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Behavior of existing non-seismically detailed reinforced concrete frames

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ABSTRACT: The behavior of common reinforced concrete frames, designed mainly for gravity loads, has been studied experimentally and analytically. In North America these frames have low amounts of column steel, very few ties in the columns and in the joint regions, lapped splices immediately above the floor, and discontinuous bottom beam reinforcement which extends only about 150 mm into the column. More than thirty full-scale interior and exterior joint regions were tested under reversed cyclic static loads, as well as a reduced-scale, three-story building on a shake table. This type of frame can carry substantial seismic loading (about half that of well-designed frames), but their flexibility may lead to excessive damage of building contents or to geometric instability.

1. INTRODUCTION

The seismic behavior and performance of lightly-reinforced concrete frames has been studied in a coordinated manner at several institutions under the sponsorship of the National Center for Earthquake Engineering Research. The research has utilized full-scale internal and external joint regions subjected to reversed cyclic static loading, shake-table tests on reduced scale model structures, and analytical simulation of building response using specifically developed numerical simulation models.

Reliable evaluation of this class of buildings is an important step in the assessment of seismic risk in regions of moderate seismicity, such as the East and Midwest in North America. In the second phase of the research, the retrofit (rehabilitation) of lightly-reinforced frames is being studied.

2. FULL-SCALE JOINT REGION TESTS

The interior and exterior frame joint region tests included specimens with low amounts of longitudinal column steel, widely spaced ties in the column, no (or very few) ties in the joints, column steel lap-spliced immediately above the floor level, and discontinuous bottom steel reinforcement embedded 150 mm into the joint. These details are illustrated in Fig. 1.

Typical beam sizes were 356 mm by 610 mm, framing into 406 mm square columns. Primary test variables were: diameter of embedded beam reinforcement, column axial force, amount of column longitudinal reinforcement (2% and 1%), presence of ties in the joint, concrete strength, and transverse joint confinement by perpendicular stub beams to simulate forces from out-of-plane framing. Interior joints were tested with both continuous and discontinuous bottom beam reinforcement. The discontinuous bottom beam reinforcement consisted of two 19 mm or two 25 mm bars and the column and joint ties were 9.5 mm. The nominal concrete strength was 24 MPa and the steel yield strength was 410 MPa.

A custom built testing frame was used to load the specimen columns with constant axial load to simulate realistic levels of gravity forces. Constant gravity forces were also applied at the ends of the beams, followed by static reversing cyclic loads to simulate seismic-type forces.

2.1 Interior joint behavior

Specimens constructed with continuous bottom beam reinforcement showed progressive cracking and crushing immediately above the joint and below the first column tie located 200 mm above the top of the beam. This region experienced vertical cracking, some crushing of concrete, and loss of cover which eventually contributed to buckling of the column bars. However, the lapped splice in this region of maximum column moment performed reasonably well.

All specimens developed shear cracks in the joint, but the level of shear stress reached was surprisingly high, about 1.0 to $1.2\sqrt{f'_c}$ (where f'_c is in MPa). This is about 2/3 of the shear capacity of well designed joints designed for severe seismic regions. The number and arrangement of column bars had negligible effect on behavior. Two 9.5 mm ties in the joint helped to distribute the cracks and moderated the rate of strength loss, but did not raise the shear stress at failure because the critical distress was mainly above the joint. The

