A CONCRETE BLOCK BENDING TEST

- A New Small-scale Test to Obtain Shear Flow-slip Relations

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ABSTRACT

A new small-scale test is proposed to obtain basic information on the amount of shear force and slip distribution at a sheet-concrete interface for a composite element. The test results were used as the material property of an interface element to simulate the interaction between the steel sheet and the concrete in a finite element analysis. A comparison of numerical simulation and experimental results has shown that the results from the concrete block bending test were reasonable and reliable.

Key-words: Composite slabs, steel sheet, bond, finite element method.

1 INTRODUCTION

Composite slabs with steel sheeting are widely used in buildings. The longitudinal slip failure is the most common failure for this type of construction. It is indicated by relative movement (end-slip) between the steel sheet and the concrete at both ends of a test specimen at a load that is lower than the flexural bending strength of the composite slab. Numerous tests have shown that the shear bond strength at the concrete-sheet interface is the key factor in determining the behaviour of composite slabs. Therefore, in order to determine the shear stress at the sheet-concrete interface, some small-scale tests were performed on composite elements.

Results of a pull-out test were reported by Daniels /1/. In the tests, each specimen consisted of two identical steel sheets that were placed back to back. The identical concrete blocks were cast on the sheet. Shear forces and external lateral forces were applied to the specimen, as shown in Fig. 1. The tests were carried out on fifteen combinations of sheet geometry and thickness. A comparison of the pull-out test and the full-scale one-way slab test showed that the average value of the shear stress calculated from the pull-out test gave reasonable, although not conservative, estimation of the slab capacity before the initiation of end slip, and gave a lower-bound estimation of slab capacity after the initiation of slip.

More recently, Patrick reported the results of a slip block test which was carried out on a small composite element /2/. Vertical and horizontal forces were applied simultaneously to a specimen, as shown in Fig. 2. After the adhesion bond broke, the longitudinal slip was measured under different vertical forces to determine the amount of resistance provided by friction and mechanical interlock of the steel sheet. The results of the slip block test were then used in a partial shear connection strength model.

In principle, a small-scale test to study the shear transfer mechanism should establish a load environment similar to that in real structures. A composite slab is loaded by bending and shear forces. Bending curvature may influence the magnitude of shear stress transferred at the interface. If the shear force was applied directly to the specimen, the small-scale test probably could not show the behaviour of indentations after the initiation of the end-slip unless there were a lateral (or vertical) external force. This raises the question of whether the resistance of the indentations would be the same with or without the influence of a lateral external force. Although vertical separation between the steel sheet and the concrete could possibly occur in full-scale tests, it would not occur in small-scale tests when a lateral external force is applied. Based on these considerations, a small-scale test, here called a concrete block bending test, was designed and carried out. The details of the test and results are presented here.

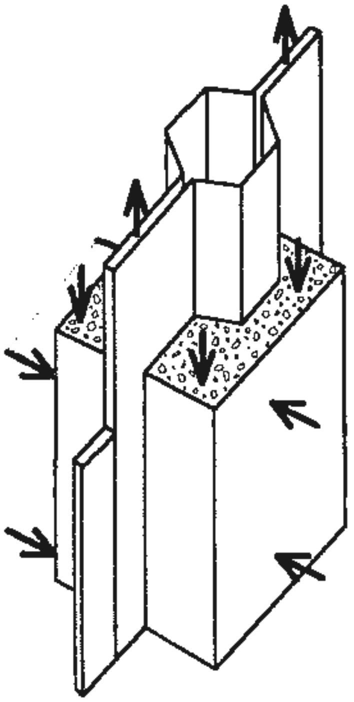


Fig. 1. Pull-out test /1/.

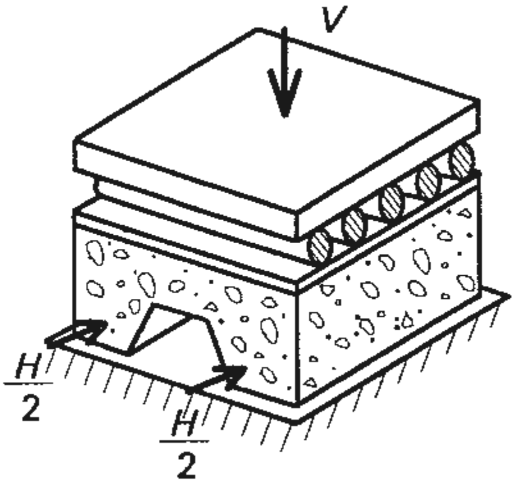


Fig. 2. Slip block test /2/.

