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R/C flat slab-column frame connections: Analytical modelling

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ABSTRACT: The basic lateral load transfer mechanism of reinforced concrete flat slab-column frame connections is analysed. An idealized analytical modelling is proposed, based on observations of experimental tests carried out by the authors. The total load carrying capacity is assumed to be the sum of the principal resistance participants, which develop and vary during the different loading stages until failure. The predicted response results in a good agreement to the measured ultimate moment.

1 INTRODUCTION

The moment transfer mechanism of reinforced concrete flat slab - column frame connections is a rather complex three-dimensional problem, which has attracted many studies. Design codes of practice, recommendations, and accepted common theories (ASCE-ACI-426 1974, ACI-ASCE-352 1988, Moehle, Kreger & Leon 1988, ACI-318-89 1989, Park & Gamble 1980) provide various simplified methods of calculation for lateral load transfer of flat slab-column frames. The most used methods of analysis commonly represent the resistance in completely different analytical models, which actually are not fully representing the real resistance behavior and failure type of the slab. The predetermined, general or local yield line patterns (Park & Islam 1976, Gesund & Goli 1979) are incompatible with the actual failure modes, and neglect the thickness of the slab with other geometrical constraints. Analogies of uninterrelated equivalent beams framing on the column faces instead of the full slab (Hawkins 1973, 1979; Park & Islam 1976) somehow oversimplify the planar behavior and stress distribution throughout the slab in the vicinity of the column. Presumed linear shear stress distributions on a critical perimeter around the column, prescribe the estimated percentage of the unbalanced moment to be transferred by flexure and by eccentricity of shear (ASCE-ACI-426 1974). Besides, attempts have been made to isolate the relative contribution in flexure and torsion of the slab around the column (Stamenkovic' & Chapman 1974), concluding a larger torsional contribution (Kanoh & Yoshizaki 1979), yet disregarding the planar behavior of the slab. At the outset, significant uncertainties still exist considering the current methods of design simplification, being based on prescribed constant assumptions throughout the loading history.

Consistent idealization of the basic behavior mechanism is significant for engineering practice in allowing easy visualization of the possible failure modes, and therefore avoiding design mistakes. The objective of this investigation was to develop an idealized moment and gravity response analysis, under increasing earthquake loading, compatible with the resistance and ultimate failure mechanisms of interior flat slab-column frame connections, representative of those frequently used in typical low and medium rise residential buildings.

The behavior idealization model is based on observations and on analysis of tests reported in the literature (Hanson & Hanson 1968, Hawkins 1973, 1979, Ghali, Elmasri & Dilger 1976, Islam & Park 1976, Park & Gamble 1980, Morrison, Hirasawa & Sozen 1983, Pan & Moehle 1988, and Hawkins, Bao & Yamazaki 1989) and particularly on tests carried out by the authors, whose specimens underwent detailed "post-mortem" dissections of their failed zones (Farhey 1991, Farhey, Adin & Yankelevsky 1991). The predicted response of a flat slab-column frame can be calculated according to the idealized model of joint resistance mechanism. To prepare the derivation of a new analytical method, the existing theories of the principal active resistances are recapitulated and developed to fit the particular constraints.

2 IDEALIZED BEHAVIOR

The results of laboratory tests on four reinforced concrete flat slab - interior column connections served as prototype. The subassemblages were subjected to cyclic, quasi-static horizontal loadings, in addition to constant vertical gravity loading. The specimens, at about two-thirds scale, were reinforced by steel arrangements representative of column strips.

A slab-column frame subjected to lateral earthquake loading is carrying a shear force, horizontal within the story, causing a bending moment at the slab-column joint. The shear force acts on the joint simultaneously with vertical gravity loads transferred from the slab to the column. The cyclic shear force and the resulting bending moments acting on the joint degrade the capacity of the slab in flexure, shear, and torsion, until failure occurs.

