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Modeling and evaluation of ductile cladding connection systems for seismic response attenuation in buildings

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ABSTRACT: Empirical models for the constitutive behavior of ductile connections between heavy cladding and the supporting building structural system are developed from laboratory measurements of their response to inplane and gravity loads. The design of the experimental facilities and the test fixture designed to carry out these specialized tests are described. The models, which include connector elements with optional inserts/anchors at both ends, are based on mechanical representations constructed from atomic elements. Parameters for the component atomic elements are identified directly from test data using parameter estimation methods. Predicted and measured energy dissipation are shown to be in excellent agreement for these models. Finally, the application of the models in DRAIN-2D is described. Simulation of the earthquake behavior of a simple 6 story steel frame structure with attached heavy cladding panels is carried out for a representative earthquake, and results that describe the behavior of both the insert and connection elements of a composite connection are discussed. The computed performance suggests that it should be possible to design and build advanced-concept ductile cladding connections that offer the potential to provide significant levels of structural ductility for a structural system.

1 INTRODUCTION

It has been well established that attenuation and control of the seismic response of tall buildings can be achieved through ductile inelastic action of the structural system. This has traditionally been achieved by deliberate design of structural details, such as eccentric bracing, that will develop well-behaved inelastic action without critical loss of general structural integrity or stability. At the same time there has been widespread interest in the possible application of pre-engineered ductile elements, devices or mechanisms that can augment the ductility of a conventional structural system. While these approaches are generally used to handle severe conditions, similar methods can also be applied to other building subsystems, such as cladding, not traditionally considered to play a structural role. The result can be an overall design capable of achieving significant response reductions for moderate seismic loads.

Research [Oppenheim 1973, Goodno 1986, Henry 1986] has pointed to the potential role that properly designed precast concrete cladding can play in providing lateral stiffness, ductility, and energy dissipation to the overall building structure, especially during strong ground motions. Experimental studies and extensive analytical modeling carried out at Georgia Tech and elsewhere point to the critical role that the cladding connections play in this process [Sack 1981,Rihal 1988]

In order to utilize this interaction and therefore develop cladding system participation in structural response, it is necessary to develop advanced connection designs. Such designs must provide superior properties of ductility and damping and result in high energy dissipation without failure during moderate or strong earthquakes. As presented in this paper, the strategy for development of such advanced connections involves:

(1) the identification of advanced cladding connection designs that by various means are able to develop high levels of ductility for inplane racking loads. Some designs can provide racking ductility only while others can also support gravity (bearing) loads.
(2) the fabrication at full scale, and testing of several designs in a specially designed laboratory fixture.
(3) the formulation of different types of highly nonlinear constitutive models to represent the observed behavior, using measured response and ultimate failure modes. These models can be combined with similar models for the panel and structural anchor systems to yield a complete cladding-connection model.
(4) the incorporation of the more promising connection models into a 2D computational structural model of a six story building subjected to seismic loading. The structural model was developed as part of a companion study and is based on DRAIN-2D with the addition of a special cladding connection element and a truss-based cladding panel model.

The behavior of the structure in response to representative earthquake records can then be compared to unclad and conventionally clad configurations.

2 ADVANCED CONNECTION ELEMENTS

The action of an advanced cladding connection can be described as follows. A cladding panel on a building facade is generally attached at four points, two at the bottom (usually bearing type connections) and two at the

top (usually tie back connections). During an earthquake the main behavior will be cyclic in-plane (racking) displacements of the panel, and the connections are subjected to three simultaneous effects:

(i) inertia forces generated by the acceleration of the panel transmitted from the panel to the main structure via shear loading of the connectors.

(ii) at the same time, the horizontal interstory drift is resisted by the panels and this results in horizontal shear forces in the connections.

(iii) finally, the bearing connections support the gravity load of the panels.

Traditional design of connections tries to cancel the second effect, through a sliding mechanism for example [PCI 1988], that will isolate the panel from the main structure. The advanced connections proposed in this research seek to take advantage of this interaction to dissipate energy, therefore reducing the response of the main structure.