2 DESCRIPTION OF THE TEST

Eight specimens were divided into four pairs according to the type of concrete and the shear span to depth ratio. Each pair consisted of two nominally identical specimens that are indicated by the same first number in the notation in Table 1. For simplicity, the normal concrete is abbreviated as NC and lightweight concrete as LWC.

The steel sheet used in the test was PEVA 45, produced by the Swedish company Svenska Byggplåt AB. The thickness of the sheet was 0.72 mm, excluding coating, and the nominal depth was 45 mm. The indentations were along the bottom rib of the steel sheet. The measured spacing of the indentations was 84 mm. The dimension of the steel sheet is shown in Fig. 3.

Two identical concrete blocks were cast on each sheet. There were eight complete indentations embedded in each concrete block. The length of the steel sheet that was in contact with the concrete at each end was 340 mm. Reinforcements, which had no connection with the steel sheet, were placed in the concrete blocks to avoid failures in the concrete other than the longitudinal slip failure. The cross section of the specimen is shown in Fig. 4.

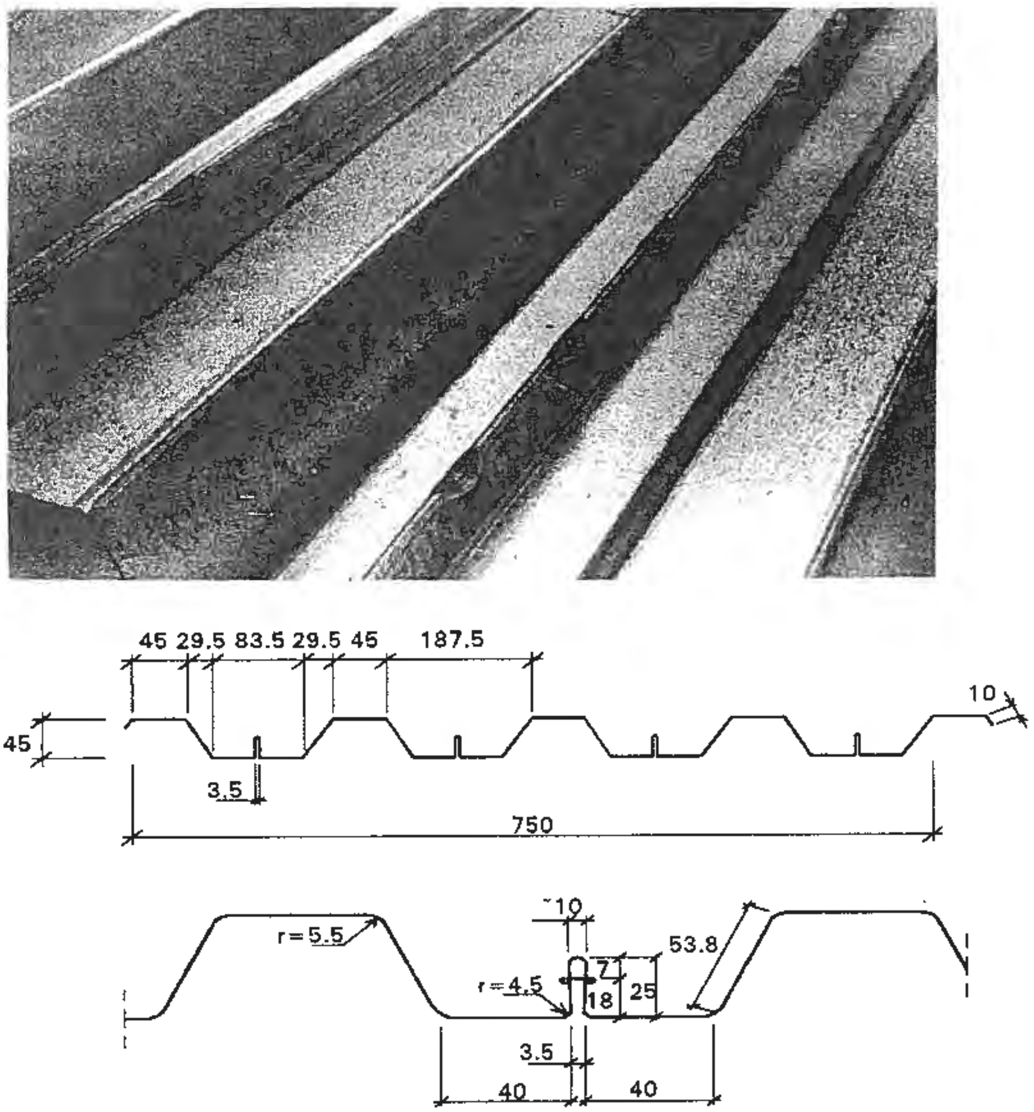


Fig. 3. Steel sheet PEVA 45 /3/.

