Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Use of advanced cladding systems for passive control of building response in earthquakes

B.J.Goodno, L.El-Gazairly & C.-C.Hsu
School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga., USA

J.I.Craig
School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Ga., USA

ABSTRACT: Deliberate design of nonstructural systems, such as heavyweight cladding and its attachments, to provide added stiffness and damping may lead to significant reduction in lateral response and resulting improvement in overall building performance in earthquakes. Analytical studies of two buildings, one a 6-story steel building frame model used in laboratory studies of active and passive control systems, and the second an actual 12-story RC building damaged in the 1985 Mexico Earthquake, were undertaken as part of a broader program of NSF-sponsored research aimed at understanding the role of nonlinear interaction between cladding and structural framing. The on-going research program has sought to identify, test and model advanced cladding connection designs capable of providing improved energy dissipation and ductility compared to those in present use; the experimental methodology and results are presented in a companion paper. The present paper presents the results of nonlinear dynamic analyses of the two case study structures which employ both conventional and advanced cladding systems for passive control of lateral response to earthquake ground motion.

1. INTRODUCTION

Traditional design practice for buildings has been to ignore the potential stiffening and/or energy dissipative role of heavy cladding systems in the lateral response of highrise buildings. Instead, designers actually try to decouple these elements from the supporting structure in order to minimize any structural forces that might be introduced into them due to seismic, wind, thermal or other environmental forces. However, recent research (Palsson 1984; Goodno 1986; Craig 1991; Wolz 1991) has demonstrated that a properly designed precast concrete cladding system can be used for passive control of building response during strong ground motions by providing predetermined increases in lateral stiffness, ductility, and energy dissipation to the building as a whole. Nevertheless, in the design of precast cladding in the U.S., most engineers continue to follow the recommendations of the Precast/Prestressed Concrete Institute (PCI). Statically determinate attachment systems are usually preferable, and typical designs incorporate two bearing connections along with one or more sliding or flexible connections to allow movement in the plane of the panel, in this way lessening panel interaction with the supporting frame. However sliding connections may be rendered ineffective by poor construction practice and lack of inspection, or by connection deterioration with time (e.g., rust or corrosion). In addition, there are some indications that low cycle fatigue could be a problem for ductile tie-back flexible connections (Craig 1988). Studies (El-Gazairly 1992) have shown that disregard of precast panels to carry lateral load or add lateral stiffness is not entirely warranted and suggest that cladding systems are not presently being used to full advantage.

Studies of building structural and cladding systems, coupled with experimental observations (Meyyappa 1984) of the actual dynamic response of these buildings, have lead to a recognition that, whether by deliberate design or not, building cladding systems (particularly heavy precast systems) can measurably affect the structural stiffness and therefore the dynamic response. These studies documented essentially linear stiffness augmentation that was confirmed by response measurements at very low (ambient) levels.

Palsson (1984) carried out an early study of cladding interaction with the supporting building structure and proposed the use of "brake pad" material in the panel connections to enhance energy dissipation through the addition of coulomb damping. Pall (1989) developed a number of commercial structural elements that rely on coulomb type damping to augment energy dissipation, and applications to building cladding were studied. In New Zealand, Matthewson and Davey (1979) designed a building with cladding connected to the main structure with energy dissipating devices. At the same time studies have pointed to the potential benefits that could be derived from dissipative or inelastic stiffening action in certain building structural elements. Skinner, et. al. (1973) proposed the use of novel ductile connection elements to achieve inelastic interaction between structural members under a variety of conditions. Many other similar studies have been carried out over the years.

On-going experimental studies (Craig 1992) and extensive analytical modeling being carried out at Georgia Tech, as well as related work at other research centers, have pointed to the critical role that cladding connections play in this process of cladding-structure interaction (Goodno 1989, 1991; Pinelli 1991). The implementation of this new concept of cladding participation depends upon the development of advanced connections (Wolz 1991; Craig 1991). In this case, an advanced connection is one which exhibits superior properties of ductility and damping resulting in high energy dissipation without failure during a moderate or strong earthquake. Cladding systems incorporating advanced connections hold considerable promise for passive control of buildings, and such systems could also be used effectively as part of a hybrid active/passive building structural control system that is the subject of on-going research.

2. ANALYSIS OF BUILDING MODELS WITH ADVANCED CLADDING SYSTEMS

The overall research program encompasses laboratory testing of both conventional and advanced cladding connection systems and corresponding analytical studies of building models with advanced cladding systems. The objective here was to use laboratory test data to calibrate building cladding models and to test the *effectiveness of ductile cladding systems in* contributing to reduced response of buildings to seismic forces. Computer models of the case study buildings and their cladding systems, and the associated software, were developed in the analytical study reported here. The laboratory test fixture, testing methodology, description of specimens, and sample data for the cladding connection components are presented in a companion paper (Craig 1992), and connection performance data were incorporated into the building cladding models described below.

