EFFECT OF CLADDING ON BUILDING RESPONSE TO MODERATE GROUND MOTION

Barry J. Goodno[I], Kenneth M. Will[II], and Hafsteinn Palsson[III]

SUMMARY

In the past little attention has been paid to nonstructural items such as decorative exterior cladding in multistory buildings although these elements represent a substantial part of the total financial investment on the part of the owner. Recent studies however have shown that heavy claddings may actually provide a considerable amount of resistance to low level excitation and thus help to control interstory drift and building motion which affect both the cladding and the comfort of building occupants. As a case study, the shear stiffness contribution of a precast concrete curtain wall was added to the lateral stiffness model for the primary structure of a 25-story steel frame office building of core construction. The curtain wall model was calibrated by adjusting analytical frequencies to match experimental values, and the response of the overall structure was computed for a number of earthquake loadings. The cladding was found to alter structure frequencies appreciably and to either increase or decrease peak displacement response depending on the overall structure frequencies and the frequency content of the input ground motions.

INTRODUCTION

The exterior facade of modern highrise buildings may play a central role in resisting moderate wind and earthquake ground motion inputs despite design assumptions to the contrary. Although the curtain wall is usually regarded as nonstructural, heavy cladding systems, such as those comprised of precast concrete panels and the like, are found not only to transfer reaction forces back to the primary structure but also to serve as additional lateral stiffening elements until their capacity or that of their connections is exceeded. Reports of distress in curtain wall systems suggest that this is the case [1,2][†]. Even cladding systems in which sliding connections are used to protect expensive exterior panels may perform as lateral stiffening elements when connection deterioration with time impedes intended function. As a result, cladding-structure interaction effects may substantially alter the dynamic properties of the overall structural system. It follows that predicted response based on a model of the structural framing alone may be considerably different from that actually experienced in the field.

The increasing cost of decorative claddings has prompted some investigators [3,5-8] to suggest their purposeful use as lateral stiffening elements.

[I] Associate Professor, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

[II] Assistant Professor

[III] Graduate Research Assistant

[†] Numbers in brackets refer to corresponding items in References.

In this way the stiffness and energy absorption capacity of claddings can be used to advantage in modern building designs. However, as a first step, a better understanding of the behavior of curtain wall systems presently in use, especially of the forces introduced into panels and connections, is needed by the designer in determining proper force levels for design. In addition, practical upper limits for the lateral stiffness contribution of curtain walls need to be established.

As a case study, the influence of heavily-contoured precast concrete panels on the lateral stiffness of a medium highrise office building of core construction was investigated [4,9]. Finite element models of the structure, the cladding, and the cladding connections were developed to analytically represent all components contributing stiffness to the structure. The effect of the cladding on the dynamic properties of the structure was studied by varying the cladding panel and connection stiffnesses and by comparing calculated vibration frequencies to experimentally-determined values for the prototype structure. The responses of the structure model to moderate earthquake ground motions,with and without cladding stiffening effects, were compared. Consideration of cladding-structure interaction effects was seen to alter building frequencies substantially and to influence peak response to moderate ground motion as well. Results are presented in the form of peak displacement response envelopes for several different ground motion inputs. Improved understanding of the behavior of cladding systems in modern highrise buildings is expected to lead to better procedures for their design as well as increased use of the curtain wall stiffness to control low level building motions.

STRUCTURE MODEL

Prototype Structure--A 25-story steel frame office building of core construction was selected for the cladding-structure interaction studies. The structure is built around a steel core with rigid framing in one direction and braced framing in the other (Fig. 1). A lightweight exterior frame supports 21 stories of curtain wall consisting of precast concrete panels bolted to clip angles which are welded to exterior spandrel beams (Fig. 2). Further description of the structure is contained in Ref. 4.

Computer Model--A finite element model of one quarter of the doubly symmetric structure was assembled which included the effects of composite action of floor beams, finite size of framing joints, and eccentric connection of bracing elements in the braced frame direction. Floor slabs were assumed to be rigid in their own planes and three degrees of freedom (two translational, one rotational) were retained per floor in the assemblage of a stiffness matrix for the primary structure. To this was added the lateral stiffness of the exterior frames supporting the cladding panels. Finally, a variety of models for the cladding panels and their connections were formulated and added to the frame stiffness terms to complete the stiffness model. The mass of the structural framing and the curtain wall tributary to a floor level was lumped at each floor in standard fashion [4].

Cladding Model--Initially, the lateral stiffness of the row of cladding panels and connections between story levels was represented by shear stiffness parameter V, and the entire curtain wall was modeled as a tridiagonal stiffness matrix [4]. Parameter V was adjusted in steps until analytical frequencies for the entire structure matched measured values from ambient vibration experiments (see Table 1); V=725 kips/inch (1.27 x 10^5 kN/m) produced the best match. Later, a finite element model of the cladding panel and the clip angle connections (Fig. 3) was formulated to study the influence of panel attachment conditions on parameter V. Results are summarized in Table 2 and discussed in Ref. 9. In general, the results in Table 2 illustrate the importance of connection details of the cladding to the structure.

