Interaction between Hollow Core Slabs and Supporting Beams

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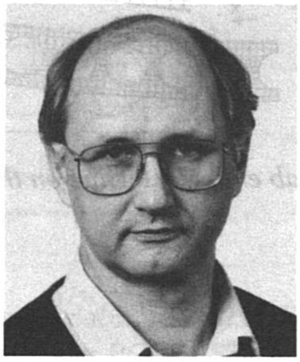


Matti Pajari, born 1948, received his DTech at Helsinki University of Technology in 1995. Since 1978, he has been involved in research and development projects concerning reinforced and prestressed concrete structures.

Summary

Ten full-scale loading tests on floors comprising prestressed hollow core slabs and steel, concrete or composite beams have been carried out. In every test the slabs underwent a web shear failure. In nine of these tests the observed shear resistance of the slabs was 40 to 74%, and in one test 98% of the shear resistance observed in reference tests. The reduction in the shear resistance can be explained by the shear interaction between the slabs and the beams. A simple calculation model to take account of this effect is presented.

1. Introduction

When loading a floor in which hollow core slabs are supported on beams, both the slabs and the beams deflect, cf. Fig. 1a. In such a floor the ends of slab units, especially those close to the columns, are subjected to both vertical and transverse shear (here transverse means the same as parallel to the beams) and deform as illutrated in Fig. 1b. This is called *shear interaction effect.* It may cause the webs of the slabs to fail under a vertical shear force considerably weaker than observed for a slab supported on a rigid bearing. The same effect occurs in other slab types, too. However, the effect is most important in prestressed hollow core slabs, because, due to the production technology, their thin webs cannot be provided with shear reinforcement.

The present paper briefly summarizes some results of ten full-scale load tests and design rules based on these results. A more comprehensive view is given by Pajari & Yang (1994), Pajari (1995, 1997), Pajari & Koukkari (1997), and Leskelä & Pajari (1995). To the author's knowledge, neither experimental nor theoretic research on this topic had been done before the first three of the present tests were performed. Since then, Leskelä has independently explained the test results of VTT, formulated theoretic and numeric calculation models and developed practical design methods (1991a,b, 1993, 1994). Borgogno & Fontana (1995) have carried out fire tests on PHC slabs supported on beams. In their tests the shear resistance of the slabs was not exceeded, which may be explained by the short slab spans (= 2.4 m), strengthening of the slabs and small loads.

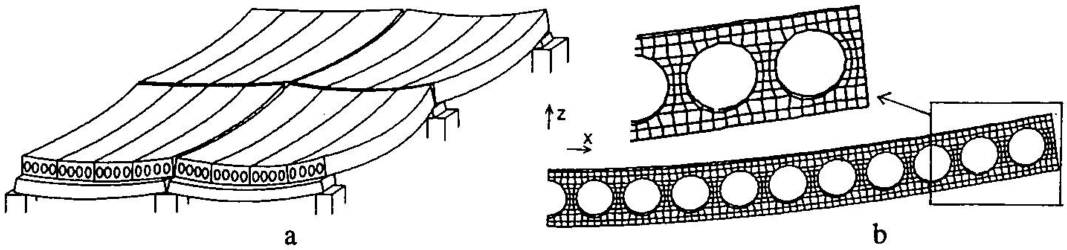


Fig. 1 a) Deformed PHC floor. b) Deformed slab end. Centerline on the left, longitudinal edge on the right

2. Test arrangements

Fig. 2 depicts the test layout and Fig. 3 the nominal slab cross-sections. Table 1 gives some characteristics of the tests.