2.1 Six Story Building Model

A 1/4 scale six story steel space frame, used in analytical and experimental studies at the National Center for Earthquake Engineering Research (NCEER) (Reinhorn 1989), was chosen to investigate the role of nonlinear cladding-structure connections in the seismic response of the frame. Due to the planar behavior of the actual frame during previous experiments, plane frame analytical models with bilinear hysteretic behavior were

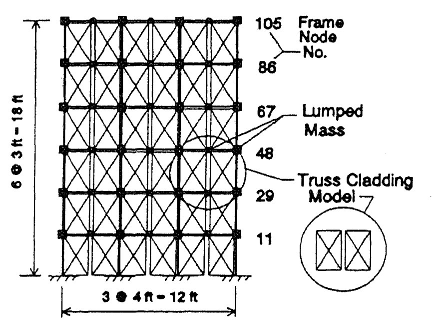

Fig. 1: 6 Story 2-D Frame and Cladding with Nonlinear Composite Connections

developed in the 3 bay direction using DRAIN-2D (Powell 1973) (Fig. 1). In the unclad frame, which served as a reference case, tributary translational mass, due to both the cladding and structural framing, was distributed to the panel nodes. The clad frame model included two rigid panels per bay, represented by truss bar assemblies (Fig. 2). No panel-to-panel contact was assumed to occur at any time during the analyses.

2.2 Cladding composite connection model

The lower panel connections, providing primary panel support and load transfer, were assumed to

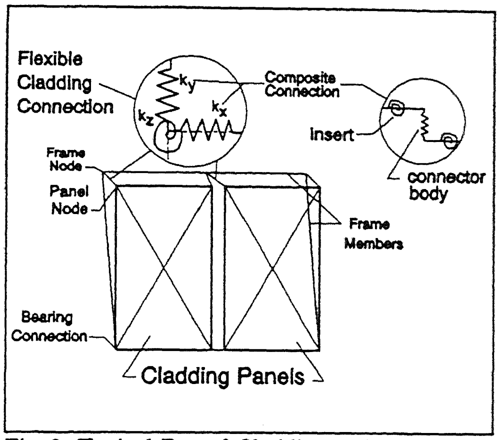

Fig. 2: Typical Bay of Cladding with Composite Nonlinear Connections

be either "rigid" or flexible, while the upper connections were assumed to be flexible. Lateral deformation, due to interstory drift, was judged to be the dominant form of connection distortion. The flexible connections (see inset in Fig. 2) were taken as a composite of two connection inserts (one in the panel and one in the structure - and represented by moment-rotation hysteresis loops patterned after those obtained from test data - see Fig. 3a) combined in series with the connector body (represented by shear force-displacement hysteresis loops - Fig. 3b). The force-deformation behavior for both components of the flexible connection was tracked using both 3-parameter and mechanical hysteresis models (Pinelli 1991). In the clad frame model, the flexible connections were represented by a new DRAIN-2D connection element. The assumed stiffness and yield force values for these connection elements dictated the level of cladding participation in frame response. The force level in each element was checked at the end of each step in the dynamic analysis, and if element yielding or unloading occurred, the global stiffness matrix was updated.

2.3 Nonlinear dynamic response studies: 6 story frame

Three cases were studied to investigate the influence of advanced bearing and flexible (tie-back) cladding connections on the total response of the 1/4 scale 6-story test frame. For the first case, no cladding stiffness contribution was assumed but the mass of the cladding was considered. In the second case, the bearing connections were assumed rigid and the tie-back connections flexible. A 6-inch long 3/8 inch thick, with initial stiffness of 4.75 kips/inch determined by laboratory testing, was used for the connector body. And in the third case, both the bearing (1/2 inch thick tube, initial stiffness of 11.2 kips/inch) and tie-back (3/8 inch thick tube) connections were flexible. The cladding connections were modeled with the composite connection mechanical hysteresis model; loops for Case 2 are shown in Fig. 3. The properties of all cladding connections were scaled from the experimental results (Craig 1992) to match the characteristics of the overall frame model. The stiffness was scaled 1:4 and the yield force 1:16, resulting in displacement at 1:4 scale. The 1940 El Centro NS record was scaled to 25% to simulate the full earthquake on a full scale frame. The top floor displacement, interstory drift and the computed force levels in the cladding connections are compared in Table 1 for the three cases; interstory drift envelopes are displayed in Fig. 4. Here it can be seen that the advanced cladding connections (in this example, ductile tube sections) were effective in reducing maximum interstory drift by up to 27% for Case 2.

