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Resistance to longitudinal shear of composite slabs with longitudinal reinforcement

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ABSTRACT

Tests are reported on composite slabs with trapezoidal sheeting and longitudinal reinforcing bars above the troughs. The contribution from this reinforcement to resistance to longitudinal shear is found to be substantial. Analyses of the results lead to a design method that allows for it. It may not be possible to take full advantage in the design of this extra resistance, because the predicted deflection in service may then become excessive. An appendix gives an elastic–plastic model that accurately predicts the deflection of the slabs just before failure. A list of the principal nomenclature is included.

1. Introduction

Longitudinal reinforcing bars are sometimes placed within the troughs of composite floor slabs for buildings to improve their resistance to fire. For 'cold' design situations, clause 9.7.3(10) of EN 1994-1-1 (Eurocode 4) [1] says that for the partial connection method for resistance to longitudinal shear, these bars may be 'taken into account'; but it does not specify a method.

A method based on simple plastic theory is given in clause 8.4.1 of Publication 087 of the European Convention for Structural Steelwork (ECCS) [2]. It refers to ENV 1994-1-1 and adds, without explanation, that '3 additional tests' are required. The scope and limitations of this method are not defined (e.g. amount of reinforcement, shape of profile), and no supporting evidence from tests is cited.

It would be uneconomic for a sheeting manufacturer to commission extra tests for each combination of the many independent variables. The objective of the work reported here was to develop an understanding of the behaviour of the reinforcement in partial-connection situations sufficient to enable its contribution to shear resistance to be predicted, without any additional testing. It is assumed that the presence of reinforcement does not alter the ultimate shear strength at the surface of the sheeting, τ_u, determined to clause B.3 of Eurocode 4 and provided by the manufacturer of the sheeting.

The reader is assumed to have some knowledge of design to Eurocode 4 for longitudinal shear in composite slabs without longitudinal reinforcement. Eurocode notation is used as far as possible, but without subscripts k (characteristic) and d (design), because most quantities used here for predictions are mean measured values from the four tests to be reported.

2. Implications of the 'plastic' model used in the ECCS method

The test layout of Eurocode 4 for composite slabs is shown in Fig. 1(a). The slabs normally have light mesh reinforcement above the sheeting, shown in Fig. 1(b), which is ignored in design for longitudinal shear. The span in Fig. 1(a), L, is so chosen that longitudinal shear failure occurs between a free end and the nearer load point (i.e. along a length that exceeds the 'shear span' L_s by the length L_0 of the end overhang), and leads to a flexural hinge at a point such as B. Predicted and test bending resistances at this point will be compared in this paper.

The ECCS method assumes that the reinforcing bars are at yield in tension at B. The distribution of longitudinal strain at this cross-section can be estimated, as follows. Assuming that the bars have just begun to yield at 500 MPa and that the concrete is beginning to crush at the top surface at a strain of 0.0035, then the strain distribution in the slab is as shown in Fig. 1(b). In the absence of uplift, the curvatures of the sheeting and the slab are the same. If the sheeting has just reached its yield stress (about 380 MPa) at its centroid, the strain there is 0.0019, and the net longitudinal force in its top half is small. This corresponds to a degree of shear connection of about 0.5, which is a level rarely exceeded in such tests at cross-section B.

The strain distribution in Fig. 1(b) shows that the bars at yield in tension are at the same level in the slab as a region of sheeting that is almost unstrained. This implies a large slip strain at this section, about 2500×10^{-6}, and significant slip along the shear span. It raises the question: can shear strength τ_u (found from slabs without added

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Principal nomenclature

A_{pe}	effective cross-section of sheeting, with embossed area of web halved, per m width
A_s	area of longitudinal reinforcing bars, per m width
e, e_s, x_{pl}, z_1 and z_2	dimensions shown in Fig. 5(b)
f_c	mean cylinder strength of concrete in a test
L	span of a simply-supported composite slab. The shear span L_s is $L/4$, except for tests RL 10
L_a	anchorage length for reinforcement, from a free end of the slab
L_1	value of x beyond which the sheeting has full shear connection, so $\eta = 1$
M_{pa}	plastic moment of resistance of sheeting, per m width
M_{pr}	bending resistance of sheeting, reduced by axial tension, per m width
M_{Rf}	bending resistance of composite slab, for $\eta = 1$ and bars at yield, per m width
M_{R1} and M_{R2}	predictions of M_{test}, per m width, by different methods
M_{test}	maximum bending moment in a test, under a point load, per m width
N_p	resistance of sheeting to direct tension, per m width, and $N_{p,p}$ where combined with bending
N_s	tension in reinforcing bars at yield, per m width; and $N_{s,e}$ in the elastic range
x	coordinate: distance from a free end of a composite slab
τ_u	mean ultimate longitudinal shear stress for sheeting, from tests
η	degree of shear connection, for sheeting

reinforcement) be maintained at the increased slips likely to occur before the bars reach yield?

