CYCLIC PERFORMANCE OF SEISMIC STEEL PANEL SHEAR WALLS

Keh-Chyuan Tsai[1] and Ying-Cheng Lin [2]

ABSTRACT

An experimental test program on Steel Panel Shear Walls (SPSW) is outlined and some key test results are presented. A total of three specimens were tested in NCREE. All the specimens utilized low yield strength (LYS) steel for the infill panel and the reduced beam sections (RBS) at the ends of the beams. Two specimens constructed either with two or three horizontal steel tube restrainers on both sides of the infill panel. One specimen has infill solid panel but no restrainer. The purposes of the restrainers were to increase the shear buckling strength and result in more energy dissipation in LYP panel. Preliminary test results suggest that the buckling restrainers are effective in improving the energy dissipation capacity of the SPSWs. It effectively reduces the amplitude of the cyclic out-of-plane buckling of the thin steel infill panel and enhances the serviceability of the SPSW system during a severe earthquake.

Keywords: *buckling-delayed shear wall, low yield strength steel, shear buckling strength, buckling restrainer*

INTRODUCTION

The selection of steel plate shear walls (SPSWs) as the primary lateral force resisting system in buildings has increased in recent years as structural engineers recognize the benefits of this option. Traditional designs did not allow for utilization of the post-buckling strength of the plate. It primarily considered elastic and shear yield behavior only and often resulted in very thick plate sizes, and as a result, very stiff structures and therefore large accelerations during a seismic event. In addition, surrounding frame members often require additional strengthening to prevent mechanism formation resulted from the forces exerted by the panel at ultimate displacements.

Research in Canada (Thorburn et al. 1983) led to a new SPSW design philosophy that reduced plate thickness by allowing the occurrence of shear buckling. After buckling, lateral load is carried in the panel via the subsequently developed tension field. Smaller panel thicknesses also reduce forces on adjacent members, resulting in more efficient framing designs.

However, the panel thickness, using a typical material yield stress, required by a given design shear is often much thinner than plate actually available from steel mills. Attempts at alleviating this problem were recently addressed by the use of light-gauge, cold-formed steel panels, in a new application (Berman and Bruneau 2003). In the meantime, the University at Buffalo (UB) and the Multidisciplinary Center for Earthquake Engineering Research (MCEER) together with the National Center for Research on Earthquake Engineering (NCREE) and the National Taiwan University (NTU) initiated a co-operative experimental program in order to further address the above issues with regards to SPSW performance. Four specimens considering low yield strength steel and various schemes of openings were tested by pseudo-static cyclic loads at NCREE in 2003 (Vian et al. 2003).

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SHAKING TABLE TESTS OF RC WALL BUILDING MODELS HAVING BOTTOM SOFT STORIES

(Submitted for possible publication to ACI Structural Journal)

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SUMMARY

Three 1:12 scale 17-story RC wall building models having different types of irregularity at the bottom two stories were tested on the shaking table to observe the seismic responses of each model due to the corresponding irregularity. The first one has only a symmetrical moment-resisting frame (Model 1), the second has an infilled shear wall in the central frame (Model 2), and the third has an infilled shear wall in only one of the exterior frames (Model 3) at the bottom stories. These models were each subjected to the same series of simulated earthquake excitations.

The test results show the followings: 1) The existence of shear wall has almost a negligible effect on the amount of the maximum base shear and base overturning moment, but reduces remarkably the shear deformation at the lower frame. 2) As the earthquake intensity increases, the structures with symmetric plan experienced the shift of rotating axis (rocking behavior) due to the overturning moment. And 3) the torsional deformation is closely related to the axial deformation of the boundary column in shear wall through warping. The warping deformation due to torsion also influences the flexural behavior of shear wall at the bottom stories.

Keywords*: concrete, buildings, shaking table tests, irregularity, overturning moment, torsion.*

INTRODUCTION

Due to the severe shortage of, and for the effective use of the sites for new constructions in metropolitan areas in Korea, the multi-purpose buildings have been built frequently during the past decade. The most common structural system for the lower stories of these buildings has been the moment-resisting space frame since they usually accommodate the parking area, commercial space, gardens, or open spaces for architectural reasons. That for the upper stories is the bearing-wall system because these stories are generally used as apartments. These types of building structures, which are called piloti-type buildings in Korea, usually have the irregularity of weak story and/or torsion since many upper bearing walls discontinue at the lower stories.

The objective of the study stated herein is to investigate, experimentally, the seismic performance of high-rise RC bearing-wall structures having irregularity of weak story and/or torsion at the bottom stories.

RESEARCH SIGNIFICANCE

Structural irregularity at the bottom stories of high-rise RC wall buildings may induce an extremely complex phenomenon at these stories. This study is one of the first experimental researches on three-dimensional high-rise RC wall buildings with irregularity at the bottom stories based on the shaking table tests. Test results were analyzed from the view points as follows: 1) effects of the existence and location of an infilled shear wall, 2) resistance mechanism of OTM, and 3) interaction between base shear, OTM, and torsion in the torsionally

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A STUDY ON THE SEISMIC FORCE RESISTING MECHANISM OF A MULTI-STORY SHEAR WALL SYSTEM CONSIDERING THE INTERACTION BETWEEN

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This paper was submitted to the 13th World Conference on Earthquake Engineering (13WCEE) held in Vancouver, Canada, from August 1 - 6, 2004.

SUMMARY

Two 1/5 scale specimens were designed and constructed as basic structural assemblage models extracted from a practical six-story shear wall system. Those specimens consisted of a bottom two-story part of the shear wall system, a foundation beam, slabs, and two piles. Static lateral load was applied with proportionally varying vertical load to simulate loading conditions of the prototype six-story shear wall system under earthquakes.
The foundation beam resisted by itself and the contribution from the piles and shear wall was less than expected. This caused unexpected shear cracking to spread extensively over the foundation beam. However, longitudinal bars in slabs worked together with the upper longitudinal reinforcement in the foundation beam. Transition of shear transfer mechanisms at the shear wall base was observed from the strain distribution of longitudinal reinforcement in foundation beams and those strain distributions of different loading stage were predicted accurately. The lateral load–drift relations obtained experimentally was simulated well with a simple superposition of flexure and shear elements.

Keywords*: shear wall; foundation beam; pile; interaction;*

INTRODUCTION

In current design procedures [1][2], cantilever structural walls are normally assumed to stand on a solid foundation, and the foundation beams, slabs and piles are designed separately without considering their interactions. This is because their interactions have not been thoroughly studied for its complexity. Also neglected in the practical design is the fact that shear transfer mechanisms along the wall base vary depending on the crack patters and inelastic deformation levels at the shear wall base. This study aims to experimentally clarify the variation of the lateral load resisting mechanisms considering the interaction between a shear wall, foundation beams, slabs and piles, and to establish more rational design procedures for each structural component.
In the experimental program, the specimen configuration was determined from typical six story residential buildings in Japan. They normally have multiple spans of a RC moment resisting frame in the longitudinal direction and a single span of shear wall system in the transverse direction. In this study, the assemblage consisting of the lowest two floors of shear wall with a foundation beam, the first floor slab, and two piles in the transverse direction was scaled to 1/5 to make model specimens. The shear wall was designed to fail in flexure

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PUSHOVER TEST OF MULTISTORY BUILDING STRUCTURES USING PARTIAL SPECIMEN

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SUMMARY

Pushover tests may be conducted to investigate seismic performance of multistory building structures subjected to earthquake loads. The test may be conducted using partial specimen when the test specimen is too large to perform the prototype test. The test on a partial specimen is expected to represent the behavior of the original structure. The behavior of a structure are governed mainly by story shear forces and overturning moments. If the loads are applied to the specimen in such a manner that would result in the same shear forces and overturning moments as those of the original structure, the member forces would be close to those in the original structure, in the case of shear wall structures. However, in the case of framed structures, member forces in partial specimen may deviate from those of original structure. An improved method to obtain the same member forces in the specimen as those of the original structure is proposed in this study.

Keywords: *pushover test; partial test frame; multistory building structure.*

INTRODUCTION

Various testing methods such as shaking table test, pseudo dynamic test, and pushover test have been used, in order to experimentally investigate the dynamic characteristics of structures subjected to earthquake ground motion. Although shaking table test may most accurately represent the effects of seismic loads on a structure, expensive testing equipments are required to apply seismic loads using a shaking table and the testing time may be too short to observe the structural response in detail and the size of specimen is restricted to small scale for a large structure (Molina 1999). To solve these problems, quasi-static testing method such as cyclic loading test, pseudo dynamic test and pushover test which reproduce the dynamic effects by the static forces have been employed by many researchers (Donea 1996, Lin 204). The quasi-static test is performed to reproduce the inelastic behaviors induced by severe earthquakes and identify the failure modes of structures. Quasi-static tests are generally conducted using a small-scale model or partial specimen (Lee 1990, Seible 1994) when it is very difficult to perform quasi-static test using full-scale model for large structures (Molina 1999, Donea 1996). Inelastic deformations are generally concentrated in lower parts of high-rise buildings subjected to a severe earthquake ground motion. Since the inelastic deformation in structural members is critical for seismic performance of a structure, tests can be performed using the partial specimen prepared only for the lower stories of a multi-story building structure.

