INVESTIGATION OF SHEAR-DOMINATED RESPONSE OF MULTI-STORY RC STRUCTURAL WALLS WITH DIFFERENT OPENING LOCATIONS

Rafik TALEB[1], Masanobu SAKASHITA[2], and Susumu KONO[3]

SUMMARY

The aim of this paper is to present the experimental results of three 40% scale reinforced concrete single span and 2.5 storied structural walls tested under lateral reversed cyclic loading. One wall specimen without openings and two specimens having different opening location. These specimens represented the lower three stories of a typical six storied reinforced concrete (RC) building in Japan and were designed to fail in shear prior to flexure. The main purposes of the experimental tests were to evaluate their shear behavior and to identify the influence of the openings location on cracks distribution and shear strength of RC structural walls. The shear strengths of the tested walls were estimated by combining the shear strength of structural wall without openings and the reduction factor that takes into account the openings. Experimental and analytical results showed that the shear strength was different depending on the loading direction due to opening locations. A two-dimensional finite element analysis was carried out to simulate the performance of the tested specimens. The constructed finite elements model simulated the lateral load-drift ratio relations with sufficient accuracy.

Keywords: *RC walls with openings; static test; shear behavior; shear strength reduction factor; FEM analysis.*

INTRODUCTION

Reinforced concrete structural walls are one of the main earthquake-resisting components for mid and high rise RC buildings. Experience from past earthquakes has shown that buildings with well-designed structural walls can significantly reduce life and economic losses. For functional reasons, the structural walls may have openings like windows, doors and duct spaces. The opening sizes, locations and shapes affect their seismic performance by reducing the stiffness and the strength of the structural wall. The structural walls with openings may be considered as irrational structures that defy solution by normal structural analysis, and only experimental studies or finite element analysis can assist to disclose their behavior (Park and Paulay 1975). During the past decades, numerous experimental studies have been conducted to study the behavior of shear-dominated RC structural walls with and without openings (e.g., Ono 1995; Lopes 2001; Brun et al. 2011). However, the case of large openings for multi-story buildings have not been deeply investigated. More experimental data are needed to clarify the shear behavior of structural walls with eccentric openings under lateral loading.

It is a common practice to model structural walls with openings with strut and tie models. However, the modeling procedure is not straightforward and requires some skills to prove the model could represent the necessary complex stress state, especially for shear-dominated RC walls. In such cases, finite element studies may be an efficient alternative. Nowadays, and due to availability of powerful computers and modeling techniques, numerical modelling approaches are able to provide an accurate assistance to the experimental investigations of reinforced concrete structural walls (e.g., Kim and Lee 2003; Balkaya and Kalkan 2004).

[1] *PhD Candidate, Dept. of Environmental Science and Technology, Tokyo Institute of Technology, Japan, e-mail: taleb.r.aa@m.titech.ac.jp*
[2] *Assistance Professor, Department of Architecture and Architectural Eng., Kyoto University, Japan, e-mail: sakashita@archi.kyoto-u.ac.jp*
[3] *Professor, Materials and Structures Laboratory, Tokyo Institute of Technology, Japan, e-mail: kono@serc.titech.ac.jp*

ANALYTICAL INVESTIGATIONS ON THE SEISMIC RESPONSE OF AN RC BOX-TYPE WALL BUILDING STRUCTURAL SYSTEM

Kyung Ran HWANG[1] and Han Seon LEE[2]

SUMMARY

The residential reinforced concrete (RC) box-type wall structural system in Korea is unique around the world and the seismic performance of these structures has been investigated with due interest, neither in Korea nor abroad. The analytical models are calibrated by using the results of shaking table test on a 1:5 scale 10-story RC box-type wall building model, and after the characteristics in the seismic behavior of walls including the effect of slabs and openings are investigated based on the numerical results obtained from the static and dynamic analyses of the box-type wall structures. The following conclusions are drawn from the analytical investigation: (1) The failure modes of the box-type wall structures indicate that the walls were mainly subjected to the flexural bending as well as to the membrane action. The membrane action in tension and compression due to coupling effect of strong wall-to-wall and wall-to-slab interaction can increase significantly the capacity of the overturning moment. And, (2) the model, which ignores the flexural rigidity of the slab and coupling beam, the natural period, initial stiffness, and maximum strength representing the global responses are considerably lower than those of the models with slab and coupling beam.

Keywords: *reinforced concrete; box-type wall structure; membrane action; coupling effect; 3D nonlinear dynamic analysis; PERFORM-3D.*

INTRODUCTION

The number of apartment dwelling units (8,576,013) is more than 58.4% of the total number (14,677,419) in Korea (Korea National Statistical Office, KNSO 2010). These residential apartment buildings such as shown in Figure 1 generally consist of high-rise reinforced concrete (RC) wall structures. The style of these RC structures is unique around the world and the seismic performance of these structures has been investigated with due interest, neither in Korea nor abroad, except a few studies.

In 1999 Turkey earthquake, the RC box-type wall buildings, constructed by using tunnel form techniques, were found to perform well under the earthquake. Balkaya and Kalkan (2003) investigated the seismic performance of these RC box-type structures by conducting three-dimensional (3D) finite element pushover analysis to evaluate the influence of the different size and location of openings and the wall-to-wall and wall-to-slab interactions. The interaction effects of the slabs and transverse walls increased the overall capacity of the pierced shear walls in spite of the door openings introducing a strong disruption of the shear flow between walls. Kalkan and Yuksel (2007) performed the experimental and analytical researches on the seismic behavior of the box-type building using two 1:5 scale 4-story specimens under quasi-static cyclic lateral loading. The global tension/compression couple of wall-to-wall interaction caused the failure mechanism by axial tension in outermost shear walls. The failure took place due to low longitudinal reinforcement ratio of walls and negative contribution of low axial load. Similar failure condition was observed in the eight-story shear-wall dominant building during 1985 Chile earthquake (Wood 1991).

[1] *Research assistant (Ph. D Student), School of Civil, Environmental, and Architectural Engineering, Korea University, Korea*
[2] *Professor, School of Civil, Environmental, and Architectural Engineering, Korea University, Korea, e-mail: hslee@korea.ac.kr*

ESTIMATION OF SHEAR STRENGTH OF INFILLED URM WALL BASED ON DAIGONAL STRUT MECHANISM

Ho CHOI[1], Kiwoong JIN[2], and Yoshiaki NAKANO[3]

SUMMARY

In this study, RC frames with URM (CB) wall for typical school buildings in Korea are experimentally investigated to evaluate their seismic capacity. One-bay, one-fourth scale specimens with CB walls having different boundary condition due to beam rigidity are tested under in-plain loading. In this paper, the diagonal strut mechanism of CB wall is discussed using principal compressive strains on CB wall. The lateral strength carried by CB wall and RC frame are also explained based on the compressive stress acting on CB wall and the curvature distribution along both columns during the test.

Keywords: *R/C building; URM wall; seismic capacity; diagonal strut mechanism; FEMA306.*

INTRODUCTION

In some regions of Asia, Europe, and Latin America where earthquakes frequently occur, serious earthquake damage is commonly found resulting in catastrophic building collapse. Such damaged buildings often have unreinforced masonry (URM) walls, which are considered non-structural elements in the structural design stage, and building engineers have paid less attention to their effects on structural performance although URM walls may interact with boundary frames. The evaluation of seismic capacity of URM walls built in boundary frames is therefore urgently necessary to mitigate earthquake damage for those buildings.

For this purpose, RC frames with unreinforced concrete block (CB) wall for typical school buildings in Korea are experimentally investigated to evaluate their seismic capacity including failure mechanism and load bearing capacity. One-bay, 1/4-scale specimens with CB walls having different boundary condition due to beam rigidity are tested under cyclic and monotonic loadings. Among these specimens, the test results on inflled frame specimen with rigid beam under monotonic loading were discussed in the reference (Jin 2012). In this paper, the test results of two specimens with different boundary conditions due to beam rigidity under cyclic loadings are discussed.

OUTLINE OF EXPERIMENT

Prototype Building and Experiment Parameters

The test specimens are designed according to the standard design of Korean 4 story school buildings (referred to as "prototype building" shown in figure 1) in the 1980's (The Ministry of Construction and Transportation 2002). In this paper, two specimens which are infilled frame with rigid beam (IFRB) and infilled frame with flexible beam (IFFB) having an axial load level of their first story under cyclic loadings are discussed.

[1] *Research Associate, Institute of Industrial Science, The University of Tokyo, Japan, e-mail: choiho@iis.u-tokyo.ac.jp*
[2] *Research Associate, Dept. of Architecture and Building Eng., Tokyo Metropolitan University, Japan, e-mail: kwjin@tmu.ac.jp*
[3] *Professor, Institute of Industrial Science, The University of Tokyo, Japan, e-mail: iisnak@iis.u-tokyo.ac.jp*

STUDY ON SLIDING SHEAR FAILURE OF REINFORCED CONCRETE BEARING WALLS

Masanori TANI[1], Susumu KONO[2], and Hiroshi FUKUYAMA[3]

SUMMARY

There are several types of brittle failure mode of flexure-dominant R/C bearing wall. Recently flexural compression failure at lower floor of multi-story bearing walls without boundary columns has attracted much attention, because this failure mode was observed in many high-rise R/C buildings which were heavily damaged in the 2010 Chile Earthquake. Meanwhile, there have been reported some experimental results that R/C wall specimens failed in sliding shear at the wall base after flexural yielding did not have enough deformation capacity. Two specimens whose experimental parameter is detail of boundary columns were tested to obtain fundamental test data about sliding shear behavior at wall base and confirm the accuracy of evaluation methods proposed in the past. Although they were designed to fail in sliding shear, the observed final failure modes were flexural compression or out-of-plane buckling of boundary columns. Hysteretic characteristics and damage condition observed in the experiment was reported and the accuracy of capacity estimation was discussed. The accuracy of the equations for sliding shear capacity was also discussed by using experimental database constructed by authors in the past.

