratio; the displacement ductility ratio becomes smaller as axial compression ratio jump; the increasing of axial compression ratio has little effect on cracking and failure of coupling beams, while it has great influence on carrying capacity, failure mode,

ductility and energy dissipation capacity of core walls. Two 1/6 scale models of concrete core walls tested under the horizontal low cyclic loading based on shear walls with concealed bracing and short-leg shear walls with asymmetric cross section were carried by Cao Wanlin (Cao, W.L., 2005), in which the crack development, failure modes, bearing capacity, restoring-force characteristics and ductility of concrete core walls were analyzed and effect of concealed bracing on concrete core walls was also studied. Simulated earthquake shaking table tests of a steel-concrete hybrid structure with a scale of 1/20 was carried by Li Guoqiang (Li, G.Q., 2001), whose purpose was to measure displacement and acceleration of the model structure, vertical dynamic strain of bottom layer and steel frame columns.

The seismic performance of concrete core walls are still lack of study in foreign countries, and the reason is that steel structures are mainly used for tall buildings in European and American countries, and different scholars have different opinions on seismic performance of frame-concrete core wall hybrid structures. Under this background, only some researches have been conducted on concrete shear walls. For example, pseudo static tests on seismic performance of a twelve-floor T-shaped reinforced concrete coupled walls with a scale of 1/3 were conducted by America and Japan in 1993(Kenichi, S., 2000), in which the failure patterns, damage features and distribution law of shear force of coupled shear walls under horizontal force were analyzed, and the results indicated that shear force of the coupled walls was related to its axial force direction and setting condition of coupling beams. The pseudo static test of a 1/12 scale model with nine H-shaped core walls was conducted by Makoto in Japanese Ludao technology institute(Makoto, M., 2000), and the main purpose was to study carrying capacity, deformation and failure mode of concrete core walls under horizontal and torsional loading. The pseudo-static test of four reinforced concrete core walls were carried by HAZAMA technology institute (Nakachi, T., 1996), and influence of different reinforcement constitution on deformability and failure patterns of core walls under lateral loads were studied. Low frequency cyclic static loading test on eight square section concrete core walls divided into three groups was conducted by earthquake engineering centre of Japan's nuclear power company whose purpose was to analyze the effect of horizontal loading angle on seismic performance of concrete core walls (Atsushi Habasaki, 2000).

The above experiments mainly focused on seismic performance of frame-core wall hybrid structures themselves, while performance of lateral force-resisting elements wasn't studied deeply at all. Meanwhile, the test conditions and parameters, loading equipments, test methods and structure forms are not all same in different experiments, so the test results are needed to be further analyzed.

4.2. The Theoretical Calculating Models

A constitutive model of concrete material under cyclic lateral loads was adopted and the nonlinear finite element model of RC core walls was established by Li Junlan (Li, J.L., 2003), and nonlinear analysis of the test model was also executed. By using the nonlinear finite element analysis model and program, the behavior of reinforced concrete core walls under cyclic loads with different axial load ratio, height-width ratio and coupled beam stiffness was studied by Lv Xilin (Lv, X.L., 2003) and comparison of the experimental and computational results showed influence of different parameters on bearing capacity, failure modes and energy dissipation capacity. Based on summarizing the mechanical behavior of concrete shear walls, a reasonable nonlinear analysis model called multiple-vertical-line-element model which could simulate concrete core walls was proposed by Guo Fengyu (Guo, F.Y.,2004), and hysteretic shear model and hysteretic axial model were selected to propose nonlinear seismic response analysis method by analyzing related test results at home and abroad. Moreover, shear lag effect of core wall structures was studied with finite element method by A. K. H. Kwan (A.K.H., Kwan, 1996).

The concrete core walls were simplified as bar element model by Franklin.Y.Cheng when proceeding elastic-plastic seismic response analysis on steel-concrete hybrid structures with member-storey model (Franklin. Y. Cheng., 1981). The concrete core walls were equivalent to frames with wide columns according to principle of equivalent rigidity by Cheng Shaoge when the elastic-plastic dynamic analysis of steel-concrete

hybrid structure under rare earthquake was discussed (Cheng, S.G., 1998), while this model couldn't well reflect stress and deformation characteristics under high axial compression ratio. Wall element was adopted to simulate concrete core walls, and influence of stiffness degradation on distribution of earthquake action was analyzed by Liu Ying and Cai Yiyan (1999). The concrete core wall was simplified as a vertical cantilever bar with box cross section by Li Guoqiang and wall element was coupled with strip element to study its elastoplastic seismic response (Li, G.Q., 2002). Zhou Xiangmin and Li Guoqiang suggested that concrete core walls could be regarded as a structure composed of shear walls with opening and simplified as shear walls parallel to earthquake action direction (Zhou, X.M., 2002).