There are generally three main parts in the advanced connection of a precast cladding subsystem (see Fig. 1). First, the attachment points built into the precast panel, which typically consist of steel inserts imbedded in the concrete panel, provide the panel anchorage. Second is the connector body which forms the structural connection between the cladding panel and the main structure. The third element is the attachment to the main building structure (e.g. another steel insert embedded in the concrete frame).

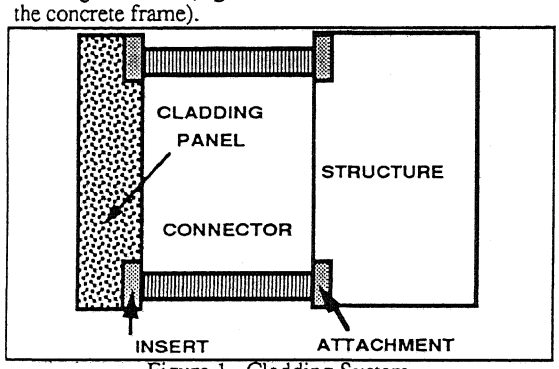

Figure 1. Cladding System

All parts are important, and the behavior of the attachment points, or inserts, has been extensively analyzed in a previous test program [Pinelli 1990]. From the data available from these tests, it is evident that currently used inserts are not by themselves capable of providing the levels of ductility and damping required from an advanced connection without loss of strength and integrity. Therefore, in an advanced connection the energy dissipation must occur in the connector body if the integrity of the concrete panels is to be maintained.

Several ideas for advanced connector bodies are summarized in Fig. 2. Ductility and damping can be developed through a number of different passive processes including:

- extrusion.
- inelastic connector action initiated through torsional or flexural effects in the connection element.
- friction effects developed in slip processes for connectors designed with layered materials and fastened with bolts in oversized holes.

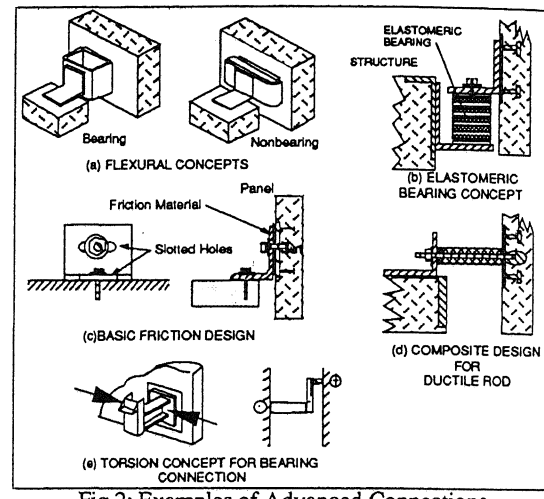

Fig 2: Examples of Advanced Connections

- use of composite systems manufactured with materials selected for strength and ductility.

Several of these processes are the basis for actual connection designs. Palsson (1984) carried out an early study of cladding interaction with the supporting building structure and proposed the use of friction material in the panel connections to enhance energy dissipation through the addition of coulomb damping. Pall (1989) has developed a number of commercial structural elements that rely on coulomb 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.

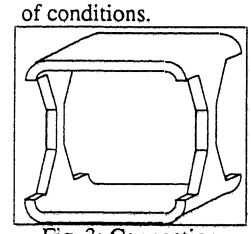
Fig. 3: Connection

Keeping in mind that the ease of manufacturing and maintenance is as important as a good performance, a series of simple designs were formulated first. They all take advantage of plastification of the steel when stressed beyond yielding in flexure. Details are shown in Fig. 3, but the connection is used as shown in Fig. 2(a).. The connector consists of a section of square tube, 0.95 cm thick and 10 cm wide, cut away as shown to create two narrow flexural elements whose widths are tapered to initiate plastification over a greater portion of material. In the following sections the results of test evaluations of these connections are provided.

3 TEST FIXTURE

In the analysis of a facade precast cladding behavior during a seismic event, the out of plane and vertical

motions of the panels are overlooked because they are judged to be of little significance when compared with the in-plane motion induced by horizontal interstory drift. The tie-back connections which hold the panel in place will therefore be subjected mainly to horizontal shear. The bearing connectors which resist the weight of the panel will experience a combination of horizontal shear and gravity load. Axial effects (perpendicular to the plane of the panel) are assumed negligible for the designs studied.