Keywords: *reinforced concrete; bearing wall; sliding shear failure; experimental database.*

INTRODUCTION

Flexural compression failure of R/C multi-story bearing wall at lower floor (Photo 1) was observed in many buildings after the 2010 Chile Maule Earthquake (e.g., Tani et al. 2011). This failure mode has attracted remarkable attention as one of brittle failure modes of R/C flexural bearing wall. On the other hand, some researchers have reported that some R/C wall specimens which failed in sliding shear (Photo 2) after flexural

Photo 1 Damage of multi-story bearing wall without boundary columns at the 2010 Chile Earthquake (Tani et al. 2011)

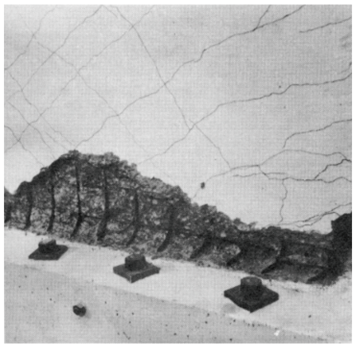

Photo 2 Sliding shear failure at wall's base (Paulay et al. 1982)

[1] *Research Engineer, International Institute of Seismology and Earthquake Engineering, Building Research Institute, Japan, e-mail: mtani@kenken.go.jp*
[2] *Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan, e-mail: kono@serc.titech.ac.jp*
[3] *Director, Department of Structural Engineering, Building Research Institute, Japan, e-mail: fukuyama@kenken.go.jp*

PREDICTION OF SHEAR STRENGTH BEHAVIOR FOR RC SHORT COLUMNS USING HIGH STRENGTH MATERIALS

Yi-An LI[1], and Shyh-Jiann HWANG[2]

SUMMARY

Short columns in building structures are generally considered to be members with high stiffness and governed by shear. They usually sustain large forces during earthquake, and are susceptible to brittle shear failure. In the mechanism of lateral load resistance, short columns are often the first members to fail. Therefore, shear strength and corresponding deflection for short columns have significant influence on seismic assessment. In this study, the shear strength of the short columns made of high strength materials is evaluated using the Softened Strut-and-Tie model, and the shear deformation of cracked reinforced concrete is estimated from the strain field in that model. A comparison with experimental results available in literature verified that the proposed curves could produce reasonable predictions. In this paper, the shear strength formulas of Architectural Institute of Japan (1990) and New RC project were also compared with the test results. Their accuracy and predicted failure mechanism were also reported.

Keywords: *high strength, reinforced concrete, short column, shear failure, strut-and-tie*

INTRODUCTION

Short columns often appear in buildings due to openings in the wall for indoor ventilation or air-conditioning. Reinforced concrete short columns are categorized as short and deep members. Due to their high stiffness and brittle shear failure during earthquake, short columns often sustain relatively large lateral forces and are the first members to fail. Therefore, their lateral load deflection curves have significant influence on seismic assessment. Short columns belong in the category of short and deep members, the shear strength of which, under current ACI 318-11 (2011) requirements, should be determined based on strut-and-tie models. According to experiments (Huang and Hwang 2008; Li et al. 2013) conducted on short columns with a height-to-depth ratio less than 2, the force transfer mechanism in short column members is consistent with the strut-and-tie model. Shear failure of short columns is presented in concrete crushing at the ends of struts, which is different from typical columns. Therefore, Li et al. (2013) suggested that Softened Strut-and-Tie model (SST model) be used to estimate the shear strength of short columns and reasonable results can be obtained.

Because high strength reinforced concrete building in Taiwan is still in developing stage, there is seldom test data of reinforced concrete columns using high strength materials. However, a five-year national research project was given impetus from 1988 to 1992 in Japan, the so-called Japanese “New RC Project” (Aoyama 2002). Lots of manpower and resources were put to develop high strength steel and high strength concrete that applied on high-rise buildings. In view of the advanced development of high strength reinforced concrete in Japan, therefore, this paper adopts experimental data of high strength reinforced concrete columns in Japan to validate the suitability of Softened Strut-and-Tie model which is applied to high strength materials. Moreover, the shear response evaluation formula of high strength reinforced concrete members will be introduced and commented its

[1] *PhD Candidate,National Taiwan University, Taiwan, e-mail: d96521008@ntu.edu.tw*

[2] *Professor, National Taiwan University, and the deputy director, National Center for Research on Earthquake Engineering, Taipei, Taiwan, e-mail: sjhwang@ntu.edu.tw*

EFFECTS OF LOADING SEQUENCES ON CONCENTRICALLY BRACED FRAME STRUCTURES

Chui-Hsin CHEN[1] and Huai-Kuo HU[2]

SUMMARY

Static cyclic loading tests are commonly used to evaluate the seismic capacity of a structure. However, it is believed that different loading sequences resulting in different structural behavior would lead to a biased assessment of structural capacity. To quantify the effects of loading sequences on the structural capacity, we investigate the experimental behavior of braces in concentrically braced frames (CBF) under different loading sequences. The variables for testing program includes six brace specimens with two different pipe sections (different slenderness as well) and three loading protocols, namely, loading sequence for beam-to-column moment connections, loading sequence for link-to-column connections and proposed loading sequence for CBF structures. After tests, we compare the critical performance parameters of different specimens including the failure modes, maximum deformation, cumulative energy, etc. Test results show that the specimens fracture at different deformation stages under different loading sequences; most brace specimens fracture at the displacement corresponding to the drift ratio of 1.5% to 4% rad. The specimens accumulate energy the fastest under the loading sequence for beam-to-column moment connections. The maximum cumulative energy is less correlated to the loading sequences. The test results also show that the rate of cumulative deformation under loading sequence for beam-to-column moment connections is too fast for CBF structures; the rate under loading sequence for link-to-column connections, on the contrary, is a little slow for CBF structures. The proposed loading sequence for CBF is more suitable for braces in regard to failure modes, cumulative deformation rate, cumulative energy rate, and deformation amplitude.

Keywords: *static cyclic loading test; loading sequence; concentrically braced frame; cumulative deformation; cumulative energy.*

INTRODUCTION

Pseudo static testing is widely used to evaluate the seismic capacity of a structural system or structural members. The capacity of structures is believed to be sensitive to the test procedures. To evaluate the capacity accurately, researchers need to use proper loading sequences and record the structural responses during testing. The loading sequence should be representative of the seismic loading while allows the researchers to investigate the structural responses at various loading levels; as such, it is cyclic with increasing amplitude. Researchers (Krawinkler et al 2000; Richards and Uang 2006) have systematically investigated the loading sequences for steel moment resisting frames (MRF) and short links in eccentrically braced frames (EBF).

Krawinkler et al. (2000) proposed a loading sequence for steel MRF system based on seismic demand parameters which are summarized from dynamic responses of steel MRF system. These parameters include number of cycles under earthquake excitations and drift parameters to describe the characteristics of the earthquake. Five of the most important parameters are total number of cycles (N_t), number of inelastic cycles (N_p), sum of drift ratio ranges ($\Sigma 7\theta_i$), maximum drift ratio range ($7\theta_{max}$), and maximum drift ratio (θ_{max}). Number of cycles was calculated by rainflow cycle counting algorithm. This loading sequence has been used to test many steel structures and adapted for different structural systems. On similar basis, Richards and Uang

[1] *Assistant Professor, National Chiao Tung University, Taiwan, e-mail: chchen.nctu@gmail.com*
[2] *Graduate Student Researcher, National Chiao Tung University, Taiwan*

COLLAPSE CAPACITY OF STEEL MOMENT-RESISTING FRAMES WITH HYSTERETIC ENERGY DISSIPATING SYSTEMS DESIGNED ACCORDING TO ASCE 7-10

Hyung-Joon KIM[1], Dong-Hyeon SHIN[2], and Jin-Young PARK[3]

SUMMARY

Recently, hysteretic energy dissipating systems (HEDSs) have been increasingly used for steel moment-resisting frames (SMRFs) to reduce structural seismic demands and to avoid structural damage on typical structural members such as beams and columns. In parallel with such applications of HEDSs, ASCE 7 introduces a simplified seismic design methodology for structures employing energy dissipating systems. The design methodology allows both an equivalent lateral force procedure and a response spectrum procedure that are similar to the seismic design procedures for typical structures without energy dissipating systems. This paper investigates the collapse capacity of SMRFs with HEDSs and compares with that of typical SMRFs. To do this, 6-story prototype SMRFs with and without HEDSs were chosen and designed according to the current seismic code, ASCE 7-10. Incremental dynamic analyses of both frames were carried out using an ensemble of historical earthquake records. The analyses show that compared with the corresponding SMRF without HEDSs, the SMRF with HEDSs presents the excellent median collapse margin ratio and the narrow variation of collapse points due to the record-to-record variation. Under maximum considered earthquakes, the SMRF with HEDSs collapses with the probability with less than 10%, which FEMA P-695 suggests as one of criteria for the collapse capacity of new building structures designed according to the current seismic code.

Keywords: *hysteretic energy dissipating systems (HEDSs), steel moment-resisting frame (SMRFs), ASCE 7-10, incremental dynamic analyses (IDA), collapse capacity*

INTRODUCTION

Energy dissipating systems have been developed and have been applicable to building construction for seismic hazard reduction. They absorb or dissipate seismic input energy throughout specially designed devices which fall into two categories; displacement-dependent and velocity dependent devices. Each device has its own intrinsic characteristics that should be fully understood by structural engineers who expect to implement to practical applications. Of various energy dissipating systems, hysteretic energy dissipating systems (HEDSs) have been increasingly used for steel moment-resisting frames (SMRFs) to reduce structural seismic demands and to avoid structural damage on typical structural members such as beams and columns. This is due to the fact that the high stiffness and strength, and excellent energy dissipating capacities of HEDSs decrease relatively large seismic displacement demands which flexible steel moment-resisting frames usually suffer during strong ground motion. The typical hysteretic energy dissipating devices are steel yielding dampers making advantage of plastic energy due to their yielding mechanism and friction dampers envisioned to dissipate seismic input energy throughout frictional mechanism.

As such advantages of HEDSs are recognized and their application is popular, ASCE 7 introduces a simplified

[1] *Associate Professor, Department of Architectural Engineering, University of Seoul, Korea, e-mail: hyungjoonkim@ uos.ac.kr*
[2] *Graduate Student, Department of Architectural Engineering, University of Seoul, Korea, e-mail: thymos19@gmail.com*
[3] *Graduate Student, Department of Architectural Engineering, University of Seoul, Korea, e-mail: jyp6727@gmail.com*

SEISMIC PERFORMACNE OF SELF-CENTERING DESINGNED CONCENTRICALLY BARCED FRAMES

Chin-Tung CHENG[1] and Chia-Yi YEN[2]

SUMMARY

Generally seismic force is resisted by the diagonal braces in the Concentrically Braced Frame (CBF). However, large residual deformation after earthquakes makes the structure difficult to repair. Therefore, this paper investigates the feasibility of applying a self-centering function on CBF to reduce the residual deformation after the earthquakes. Similar to literatures, beam-column interfaces are separated so that beams can rock on the column face without inducing any damage during earthquakes. Seismic energy is dissipated through the friction dampers installed on beam bottom flange or on the braces. Investigation parameters include types of dampers, various normal force and frictional materials such as brass or phosphor bronze applied on dampers. To validate the proposed idea, a full-size one storey-one span CBF was constructed and tested under lateral cyclic reversed loads. Test results show that the self-centering function on CBF can be achieved with little residual deformations and adequate seismic performance. Among all tests, it can be seen that friction dampers with phosphor bronze installed on the brace dissipated more energy than the other types. And, proposed analytical model could predict the force and displacement relations of the self-centering designed CBFs, except the frame with dampers installed on the beam bottom flange.

