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Published by Elsevier Science Ltd 1996
Paper No.1542. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DESIGN OF OPTIMAL PASSIVE/ACTIVE HYBRID CONTROL SYSTEMS FOR EARTHQUAKE STRUCTURAL CONTROL

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ABSTRACT

A new methodology for determining optimal combinations of passive and active control to minimize the seismic response of a building is presented. The approach is an iterative method that attempts to minimize the response by successively optimizing the action of selected passive elements and active control components. Passive control is provided by use of specially designed structural elements for hysteretic dissipation of energy, while active control is provided applying controlled forces within the structure (e.g., so-called active bracing or similar systems). The passive elements are first designed to optimize the structural performance in the absence of any other control. Next, mu-synthesis is used to design a robust controller for the selected active control elements operating in conjunction with the passive elements. Finally, the passive elements are iteratively redesigned in the presence of the robust controller in order to achieve the final design. The resulting active/passive hybrid control system provides performance that is superior to that obtained by either control system alone.

KEYWORDS

Active control; robust control; earthquake control; hybrid control; passive control; passive-active control

BACKGROUND

Damping has long been recognized as an attractive mechanism for passively dissipating dynamic energy introduced into a building structure during an earthquake. It is widely accepted in seismic resistant design that engineered inelastic action in the primary structural system can be utilized to control dynamic response. The authors have been studying the possibility of employing engineered inelastic action in the interactions between heavy cladding and the supporting building structure to provide seismic energy dissipation and in so doing to produce a significant reduction in structural response and seismic damage (Goodno, *et al.* 1989). Normally, the objective in the design of precast or similar heavyweight cladding systems is to provide as nearly to complete isolation from interaction forces with the main structure as is practical, and various methods to accomplish this have been accepted in practice and in codes (PCI, 1988). By structurally isolating the cladding, the structural designer can protect these often fragile and costly nonstructural architectural elements from possible damage due to a variety of causes including seismic-induced interaction forces and environmental forces (for example, thermal expansion and contraction).

One of the simplest approaches to accomplishing this isolation is to provide a simple statically determinate method for attaching the panels to the building. This eliminates the possibility of introducing difficult to control redundant interaction forces into the panels, but by itself it does not eliminate the introduction of forces caused by relative lateral displacement of adjacent floors caused by the normal shear deformation in the main building structure. When considered in the plane of the cladding, the interstory shear deformation will introduce racking forces into any panel that is fixed between adjoining stories. A popular approach to reducing this kind of interaction force is to fix the panels securely to one floor and then use flexible elastic connection to the adjoining floor. The fixed connections are used to support the gravity and seismic loads while the flexible connections are used primarily to maintain panel vertical and lateral alignment on the building. A popular and widely employed flexible connector is a thin (12-15 mm) threaded rod that is screwed into a threaded insert in the panel and anchored at the other end to the floor slab. Nuts and washers on the threaded rod can be used to adjustment the in/out panel position for correct vertical alignment. Figure 1 illustrates such a configuration.

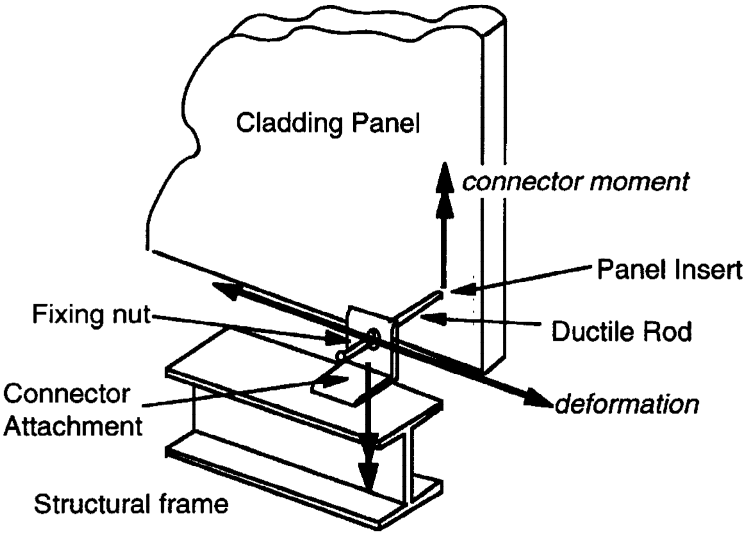


Fig. 1. Example of conventional isolating cladding connection system using flexible rods.