For the test using a partial specimen, it is necessary to produce the same member forces in the partial specimen as those of the original structure. The original structure and the partial specimen may have the same stress distribution if their overturning moment, axial force and shear force in each level are the same in the case of shear wall structures. The overturning moment and story shear force in each story are resisted by the axial force and shear force in columns, respectively, when a framed structure has rigid beams. However, the bending moments in columns and beams are influenced by the reduction in column axial forces due to the flexural deformation of beams in multi-story building frames. Therefore, the member forces in a partial specimen may be

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DYNAMIC GRAVITY LOAD COLLAPSE EXPERIMENTS OF LOW-DUCTILITY RC COLUMNS AND PRELIMINARY NUMERICAL SIMULATOIN

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A major part of this paper has been presented in the International Conference in Commemoration of 5th Anniversary of the Chi-Chi Taiwan Earthquake, 2004.

SUMMARY

During the September 21 (local time) 1999 Chi-Chi Taiwan earthquake, a large number of older buildings built before 1982 sustained severe damage and many others suffered from complete failure. These old buildings, having low ductility RC columns, are known to have poor seismic performance in terms of ductility and energy dissipation capacity during severe seismic events. Therefore, it is the main concerns of structural engineers and, at the same time, benefit of building owners how to retrofit these old buildings to match more strict requirements of the next generation building code to get better odds to survive probable future earthquake events. To reach this goal, dynamic nonlinear behaviors of these low ductility columns must be first thoroughly studied. Shake table tests using near-fault input motions, therefore, were conducted to yield experimental data on structural post-peak behaviors involved in global collapse mechanism. Preliminary numerical simulation using fiber section models is conducted and presented here. In addition, image processing technique was employed in this study to monitor large displacement of the specimen.

Keywords: *Low ductility RC columns, collapse mechanism, numerical simulation, image processing*

INTRODUCTION

While considerable advances have been made in the use of analytical and/or numerical methods to evaluate seismic performance of civil structures, recently there is a clear trend that more RC collapse experiments are being conducted or planned worldwide to gain more knowledge on failure mechanism in view that the fundamental characteristics of structural collapse are not easily amenable to an analytical/numerical treatment at the present stage. On the other hand, older buildings built before 1982 in Taiwan are known to have poor seismic performance in terms of ductility and energy dissipation capacity during severe seismic events. During the September 21 (local time) 1999 Chi-Chi Taiwan earthquake, a large number of older buildings sustained severe damage and many others suffered from complete failure. Shake table tests, therefore, were conducted in this paper to study low-ductility collapse of old RC columns due to poor detailing. On the other hand, shake table test results will be very helpful in validating numerical hysteretic models with consideration of post-peak behaviors, and determining key parameter values of such models. Although not many, a few collapse experiments had been conducted to this date. Among those are gravity load collapse of ½-scale RC frames by Elwood (2002), small-scale steel frame tests by Vian et al. (2003), and others (Kim and Kabeyasawa, 2004, etc.) This type of instrumented observation of dynamic collapse helps gain further insight into dynamic stability problems. During our tests, digital camcorders were used to record the progress of structural collapse; displacement histories were obtained through both LVDTs and image processing technique, the latter of which was shown very helpful when

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SHEAR STRENGTH DETERIORATION OF REINFORCED CONCRETE MEMBERS SUBJECTED TO CYCLIC LOADING

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SUMMARY

The behavior of reinforced concrete (RC) members dominated by shear action, such as coupling beams, reveals a dramatic reduction of energy dissipation in the hysteretic response due to the severe pinching effects. The behavior of these beams was governed by shear force because of their relatively short-span-to-depth ratios. The research reported in this paper presents a method to predict the ductility of RC members with short-span-to-depth-ratios failing in shear after flexural yielding. The proposed method takes into account shear deterioration due to the degradation of the diagonally compressed concrete in the post yield range. The shear ductilities of RC test members, reported in the technical literature with variable shear span-to-depth ratios and different compressive strengths of concrete, were compared to the shear ductilities as given by the equation reported in this paper.

Keywords*: shear strength deterioration; ductile capacity; compatibility aided truss model; reinforced concrete members.*

INTRODUCTION

To design earthquake-resistant shear-dominated reinforced concrete (RC) beams, it is necessary to know not only the shear strength but also the ductility of these members. The usual earthquake resistant design philosophy of ductile frame buildings allows the beams to form plastic hinges adjacent to beam-column connections. In order to carry out this design philosophy, the ultimate shear strength of the beam should be greater than the flexural yielding force and should not degrade before reaching its required ductility. The behavior of RC members dominated by shear action, such as coupling beams, reveals a dramatic reduction of energy dissipation in the hysteretic response due to the severe pinching effects. After flexural yielding, plastic hinges develop near both ends of these beams, followed by yielding of the shear reinforcement and crushing of the diagonal compressive concrete struts in the plastic hinge regions, which leads to a sudden failure of the beam. The energy dissipation of these beams are relatively small due to the severe pinching effects when compared to the energy dissipation of a similar beam with a larger span-to-depth-ratio. Thus the design of RC beams with short-span-to-depth ratios under reversed cyclic loadings necessitates the prediction of not only the shear strength after flexural yielding but also the corresponding ductility of such structural members.

ACI (2002) code places a priority in the prediction of the shear strengths of RC members and indirectly allows for the ductile capacity by providing some conservatism in the calculation of the shear strength of the concrete. Recently, a shear design guideline (1990) was proposed by AIJ. This guideline evaluates the shear strengths of RC members by combining the shear contribution of the steel reinforcement by considering a truss mechanism to the concrete contribution considering an arch mechanism based on the lower bound plastic theory. Furthermore, the ductile capacity is accounted for by limiting the inclination of the concrete strut in the truss model and imposing deterioration in the effective compressive strength of the cracked concrete. Furthermore some

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ESTIMATION OF RESTORING FORCE CHARACTERISTICS IN THE INTERIOR BEAM-AND-COLUMN SUBASSEMBLAGES OF R/C FRAMES

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SUMMARY

The objectives of this study were to investigate seismic behavior and to estimate restoring force characteristics of interior beam-and-column subassemblages using normal-to high-strength materials. At first, cyclic loading tests on sixteen half-scale interior beam-and-column subassemblages using high-strength materials were carried out to investigate their seismic behavior. Secondly, multiple regression analysis, taking the various factors into account, was carried to estimate the restoring force characteristics of subassemblages. In the multiple regression analysis, the test data of this study and authors' previous work using normal-strength materials were used.

The following statements can be made from this study;

(1)The anchorage capacity of beam longitudinal bars passing through the interior beam-column joint affects the energy absorption of a frame.

(2)The plastic deformation performance of subassemblages of a beam yielding frame is greatly effected by the joint input shear force level and the amount and strength joint shear reinforcement.

(3) A method to estimate restoring force characteristics of the subassemblages that takes the above effects into account was developed. Even under various conditions, the calculated results by proposed method accurately almost predicted the ductility performances and hysteresis characteristics measured in the test subassemblages using normal-to high-strength materials.

***Keywords**: R/C frame; restoring force characteristic; ductility performance; estimation; normal-to high-strength material; interior beam-and-column subassemblage.*

INTRODUCTION

To estimate the seismic behavior of the RC ductile moment-resisting frame, it is important to clarify the effect of the anchorage performance of beam longitudinal bars passing through the interior beam-column joint and the joint shear stress level on restoring force characteristics of the frame (Leon 1988, Kaku et al. 1991).

The main objectives of this study were to investigate seismic behavior and to estimate restoring force characteristics of interior beam-and-column subassemblages using normal-to high-strength materials. At first, sixteen half-scale cyclic loading tests on interior beam-and-column subassemblages using high-strength materials were carried out to investigate their seismic behavior. Secondly, multiple regression analysis, taking the various factors into account, was carried to estimate the restoring force characteristics of subassemblages. In the multiple regression analysis, the test data of this study and authors' previous work using normal-strength materials were used. A part of this research is already published (Teraoka et al. 1992, 1998).

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DEFORMABILITY of NON-FLEXURAL MEMBERS♦

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SUMMARY

The estimation of deformation capacity of non-flexural reinforced concrete members is proposed using the basic concepts of limit analysis and the virtual work method. This new approach starts with construction of an admissible stress field used as equilibrium set for the virtual work equation. Failure mechanisms compatible with admissible stress fields are used as displacement sets for the equation of virtual work. It is assumed that the ultimate deformations resulting from selected failure mechanisms are controlled by ultimate strain of concrete in compression. The derived formula for deformability of deep beams in shear shows reasonable range of ultimate displacement.