Ordinary Portland cement was used in all of the specimens. The maximum size of the aggregate was 16 mm in the NC specimens and 10 mm in the LWC specimens. The aggregate in the lightweight concrete was an expanded clay, Leca. An admixture, Cemos 110, was used to improve the workability of the lightweight concrete. Although the same recipe of concrete was used, there was some difference in the strength of concrete for different batches.

Standard 150× 150× 150 mm cubes were cast at the same time as the specimens. The concrete tensile strength was obtained from the cube tensile splitting test and the compression strength from the cube compression test. The strength of the concrete at testing is listed in Table 1. The density of the concrete was determined from the weight and volume of the cubes. The yield stress and modulus of elasticity of the steel sheet were determined as 365 MPa and 195 GPa, respectively.

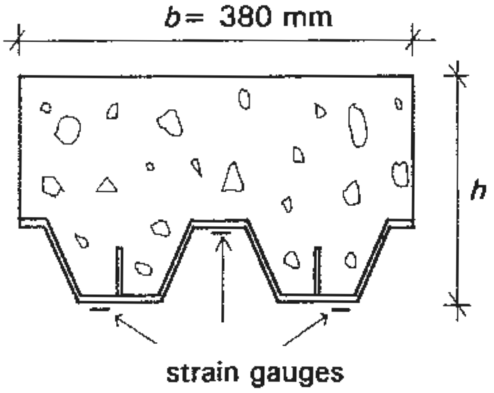


Fig. 4. Cross section of the specimen.

Table 1. Test Data

No.	h [m]	L [m]	L_s [m]	$f_{c,cub}$ [N/mm^2]	$f_{ct,sp}$ [N/mm^2]	density [kg/m^3]
NC11	0.18	1.86	0.9	32.1	2.8	2318
NC12	0.18	1.86	0.9	28.1	2.6	2314
NC21	0.18	1.32	0.63	32.1	2.8	2318
NC22	0.18	1.32	0.63	28.1	2.6	2314
LWC31	0.18	1.86	0.9	9.9	0.93	1137
LWC32	0.18	1.86	0.9	11.7	0.93	1155
LWC41	0.18	1.32	0.63	9.90	0.93	1137
LWC42	0.18	1.32	0.63	11.7	0.93	1155

In Table 1, $f_{ct,sp}$ is the mean tensile strength of the concrete from a cube tensile splitting test, $f_{c,cub}$ is the mean cube compression strength, h is the thickness of a specimen, L is the length of a span and L_s is the length of a shear span.

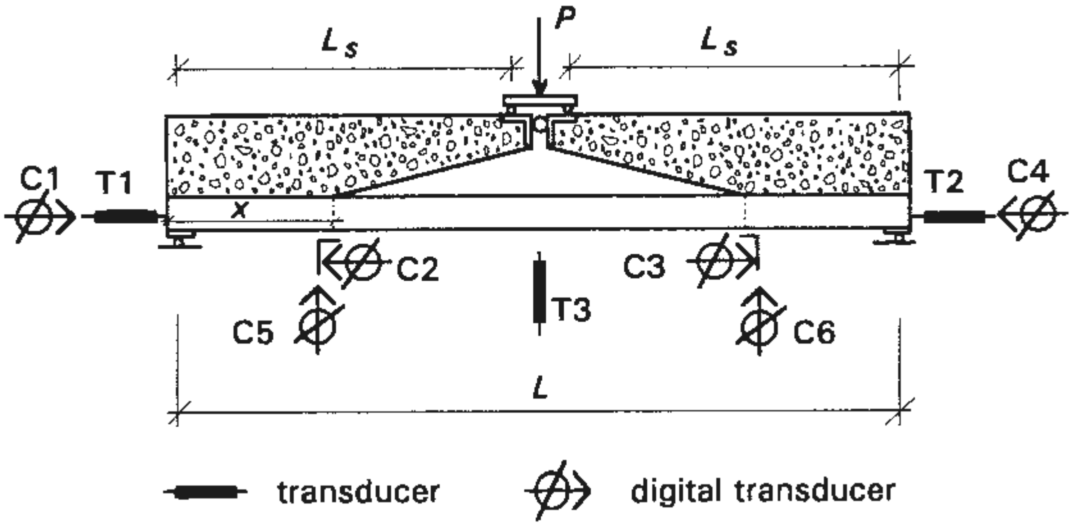


Fig. 5. Test set-up and instrumentation.