***Keywords**: Concentrically Braced Frame, Self-centering, Friction Damper.*

INTRODUCTION

In general, braced frame can be characterized into following categories: Special Concentric Braced Frame (SCBF), Buckling Restrained Braced Frame (BRBF) and Eccentric Braced Frame (EBF). This research aims to investigate the seismic behavior of CBF with supplementary energy dissipating devices. To resist the lateral loads, braced frames have the advantages of reducing the self-weight of structures. Due to the increase of the lateral stiffness, the structural drift in braced structures may be significantly reduced to meet the requirement of performance-based design. However, large amount of residual deformation results in difficulty in repairing the structure after earthquakes.

This paper investigates the feasibility of the self-centering function in order to avoid the damage due to earthquakes for CBF. Regarding the research of self-centering function in structures, Mander and Cheng (1997) have proposed a seismic design concept referred to as Damage Avoidance Design for bridge piers in 1997. In 2002, Christopoulos et al. investigated feasibility of self-centering function applied for the steel structures, using post-tensioned strands to connect beams and columns. Test results showed that connections did have self-centering function and provided buckling restrained high strength bar, which showed enough energy dissipation capacity. However, its fan shape hysteretic loop had less energy dissipation capacity than the traditional one with elasto-plastic hysteretic loop. Similar research was done by Ricles et al. (2002), steel angles were applied to dissipate energy in concrete-filled steel tubular connections. Tsai et al. (2008) used friction force to dissipate seismic energy in self-centering steel structures.

In this research, similar to literatures that separated the beam on column faces (rocking interface) to release its

[1] *Professor, Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan , e-mail: ctcheng@nkfust.edu.tw*
[2] *Graduate Student, Kaohsiung First University of Science and Technology, Kaohsiung, Taiwan.*

NUMERICAL ANALYSIS OF COLLAPSING BEHAVIOR FOR MULTI-STORY STEEL MOMENT FRAMES CONSIDERING STRENGTH DEGRADATION BY LOCAL BUCKLING

Seiji Mukaide[1] and Motohide Tada[2],

SUMMARY

In this paper, parametric analyses with fishbone shaped model considering strength deterioration of members are conducted in order to investigate the complete collapse behavior of steel moment frames. *COF* and width-thickness ratio et al. are adopted as parameters. In the greater part of cases, the collapse mechanism varies from the total collapse type to the story-collapse type due to strength deterioration by local buckling. The analytical results show that the collapse mechanism at the time of the complete collapse affects the energy capacity.

***Keywords**: seismic response analysis; complete collapse; collapse mechanism; column overstrength factor.*

INTRODUCTION

An accurate prediction of earthquake is unrealized with current technology, and exceedingly large ground motions sometimes wreak very heavy damage, for example, the 1994 Northridge, the 1995 Kobe and 1999 Jiji earthquakes. It is beneficial to evaluate not only structural performance under design-level ground motions but also the safety margin against complete collapse under larger ground motions than current seismic code. However, there are few studies on complete collapse of steel moment frames.

A shaking table test on a full-scale steel building was conducted at the E-Defense three-dimensional shake table facility (Yamada et al 2008 and Suita et al 2008). The specimen is a 4-story moment resisting frame. By 40% and 60% scaled Takatori records of Kobe earthquake, which corresponds to the level 2 and larger seismic load, maximum inter-story drift exceeds 0.01 radians and the mechanism of the moment frame was total collapse mechanism. By 100% Takatori records, the mechanism of the specimen changed to a story-collapse type mechanism in the first story by strength deterioration of columns due to local buckling at the top and bottom ends, and the specimen collapsed.

Numerical simulation of collapsing behavior for complete collapse specimen at E-defense was conducted by Tada et al (2010). The collaborative structural analysis (CSA) system was utilized for the purpose of the simulation, which is capable of performing highly sophisticated structural analysis by utilizing the beneficial features of existing individual structural analysis programs. The host program, NETLYS, can deal with geometrical and material nonlinear analysis, and one of the station programs, MARC, can simulate the deteriorating post-buckling behavior in detail. The analytical results were compared with shaking table test results to show the reliability of analysis.

Strength degradation has recently been taken into consideration in response analysis with one-dimensional mass-spring systems (generally called ‘single or multiple degrees of freedom systems’) by researchers. However, a fishbone shaped model is more suitable models for nonlinear response analysis than these systems because the

[1] *Assistant Professor, Graduate School of Engineering, Osaka University, Japan, e-mail: mukaide@arch.eng.osaka-u.ac.jp*
[2] *Professor, Graduate School of Engineering, Osaka University, Japan, e-mail: tada@arch.eng.osaka-u.ac.jp*

SEISMIC PERFORMANCE AND FINITE ELEMENT ANALYSIS OF A NOVEL STEEL DUAL-CORE SELF-CENTERING BRACED FRAME

Chung-Che CHOU[1], Ying-Chuan CHEN[2], Dinh-Hai PHAM[3], Alexis R. Ovalle BEATO[3], Tsung-Han WU[3]

SUMMARY

A new steel dual-core self-centering brace (SCB) has been developed with a flag-shaped re-centering hysteretic response under cyclic loads. Axial deformation capacity of the brace is doubled by serial deformations of two sets of tensioning elements arranged in parallel in the brace. The mechanics and cyclic behavior of the brace are first explained; 5350-mm long dual-core SCBs are tested and modeled to evaluate their cyclic performances. All SCBs exhibit excellent performance up to a drift of 2.5% with a maximum axial load of 1300 kN. A three-story braced frame with dual-core SCBs as an earthquake-resisting mechanism is designed and analyzed using 20 ground motion records to obtain seismic demands. A test program for a one-story braced frame with the proposed dual-core SCB is planned in early 2104. Finite element analyses are first conducted on the one-story self-centering braced frame (SCBF), moment-resisting frame (MRF), and buckling restrained braced frame (BRBF) to evaluate their cyclic performances.

Keywords: *Dual-Core Self-Centering Brace; Cyclic Test; Frame Test; Finite Element Analysis.*

INTRODUCTION

Extensive research has been devoted in the last two decades to improve the seismic performance of steel braced frames. A Buckling-Restrained Braced (BRB) has been developed to provide energy dissipation without buckling as seen in the specially Concentric Braced Frame (CBF). A strong gusset connection which considers both the brace and frame action effects on the gusset is proposed to ensure stable energy dissipation of the BRB (Chou and Liu 2012, Chou et al. 2012a, 2012b). However, under earthquakes, both braced frames are prone to residual lateral deformations over the building height (Fahnestock et al. 2003, Uang and Kiggins 2003). A post-tensioned (PT) self-centering (SC) moment frame that uses post-tensioning steel tendons to compress beams against columns has been proposed as a new system to minimize residual lateral deformations of the frame (Ricles et al. 2001, Christopoulos et al. 2002, Chou et al. 2006). Static and dynamic tests of steel SC moment frames confirm their good SC property and energy dissipation as seen in nonlinear time-history analyses of the frames (Chou and Chen 2010a, 2010b, 2011a). Christopoulos et al. (2008) proposed a Self-Centering Energy-Dissipating (SCED) brace, which uses two steel bracing members for compression, friction devices for energy dissipation, and one set of FRP tensioning elements for the SC property. Chou et al. (2012c, 2012d) and Chou and Chen (2012, 2013) proposed a new dual-core self-centering brace (SCB), which uses an additional inner core and a second parallel set of PT elements in the brace to double the self-centering deformation capacity of the SCED brace. The same design concept was adopted in the T-SCED brace (Erochko et al. 2012) and validated with different bracing member geometry, layout, and types of FRP tendons.

The proposed dual-core SCB increases the potential applications of PT elements with low elastic strain capacity such as steel strands, glass fibers, or carbon fibers. After introducing the mechanics and hysteretic responses of the dual-core SCB, this study presents the results of cyclic tests of several dual-core SCBs. A three-story frame

[1] *Professor, Department of Civil Engineering, National Taiwan University, Taiwan, e-mail: cechou@ntu.edu.tw*
Director, Center for Earthquake Engineering Research, National Taiwan University, Taiwan
Research Fellow, National Center for Research on Earthquake Engineering, Taiwan
[2] *Research Assistant, Department of Civil Engineering, National Taiwan University, Taiwan*
[3] *Graduate Student Researcher, Department of Civil Engineering, National Taiwan University, Taiwan*

Lateral-Force Resisting Mechanisms of Flexure-Dominant Multi-Story Structural Walls with Soft-First-Story

Yuki IDOSAKO[1], Masanobu SAKASHITA[2], Xiaoshan FENG[3] and Minehiro NISHIYAMA[4]

SUMMARY

This paper presents lateral-force resisting mechanisms of flexure-dominant multi-story structural walls with a soft-first-story. Two reinforced concrete specimens consisted of the soft-first-story and the 3-story structural wall were constructed in 30% scale and tested under cyclic loading to simulate earthquake motions. The test variable was the longitudinal reinforcement ratio in the boundary beam of the 2nd floor, which was 1.19% or 2.56%. The structural walls yielded in flexure as intended, which, however, did not result in the concentration of deformation only on the 2nd story. This is because the boundary beam yielded in flexure and other yielding mechanisms were formed. The mechanism needed large drift angle of approximately 2% to attain the design load capacity. The difference in load capacity between the two specimens was not of significance. The beam strength was not sufficient to resist the moment acting when the shear wall yielded in flexure. The beam-column joint on the 2nd floor failed and the specimens were not able to sustain the axial load.

Keywords: *RC building; soft-first-story; multi-story structural wall; flexural yielding; collapse mechanism.*

INTRODUCTION

In the previous earthquake disasters, collapse or severe damage has been observed in soft-first-stories of many RC buildings which had structural walls in the upper stories. More specifically, columns in soft-first-stories failed in flexure or shear due to the difference in stiffness from the upper stories. Those cases in 1978 Miyagi and 1995 Kobe earthquake are well known in Japan.