On the other hand, the authors have been studying for a number of years the possibility of actually utilizing the potential structural interaction between cladding panels and the building structure, rather than simply trying to eliminate (and thereby ignore) it (Goodno, *et al.* 1992). Of course in order to be able to effectively utilize this type of interaction, one must first fully understand all of the structural mechanisms involved. The situation is further complicated by the obvious fact that such a design approach directly violates the spirit if not the letter of current building codes governing cladding design and installation (all of which specify a design philosophy of structural isolation). Nonetheless, the authors have persisted in studying cladding interaction forces with an objective not unlike that of the first structural engineers at the start of this century who began to seriously consider using redundant structural systems. Such a radical step became practical only after a sufficient understanding of the mechanisms involved was reached, and suitable analysis and design methods were developed and successfully tested.

Passive Control Using Architectural Cladding

The authors have shown that hysteretic interaction between heavy cladding and the building structure can be effectively employed to provide passive damping for seismic response attenuation (Pinelli, *et al.* 1993). Response reductions on the order of 50% are possible using specially engineered "advanced" cladding connection systems such as those that have been designed and tested in the laboratory to verify the assumed levels of strength, hysteresis, ductility and stability (Pinelli, *et al.* 1992). Figure 2 illustrates a number of possible designs based on different inelastic, hysteretic mechanisms. A practical connector design procedure was also developed.

Practical experience has shown, however, that the effectiveness of purely passive approaches may be highly dependent on the spectral distribution of energy in the earthquake ground motion and the particular structural dynamics of the building in question (Pinelli, *et al.* 1995; Hsu, 1995). This is because passive dissipaters providing hysteretic damping (e.g., the cladding connections) also measurably alter the overall structural dynamics of the building. The result can shift the spectral sensitivity of the building either towards or away from the spectral energy in a particular earthquake.

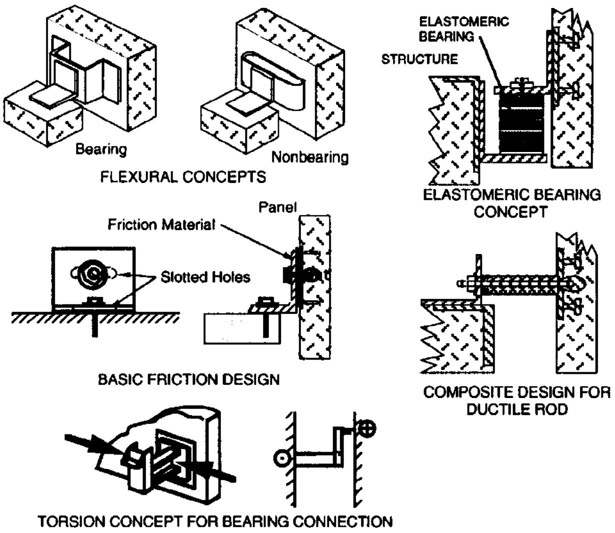


Fig. 2. Examples of possible cladding connectors that will provide passive hysteretic damping.

Active Control

Active control, on the other hand, offers the promise of providing structural control forces that can be dynamically tailored to a specific structure and yet capable of handling a broad range of earthquakes. However, commonly cited difficulties are the control system power requirements and the question of reliability over the long repetition intervals common to earthquakes. Hybrid systems incorporating both passive damping and active control offer the potential benefits of both approaches while minimizing the disadvantages. Passive damping is always active and can reduce the demands on an active system (possibly improving reliability), while active damping minimizes the sensitivity to seismic spectral distribution.

The authors have studied the potential of active control systems, and recent studies have examined the problem from the point of view of robust control practice (Calise, *et al.* 1993). Robust control systems have been designed to augment the performance of typical building structures already fitted with passive systems. In these cases the passive systems were designed using cladding-structure interaction implemented with "advanced" ductile cladding connector systems as outlined above. The design parameters for the passive system (e.g., the ductile connectors) were specified by employing numerical optimization methods to maximize the fraction of the input seismic energy passively dissipated in the cladding system (Pinelli, *et al.*, 1995). H-infinity and Mu-synthesis methods were then used to determine feasible design approaches and practical design implementations for active control systems that, in concert with the passive system, would provide additional structural control. In particular, the presence of the passive damping was modeled as plant uncertainty while the earthquake was treated as input uncertainty. Hsu (1995) has described this design process in detail and has provided a number of illustrations to show the simulated performance of the hybrid active/passive systems for a six-story building subjected to the 1940 El Centro NS earthquake record. A summary of the design process is also provided in (Hsu, *et al.*, 1994).