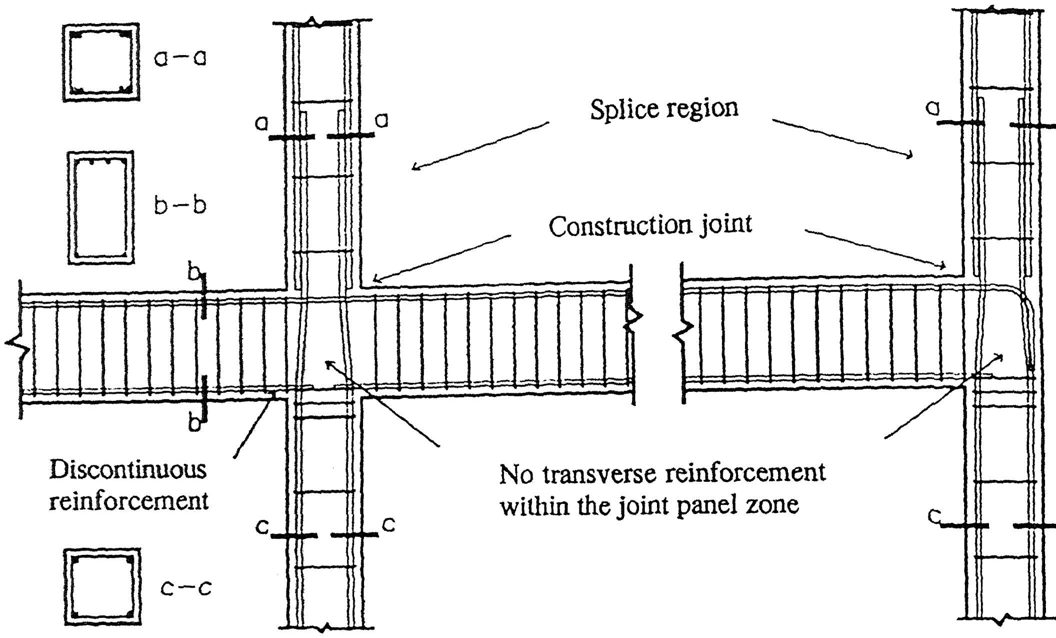


Figure 1. Elevation view of interior and exterior beam-column connection regions

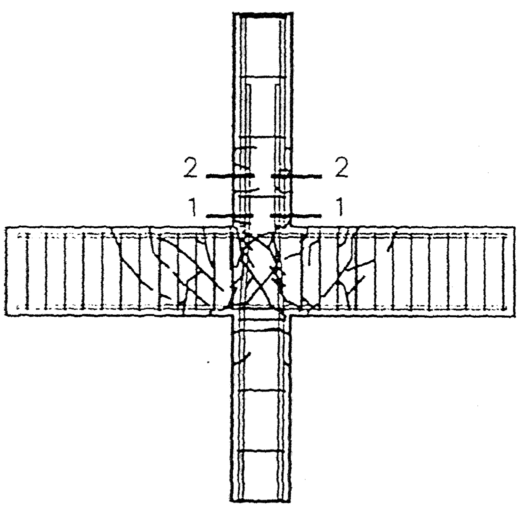


Figure 2. Interior joint, continuous reinforcement

cracking patterns at the conclusion of the test are shown in Fig. 2.

The axial column force had an appreciable effect on the response. Higher levels of axial force (1550 kN) reduced the deformations, produced higher initial stiffnesses, and and an increase in capacity.

The test specimens with discontinuous bottom beam reinforcement exhibited gradual loss of stiffness and unsymmetric hysteretic behavior. Eventually, the bottom bars began to pull out but they did carry about 2/3 of the yield stress. A large, nearly vertical crack appeared in the joint, parallel to the beam-column interface. This crack widened and merged with the dominant shear cracks. Again, vertical cracking and some crushing occurred just above the joint, but the splice remained fully effective. The joint shear stress at failure was only 20 to 40% lower than in specimens with continuous bottom steel. Increased levels of axial load on the column again assured higher capacity and greater energy absorption.

Final cracking patterns for a typical specimen are shown in Fig. 3.

Several specimens had short transverse beam stubs, compressed by a 315 kN force, to simulate the effects of transverse beams. The behavior of these specimens was similar to those without the stubs.

2.2 Exterior joint behavior

The lack of ties in the joint had a rather adverse effect on the response of exterior joints. The outward bending of the bent-down negative (top) beam reinforcement contributed to the formation of a large vertical crack near the outside face. This crack propagated up into the splice region and considerable outside cover spalled away from the back of the joint region. The shear crack within the joint panel extended to the back face of the joint and joined up with the vertical splitting crack; this behavior was accelerated by the presence of the axial column force. Hysteretic behavior was highly unsymmetrical. Final cracking patterns are shown in Fig. 4.