Initially, at a very early stage of loading, top flexural cracking occurs in front of the column face, due to tensile stresses which are summed up in the same direction from both gravitational and lateral loadings (see fig. 1a). The rectangular box of fig. 1 represents the connection core and the projected dashed lines come to ease the distinction between the top and bottom surfaces of the slab. Thereafter, the foregoing top front edge flexural crack continues to the sides in a straight line. Then, in front of each side face of the column, this crack develops into diagonal torsional cracking as side extensions at a certain distance from the column, as shown in fig. 1b. Subsequently, the same crack branches off into another diagonal, parallel to the previous one, directly turning around the column corners, as demonstrated in fig. 1c. At this late stage, the bottom back face flexural cracking occurs, because of the opposing influence of gravitational and lateral loadings. Next, crushing of concrete at the front face bottom flexural compression zone begins. In the absence of adequate reinforcement, the shear stresses at the front face of the column were transferred only by the decreasing flexural compression zone. Therefore, the diagonal tensile cracking of the slab there occurs, through its thickness, in a rather brittle manner of failure, as demonstrated in fig. 2. Eventually, the same collapse crack continues upwards peeling off the concrete cover over the top reinforcement. The final configuration resembles a one-side punching failure, as observed in experimental tests.

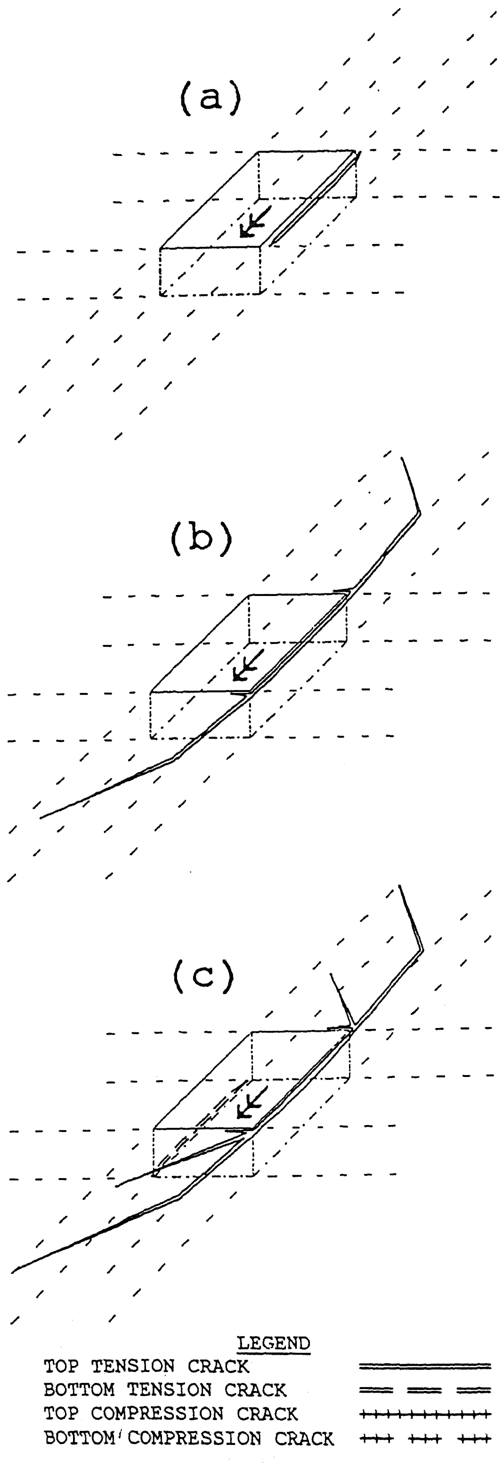

Figure 1. Idealized connection resistance

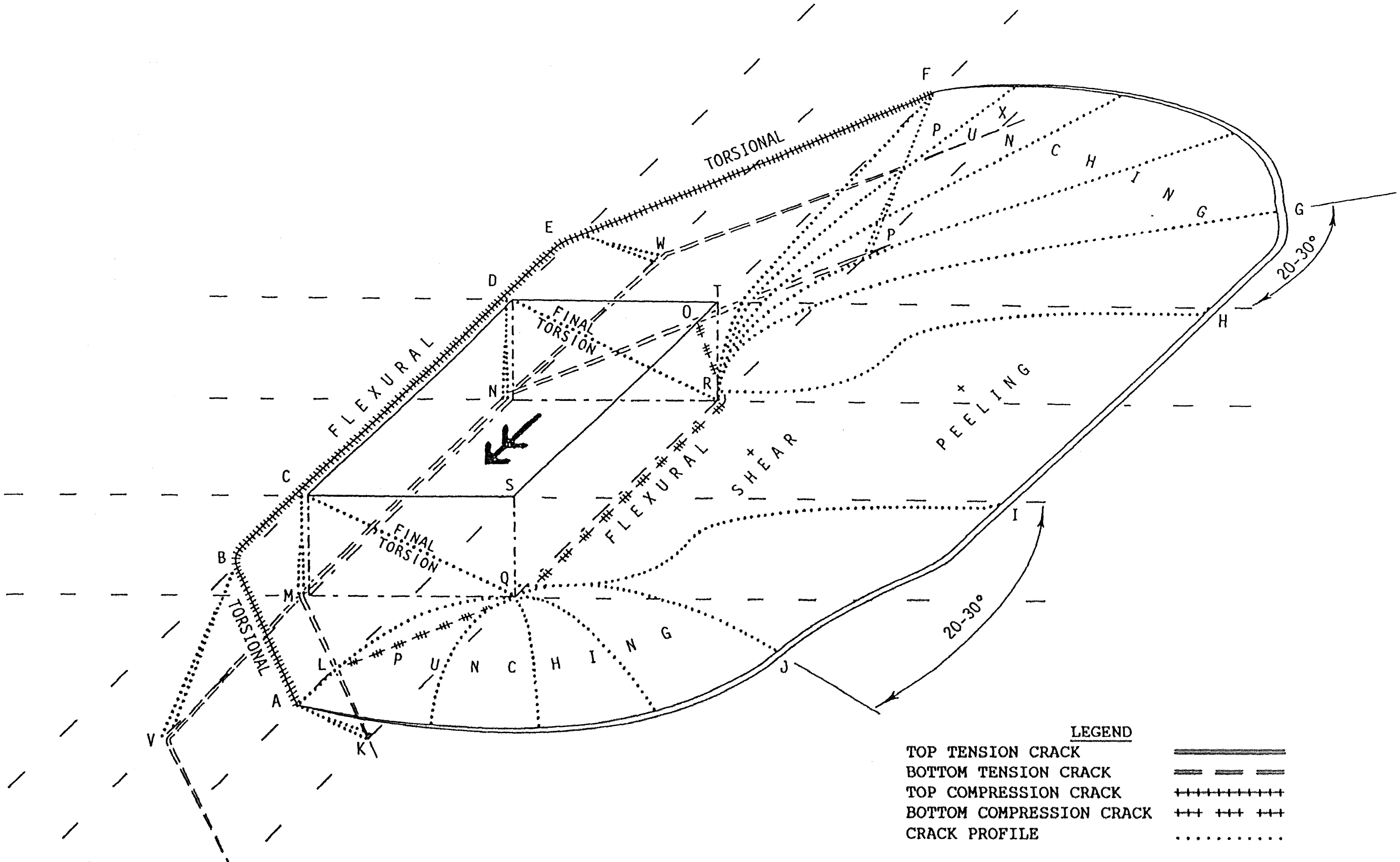

Figure 2. Idealized ultimate collapse mechanisms

3 ANALYTICAL MODEL

The response of a flat slab-column frame connection can be predicted according to the idealized basic mechanism. The slab's resistance and ultimate failure components at the connection and its surroundings are evaluated according to the observed modes and dimensions. The principal resistance participants, seen to dominate the behavior during the advance of the loading stages, are the flexural resistances transferred at the front and back faces of the column, the flexural shear resistance transferred by the decreasing front and back flexural compression zones, and the torsional resistances transferred in front of the side faces of the column.