OPTIMAL HYBRID RESULTS

In the previous studies, the active control system was designed for a given passive system configuration as determined from prior numerical optimization of the cladding connector system parameters. While the simulated performance of such hybrid systems showed a marked reduction in seismic response, no consideration was given to further redesign of the passive system in the presence of the active system. As a result, these designs can only be referred to as sub-optimal hybrid configurations.

The present study combines these passive and active control design processes by seeking to determine the overall optimal combination of both passive and active control for seismic response attenuation. The approach involves an iterative "redesign" process in which the optimal passive system is augmented with a robust control system designed using Mu-synthesis methods. Then, this system is redesigned for optimal passive control using the numerical optimization approach described by Pinelli, *et al.* (1995). Details of the process, which is summarized in this paper, are provided in a doctoral thesis by Hsu (1995).

The building configuration used for these studies was a 1/4 scale building structural frame constructed at NCEER and used for 2D seismic testing on the large shake table. Since the shake tests were performed in a single horizontal direction, the structure was designed to behave like a plane frame and very stiff bracing was used in the narrow depth direction to minimize out-of-plane response. The structure has been studied extensively by the authors in previous work (e.g., Hsu, 1995), and a detailed and accurate DRAIN-2D structural model has been developed (Pinelli, *et al.* 1993). As for the previous studies, the building was assumed to be fully clad on the planar faces using appropriately 1/4 scaled precast cladding panels with an "advanced" ductile cladding connection system attaching the lower ends of each panel to the structure and rigid attachments at the upper ends. Figure 3 shows the typical ductile connection, in this case implemented using a double tapered flexure (Pinelli, *et al.*, 1994). Note the similarity to the conventional "isolating" connector shown in Fig. 1 which would meet most code requirements today.

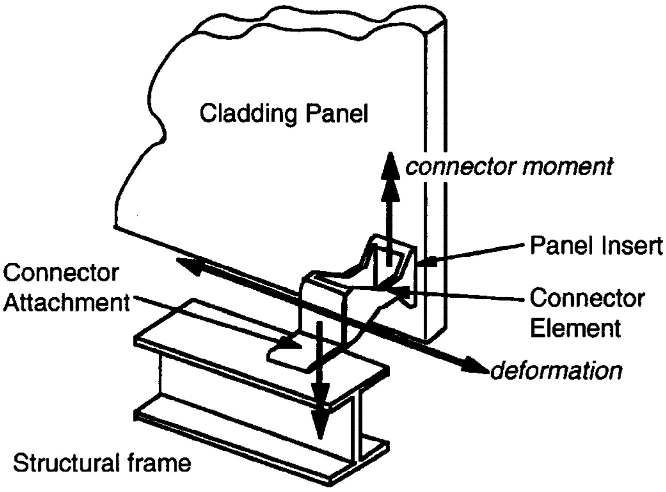


Fig. 3. Typical "advanced" ductile cladding connector used in hybrid control study.

Passive Control System Design

The numerical optimization procedure developed by Pinelli, *et al.* (1995) was used to determine the geometric parameters of the "advanced" tapered flexural connector similar to the one shown in Fig. 3 above that maximized the fraction of the input seismic energy to structure that was dissipated in the connectors (compared to inelastic dissipation in the structural frame). Figure 4 shows a typical plot of the objective function contours as a function of the connector design parameters, in this case, connector yield force and connector stiffness. Superposed on these contours are connector ductility constraint lines defining the limits of dynamic ductility for the connector (Pinelli, *et al.* 1993). The optimal passive system design for this case is shown by the point symbol located against a constraint on maximum connection stiffness (vertical line) but within the ductility constraint. The constraint on connector stiffness must be included to accommodate practical connector sizes while limiting maximum forces introduced into the panels.

