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AN OPTIMAL DESIGN APPROACH FOR PASSIVE DAMPING OF BUILDING STRUCTURES USING ARCHITECTURAL CLADDING

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ABSTRACT

Architectural cladding panels with special energy dissipative connections can be an effective passive control system for buildings in seismic regions. Advanced cladding connections utilize the interaction between the panels and the building structure to dissipate energy. At the same time, like other passive control devices, they provide additional lateral stiffness to the structure and alter its dynamic characteristics. A design criterion formulated in terms of energy provides the optimal balance of stiffness and energy dissipation to be added to the structure by the cladding connections. Nonlinear models of advanced connections were incorporated into a two dimensional structural model of a building with two cladding panels per bay. The response of the structure to a variety of seismic motions is presented, along with time histories of energy demand and supply for several earthquake excitations. Results show that, when designed according to the proposed criterion, energy dissipative cladding connections can provide the total hysteretic energy required of the structural system. The reduction in floor and interstory displacements depends on the relationship between the modified fundamental frequency of the structural system and the critical frequency of the ground motion.

KEYWORDS

nonstructural elements; cladding; ductile connections; energy dissipation; hysteresis; optimization; design integration; passive control; nonlinear dynamic analysis.

INTRODUCTION

Architectural cladding on buildings is normally considered nonstructural and special attachments are used to isolate the exterior panels from potentially damaging interstory motions due to wind or earthquake. The main advantage of this approach is that it greatly simplifies the design process. However, the interaction between the nonstructural elements and the structure, when not accounted for, can be detrimental to the performance of the structure, possibly leading to damage or collapse of the entire system. The interaction between the different elements can be underestimated due to a lack of understanding of the complexity and magnitude of the seismic loading. The attachments meant to isolate an element can be overstretched, a gap might be too small, a connection not flexible enough, a slot too short. In other cases due to lack of maintenance and passing of time, the efficiency of some connections may be reduced (e.g. rust might prevent the sliding of slotted connections).

Nonstructural elements act as links between different parts of a structural system. When these different parts have different motions as a result of an earthquake, a displacement induced energy dissipation can be triggered in the links between the parts. If the links, i.e. the nonstructural elements, are specially designed for this purpose, they could dissipate most of the energy input to the structure by the seismic event. Such an approach requires a change in design philosophy. If an integrated approach is to be followed, then it is preferable to use global energy as a measure of the seismic performance. In addition, it must be recognized that using nonstructural elements as physical links between part of the structure to dissipate energy through hysteresis, the overall lateral stiffness of the structure will be increased by the "bracing" effect of these links. This stiffening, and the damping resulting from the energy dissipation may not result in better performance. While damping will attenuate the dynamic response, concurrent stiffness changes may amplify the response by shifting key structural frequencies into critical ground motion spectral ranges. The key to this new concept of cladding participation is the development of so-called advanced, or engineered, connections. Advanced connections should exhibit superior properties of ductility and damping that would result in high energy dissipation without failure during moderate or strong earthquakes. These connections must also limit the forces transmitted into/through the panel. By using advanced cladding connections with structural cladding, significant advantages can be achieved over more conventional designs (*Goodno and Palsson, 1986*). The energy dissipation can be distributed more evenly over the height of the building, and does not involve structural members, therefore structural integrity is preserved. Due to the increased damping, the overall response of the building can be reduced, and displacements and interstory drifts in some cases can be maintained between acceptable limits. Such an approach leads to improved and economically achievable levels of safety and performance that are comparable to or even better than more traditional design alternatives.

ADVANCED CLADDING SYSTEM

Cladding connection systems can be broken down into three basic component parts: an anchor or insert in the precast concrete panel; the connector body; and an anchor or insert in the structure (Fig. 1). There is considerable variation in the design of each of the three major components depending upon the function of the connection (bearing or tie-back), the type of connection (welded or bolted), the architectural requirements, and other considerations (*PCI 1988*). An experimental test program (*Pinelli, et al. 1990*) provided information on the behavior of cladding connections anchors when subjected to these combined shear and bending actions. The data available from the tests showed that inserts embedded in concrete are not by themselves capable of providing the levels of ductility and damping required from an advanced connection without loss of