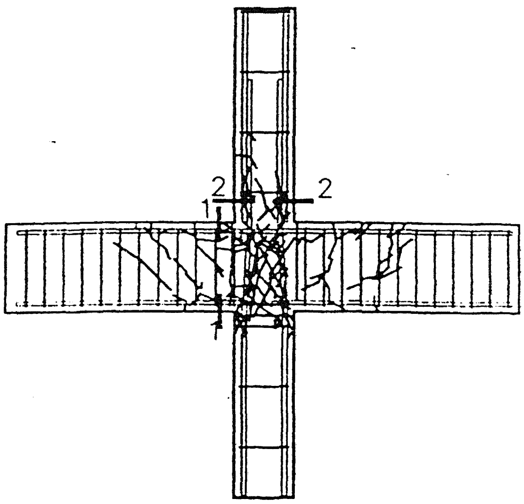


Figure 3. Interior joint, discontinuous reinforcement

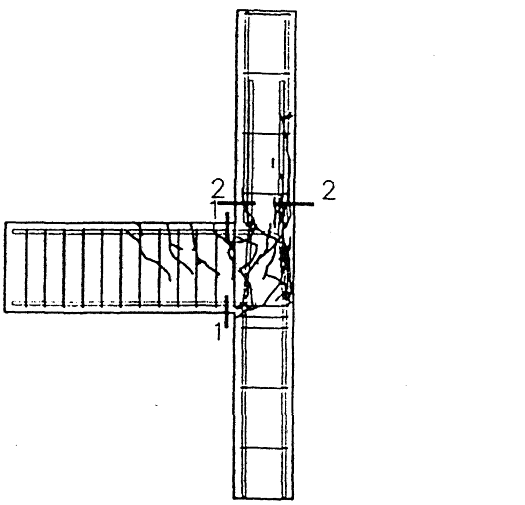
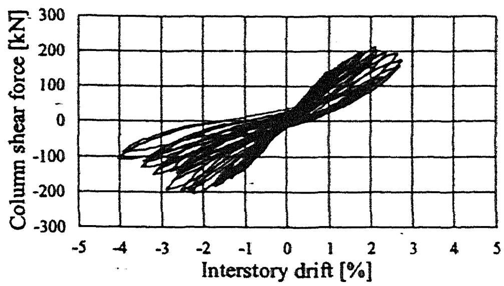


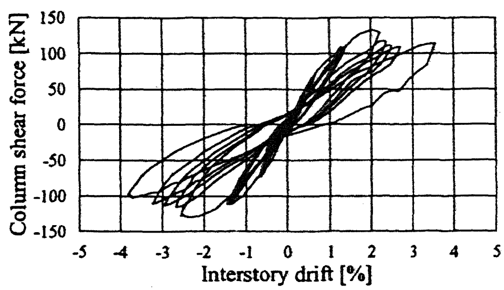
Figure 4. Exterior joint, discontinuous reinforcement

The failure of exterior joints was not dominated by pullout of the embedded bottom steel, but as a result of negative moment on the beam which accentuated the prying action of the bent-down reinforcement and the severe cracking action described above. The peak load was comparable or even higher than that for interior joints. However, the strength deterioration was more rapid.

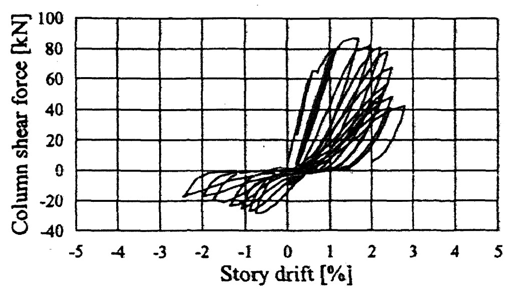
The presence of only two 9.5 mm ties in the joint was sufficient to provide enough confinement to increase the peak load by 25 to 40% and to delay strength deterioration.