One of the solutions to prevent the collapse or the severe damage is to avoid the concentration of deformation in the first story that is less stiff and weaker than the upper stories. This goal is achieved by making the upper walls fail in flexure or shear. For the case that the upper walls fail in shear, various investigations have been carried out by Ichinose et al. (e.g., 2012) and a design method is being established. On the other hand, experimental researches for the case that the upper walls fail in flexure are not enough. It is assumed that the boundary beams, which sustain flexure-dominant multi-story structural walls, are subjected to large moment (acting from shear walls, the top of columns of the 1st floor, and so on.) when the upper walls reach their flexural yielding strength. There are some suggestions but no clear rules to design the boundary beam in AIJ Standard for Structural Calculation of Reinforced Concrete Structures (2010). Those boundary beams currently designed might be not strong enough to resist such acting moment, which leads to a different collapse mechanism from designed. To investigate the issues above, the authors constructed two 3-story structural walls with the soft-first-story and conducted cyclic loading tests simulating seismic loads.

[1] *Graduate student, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: rc.idosako@archi.kyoto-u.ac.jp*
[2] *Assistant Professor, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: sakashita@archi.kyoto-u.ac.jp*
[3] *Graduate student, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: rc.feng@archi.kyoto-u.ac.jp*
[4] *Professor, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: mn@archi.kyoto-u.ac.jp*

EFFECT OF AXIAL COMPRESSION ON SHEAR STRENGTH OF REINFORCED CONCRETE COLUMNS WITH HIGH-STRENGTH STEEL AND CONCRETE

Yu Chen OU[1], and Dimas Pramudya KURNIAWAN[2]

SUMMARY

In total, 77 high-strength columns having concrete compressive strength anging from 73.5 to 200 MPa with shear failure were collected from this study and literature and evaluated using ACI 318 shear strength equations. Axial compressive stress is ranging from 0.1 to 0.6 $f_c^{'}$. Evaluation results shows that the ACI simplified shear strength equation provided conservative estimation for most of the columns except for 4 columns that were tested under high axial compression. The ACI detailed shear strength equation yielded non-conservative prediction for 48 columns. Modification of ACI 318 shear strength equations was proposed to consider the interaction between concrete shear strength and axial compression. The proposed shear strength equation yielded conservative prediction for most of the columns.

Keywords: *reinforced concrete columns; cyclic loading; double curvature; shear; high-strength reinforcement; high-strength concrete; axial compression; diagonal cracking strength.*

INTRODUCTION

The advantages of high-strength concrete and steel have been perceived in practical use. Dimension of columns in lower stories of tall buildings can be reduced to increase available floor area and reinforcement congestion can be relieved. Advanced technology has enabled the development of high-strength materials in many countries *e.g.* Japan and Taiwan. For instance, high-strength concrete with specified compressive strength up to 100 MPa, deformed reinforcement with specified yield strength of 685 MPa and 785 MPa for main and transverse reinforcement, respectively, have been commercially available in Taiwan. However, in shear design for columns, the current ACI Building Code (ACI 318M-11 2011) limits concrete compressive strength ($f_c^{'}$) to 70 MPa (ACI 318-11 11.1.2) due to lack of data and practical experience with $f_c^{'} \geq 70$ MPa. Moreover, yield strength of shear reinforcement is limited to 420 MPa (ACI 318-11 11.4.2) to control diagonal crack width and ensure yielding of shear reinforcement before shear failure (Lee *et al.* 2011).

The ACI code (ACI 318M-11 2011) shear strength equations for non-prestressed members subject to axial compression were developed based on research (Baldwin and Viest Nov. 1958, Baron and Siess June 1956, Diaz de Cossio and Ciess Feb. 1960, Morrow and Viest Mar. 1957) with 67 specimens having axial compressive stress ranging from 0.02 to 0.81 $f_c^{'}$ as reported by ACI-ASCE Committee 326 (ACI-ASCE Committee 326 Report 1962).

[1] *Associate Professor, Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan. E-mail: yuchenou@mail.ntust.edu.tw*

[2] *Research Assistant, Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan.*

PUNCHING SHEAR DESIGN METHOD OF KCI 2012

Kyoung-Kyu CHOI[1] and Hong-Gun PARK[2]

ABSTRACT

For the new version of the Korea Concrete Institute design code, KCI committee 103 developed a new punching shear design method to accurately predict the punching shear strength of slab-column connections subjected to direct punching shear and unbalanced moment. Unlike the majority of current design codes using empirical methods, the proposed method was based on material failure criteria of concrete. Basically, flat plate slabs are a flexural member where usually punching shear failure occurs after flexural cracking and yielding of the slab. Thus, the effect of the slab flexural damage was considered in the definition of the punching shear strength. The shear failure mechanism of the critical section was simplified as the failure of the compression zone of the cross-section subjected to combined shear and compressive stresses. Thus, the punching shear strength was defined as the function of the compressive stress and the compression zone depth, which are affected by the slab flexural action. For the unbalanced moment-carrying capacity, the punching shear strengths were defined differently at each face of the critical section. The proposed strength model was applied to existing test specimens of interior and exterior slab-column connections. The results showed that the proposed strength model predicted the test results with reasonable precision.

Keywords: *slab-column connections, punching shear strength, eccentric shear, unbalanced moment.*

INTRODUCTION

In flat plate structures, slab-column connections are susceptible to punching shear failure under strong earthquake. In particular, exterior slab-column connections, which have smaller critical section and are subjected to unbalanced moment by gravity load as well as lateral load, are vulnerable to punching shear failure.

Although various experimental and theoretical studies have been performed to investigate the failure mechanism and structural performance of slab-column connections, the majority of current design methods still use empirical design equations which were developed by parametric studies without firm theoretical background. Such design methods are convenient in use for engineers. However, previous studies reported that current design methods do not accurately predict the punching shear strength of existing test specimens. Furthermore, to expand the application of the design methods to high strength materials and new materials in the future, substantial amount of experimental evidences and parametric studies are required. For this reason, in KCI 2012 (2012), development of a theoretical method was attempted to pursuit better accuracy in the strength prediction.

DIRECT PUNCHING SHEAR STRENGTH

Recent studies for slender beams with rectangular cross-section showed that the shear strength of concrete beams is closely related to the depth of the compression zone. These results imply that after the tension zone is severely

[1] *Assistant Professor, School of Architecture, Soongsil Univ., 369 Sangdo-ro, Dongjak-gu, Seoul 153-743, Korea*
[2] *Professor, Dept. of Architecture & Architectural Engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 151-744, Korea*

Seismic Performance of Pre-tensioned Beams Using Steel-Fiber Reinforced Concrete

Mitsuya MORI[1], Hyeong Jae YOON[2] and Minehiro NISHIYAMA[3]

SUMMARY

Pre-tensioned members have been used to control crack width and deflection under service load. However, pretensioned members subjected to flexure tend to fail in compression in concrete, which is brittle. In addition, they have larger crack spacing and crack width than ordinary reinforced concrete members because of inferior bond properties of prestressing steel to deformed steel bars, and this might cause durability problems. Steel-fiber reinforced concrete (hereafter referred to SFRC) enhances the tensile properties of concrete. The drawbacks written above in pre-tensioned members can be improved by using SFRC, which can result in higher performance in terms of flexural resistance. This paper addresses the seismic performance of pre-tensioned beams using steel-fiber reinforced concrete. Cyclic loading tests, which simulate earthquake motions, were conducted on three pre-tensioned beams constructed with SFRC. The experimental parameter was the volume fraction of steel fibers: 0.0, 0.5 and 1.0%. By using SFRC in prestressted concrete beams, flexural strength and energy absorption capacity were improved, and shear crack width was made smaller than in beams without SFRC. Equivalent viscous damping was also improved by SFRC.

Keywords: *seismic performance, prestressed concrete, steel-fiber reinforced concrete, pre-tension, energy absorption capacity*

INTRODUCTION

In recent years, Fiber Reinforced Concrete (hereafter referred to FRC) material has been developed and studied for application to structural members. A property of this material is Pseudo-Strain-Hardening behavior (hereafter referred to PSH behavior) caused by the distribution of multiple fine cracks under tensile stress (Kunieda et al. 2006, Suwada et al. 2006, 2007, Fisher et al. 2003). Fibers have been used to enhance tensile characteristics of concrete by suppressing crack growth (Bilal S. 2001). Concrete with fibers is characterized by its fiber content. The fiber content is the weight of fibers per unit volume in concrete, it is the product of the volume fraction V_f (volume of fibers per unit volume of concrete) and the specific gravity of the fibers. It is still uncertain how the tensile characteristics of FRC affect the flexural resistance mechanism of structural elements (Suwada 2006). Various analytical and empirical methods have been proposed to predict the flexural strength of the composite material reinforced with fibers (Swamy 1982, Henager 1976). Of all the fibers currently in use to reinforce cement matrices, steel-fibers are the only fibers that can be used for carrying long-term load (Swamy et al. 1982, Padmarajaiah et al. 2001).

Prestressed concrete requires the concrete to attain high compressive strength at an early age. In addition to its higher compressive strength, high-strength concrete possesses an increased tensile strength, and reduced shrinkage and creep strains than normal-strength concrete. High-strength concrete has been found, however, to

[1] *Graduate Student, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, email: rc.mori@archi.kyoto-u.ac.jp*
[2] *JSPS Research Fellow, Department of Architectural Engineering, Kyoto University, Japan, email: rc.yoon@archi.kyoto-u.ac.jp*
[3] *Professor, Dr.Eng., Department of Architectural Engineering, Kyoto University, Japan, email: mn@archi.kyoto-u.ac.jp*

ANALYTICAL MODEL FOR LOAD-DISPLACEMENT CURVE OF SLENDER MASONRY PIERS

Yi-Hsuan TU[1] and Tsung-Hua CHUANG[2]

SUMMARY

Slender unreinforced masonry (URM) piers subjected to in-plane lateral loading usually exhibit rocking behavior. The rocking strength is found to be proportional to the vertical force applied on the pier and therefore can be estimated from given vertical force. For example, the equation for rocking strength in FEMA 356 can provide quite accurate estimation. However, the load-displacement relationship of rocking piers was not clear. The vertical force applied on a pier with fixed vertical boundary is also difficult to determine.

This paper presents a displacement-based analytical model for the load-displacement curve of slender URM piers in rocking behavior. On the basis of two-hinged arch mechanism, the model calculates corresponding lateral load from given displacement. The load-displacement curve can be derived for two different types of boundary conditions: constant vertical force or fixed vertical boundary. The rocking strength is given by the maximum load in the curve, and the ultimate displacement can be derived with assumed failing strain.

The proposed model has been validated with specimens tested by different researchers. The model shows reasonable estimation for both strength and displacement. The comparison with experimental load-displacement curves also indicates a good fit.

