INFILLED FRAMES IN ASEISMIC CONSTRUCTION

by

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SYNOPSIS

Results obtained in the experimental phase of an investigation of the effects of engineered masonry infill panels on the seismic hysteretic behavior of R/C frames are presented and evaluated. This experimental phase consists of quasi-static cyclic load tests on a series of 1/3-scale model subassemblages of the lower three stories of an 11-story, 3-bay frame with infills in the two outer bays. Emphasis is placed on simulation of the proper force and displacement boundary conditions, and on the reinforcing details required to attain ductile frame action. The engineered infilled frames offered several advantages over comparable bare frames, particularly with respect to their performance under strong ground motions.

INTRODUCTION

Analyses of building damage from strong earthquakes reveal many instances in which the presence of masonry infills has adversely affected the seismic resistance of R/C multistory structures. Some of these effects may be explained in the light of previous research. Experimental investigators(1,2) have concluded that in the elastic range, infill panels act essentially as equivalent diagonal compression struts, stiffening the bounding frame. In the inelastic range, distributed infill cracking produces considerable energy dissipation through friction.(3) Several investigations have shown that the usual failure mode of a bare frame may be significantly affected by the presence of infilling. Early studies by Benjamin and Williams(4) have indicated that after the onset of panel cracking, the ultimate lateral resistance of the infilled frame depends on the resistance of the columns to flexure, compression, and the shear induced by the action of the equivalent compression strut. Fiorato et al.(5) found that after panel cracking, a five-story, single-bay infilled frame model behaved as a knee-braced frame. Kahn(6) has recently observed that the action of the infill on the bounding frame increased the tendency for the frame members to fail in shear.

OBJECTIVES AND SCOPE. - After a comprehensive review of the literature,(7) integrated experimental and analytical studies were planned to investigate the hysteretic behavior of specially designed infilled frames under actions similar to those expected under severe earthquake ground motions. The study reported herein is concerned only with the results obtained in a first series of tests of frame models under quasi-static loads simulating the principal effects of severe seismic excitations. A bare frame was first tested to obtain its mechanical behavior; all other tests were carried out on infilled frames. The frames and infill panels were designed according to the following guidelines: (1) to maximize energy dissipation through distributed infill cracking, closely-spaced horizontal and vertical reinforcement was adopted; and (2) to minimize the possibility of brittle frame failure which could result from panel failure, the frames were specially reinforced against

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shear, and the thickness of the infill was based on the column shear resistance.

DESCRIPTION OF TEST SPECIMENS

PROTOTYPE SUBASSEMBLAGE. - An eleven-story apartment building having plan dimensions of 18.3 m by 61.0 m was selected as the prototype. Each story had a height of 2.74 m. The structural system consisted of R/C moment-resisting space frames supporting a two-way slab floor system. Other details may be found in Ref. 8. Although the preliminary design of a transverse frame (Fig. 1) was carried out using the seismic design provisions of the 1970 UBC and the 1971 ACI Code, the final proportioning and detailing of the frame members to resist strong earthquakes were done using Newmark's standard inelastic response spectra(9) and accepted principles of inelastic analysis and limit state design for high rotational ductility. To increase the lateral stiffness of the frame, it was decided to infill the two outer bays with 15-cm thick panels. In accordance with the capacity of the available testing facility, it was decided to test models of the lower three stories of this transverse end frame. Geometric and structural symmetry about the frame centerline suggested a realistic simulation of actual boundary conditions using a model of a prototype subassemblage 1-1/2 bays wide and 3-1/2 stories high (Figs. 1 and 2). It is believed that the lack of symmetry in the inelastic range due to the effect of axial forces in the infilled frames, and the effect of gravity forces in the coupling girders, are of secondary importance.

MODEL SUBASSEMBLAGES. - The prototype subassemblage was modeled to 1/3-scale. To facilitate loading and instrumentation, the models were tested in a horizontal position. As shown in Fig. 2, the loads and/or deformations to the specimens were applied by hydraulic actuators which form part of a servo-hydraulic system specially designed for this type of test.(10) This system permits any selected ratio to be maintained between the axial forces (simulating the effect of gravity loads and overturning moment), and the lateral force. The model was extensively instrumented; while all the transducer output was read at discrete intervals using a low-speed scanner, some data were monitored continuously.

The results presented herein correspond to tests carried out on the following models: (1) a bare frame (test #1); (2) this same frame, infilled with clay blocks after test #1; (3) a virgin frame, infilled with clay blocks; and (4) a virgin frame, infilled with concrete blocks. Each frame model was cast in the horizontal position using a single pour. All frames were identical. The sizes and detailing of the main members of the frame (Fig. 2) are given in Fig. 3. The main reinforcement for these members consisted of steel bars conforming to ASTM Designation A-615-68 Grade 60 (422,000 KPa). The strength of the concrete was about 27,000 KPa. After casting, the frames were rotated to a vertical position and infilled with hollow-core blocks, and were grouted one story at a time by the "high-lift" technique. Infills were approximately 5 cm thick, reinforced horizontally and vertically every 10 cm by deformed #2 bars (f_y = 422,000 KPa) spliced to dowels anchored in the frame members. Prism tests showed the compressive strength of both types of infill to be about 24,700 KPa.