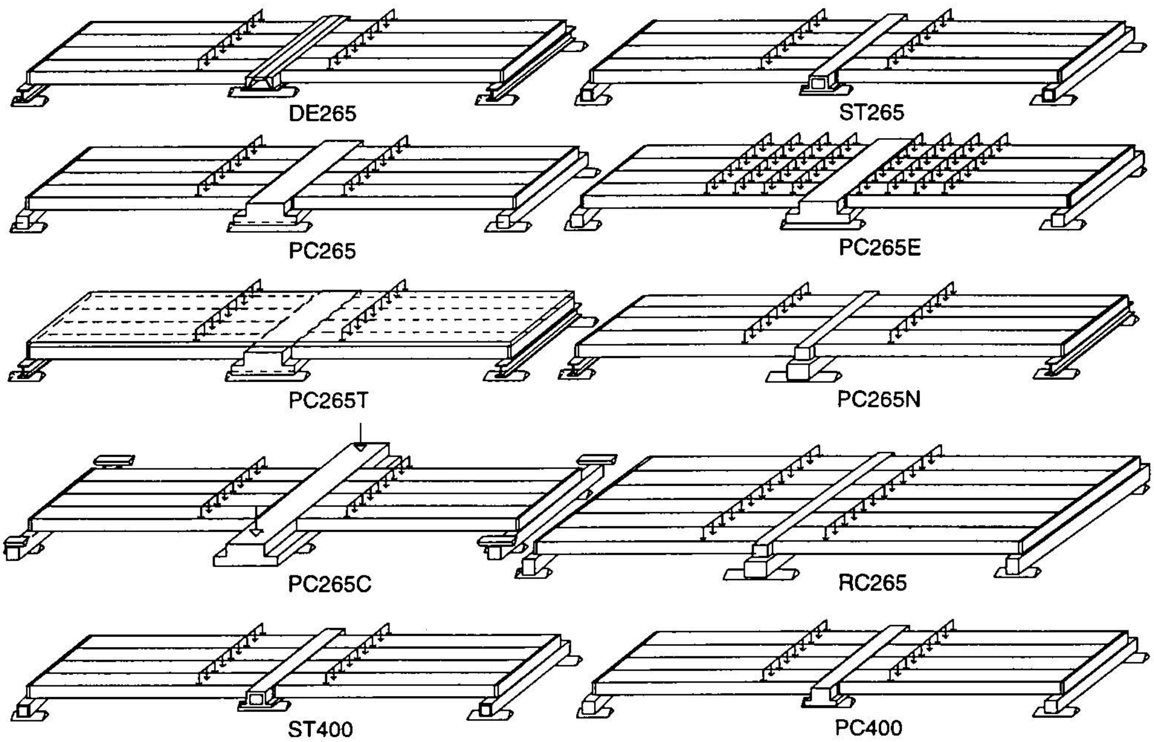


Fig. 2 Layout for floor tests

The test codes are of type XYABCZ, where XY refers to the middle beam (PC and RC for prestressed and reinforced concrete beam, respectively, ST for top-hat steel beam and DE for Delta beam which is a certain type of composite beam). ABC is the slab thickness in mm and Z an optional suffix (E refers to evenly (uniformly) distributed load, T to topping concrete, C to clamping of beams and N to normal beam which is positioned totally below the slabs).

Some of the tests were basic tests which aimed at simulating the behaviour of the floor when no special measures are taken; others clarified the effect of special measures like void filling or reinforced concrete topping. The loading arrangements were planned to exclude failure modes other than the failure of the middle beam or shear failure of the slabs. The end beams were designed to undergo the same deflection as the middle beam.

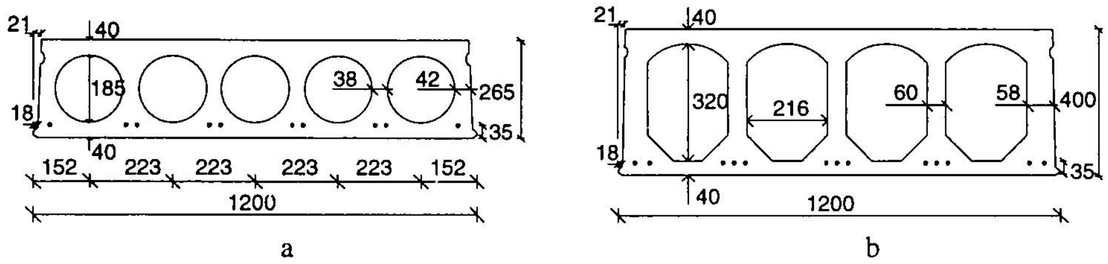


Fig. 3 Nominal cross-section of slabs. a) Tests DE265, ST265, PC265, PC265E, PC265T, PC265N, PC265C, RC265. b) Tests PC400, ST400

Table 1 Types of beam, slab length (L_{sl}), span of the middle beam (L_b) and distance of the line load(s) from the slab end a (a_i)