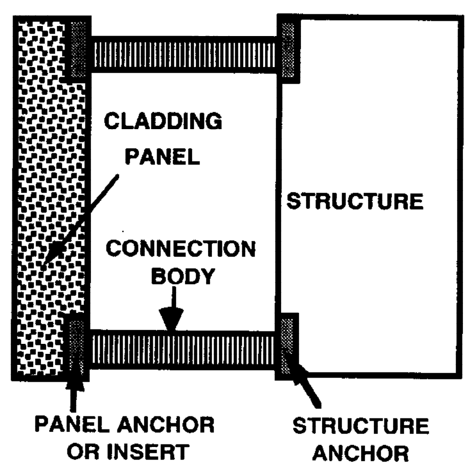

Fig. 1 Typical Cladding System

strength and integrity due to extensive cracking of the concrete surrounding the insert. In an advanced connection, the energy dissipation must occur in the connector body if the integrity of the concrete panels is to be maintained, and the anchor must be kept in the linear elastic range (*Pinelli, et al, 1995*). The yielding of the connector produces the necessary energy dissipation and protects the anchors by limiting the load that can be transferred through the connection. A series of simple flexural designs for advanced cladding connection bodies was formulated. Similar energy absorbing steel devices have been reported in the literature for energy dissipating bracing connections (*Whittaker et al. 1991*). A sample advanced cladding connector is shown in Fig. 2. It consists of a segment of square structural tube with portions cut away to create two narrow flexural elements whose widths are tapered to initiate plastification over a greater portion of material. The two tapered beams in flexure have a smaller maximum width through the cut-away than the fixed untapered elements, to ensure that they will deform with double curvature. Several tubes with different thicknesses were tested in a specially designed laboratory test machine (*Pinelli et al. 1992*). A typical hysteresis curve from the tests is shown in Fig. 3. The tapered advanced connections performed well in the tests, providing desirable levels of energy dissipation, fatigue behavior, ductile failure, and combined lateral and vertical load carrying capability (*Pinelli et al. 1995*).

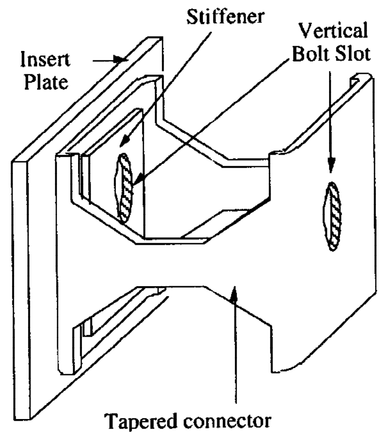

Fig. 2 Advanced Connection

ANALYTICAL MODEL OF CASE STUDY STRUCTURE & CLADDING

The advanced connection model, for both the bearing and tie back connections, is represented in Fig. 4. The anchors of each connection were modeled as linear elastic rotational springs with a stiffness equal to the initial stiffness measured in the tests for a steel insert. In the horizontal and vertical directions of the bottom bearing connections, the connection body was assumed to be a very stiff linear elastic spring. The connection body of the upper tie-back connections was represented in the horizontal direction with a nonlinear translational spring with varying stiffness k and yield load fy. When incorporated into the 2D model of the building (Fig. 5) (an existing 1:4 scale, 546 cm. high and 366 cm. wide, steel test frame used in passive and active control studies at NCEER - see *Reinhorn 1989*), at each panel connection location, the connection model of Fig. 4(a) was reduced to a single unidirectional nonlinear translational spring with stiffness kc (Fig. 4(b)). For the cladding-to-frame interaction studies, two cladding panels per bay were attached as shown in Fig. 5(b), with one fourth of their mass lumped at each panel node. The panels were assumed rigid and each one was modeled with a single plane stress element. The mass of the

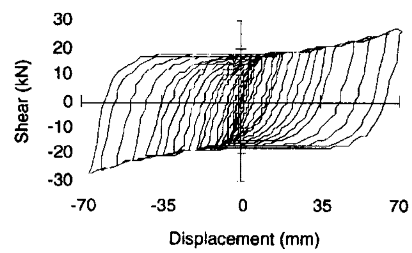

Fig. 3 Hysteresis Loops for Advanced Connection

complete unclad frame is 19051 kg. Addition of cladding increased the total building mass to 26400 kg. Additional mass provided by the cladding can result in a shift of vibration frequencies of the building toward either a more or a less critical earthquake ground motion frequency range, resulting in higher or lower seismic response. The outcome depends on how the frequency of the unclad structure is positioned with respect to the critical frequency range of the earthquake. The unscaled frequencies for the two lowest modes were measured to be 1.17 Hz and 3.88 Hz. A more detailed description of the model is given in (*Craig, et al, 1992, & Goodno, et al, 1992*).