Therefore, in the test machine, the main goal was to achieve shear loading of the specimen without inducing any axial or torsional effects and while maintaining the two end faces of the specimen parallel to each other. In addition, in view of the relatively small inertia of the connector, and the fact that the energy dissipation mechanisms being investigated are assumed to be mainly hysteretic, it was decided that the tests could be quasi-static with the ability to apply cyclic loads or displacements of varying amplitude.

All the requirements for the test fixture were met by a mechanism whose planform schematic is presented in Fig. 4. The plain line drawing represents the mechanism in its initial undisturbed position, while the dashed line drawing represents the configuration of the mechanism after some load or displacement has been applied. The connection being tested is represented by a line segment between a rigid panel anchor member and a rigid building anchor member. The panel anchor member is supported by articulated arms which rotate around their fixed supports. When a displacement or force is applied, the panel anchor displaces parallel to itself but also moves laterally to the forcing direction. At the same time, the connector is subjected to a load at one end and

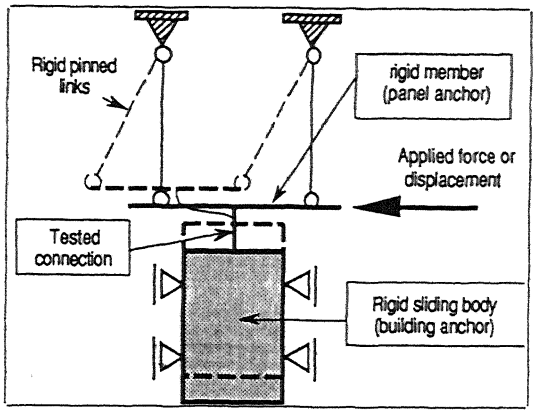

Figure 4: Schematic of the Test Fixture

bends as shown. Because the rigid support at the other end is free to slide in an axial direction with respect to the connection element, it moves to cancel any axial forces in the connection and compensate for the lateral motion of the horizontal member and the bending curvature of the connector.

This mechanism is the basis for the test fixture shown in Fig. 5, where the top view is a realization of the schematic of Fig..4. The fixture is mounted on a pair of steel I-beams welded to a reaction wall. The device is composed of:

(a) a rigid steel box (the building anchor) supported on eight roundway bearings. As shown in Fig. 5, the bearings are attached to two steel frames which are mounted on one of the steel I-beams. The box

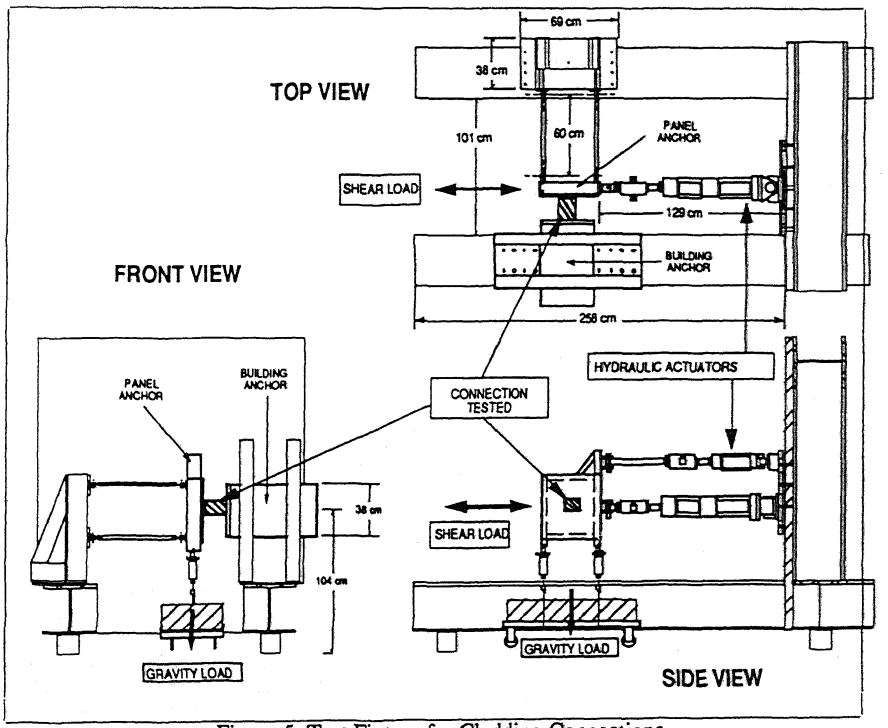

Figure 5:.Test Fixture for Cladding Connections.