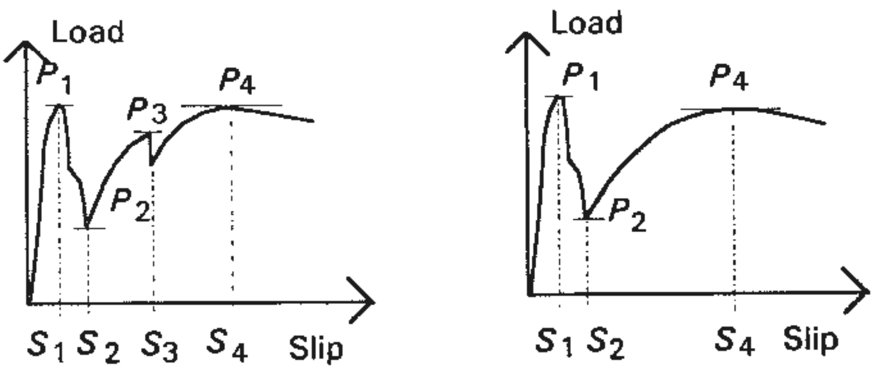
The test set-up and instrumentation are shown in Fig. 5. The top hinge between the two concrete blocks was a 12 mm reinforcement bar. The horizontal longitudinal slip and the vertical separation between the steel sheet and the concrete block were measured by transducers. Electrical resistance strain gauges to detect yielding of the sheet were attached to the sheet at mid-section. The load was controlled by the deflection at the middle of the span. The loading speed was 0.4 mm/min until the slip at the end developed to about 1 mm. The speed was then changed to 0.8 mm/min and 1.6 mm/min until the test was completed.

3 TEST RESULTS AND DISCUSSION

3.1 General Behaviour

In the test, the behaviour of the composite element was recorded not only before the failure of the adhesion bond, but also after the initiation of the end-slip. At the beginning of loading, the horizontal shear force at the concrete-sheet interface was resisted mainly by the adhesion bond. A dynamic jump and a sudden decrease of the load occurred when the adhesion bond broke. Due to variation of the adhesion bond, this failure occurred generally first at one concrete block and then at the other. Thereafter the slip increased with the load. The horizontal slip developed at both concrete blocks simultaneously in some specimens. However, it developed unevenly in others. In three of the four LWC specimens, the slip developed only in one block.

Typical measured load-slip curves are shown in Fig. 6. The concrete block that had the end-slip first is called here a first-slip block and the other is called a second-slip block. The measured values for different specimens are summarized in Table 2. Here P_1 and P_4 show the maximum loads before and after the adhesion bond fails, P_2 represents the lowest load at which the adhesion bond breaks, and P_3 is the load at which the second end-slip occurs. The value of slip is denoted by S with a corresponding subscript number, e.g., S_3 denotes the slip at load P_3. More details about the actual curves have been reported in /4/.



(a) First-slip block (b) Second-slip block

Fig. 6. Typical load-slip curves.

Table 2. Measured values of load-slip curves

No.	First-slip block				Second-slip block		
	P_1/S_1 [kN]/[mm]	P_2/S_2 [kN]/[mm]	P_3/S_3 [kN]/[mm]	P_4/S_4 [kN]/[mm]	P_1/S_1 [kN]/[mm]	P_2/S_2 [kN]/[mm]	P_4/S_4 [kN]/[mm]
NC11	12.8/0.0	10.0/0.24	13.6/0.93	15.8/3.59	13.6/0.0	11.0/0.04	15.7/0.86
NC12	12.0/0.0	9.4/0.11	14.7/0.93	17.4/2.88	14.7/0.0	12.6/0.2	17.4/1.88
NC21	18.0/0.0	13.4/0.26	18.1/3.86	20.9/5.95	18.1/0.0	15.5/0.08	20.9/3.46
NC22	21.4/0.0	14.2/0.35	19.6/4.02	21.5/5.72	19.6/0.0	16.1/0.18	21.5/3.29
LWC31	12.0/0.0	7.9/0.6	-	8.7/3.22	-	-	-
LWC32	14.0/0.0	8.8/0.4	-	10.9/4.38	-	-	-
LWC41	20.0/0.0	9.2/0.6	-	13.7/7.7	-	-	-
LWC42	21.5/0.0	14.4/0.65	17.2/5.75	17.2/5.75	17.2/0.0	15.4/0.5	17.0/2.03

