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A REFINED MODEL FOR PRECAST CLADDING AND CONNECTIONS

Barry J. GOODNO[1], Murugappan MEYYAPPA[2] and Satish NAGARAJAIAH[3]

[1] Professor, School of Civil Engineering, Georgia Tech, Atlanta, GA, USA
[2] Research Engineer, School of Aerospace Engineering
[3] Graduate Research Assistant, School of Civil Engineering

SUMMARY

A wide variety of panel and connection designs have been used for architectural cladding on modern buildings, often without consideration of the possible interaction of the structure and its facade during lateral interstory motions due to wind and earthquake. However, past studies have shown that heavyweight cladding can measurably influence the lateral stiffness, dynamic properties and response of highrise buildings. The objective of the study described below was to develop a more refined model for a portion of a typical heavy cladding system and to use it in a seismic response evaluation of a case study building to determine cladding panel, panel insert, and connection forces due to interstory drift motions. The overall cladding system was envisioned as comprised of a series of superelement models which detailed the localized response of representative portions of the facade. The superelement model included the effects of separate connection and insert models developed in conjunction with laboratory experiments on wedge and loop ferrule inserts embedded in concrete slabs. Individual components of the model and sample response values are described below.

INTRODUCTION

As models of building structural systems have become increasingly sophisticated, more attention has been devoted to study of costly nonstructural elements such as exterior cladding and its effect on dynamic properties and lateral response of the overall structure (Refs. 1-7,13,14). Heavy cladding systems have been shown to possess sufficient initial stiffness to alter linear seismic response predictions based on a model of the bare frame structure only. The vast majority of existing cladding systems, employing a wide variety of designs, have received only minimal investigation for seismic effects. Even if positive steps have been taken to isolate the cladding from interstory drift through use of sliding or flexible rod connections, cladding may affect the torsional response of the structure and either increase or decrease its sensitivity to particular ground motions (Ref. 1). Isolation connections may not function as intended due to deterioration with time, fatigue, and other factors. Very few cladding designs have actually been tested in the laboratory to determine connection forces and panel stresses likely to be experienced in the field (Ref. 7).

In the on-going study discussed below, various components of a typical heavy precast concrete cladding system have been modeled using finite elements and results compared to companion laboratory tests of several different types of panel connection inserts (Refs. 8-10). The principal objectives have been to develop an improved understanding of cladding and connection behavior and to determine proper force and displacement levels to guide future designs.

LOCALIZED RESPONSE MODEL

A number of different linear and nonlinear models have been developed in past studies of the precast cladding system on a 24 story steel frame office building (Refs. 4-6,12). A typical portion of the facade is shown in Fig. 1(a) and includes two precast panels per bay, each supported by four clip angle connections attached to wedge inserts (Fig. 1(b)) embedded in the panel. The clip angles are welded to spandrels in the lightweight exterior frames which support the cladding; braced and moment core frames carry the majority of vertical and lateral forces. Initially, an interstory shear stiffness model (Ref. 4), in the form of a tridiagonal stiffness matrix, was developed for the entire facade and added to the 3D computer model of the structure in order to match computer and measured building frequencies from forced vibration testing. Then, a localized response model (Fig. 2) was developed for the portion of the facade shown in Fig. 1. The panels were assumed to be flat and rigid, and elastic spring elements were employed at connection points to represent the clip angles and panel inserts. Connection spring stiffnesses for the localized response model were computed from interstory shear stiffness model values. The resulting spring stiffnesses are reported in Table 1 along with the interstory shear stiffness value (V) for each cladding bay, top and bottom connection forces, and maximum shears and moments in the spandrels and columns of the exterior frame members resulting from an interstory displacement of 0.005 times the story height (0.72 in, 18 mm) as required by modern seismic codes.

Table 1 - Response Values for Localized Response Model: Clip Angle vs. Ductile Rod Cladding Panel Connections

Response Quantity	Connection Type	
(1)	Clip Angle (2)	Ductile Rod (3)
Connection Stiffness (Kips/in)		
Top Connection	374.2	374.2
Bottom Connection	374.2	0.463
Interstory Shear Stiffness V (K/in)	63.19	12.89
Connection Forces (Kips)		
Top, horizontal	9.534	0.324
Top, vertical	37.014	2.045
Bottom, horizontal	9.492	0.317
Bottom, vertical	29.338	0.002
Max. Spandrel Shear (Kip)	28.253	6.095
Max. Spandrel Moment (Kip-in)	314.310	220.661
Max. Column Moment (Kip-in)	295.672	288.457
Max. Spandrel Vert. Displ. (in)	0.0075	0.0037
Max. Displ. of Ductile Rod (in)	---	0.6853