Keywords: *Shear; Required deformation; Bending mechanism; Translational mechanism; Rotational mechanism; Hyperbolic curve.*

INTRODUCTION

Limit analysis methods in the framework of the theory of plasticity have been applied to engineering problems for a long time. Development of efficient methods to obtain the ultimate load of structural problem in a simple and more direct manner without recourse to an iterative and incremental analysis is of great value to practicing engineers. In particular, methods of limit analysis provide a uniform basis for the ultimate state design of concrete structures [1, 2, 3].

Methods for constructing discontinuous stress fields in equilibrium which does not violate the yield condition have been developed for dimensioning of reinforced concrete structures. Especially, strut-and-tie models have been successfully used for detailing of disturbed regions (D-regions) of reinforced concrete structures since these models show explainable force flows within D-regions [4, 5, 6, 7]. These models are based on the limit theorem within the theory of plasticity and give us lower bounds of strengths. In other words strut-and-tie models provide static systems at ultimate state.

Currently performance-based design (PBD) methods require not only strength prediction but also deformation capacity [8, 9]. Deformability of non-flexural members is controlled by strain limit of primary force transfer components. Recently many of research have focused on topics on deformability for implementation of PBD. The prediction of deformation demands imposed on reinforced concrete members by severe loading condition has been one of important issues. A rational evaluation of deformation capacities with elastic and post-elastic response, satisfying specified performance criteria, should enable acceptable deformation demand to be more established. To allow deformation capacity to be realistically estimated a simple, direct, and easily qualified methodology should be proposed with some definition of materials. One of rational methods for deformation capacity evaluation is a mechanism-based approach which is based on limit analysis. For torsional behavior of building structures of shear wall structures a mechanism based approach proposed by Paulay showed a clear, rational method of estimation of system ductility [10, 11]. For given ductility limits of elementary components with governing failure modes, the limit of ductility of system is obtained. This concept can be extended to other

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SEISMIC EVALUATION OF EXISTING REINFORCED CONCRETE BUILDING －SHAKING TABLE TESTS AND PUSHOVER ANALYSIS

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SUMMARY

In the 1999 Chi-Chi Taiwan earthquake, significant amounts of low-rise reinforced concrete buildings in Taiwan damaged in a common failure mode of weak-column and strong-beam. It is due to underestimations in the past design methodology which considered a building as a moment-resisting frame without partition walls and floor slabs. According to the post-earthquake reconnaissance of 1999 Chi-Chi Taiwan earthquake, a simplified nonlinear static pushover analysis is proposed to evaluate low-rise reinforced concrete buildings in which the capacity of an existing building is estimated by superposing the load-displacement response of vertical members in the damage story. Shaking table tests of two three-story 2:5 reduced scale model buildings were conducted to observe the behaviors of low-rise building frames with or without lightly reinforced concrete walls. Although both two model buildings were designed as ductile moment-resisting frames, the expected beam-sway mechanisms did not develop. In contrast, the high rigidity of the floor slabs restrained the girder deformation and led to a column-sway mechanism at the ground floor of the model buildings. The test values are compared to the proposed pushover analysis. Good agreement is found in the predictions of ultimate strengths, displacements, and failure modes.

Keywords*: seismic evaluation; reinforced concrete; pushover analysis; shaking table test.*

INTRODUCTION

Since the 1960s, it has been well-accepted in earthquake engineering that a building is not necessary to remain elastic under intense ground motion. In general, the tenets of the modern seismic design philosophy are to provide a safe structure, to limit damage in small/frequent earthquakes, and to allow ductile/inelastic response to reduce construction costs. In the design of new buildings, these goals are generally achieved by: (a) selecting a desirable controlling behavior, (b) providing well-through-out detailing to promote ductile response, and (c) carefully controlling material properties. However, the practitioners could not apply the seismic design philosophy to evaluate and rehabilitate existing buildings because the materials, detailing, and controlling behaviors of existing concrete buildings often violate rules of modern seismic-resistance design. It should be noted that: (1) Elements with undesirable controlling modes of behavior may not be able to survive cyclic/inelastic demands. (2) The existing detailing may not provide adequate confinement, ductility, or reliable reserve gravity capacity. (3) The properties of the existing materials may not be known if test results and/or drawings do not exist.

The criteria for seismic evaluations and rehabilitations are generally based on post-earthquake reconnaissance, laboratory testing, and structural analysis. Post-earthquake reconnaissance is an important source of information that leads to better designs for seismic resistance. However, the seismic hazard, soil conditions, construction

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AN EXPERT SYSTEM FOR PRELIMINARY ASEISMIC CAPACITY ESTIMATION OF TRADITIONAL SCHOOL CLASSROOM BUILDINGS USING CASE-BASED REASONING*

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SUMMARY

This paper presents the development of an expert system for preliminary aseismic capacity assessment of traditional school classroom buildings in Taiwan. First, characteristics in the modeling of school classroom buildings are parameterized, and an automatic process is developed for detailed aseismic capacity assessment of parametric school building cases. Making full utilization of a large amount of often-idle computer CPU cycles, this research develops an automatic process to construct a large case base containing detailed aseismic capacity estimation results of various numerically simulated school building cases. Based on the case base constructed, the proposed expert system employs a case-based reasoning technique to estimate the aseismic capacity of school classroom buildings in terms of the building's collapse ground acceleration in a quick and reasonably accurate fashion.

Keywords*: Numerically simulated case base; Case-based reasoning; Expert system; Preliminary aseismic capacity assessment of buildings.*

1. INTRODUCTION

The structural safety of a school classroom building is very important because it usually serves as the temporary shelter after severe natural disasters. After the 1999 Chi-Chi earthquake collapsed many school classroom buildings in the central Taiwan, there has been a great concern on the aseismic capacities of all school classroom buildings in the country. Due to the fact that it would require remarkable work, time, and budget to perform detailed aseismic capacity assessment on large amount of traditional school classroom buildings in Taiwan, a form-based preliminary seismic safety assessment through visual inspection, such as the one proposed by Chern et al. (2000), is usually employed to get quick and rough assessments on the buildings. Then, only buildings still in question of danger are further investigated by detailed aseismic capacity assessment. Currently in Taiwan, the Strength Ductility Method (SDM) (Ho et al., 1999) is the most popular detailed aseismic capacity assessment method. In this method, a building model is first constructed and a linear elastic analysis is performed with 0.1g earthquake input by a building analysis computer program, such as ETABS (Habibullah, 1994). The member forces computed by the computer program are then used to estimate the ultimate capacity of the beams, columns, and joints. Next, each floor's collapse ground acceleration is estimated. The smallest value of collapse ground acceleration among all floors is usually denoted as Ac and used as an indicator for the building's aseismic capacity. The greater the value of a building's Ac is, the greater the building's aseismic capacity is. Furthermore, the seismic safety condition of a building can be determined by comparing the value of the building's Ac with that of its required design ground acceleration.

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* Some preliminary results of the research work presented here have been published in Wang H. C., and S. H. Hsieh (2003). "On Development of a Computer System for Preliminary Aseismic Capacity Estimation of School Classroom Buildings Using Case-Based Reasoning," *Proceedings of IASS-APCS 2003 International Symposium on New Perspectives for Shell and Spatial Structures*, Taipei, Taiwan, October 22-26, 2003 [in CD format].

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REAL TIME CONTROL PERFORMANCE VERIFICATION OF A COMMUNICATION TOWER

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SUMMARY

In view of broadening application of active control devices on modern civil engineering infrastructures, verification of active control algorithms prior to real implementation has always been a time-consuming and costly process. At the minimum, they need to be examined through analytical simulation. Laboratory testing using a scaled-down model on a shaking table or in a wind tunnel is another possible option. The investment in experimental hardware and inherent inaccuracies in experimental set-up or modeling can be a major obstacle in structural control implementation. In this paper, an alternative real-time verification procedure via a simulator is addressed. Based on proposed procedures, the control strategy is implemented inside a dedicated PC controller with an independent Digital Signal Processor (DSP) to calculate the required control force. The DSP performs the function of data acquisition through communication with an Analog to Digital Converter (A/D) and a Digital to Analog Converter (D/A). Another PC structural simulator with a similar dedicated hardware is constructed to emulate the real time response of a communication tower installed with an Active Mass Damper (AMD) in order to verify the real time control effect. A sixteen degree-of-freedom (DOF) lumped-mass model based on the tower identified structural parameters is constructed inside the real time structural simulator. The integrated system is dedicated to verify the effectiveness of the proposed digital control algorithm and to provide also a pre-implementation testing base to test the functions required for practical utilization.