DYNAMIC RESPONSE RESULTS

The response of the structure model with (V=725) and without (V=0) cladding effects was determined for a number of different earthquake ground motions (see Table 3). Five percent modal damping was assumed and the equations of motion were integrated directly using linear extrapolation and the trapezoidal rule. Displacement response results are summarized in Table 4 for the six ground motion cases considered. Peak displacement responses at the roof and the square-root-of-the-sum-of-the-squares (SRSS) of the maximum floor responses at floors 4-24 (i.e., curtain wall story levels 1-21) are reported for the clad and unclad cases for both the braced and rigid frame directions of the structure. In the braced frame direction in which cladding effects increased structure frequencies by 19% or less (see Table 1), peak and SRSS values are reduced for all cases when curtain wall stiffness is included. On the other hand, in the rigid frame direction in which cladding effects increased structure frequencies by about 50%, the clad and unclad structures are substantially different. As a result, peak and SRSS response values are increased for cases 2 and 3 (i.e., El Centro and Olympia records) by more than 50% because of the match between the dynamic characteristics of the clad structure in the rigid frame direction and the frequency content of the input ground motions. For cases 1 and 4-6, rigid frame direction response is reduced by cladding effects. These results are further illustrated in the roof displacement time-history plots for El Centro (case 2) in Fig. 4, and in the peak floor displacement envelopes for El Centro and Taft (cases 2,4) in Figs. 5 and 6.

CONCLUSIONS

Reported failures of curtain walls in modern highrise buildings demonstrate that cladding components are participating structural elements despite design assumptions to the contrary. Results reported above for a heavy precast cladding on a steel frame structure demonstrate that cladding can alter structure frequencies and response appreciably and that it may not always be conservative to neglect cladding-structure interaction effects. The results presented are for the linear range only. When story drifts exceed a certain threshold, cladding stiffness effects are likely to be substantially reduced. In the event of partial cladding failure at different story levels on opposite faces of the structure, the deleterious effects of torsion would be introduced. In the prototype structure, cladding has a considerable influence on torsional frequencies (see Table 1) and the consequences of partial curtain wall failure on three dimensional structure response need to be investigated.

Further study of cladding-structure interaction in the nonlinear range is needed, including panel racking tests in the laboratory for several cladding types, to determine its basic behavior and to establish proper force levels for design of cladding and connections. Rational design procedures for cladding as a lateral stiffening element to control low-level structure motions are expected to result from these studies.

ACKNOWLEDGMENTS

Support for this study, provided in part by National Science Foundation Grant ENV77-04269, is gratefully acknowledged.

REFERENCES

1. Eaton, K. J., "Cladding and the Wind", Journal of the Structural Division, ASCE, Vol. 102, No. ST5, Proc. Paper 12114, May 1976, pp. 1043 - 1058.

2. "Facades: Errors can be Expensive", Engineering-News Record, Vol. 204, No. 5, January 24, 1980, pp. 30 - 34.

3. Gjelsvik, A., "Interaction Between Frames and Precast Panel Walls", Journal of the Structural Division, ASCE, Vol. 100, No. ST2, Feb. 1973, pp. 405 - 426.

4. Goodno, B. J., Will, K. M., "Dynamic Analysis of a Highrise Building Including Cladding - Structure Interaction Effects", Proceedings, ASCE Specialty Conference on Computing in Civil Engineering, Atlanta, Georgia, June 1978, pp. 623 - 638.

5. McCue, G. M., et al., "Building Enclosure and Finish Systems: Their Interaction with the Primary Structure During Seismic Action", Proceedings, U. S. National Conference on Earthquake Engineering, Ann Arbor, Michigan, June 18-20, 1975, pp. 235 - 244.

6. Oppenheim, I., "Dynamic Behavior of Tall Buildings with Cladding", Proceedings, Fifth World Conference on Earthquake Engineering, Rome, Italy, June 1973, pp. 2769 - 2773.

7. Sharpe, R. L., "Seismic Design of Nonstructural Elements", Proceedings of the International Conference on Planning and Design of Tall Buildings, ASCE-ISABE Joint Committee, Bethlehem, Pennsylvania, Vol. Ia-12, pp. 1143 - 1148.

8. Weidlinger, P., "Shear Field Panel Bracing", Journal of the Structural Division, ASCE, Vol. 99, No. ST7, Proc. Paper 9870, July 1973, pp. 1615 - 1631.

9. Will, K. M., Goodno, B. J., and Saurer G., "Dynamic Analysis of Buildings with Precast Cladding", Proceedings, ASCE Seventh Conference on Electronic Computation, St. Louis, Missouri, August 6-8, 1979, pp. 251 - 264.