slides back and forth inside the two frames;

(b) a rigidly framed square platform (the panel anchor), facing the steel box. It is prevented from out of plane rotations by means of four rigid links, hinged at both ends through the use of Teflon lined spherical bearings. Therefore, it can move parallel to itself in the horizontal and vertical directions. The links connect the platform to,

(c) a framed rigid support, mounted on the other I-beam. The link attachments are fully adjustable for proper alignment of the fixture for any specimen;

(d) two hydraulic actuators with force capacity of +/- 67 kN, connected to the square platform and mounted against the reaction wall. The lower (main) actuator applies shear loads or displacements while the upper actuator prevents the platform from rotating in its own plane. Both are coupled with 89 kN load cells;

((e) two smaller hydraulic actuators that lift the required masses to simulate gravity load in the case of bearing connections.

All the objectives governing the design of the machine as described above were addressed by this design. The machine creates a reasonable approximation of the service conditions for a connector, and any kind of specimen can be tested, scaled as desired, and oriented as necessary with respect to the direction of loading.

In this research program only displacement controlled quasi-static cycles were applied, simulating interstory drifts. Cycles of increasing displacement are applied in small step increments. Alternatively, the specimen can be tested in fatigue by applying a number of cycles of equal amplitude.

4 TEST PROGRAMS

The machine was used to test a variety of advanced cladding connections of the type shown in Fig. 3. A brief summary of the results of these test programs is presented here. A more exhaustive presentation of the test results will be presented in a future publication.

The corresponding test results are shown in Fig. 6, for the tapered case (see Fig. 3). This connector shows an advantageous hysteretic behavior, with fat, stable loops. In the case of an untapered specimen, the plastic deformation is limited to a finite region at both ends of the webs which results in a high demand in curvature and strain at these locations. This leads to a premature failure of the specimen. On the contrary, the tapered specimen , by distributing uniformly the plastic deformation over the webs, dissipates more energy, and can sustain a large number of cycle reversals without failure. Further tests showed that:

(1) the specimen exhibits good fatigue behavior

(2) whether the specimen is bolted or welded has no influence on its behavior.

(3) the specimen can sustain gravity loads without losing its energy dissipation capabilities.

In previous test reports on tapered specimens [Skinner 1973], the key issue has always been the provision of a sufficiently fixed condition for the ends of the tapered beams. The design presented here provides a simple and elegant solution through the reduced width of the flexural elements. In addition, the fact that the connector can be bolted to the insert with a single bolt makes it very attractive from an installation and maintenance point of view. Finally, the results indicate that some of these designs could be used for combined bearing and energy dissipating connections.

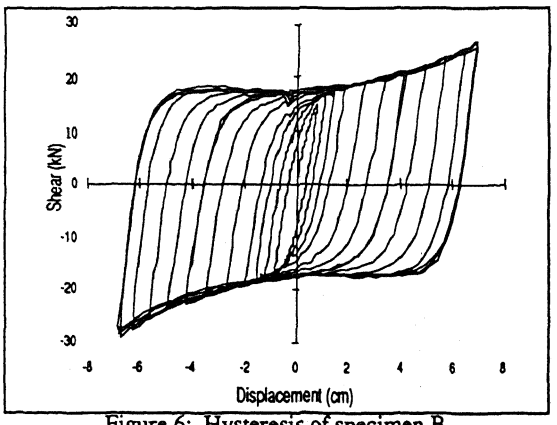

Figure 6: Hysteresis of specimen B
(1 in = 2.54 cm - 1 kip = 4.45 kN).

5 CONNECTION MODEL

Based on the experimental results from the tests outlined above, analytical flexural models of the connector which closely reproduce the observed nonlinear hysteretic characteristics were developed. A mechanical modeling philosophy was pursued. The distributed deteriorating element model [Iwan et al. 1986] is one such approach and was adapted in this research. The physical system is represented by a parallel-series model made of a combination of linear springs and Coulomb slip elements whose properties (stiffness, friction load, etc.) are based on the observed properties of the system.