TEST RESULTS

BARE FRAME TEST. - After the application of simulated gravity loads using the axial jacks (Fig. 2), this frame was subjected to the first few cycles of the history of lateral load (and the associated overturning moment) shown in Fig. 4. Figure 6 shows the resulting tip displacement as a function of the lateral load. Failure occurred through the formation of a sidesway mechanism, at a maximum lateral load which agreed very well with that predicted by a collapse analysis using individual member resistances and a failure mechanism consistent with the observed damage. The seismic resistance of the bare frame was significantly affected by its lateral flexibility and consequent susceptibility to P-Δ effects.

INFILLED FRAME TESTS. - The loading program and lateral load-deflection curves for the three infilled models are shown in Figs. 4, 5, 7, 8 and 9. The general failure sequence was similar for all three frames: initial cracking patterns in each panel were consistent with the principal tensile stress orientations predicted by deep beam theory. After the formation of cracks along the boundary between the frame and infills, the assemblage behaved essentially as a frame braced by equivalent diagonal compression struts. Spalling occurred at those frame regions subjected to critical combinations of axial load, moment, and infill-induced shear. Reduced frame member stiffness at these regions resulted in increasing local inelastic deformations. Eventually, the number of such regions increased sufficiently to produce a sidesway mechanism (shown schematically in Figs. 7-9), whose lateral resistance was controlled by the strength of these inelastic regions as well as the residual infill resistance. Repeated cycles of reversals produced an increased amount of pinching in the load deflection curve, characteristics of shear-degrading structures, and the strength of the subassemblages asymptotically approached that of the corresponding bare frame mechanism. As may be seen from Figs. 7-9, although all three infilled frame models exhibited a decrease in strength following the initial drop in panel resistance, this decrease was gradual. All models exhibited excellent energy dissipation characteristics, even at tip deflections greater than ±10 cm., corresponding to average story drifts in excess of 0.03. As an index of the efficiency of these different systems against a major earthquake, Fig. 10 shows, for each specimen tested, the energy dissipated per complete cycle. When the results presented in Fig. 10 as well as those of Figs. 6-9 are compared, it is clear that with respect both to the stiffness at service levels and to the maximum energy absorption and dissipation capacity, tremendous gains were effected by infilling the frames. In all cases, it was possible to achieve distributed infill cracking and high energy dissipation and to minimize brittle shear failure.

CONCLUSIONS

Infilled frames designed and constructed in accordance with the guidelines mentioned in the introduction have several advantages over comparable bare frames, particularly if they may be subjected to severe ground motions:

(1) Owing to the increased stiffness (500%) and strength (from 60 kN to 280 kN) provided by infills, behavior is greatly improved under service loads, moderate ground shaking, and even under the largest expected overload of standard live loads. The increase in strength and energy absorption and dissipation capacities achieved by the addition of engineered infills is so large that it far exceeds the detrimental effects of possible increases in inertial forces due to increased stiffness. Architectural damage due to interstory drifts is reduced.

(2) For severe ground motions demanding elastic base shears in excess

of that corresponding to the bare frame collapse load, the stiffness provided by infills significantly reduces the influence of P-Δ effects on seismic response. Local panel failures occurred at tip deflections of at least 1.3 cm (average story drifts of 0.004). Prior to this, infilled frame damage was restricted to cracks less than 1.6 mm in width.

(3) For extreme ground motions demanding average story drifts in excess of 0.02, the engineered infilled frame is superior to the bare frame with respect to energy dissipation and resistance to incremental collapse. A bare frame dissipates energy primarily through large inelastic rotations at hinge regions near beam-column connections. Strain-hardening at these regions often results in anchorage deterioration at beam-column connections. The consequent loss of connection stiffness increases the danger of incremental collapse of the bare frame. However, in the engineered infilled frame, the panels dissipate very large amounts of energy through hysteretic behavior (gradual degradation of their high initial stiffness and strength). Because of this, the danger of incremental collapse is reduced. Gradual panel degradation is achieved by closely-spaced infill reinforcement, and by frame details providing high rotational ductility and cyclic shear resistance.