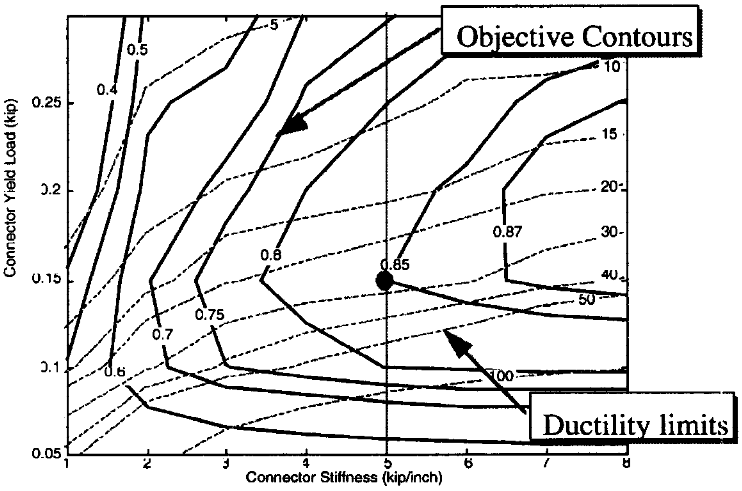


Fig. 4. Optimal passive system design

Active Control System Design

The active control system was assumed to be a simple "active" bracing system with the interstory bracing (shear) forces introduced between the ground and first floors via diagonal bracing elements modeled as servohydraulic actuators. A robust control system was designed using mu-synthesis methods with model order reduction to limit the system to a total of twelve degrees of freedom (basic structural frame had six degrees of freedom). Details are presented in Hsu (1995). Key features of this design process were:

- effects of passive elements were represented as uncertainties in the structural model and modeled as uncertainty blocks, and
- the earthquake was represented as uncertainty in the input.

A comparison of time history responses for the 1940 El Centro NS component applied to a DRAIN-2D simulation of the building with the combined passive/active control system revealed an approximately 40% reduction in peak response on the top floor.

Iterative Redesign of Hybrid Control System

The passive system, designed initially in the absence of an active control system, was next redesigned assuming the presence of the active control system. Basically, the same numerical optimization procedure was applied again to the building model with the active control present and operating. The process was much the same but actual computational times were significantly increased due the presence of the active controller. The faster dynamics introduced by the controller, even with model order reduction used in the controller design, required an order of magnitude smaller time steps for accuracy equivalent to the initial optimization.

The numerical optimization results shown in Fig. 5 are similar to the previous results in Fig. 4, as expected, but in this case the objective function contours and ductility constraint lines shift downwards, and the optimal design point moves downward along the connector stiffness constraint.

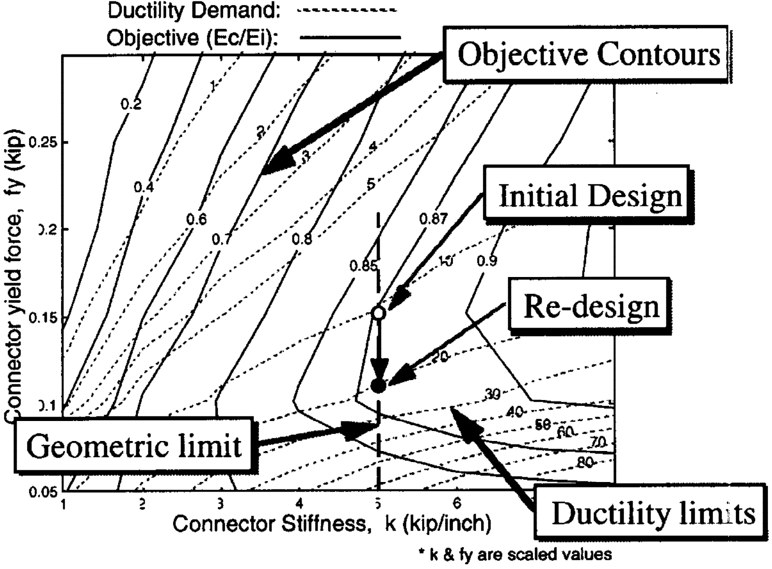


Fig. 5. Iterative optimal redesign of passive system with active control present.