Keywords*: active structural control; real time structural simulator; discrete-time control; output feedback; system integration.*

INTRODUCTION

The hardware function of an active control system can be represented by the block diagram in Fig. 1. The response of a structure under external excitation, the active device status, the remote control status, and the fail-safe monitoring status of Active Control Force Generation System are measured by sensors and then sent to a Custom-Designed Signal Interface System. When some high frequency components are significant, an appropriate analog low-pass filter should be applied to filter out the effects of unmodeled dynamics in the measured responses, and minimize the possibility of instabilities when the controller responds to these responses. However, this also introduces a time lag in the feedback loop, which must be accounted for in practical implementation. The required information is filtered and collected and sent to a Digital Control System, which is usually implemented using a Data Acquisition/Conversion System located in the expansion slots of personal computer. The required control forces are calculated by Control Command Calculator and send to the force generator ACFGS through the interface CDSIS. The core of an active control system is the control software that generates the appropriate control command signals. The required knowledge for programming issues such as access to the hardware, analog I/O, fixed- and floating- point arithmetic, saturating, fixed- and floating- point scaling, error detection and correction, and communication interface must be considered and clearly understood before real implementation (Åstrom and Wittenmark 1997; Franklin, et al. 1990). More detailed illustrations are

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FULL-SCALE TESTS FOR SEISMIC PERFORMANCE VERIFICATION OF STEEL BUILDING STRUCTURES WITH KNEE BRACE DAMPERS

Keiichiro SUITA[1], Kazuo INOUE[2], Yuji KOETAKA[3], Masakazu ANDO[4], and Yasuki BYAKUNO[5]

SUMMARY

This paper presents an innovative structural system, named weld-free system, developed to overcome the difficulty in quality assurance encountered in construction of steel moment resisting frames with conventional welded connections. The proposed structural system adopts a mechanical joint equipped with knee brace damper, which can be classified as a kind of buckling restrained braces. An experimental verification was conducted on a full-scale three-story weld-free building structure. The primary objective is to verify the constructability, seismic performance, and collapse mechanism of weld-free structures under bilateral loading. The test clearly reveals the efficiency of the weld-free system in enhancing large and stable hysteresis loops, while beams and columns above the base can be proportioned to remain elastic under the design earthquakes.

Keywords: *weld-free steel structure, buckling restrained knee brace, hysteretic damper, full-scale frame, loading test*

INTRODUCTION

Steel structure has long been the most popular in construction of commercial buildings in Japan with the vast majority of low-rise constructions. During the 1995 Hyogoken-Nanbu earthquake, a large number of steel buildings sustained severe damage or even collapsed, notably for low-rise structures (*Reconnaissance,* 1995; Nakashima et al., 1998). One of the most serious damage appeared to be cracks and brittle fracture at welded beam-to-column connections. The damage was inevitable for old steel structures having non-ductile connection details. Damage was also observed in relatively new buildings designed in accordance with the Japanese seismic codes. Similar to the observation in the U.S. 1994 Northridge earthquake (Youssef et al., 1995), the location where premature fractures initiated was typically in the vicinity of the weld between the beam flange and the column flange.

To assure sufficient plastic deformation capacity of welded beam-to-column connections, several attempts have been made in the U.S. and Japan. After extensive investigations, the reduced beam section design (*Recommended,* 2000) has been widely accepted in the U.S. as an effective and economic solution. On the contrary, based on the observation that cracks often initiated at the toe of the weld access hole, Japanese researchers placed more emphasis on connection details to mitigate stress concentrations at welds and finally adopted the connection without weld access hole as an alternative for building construction (*Technical,* 1996). Although these modified connections have shown satisfactory performance in laboratory, it is realized that the quality of welds is difficult to control in practice as long as the structural fabrication relies on workmanship. A recent survey of experimental data of beam-column subassemblies (*Report,* 2000) has confirmed some degree of uncertainty in the quality assurance of welds. Of 339 test specimens reviewed, 30 specimens exhibited premature fracture at welded metals as a result of weld defects. The defects as well as insufficient deposition are often of

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EXPERIMENTAL STUDY ON THE PERFORMANCE OF THE ROTATIONAL FRICTION DAMPER SYSTEM

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SUMMARY

The control performance of the rotational friction damper system (RFDS) including brace is evaluated using system identification technique. Shaking table test of a small scale 3-story building model with RFDS is conducted and the modal shapes, natural frequencies and damping ratios are identified. From these identified modal properties, structural model composed of mass, damping and stiffness matrices is constructed, and the increment of the stiffness and damping by the RFDS is estimated for various friction moment levels. Finally, experimentally obtained results are compared with ones predicted by the equivalent linear system theory.

***Keywords**: rotational friction damper; system identification; equivalent linearization.*

INTRODUCTION

Various damping devices have been developed and widely applied to the control of seismically induced responses of civil engineering structures (Soong and Dargush 1997). According to the force characteristics, the damping devices are classified as velocity-dependent ones and displacement-dependent ones. Displacement-dependent damping devices reduce the structural response using the energy dissipation resulting from hysteretic behavior. Friction damper, one of the displacement dependent damping devices, has advantages that its energy dissipation mechanism is simple and manufacturing and installation are relatively easy. Also, it was experimentally verified that commonly used friction damper showed stable hysteretic behavior under cyclic loads. The performance of friction damper is strongly dependent on the property of material consisting of friction surface and the maximum friction force can be easily modulated by changing the magnitude of normal clamping force applied to the friction surface. Also, this clamping force is linearly proportional to the torque applied to the bolt. Consequently, the desired maximum friction force can be accurately realized simply by adjusting the torque to a certain value. Also, the installation mechanisms for friction damper have been investigated so as to prevent the buckling of bracing system, which is one of important problems for practical application of friction dampers (Filiatrault and Cherry 1990, Mualla and Belev 2002). However, since friction damper has severely nonlinear force-displacement relationship, its design and analysis of the structure with friction dampers become complicated. In order to solve this problem, equivalent linear system substituting equivalent linear stiffness or damping for the effect of friction damper has been studied.

Friction damper under stochastic loads such as earthquakes or winds shows the alternating occurrence of sip and lock of friction surface. In the slip stage, structural energy is dissipated to increase the damping of entire structure. Otherwise, in the lock stage, only the stiffness of structure is increased by the addition of the stiffness of bracing system. It depends on the relative magnitude of excitation and slip load of friction damper which stage governs the behavior of friction damper. These two effects can be assessed only statistically because the earthquake load which a structure will undergo is given statistically and the equivalent linear system for friction damper should consider this statistical characteristic of structure with friction damper.

In this study, the equivalent stiffness and damping of rotational friction damper system (RFDS) are evaluated using two linearization techniques based on the results from shaking table test of 3 storey building structure with RFDS. First, model updating of structural stiffness and damping matrices based on the system identification result obtained from transfer function is applied. Transfer function provides the statistical dynamic characteristics of structure because it uses averaging procedure in order to remove noise. Second, probability density function (PDF) of peak response, which includes the statistical information on structural response under uncertain dynamic loads is used so as to obtain mean secant stiffness and the magnitude of energy dissipation

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A DESIGN METHOD FOR FLEXURAL STRENGTH AND CURVATURE DUCTILITY OF SRC BEAM SECTIONS

Cheng-Cheng Chen[1] and Chao-Lin Cheng[2]

SUMMARY

A design method, which fulfills the assumption of plane section remains plane, was developed for flexural strength of steel reinforced concrete (SRC) beam sections. In addition, the proposed design method enable the designer to design beam sections for selected curvature ductility ratio, and, consequently, to acquire better control of concrete spalling during major earthquakes. From the aspect of performance based design, the proposed design method can facilitate beam design for concrete spalling limit state. With the same strength and ductility demand, the sections designed by the proposed method are more economical then the sections designed based on superposition method. More over, a simplified method, which can be used to evaluate the flexural strength of SRC beam sections without iteration procedure, was also developed with plastic stress distribution of the section. And, it is found in this study that the curvature ductility ratio of SRC beam sections is closely related to the position of neutral axis.

***Keywords**: SEEBUS; SRC construction; composite construction; beam design method.*

INTRODUCTION

A steel reinforced concrete (or SRC) section is composed of concrete, steel shape, longitudinal steel bars, and transverse steel bars. Fig. 1a shows a typical SRC beam section. This type of construction is developed mainly in Japan and is used more often in Taiwan recently. Japan and Taiwan use the method of superposition to evaluate the flexural strength of SRC beam sections, and, Fig. 2a shows the stress distribution of the sections. Japanese specifications use working stress method to design SRC beam sections for bending moment. While Taiwanese specifications use the method of superposition along with plastic stress distribution of the section to design SCR beam sections. These design methods neglect the composite effect of the section, which is likely to result in uneconomical design.

Previous research (Chen & Chen, 2001) shows that SRC beams, when horizontal shear failure is excluded, basically remain fully composite up to the flexural strength of the section is developed. Fig. 3 shows a typical strain distribution of a series of beam specimen tests (Chen & Chen, 2001). It is concluded that fully composite (or single neutral axis) is a more reasonable assumption for the calculation of flexural strength and curvature ductility for SRC beam sections.