ACKNOWLEDGEMENTS

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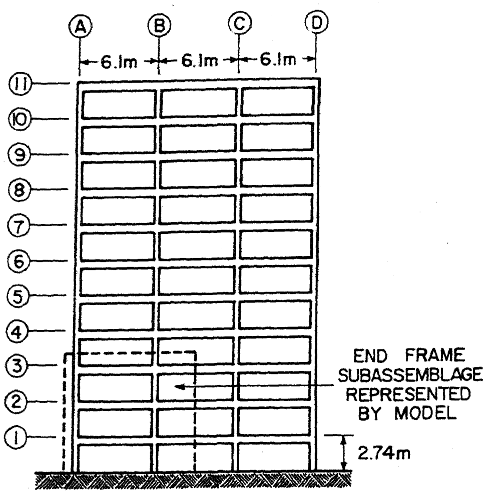


FIG. 1 END FRAME ELEVATION - PROTOTYPE

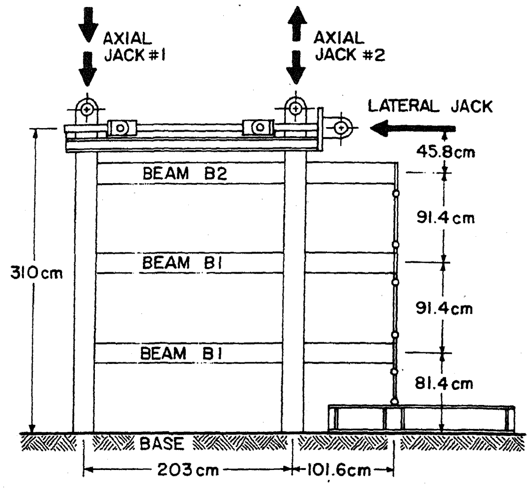
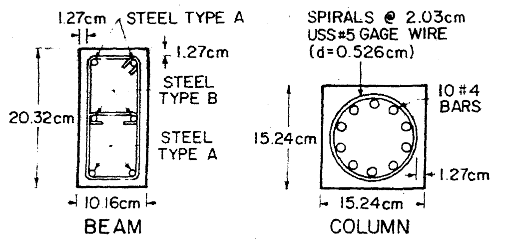


FIG. 2 TEST SPECIMEN AND TESTING ARRANGEMENT



	STEEL TYPE		
BEAM TYPE*	A	B	TRANSVERSE REINFORCEMENT
B1	#3	#2 DEFORMED	HOOPS AND CROSSTIES @ 2.54 cm
B2	#3	USS #11 GAGE WIRE	USS #11 GAGE WIRE (d=0.306 cm)