1 Kip = 4.45 kN, 1 in = 25.4 mm

DUCTILE ROD (PUSH-PULL) CLADDING CONNECTIONS

The localized response model was later modified as part of an analytical and experimental study (Ref. 11) of ductile rod (push-pull) connections which are widely used for isolation of precast cladding panels in the western U.S. (Fig.3). Cyclic lateral displacements were applied by a test fixture to 8, 9, 11 and 12 in. (20 to 30 cm) long, 5/8 in. (1.59 cm) diameter, threaded A-36 ductile rods attached to Dayton F-42 loop ferrule inserts to study the effects of lateral drift on these connections. Strain gages were attached to both the insert and rod, and three resistive potentiometers were used to measure rod lateral deflections. The average lateral linear stiffness of the three 12 in. (30 cm) long rod specimens tested was 0.463 k/in. (0.8 kN/cm). The ductile rod stiffness values were used in the localized response model in place of the spring elements representing the bottom clip angle connections. The resulting connection and framing member forces are reported in Table 1. The ductile rod connection was effective in isolating the cladding from interstory drift in that the cladding interstory shear stiffness per bay (V) was reduced by a factor of five and panel connection forces were also greatly reduced. However, experimental results showed that the 12 in. (30 cm) long rod yielded at 0.5 in (1.3 cm) and was very susceptible to low cycle fatigue failure.

SUPERELEMENT MODEL

To further refine the localized response model discussed above, a superelement model was assembled using GTSTRUDL to represent one half of a typical bay of cladding and supporting framing on the case study building (see Fig. 1(a)). The flat rigid panels, frame elements and spring connections of the original model (Fig. 2) were replaced by 388 triangular and quadrilateral shell elements, 40 isoparametric linear solid elements, and 24 space frame members in the half symmetry superelement model. In the new model which contains 532 joints, antisymmetry boundary conditions were specified on the plane of symmetry so that relative displacement of the top panel connections with respect to the bottom connections could be handled by the model. The upper and lower spandrel members and the top and bottom clip angle connections were explicitly modeled by shell elements, and four stiff frame elements were used to model the connecting bolts between panel inserts and clip angles. The deformations of the model resulting from a unit (1 in., 25.4 mm) static interstory drift are shown in Fig. 4. Tributary masses were lumped at preselected dynamic degrees of freedom to form a reduced mass model for dynamic analysis. The time history of relative interstory displacements obtained by dynamic analysis of a tier building model of the entire case study building for selected ground motions was specified at the upper connection points of the superelement model. Results of these analyses are now under study. The superelement model is expected to provide a better estimate of cladding stiffness as well as the peak panel, connection and framing member stresses experienced by an actual cladding system. It remains to verify these response estimates by full scale testing.

CONNECTION INSERTS

To complement the above on-going studies of panels and connections, a companion analytical and experimental research effort is currently underway to study the behavior of both wedge (Fig. 1(b)) and weld plate inserts typical of both U.S. and Mexican practice (Ref. 7). The inserts are embedded in concrete slabs and are being tested to study their behavior to failure under pull out, in-plane shear and moment loadings. The finite element model developed for the wedge insert embedded in the concrete test slab is shown in Fig. 5. Because of the symmetry of the structure and the boundary and loading conditions with respect to the middle vertical plane, only one half of the slab and the insert was considered in the analysis. The model was constructed using MSC/NASTRAN and a relatively fine mesh in the region of the insert itself, combined with a progressively coarser mesh to represent the surrounding concrete. The insert was modeled with 106 four-noded quadrilateral and 23 three-noded triangular shell (plate) elements, and 10 eight-noded hexahedron and 2 six-noded pentahedron solid elements. The concrete slab was represented by 199 hexahedron, 600 pentahedron, and 605 four-noded tetrahedron elements. Initially, perfect bonding was assumed between insert and concrete on all contact faces, with one set of nodes being used for the steel/concrete interface. But to consider other types of bonding conditions, the interface was later represented by two coincident sets of nodes, one for the insert elements and the other for concrete. Rigid links were used at different locations to simulate variable coupling between corresponding nodes. The steel and concrete along the interface can have different amounts of deformation in those degrees of freedom that are not linked. The result of the separation of the interface nodes was to increase the total number of nodes from 879 used in the original model to 1043 in the modified model. The deformed shape of the wedge insert under pull out loading is shown in Fig. 5. Refs. 8-10 should be consulted for further discussion of the overall program and results.

CONCLUSIONS

The primary objective of these studies has been to obtain a better understanding of the behavior of one of the major nonstructural systems present in modern buildings, the exterior facade. The financial loss associated with nonstructural damage in modern buildings due to earthquakes often exceeds the cost of repair of structural damage and this provides the primary motivation for these studies. Heavy cladding systems offer the potential for increased stiffness and damping in buildings, but their interaction with the structural framimg under seismic motions must be better understood if they are to be designed properly. Improved analytical modeling, combined with comprehensive experimental testing programs and increased efforts to document nonstructural damage more thoroughly in actual earthquakes, are expected to provide insight into cladding behavior to guide future design improvements.

