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Local strength at column heads in flat slabs subjected to a combined vertical and horizontal loading

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With reference to § 38, the application of the correction factors $\sqrt{(5000/U_w)}$ and $5000/U_w$ to allow for the variation in concrete strength may have influenced the interpretation of the test results even though equations (1) and (9) would suggest their use. For example, application of the latter factor would imply that test specimen $M/I_b/2$ should be capable of sustaining a considerably higher moment than $M/I_b/1$ (of the order of 6980/5500), whereas M_{test} for each was the same, and similarly for $M/I_t/1$ and $M/I_t/2$. Is the use of $\sqrt{(5000/U_w)}$ for vertical loading justified when for slabs of a similar percentage reinforcement ($p = 1{\cdot}15\%$) tested by Elstner and Hognestad[15] the test results indicate that the value of V_{test} is largely independent of U_w (see Table 11)? Perhaps a simpler and more appropriate approach to obtaining the interaction diagram would have been to leave the test results uncorrected. Alternatively values of V_u and M_u, based on the properties of individual slabs, could have been computed and used in conjunction with V_{test} and M_{test} to produce the interaction diagram. This approach would also have served as a verification of the interaction formula presented in equation (11). The latter approach has been applied to the test results of Moe[5] and Frellick[16] and the resulting interaction diagram (Fig. 19) is of the same form as that of the Authors.

64. The loading rig (Fig. 11), although ideal from the convenience viewpoint, cannot be said to simulate accurately the boundary conditions which exist in slabs. For example, in the particular case of interior columns, the use of the tie rods prevents the slab corners from lifting. As corner lifting is desirable, bearing in mind that for vertical loading the line of contraflexure is approximately circular, this would suggest that the Authors' test results would tend to be high relative to those of other

Table 11

Slab	U_w, *lb/sq. in.*	V_{test}, *lb*
A 1(b)	4570	82 000
A 1(c)	5260	80 000
A 1(d)	6680	79 000
A 1(e)	3680	80 000

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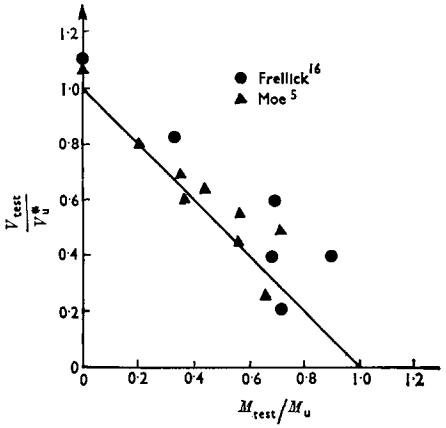

Fig. 19. Interaction curve—internal square column (V_u^* and M_u^* computed using Long's[23] method)

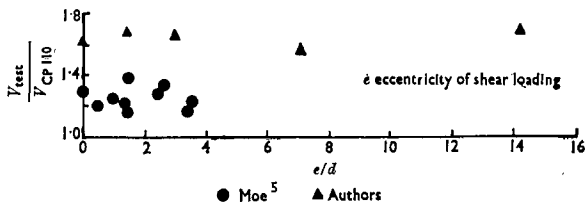

Fig. 20. Comparison of Moe's[5] and the Authors' results with predictions based on CP 110[17]

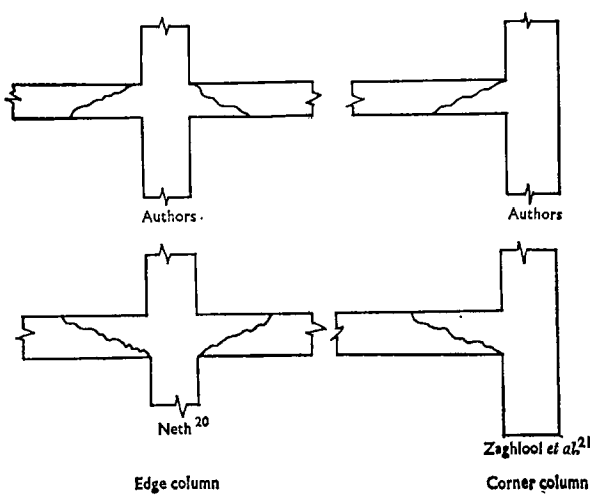

Fig. 21. Comparison of typical failure crack patterns

researchers. I found this the case when comparing the Authors' combined loading test results with those of Moe[5] using the CP 110[17] method of prediction (Fig. 20). Regan[18] supports this finding.