DESIGN OF ADVANCED CONNECTIONS

The best advanced connection design is that which provides the highest ratio Ec/Ei, where Ec is the total hysteretic energy dissipated in all the connections on the facade, and Ei is the relative energy input to the structure at the end of the motion. Input energy Ei is the sum of: Ek (relative kinetic energy); Es (recoverable elastic strain energy); Ed (viscous damping energy); and Eh (irrecoverable hysteretic energy) (*Uang and Bertero 1990*). The key is to find the optimal balance of stiffness and yield strength to be added to the system by the cladding connectors that will result in a maximum energy dissipation and reduced overall response. The advanced connections concentrate the energy dissipation away from the structural members in discrete replaceable devices.

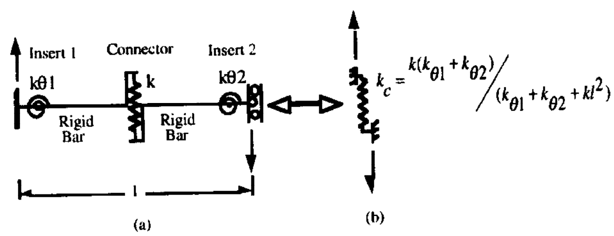

Fig. 4 Advanced Connection Model

The design criterion as stated above is a constrained optimization problem. The objective function to be optimized (maximized in this case) is the ratio of energies Ec/Ei, and the constraints are as follows: (1) the ductility demand on any of the connections should not exceed an allowable value (50, not the actual maximum ductility that the connector would exhibit during the loading history - see below); (2) the connection should be able to satisfy the minimum code requirement regarding strength (44.5 kN is the upper bound placed on fy to avoid damaging the cladding panels); and (3) the forces induced in the panel by the connections should not exceed the panel capacity (here taken as 4.27 kN). For purely practical reasons, additional constraints must be added for: connector length (at least 15 cm, for ease of manufacturing and installation); connector taper (min. width of 15 mm); and connector thickness (min. of 6.4 mm). Note that a more comprehensive definition of ductility (*McCabe and Hall (1989)*) was adopted. Here, equivalent monotonic plastic ductility, or ductility demand, is the maximum plastic ductility that the system should exhibit in a monotonic loading test in order to dissipate the same amount of energy as that obtained

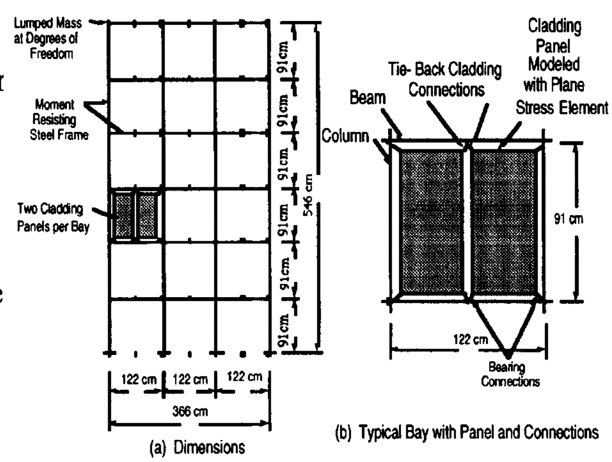

Fig. 5 NCEER Test Frame With Cladding

during the cyclic loading. To solve this standard optimization problem, a modified version of program DRAIN-2D (*Kanaan and Powell 1973*) was combined with the optimization program CONMIN (*Vanderplaats 1973*). Since no explicit functions exist for the objective function and the first constraint, their gradients were computed by finite differences, and the optimizer solved the optimization problem by the method of feasible directions.

PARAMETRIC STUDIES OF BUILDING WITH CLADDING

The validity of the proposed design criterion was investigated through different case studies. The *reference case* was the conventionally clad structure with the cladding contributing only mass but no lateral stiffness to the dynamic properties of the building. For the reference case, the unscaled frequencies for the two lowest modes were computed to be 1.11 Hz and 3.46 Hz. Next, cladding participation was activated through advanced upper tie-back connections, and the building model was subjected to a variety of different ground motions. For each ground motion, the reference case was compared to that of the actual tapered connector described previously (Fig. 2). The yield load, fy, and the initial stiffness, k, of the energy dissipative upper tie-back connectors were varied to obtain an optimal solution satisfying the contraints listed above.