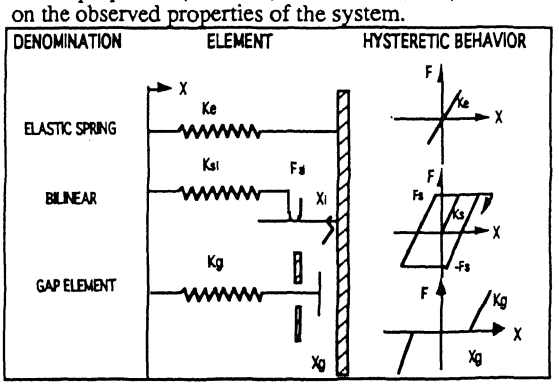

Figure 7. Schematic of the Deteriorating Degrading Element Model

Figure 7 shows the basic three elements used in the mechanical models for the present study together with a representation of their hysteretic behavior:

(1) a linear elastic element defined by its stiffness;

(2) a bilinear element defined by its stiffness and yield load, that provides the hysteretic behavior

(3) a "gap" element defined by its stiffness and gap width, that provides the strain hardening.

Ideally, for a parallel-series mechanical model, it might appear that any type of behavior could be satisfactorily

approximated by a sufficient number of elements with suitable properties. But with no limit to the number of parameters, it can easily become difficult to determine the correct (optimal) values of the parameters, and the computational effort may rapidly increase.

To solve this problem, an optimization procedure was developed. The objective was to be able to reproduce consistently an observed hysteresis behavior without having to go through a time consuming process of trial and error when selecting the parameters. The procedure ensures that the difference between the experimental behavior of the connection and its modeled analytical behavior be kept to a minimum with a special care in preserving in the model the observed properties of stiffness, damping and ductility. In this procedure, the objective function being minimized is the sum of squares of the differences in selected parameters of the analytical hysteresis loops with respect to the test loops. The constraints are related to the model formulation, e.g. the stiffnesses of the atomic elements have to be positive, or the ratios yield force over stiffness are bracketed by given values. The resulting optimization problem is nonlinear, with several constrained variables.

The optimization procedure is described with more details in a paper currently being prepared. An example is presented here where the behavior of one of the tapered connections was modeled. Fig. 8 shows the resulting hysteretic cycles for a tapered specimen identified as TB250, superimposed against the experimental results. In addition to the linear element, and the gap element, a total of four bilinear elements was necessary for the modeling of the connector. This is a reasonable number which provides eleven parameters in total. It can be seen that the agreement is indeed very satisfactory. The total energy dissipated by the analytical model in the twenty recorded cycles differs only in 6.15% from that measured in the lab.

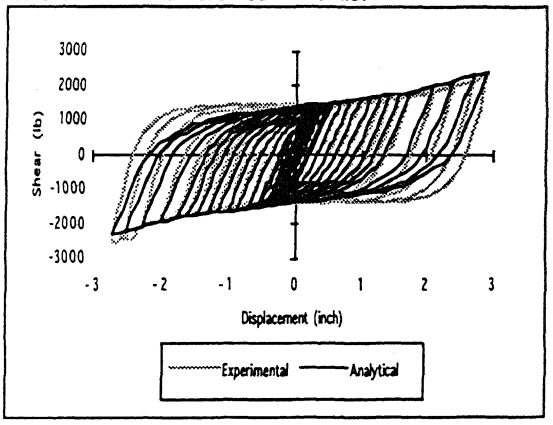

Figure 8 . Mechanical Hysteresis Cycles - Connector TB250 (1 in = 2.54 cm - 1 kip = 4.45 kN)

6 CLADDING SYSTEM MODELING

The mechanical model of the connection were incorporated into a two dimensional structural model of a six story building, scaled to 1:4 of its actual dimensions. The structural model was developed as part of a companion study [Goodno 1992] and is based on DRAIN-2D with the addition of a special cladding connection element and a truss-based cladding panel model.