(a) interior joint, continuous reinforcement



(b) interior joint, discontinuous reinforcement



(c) exterior joint, discontinuous reinforcement

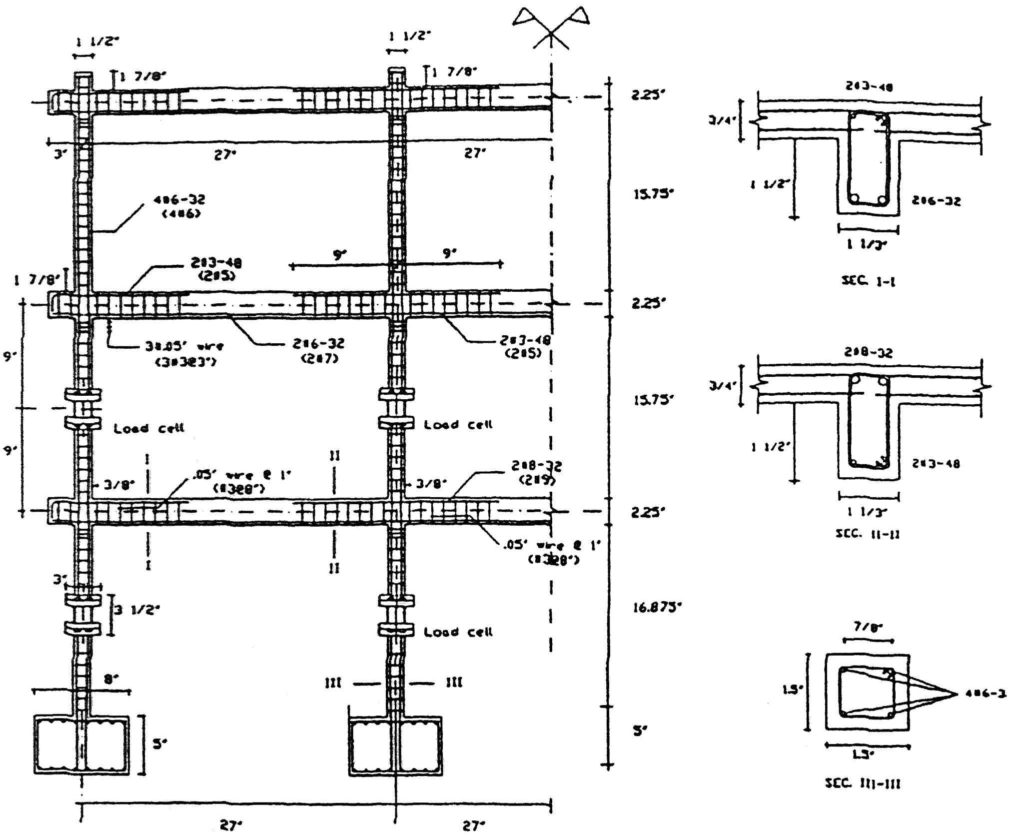
Figure 5. Shear force vs. interstory drift relationships

2.3 Shear force - interstory drift results

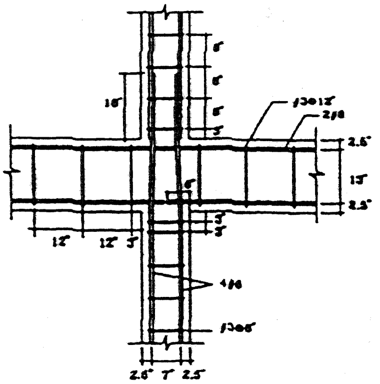
Plots of shear force vs. interstory drift are given for typical specimens in Fig. 5 (one for each of the three types of joint details studied).

3. DYNAMIC TEST OF MODEL BUILDING

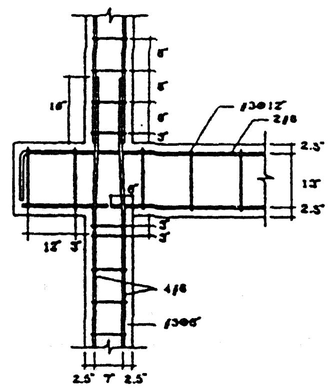
A three-story three-bay 1/8 scale building model was tested on the Cornell University shake table to study overall flexibility and stiffness deterioration of a lightly-reinforced concrete frame building designed to resist gravity loads only. The reinforcement details of the prototype structure are shown in Fig. 6. The model structure was subjected to four seismic tests using the



(a) main frame reinforcing details; model instrumentation



(b) prototype interior joint region



(c) prototype exterior joint region

Figure 6. Reinforcement details, 3-story prototype office building

time-scaled Taft 1952 S69E earthquake with increasing intensities of 0.05g, 0.18g, 0.35g, and 0.80g peak ground accelerations. An important goal of the experimental program was to aid in the validation and the calibration of the analytical model.

