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EXPERIMENTAL STUDIES OF THE PERFORMANCE OF PRECAST CLADDING CONNECTIONS

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SUMMARY

An experimental program involving the design and execution of laboratory tests of cladding panel connection subsystems is described. The program was design and carried out as part of a larger study that included both analytical and experimental modeling of cladding systems. The design of the test program is described and results of studies of bolt-insert and ductile rod push-pull connections are presented. Linear and nonlinear constitutive characteristics are described for these connections. The use of this information in detailed analytical models of cladding on typical highrise buildings (part of the larger study) is outlined. The results indicate that commonly-used connection designs may be susceptible to low-cycle fatigue failure. This observation suggests that current connection design practice may need to be reevaluated for adequate performance over several earthquakes.

INTRODUCTION

The performance of nonstructural building subsystems, including heavyweight exterior cladding, is better understood as a result of major research over the past decade (Ref. 1-3). In particular, building cladding subsystems are being studied to determine the potential applications for augmenting lateral stiffness under normal loading conditions and for increasing structural damping during earthquake loading (Ref. 4-8). Unfortunately, while analytical methods for evaluating these effects are at relatively sophisticated levels (Ref. 5,9), it is generally not possible to establish realistic models for the cladding and the cladding-structure connections due to the widespread lack of test and field data. Analysis of the damage from past earthquakes has provided much insight, but at the present time, there is a relatively good understanding of the influence of building configuration and structural design on seismic performance but much less knowledge of the performance of cladding and other nonstructural subsystems. In addition, architectural diversity and innovation has frequently led to cladding subsystem designs that either avoid potential useful structural participation altogether or fail to properly account for the interaction forces under earthquake loading.

Background Previous analytical studies of heavyweight precast cladding elements have demonstrated that cladding contributions to the overall stiffness of the primary structure can measurably affect both the natural frequencies and the linear dynamic response to moderate ground motion (Ref. 5). Torsional response is particularly affected, especially if partial cladding failure occurs. Cladding stiffness assessments are highly variable and have been shown to depend quite heavily on the connection performance. Some connections such as the so-called "push-pull" or ductile rod configurations are designed to isolate the cladding and provide very little stiffness augmentation. In other cases, connections designed to slip through use of slotted connections, over-sized holes, etc., can yield significant initial stiffness that suddenly decrease on breakaway only to increase when geometric limits are reached. Attachment of panels using weld plates and clip angles can result in relatively large stiffness contributions, with the total range being as much as an order of magnitude. Time variation of these properties due to aging introduces additional complexity.

Objectives The objective of the present study was to examine in the laboratory the behavior of different types of precast cladding connections and to accurately characterize their kinematic and constitutive properties. These properties will ultimately be used in highly refined analytical models for cladding systems (Ref. 9) developed as a part of a larger research program. Specifically, the concern is with both the actual and the potential contributions of cladding to the lateral stiffness under normal loading conditions and the potential energy dissipation (damping) that can be developed under severe loading conditions. Secondary objectives include an assessment of the appropriateness of existing code provisions related to cladding and the identification of potential modifications or extensions that could lead to improved performance.

LABORATORY TESTING

A precast cladding subsystem is defined as the precast cladding panels, the attachments points built into these panels, the connection elements, and the building attachment points. Together, the various components act to position and retain the cladding panels on the exterior faces of the building and to resist environmental loadings. The experimental program was designed to systematically study this subsystem in three stages:

(a) Evaluation of the connections themselves including panel attachments and connection elements,
(b) Study of the behavior of the precast panels alone, and
(c) Study of a complete subsystem, either in reduced or full-scale form in the laboratory.

The present paper reports on a portion of the phase (a) work only. The phase (b) and (c) research programs are currently under development.

Test Facility Design A special testing facility and data acquisition system was developed to carry out the experimental testing. The facility was designed to handle a variety of cladding panel attachment inserts that are cast into a precast concrete test specimen measuring 3 ft. (92 cm) square by up to 8 in. (20 cm) thick. The specimen is fixed to the reinforced concrete base of a special test frame using up to 8 tie rods and grouting. Figure 1 shows the basic facility which is approximately 10 ft. (3 m) on each side and 12 ft (3.6 m) tall. While the specimen orientation is horizontal rather than vertical, the facility does allow testing of either the precast insert alone or in combination with different connection elements.