65. A further criticism of the testing set-up—for edge and corner columns in particular—is that although it approximately satisfies the equilibrium conditions which exist in a slab system it is far from satisfactory with regard to compatibility of deformations. This may lead to the development of the incorrect mode of failure and evidence to this effect has been observed by Hall.[19] In addition a comparison of the Authors' distributions of cracking at failure (Figs 16 and 18) with those of Neth[20] and Zaghlool *et al.*,[21] whose slabs more accurately satisfied the boundary conditions, would support this observation. The basic difference in the failure crack patterns is shown in Fig. 21. Perhaps this latter criticism should be tempered because of the widespread use of testing set-ups for edge and corner columns which are similar to those of the Authors.

66. As these tests were carried out on model slabs a more realistic estimate of the compressive strength would have resulted if appropriately scaled model cubes had been used.[22] The fact that 6 in. cubes will tend to yield lower compressive strengths than scaled cubes could be another reason why CP 110 predictions are low for the Authors' tests.

67. The provision of split cylinder tests would also have been of value as they would have indicated whether or not the ratio of tensile to compressive strength of the model concrete was representative of concrete in a full-scale slab system.

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The choice of correction factors $\sqrt{(5000/U_w)}$ and $5000/U_w$ was indeed based on equations (1) and (9). For the vertical loading, Moe's[5] formula was modified when calculating punching strength of flat slabs with internal, edge and corner columns; the original formula was based, among others, on tests by Elstner and Hognestad,[15] which showed that for a given column size and slab thickness, punching strength depended mainly on the concrete strength and to some extent on the flexural strength of the slab.

69. No loading rig for punching shear, especially when the horizontal loading is also included, can be ideal, convenient or easy to make. The use of square slab specimens and the type of loading rig we used followed on the whole the accepted practice of earlier investigations.[4–6,9] Of course it cannot completely represent the prototypes, but some limitations in this respect had to be accepted.

70. Modes of failure can only be compared when loading conditions are similar. Figs 16 and 18 show crack patterns and modes of failure which are to be expected in specimens predominantly subjected to moments due to horizontal shear forces; for specimens shown in Figs 16 and 18 the ratio M/M_u is high while V/V_u is quite low (Table 9). It is interesting to compare the mode of failure shown in Fig. 16 with that shown by Hanson and Hanson[9] for test D15; both are obtained for slabs with high M/M_u ratios and small V/V_u ratios and their modes of failure are almost identical.

71. All the test specimens described in the Paper represent the prototype to a scale of one half. Initially, exploratory tests (Tables 2 and 3) were carried out with one aim being to confirm that the results of previous investigations, such as Moe's,[5] could be reproduced in specimens of the size chosen in this investigation. This proved very satisfactory in the specimens with tension and compression reinforcement—such as used in this investigation. Six-inch cubes were used to provide a standard measure of concrete compressive strength; we are not aware of any evidence to suggest that the ratio of cube strength to in situ strength depends on aggregate size in the range $\frac{3}{4}$–$\frac{3}{8}$ in., or that a 4 in. cube with $\frac{3}{8}$ in. aggregate would better represent the value of this ratio for $\frac{3}{4}$ in. aggregate and a full-scale slab.

References

15. ELSTNER R. C. and HOGNESTAD E. Shearing strength of reinforced concrete slabs. *J. Am. Concr. Inst., Proc.*, 1956, **53**, No. 1, July, 29–58.
16. FRELLICK J. S. *Comparison of different methods of conducting punching tests on reinforced concrete slabs subjected to combined loading.* MSc thesis, Queen's University, Kingston, Canada, 1971.
17. BRITISH STANDARDS INSTITUTION. *Code of practice for the structural use of concrete.* British Standards Institution, London, 1972, CP 110.
18. REGAN P. E. Design for punching shear. *Struct. Engr*, 1974, **52**, 6, June, 197–207.
19. HALL C. G. *Model studies on punching of reinforced concrete flat slabs at edge columns.* Honours project report, Civil Engineering Department, Queen's University, Belfast, 1974.
20. NETH V. W. *Model studies on punching of reinforced concrete flat slabs at edge columns.* MSc thesis, Queen's University, Kingston, Canada, 1971.
21. ZAGHLOOL E. R. F. *et al.* Experimental investigation of reinforced concrete flat plate floors. *J. Struct. Div. Am. Soc. Civ. Engrs*, 1970, ST3, Mar., 487–507.
22. ROLL F. *et al.* Shear resistance of perforated reinforced concrete slabs. In *Cracking, deflection and ultimate load of concrete slab systems.* American Concrete Institute, Detroit, 1971, SP 30, 77–101.
23. LONG A. E. Punching failure of slabs—transfer of moment and shear. *J. Struct. Div. Am. Soc. Civ. Engrs*, 1973, **99**, ST4, April, 665–685.