The following tests on composite slabs RL 4 to 7 (unreinforced) and RL 8 to 10 (reinforced) provide evidence that it can.

3. The tests

The following data apply to all of the tests. Results are quoted per metre width of slab.

- Equivalent cross-sectional area of Ribdeck AL 0.9-mm sheeting: $A_{pe} = 1105$ mm^2/m for a nominal cover width $b_p = 900$ mm, allowing for the effect of embossments on the webs.
- Nominal width and thickness of the slabs tested: 0.9 m and 140 mm.
- Measured yield strength of sheeting: $f_{ypm} = 402$ MPa.
- Force in sheeting at yield in tension: $N_p = 444$ kN/m.
- Plastic resistance moment of sheeting: $M_{pa} = 10.68$ kNm/m.
- Measured 0.2% proof stresses of reinforcing bars: 10 mm, 494 N/mm^2; 16 mm, 457 N/mm^2.
- Average weight of composite slab: 2.41 kN/m per 0.9 m width.
- End overhang of composite slab: $L_o = 100$ mm.
- Propped construction was used. Crack inducers were placed under the two point loads.
- No mesh reinforcement was used.

3.1. Tests on unreinforced slabs

Tests RL 1 to 3, with a short shear span, were done for the *m–k* method for the prediction of shear resistance and are not reported here. Tests RL 4 to 7 all had a span $L = 4.80$ m (so $L_s = 1.2$ m) and a mean compressive strength of 100×200 mm cylinders (after conversion from cube results) of 22.5 N/mm^2.

The tests were fully in accordance with Annex B of Eurocode 4, including cyclic loading to clause B.3.4. The criterion for 'ductile' behaviour in clause 9.7.3(3) was well exceeded in seven of the eight end slips measured. The marginal shortfall at one end of specimen RL 5 was ignored.

The mean of the four values for ultimate shear strength from these tests, τ_u, is *0.188 MPa*, with coefficient of variation 14%. Variations found in similar test series at other laboratories range from 7% to 17%, so 'prior knowledge' can be assumed in finding τ_{Rk} to Annex D of EN 1990. The result is $\tau_{Rk} = 0.14$ MPa, further reduced in practice to τ_{Rd} by a partial factor of 1.25.

From clause B.3.1(4), this result is applicable for sheetings at least 0.86 mm thick, with characteristic yield strength above 320 MPa and concrete strength f_{ck} exceeding 17 MPa.

3.2. Tests on reinforced slabs

Each slab had one reinforcing bar (diameter, 10 mm or 16 mm) at the centre of each of its four troughs, at the level shown in Fig. 1(b), and held in place by 8-mm transverse bars resting on the sheeting. Specimens RL 8 and 9 were as similar as possible to specimens RL 4 to 7, except for the additional reinforcement, with shear spans (L_s) of 1.2 m. The subsequent columns of Table 1 give the area of the added reinforcement, A_s, the mean cylinder strength of the concrete at the time of testing, f_c, and the product N_s of the area A_s of the reinforcing bars and their yield strength.

Tests RL 10 were devised to find whether the bars are less effective at shorter shear spans. The layout for test RL 10a is shown in Fig. 2.

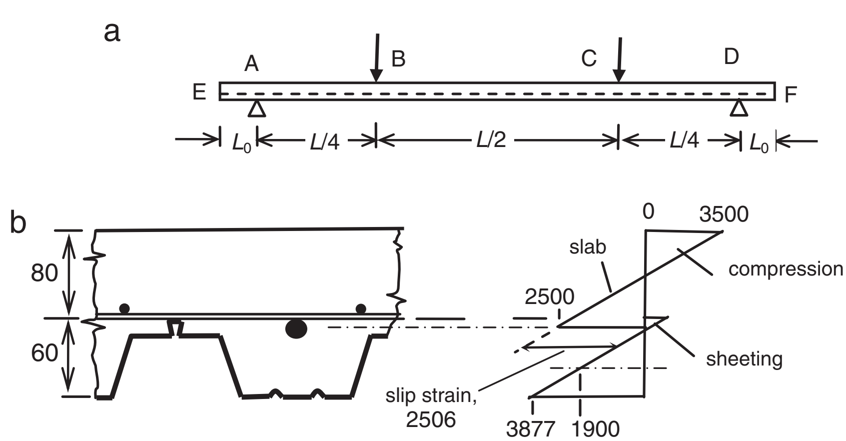

Fig. 1. (a) Layout of standard test on composite slab. (b) Part cross-section of slab and longitudinal strains (in 10^{-6} units) at section B.