Various load conditions can be applied to the test specimen by means of a multi-axis arrangement of conventional servo-controlled hydraulic actuators. The present fixture was designed to allow the following combinations of loading:

(a) Direct pullout (normal to slab),
(b) Single axis inplane shear load (parallel to slab which simulates gravity or inplane lateral or racking loads),
(c) Single axis bending (about an axis parallel to slab which simulates out-of-plane bending loads),
(d) Combinations of (b) and (c).

Case (a) is handled by a vertical actuator connected through a flexible link to the connection. Cases (b) and (c) are generated by means of two actuators mounted horizontally and inline with each other. The line of action of one actuator is above the other so that combinations of both shear and bending can be provided. Figure 2 shows the arrangements schematically. For case (d) a simple analog circuit was designed to proportion the control signals for each actuator so that the shear and bending loads could be controlled independently. The current arrangement does not allow application of torsion loads (moment loads about an axis normal to the specimen) which would simulate a secondary component of the loading due to inplane racking motion of the building face.

The data acquisition system consists of an IBM PC/XT with associated hardware and software that can be used to monitor and control each test. Monitoring functions are handled by multi-channel strain and voltage measuring instruments, and control is accomplished either manually or with a custom-built D/A converter subsystem that drives each actuator directly or for cases (b)-(d) through the analog proportioning circuit. All programming for test control is handled in Turbo Pascal with output files designed to support analysis using spreadsheet software or other programs.

Push-Pull (Ductile Rod) Connections This type of connection design is widely employed in West Coast US practice as a means for providing cladding-structure isolation for inplane motion while at the same time providing adequate out-of-plane (push-pull) resistance to seismic and environmental loads. These connections are typically used for two of the panel connections (top or bottom) and rigid inplane connections are used at the remaining two locations. Under strong motion, the connections allow large inplane movement between the cladding and the supporting building structure but restrain inward or outward movement. Figure 3 shows a typical configuration.

In order to model this type of connection standard 5/8 in. (16 mm) diameter Dayton F-42 loop ferrule inserts, both with and without reinforcement, were embedded in 5000 psi (725 kN/m^2) reinforced concrete test specimens (Ref. 10). The connection elements were fabricated from different lengths of 5/8 in. (16 mm) diameter threaded A-36 steel rods and were tested under inplane (shear) and normal (pullout) loading.

The test fixture was modified to allow testing of the panel attachment insert and connection element together as shown in Fig. 4. It should be noted that this test configuration has the push-pull connection arranged vertically, but in actual service the connection rod is oriented horizontally between the panel and the building structure. A secondary test frame was added above the specimen to support the upper end of the connection rod and to simulate the building attachment. This frame was supported directly on the specimen using simple steel wheels. Inplane (shear) loads were applied by two coaxially opposed actuators operated with the master under stroke control and the slave under load control (programmed to zero load to follow the master). Adjustments were provided to accommodate a range of connection lengths typical of practice. Pullout forces were applied to the insert directly using the vertically mounted actuator (Fig. 1).

Strain gages were placed at various locations on the insert, the reinforcing members and the ductile rod itself. Inplane (shear) and normal (pullout) displacement measurements across the connection were taken in order to determine the stiffnesses and load histories for both the connection and the insert. A combination of LVDT's and simple potentiometric displacement sensors was used for this purpose.

Elastic Limit: Elastic limits of the connection under inplane (shear) loading for various rod lengths were measured by applying successively greater cyclic displacements across the connection. As expected, bending strains in the rod showed ductile behavior with well-defined elastic limits while strains in the insert remained relatively small and elastic. Inplane displacement across the connection also exhibited clear ductile behavior as shown in Fig. 5. In practice this type of connection is designed on the basis of simple elasto-plastic beam models for the connection rod assuming either pinned or fixed end conditions. Figure 6 summarizes the test results by superposing the measured limit loads and displacements for various rod lengths on a typical set of design curves (Ref. 11). It can be seen that the measured deflection limits are approximately two times the design values (conservative margin) while the force limits fall almost precisely on the design curves.