*REFER TO FIG. 2

GRADE 60 STEEL
NOMINAL $f_y = 4220 \frac{kg}{cm^2}$

FIG. 3 DESIGN DETAILS OF FRAME MEMBERS

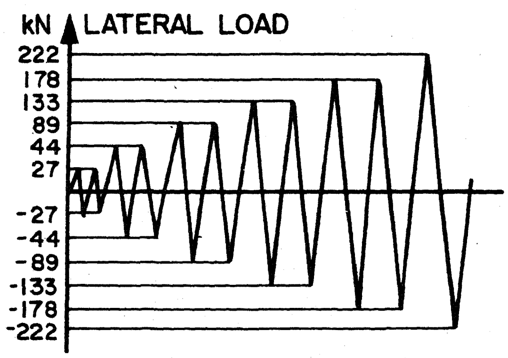


FIG. 4 LOADING PROGRAM - TESTS #1, 2 & 4

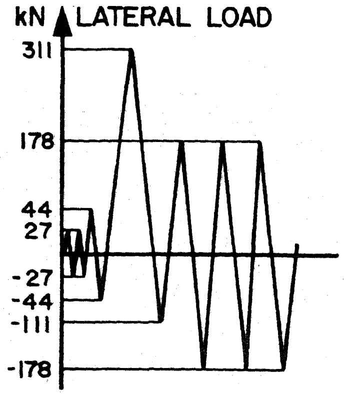


FIG. 5 LOADING PROGRAM - TEST #3

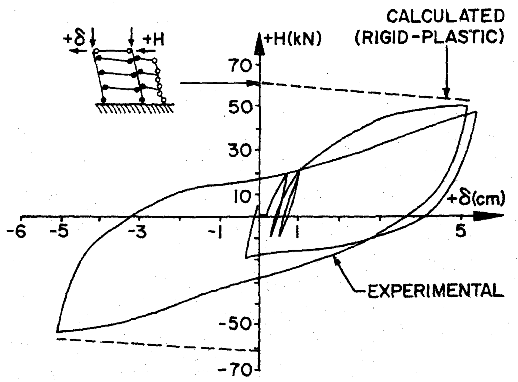


FIG. 6 LATERAL LOAD-DEFLECTION RELATIONSHIP - BARE FRAME

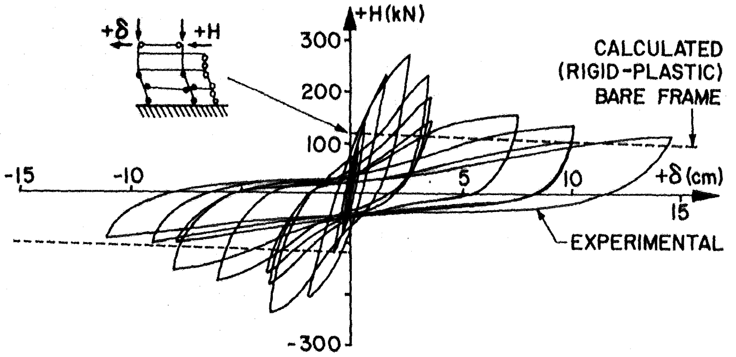


FIG. 7 LATERAL LOAD-DEFLECTION RELATIONSHIP - INFILLED BARE FRAME

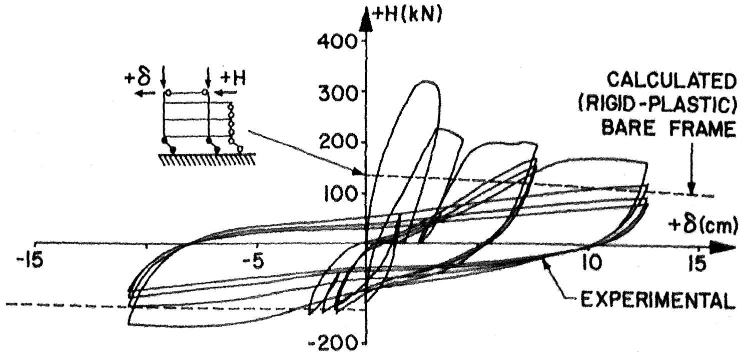


FIG. 8 LATERAL LOAD-DEFLECTION RELATIONSHIP - VIRGIN FRAME, CLAY INFILL

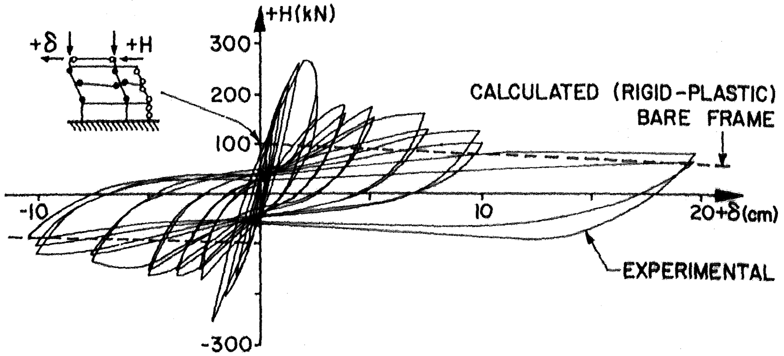


FIG. 9 LATERAL LOAD-DEFLECTION RELATIONSHIP - VIRGIN FRAME, CONCRETE INFILL

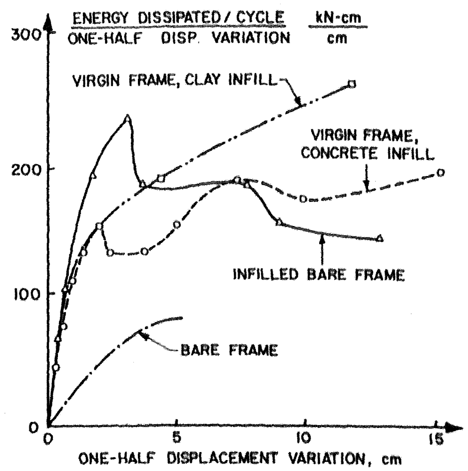


FIG. 10 ENERGY DISSIPATION

DISCUSSION

S.S. Rihal (U.S.A.)

The discussor is interested in knowing that are there any tests on frames with discontinuous infill panels, have been conducted and how in author's opinion the dynamic behaviour of such systems differs from the case of infilled frames reported.

H.K. Barua (India)

The authors deserve congratulations on the beneficial results on strength, stiffness and energy dissipation of infilled frames. The discussor has worked on infilled frames under static loading. Two types of infilled frames were investigated: (a) Steel frames infilled with mortar (b) Reinforced concrete frames infilled with masonry panel.

A paper containing the results on the second type of infilled frames has been presented in this conference (page 11-219). A plain brick work infill was used. The discussor during the investigations, felt the necessity of carrying out a secondary investigation on the determination of the mechanical properties of brick work, i.e. modulus of elasticity, crushing strength, bond - shearing strength, bond - tensile strength, coefficient of friction, Poisson's ratio. The necessity of a general expression particularly for modulus of elasticity of brick work in terms of crushing strength was greatly felt. The discussor has been conducting a project to develop some general expressions.

The discussor would like to know how the authors determined these properties for their engineered infill.

Author's Closure

Not received.