3.2 Shear Flow-slip Relation

From the external load, the resultant tensile force in the steel sheet can be determined. The analysis focuses on the behaviour of the specimens after the initiation of end-slip. The tensile force - slip curves obtained had their origin corresponding to S_2, as shown in Fig. 6. The tensile force, T, is determined by the equilibrium of moment with regard to point "a", see Fig. 7.

$$T = [0.5\, P_{mea}\, L_s + M_q - M_s] / z$$

where M_q is the moment due to dead weight of a specimen, P_{mea} the applied external load and z is the level arm.

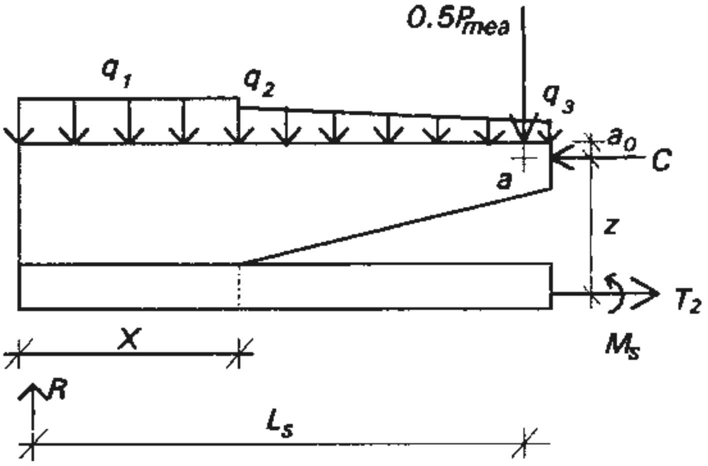


Fig. 7. Force equilibrium of the specimen.

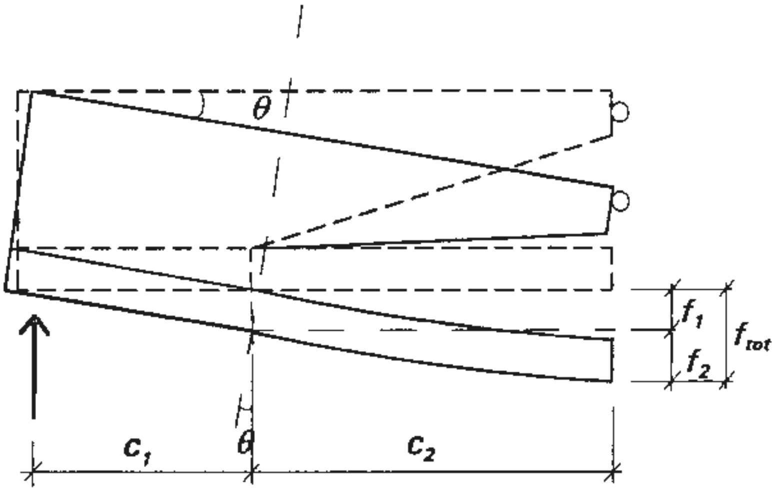


Fig. 8. Deformation of a concrete block.

The moment taken by the steel sheet, M_s, can be determined from the deformation of the specimen. As shown in Fig. 8, the deflection at the midspan, f_{tot}, consists of two parts. The concrete block rotated at an angle (θ) around the hinge when it was deformed downwards. The sheet, in contact with the concrete, followed this rotation and produced the deflection f_1. The second part of deflection, f_2, came from the bending deformation of the steel sheet under a constant bending moment, M_s, along the part of the sheet that was not in contact with the concrete block. Therefore

$$M_s = \frac{E_s I_s}{c_1 c_2 + 0.5 c_2^2} f_{tot}$$

where E_s and I_s are the modulus of elasticity and the moment of inertia of the steel sheet, respectively.

The tensile force in the steel sheet was transferred to the concrete block by means of the shear stress and was equal to the horizontal shear stress at the interface. To obtain the shear flow (shear force per unit length and per line of indentation) at the interface, the tensile force in the steel sheet was divided by the number of lines of indentations and then by a contact length x. That is, $T_{flow} = T/(2x)$.