Test	Middle beam	End beam	L_{sl} mm	L_b mm	a (a_i) mm	Note
DE265	Delta	ST, I	6000	5000	1000	Composite beam
ST265	ST, top-hat	ST, box	6000	5000	1000	Basic test
PC265	PC, invert. T	RC, rectangle	6000	5000	1000	Basic test
PC265E	PC, invert. T	ST, I	6000	5000	375, 1125, 1875, 2625	Filled voids (185 mm) eight line loads
PC265T	PC, invert. T	ST, I	6000	5000	1000	RC topping
PC265N	PC, rectangle	ST, I	6000	5000	1000	Normal beam
PC265C	PC, invert. T	ST, I	6000	5000	1000	Beam with clamped ends
RC265	RC, rectangle	RC, rectangle	6000	7200	1200	Cracked normal beam
PC400	PC, invert. T	RC, rectangle	7200	5000	1260	Filled voids (320 mm)
ST400	ST, top-hat	ST, I	7200	5000	1260	Basic test

3. Test results

All tests ended with web shear failure of the slabs close to the middle beam. In test PC265C with clamped beams, all slab units failed simultaneously on one side of the middle beam. In other tests, the failure took place in one to four slab units close to the supports of the midlle beam. Table 2 gives the shear resistance observed in the floor test and in reference tests carried out on similar slab units supported on non-settling supports.

In nine tests, the observed shear resistance of the slabs was 40 to 75% of the resistance observed in the reference tests, and 98% in test PC265C with clamped beams. The measurements and analytical considerations showed that only in test PC265E was the middle beam yielding when the slabs failed. In other tests, the slabs were not capable of carrying a load corresponding to the resistance of the beams. This contradicts the conventional design methods according to which the failure should have been governed by the resistance of the beams, not by the resistance of the slabs. Therefore, the shear interaction effect must be taken into account when designing hollow core floors supported by beams.

Filling the voids and applying reinforced concrete topping proved to be effective, but they could not totally eliminate the reduction in the shear resistance of the slabs. Clamping the ends of the beams was still more effective: in test PC265C no reduction in shear resistance was observed.

The deflections of the middle beams were small, typically 1/800 to 1/300 of the span of the beam.

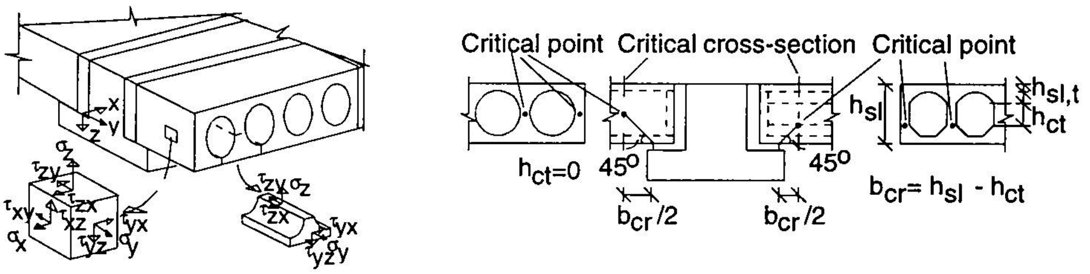
Table 2 Comparison of shear resistance observed in floor test (V_{obs}) with that observed in reference tests (V_{ref}) and with the support reaction corresponding to the predicted resistance of the middle beam ($V_{sl,b}$) (no contribution from the slabs or joint concrete assumed)

Test	V_{obs} kN	V_{ref} kN	$\frac{V_{obs}}{V_{ref}}$	$V_{sl,b}$ kN	$\frac{V_{obs}}{V_{sl,b}}$
DE265	113.6	284.5	0.40	147.0	0.77
ST265	166.1	231.1	0.72	169.7	0.98
PC265	103.8	231.1*	0.45	116.6	0.89
PC265E	146.8	251.8	0.58	121.6	1.21
PC265T	142.8	193.3	0.74	135.0	1.06
PC265N	163.4	217.5	0.75	172.1	0.95
PC265C	191.7	194.9	0.98	191.8	1.00
RC265	106.8	226.2	0.47	78.0	1.37
PC400	255.4	483.0	0.53	312.5	0.82
ST400	293.9	516.3	0.57	308.6	0.95