Cyclic Loading: The overall connection ductility was measured by applying 10 repetitive cycles of inplane (shear) displacements across the connection for successively increasing levels of displacement until failure occurred. The building attachment end of the connection was simulated using an oversized hole and washers (Fig. 3) which are often specified for alignment purposes. Three out of eight connections tested eventually exhibited slip of the rod in the oversized hole even though the nuts were securely tightened to begin with. This type of behavior extended the number of cycles to failure by effectively decreasing the connection stiffness. The practical desirability of this is debatable, but it can be prevented by tack-welding the washers.

Figure 7 summarizes the results of these tests and provides what is perhaps the most significant finding of this study. The push-pull connections exhibit a clear low-cycle fatigue behavior with failure of the rods due to fracture occurring after 47 to 90 cycles. All failures occurred at displacements of less than +/-2 in. (51 mm) which is less than the UBC interstory drift requirement for an 11 ft. (3.35 m) story height. On the basis of these tests it appears that the push-pull connection exhibits the desirable and intended ductile behavior but it may be vulnerable to low-cycle fatigue failure at numbers of cycles well within what might be expected over several moderate earthquakes.

Pullout Tests: The pullout capacity of the loop ferrule insert itself was measured by application of cyclic tensile pullout (normal) forces using the vertical actuator. Only two specimens were tested, and both exhibited good elastic behavior to almost 4 times the specified working load. A typical shear cone failure occurred in both instances, and the reinforcing elements were effective in retaining the insert and in maintaining a minimal level of connection integrity.

Connection Models: A numerical beam model with 24 beam elements and spring-supported ends was used to model the push-pull connection. Strain and displacement measurements were used to estimate model parameters. The effectiveness of this connection model in isolating the panel from the structure was verified using an existing numerical linear frame-panel model of a portion of a typical steel frame building. The possibility of low-cycle fatigue failure will be explored in future studies of overall building models with precast cladding panels supported by push-pull ductile rod connections.

Taken together, these observations confirm the accuracy of both the elastic and inelastic static connection design models, but they strongly indicate that a static analysis alone is inadequate for predicting the earthquake behavior. While it is doubtful that virgin connections will fracture under a single earthquake, it appears likely that some connections will fail after exposure to several moderate or strong earthquakes.

Rigid Connections A variety of different rigid panel connections are employed to support panel gravity loads and to react environmental forces. Of these, the studded weld-plate and to a lesser degree the bolted insert are common to US practice in the Southeast. Both are the subject of ongoing testing using the combined bending and shear loading capabilities of the connection test fixture. In contrast to the push-pull connection, however, these designs have much more complex panel inserts and connection load paths that must react multiaxis loads.

Due to the greater complexity of these designs, testing started first with the inserts alone without the connection elements. The initial series of tests involved a wedge-insert type of bolted connection that employs an askew head bolt wedged in the insert. The bolt attaches the connection element to the insert. The second series of tests involved a more common studded weld plate to which the connection element is welded directly. Figure 8 shows examples of both designs. The first phase of the test program involved application of multi-axis loading (shear, moment and pullout) directly to the insert using the fixture shown in Fig. 1. Response measurements included bending and shear strain at numerous locations on the insert itself and overall rotations and displacements across the insert-connection interface. The test program began with purely elastic loading to characterize the elastic response model. This was followed by cyclic loading to successively greater load levels to characterize the nonlinear response. Testing was continued until the insert failed so that ultimate capacities could be estimated.

Insert Models: Due to the greater complexity of the inserts, it was necessary to develop more detailed numerical models for the inserts themselves in order to properly interpret the test results. The finite element models were of moderate size with a relatively fine mesh for the insert itself and a progressively coarser mesh in the surrounding concrete. Perfect bonding and simple gap models were used to study the effect of concrete bonding on insert behavior. While such representations are less sophisticated than some bond-slip models, they do provide a starting point to study nonideal bonding conditions. Correlation between analysis and experiment was poor due to the variability in behavior of different insert specimens during the tests. Good agreement was found between test data and a linear finite element analysis with perfect bonding for one specimen that showed nearly linear behavior over the loading range. Other specimens exhibited significant nonlinear behavior for loads above a certain level. Gaps with interface friction were introduced to model nonlinearities, but these efforts have been only partially successful to date, indicating that the appropriate boundary conditions for several of the specimens over a portion of their full range of behavior lie somewhere between the debonded and fully bonded states. This clearly indicates the high variability or nonuniformity that may be expected in aspects such as bonding. This phase of the work is described in more detail in Refs. 9 and 12.