Table 1: Response of 6 story frame

Max. Response Quantity	Case No.		
	1	2	3
Top Floor Displ (in.)	1.12	0.72	0.86
Drift (in.)	0.26	0.19	0.23
Bearing Conn. Force (kips)	0.79	1.15	0.33
Tie-back Conn. Force (kips)	--	0.26	0.26

2.4 Twelve story RC building in Mexico City

A case study building was chosen from a survey (Goodno 1989) of 25 buildings which sustained cladding and structural damage in the 1985 Mexico Earthquake. The building is a 12 story reinforced concrete frame structure with waffle slabs, shear walls and heavy precast cladding located in the old lake bed area of Mexico City. The front of the building was clad with heavy precast concrete spandrel panels with additional cladding provided to enclose the columns at the front corners of the building. The cladding connection inserts were fabricated from steel plate with welded reinforcing bars arranged to conform to panel geometry. The weld plates were attached directly to embedded inserts in the slabs using simple clip angles, rectangular bar stock, or direct welding. Unreinforced masonry walls were used as exterior nonbearing walls and interior partitions. The structure was supported on a cellular arrangement of deep beams carried by friction piles. Details of the structure and its nonstructural elements can be found elsewhere (Goodno 1989). The structure experienced severe cracking at waffle slab-column connections including several cases of punching failure. Masonry infill walls suffered diagonal shear cracks and lost contact with floor slabs. The precast column cover panels were cracked at the location of the plate inserts in the panels; the cracks were visible on the front face of the building at almost every level but no panels were ejected from the structure. The spandrel facade panels along the front face of the building were not damaged because they were not connected between successive floors. The building underwent extensive repair and rehabilitation and was later reoccupied.

2.5 Nonlinear dynamic response studies: 12 story RC building in Mexico City

A nonlinear dynamic analysis computer program, GT-IDARC (El-Gazairly 1992), was developed for the study and used to evaluate the seismic performance of the building. The objective of the analysis was to explain the observed damage to the structure, study the effect of nonstructural elements, and explore the potential benefits of advanced cladding connections in providing additional damping and reduced structural response. The unreinforced masonry walls were represented as nonlinear shear elements whose inelastic force deformation behavior was represented by the three parameter model, with values of the parameters specified to insure pinching of the infill masonry wall element. Cladding panels were modeled using four-node rectangular finite elements with two degrees of freedom per node. Panel properties were adjusted to produce essentially rigid in-plane behavior. The lower panel connection elements were considered to be bearing connections providing gravity support, and the upper connection elements were assumed flexible under interstory motions as shown in Fig. 2.

Two analytical models of the building were prepared: Model(1) included only the bare frame structure with no stiffness contribution from cladding or infill masonry walls; both cladding and infill walls were added to form Model(2). Both models were subjected to the first 80 seconds of both horizontal components of the SCT record: N90W (applied normal to the front face of the building and scaled to 0.172 g) and S00E (applied parallel to the street face and scaled to 0.10 g), acting simultaneously. The two models experienced yielding and cracking of various building components, indicating partial failure of the structure, after the first 50 seconds of the record. Analysis of Model(1) required approximately 12 hours of CPU time while Model(2) required more than 15 CPU hours on a Cray Y-MP/832. Results from the analysis of both models demonstrated that the nonstructural infill and exterior cladding contributed to substantially reduced top story displacement, interstory drift, floor rotation, and damage index values for Model (2) compared to Model (1) (Fig. 5). The analyses verified the extensive damage to the beam-column connections at different floor levels and locations which was observed in the field. Unreinforced masonry walls sustained diagonal shear cracks and lost contact with floor slabs. Force levels in most of the cladding connections, especially in the horizontal direction, exceeded available capacity resulting in panel damage and connector body yielding. Studies aimed at determination of possible modifications to the overall structure and its cladding, including use of advanced cladding connection systems to improve its seismic performance, are continuing.

3. CONCLUSIONS

The analytical studies reported above, along with laboratory experimental studies described in a companion paper (Craig 1992), show that heavy cladding systems which utilize ductile cladding connections can be used as an effective passive control system for buildings. These advanced cladding systems contributed to significant response reductions for the two case study structures considered in this investigation. The results suggest that provision for ductile inelastic action in the connections for heavy concrete cladding panels can provide levels of seismic response attenuation comparable to those achieved by other means. Cladding systems incorporating advanced connections hold considerable promise for passive control of buildings, perhaps as part of a hybrid active/passive building structural control system. It remains to develop simple and cost-effective advanced connections that use standard construction materials fabricated in simple shapes that are easy to manufacture and reliable in service. Critical evaluation of these designs by practicing engineers is essential if passive cladding systems are to gain acceptance in the field.

