DESIGN OF DUCTILE FLAT PLATE STRUCTURES TO RESIST EARTHQUAKES

by

J. E. Carpenter, P. H. Kaar and W. G. Corley[1]

SYNOPSIS

This paper presents a design procedure for earthquake resistant "ductile frame" flat plate structures without shear walls. The "ductile frame" is made up of columns and "integral beams" contained within the slab thickness. Stiffness assumptions and slab-column junction reinforcing details to be used in combination with established design procedures for earthquake resistant concrete frames are given. Results of tests on a full-size portion representative of a structure incorporating the recommended details show that considerable ductility is provided.

BACKGROUND

In the book Design of Multistory Reinforced Concrete Buildings for Earthquake Motions,(1) procedures are given for designing and detailing "ductile frame" concrete structures. These procedures form the basis for earthquake design provisions in both the Uniform Building Code(2) and the 1971 ACI Building Code.(3) This paper provides stiffness assumptions and slab-column junction details necessary to apply these established procedures to flat plate structures without shear walls.

When designing a "ductile frame" structure, it is essential to avoid shear or torsional distress in the vicinity of the column floor junction. Since little data is available on the behavior of this junction in flat plate structures, frame action is often discounted in design and shear walls are used to resist the lateral loads.

The problem of moment transfer between flat plates and columns has received some attention in experimental studies.(4,5,6) Some of these findings were incorporated into the 1971 ACI Building Code.(7,8) Ref. (6) suggests that the strength of any slab-column junction can be calculated by assuming that four "integral beams" within the slab depth frame into the column. This simple concept provides the basis for the analysis and design of "ductile frame" flat plate structures as described in this paper.

DESIGN PROCEDURE

Stiffness - In the lateral load design of any structure, it is important that the stiffness be based on appropriate assumptions. Either overestimating or underestimating the stiffness can provide an erroneous estimate of lateral deflections and P-Δ effects, both important considerations in unbraced flat plates.

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[1]Principal Structural Engineer, Senior Structural Engineer and Manager, respectively, Structural Development Section Portland Cement Association, Skokie, Illinois, U.S.A.

It is recommended that stiffness be based on a hybrid structure using procedures of the 1971 ACI Code. Vertical elements consist of the usual columns. Horizontal elements consist of the flexible transverse member of the "equivalent column" of Chapter 13 linked to the partially cracked slab of (Eq. 9-4).

Strength - To design the slab-column junction for transfer of unbalanced moments, it may be assumed that "integral beams" the same width as the design section for shear (the column width plus one slab depth) frame into each face of the column where a slab exists. Each beam is then designed for shear as described in Section 11.11.1 of the 1971 ACI Code.(3)

Following established procedures for analysis, earthquake loadings are determined. The beams are then designed for a combined flexural and torsional strength adequate to resist the moments attributed to them.

Reinforcement Details - To assure that ductility will be available after a shear crack or torsional crack develops, minimum reinforcement should be provided in the "integral beams" even where calculations indicate that the plain concrete section is adequate. The greater of the required minimum reinforcement for torsion or beam shear is recommended for use throughout the length between columns.

Confinement reinforcement, as described in the Appendix to the 1971 ACI Code, should be provided in the columns.

Although it will seldom govern, the adequacy of the slab-column intersection to transfer forces from the slab to the column must also be checked. If required, closed hoop reinforcement should be provided within the slab-column intersection.

COMPARISON WITH TEST RESULTS

At the Portland Cement Association Structural Laboratory, five full-size portions of a flat plate structure were tested under a realistic service load combined with reversed applications of unbalanced moment. One of these was designed using the procedure described in this paper. Two of the other specimens contained shearheads, the final two contained no shear reinforcement.

Fig. 1 shows the reinforcement for the "integral beam" test specimen. The closed hoop reinforcement is indicated by the arrows.

No difficulty in placing the stirrups for the "integral beam" reinforcement was encountered. Stirrups were placed simply by sliding them into position over the ends of the slab flexural reinforcement. Concrete was placed with the ease normally associated with casting slabs.

Fig. 2 shows the test specimen subjected to its maximum unbalanced load. At this stage, the slab had deflected 8 in. downward on one side and a similar amount upward on the other side. Even under these extreme deflections, it was still carrying its maximum load.

Fig. 3 shows the observed unbalanced load versus deflections relationship for the test specimen. In this figure, zero deflection was taken as the position of the slab under service load. The line marked calculated average stiffness is based on the assumptions described above.

It can be seen that a considerable amount of ductility was available during the test. Even after several inches of deflection had been sustained, the resisting moment was still at its maximum. In contrast, the other four specimens showed a complete sudden loss of unbalanced moment capacity at a smaller deflection.

After application of the final cycle of loading, the damaged slab was tested to destruction under vertical loads. The test was ended after a flexural hinge formed across the full width of the slab. The calculated shear capacity of the integral beams was nearly reached before the failure in another mode occurred.

CONCLUDING REMARKS

This paper describes a design procedure that can be used for proportioning "ductile frame" flat plate structures.