Figure 9 summarizes the analytical procedure. The structure carries two heavy cladding panels per bay. The lower (bearing) connections of the panels are forced to be rigid. At the upper connection, between the panel nodes and the structure nodes, the connection system is simulated by a combination in series of two rotational springs (simulating the attachments), and a translational spring (simulating the connector body). Each of these springs is assigned a hysteretic mechanical model, and the parameters of each model are based on the experimental results. All model parameters were scaled to match the characteristics of the test frame. For the connector body, the stiffness was scaled 1:4 and the yield force 1:16, resulting in a yield displacement of 1:4. The action of the three springs in series is condensed into one translational spring, one in the horizontal direction, one in the vertical direction.

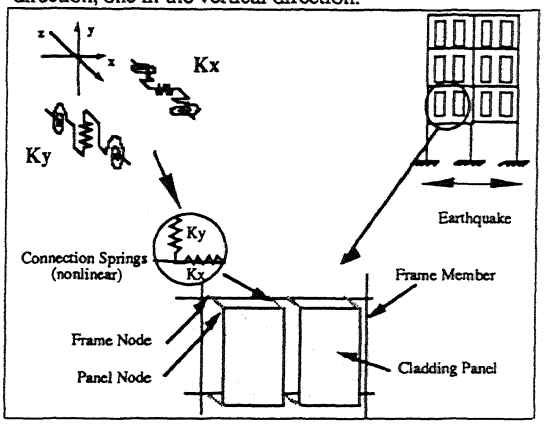

Figure 9: Cladding System Modeling

The frame was subjected to the first 9 seconds of 25% of the 1940 El Centro Earthquake, which corresponds to the full earthquake loading on a real structure. In Figs. 10 and 11, horizontal motion hysteresis loops for the connector body and the insert are given for the tie-back connection at the first floor level. The connector body is responsible for the majority of energy dissipation, while the inserts remain largely within the elastic range. Results for typical cases show that the connector

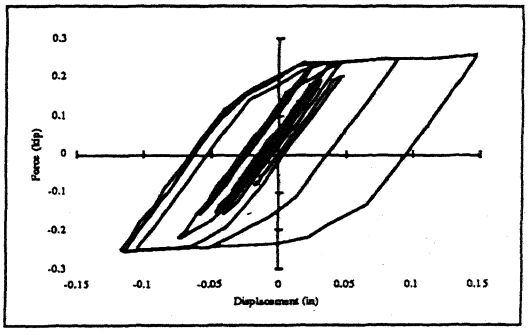

Figure 10: Hysteresis Connector Body

elements are responsible for over 95% of the energy dissipated in the connector system. This shows that the damping can be successfully concentrated in the connector element, as intended, and that the insert can be spared serious damage. Comparisons between the clad and unclad behavior of the building are given in [Goodno 1992].

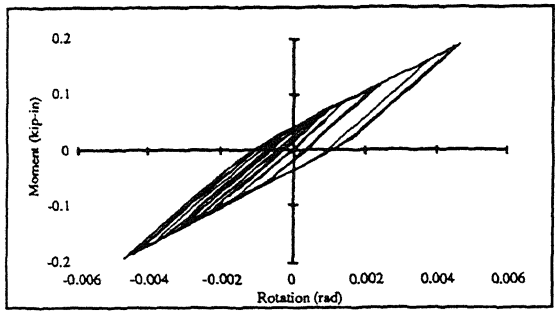

Figure 11: Hysteresis Insert

7 CONCLUSION AND FUTURE RESEARCH

A machine has been presented that permits the testing of cladding connections under a reasonable approximation of their actual service conditions. A main advantage of the facility is its versatility for testing different kinds of damping connections, without geometric or attachment limitations and with or without geometric scaling. Another advantage is its ability to load the specimen in shear and flexure without inducing significant axial effects. The tests yield hysteresis plots from which the properties of damping, ductility, strength, and stiffness are evaluated.

The results of the first tests carried on have been briefly presented. A series of additional tests, involving different types of energy dissipation mechanisms for the connector body in a connection system will follow. It is anticipated that this research will lead to innovative ways of viewing the entire cladding system. Test results coupled with the appropriate analytical studies should confirm the possibility of integrating cladding into the structural system of a building through utilization of the cladding connections as a passive system to attenuate seismic response

ACKNOWLEDGMENT

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