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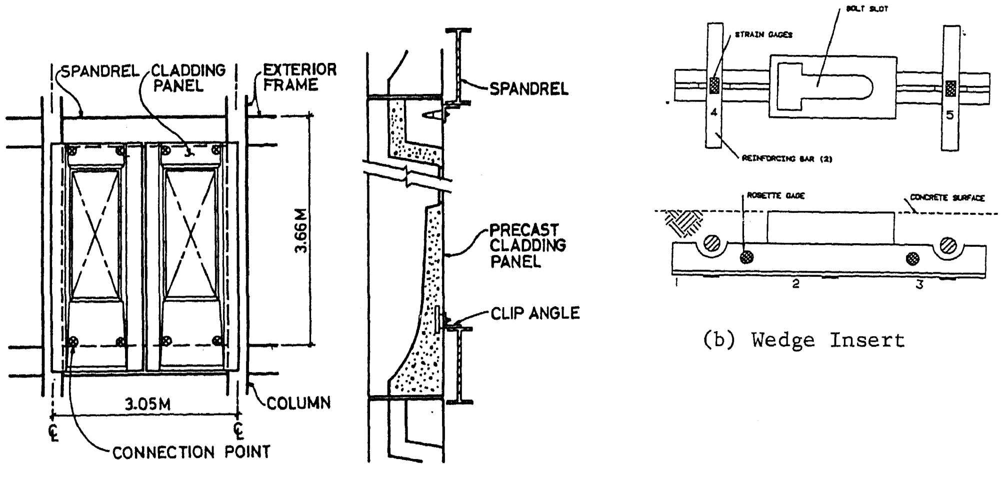


(b) Wedge Insert

(a) Typical Bay of Cladding

Fig. 1 Precast Cladding on Case Study Building

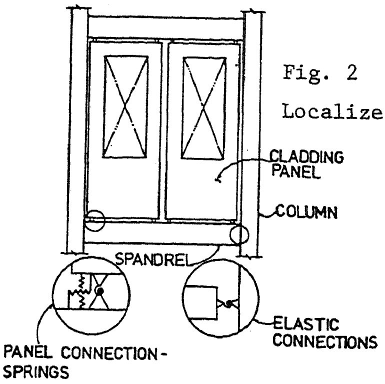


Fig. 2 Localized Response Model

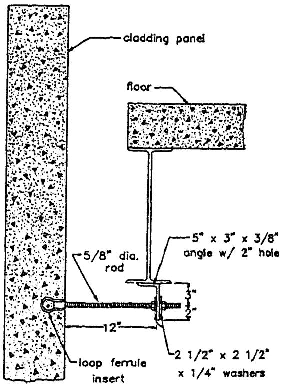
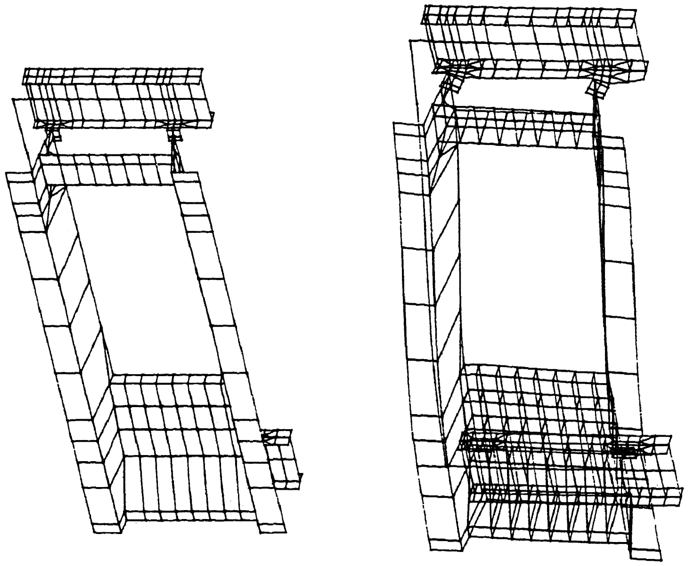


Fig. 3 Ductile Rod Connection



(a) Finite Element Model

(b) Deformed Shape

Fig. 4 Superelement Model

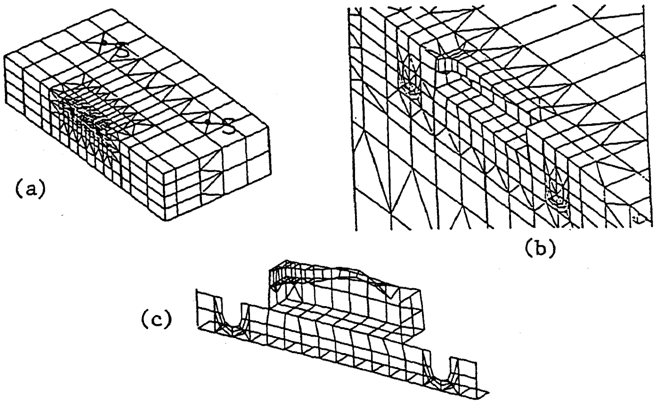


Fig. 5 Finite Element Model of Wedge Insert in Concrete (a,b) and Deformed Shape (c)