In the test, NC specimens were designed as K25 and LWC specimens as K8. The actual concrete strength, however, varied a little among the specimens. This was mainly due to the different batches in casting of the concrete. In most cases, high capacity was obtained from the specimens with high concrete strength. In order to consider this effect, the shear flow was normalized by dividing by $\sqrt{f_{c,cub}}$.

$$T_{flow} = \frac{T\xi}{2x\sqrt{f_{c,cub}}}$$

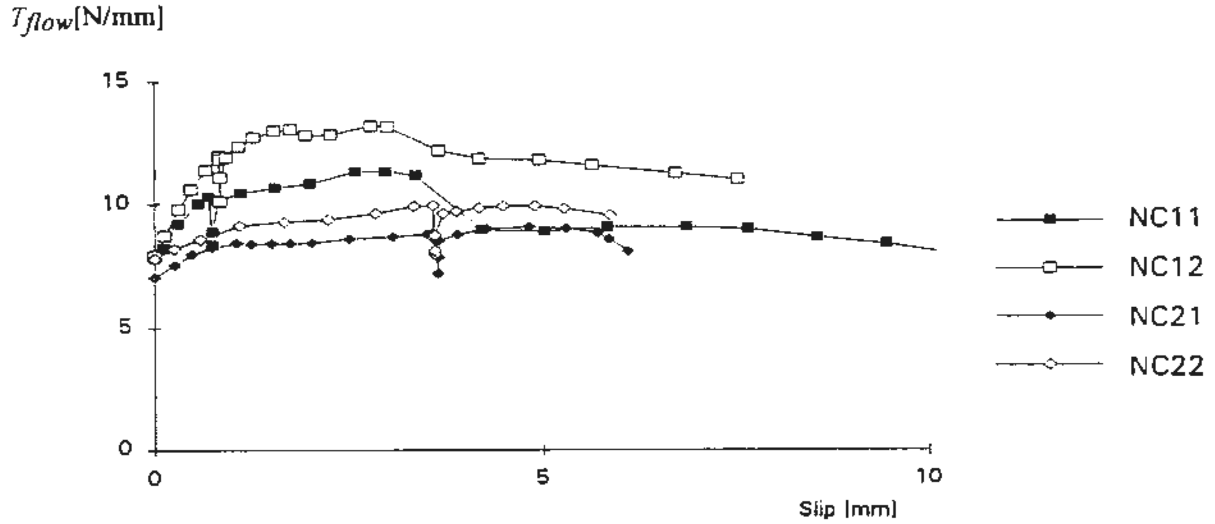
where $\xi = 1.0\ \sqrt{N}/\text{mm}$, which was used to get the correct unit in T_{flow}. The calculation was based on T-slip curves. The normalized shear flow-slip curves are shown in Fig. 9.

For LWC specimens, the shear flow curves were rather flat, which indicated that the shear resistance at the interface was nearly constant after the failure of the adhesion bond. It seemed that the effect of concrete strength was not completely removed by dividing by $\sqrt{f_{c,cub}}$. The specimens with high concrete strength had high shear flow in the test. The influence of the shear span may be hidden by the influence of concrete strength. Therefore, the regression was carried out without taking into account the effect of the shear span. The same number of testing points was used for each specimen in order to make each test have the same weight in the regression analysis. The mean value of shear flow obtained was 10.5 N/mm irrespective of the magnitude of the slip.