RELATIONSHIP BETWEEN THE CURVATURE DUCTILITY RATIO AND THE POSITION OF NEUTURAL AXIS FOR SRC BEAMS

A total number of 135 SRC beams sections were analyzed using a commercial program named XTRACT to

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PREDICTION OF LATERAL CAPACITY OF CONCRETE-FILLED CARBON COMPOSITE COLUMNS

Hong, Won-Kee[1], Dong-Hyeok Kim[2]

SUMMARY

Full scale concrete-filled carbon composite columns without longitudinal and transverse reinforcing steels are tested to investigate the lateral behavior of columns confined with carbon composite tube. In the present study, the full-scale circular and square concrete-filled carbon composite tubes (CFCT) with various winding angle with respect to longitudinal axis of tube are subjected to lateral loads under constant axial load. The influence of thickness and winding angle of carbon tube on the lateral behavior of concrete columns is studied both experimentally and analytically, demonstrating the calculated ultimate moment capacity of confined columns compares well with test data. For this analytical process, stress-strain relationships of confined concrete columns uncovered by the authors are used to identify the distribution of confined compressive concrete strength at failure. This stress-strain model considers the influence of winding orientation of carbon fibers on the confining capability of concrete core.

Keywords: *carbon composite; lateral capacity of confined column; strength; filament winding.*

INTRODUCTION

This paper recognizes that the development of winding technique to manufacture carbon tubes and its application in infrastructure are gaining considerable interests from engineering sector recently. The concrete-filled carbon tube designed to replace or supplement conventional reinforcing steel also provides many advantages including outstanding confining capability and durability under seismic loadings. Concrete-filled carbon tube improves moment capacity by both its high tensile strength and increased compressive strength of confined concrete core. Concrete core also keeps concrete-filled carbon tube from buckling. The predominant advantage of utilizing carbon composite tubes is to choose fiber orientation and lamination sequence to effectively resist stresses caused by seismic loadings. This research also performs to investigate the influence of fiber orientation and lamination sequence on the lateral load resisting capacity of concrete-filled carbon tubes through the experiment program of carbon composite tubes manufactured with fiber orientation of various winding angle. Full scale concrete-filled carbon composite columns with no longitudinal and transverse reinforcing steels are evaluated experimentally under simulated seismic excitation. The conventional concrete columns with maximum reinforcement are also tested to be compared with the performance of the concrete-filled carbon tube columns. Easy and fast application of this innovative technique to the construction of new structures requires development of comprehensive design methodology since the conventional design procedure cannot be used for the design of concrete-filled carbon tubes. The precise identification of compressive strength of concrete core and tensile strength of carbon tube constitutes important basis for the analytical estimation of lateral load resisting capacity. In this paper, the compressive strength of confined concrete core at failure determined from the realistic stress-strain relationships of carbon tube-encased concrete columns is incorporated into the conventional concrete column design procedure to estimate the flexural moment capacity of this innovative structural system. The test results help engineers select proper carbon tube with fiber orientation and thickness for the most economical and efficient solutions.

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EXPERIMENTAL INVESTGATIONS ON AXIAL BEHAVIOR OF LARGE-SCALE CONCRETE COLUMNS CONFINED BY CARBON COMPOSITE TUBES

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SUMMARY

Both the experimental and analytical investigations of axial behavior of large-scale circular and square concrete columns confined by carbon composite tube are presented in this study. The specimens are filament-wound carbon composite with different winding angles with respect to longitudinal axis of tube. The instrumented large-scale concrete-filled composite tubes (CFCT) are subjected to monotonic axial loads exerted by 10000KN MTS. The influence of transverse dilation, winding angle, thickness of tube as well as shape of the column section on stress-strain relationships of the confined columns is identified and discussed. Proposed equations to predict both the strength and ductility of confined columns by carbon composite tube demonstrate good correlation with test data obtained from large-scale specimens.

Keywords: *carbon composites, glass fibers, strength, filament winding*

INTRODUCTION

Behavior of FRP-confined concrete was studied by Nanni and Bradford(1995), suggesting that bilinear curve with a transition zone at a strain of about 0.003 can be used to model the FRP-confined concrete. The columns retrofitted by wrapping and bonding of fiber-reinforced plastic(FRP) sheets showed no damage against the 1994 Northridge earthquake (Loud, (1995)). The concrete-filled glass FRP tube was the next application for better axial performances of columns by Mirmiran and Shahawy(1995). Mirmiran and Shahawy(1997) carried out uniaxial compression tests on concrete-filled FRP tubes with findings that fiber composites are effective way of confining columns, providing strength, ductility, and large energy absorption capacity. In their study experiment on a total of thirty 152.5x305mm cylindrical specimen which was filament-wound of E-glass at $\pm 75°$ angle was presented to show a unique characteristic of confinement with E-FRP. Mirmiran(1998) also investigated the effect of column parameters such as shape, length, and bond on FRP-confined concrete.

Effect of length to diameter ratio on the confinement of columns was studied in this effort. Saafi et al.(1999) performed experimental and analytical study of concrete columns confined by carbon and glass FRP composite tube. They proposed equations to predict the compressive strength, failure strain and the entire stress-strain curve of concrete-filled FRP tube. Another important work with regard to the confinement of reinforced concrete columns with fiber-reinforced composite sheets was presented by the K.W. Neale and M. Demers. K.W. Neale also dealt with effective way to strengthening reinforced concrete structures with externally-bonded fiber reinforced polymers at Design Guidelines Manual 4. In his paper, the influence of parameters including concrete strength, longitudinal steel reinforcement, steel stirrups, steel corrosion, and concrete damage on the structural behavior of the confined concrete columns was investigated.

Studies with regards to the confining effects of carbon composite tube are necessary since it is recognized that

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SEISMIC RESPONSE SPECTRA CONSIDERING THE EFFECT OF THE NONLINEARITY OF THE SOFT SOIL

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SUMMARY

Elastic or inelastic seismic analysis of a structure are necessary in the weak or strong seismic area due to the nonlinear behavior of a soft underlying soil, and the importance of the performance based design considering the structure-soil interaction is recognized for the reasonable seismic design. In this study, elastic and inelastic seismic response analyses of a single degree of freedom system on the soft soil layer were performed considering the nonlinearity of the soil for 11 weak or moderate earthquakes scaled to the nominal peak acceleration of 0.075g, 0.15g and 0.2g, and 5 strong ones scaled to the nominal peak acceleration of 0.3g. Seismic response analyses for the structure-soil system were performed in one step applying the earthquake motions to the bedrock in the frequency domain, using a pseudo 3-D dynamic analysis software of P3DASS. Study results indicate that it is necessary to consider the nonlinear soil effects and to perform the performance based seismic design for the actual soil conditions rather than to follow the routine procedures specified in the seismic design codes, and they are compared with the response spectra of IBC2003. Nonlinearity of the soft soil layer excited even with the weak earthquakes affects significantly on the elastic and inelastic responses of a structure due to the soil amplification of the earthquake motions and structure-soil interaction, and it was pronounced especially for the elastic ones.

Keywords: *inelastic, structure-soil interaction, nonlinear soil, performance based seismic design, IBC2003, weak earthquakes*

INTRODUCTION

The effects of the structure-soil interaction on the seismic design of structures are important, and the importance of the performance based seismic design is also recognized for the rational design of a structure making the structure safer with the different levels of earthquakes. Structure-soil interaction analysis of a structure considering the site soil condition is necessary to predict the reasonable seismic response of a structure in the performance based seismic design. [Krawinkler, 1997] But true nonlinear seismic analyses for the structure-soil interaction problem are practically difficult, and nonlinear analyses are performed for the approximate solutions.

In this study, seismic response analyses of a single degree of freedom (SDOF) system built on the soft soil layer were performed in one step applying the earthquake excitations to the bedrock. For the nonlinear analyses, a linearized iterative method was utilized. Effects of the nonlinear soil layer on the seismic responses were investigated comparing the responses for the nonlinear soil with those for the linear soil and IBC2003. [IBC, 2002] Study was carried out for the surface medium size mat foundation built on the IBC soil profile type of S_D using the 11 weak or moderate, and 5 strong earthquake records shown in Table 1 and 2 with the peak accelerations between 0.047g and 0.316g.[PEER]

MODEL

To investigate the effects of nonlinear soft soil layer on the seismic horizontal response of a structure, seismic

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SEISMIC EARTH PRESSURE ACTING ON PILE-CAP DURING SOIL LIQUEFACTION BY LARGE-SCALE SHAKING TABLE TEST

Shuji TAMURA

SUMMARY

Shaking table tests are conducted using a large-scale laminar shear box to investigate the effects of non-liquefied crust overlying liquefied soils on an embedded footing. It is shown that (1) The total earth pressure before liquefaction is induced mainly by the inertial force of the building. The shear force at the pile heads corresponds to the difference between the total earth pressure and the inertial force; (2) The total earth pressure after liquefaction is induced mainly by the soil deformation. The shear force at the pile heads corresponds to the sum of the total earth pressure and the inertial force of the building; (3) The relation between the relative displacement and the total earth pressure is linear before liquefaction. It becomes nonlinear with the development of pore water pressure and the total earth pressure decreases with cyclic loading after liquefaction; (4) The peak value of the total earth pressure for the super-structure with a low natural frequency is larger than that with a high natural frequency. This is probably because the inertial force of the super-structure with a low natural frequency may interrupt the response of the footing that tends to move with the ground.