Keywords: *unreinforced masonry, rocking, strength, load-displacement relationship, in plane.*

INTRODUCTION

A pier is the vertical wall segment between two openings. As shown in Figure 1, piers may be found in a pure masonry building or a confined masonry (CM) building when there is no tie members placed around the openings. Magenes and Calvi (1997) summarized that the principal failure modes of unreinforced masonry (URM) piers include rocking failure, shear cracking, and sliding. Piers failed in rocking have tensile bed-joint cracks and toe crushing at the compressive corners. Shear cracking shows as inclined diagonal cracks that follow the path of bed- and head-joints and may go through the bricks. Sliding happens along the cracked bed-joints; it is possible for low level of vertical load or low friction coefficient. FEMA 356 (2000) proposes four failure modes and corresponding equations for estimating the strength. The four modes include bed-joint sliding, rocking, diagonal tension, and toe compression. Lee et al. (2008) studied the equations and concluded that the failure mode is related to the axial stress and the aspect ratio. Slender panels tend to fail in diagonal tension if they have higher axial stress, otherwise they fail in rocking. Squat panels with high axial stress usually fail in toe compression and those with low axial stress fail in bed-joint sliding.

This paper is focused on the slender masonry piers that fail in rocking. Abrams et al. (2007) tested original and retrofitted URM piers to evaluate the effectiveness of various rehabilitation techniques. However, the experimental results suggest that rocking behavior may be equal to, or superior to that of retrofitted piers because of the large ductility capacity. Lee et al. (2008) tested URM piers with different aspect ratio; the deformation capacity increases as the aspect ratio increases. The authors (Tu et al. 2009, 2011) performed a series of lateral

[1] *Associate Professor, Department of Architecture, National Cheng Kung University, Taiwan, e-mail: yhtu@mail.ncku.edu.tw*
[2] *PhD, Department of Architecture, National Cheng Kung University, Taiwan*

PREDICTION OF FRACTURE OF STEEL MOMENT CONNECTIONS SUBJECTED TO LONG PERIOD GROUND MOTIONS

Kouhei TAKATSUKA[1], Keiichiro SUITA[2] and Tsuyoshi TANAKA[3]

SUMMARY

This paper presents a method to evaluate plastic deformation capacity of welded beam–to-column connection used for moment frames until ductile fracture due to cyclic loading with varying deformation amplitudes. Cyclic loading tests by constant deformation amplitude were conducted to investigate the relationships between deformation capacity until fracture and deformation amplitude. From test results, the crack propagation is formulated as the function of number of cycles and the deformation amplitude to evaluate the damage to the welded connection of a beam flange. In order to verify validity of the proposed crack propagation formulation, cyclic loading tests by varying deformation amplitudes were conducted. From test results, it is found that the deformation capacity are affected not only the amplitudes but also the orders, which indicates that the Miner rule is not suitable for the prediction of fracture with varying deformation amplitude. The proposed formulation well evaluates damage and simulates crack propagation until fracture.

Keywords: *beam-to-column connection; deformation capacity; cyclic loading test; loading protocol; crack propagation.*

INTRODUCTION

Recent advancement of prediction methods has enabled precise prediction of long-period ground motions produced by ocean-trench earthquake such as the Nankai trough earthquake in Japan. The characteristics of these ground motions are different from conventional strong motion records by near fault earthquakes such as El Centro 1940, Taft 1952 and so on. The predominant periods are longer by two second or more and the duration of motion can be as long as ten minutes or so. Therefore, the response of earlier highrise buildings against long-period ground motions is drawing attention (Suita, 2012). The 2011 Great East Japan Earthquake was a typical ocean-trench earthquake and many tall buildings in Tokyo metropolitan area were strongly shaken (Kasai et al. 2012). For a tall building constructed by steel structure, it is necessary to evaluate the deformation capacity of moment connections subjected to a very large number of cyclic deformation in plastic range.

A number of studies about the effect of weld access hole were done in Japan by Inoue (1997), et al and in USA by Miller (1998), et al summarized in FEMA, which revealed stress concentration at the toe of the weld access hole and it causes early fracture. Failure of welded moment connections due to cyclic inelastic behavior was investigated using the concepts of low-cycle fatigue by Kuwamura and Takagi (2004), Stojadinovic (2003), Campbell et al. (2008) and many other researchers. Deformation capacity until failure of connection is usually estimated by the fatigue damage index of Miner rule (Miner, 1945) as cumulative damage calculated from the numbers of cycles. However, Zhou et al. (2008) and Kadono et al. (2008) show that the fatigue damage index is affected by the order of loading amplitude when the tests are conducted by varying amplitudes. Namely, the deformation capacity by increasing amplitude loadings are smaller than that by decreasing amplitude loadings, but the effect of the order of varying amplitudes is not considered in the previous researches.

[1] *Ph. D student, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: takatsuka.kohei.33n@st.kyoto-u.ac.jp (Research Fellow of Japan Society for the Promotion of Science, DC)*

[2] *Professor, Dept. of Architecture and Architectural Engineering, Kyoto University, Japan, e-mail: suita@archi.kyoto-u.ac.jp*

[3] *Professor, Dept. of Architecture, Kobe University, Japan, e-mail: tanaka@arch.kobe-u.ac.jp*

PREDICTION OF LOW-CYCLE FATIGUE FRACTURE OF WELDED SEISMIC STEEL MOMENT CONNECTIONS: A CONTINUUM DAMAGE MECHANICS APPROACH

Jae-Hoon KIM[1]; Cheol-Ho LEE[2]; Dae-Kyoung KIM[3]; Dong-Guen LEE[4]

SUMMARY

A continuum damage mechanics-based finite element approach was presented in this paper that can be used to predict low-cycle fatigue fracture of welded seismic steel moment connections. Many fracture mechanics-based approaches have been tried to predict cracking in welded seismic steel moment connections after connection failure observed in the 1994 Northridge and 1995 Kobe earthquakes. However, studies which can realistically simulate the damage evolution due to cyclic seismic loading have been very few. As an alternative, a damage mechanics approach is used in this study to tackle connection fracture issue under cyclic seismic loading. The key parameters required for the damage mechanics modeling were first calibrated in a hybrid manner based on available material test data and associated numerical fracture simulation. The damage rate modeling, originally proposed by Lemaitre, was also slightly modified considering the compressive damage evolution. The fracture process of welded steel moment connections subjected to cyclic seismic loading was then simulated by developing and incorporating the damage analysis subroutine into the commercial code ABAQUS. The numerical predictions of this study correlated well with full-scale cyclic seismic test results in terms of the instance and location of fracture occurrence. The approach proposed can be used to supplement or replace costly full-scale cyclic seismic testing.
Keywords: *Damage mechanics; Fracture; Low cycle fatigue; Seismic; Welded steel moment connections.*

INTRODUCTION

After the unexpected steel connection fracture observed in the 1994 Northridge and 1995 Kobe earthquakes, many experimental and analytical studies on fracture have been conducted. For example, El-Tawil et al. (1999) tried to examine the effect of panel zone yielding on the potential for fracture of welded steel moment connections based on detailed finite element analyses. In their study, a number of different stress, strain, and combined stress/strain indices such as the pressure index and the rupture index were employed to compare the potential for fracture for different connection configurations. However, this methodology should be considered as a convenient way for qualitatively comparing different analyses since it does not account for the cyclic damage accumulation due to seismic loading. For example, the key factors which affect fracture process such as the plastic strain at which ductile damage starts to accumulate and a certain minimum characteristic length that represents fracture are not accounted for in above indices.

The fracture of steel moment connections subjected to cyclic loading resulting from a strong earthquake is

[1] *Post-doctoral Researcher, Department of Architecture and Architectural Engineering, Seoul National University, Korea, e-mail: kaine00@naver.com*
[2] *Professor, Department of Architecture and Architectural Engineering, Seoul National University, Korea, e-mail: ceholee@snu.ac.kr*
[3] *Graduate Student, Department of Architecture and Architectural Engineering, Seoul National University, Korea, e-mail: solarbim@naver.com*
[4] *Professor Emeritus, Department of Architectural Engineering, Sungkyunkwan University, Korea, e-mail: dg19491947@gmail.com*

STRENGTH OF SELF-DRILLING SCREW CONNECTION USED IN STEEL FRAMED HOUSE SYSTEMS NOMINAL STRENGTH OF HOLD-DOWN COMPONENT CONNECTION

Atsushi SATO[1], Takuya TORIYAMA[2], Hisayuki OKADA[3], and Tetsuro ONO[4]

SUMMARY

Steel framed house is the structural system fabricated from light gage members, structural plywood, and gypsum boards. Light gage framings are sheathed by structural plywood and gypsum board panels, and self-drilling screws are used in the connections. Furthermore, self-drilling screws are used to assemble the light gage framings. Thus mostly self-drilling screws are used to connect components, the use of welding is extremely limited. In this system, shear walls, i.e., lateral force resisting components, are tightened to the base by the anchor bolts through hold-down components. The hold-down components, which will transmit the force to the base, are also connected to framing (i.e., studs) by self-drilling screws. To guarantee the seismic safety of the structure, the strength of the hold-down component connection must be greater than the required strength. Current design formula overestimated the connection strength; therefore, the design formula which can predict the connection strength in a reasonable accuracy is needed. To clarify the strength of the hold-down connection, component tests were conducted in this study. Finally, design formula is derived, and the accuracy of the formula is verified by the test data.

Keywords: *steel framed house; light gage; connection; self-drilling screw; eccentricity; nominal strength.*

INTRODUCTION

Steel framed house (SFH) is the structural system fabricated from light gage members, structural plywood and gypsum boards (referred to as steel house). This system is similar to wood framed construction commonly referred to as two-by-four system. SFH is the system where the timbers of the framing in two-by-four system are replaced by light gage members. Moreover, thickness of the light gage is limited to less than 2.3mm in SFH system. According to the Building Standard Law of Japan (BCJ 2013), SFH system can be used up to four story buildings. To design the middle story buildings, shear walls are installed to resist the lateral forces, e.g., seismic forces, and the shear wall in the first floor shall be connected to the base to transmit these forces. Usually, hold-down components are used to connect the shear wall with the anchor bolt which is embedded in the base. Fig.1 shows the detail of the hold-down connection in SFH system. As can be seen from Fig.1, hold-down component is connected to the stud by self-drilling screws; the axial force from the stud (shear wall) will be transmitted by shear at the screws to the hold-down component. To guarantee the structural safety, the connection strength of the hold-down component must be greater than required strength in the ultimate stage. If fracture will occur in the connection, this phenomenon will directly connect to the structural failure. Therefore, it can be said that the hold-down connection is one of the most important structural element in the system.