3.1 *Results*

The model response was dominated by the first mode during all four seismic loading tests. The model showed little visible damage but the comparison of dynamic responses with static test results measured between each of the dynamic loading runs showed large reductions in lateral stiffness. For example, during the 0.18g PGA run, stiffness decreased 50% and the top story drift exceeded 2%, with a recorded base shear equal to 8.8% of the total load on the structure. In the 0.35g PGA run, maximum top story drift increased to nearly 3% and stiffness was reduced to 22% of the uncracked stiffness.

The building model collapsed as the loading intensity was increased above the 0.35g level; failure originated in the two interior columns in the first story. The maximum recorded base shear of 0.095W was only 3% greater than the value during the 0.35g PGA run, indicating that the structure became so flexible that the simulated ground motion could not introduce much additional energy into the structure. No observable distress was produced by the presence of the discontinuous bottom beam reinforcement nor by the lapped splices in the columns, indicating that these details were not critical for this particular structure.

3.2 Summary of findings

(a) lightly reinforced concrete frames are highly flexible and may show a significant P-delta effect during moderate earthquake loadings.

(b) although the non-seismic detailing may be a potential source of damage, it was not a critical factor in the failure process of the test structure.

(c) the floor slabs play a major role in increasing the flexural capacity of the beams as compared to that of the columns, thus leading to a soft-story mechanism as the expected failure mode for low-to-medium rise versions of this type of building.

4. SIGNIFICANCE OF TEST RESULTS

This investigation of the response of typical lightly-reinforced concrete buildings is part of a broad coordinated effort within the National Center for Earthquake Engineering Research to study the risk to existing buildings in regions of moderate seismicity.

Parallel research programs at several institutions provide confirmation of measured behavior as well as test results on different geometries, and development and refinement of analytical approaches. For example, a 1/3 scale shake-table test of a similar three-story building was conducted at SUNY/Buffalo, lightly reinforced flat-plate buildings were studied at Rice University, and the development and application of the computer code IDARC (Inelastic Damage Analysis for Reinforced Concrete) for the nonlinear dynamic analysis of concrete buildings has been conducted at a number of participating institutions, based on the original development of IDARC done at SUNY/Buffalo.

The availability of reliable analytical tools is especially important in evaluating lightly reinforced concrete structures because one of their primary problems is relatively high flexibility, which can lead to amplified forces and drifts. Parametric studies of the response of typical buildings are under way to better quantify the demands placed on both interior and exterior joint regions and to enable more rational and reliable estimates of actual seismic capacities.

Analytical tools will also be essential when the effects of repair, rehabilitation, and retrofit techniques are evaluated. Most retrofit methods increase both the stiffness and the strength of elements and the entire frame. The increased stiffness will attract larger seismic forces and the failure may shift to other, more brittle regions, for example, to splices. These questions will be answered in the current continuation of the NCEER research, which also includes new studies on the influence of infill walls on the performance of lightly reinforced concrete frames.

5. ACKNOWLEDGEMENTS

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REFERENCES

Pessiki, S.P., C.H. Conley, P. Gergely & R.N. White, 1990. Seismic behavior of lightly-reinforced concrete column andbeam-column joint details. NCEER-90-0014.

Beres, A., S.P. Pessiki, R.N. White, & P. Gergely 1991. Behavior of existing reinforced concrete frames designed primarily for gravity loads Proc. Int. Mtg. on Earthquake Protection of Buildings, Ancona., June 1991.

El-Attar, A.G., R.N. White, P. Gergely, & T.K.Bond, 1991. Shake table test of a one-eighth scale three-story reinforced concrete frame building designed primarily for gravity loads. Proc. 6th Canadian Conference on Earthquake Engineering, Toronto, Canada.