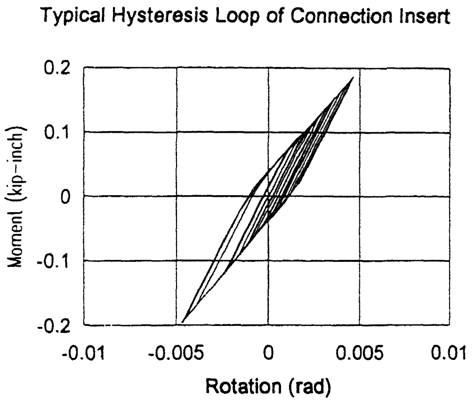

Fig. 3a: Hysteresis loop for cladding connection insert (Case 2) in composite model

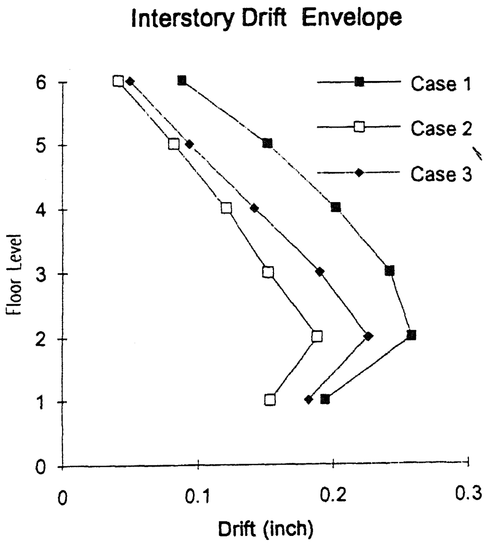

Fig. 4: Interstory drift envelopes for 6 story test frame, Cases 1 to 3

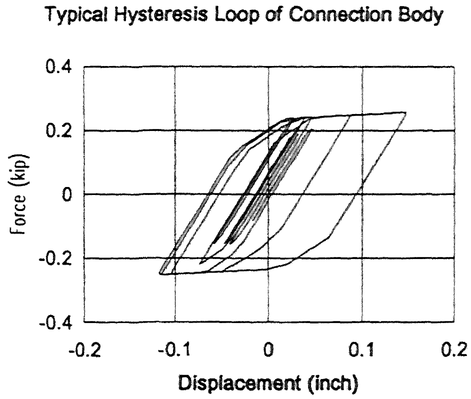

Fig. 3b: Hysteresis loop for cladding connection body (Case 2) in composite model

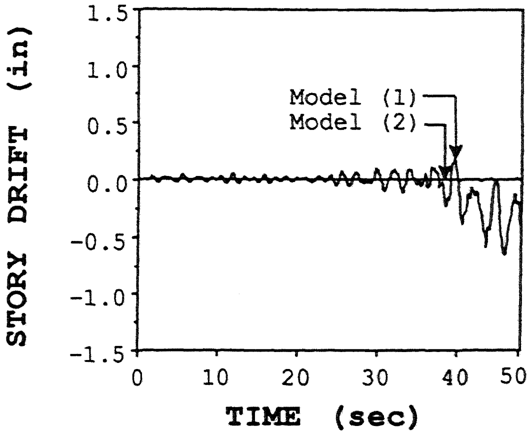

Fig. 5a: Interstory drift for Models 1 and 2 of Mexico case study building

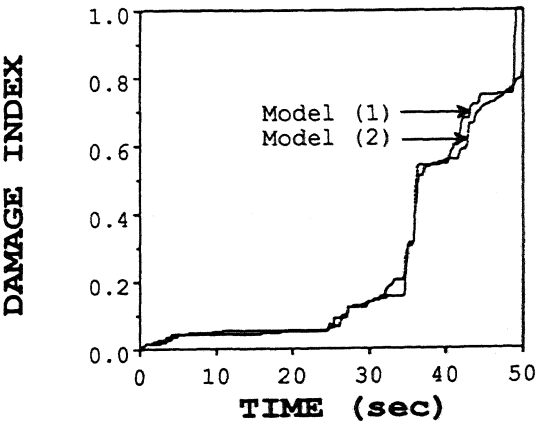

Fig. 5b: Damage index for Models 1 and 2 of Mexico case study building

4. REFERENCES

Craig, J. I., Leistikow, R., and Fennell, C. J., "Experimental Studies of the Performance of Precast Cladding Connections," Proceedings, 9th World Conference on Earthquake Engineering, Tokyo and Kyoto, Japan, August 2-9, 1988, Vol. VI, pp. 201-206.