Keywords: *Seismic Earth Pressure, Soil Liquefaction, Pile foundation, Shaking Table Test*

INTRODUCTION

During the 1995 Hyogoken-Nambu earthquake, extensive soil liquefaction occurred on the reclaimed land areas of Kobe. Many damaged piles in such liquefied soil have been reported. It indicates that the effects of liquefaction on piles should be taken into account in foundation design.

Soil-pile-structure interaction during liquefaction has been studied by field investigations (Oh-Oka et al, 1998), numerical analyses (Fujii et al., 1998, Tokimatsu et al., 1998), centrifuge tests (Sato et al., 1995) and large-scale shaking table tests (Tamura et al., 2000). Most research efforts of these studies have focused on the evaluation of soil-pile interaction including p-y relations during soil liquefaction. Thus, knowledge of the effects of non-liquefied crust overlying liquefied soil on an embedded footing remains limited. The evaluation of the kinematic force acting on an embedded footing is an important consideration in the seismic design method using p-y curve for pile foundations.

This paper investigated earth pressure acting on an embedded footing of a building during soil liquefaction, using a large-scale laminar shear box. The objects of this paper are; 1) to study major factor affecting earth pressure; 2) to study the relation between the relative displacement and earth pressure; 3) to study phase difference between the inertial force of the building and earth pressure, and 4) to study the effects of a natural frequency of the super-structure on earth pressure.

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DEVELOPMENT AND APPLICATION OF AN OBJECT-ORIENTED FRAMEWORK FOR NONLINEAR STRUCTURAL ANALYSIS SOFTWARE

Bo-Zhou LIN[1] and Keh-Chyuan TSAI[2]

SUMMARY

This research adopts the Design Pattern and the Unified Process to develop a software framework for nonlinear static and dynamic structural analysis. The develop process of the framework and the applied object-oriented mechanisms are explained. This paper also introduces a new structural analysis computational platform entitled "Platform of Inelastic Structural Analysis for 3D Systems", PISA3D, which is constructed on the software framework. The software is well extendable and easy to maintain due to its object-oriented nature. Following researchers can efficiently expand functions in PISA3D without modifying any original source codes. Users can make replacements, derivation, or combination of the object libraries in PISA3D to solve different types of nonlinear structural analysis. Currently 6 materials and 5 elements have been developed. Users can apply PISA3D to simulate the nonlinear responses of structural systems. To verify the correctness and practicability of PISA3D, this paper presents some models simulated by PISA3D.

Keywords: *Nonlinear structural analysis, Object-oriented, Design Pattern, PISA3D.*

INTRODUCTION

Computational structural analysis is a very important procedure in modern research and practice of earthquake engineering. The demands on nonlinear structural analysis are increasing and varying rapidly. In general, structural analysis computer codes can be classified into two categories. One of them is commercial package, popular example is like SAP2000 [Habibullah 1997]. These programs have friendly graphic user interfaces and can analysis 3D systems. Nevertheless, their shortcoming is that it is difficult to extend functions. The other type of nonlinear structural analysis programs are often applied in the field of earthquake engineering research, examples include the DRAIN series [Allahabadi and Powell 1988] and the OpenSEES [Mazzoni et al. 2003]. These programs have a number of nonlinear material and element libraries, allowing users to extend their functions or add elements. However, a lack of graphic pre/post-processing and friendly interfaces is their shortcoming. In addition, except OpenSEES, these software frameworks have been implemented following the procedure-oriented framework, so their maintainability and extendibility are insufficient. As a result, this research adopts the Unified Process and C++ language, a programming language with the object-oriented mechanisms, to create a new analysis computational framework. Then develop a nonlinear structural analysis platform basing on this framework. The platform has verified usability and target users include practical structural engineers and academic researchers.

DEVELOPMENT PROCESS AND OBJECT-ORIENTED FRAMEWORK FOR NONLINEAR STRUCTURAL ANALYSIS SOFTWARE

From 90's, the software engineering tends to adopt the iterative developing process. The main spirit is to disperse the whole developing process to many small phases. After the extensive experience gained in developing many of such software, the

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Formulas for Vibration Period of Steel Buildings in Taiwan Derived from Ambient Vibration Data

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SUMMARY

The fundamental vibration period of a building is an important parameter for determining the design base shear. The empirical formula for calculating the fundamental vibration period given in the Specification for Seismic Design of Buildings (SSDB) of Taiwan is mainly based on that of the Uniform Building Code (UBC). However, given that the design and construction methods between Taiwan and US are not the same, it is necessary to evaluate the appropriateness of the empirical formula currently used in Taiwan. This study applies system identification techniques in analyzing the ambient vibration measurement data of 30 steel buildings located in Taipei to obtain the fundamental vibration period. On the basis of these identified periods, new empirical formulas for the translational and torsional fundamental vibration periods are then proposed. The difference between the periods predicted by the new formulas and the current empirical formula ranges from 10% to 42%.

Keywords: Ambient Vibration Measurement, Steel Buildings, Fundamental Vibration Period, System Identification, Empirical Formula

INTRODUCTION

The fundamental vibration period of a building is an important parameter in the determination of the design base shear in building codes. For buildings with a medium or long fundamental vibration period, the design base shear is in general inversely proportional to the fundamental vibration period. In other words, the longer the fundamental vibration period the smaller the design base shear. According to SSDB of Taiwan (ABRI 1997), the fundamental vibration period of a building can be calculated using the given empirical formula or other rational analysis methods. Being a rational analysis tool for building design, the commercial software ETABS is commonly used by the structural engineers in Taiwan to obtain the fundamental vibration period. However, according to SSDB the fundamental vibration period obtained using any rational analysis method shall not be 1.4 times larger than that predicted by the empirical formula if it is to be used in calculating the design base shear. The value 1.4 is referred to as the upper bound factor in this study for convenience of discussion.

The objective of this paper is to propose new empirical formulas for the fundamental vibration period of steel buildings in Taiwan. This is needed since the current empirical formulas are mainly based on the UBC but the ways how steel buildings are designed and constructed in Taiwan and US are not exactly the same. To this end, ambient vibration measurements are carried out first and system identification techniques are then employed to determine the fundamental vibration periods for 30 steel buildings located in Taipei. By making use of the identified periods, new empirical formulas are proposed. Moreover, whether the value of the upper bound factor 1.4 is appropriate will be investigated in this paper.

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Internet-Based Numerical Analysis of Steel Building Frame in Collaboration of Frame Analysis and Local Buckling Analysis

Motohide TADA[1] and Katsuki OHGAMI[2]

SUMMARY

Structural analysis of three story steel building frame was conducted in collaboration of two different analysis tools. One is the frame analysis tool developed by Tada, which behaves as "Host" and analyzes entire behavior of building. The other is the precise analysis tool of plate elements developed by Ohgami, which behaves as "Station" and analyzes local buckling at column-bases. Incremental pushover analysis was conducted by exchanging numerical data. Tangential stiffness-matrix and restoring forces of boundary nodes are transmitted from Station to Host in each step, and incremental displacements of boundary nodes are returned from Host to Station. Numerical data was automatically transmitted through Internet by utilizing file-sharing system prepared in standard OS.

The feature of this analysis system is summarized as follows;

(1) We do not need to exchange source-codes nor application in combining two analysis tools. All we need is the exchange of numerical data (stiffness, forces, and displacements).

(2) It is easy to participate as Station because modification of only I/O routine is needed.

(3) As one cannot know the behavior of another components, prudent discussion among operators is necessary to study the analytical results. This is good for analysis tools not to be black boxes.

Keywords: Internet, Collaboration, Numerical Analysis, Pushover Analysis

INTRODUCTION

Tada et al. have proposed the Internet linkage in structural numerical analyses (Tada et al. 2003, 2004a, 2004b). In this linkage, various precise analysis tools developed by different researchers are combined with frame analysis tool, and whole building structure can be analyzed under the consideration of precise behavior of structural components. The collaborative analyses with the local buckling analysis (Ohgami et al. 2004) and with the exposed column base analysis (Tamai et al. 2004) are reported.

Characteristics of proposed linkage system are described as follows;

1) Collaboration of plural investigators can be achieved by unifying respective analysis tools. The combination of members can vary depending on project.

2) Information to be exchanged is numerical data of instantaneous stiffness matrices, restoring forces, and deformations in step-by-step incremental analysis. We do not need to exchange source codes nor libraries. The copyright of applications can be perfectly protected.

3) Participation to the project is easy because modifications only at input and output routine are necessary.

4) The procedure of communication through Internet is easy, it just uses general file-sharing system and FORTRAN77.

5) The collaboration among all operators is necessary to study the analytical results, because one cannot grasp the behavior in other stations. This is good for analysis tools not to be black boxes.

This paper deals with the analytical example under the collaboration of frame analysis tool (NETLYS) developed by Tada and local buckling analysis tool (NASP) developed by Ohgami.

TWO ANALYSIS TOOLS FOR FRAME BEHAVIOR AND LOCAL BUCKLING BEHAVIOR

Analysis tool for frame behavior (NETLYS)

Outlines of frame analysis tool are described as follows;

1) Static and dynamic earthquake response analysis for arbitrary plane frames can be dealt with.