3.1 Torsion

The relative torsional contribution, to the total moment transfer resistance of the connection, is received by the participation of the slab portion in front of the side faces of the column. The two representative parallel torsional cracks, mentioned as side extensions of the flexural cracking and idealized by bilinear cracks (see fig. 1c), occur in reality as smooth curves in addition to insignificant smaller cracks. The cross section width participating in torsion is taken approximately as the width of the respective column face. A basic, compatible, discontinuous torsion failure mechanism is used for the solution. This mechanism, derived by Müller (1976), satisfactorily fits the slab behavior in the projection of the side faces of the column. The facial inclination of torsional tensile cracks and compression lines is obtained from the torsional equilibrium equation on the section, according to the properties of the concrete, and the amount and properties of the reinforcement.

3.2 Flexure

The relative flexural contribution, to the total moment transfer resistance of the connection, is obtained by the participation of the slab portion in the front and back faces of the column. The participating cross section width in flexure is taken between the diagonally crossing torsional cracks from the two sides (see figs. 1c and 2). Consequently, the value of the width and the amount of the participating flexural reinforcement may be derived from the geometry of the torsional resistance mode. The load stage dependent slab width participating in flexure is different for the front and back faces of the column, based on the column cross section dimensions, the slab thickness, the concrete strength and the slab reinforcement properties.

3.3 Shear

In the cross sections cracked by flexure, the shear is almost exclusively carried by the concrete compression zone according to its decreasing height. If the stress in the tensile flexural reinforcement reaches the yield strength, or the stress in the compression zone approaches the crushing strength, any possible shear-carrying capacity by aggregate interlock is lost, and the dowel action of the tensile reinforcement is usually insignificant. The relative contribution from the shear resistance mechanism, depends greatly on the tensile strength of the concrete with all its deviation and degradation characteristics.

4 COMPARISON WITH EXPERIMENTS

Based on the suggested idealized resistance mechanism model, the calculated ultimate moments of experimental test specimens are compared to their measured ultimate moments. Table 1 represents the general properties of the specimens of Farhey, Adin & Yankelevsky (1991), and a comparison between measured ultimate moments and calculated ultimate moments, according to some methods. It may be seen that the results of the suggested model are not excessive at all. The predicted strengths by other methods generally are not in good agreement, neither between them, nor with the experimental tests, in addition to their inability to base the assumptions on actual behavior mechanism.

5 CONCLUSIONS

The proposed idealized resistance mechanism model, and the consequent analytical solution agree qualitatively and quantitatively with test results, which cannot be said about the codes of practice and current oversimplified solution methods, based on analogies with constant assumptions throughout the loading history. The concept, to assume that "the slab portion given by the projection of the column acts as a beam", distracts from the real behavior of the slab.

This stage of work emphasizes the need for more experimental work to deepen the comprehension of the behavior, at various loading stages. Understanding of the full range behavior may be a solid foundation for a general theoretical model.

Table 1. Comparison of measured and calculated ultimate moments [kN-m]

Spe- -ci- -men	Slab section [cm^2]	Column section [cm^2]	f'_c test [MPa]	Load type	M_{test} ult.	Yield line theory	ACI 318-89 linear shear	ASCE -ACI -426	Park& Islam beam an.	$M_{calc.}$ idealized mechanism model	$\frac{M_{test}}{M_{calc.}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1,2	269x8	20x30	35.09	H	33.0	29.2	37.4	-	43.1	32.9	1.003
3	269x8	20x30	15.04	H+V*	19.0	27.6	17.6	16.5	38.4	17.1	1.111
4	269x8	12x30	15.04	H+V*	15.0	27.6	10.3	10.3	35.0	14.8	1.014

* Vertical load V = 25 kN (5.6 kips).

Note: 1 kN-m = 0.737 k-ft; 1 cm = 0.3937 inch; 1 MPa = 145 psi.

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