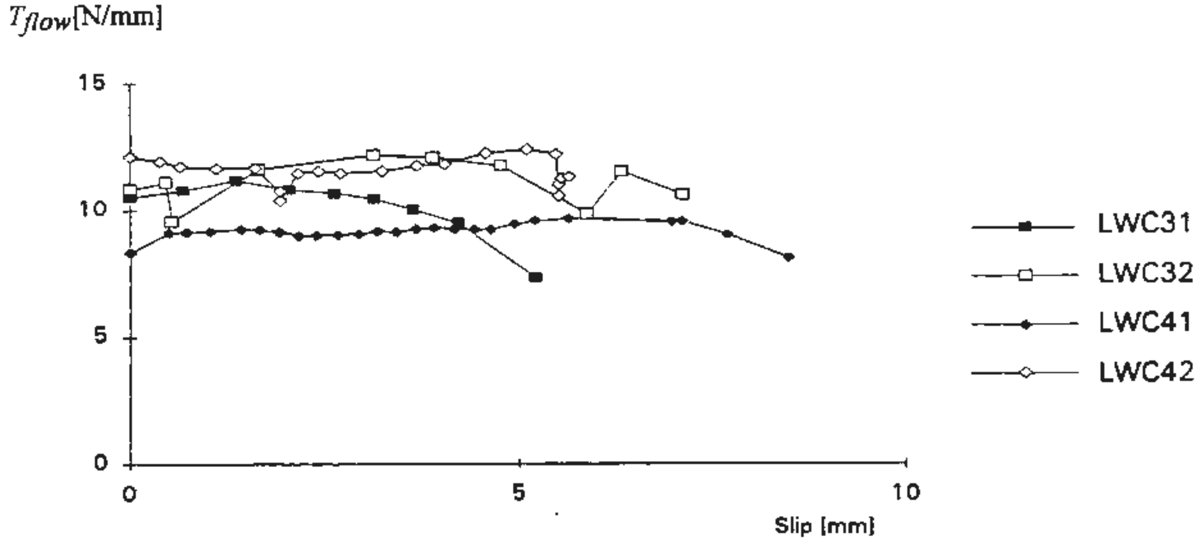
For NC specimens, NC11 and NC12 were tested with a long shear span. After the failure of the adhesion bond, the slip increased with the load. A crack formed at the end of the concrete block when the slip was about 3.5 mm. The load on the specimen then decreased. Specimens NC21 and NC22 were tested with a short shear span. The shear resistance obtained at the interface was lower than that of NC11 and NC12. As shown by Fig. 9, there was a difference in the first part of the shear flow curves for the specimens tested with different shear spans. This may be because of the high shear force, which reduced the bending capacity of the specimens. Due to the lack of suitable systematic way to interpret this difference, the regression was carried out by omitting the effect of the shear span. The fourth-order polynomial is

$$T_{flow} = 7.585 + 4.64\ Ss - 2.33\ S^2 + 0.456\ S^3 - 0.032\ S^4$$

The expression of the shear flow-slip relation can be used as the material property for an interface element to simulate the interaction between the steel sheet and the concrete in a finite element analysis.



(a) NC specimens



(b) LWC specimens

Fig. 9. Normalized shear flow-slip diagrams.

4 SIMULATION OF THE BEHAVIOUR OF COMPOSITE SLABS BY USING THE RESULTS FROM THE CONCRETE BLOCK BENDING TEST

Six full-scale composite slabs with profiled steel sheet PEVA 45 were tested under two symmetrically placed line loads. The length of the span varied from 5.0 to 7.0 metres and the length of the shear span varied from 0.54 to 1.08 metres. The deflection, strains and end-slip were measured at each loading increment. More details about full-scale tests can be found in /5/.

The simulation of the behaviour of composite slabs was carried out by the finite element program ABAQUS /6/. Both the steel sheet and the concrete were modelled by beam elements. The concrete section was simplified as a rectangular section. The steel sheet was simplified as an I-beam section. The non-linear elastic-plastic properties of the steel sheet and the concrete were taken into account. The interaction between the steel sheet and the concrete at the interface was simplified as springs. The shear flow-slip relations obtained from the concrete block bending test were used as a material property of the spring.

The comparison between the numerical simulation and experimental results is shown by the load-deflection, load-slip and load-strain diagrams in Fig. 10. In general, good agreement was obtained for the slabs tested with the long shear span. The numerical analysis underestimated the capacity of the slabs that were tested with the short shear span. The reason for this was mainly that the effect of the reaction force at the support was not totally included in the numerical model. The comparison also showed that the results from the concrete block bending test and the expression of the shear flow-slip relation were reasonable and reliable.

5 SUMMARY

The concrete block bending test and the results has been described. The test can quantitatively determine the shear flow and the slip distribution at the concrete-sheet interface after the adhesion bond has been broken. The results were used as material properties in the simulation of the behaviour of the composite slabs. Rather good agreement between the numerical simulation and the experimental result was obtained, which indicated that the results from the concrete block bending test were reasonable and reliable. For this new type of experiment, a load environment was similar to reality, and the test was easy to carry out. This provides an alternative approach for determining the shear resistance at the concrete-sheet interface for a composite element.