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CAPACITY SPECTRUM METHOD WITH MODE-ADAPTIVE PUSHOVER ANALYSIS

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SUMMARY

Capacity Spectrum Method (CSM) has been adopted as a seismic evaluation method in the Japanese structural design code for buildings, which was revised toward a performance-based structural engineering framework in June 2000. In CSM, the lateral force resisting capacity of a building is represented by the acceleration-displacement response spectrum (i.e., the capacity spectrum) obtained from pushover analysis. Since the capacity spectrum is what represents the response of the equivalent single degree of freedom system (ESDOF) for the building, how to reduce appropriately the building to ESDOF is a key to improve the accuracy of CSM. In order to construct the appropriate capacity spectrum corresponding to ESDOF, the use of lateral force distributions corresponding to the first mode of vibration of the building is necessary for the non-linear pushover analysis. On the other hand, considering the higher mode effect is also important for predicting the earthquake responses of medium/high-rise buildings.

A mode-adaptive pushover (MAP) procedure, which uses a stiffness-dependent lateral force distribution at each loading step without the eigenvalue analysis, is proposed in this paper. 4 and 12 story RC frame buildings and a 6 story RC building with the soft first story are analyzed using MAP procedure to estimate the responses by CSM. Three kinds of MAP analyses with the lateral force distributions corresponding to the first to third modes of vibration are conducted for each building to consider the higher mode effect. Non-linear response history analyses using several earthquake ground motions are also executed for each building to compare with the predicted maximum responses by CSM. This paper indicates that a modal analysis combined CSM with MAP analysis for the first mode and elastic analysis for the second and third modes gives good predictions for the maximum story shears and drifts of the buildings.

***Keywords**: Capacity spectrum method, mode-adaptive pushover analysis, non-linear response history analysis, higher mode effect.*

INTRODUCTION

The Capacity Spectrum Method (CSM)(Freeman S. A. 1978) has been adopted as a seismic evaluation method in the Japanese structural design code for buildings, which was revised toward a performance-based structural engineering framework in June 2000 (Ministry of Land, Infrastructure and Transport 2001). In CSM, the lateral force resisting capacity of a building is represented by the acceleration-displacement response spectrum (i.e., the capacity spectrum) obtained from pushover analysis. Since the capacity spectrum is what represents the response of the equivalent single degree of freedom (ESDOF) system for the building, how to reduce appropriately the building to ESDOF system is a key to improve the accuracy of CSM. In order to construct the appropriate capacity spectrum corresponding to ESDOF system, the use of lateral force distributions proportional to the first mode of vibration of the building is necessary for the non-linear pushover analysis. On the other hand, consideration of the higher mode effect is also an important issue for predicting the earthquake responses of medium/high-rise buildings.

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SIMULATION OF DAMAGE PROGRESSION IN LOWER STORIES OF 11-STORY BUILDING

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SUMMARY

Seismic behavior of two reinforced concrete frames with two stories and one span were investigated in Kyoto University. These frames were scaled to 1/4 and represented the lower part of an 11-story reinforced concrete frame building prototype. They were identical and designed with the 1999 Japanese guidelines. Axial load variation was the only test parameter for this experiment. From the test results it was found that, slight difference was observed between the two frames from the experimental load-drift relationship. Both frames did not show any strength degradation even though they were loaded beyond 6 % drift. The second floor beam elongated as much as 1.50% of the total span length for both frames. Some of the beam's longitudinal reinforcements buckled near the column face due to high compression. Frame under high axial load showed more cracks than the one under moderate axial load. Analysis of the frame specimens was carried out with the nonlinear IDARC program. The analytical curvature-drift relationships for frame components matched well the experimental ones, for a plastic hinge lengths equal half of the column depth and half of the beam height. Good agreement was also found for the load-drift at the first story, second story and the entire frame. Pushover analysis carried out using the nonlinear SAP2000 predicted with a very good accuracy the envelope curves of the experimental hysterises curves. The plastic hinge region was modeled in SAP2000 using the tri-linear model suggested in the Japanese design guideline.

Keywords*: Plastic hinge, RC frame, damage assessment, cracking,.*

INTRODUCTION

Many researchers [1][2] investigated deeply the seismic behavior of cantilever column under different types of loading in the past. However, tests data for frame structures or beam-column assemblages are still not available in the same amount as that for isolated columns or beams. Presence of beams and slabs in structure may change the column's seismic behavior dramatically. During Northridge earthquake many buildings collapsed as a results of flooring units loosing their seating due to beam elongation [3].

Stanton et al. [4] proposed a new "yielding gap frame" joint connection to avoid the beam elongation in the precast prestressed frame structures. The beam is connected to the column at the bottom by post tensioning tendon that passes through, and pre-compresses, a grout. At the top, the connection is made by deformed bars grouted into ducts. The grout pad exists only at the bottom of the beam, so there is no contact between the two concrete faces at the top of the beam. During earthquake, the end of the beam rotates about the grout pad, which acts as a hinge. The distinguishing characteristic of the connection is that it overcomes the problems associated with the beam elongation that typically occurs under plastic rotation.

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EVLUATION OF SHEAR CAPACITY IN THE STEEL BEAM AND REINFORCED COLUMN CONNECDTIONS

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SUMMARY

This investigation aims to propose a new theory, using strut and tie model, to evaluate the shear transfer in the steel beam and reinforced concrete column connections. In order to validate the proposed theory, shear strength of thirty-one connections from literature was calculated. For comparison, shear strength based on code provisions as well as an analytical model proposed by researchers Parra-Montesinos and Wight are also presented. In addition to the evaluation of panel shear strength, nonlinear shear force-distortion behavior in several joints can also be simulated. The comparison shows that the proposed model can accurately predicted the shear strength of the steel beam and reinforced concrete column connections. And simulation of shear force-distortion behavior for the connections agrees well with the test results from literature.

Keywords*: beam-column connections; composite structures; shear strength.*

INTRODUCTION

Composite structures such as concrete filled steel tube (CFT) and steel reinforced concrete (SRC) structures, etc. are popular recently in worldwide. One of the composite systems investigated starting from 1989 is referred to as the RCS system. RCS composite systems resist seismic moments based on the connection between reinforced concrete columns and steel beams. Using RC rather than structural steel as columns can result in substantial savings in material cost, increasing of the structural damping and lateral stiffness of the building. To date, two main categories in RCS connections can be characterized as: beam through type and column through type. Based on the literature, beams continuously passing through column panel zone (beam through type) behaved in a ductile manner under seismic loading; however, orthogonal moment connection in the panel zone may be labor intensive. Column through type using diaphragms or cover plates to connect steel beam and column may facilitate field construction; however, additional effort in connection details to ensure a better seismic capacity in terms of strength and ductility is needed.

Since 1989, researches on RCS composite system have been started by Deierlein et al. (1989), and Sheikh et al. (1989) in Texas University, where 15 beam-through-type connections were tested. Two failure modes were distinguished such as panel zone yielding and bearing failure of column concrete due to the cyclic loads from beams as shown in Figure 1. In 1993, Konno (1993) tested a series of RCS connections. Research parameters included hoop details in panel zone, column axial load, and bearing strength of concrete. Test results showed that seismic capacity of RCS systems is not less than RC or Steel structures. Since 1997, cooperation for research on RCS construction system have been conducted in US and Japan such as Baba and Nishimura (2000), Kim and Noguchi (1997), Nishiyama et al. (1997), Parra-Montesinos and Wight (2000), and Bugeja et al. (2000).

Until now, some code provisions as well as analytical models such as Kanno (1993), ASCE Guidelines, AIJ-SRC Standards (2001), and Parra-Montesinos and Wight (2000) have been proposed to evaluate the shear resistance of RCS beam-column joints. Generally, ASCE Guidelines, based on the suggestions of Kanno and Deierlein

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ANALYTICAL EVALUATION OF RIB-REINFORCED STEEL MOMENT CONNECTIONS

Cheng-Chih CHEN[1], Chun-Chou LIN[2], and Cheng-An LU[2]

SUMMARY

A flange rib used to reinforce moment connections can enhance the seismic performance of moment connections in steel moment-resisting frames. This study is conducted to investigate the effects of design parameters of the flange rib on the connection behavior through three-dimensional nonlinear finite element analyses of the connection subassemblage. A series of parametric studies is performed to elucidate the effects of the flange rib. Three geometrical parameters were set for the rib characterized with an extension. Besides, the distribution of stresses and plastic strain demands for various parameters are also presented and compared. The analytical results demonstrate that the single lengthened rib can eliminate the concentrations of stresses and strains of the unreinforced connection, and reduce the potential for brittle fracture of the connection especially at the root of the weld access hole.