[1] *Associate Professor, Dept. Scientific and Engineering Simulation, Nagoya Institute of Tech., Japan, e-mail: sato.atsushi@nitech.ac.jp*
[2] *Graduate Student, Dept. Scientific and Engineering Simulation, Nagoya Institute of Tech., Japan, e-mail: cht16046@gmail.com*
[3] *Professor, Dept. of Architecture, Aichi Institute of Tech., Japan, e-mail: h_okada@aitech.ac.jp*
[4] *Professor, Dept. of Human Science, Sugiyama Jogakuen University, Japan, e-mail: tetsu@sugiyama-u.ac.jp*

SELF-CENTERING OF POST-TENSIONED COLUMN BASE

Cheng-Chih CHEN[1], Huan-Wei LIN[2], and Rung-Shiuan TSAI[3]

SUMMARY

This research aims to investigate the seismic behavior of a post-tensioned steel column base with friction dampers, and study the effects of initial post-tensioned force of strands and energy dissipation dampers. The column and foundation was joined by using high-strength strands to provide self-centering behavior, and the friction type energy dissipation dampers were used to provide hysteretic behavior. Therefore, the subassembly possessed characteristics of self-centering and no residual deformation. The behavior of the joint was established analytically and experimentally. The results demonstrated that increasing post-tensioned force of the bolts used for friction dampers could effectively increase the area of the energy dissipation. The friction dampers installed at the column flange rather than column web led to better energy dissipation behavior and more economic. The column base connection, with friction dampers, possesses self-centering, gap opening and closing at the column-to-foundation interface, energy dissipation characteristics, and no residual deformation of the column. Moreover, analytical prediction correlated well with experimental results.

Keywords: *post-tensioned, self-centering, energy dissipation, friction damper, foundation.*

INTRODUCTION

In high seismic regions, special moment frames are generally used to resist forces exerted by earthquake. Structural members will undergo inelastic behavior during a major earthquake. Plastic hinges formed on beams will be expected to dissipate energy. As a result, residual deformation of the frames will occur and cause problems such as functions of the structures and retrofitting of the damaged frames. Therefore, post-tensioned frames have been developed (Sause et al. 2006; Garlock et al. 2007) to achieve no residual drifts of the frame after the earthquake. Post-tensioning force is employed to join the beam and column members as well as the column and foundation. The self-centering beam-to-column connections have been intensively studied (Ricles et al. 2001 and 2002; Christopoulos et al. 2002; Chou and Lai 2009). Chi and Liu (2012) recently studied the post-tensioned column base connection using buckling restrained steel plates as energy dissipator. The post-tensioning forces applied through strands will provide restoring forces and accomplish the self-centering nature of the frames. Friction dampers are one of the effective means to dissipate energy. Friction devices are used in either braces or beam-to-column connections (Rojas et al. 2005; Zhu and Zhang 2008; Kim and Christopoulos 2008; Wolski et al. 2009).

In this paper, post-tensioned column base connections are evaluated analytically and experimentally. After determining the friction coefficient by bolted friction tests, friction dampers were incorporated at the column base to dissipate earthquake induced energy. A steel column was post-tensioned and fasten to the reinforced concrete foundation using strands. Hysteretic behavior of the column base connections was analytically established, and large-scale test was conducted to elucidate the cyclic behavior.

[1] *Professor, Dept of Civil Eng., National Chiao Tung University, Taiwan, e-mail: chrischen@mail.nctu.edu.tw*
[2] *Graduate student, Dept of Civil Eng., National Chiao Tung University, Taiwan, e-mail: ball1017.cv96@g2.nctu.edu.tw*
[3] *Graduate student, Dept of Civil Eng., National Chiao Tung University, Taiwan, e-mail: jason771016@hotmail.com*

BI-DIRECTIONAL LATERAL BEHAVIOR OF POST-TENSIONED CORNER SLAB-COLUMN CONNECTIONS

Thomas H.-K. Kang[1]

SUMMARY

The behavior of post-tensioned (PT) "corner" slab-column connections was rarely studied. This study performs in-depth research for better understanding of complicated moment and shear transfer mechanism at PT corner slab-column connections. Literature was reviewed and finite element simulations were performed on two previously tested isolated PT corner connections, which were subjected to bi-directional reversed cyclic deformations. The documented seismic test results, along with the finite element simulations, provide an innovative way to review the scarce test data in detail. Using such a unique approach, the shear-moment transfer mechanism at PT corner connections and the eccentric shear stress model, which was used in ACI 318 punching shear provisions, were assessed in depth. Particularly, the bi-directional lateral behavior during various drift levels was closely observed.

Keywords: *Post-tensioned concrete; bi-directional lateral behavior; slab-column connection; corner connection; nonlinear finite element modeling.*

INTRODUCTION

Post-tensioned (PT) concrete is essential in many applications today in order to fully utilize concrete compressive strength and steel tensile strength especially in cast-in-place concrete construction, and through proper design, to control cracking and deflection. Although design methods have been developed over the decades, an understanding of the ultimate mechanism in the PT concrete system is still greatly needed in many aspects. Such aspects include the intricate problems of punching shear failure of a PT two-way slab system. However, it is expensive and time-consuming to perform extensive experimental tests on each prototype. The finite element method can be developed to supplement the experimental research. The efforts and developments made by many pioneering researchers over the past five decades have enabled the finite element method to become a versatile and powerful approach in structural analysis of PT structures. The principal goals of this study are to develop modeling schemes for corner PT slab-column connections that were tested by Moehle et al. (1994) based on general purpose finite element packages and to evaluate the current building code regarding the corner PT connections.

PREVIOUS EXPERIMENTAL PROGRAM

Moehle et al. (1994) investigated two 3/7 scale isolated corner PT connections (**Fig. 1**). The slabs with the corner connection had an overall length of 2.17 m in each direction and 92 mm thickness. The corner connection was in the south-west corner, whereas other corners of the slab were supported by pin connections simulating an inflection boundary in the prototype structure. Additional dead loads were applied to the slab before testing to achieve the desired gravity load in the column at the initialization of the test. Bi-directional reversed cyclic loading was applied to the column top with several cycles of different drift ratios for the purpose of simulating

[1] *Associate Professor, Seoul National University, Korea, e-mail: tkang@snu.ac.kr*

CONFINEMENT EFFICIENCY OF HIGH STRENGTH STEEL FIBER IN HIGH STRENGTH CONCRETE

Wen-Cheng Liao[1], Yao-Jen Kuo[2], En-Jui Liu[2]

ABSTRACT

This study presents the improvement of mechanical properties and confinement efficiency of high strength concrete by adding high strength steel fibers. Due to brittleness of high strength concrete, more confinement is needed to enhance the ductility and satisfy seismic requirements for high strength reinforced column, particularly under high axial loading demands. Furthermore, early cover spalling trigs substantial compressive strength loss and thus sudden failure occurs. Many studies show that addition of steel fibers can not only effectively prevent the early cover spalling, but also increase the toughness and ductility of high strength concrete.

The relationship between the toughness and three main fiber parameters, including fiber volume fraction, aspect ratio and bond strength between fiber and matrix, is investigated in this study. The confinement efficiencies in terms of toughness ratio provided by steel fibers or stirrups of the high strength steel fiber reinforced concrete are also conducted and verified with experimental data. The toughness ratios of high strength steel fiber reinforced concrete columns obtained from the proposed regression equations are in good agreement with those got from the test results.

Keywords: *compressive ductility, confinement efficiency, high strength concrete, steel fiber, toughness ratios, steel fiber reinforced concrete, transverse reinforcement*

INTRODUCTION

The nature of high strength concrete, HSC, presents brittle failure right after ultimate compressive strength loaded. The compressive strength of HSC suddenly drops to almost zero without any ductility while stress level beyond its capacity. In current reinforced concrete design concept, transverse reinforcement is commonly used to provide the toughness of concrete in compression. The lateral expansion of concrete resulting from compression can be well confined by the hoop tension from transverse reinforcement. The enhancement of the compressive toughness by using transverse reinforcement is reflected by the decrease in the slope of the descending branch of the stress-strain curve of concrete in compression.

The addition of fibers can be an alternative to turn the brittle nature of HSC to ductile responses in compression. Several researches show that the addition of fibers to HSC can not only enhance the tensile strength but significantly improve the compressive toughness of HSC. Song and Hwang (2004) investigated the compressive stress and strain relationships of fiber reinforced high strength mortars with different volume fractions of hooked-end steel fibers. The results show that the addition of fibers with the volume fraction of 1.0% and 1.5% increase the 11.8% and 15.0% of ultimate compressive strengths, 50.0% and 86.2% of splitting tensile strengths, 57.8% and 92.0% of modulus of rupture, respectively. While only around 10 ~15% improvement on the ultimate compressive strength, the enhancement on the splitting tensile strength and bending strength is much

[1]*Department of Civil Engineering at National Taiwan University, Taiwan, No. 1, Sec. 4, Roosevelt Road, Taipei, 10617 Taiwan,* *wcliao@ntu.edu.tw*
[2]*Department of Civil Engineering at National Taiwan University, Taiwan, No. 1, Sec. 4, Roosevelt Road, Taipei, 10617 Taiwan.*

STRUCTURAL BEHVIOR OF RC BEAM-COLUMN ASSEMBLAGES

Jung-Yoon Lee[1], Jongwook Park[2], and Mohamad Y. Mansour[3]

SUMMARY

Since RC beam-column joints are crucial elements in the survival of RC frame structures, a brittle failure such as that associated with shear failure or bond failure in the joints must be avoided. RC frame-structures, designed according to present building codes, are expected to deform well into the inelastic range and dissipate high energy through stable hysteretic behavior when subjected to seismic loading. Various experimental studies of RC beam-column joints indicated that the slippage of the steel reinforcements, concrete strength deterioration, and strain penetration of beam-column assemblages affect the structural response of the RC joints subjected to seismic inelastic loading. Since 1970's many research has been conducted to predict the strength of RC beam-column joints. However, most of the previously conducted research focused on predicting the strength of the RC joint. Limited research was carried out to evaluate the deformation capacity of an RC joint. This paper presents the results of an analytical and experimental study aiming on predicting not only the strength but the deformation of RC joints failing in shear, after plastic hinge develop at the end of the adjacent beams. Thirty five experimental results of RC joints reported in the technical literature were compared with the deformation as predicted by the proposed method. Comparisons between the observed and calculated deformation capacities of the considered RC beam-column joint assemblies showed reasonable agreement.