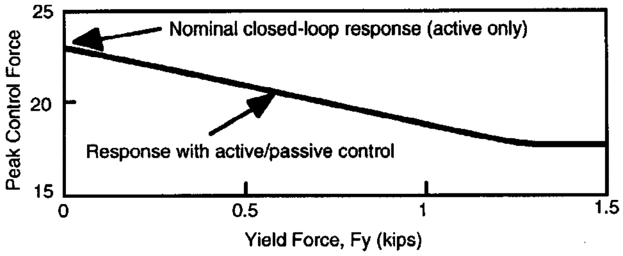


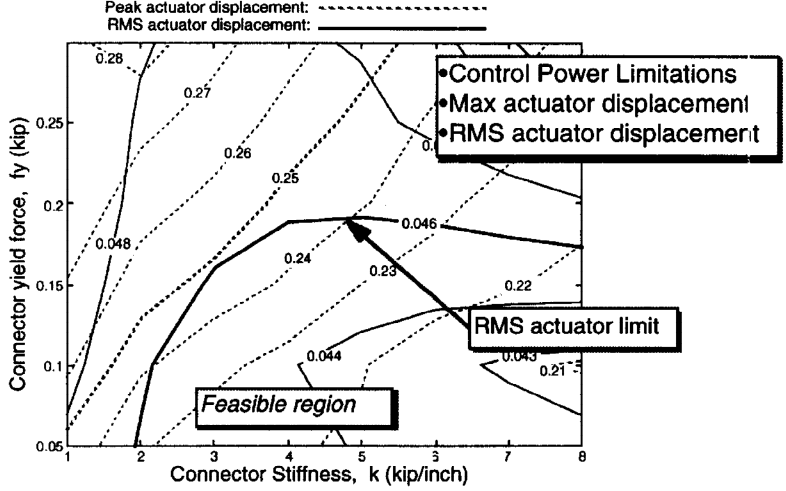
Fig. 6. Required peak control force as a function of the amount of added passive damping.

Hybrid System Performance

Overall performance of the optimal hybrid system can be characterized in a number of ways depending on the point to be emphasized. Maximum displacements at the top floor were reduced by as much as 50% from the configuration without either passive or active control (but including the installed mass of the cladding panels). Perhaps more interesting results are obtained by studying the tradeoffs between the passive and active systems and the robustness of the active system itself.

Figure 6 illustrates the synergistic interaction between the passive and active control systems. The presence of the passive elements places less demand on the active control system and results in diminished peak control force levels as the level of passive damping is increased (by adjusting the connector parameters).

Figure 7 shows a plot of contours of RMS actuator displacements and MAX actuator displacements for the same range of passive system design parameters as shown in Fig's. 4 and 5 above. The RMS contours represent control power limits (increasing RMS actuator displacements require proportional increasing control power), while increasing MAX contours represent increasing peak control power requirements. Note that the iterative redesign of the passive system yields a reduction in both the MAX and RMS actuator displacements, or equivalently, a reduction in the overall size and power of the active controller system.



* k & fy are scaled values

Fig. 7. Practical limitations due to finite actuator capacity and power.

Measures of the robustness of the active controller are typically illustrated to control engineers by plots of Nominal Stability and Robust Stability as a function of frequency. These are basically measures of the loop transfer functions with and without the control loop closed, and their usefulness is often lost on the structural engineer. Figure 8, on the other hand, dramatically shows the robustness of the present active control system by showing the behavior of the active control system as the overall building structural stiffness is deliberately

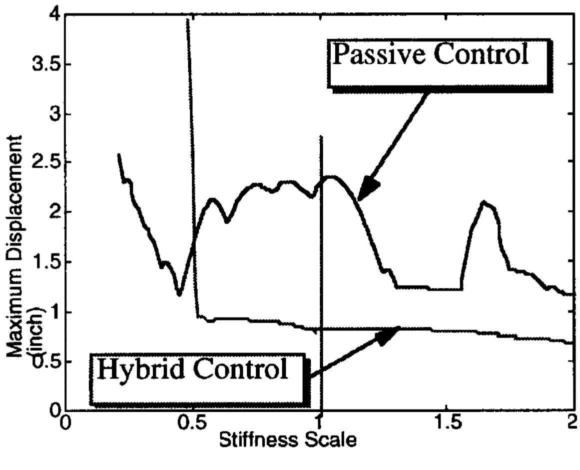


Fig. 8. Effect on displacements of changing interstory stiffness (shows instability only when stiffness drops below 50% of nominal)