5. THE MAIN PROBLEMS AND FUTURE RESEARCH DIRECTION

The present nonlinear analysis models of concrete core walls are much simpler and they couldn't well reflect structural performance under earthquake action, such as stress and deformation properties under high axial compression ratio and influence of changing neutral axis of cross section. It is obvious that the present test data for seismic performance, theoretical analysis and numerical simulation of concrete core walls couldn't satisfy the demands of actual engineering. Especially in strong earthquake district, it is very important to ensure the safety and reliability of concrete core walls under earthquake action. Therefore, there are many problems needed to be solved urgently for concrete core walls and they are proposed as following.

1) Understanding on seismic performance of concrete core walls is insufficient. Ductility design method for continuous shear walls is mainly used for reinforced concrete core walls in present engineering, and some measures are adopted to ensure enough ductility of plastic hinge region according to principle of strong shear weak bending. While the core walls are space elements and shear walls are flake elements and there is much difference between their mechanical behaviors, it is unreasonable to use seismic design method of shear wall for concrete core walls. Thus, it is necessary to study the failure mechanics, weak parts, carrying capacity, deformation performance and energy dissipating capacity deeply for experimental study and theoretical analysis of concrete core walls.

2) Seismic performance of concrete core walls under high axial compression ratio needs further research. The concrete core wall structures are mainly used in steel-concrete hybrid buildings and the large vertical load at the bottom makes core walls be in high compressive stress state which effects structural ductility and stability when resisting side force. A group of tests measuring carrying capacity, failure patterns and ductility of concrete core walls under high compression ratio (0.4 and 0.6) have been conducted by Lv Xilin. Although some valuable test data has been acquired, it is far from enough for concrete core wall structures with high axial compression ratio which needs more experimental data.

3) Seismic performance of concrete core walls with large height-width ratio also needs further research. The concrete core walls are main lateral force resisting elements in tall buildings which require higher bearing capacity and ductility, and proper seismic fortification measures should be adopted to improve ductility. The present seismic design methods and construction measures are proposed based on experimental study and theoretical analysis of concrete shear walls, while they are not suitable for concrete core walls with large height-width ratio. The height-width ratio is usually large in Chinese concrete core wall buildings, such as Dalian Ocean Edifice, Shanghai Finance Building and Shenzhen Diwang Mansion, so more deeply study and analysis are needed for concrete core walls with large height-width ratio.

4) Theoretical basis is insufficient for the strengthened parts and construction measures. One construction measure for shear walls is to set restrained edge member on the end and the present code makes specific regulations about it. There are obvious differences between working performance of core walls and shear walls under earthquake action, so it is unreasonable to use the design regulations of shear walls for concrete core walls in the present code. Meanwhile, the wall pieces of concrete tube perpendicular to seismic action direction will be in tension under rare earthquake, so it is not suitable to set only restrained edge members on the end

because of large height-width ratio and reasonable strengthening measures such as hardening reinforcement and setting steel columns should be considered.

5) Researches on shear lag of concrete core walls are deficient. Much theoretical analysis and researches on shear lag of frame-concrete core wall hybrid structures have been carried, while shear lag of concrete core walls and the solid web tube hasn't been understood insufficiently in china. The problems that effect of shear lag on mechanical behavior of concrete core walls and factors influencing shear lag needs to be solved urgently.

6) Tests on seismic performance of steel reinforced concrete core walls are needed to be developed further. Performance and economic advantages of steel reinforced concrete structures are more and more affirmed with their widely use, while seismic performance including experimental study and theoretical analysis of steel reinforced concrete core walls are nearly empty. Thus, the failure mechanism, energy dissipation capacity and bearing capacity of this structure should be studied deeply.

7) How to distribute horizontal force of frame-concrete core wall hybrid structures needs to be further studied. The present engineering practice and experimental study indicate that the stiffness is enough and strength is insufficient for concrete core walls while the external frame is opposite, and this causes incoordination between two parts of this hybrid structure. The mechanism that plastic hinge mainly appears on concrete core walls has adverse impacts on structural system under major earthquake, because the structure or substructure will collapse because of insufficient stiffness of external frame once the core walls suffer from severe damage. So, how to ensure better deformation and mutual coordination of external frame and concrete core walls is a question needed to be solved. The cooperation work principle of frame-concrete core wall hybrid structure is similar to that of frame-shear wall structure and the lateral deformation of frame is regared as shear type, while the lateral deformation is mainly bending type when height-width ratio of outer frame is very large. In this situation, distribution of lateral force between frame and core walls will change, and this problem needs to be further studied.

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