Keywords *: RC beam-column joints; deformation; strain penetration; strength degradation*

INTRODUCTION

Beam column joints are critical regions in multi-story moment resisting reinforced concrete frames subject to inelastic response under severe seismic attack. For seismic moments in columns and beams act in opposite directions across the joint, the beam-column joint is subjected to horizontal and vertical shear forces whose magnitude is often many times higher than those found in the adjacent beams and columns. Since joints are also connecting elements of the load carrying columns, a brittle failure such as shear or bond failure in the joints must be avoided. Therefore, in the design of the reinforced concrete beam-column joints against seismic load, it is desirable to limit joint strength degradation until the ductility capacity of the beam reaches the designed capacity [1, 2]. In addition, in order to develop an improved method for predicting the nonlinear response of multistory reinforced concrete (RC) frames subjected to seismic loading, the displacement contribution to story drift of the individual structural components such as beams, columns, and joints should be considered. In particular, because the slippage, strength deterioration, and strain penetration of beam-column assemblages effect on the dynamic response of the RC frames subjected to large cyclic deformation reversals, the structural response of RC beam-column joints should be considered.

Before 60's, columns, beams and walls exhibited the most damage by the earthquake, not joints. However,

[1] *Professor, Sungkyunkwan University, Republic of Korea, e-mail: jylee@skku.ac.kr*
[2] *Engineer, Lotte Engineering and Construction Lnc, Republic of Korea e-mail:zusaq@skku.edu*
[3] *Bennett & Associates, Houston, TX, USA*
(This paper is a part of the paper submitted to the ACI structural journal [2])*

SEISMIC STRENGTHENING WITH A NEW STEEL DEVICE FOR R/C EXTERIOR BEAM-COLUMN JOINTS

Yuebing LI[1], Yasushi SANADA[2], Yasuhiro WATANABE[3], and Takuya TOMONAGA[3]

SUMMARY

A large number of reinforced concrete (RC) buildings designed for gravity loads according to older seismic design code exist even in regions of moderate seismicity, and some of them contain no transverse reinforcement in the beam-column joints. The ultimate purpose of this research is to propose a seismic strengthening method for this kind of joint that is acceptable for economic and technical conditions in developing countries. In this feasibility study to clarify the necessary design conditions for strengthening, a new seismic steel device was designed and implemented to improve the seismic performance of beam-column joints. Two 3/4 scale specimens simulating exterior beam-column joints without transverse reinforcement were constructed, one was not strengthened as a control specimen and the other was strengthened by the proposed device. The specimens were tested under static cyclic loading with a new experimental technique using shortened beam-exterior column joint specimens, which was also presented in this paper. The test results showed that the un-strengthened control specimen reached its ultimate strength without yielding of beam/column and behaved in a typical manner of joint failure. Nevertheless the strengthened specimen exhibited ductile failure modes with a beam yielding preceded. The strengthened specimen exhibited more than twice the strength of un-strengthened one as well as much higher ductility. Effectiveness of the seismic strengthening device proposed in this study was experimentally examined, which means that the design concept also presented herein can be applied to seismic strengthening for this kind of structure.

Keywords: *reinforced concrete, RC, exterior beam-column joint, steel device, seismic strengthening*

INTRODUCTION

According to the damage investigation (Sanada, 2009) of the 2009 Sumatra earthquake occurred in Indonesia, a large number of relatively large-scale reinforced concrete (RC) buildings, including engineered structures, suffered great damage. One typical damage to RC structures is failure of beam-column joints where no transverse reinforcement was provided. Because many old buildings with this kind of joints exist even in the regions of moderate seismicity, developing of effective and reasonable seismic strengthening method for such existing buildings is urgently needed.

Many studies have been conducted on seismic strengthening of this kind of beam-column joints using steel prop (Kazem et al, 2012), GFRP sheets (Ghobarah and Said, 2002), haunches (Giovacchino, 2012), etc. and significant strengthening effectiveness have been achieved.

[1] *PhD Candidate, Department of Global Architecture, Graduate School of Engineering, Osaka University, Japan, li_yuebing@arch.eng.osaka-u.ac.jp*
[2] *Associate Professor, Department of Global Architecture, Graduate School of Engineering, Osaka University, Japan, sanada@arch.eng.osaka-u.ac.jp*
[3] *Graduate Student, Graduate School of Engineering, Toyohashi University of Technology, Japan*

STRUT-AND-TIE MODELS FOR BAR DEVELOPMENT AND ANCHORAGE

Sung-Gul HONG[1]

SUMMARY

The bar development and anchorage is most critical subject for the successful performance of structural concrete. This paper reviews on the previous application of strut-and-tie models (STM) for bond behaviors. From the viewpoint of structural configuration surrounding nodal zones including tension ties, bar development in compression-compression-tie nodal zone is a basic subject to understand bond behavior. The strength of ties depends on transverse reinforcement and geometric configuration surrounding the nodes. This study proposes classification of STM for bar development and anchorage to improve detailing of bars in structural concrete involving bond strength problems. Current design code provisions for bar detailing can be modified for safer behaviors.

***Keywords**: Bar development; strut-and-tie models; structural configuration; cut-off points; bar detailing*

INTRODUCTION

Judicious detailing of reinforcement for structural concrete is of great importance, especially, in disturbed regions. Detailing of reinforcement dependent on bar development and anchorage often controls the strength of disturbed regions. In case of exterior of corner joints, where one or more of beams do not continue beyond the joint, the safe detailing of bar anchorage is essential for the sound structural performance of joints. Using strut-and-tie models (STM) the required forces in the reinforcement can be estimated for design. The forces in the struts in joints are in equilibrium with the forces in the ties by bearing plates outside of nodal zones or by bond along the reinforcement inside of nodal zones. This study shows how to deal with tension ties insides of zones from the viewpoint of STM and the failure mechanisms with simple yield criteria for bond along the interface between concrete and ties. The limit analyses (lower bound solution as STM and failure mechanisms) have been performed under assumption of perfectly plastic behavior of material. The stress-strain relationship of such material with sufficient ductility may be idealized by a horizontal relationship line beyond the yield point either a perfectly rigid plastic material

MODELING OF BOND AND CLASSIFICATION OF STM FOR BOND

Modeling of bond

It is well accepted that the bond stresses at ultimate state of deformed bars can be developed in the form of reactions due to action from diagonal compression force after losing adhesion between concrete and reinforcing bars at initial stage. Such interaction has been interpreted as local truss action. Most existing models of bond transfer focus on the local behavior and do not consider the interaction between surrounding internal force flows and the local bond transfer. The proposed STM for bar development and bar anchorage in this study, plane stress teats the state of stresses in concrete and along a bar developed by bond as plane stress state.

[1] *Professor, Dept. of Architecture, Seoul National University, Seoul, Korea, e-mail : sglhong@snu.ac.kr*

HYBRID MASS DAMPERS FOR REDUCING WIND RESPONSES OF BUILDINGS

Kyung-Won Min*[1], Jae-Sung Heo[2], Young-Wook Kim[2]

SUMMARY

A tuned liquid mass damper (TLMD) is proposed for bi-directionally controlling wind responses of a building in orthogonal directions. It is a damper which behaves as a tuned liquid column damper (TLCD) and also as a tuned mass damper (TMD) in the orthogonal direction of TLCD. First, experiments are performed for the TLMD installed by angles on a uniaxial shaking table in order to describe bi-directional wind responses. Finally, a real size TLMD is manufactured and installed on the fifth floor of a full scale five story steel building. Three tests are performed for TLMDs placed in the TMD direction, TLCD direction and coupled direction by rotating the TLMD by 45°. Independent TMD and TLMD behaviors are observed as found in the shaking table test.

Keywords *: tuned liquid mass damper, tuned mass damper, tuned liquid column damper, full scale building, bi-directional wind responses, control performance, effective mass, effective mass ratio, natural frequency, acceleration*

1. INTRODUCTION

Various types of TMDs were proposed to control the multi-directional responses of a structure. The multiple tuned mass damper (MTMD) was developed to control the bi-directional responses of a structure by installing two TMDs in two orthogonal directions. [1-5]. A bi-directional tuned mass damper (BTMD), having two springs with different stiffness, which are jointly connected to one mass in two orthogonal directions, respectively, was proposed to reduce bi-directional building responses. Desu et al.(2006) proposed the coupled tuned mass damper (CTMD) which has different stiffness of springs and damping coefficient to control both the translational and torsional responses of a building structure [6]. They also performed a comparative study on the control effect of the MTMD, BTMD and CTMD installed in an asymmetric building. However, MTMDs require a large space for installation. Moreover, not only they cause a dynamic eccentric force produced by two additional masses but also it is required to reinforce the slab, on which additional masses are located. In the case of BTMDs and CTMDs, there are difficulties in designing guide rails in multi-directions, through which heavy mass moves. Heo et al.(2008) proposed a tuned liquid mass damper (TLMD) for reducing the bi-directional wind responses of buildings [7]. The damper behaves as a TMD and a TLCD corresponding to building motions. They verified the control performance experimentally for a small-sized TLMD mounted on a single-degree-of-freedom structure. Also they performed a real-time hybrid shaking table testing to assess the control efficiency of the total system by adopting the TLMD and the building model as experimental and numerical parts, respectively. However, they did not verify the control performance of the TLMD in the case of coupled behavior of the TMD and TLCD for a full scale building.

The aim of this study is to verify experimentally the coupled control performance of two orthogonal wind-

[1] *Professor, Department of Architectural Engineering, Dankook University, 126, e-mail: kwmin@dankook.ac.kr*

[2] *Graduate Student, Department of Architectural Engineering, Dankook University, 126*

A LEVERAGE-TYPE STIFFNESS-CONTROLLABLE MASS DAMPER FOR VIBRATION MITIGATION OF STRUCTURES

Shih-Yu Chu[1], Lyan-Ywan Lu[2], Shih-Wei Yeh[3] and Chih-Hua Peng[4]

SUMMARY

It is well recognized that the tuned mass damper (TMD) is an effective technology for mitigating the structural vibration due to wind loads. Therefore, some researchers have advocated to applying TMDs for vibration mitigation of structures subjected to earthquake in the last decade. Nevertheless, because the frequency contents and magnitude of earthquakes are usually unpredictable and far more complex than wind loads, the control performance of a conventional TMD may not be as effective as it is expected. To resolve this problem, a semi-active mass damper named the leverage-type stiffness controllable mass damper (LSCMD) is proposed in this paper. The LSCMD has a lever-arm with a movable pivot, so it is able to control the damper stiffness and force in real-time by adjusting the pivot position. To evaluate the control effectiveness of the LSCMD, the seismic responses of a structural system equipped with the LSCMD are simulated and compared to the responses of the same structure controlled by an optimally-designed passive TMD and a hybrid mass damper (HMD) that adopts the same control law of the LSCMD. The simulation results demonstrate that while all three mass damper systems are equally effective in suppressing the maximum responses of the structure, the LSCMD demands less damper stroke than the passive TMD, and less control energy than the HMD. This indicates that the proposed LSCMD is more desirable if the damper installation space and energy consumption are of major concerns.