Three different earthquake records were selected on the basis of their frequency content to investigate cases in which the fundamental frequency of the building was below, very close to, and above the critical frequency range of the earthquake. The earthquake records considered were: 1940 El Centro NS; 1985 Chile 20SW; and 1952 Kern County 48SE; each was scaled so as to produce substantial damage in the reference case structure. Potential damage was measured as the amount of energy dissipated through plastification in the structural members, the magnitude of the top floor displacement, and the maximum interstory drift.

First, 42 cases were investigated for the Kern County record, with the stiffness (k) of the cladding connections ranging from 0 to 53 kN/cm, and their yield load (fy) ranging from 3.6 to 9 kN. The results are summarized in a contour plot of energies Ec/Ei and ductility demand (DD), for varying combinations of k and fy (Fig. 6). For an ideal case (elasto-plastic connectors), the optimal values of k and fy were found to be 35.0 kN/cm, and 6.4 kN respectively, for a maximum ductility demand of 50 (see black dot on ductility constraint line in Fig. 6). The optimal design point for the *tapered connector case* is also shown in Fig. 6. This case is limited by the additional constraints on connector dimensions noted above, and these constraints define a wedged-shaped feasible region for the tapered connector which does not include the ideal optimal point, which is limited only by the ductility constraint. Now the optimal values of k and fy are 13.7 kN/cm, and 6.4 kN respectively. Hence, the ideal optimum and tapered optimum connectors do not coincide, at least in this case. However, even when away from the optimal point, results shown below will demonstrate that a tapered dissipator can still provide

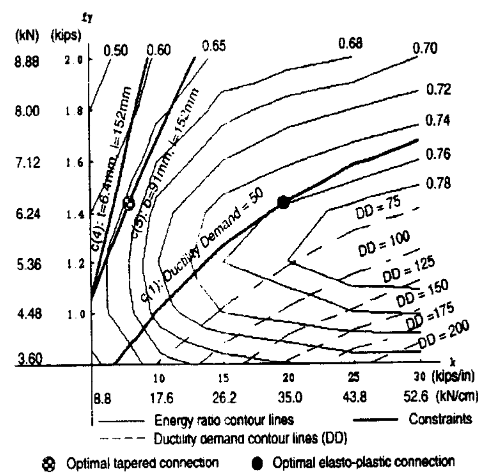

Fig. 6 Contour Plot of Ec/Ei and Ductility Demand (DD) for Kern County Earthquake

sufficient energy dissipation to protect the structure and reduce its response for this ground motion case.

Interstory drift envelopes (expressed as a fraction of story height) are presented in Figures 7-9 for the three ground motions considered. The effectiveness of the advanced connections dissipating input energy and controlling displacements depends on the relation between the fundamental frequency of the structure and the critical frequency of the earthquake. For the El Centro ground motion (Fig. 7), the building frequency is lower than the critical frequency, and the stiffening effect of the cladding tends to increase the response of the structure, partially counteracting the reduction due to the energy dissipation. For the Chilean earthquake, the frequency of the clad structure is very close to the critical frequency of the earthquake and the energy input to the structure increases from 1027 kJ to 1846 kJ when the advanced connections are added. The ductility demand on the connection is also increased but 70% of the input energy is dissipated in the connections, resulting in a reduction in interstory drift of from -23% between floors 5 and 6, to -13% between floors 3 and 2 (Fig. 8). Finally, when the fundamental frequency of the building is higher than the critical frequency of the earthquake, both the stiffening effect of the cladding and the energy dissipation contribute to a reduction in the seismic response. This is the case for the Kern County earthquake, where the input energy is reduced from 721 kJ to 318 kJ, at the same time that maximum interstory drift is reduced by 53% with tapered cladding connectors (Fig. 9). The effectiveness of advanced tapered connections vs conventional isolating cladding connectors is also compared in the energy-time history plots in Figs. 10 and 11. Here it can be seen that the hysteretic dissipation in the structural members was totally eliminated by the addition of the advanced connections.