CONCLUSIONS

A program of experimental testing and analytical modeling is currently underway to provide quantitative information about the performance of a representative set of connection designs (Ref. 10,12-13). While the initial focus of this work is on the connections, it is anticipated that continuing work will address the properties of the cladding panels, both by themselves and in association with the connections. Specific conclusions at this point in the program can be stated as follows:

1. Experimental tests, along with the analytical models have confirmed the basic behavior assumed for push-pull ductile rod connection designs. Measured stresses and deflections agreed well with linear elastic beam models. The models were able to accurately predict the onset of inelastic behavior at large levels of inplane displacement. The most significant result of these tests was the observation of low-cycle fatigue failure of the ductile rod. In all 8 cases tested, the rods

experienced low-cycle fatigue cracking at one or both ends for displacement amplitudes up to but not exceeding typical (UBC) code provisions for interstory drift. In one half of the cases complete fracture occurred at one or the other end within 25 displacement cycles. This is a cumulative effect and could be reached after several strong earthquakes over a period of time.

2. Initial multi-axis tests of several rigid connection types has yielded information for simple linear and nonlinear models. Agreement with detailed linear finite element models incorporating nonlinear gap elements was generally poor but stated design capacities were found to be conservative. Further tests will be needed to complete more accurate models.
3. The authors are confident that rational engineering principles can be applied to the design of cladding systems on buildings. It is possible that heavy cladding systems will be used in the future for both lateral stiffening and increased damping in buildings (Ref. 5,8-9). However, it must also be recognized that improper or inadequate design of building cladding may lead to failures that could have a detrimental effect on the overall performance of structures during earthquakes.

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REFERENCES

1. Arnold, C., Hopkins, D., and Elsesser, E., "Seismic Design of Architectural Elements," Final Report, Building Systems Development Inc., 3130 La Selva, San Mateo, California 94403, March 1987.
2. Craig, J. I., Goodno, B. J., and Deo, R. B., "Window and Curtain Wall Performance in Highrise Buildings," Report No. GITAER-78-100/SCEGIT-78-170, Schools of Aerospace and Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia, March 1978, 351 pages.
3. Goodno, B. J., Craig, J. I., Meyyappa, M., and Palsson, H., "Cladding-Structure Interaction in Highrise Buildings," Final Report, NSF Grant No. CEE-7704269, (NTIS Report No. PB83-195891), January 1983, 614 pages.
4. Goodno, B. J., Palsson, H. P., and Pless, D. G., "Localized Cladding Response and Implications for Seismic Design," Proceedings, *Eighth World Conference on Earthquake Engineering*, San Francisco, CA, July 21-28, 1984, Vol. V, pp. 1143-1150.
5. Goodno, B. J., and Palsson, H., "Analytical Studies of Building Cladding," *Journal of Structural Engineering*, ASCE, Vol. 112, No. 4, Paper 20498, April 1986, pp. 665-676.
6. Goodno, B. J., and Pinelli, J. P., "The Role of Cladding in Seismic Response of Lowrise Buildings in the Southeastern U.S.," Proceedings, *The Third U.S. National Conference on Earthquake Engineering*, held in Charleston, S.C., on August 24-28, 1986, Vol. II, pp. 883-894.
7. Palsson, H., and Goodno, B. J., "A Degrading Stiffness Model for Precast Concrete Cladding," Proceedings, *Seventh European Conference on Earthquake Engineering*, Athens, Greece, September 20-25, 1982, Vol. 5, pp. 135-142.
8. Palsson, H. P., 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.
9. Goodno, B. J., Meyyappa, M., and Nagarajaiah, S., "A Refined Model for Precast Cladding and Connections," to be presented at the *9th World Conference on Earthquake Engineering*, to be held in Tokyo, Japan on August 2-9, 1988.
10. Leistikow, R., "The Behavior of the Ductile Rod/Push-Pull Connection for Precast Cladding Panels," MSCE Special Problem Report, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia, March 1988, 252 pp.
11. McCann, Ray A., private communications, August 19, 1987.
12. Meyyappa, M., Goodno, B. J., and Fennell, C. J., "Modeling and Performance of Precast Cladding Connections," Proceedings, *The Fifth ASCE Specialty Conference on Computing in Civil Engineering*, held in Alexandria, Va., on March 29-31, 1988, pp. 209-218.
13. Craig, J.I., Goodno, B.J., Keister, M.J., and Fennell, C.J., "Hysteretic Behavior of Precast Cladding Connections," Proceedings, *Third ASCE Engineering Mechanics Specialty Conference on Dynamic Response of Structures*, held at UCLA on March 31-April 2, 1986, pp. 817-826.