Keywords*: Rib-reinforced connection; weld access hole; von Mises stress*

INTRODUCTION

Steel moment-resisting frames are generally designed assuming that structural systems have to provide sufficient strength and ductility under seismic excitation. The energy induced from strong ground excitation is primarily dissipated by forming plastic hinges at connections between beams and columns. Therefore, the development of seismic performance in these moment-resisting frames would depend on the hysteretic behavior of beam-to-column connections. However, numerous moment connections did not behave in a ductile manner, and failed to provide expected inelastic deformation in the 1994 Northridge earthquake (Youssef et al. 1995). Since this earthquake, many studies have been undertaken to investigate the behavior of the moment connection. Several tests have displayed that connections with pre-Northridge details may fail at low plastic rotation (Lu et al. 2000; Stojadinovic et al. 2000; Chen et al. 2005); in most cases those unreinforced connections fail to develop the plastic rotation of 3% radians required by the AISC seismic provisions (1997). The specimens typically failed owing to fracture of the beam flange and groove weld, caused by through-thickness crack originating at the root of the weld access hole.

As demonstrated in the experiments, satisfactory plastic rotation can be achieved generally by strengthening the connection or weakening the beam section. Flange rib reinforcing is one of the strengthening schemes to improve the seismic performance of steel moment connections. A tapered triangular plate is usually used. The ribs welded to the top and bottom beam flanges at the column face are used to reduce the stresses at the beam flange groove weld, and to move the critical section away from the column face. Tests conducted by Engelhardt et al. (1995) and Anderson and Duan (1998) demonstrated that connections reinforced with tapered triangular ribs exhibited sufficient hysteretic behavior with plastic rotation ranging from 2.5% to 3.0% radians. Engelhardt et al. tested two connections reinforced with two tapered ribs welded to the top and bottom beam flanges. Gradual tearing of the beam bottom flange at the rib tips caused the connection failure. Anderson and Duan tested three connections using a single rib welded to each beam flange. Failure was caused primarily by cracking

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PERFORMANCE EVALUATION OF POSTTENSIONED STEEL CONNECTIONS FOR MOMENT-RESISTING FRAMES

Chung-Che CHOU[1], Jun-Hen CHEN[2], and Yu-Chih CHEN[2]

SUMMARY

Cyclic performance of posttensioned steel connections for moment-resisting frames was investigated experimentally and analytically. Cyclic tests were conducted on three full-scale subassemblies, which utilize unbonded strands to provide a re-centering response and Reduced Flange Plates (RFPs) to increase energy dissipation. The test results showed that (1) the proposed buckling-restrained RFP was effective in dissipating energy in axial tension and compression, (2) the beam could reach an interstory drift of 4% without strength degradation, and (3) buckling of the beam was observed at an interstory drift of 5%, resulting in a significant loss of the strand force, re-centering response, and moment capacity. The analytical study involved the use of an iterative sectional analysis and the development of the posttensioned beam stiffness to predict the moment-rotation relationship.

Keywords: *posttensioned steel beam-to-column connection, strand, reduced flange plate, moment-resisting frame*

INTRODUCTION

The flexural behavior of an unbonded posttensioned beam-to-column connection is characterized by gap opening and closing at the beam-column interface upon cyclic loading. The behavior of the unbonded posttensioned precast concrete beam-to-column connections was verified experimentally and analytically (Cheok and Lew 1993, Cheok and Stone 1994, and Priestley and MacRae 1994). Although these responses had little energy dissipation, the connections were able to return to the original position with minor residual deformation, so called a re-centering response.

As an alternative to the welded steel moment connection, the same posttensioned technology has been applied to the steel connections by Ricles et al. (2001, 2002) and Christopoulos et al. (2002). The systems in both of these studies incorporated seat angles and round bars to dissipate energy, and high strength strands and posttensioned bars to provide a re-centering capability. It was demonstrated that the damage was limited to the energy dissipating devices such as angles or bars and no damage of the beam and the column was reported. No information has been reported on the behavior of the steel beam in combined axial and flexural loading, and potential damage of the beam to the behavior of the system should be different in the welded moment connections (Chou and Uang 2002). This paper presents the experimental results of the proposed posttensioned connection using the high strength strands with Reduced Flange Plates (RFPs) for energy dissipation. The beam was designed to remain elastic at the target interstory drift of 3%, but loaded to a maximum interstory drift of 5% to investigate its failure modes to the subassembly behavior.

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Seismic Design of Reduced Beam Section Steel Moment Connections with Bolted Web Attachment

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SUMMARY

Recent test results on reduced beam section (RBS) steel moment connections showed that specimens with a bolted web connection tends to perform poorly due to premature brittle fracture of the beam flange at the weld access hole. The measured strain data appeared to imply that a higher incidence of base metal fracture in specimens with bolted web connections is related to, at least in part, the increased demand on the beam flanges due to the web bolt slippage and the actual load transfer mechanism which is completely different from that usually assumed in connection design. In this paper, the practice of providing web bolts uniformly along the beam depth was brought into question. A new seismic design procedure, which is more consistent with the actual load path identified from the analytical and experimental studies, was proposed together with improved connection details. The full-scale pilot specimen designed following the proposed procedure exhibited sufficient cyclic connection rotation capacity without fracture.

***Keywords**: connections; steel frames; seismic design; brittle fracture; moments.*

INTRODUCTION

The 1994 Northridge and the 1995 Kobe earthquakes caused widespread damage in connections of steel moment-resisting frames. After these earthquakes, a number of improved beam-to-column connection design strategies have been proposed. Of a variety of new designs, the reduced beam section (RBS) connection has been shown to exhibit satisfactory levels of ductility in numerous tests and has found broad acceptance in a relatively short time (Chen 1996; Plumier 1997; Zekioglu et al. 1997; Engelhardt et al. 1998). In the RBS connection a portion of the beam flanges at some distance from the column face is strategically removed to promote stable yielding at the reduced section and to effectively protect the more vulnerable welded joints. Although this type of moment connection has been widely used in the past few years, there remain several design issues that should be further examined (for example, Jones et al. 2002; Gilton and Uang 2002; Chi and Uang 2002). An issue on RBS performance, which requires further examination, is the influence of the beam web connection method. Most of the past tests have been conducted on specimens with a fully welded beam web. While both welded and bolted web specimens have shown good performance, Jones et al (2002) indicated that the use of a welded web connection does provide some benefit to the connection performance and it tends to reduce the vulnerability of the connection to weld fracture. In recent test conducted by Lee et al. (2003) to further investigate the influence of the beam web connection type, bolted web specimens that were slip-critically designed according to the common design practice performed poorly due to premature brittle fracture of the beam flange at the weld access hole. No consensus seems to exist on whether or not a bolted web attachment should be permitted for the prequalified RBS connections. The first objective of this study was to identify the actual load path of the connection. The second objective was to propose a more rational seismic design procedure for bolted web attachment in RBS steel moment connections based on the experimental and analytical studies.

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SEISMIC BEHAVIOR OF WELDED STEEL MOMENT CONNECTIONS TO BUILT-UP BOX COLUMNS

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SUMMARY

The FEMA connections are prequalified only for steel moment connections to W-shape columns. Built-up box columns with inner diaphragm plates are often used, but there are no test data upon which to base a performance evaluation or develop retrofit solutions for the connection to typical box columns. The objective of this paper is to investigate the seismic performance of steel moment connections to box columns fabricated using pre-Northridge connection details. Two full-scale cyclic tests were conducted for the steel moment connections, one between ASTM A572 Grade 50 W33×118 beam and BC18×18×257 built-up box column, and one between ASTM A572 Grade 50 W36×232 beam and BC31.5×13×464 built-up box column. Both test specimens failed by brittle fracture of the CJP welds between the beam flange and the column. Solid element models for each test specimens were made and analyzed to investigate the stress and strain states at the critical section of the joint between a W-shape beam and a box-shape column. The stress and stain distributions across the width of the beam flange near the column were affected by out-of-plane stiffness of the column flange plate. As the stiffness increased, the axial strain distribution became uniform. Local yielding of the beam flange may delay the brittle crack propagation in the CJP welds. Careful detailing and using the notch-tough weld metal are required to join the continuity plates and column plates.

***Keywords**: Built-up box columns; steel moment connections; building structures; brittle fracture; pre-Northridge connection details.*

INTRODUCTION

Practical design guidelines, published in a series of FEMA documents, gave designers new tools to design special steel moment frames and provided a portfolio of new connection solutions. Satisfactory seismic behavior of the new connections was proven in a comprehensive series of pre-qualification tests. Such tests are now mandatory for every new connection that falls outside the parameter space tested to date (Kim et al. 2004). FEMA connections are prequalified only for W-shape columns, but box-shaped columns were not considered. There is not enough test data upon which to base a performance evaluation or develop retrofit solutions for the connection to typical box columns. Built-up columns are often used, because they can be made stronger than cold formed tubes. Continuity plates (inner diaphragms) are usually installed inside the box at the levels of both beam flanges.

The objective of this study is to investigate the seismic performance of welded steel moment connections to box columns. Two full-scale tests of steel moment connections between W-shape beams and built-up box columns were conducted under cyclic loading. Solid element models representing both test specimens were prepared and response analyses were conducted under monotonic loading. This paper summarizes the key findings of these studies.

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