* Value measured for slab units in test ST265

4. Analysis of web shear failure using composite beam model

Consider an infinitesimal cube taken from a web of a hollow core slab as shown in Fig. 4a.



a b

Fig. 4 Stress components in the web

The critical point may be assumed to be so far from the supporting beam that the local effect of the support reaction on the stress state may be ignored, i.e. the resultant of σ_z in a horizontal cross-section may be ignored. σ_x and τ_{xy} are obviously insignificant at the mid-depth of the web and may be ignored. σ_y and τ_{zy} can be calculated as in the conventional design of hollow core slabs. For reasons explained elsewhere (Pajari 1995), a failure criterion based on the interaction of the transverse and vertical shear in the webs of the slabs is adopted. The transverse shear flow v in the webs is calculated using the composite beam model shown in Fig. 5.

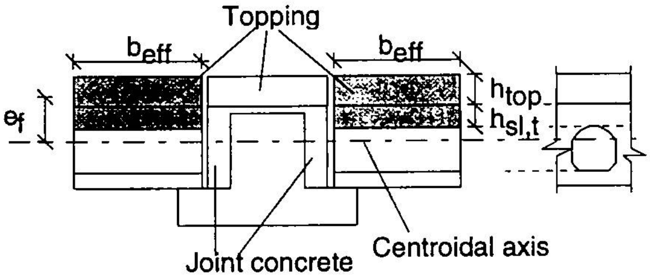


Fig. 5 Composite beam model

The value of effective width b_{eff} depends on the slab, beam and their interaction. By dividing v over a critical length b_{cr} defined in Fig. 4b, τ_{zy} is obtained. The adopted failure criterion is

$$f_{ct} = \frac{\sigma_y}{2} + \sqrt{\frac{\sigma_y^2}{4} + \tau_{zy}^2 + (\beta\tau_{zx})^2} \tag{1}$$

where f_{ct} is the axial tensile strength of the concrete and β a reduction factor which takes into account extra measures like void filling, topping reinforcement etc. Both b_{eff} and β are determined experimentally. Table 3 gives recommended values of b_{eff} based on the tests.

Table 3 Effective width for floors similar to test floors

Beam	Slab mm	b_{eff} / L_b %
Concrete beam	265	3.72
	400	8.00
Steel beam	265	1.76
	400	2.30
Delta beam	265	2.74

As an example, consider how the span of the beam affects the resistance of the slabs when other parameters are constant (see Pajari 1995 for the structural data). For short spans the resistance of the slab is critical (Fig. 6). The resistance of the beam is critical for long spans. The arrow shows where the difference between the conventional and the proposed design criteria is greatest.

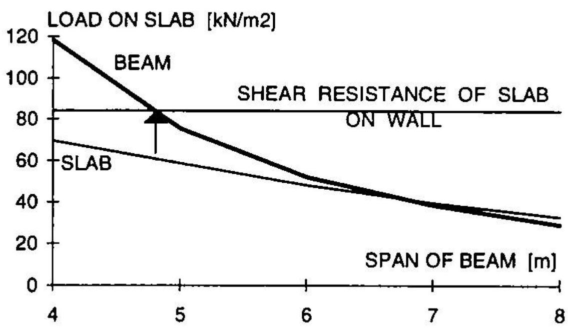


Fig. 6. Effect of span of beam on resistances of beam and slab.

5. Concluding remarks

According to the test results, the shear resistance of hollow core slabs may be considerably reduced due to the deflection of the supporting beams. Typical reductions in the tests were 25 - 60%. The amount of reduction depends on the interaction of the slabs and the beams.

It has been common practice to assume that the composite action, if present but not taken into account in the design, provides the structure with extra safety. Most of the tests showed opposite behaviour: the load-carrying capacity of the floor was lower than that corresponding to the resistances of isolated beams and slabs. The composite action transfers strain energy from the beams to the slabs, which gives rise to web shear failure in the slabs under a relatively low load. The shear resistance can be enhanced by filling the voids of the slabs at their ends, by using reinforced concrete topping, by making the beams stiffer or continuous etc. However, the reduction of shear resistance cannot be ignored in the design of hollow core slabs supported on beams. A simple, semiempiric calculation model is presented. It is currently being used in Finland, Sweden and in The Netherlands.

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