Based on the concept of "integral beams," the flat plate is reinforced to avoid shear and torsion distress at the slab-column junction. Existing procedures are used for calculating stiffness for evaluating P-Δ effects and for detailing reinforcement. It should be emphasized that due to the inherent low stiffness of flat plate to column connections, shear walls may often be required to provide adequate drift control.

Test results indicate that considerable ductility is provided in flat plates designed with "integral beams."

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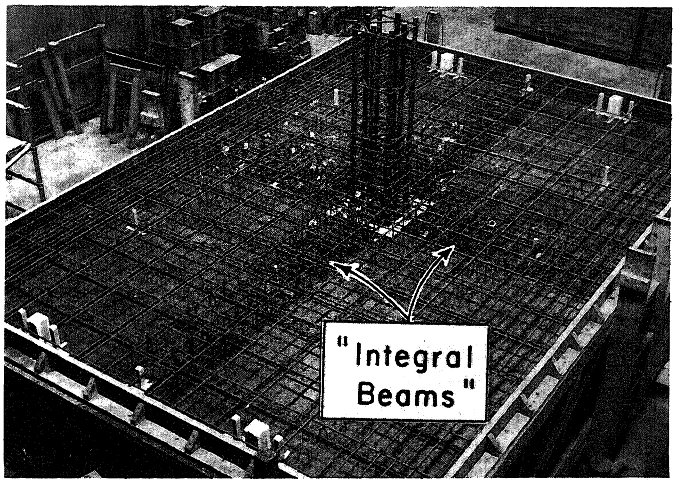
Fig. 1 Reinforcement for Test Specimen Containing "Integral Beams"



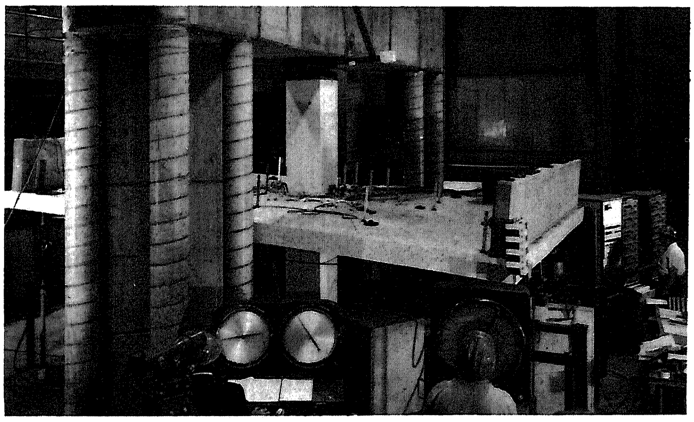


Fig. 2 Test Specimen at Maximum Deflection

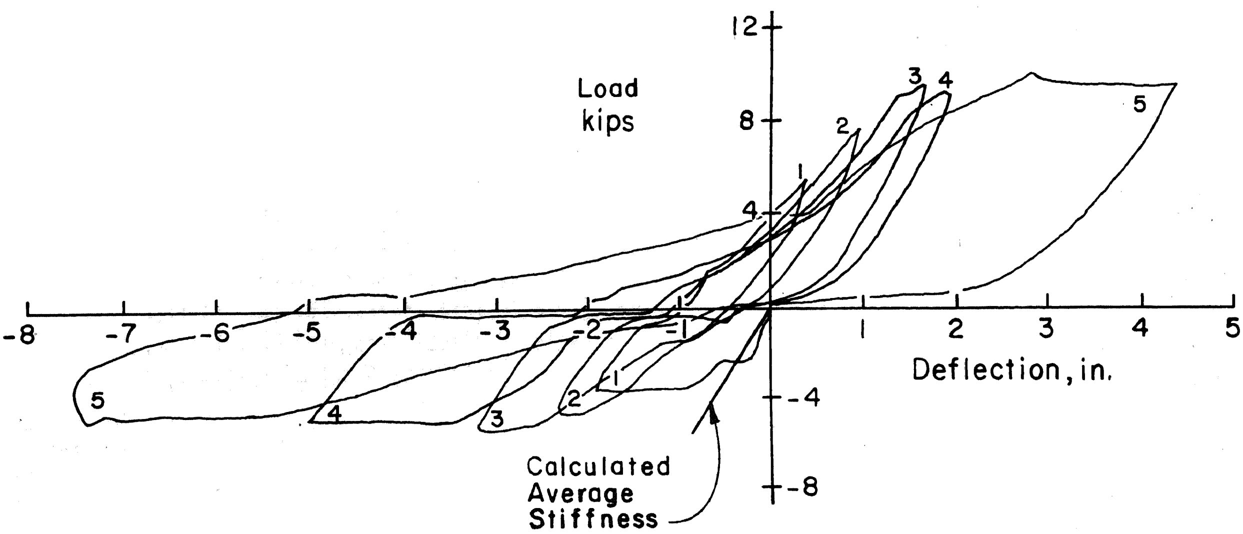


Fig. 3 Load Versus Deflection for Salb with "Integral Beams"