changed by far larger amounts than could be tolerated from a purely structural standpoint. The active control system is able to maintain stable performance in the presence of an almost 50% decrease in the system structural stiffness. This contrasts to the failure of conventional LQR controller designs to maintain stable performance when the structural system stiffness changes by as little as 4 or 5% from the design values. The passive control curve shows the displacement behavior for the passive system alone, which of course, does not show instability, but which does show large variations in resulting maximum displacement as a result of the changing dynamics of the structure as the stiffness is changed. The active system is far more tolerant until the instability limit is reached.

CONCLUSIONS

This iterative design approach is shown to converge and to provide optimal hybrid combinations of passive and active control for practical situations. While based on a computational response simulation, the approach is still quite suitable for practical structural design purposes.

ACKNOWLEDGEMENT

The support of the National Science Foundation through Grants BCS-9202039 and CMS-9402572 is gratefully acknowledged. However, the findings and opinioins expressed here are those of the authors and do not represent the position of the NSF.

REFERENCES:

Calise, A. J., Sweriduk, G. D., Hsu, C-H., Craig, J. I. and Goodno, B. J., (1993) "Active/Passive Damping of Building Structures using Robust Control and Architectural Cladding," Proceedings, 9th VPI&SU Symposium on Dynamics and Control of Large Structures, Blacksburg, VA, May 10-12, pp. 191-205.

Goodno, B, and Palsson, H, (1986), "Analytical Studies of Building Cladding,"*J. of Structural Engineering*, ASCE,,V112, N4, P 20498, p.665-676.

Goodno, B. J., and Craig, J. I., (1989), "Historical Overview of Studies on the Contribution of Cladding to Lateral Resistance of Buildings," Proceedings, The International Symposium on Architectural Precast Cladding - Its Contribution to Lateral Resistance of Buildings, organized by the Precast/Prestressed Concrete Institute, Chicago, Illinois, November 8-9, pp. 36-47.

Goodno, B. J., and Craig, J. I., (1992), "Use of Advanced Cladding Systems for Passive Control of Building Response in Earthquakes," Proceedings, 10th World Conference on Earthquake Engineering, Madrid, Spain, July 19-24, V. 7, pp. 4195-4200.

Hsu, C. C., Calise, A. J., Sweriduk, G. D., Goodno, B. J., and Craig, J. I., (1994), "Building Seismic Response Attenuation Using Robust Control and Architectural Cladding," Proceedings, American Controls Conference, Baltimore, MD, June 28-July 1.

Hsu, C-C., Calise, A. J., Craig, J. I., and Goodno, B. J., (1995), "Performance Evaluation of Robust Controllers in Earthquake Structural Dynamics Problems with Large Hysteretic Nonlinearities," Paper Inv-42-3, Proceedings, American Control Conference, Seattle, WA, June 21-23.

Hsu, C-C, (1995), “Control of Seismic response of Building Structures Using Passive Cladding and Active Tendon Systems”, Doctoral Dissertation, School of Civil and Environmental Engineering, Georgia Institute of Technology, August.

PCI Manual on Design and Typical Details of Connections for Precast and Prestressed Concrete, (1988), Second Edition, Prestressed Concrete Institute, 175 W. Jackson Blvd., Chicago, Illinois 60604.

Pinelli, J-P., Moor, C., Craig, J. I. and Goodno, B. J., (1992), "Experimental Testing of Ductile Cladding Connections for Building Facades," *The Structural Design of Tall Buildings*, Vol. 1, No. 1, John Wiley & Sons, London, October, pp. 57-72.

Pinelli, J-P, Craig, J. I. and Goodno, B. J., (1993), "Passive Control of Building Response Using Energy Dissipating Cladding Connections," *Earthquake Spectra*, Earthquake Engineering Research Institute, V. 9, N. 3, August, pp. 529-546.

Pinelli, J-P, Craig, J. I. and Goodno, B. J., (1995), “Energy-Based Seismic Design of Ductile Cladding Systems,” *Journal of Structural Engineering*, ASCE, Vol. 121, No. 3, March, pp. 567-579.