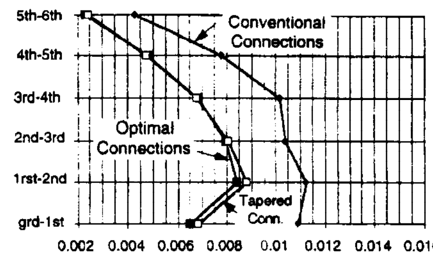

Fig. 7 Drift Envelopes, 1940 El Centro

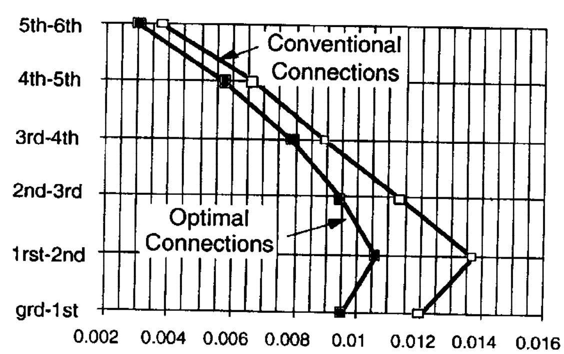

Fig. 8 Drift Envelopes, 1985 Chile

CONCLUSIONS

These experimental and analytical investigations demonstrate the feasibility of the concept of passive control of structures through use of heavy exterior cladding. Ductility demand and geometric constraints govern the selection of an optimal cladding connection design. As an example, a very simple prototype for an advanced cladding connection was presented. The analyses revealed that this prototype, a tapered connector, was not able to always satisfy the ideal optimum conditions in all cases. Stiffening and damping are the conflicting attributes of such energy dissipating devices. While damping will attenuate the dynamic response, concurrent stiffness changes may amplify the response by shifting key structural frequencies into critical ground motion spectral ranges. The optimal design philosophy presented here for advanced cladding connections reconciles the two through the integration of nonlinear analysis software with optimization techniques.

The design approach is based on the optimization of the entire building system in terms of energy dissipation. It results in an overall seismic response reduction along with preservation of the structural integrity of the framing members. The design method itself is a constrained optimization problem which can be used to investigate different types of connections, and which can be adapted to any panel configuration as well as to any specific site ground motion. The tapered energy dissipator will always be successful in preserving the structural integrity of the building, if its ductility capacity is not exceeded. Depending on the earthquake record, the control of displacement might be less successful which suggests that in some cases advanced cladding could be combined with other active control devices in a hybrid system. Although much more experimental data on the behavior of entire cladding systems will still be needed and there are no current code provisions, advanced energy dissipating cladding systems are ready for serious practical consideration. This technology could be applied to both new and retrofitted structures. The introduction of a structural dimension to architectural cladding, and other traditionally non-structural elements, will lead to safer and more economical buildings.

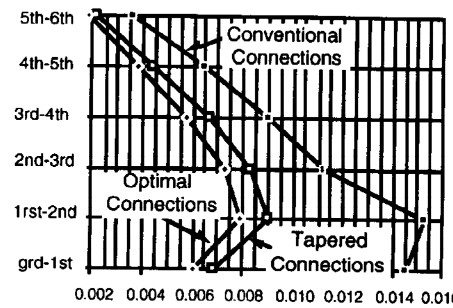

Fig. 9 Drift Envelopes, 1952 Kern County

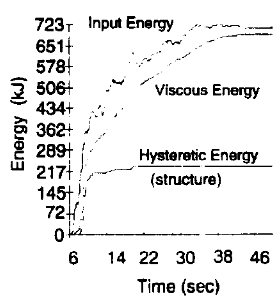

Fig. 10 Energy-Time History, Isolated Cladding, 1952 Kern County Earthquake

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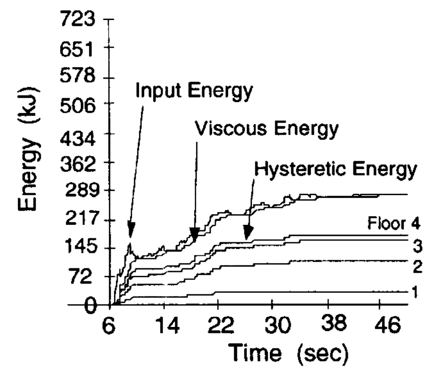

Fig. 11 Energy-Time History, Tapered Cladding Connections, 1952 Kern County Earthquake

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