Craig, J. I. and Goodno, B. J., Wolz, M. W., and Pinelli, Jean-Paul, "Analytical and Experimental Evaluation of Advanced Cladding Systems for Buildings," Proceedings, Second Conference on Tall Buildings in Seismic Regions, 55th Regional Conference, held on May 16-17, 1991, in Los Angeles, California, pp. 99-108.

Craig, J. I., Goodno, B. J., Pinelli, J-P., and Moor, C., "Modelling and Evaluation of Ductile Cladding Connection Systems for Seismic Response Attenuation in Buildings," to appear in the Proceedings of the 10th World Conference on Earthquake Engineering, Madrid, Spain, July 19-24, 1992.

El-Gazairly, L., Goodno, B. J, and Craig, J. I., "Nonlinear Dynamic Analysis of RC Structures with Precast Cladding Using GT-IDARC," to appear in the Proceedings of the ASCE 8th Computing in Civil Engineering Conference, to be held in Dallas, TX, June 7-9, 1992.

Goodno, B., and Palsson, H., "Analytical Studies of Building Cladding," Journal of Structural Engineering, ASCE, V.112, N4, Paper 20498, 1986, pp.665-676.

Goodno, B. J., Craig, J. I., and Zeevaert Wolff, A., "Behavior of Architectural Nonstructural Components in the Mexico Earthquake," Earthquake Spectra, V5, N1, Feb. 1989, p 195-222.

Goodno, B. J., and Craig, J. I., "Modeling of Advanced Precast Cladding Connections for Seismic Design," Proceedings, International Symposium on Building Technology and Earthquake Hazard Mitigation, Kunming, China, March 25-29, 1991, pp. 99-114.

Goodno, B. J., Craig, J. I., and Hsu C., "Experimental Studies and Analytical Evaluation of Ductile Cladding Connections," Proceedings, Pacific Conference on Earthquake Engineering, held in Auckland, New Zealand, November 20-23, 1991.

Matthewson, C. D., and Davey, R. A., "Design of an Earthquake Resisting Building Using Precast Concrete Cross-Braced Panels and Incorporating Energy Absorbing Devices," Bulletin of the New Zealand National Society for Earthquake Engineering, 12 (4), 1979, pp. 340-349.

Meyyappa, M. and Craig, J. I., "Highrise Building Identification Using Transient Testing," Proceedings, 8th World Conference on Earthquake Engineering, San Francisco, CA, July 1984, Vol. VI, pp. 79-86.

Pall, Avtar S., "Friction Damped Connections for Precast Concrete Cladding," Proceedings, Architectural Precast Concrete Cladding-Its Contribution to Lateral Resistance of Buildings, Precast/Prestressed Concrete Institute, Chicago, IL, November 8-9, 1989, pp.300-309.

Palsson, H., Goodno, B. J., Craig, J. I., and Will, K. M., "Cladding Influence on Dynamic Response of Tall Buildings," Earthquake Engineering and Structural Dynamics Journal, Vol. 12, No. 2., March-April, 1984, pp. 215-228.

Pinelli, Jean-Paul, Craig, J. I. and Goodno, B. J., "Development of Nonlinear Dynamic Models for Precast Cladding Connections in Seismic Design," Proceedings, ASCE 7th Conf. on Computing in CE and Symposium on Data Bases, Washington, D. C., May 6-8, 1991, pp. 739-748.

Powell, G. H. (1973), "DRAIN-2D User's Guide," Report Number EERC 73-22, University of California, Berkeley.

Reinhorn, A. M., Soong, T. T., Lin, R. C., and Wang, Y. P., "1:4 Scale Model Studies of Active Tendon Systems and Active Mass Dampers for Aseismic Protection," Report NCEER-89-0026, National Center for Earthquake Engineering Research (NCEER), SUNY, Buffalo, NY, November 22, 1989.

Skinner, R., Kelly, J., and Heine, A., "Energy Absorption Devices for Earthquake Resistant Structures," Proceedings, 5th World Conf. Earthq. Eng., Rome, Italy, 1973, pp. 2924-2933.

Wolz, M., Hsu, C., El-Gazairly, L., Goodno, B., and Craig, J., "Nonlinear Dynamic Analysis of Buildings with Advanced Cladding Connections," Proceedings, ASCE 7th Conf. on Computing in CE and Symposium on Data Bases, Washington, D. C., May 6-8, 1991, pp. 729-738.