Table 1 Comparison of Experimental and Analytical Frequencies

Direction (1)	Mode (2)	Vibration Frequencies, in Hertz: Analytical: Without Cladding[a] (3)	With Cladding[b] (4)	Percent Increase (5)	Experimental: June 21 (6)	Sept. 5 (7)	Sept. 13 (8)
Braced Frame	1	0.36	0.43	19	0.41	0.40	0.40
	2	1.18	1.36	15	1.32	1.30	1.29
	3	2.28	2.53	11	2.38	2.38	2.38
Rigid Frame	1	0.21	0.31	48	0.32	0.30	0.30
	2	0.60	0.91	52	0.98	0.95	0.93
	3	1.14	1.58	39	1.69	1.65	1.66
Torsion	1	0.15	0.37	147	0.43	0.40	——
	2	0.67	1.20	79	1.26	1.22	——
	3	1.25	2.06	65	2.16	2.12	——

[a] Interstory shear stiffness V=0

[b] Interstory shear stiffness V=725 kips/inch (1.27×10^5 kN/m)

[c] Date of test (1979)

Table 2 Description and Results of Finite Element Analyses

Model[a] (1)	Interstory Shear Stiffness in kips/inch (kN/m): Case A[b] (2)	Case B[c] (3)
I	741(1.3×10^5)	526($.92 \times 10^5$)
II	497($.87 \times 10^5$)	362($.63 \times 10^5$)
III	367($.64 \times 10^5$)	41($.07 \times 10^5$)

[a] I - clip angle and bolt not included
II - clip angle and bolt included, clip angle welded on three sides to spandrel
III - same as II except clip angle welded on far edge only

[b] No relative vertical motion permitted between cladding and connection at top of cladding

[c] Relative vertical motion permitted

Table 3 Ground Motion Input Cases

Case (1)	Earthquake (2)	Date (3)	Component (4)	Duration[a] (5)	Peak[b] Accel. (6)	RMS[b] Accel. (7)
1	Parkfield, CA	27 June, 1966	N65E	43.77	49	5.2
2	Imperial Valley	18 May, 1940	S00E	53.73	35	4.9
3	Western Washington	13 April, 1949	N86E	89.15	28	3.0
4	Kern County, CA	21 July, 1952	S69E	54.38	18	2.7
5	San Francisco, CA	22 March, 1957	N10E	39.86	8	0.7
6	San Fernando, CA	9 February, 1971	N00E	10.41	3	0.6

[a] in seconds

[b] in percent g

Table 4 Earthquake Response Summary

Case[a]	Displacement Response (inches)[e]							
	Braced Frame Direction				Rigid Frame Direction			
	V=0		V=725[b]		V=0		V=725[b]	
(1)	Peak[c] (2)	SRSS[d] (3)	Peak (4)	SRSS (5)	Peak (6)	SRSS (7)	Peak (8)	SRSS (9)
1	23.1	63.2	19.8	59.7	24.8	64.8	21.3	68.8
2	17.0	42.6	14.6	40.5	9.5	27.2	14.6	40.3
3	11.6	31.7	8.4	24.1	7.2	21.5	13.1	40.4
4	6.0	16.0	5.1	13.8	9.5	26.5	5.9	17.6
5	1.3	3.7	1.0	2.8	1.8	4.9	1.4	4.2
6	0.6	1.7	0.6	1.6	0.5	1.7	0.5	1.3

[a] see Table 3

[b] kips per inch (1 k/in=175 kN/m)

[c] at roof

[d] square root of sum-of-squares of maximum floor responses

[e] 1 in = 25.4 mm

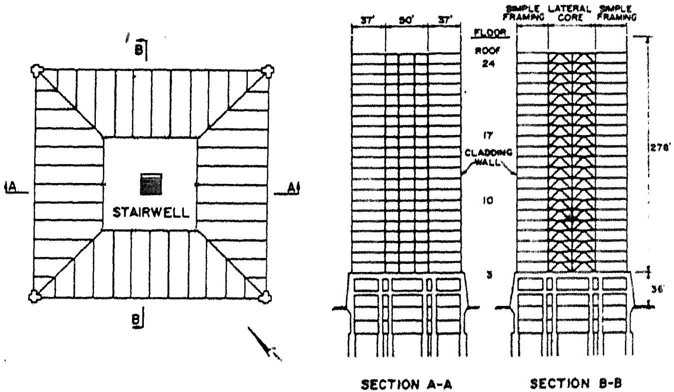

Fig. 1

Structural Framing

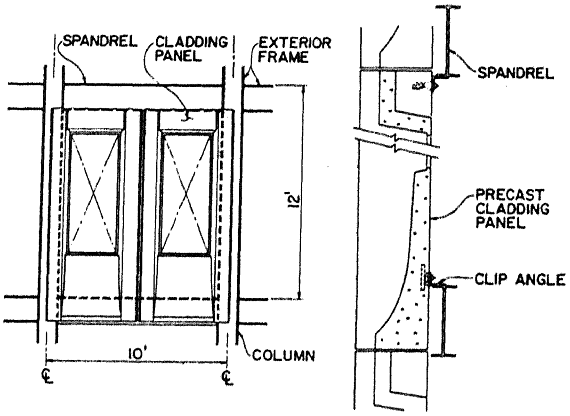

Fig. 2

Typical Exterior Bay of Curtain Wall