Keywords: *Tuned Mass Damper, Leverage-Type Stiffness Controllable Mass Damper, Variable Stiffness, Semi-Active Control, Discrete-Time Direct Output Feedback, Time Delay.*

INTRODUCTION

It has been demonstrated that tuned mass damper (TMD) is an effective technology for reducing the structural vibration caused by wind loads (Chung et al., 2011; Warburton, 1982; Chase et al., 2006). Based on the findings, some researchers have investigated the possibility of applying TMD to mitigate the structural motions induced by seismic excitations (Ikago et al., 2012; Rakicevic et al., 2012; Marano and Greco, 2011; Miranda, 2005). In order to attain a better control performance, the frequency and damping ratio of a TMD have to be tuned to its optimal values, which usually depend on the characteristics of the excitations (Ikago et al., 2012; Marano and Greco, 2011; Marano et al., 2010; Marano and Quaranta, 2009; Marano et al., 2007). Unfortunately, the frequency contents and magnitudes of a seismic load is usually complicate and difficult to be predicted precisely. As a result, the control performance of a TMD under a real earthquake may not be as ideal as designed. In order

[1] *Associate Professor, Department of Civil Engineering, National Cheng Kung University, Taiwan, e-mail: sychu@mail.ncku.edu.tw*
[2] *Distinguished Professor, Department of Construction Engineering, National Kaohsiung First University of Science & Technology, Taiwan.*
[3] *PhD Candidate, Department of Civil Engineering, National Cheng Kung University, Taiwan.*
[4] *Graduate Student, Department of Civil Engineering, National Cheng Kung University, Taiwan.*

LOAD-DRIFT RELATIONSHIP OF DOWEL BAR IN REINFORCED CONCRETE MEMBER

Susumu TAKAHASHI[1], Eiji ANODA[2], and Toshikatsu ICHINOSE[3]

SUMMARY

Dowel action is an efficient shear-transfer mechanism for reinforced concrete members in many cases, e.g. connections between precast concrete members, construction joints and beam ends where longitudinal bars are pulled out from the joint. Lateral strength of dowel bars have been discussed by many researchers, however, the stiffness of dowel action is not well-argued. In this research, a nonlinear analysis is conducted to investigate the load-drift relationship of dowel bars. Discrete model is used in this analysis, i.e. dowel bars embedded in concrete are divided into elements along the depth. In the analysis, tri-linear models are used for moment-curvature relationship of dowel bars and bearing stress-strain relationship of concrete. Load-drift relationship given as a result of the analysis is compared with the experimental results of dowel bars reported in a paper. The analytical results have good agreement with test results. Based on the analytical results, a simple method to evaluate the load-drift relationship of dowel bars is proposed. Load-drift relationship given by the method is tri-linear model and has good agreement with that given by the nonlinear analysis.

Keywords: *dowel action; reinforced concrete; load-drift relationship; discrete model; bearing stress.*

INTRODUCTION

Dowel bars embedded in concrete resist shear force when reinforced concrete member deforms along the connection between precast concrete members or construction joint (Fig. 1). Dowel bars also resist shear force when longitudinal bars in beams are pulled out from the joint (Fig. 2). For understanding of this mechanism, many researches to investigate the shear capacity of dowel bars were conducted (e.g. Vinteleou and Tassios, 1986). However, stiffness of dowel action is still not well-known. Poli et al. (1992) conducted a set of tests to investigate the stiffness of dowel bars and proposed a fitting curve for load-drift relationship of dowel bars. Although the fitting curve includes many parameters, it is not clear how the yielding of dowel bars and the fracture of concrete act on the load-drift relationship.

Tanaka and Murakoshi (2011) investigated the moment distribution of dowel bars along the embedment length. It is also important to understand dowel behaviors as well as the load-drift relationship. They discussed about moment distribution as first yielding of dowel bars. Therefore, it is not fully discussed about moment distribution and deformation shape of dowel bars after its yielding.

In this research, a nonlinear analysis is conducted to investigate the load-drift relationship of dowel bars. In this analysis, dowel bars are divided into elements along the embedment length. Analytical results show the moment distribution and the deformation shape of dowel bars after their yielding. On the basis of these results, a method

[1] *Assistant Professor, Nagoya Institute of Technology, Japan, e-mail: takahashi.susumu@nitech.ac.jp*
[2] *Graduate Student, Nagoya Institute of Technology, Japan*
[3] *Professor, Nagoya Institute of Technology, Japan*

AN EXPERIMENTAL STUDY ON DUCTILE BEHAVIOR OF DIAGRID STRUCTURE

Yong-Wan KIM[1], Myoung-Kyu LEE[2], Taejin KIM[3] and Byung-Min CHO[4]

SUMMARY

Although there have been a number of researches on seismic design of building frames, the studies on ductile behavior of the diagrid system have not been conducted sufficiently. Regarding the buildings having diagrid frame system, it is expected that they will show low horizontal ductility since the diagrid members receive high compression force and lateral force simultaneously. Therefore, engineers should check how the diagrid frame members behave when the seismic forces are acting, especially focusing on buckling occurrence due to the high compression in diagonal members. In this study, several full-scale diagrid substructures were tested by experiments. The purpose of these experiments was to find relationship between horizontal ductility of diagrid members and vertical load. Since the result showed that the diagrid members have poor ductility, additional experiments were conducted with diagrid substructures which have frictional dampers.

Keywords: *Diagrid, experiment, ductility, buckling, energy dissipation, frictional damper*

INTRODUCTION

The newest trend of architecture pursues free-form buildings, inspiring architects and engineers to introduce various complex-shaped structures. Especially, development of triangular module of tall building frame such as diagrid system has enabled construction of a number of landmark buildings in many countries. According to recent studies, the diagrid system also has been proved to be effective in resisting both gravity and horizontal loads simultaneously.

These days, a lot of buildings are being built on high seismic region, so it became a big issue among engineers that there should be enough researches on ductile capacity of these buildings. This consideration has been drawn numerous efforts to identify ductile behavior of many different building frame systems, including experiment and nonlinear analysis. However, the studies on ductile behavior of the diagrid system have not been conducted sufficiently. Consequently, engineers have had to assign nonlinear properties to their analysis model using only brace element which has different role with diagrid members.

For tall buildings having diagrid system, it is expected that they will show low ductility against strong earthquake ground motions since the diagrid members are designed to receive high compression force as well as lateral force. In other words, it is necessary to carefully observe how the diagrid members behave under the combination of vertical and lateral loads and verify how the buckling occurrence due to the high compression which affects ductile capacity.

In this study, diagrid substructures designed based on 60-story diagrid frame prototype were tested by full-scale experiments. The experiment specimens were loaded both vertically and horizontally. This experimental study ultimately aimed to identify the relationship between ductility of diagrid members and size of vertical load. As a result of the experiment, it was proved that, as the vertical load increases, the diagrid member behaves more brittle due to its buckling.

[1]*Senior Engineer, Chang Minwoo Structural Consultants, Korea*
[2]**Presenter, General Manager, Chang Minwoo Structural Consultants, Korea*
[3]*President, Ph.D., PE, Chang Minwoo Structural Consultants, Korea*
[4]*Engineer, Chang Minwoo Structural Consultants, Korea*

RESPONSE-BASED PROBABILISTIC RISK ASSESSMENT OF NUCLEAR POWER PLANTS

Yin-Nan HUANG[1], Ying-Hsiu SHEN[2], Chang-Ching CHANG[3], and Ching-Ching YU[4]

SUMMARY

Seismic probabilistic risk assessment (SPRA) has been widely used to compute the core damage frequency of a nuclear power plant (NPP) and typically involves the use of component fragility curves defined as a function of ground-motion parameters, such as peak ground acceleration and spectral acceleration. In this study, seismic risk of a sample NPP is computed using a new SPRA methodology, where the component fragility curves are defined as a function of structural-response parameters, such as floor spectral acceelration. The results of risk computed using conventional and new SPRA methodologies are compared and the advantages and disadvantages of the new methodology are discussed.

Keywords: *nuclear power plant, seismic risk assessment, fragility, uncertainty*

INTRODUCTION

The United States Nuclear Regulatory Commission (USNRC) issued Supplement 4 to Generic Letter No. 88-20 (USNRC 1991) in 1991 requiring nuclear power plant utilities to perform an Individual Plant Examination of External Events (IPEEE) and also issued NUREG-1407 (Chen et al. 1991) to help guide the IPEEE. For an Individual Plant Examination (IPE) of seismic events, NUREG-1407 identified Seismic Probabilistic Risk Assessment (SPRA) as an acceptable methodology for the examination of earthquake-induced risks. SPRA provides a formal process in which the randomness and uncertainty in seismic input, structure response and material capacity is considered in the computation of risk. NUREG/CR-2300 (USNRC 1983) provides general guidance for performing SPRA for NPPs. The guideline describes two SPRA methods: (1) Zion and (2) the Seismic Safety Margin (SSM). The Zion method was first developed and applied in the Oyster Creek probabilistic risk assessment and later improved and applied in 1981 to estimate seismic risk for the Zion Plant (Pickard et al. 1981). The SSM method was developed in an NRC-funded project termed “the Seismic Safety Margin Research Program (SSMRP)” at the Lawrence Livermore National Laboratory (Smith et al. 1981).

Huang et al. (2011a, 2011b) proposed a SPRA methodology, which is based on the conventional methods described above and the new tools developed for the next-generation performance-based earthquake engineering (ATC 2012, Der Kiureghian 2005, Yang 2009). The method of Huang et al. differs in many regards from methods used to date for the probabilistic risk assessment of NPPs. Key differences include 1) the use of component fragility curves that are expressed in terms of structural responses (e.g., story drift and peak floor acceleration) and not on ground-motion intensity (e.g., peak ground acceleration), 2) the characterization of earthquake shaking using seismic hazard curves, and 3) procedures for both scaling earthquake ground motions and assessment of component damage.

[1] *Assistant Professor, National Taiwan University, Taiwan, e-mail: ynhuang@ntu.edu.tw*
[2] *Research Assistant, National Center for Research on Earthquake Engineering, Taiwan, e-mail: yhshen@ncree.narl.org.tw*
[3] *Assistant Researcher, National Center for Research on Earthquake Engineering, Taiwan, e-mail: ccchang@ncree.narl.org.tw*
[4] *Graduate Student, National Taiwan University, Taiwan, e-mail: r01521221@ntu.edu.tw*