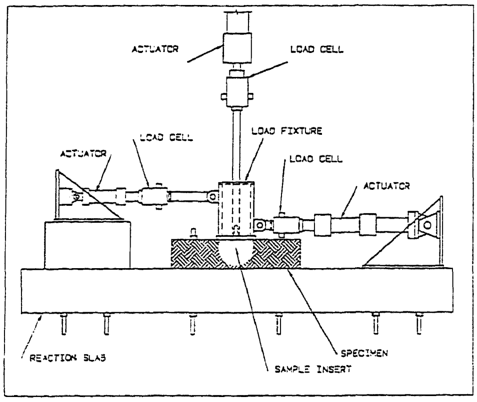

Fig. 1 Connection Test Facility

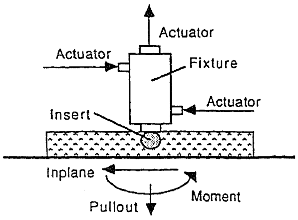

Fig. 2 Connection Loading Schematic

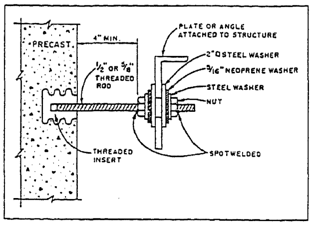

Fig. 3 Typical Push-Pull Connection

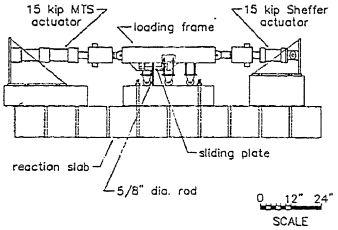

Fig. 4 Push-Pull Connection Test Fixture

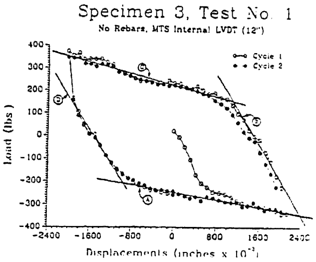

Fig. 5 Typical Push-Pull Connection Behavior

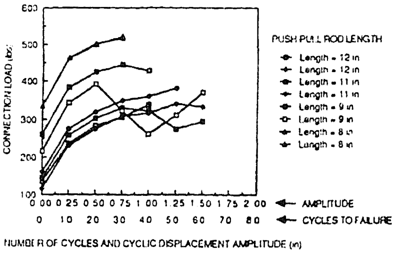

Fig. 6 Push-Pull Comparison with Design Chart

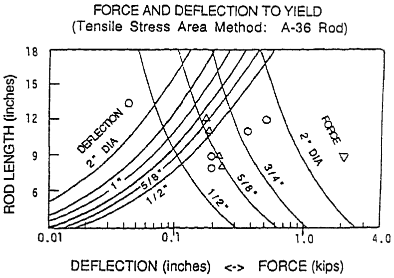

Fig. 7 Push-Pull Cyclic Performance to Failure

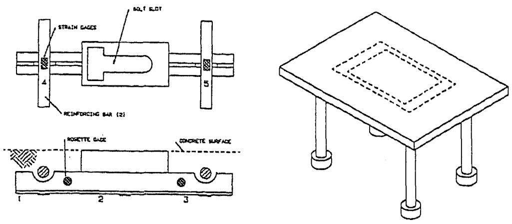

Fig. 8 Typical Wedge-Insert and Weld-Plate Connections