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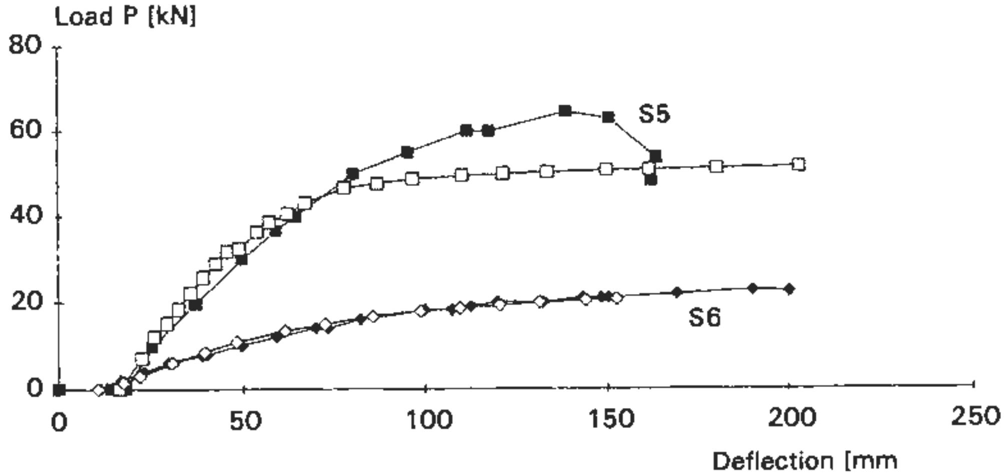
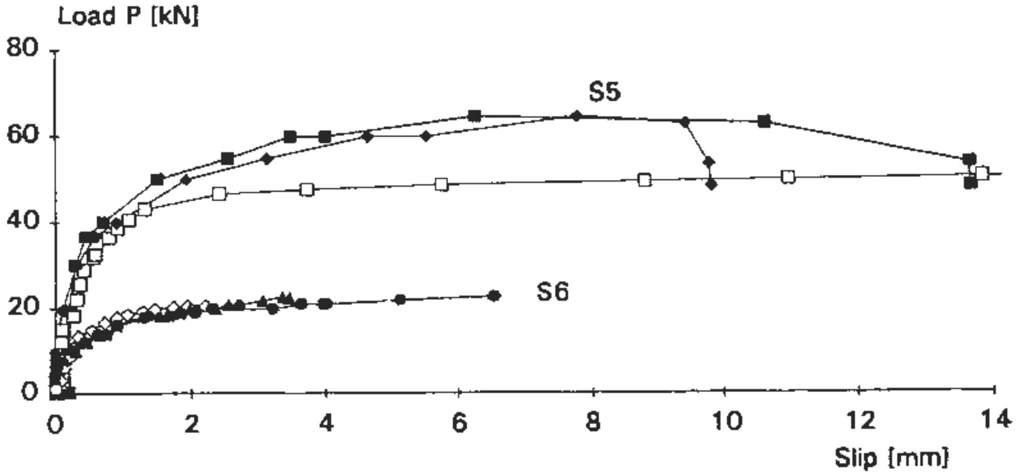
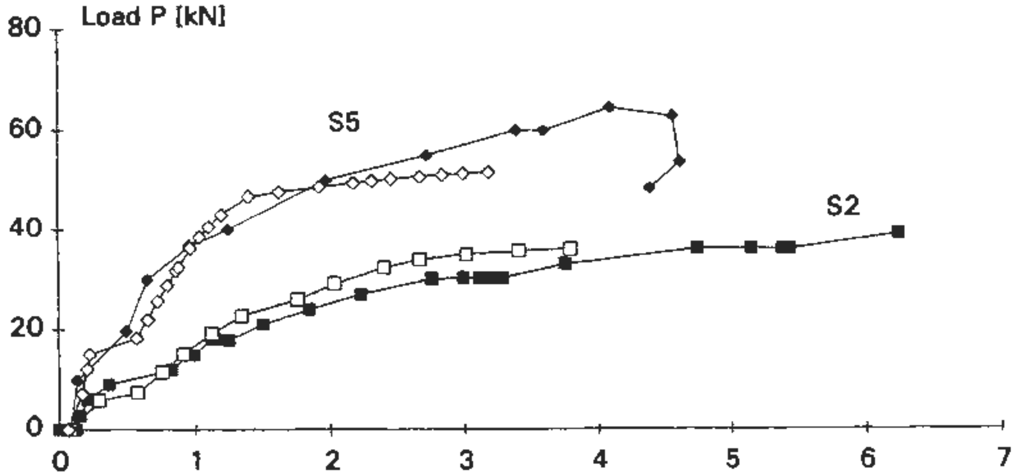


(a) Load-deflection diagrams.



(b) Load-slip diagrams.



(c) Load-tensile strains in the steel sheet at the loading section.

Fig. 10. Comparison of the measure and the calculated results.
Solid points are the measured results and hollow points come from the numerical simulations. S2: L=6.0 m, L_S=1.08 m and h=0.18 m; S5: L=7.0 m, L_S=0.75 m and h=0.24 m; S6: L=5.0 m, L_S=1.08 m and h=0.12 m.

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