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Comparison of Methods of Testing Composite Slabs

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***Abstract*—**Composite steel-concrete slabs using thin-walled corrugated steel sheets with embossments represent a modern and effective combination of steel and concrete. However, the design of new types of sheeting is conditional on the execution of expensive and time-consuming laboratory testing. The effort to develop a cheaper and faster method has lead to many investigations all over the world. In our paper we compare the results from our experiments involving vacuum loading, four-point bending and small-scale shear tests.

***Keywords*—**Composite slab, embossment, four-point bending, small-scale test, steel sheet, thin-walled, vacuum loading

I. Introduction

Composite steel-concrete structures profit from the benefits of both the materials used in their construction: steel and concrete. A necessary condition for the attainment of this desirable situation is that the mutual connection of these materials is maintained. This paper is focused on composite slabs with thin-walled cold-formed steel sheeting.

In this type of structure the shear connection may be achieved by various means, such as prestressed embossments, the use of ribs with a dovetailed shape or deformed ends, or via connection studs at the supports.

Our field of interest is prestressed embossments. Their main advantage is the ease and speed with which they can be constructed. Embossments are pressed into the steel sheeting, which is then rolled into the desired shape. The sheeting is then prepared for use without any additional work and serves both as permanent formwork as well as a tension bearing member after the hardening of concrete.

A significant disadvantage of composite slabs with thin-walled sheeting is the necessity of laboratory testing when designing a new type of sheeting. Such tests must be carried out on whole-span "full-scale" specimens, and therefore are expensive and time-consuming. Efforts are being made to use "small-scale" specimens in push-out (or pull-out) tests similar to the push-out test employed in the designing of connection members for composite beams. Finite element analysis is also considered.

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II. Composite Action

A. Effect of embossments

The chemical bond created at the interface between steel and concrete can reach significant values, but its magnitude is strongly influenced by surface conditions when casting and can be damaged during repeated loading. It therefore cannot be included in design slip resistance. Embossments in steel sheets prevent longitudinal slip between steel sheet and concrete after chemical bond failure. Its effect is analogous to the effect of corrugation on reinforcement bars in reinforced concrete. The corrugations of reinforcement bars transform longitudinal slip into the radial compression of the steel and the radial tension of the concrete. The wedge effect of embossments, on the other hand, transforms longitudinal slip into local buckling of the steel sheet (Figure 1) and vertical separation of the steel sheet from the concrete [1].

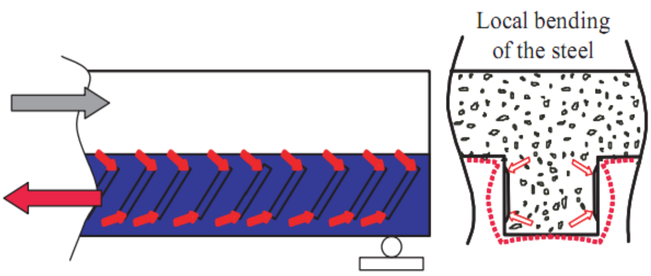

Fig. 1 Behaviour of steel sheeting with embossments [1]

The horizontal shear strength of embossed steel sheeting is influenced by many factors, such as the thickness of the sheet, the shape and frequency of embossments, the arrangement of load, the length of the shear span, the thickness of the concrete, the strain in the steel sheeting, support friction, curvature due to bending, and others.

The use of finite element analysis instead of laboratory testing is very problematic because of the lack of quantitative information describing the aforementioned factors and their contribution to shear strength [2].

B. Composite slab behaviour

Three failure modes are possible in relation to three possible critical cross sections in composite slabs: critical cross section in bending, critical cross section in shear and critical cross section in longitudinal shear. Eurocode 1994-1-1 describes two methods of designing a new type of sheeting: the *m and k* method and the *partial connection* method. Tests performed via both methods must produce longitudinal shear failure in slabs. Moreover, the partial connection method may only be used for slabs with ductile shear behaviour. Shear behaviour can only be considered as ductile if the failure load exceeds the load causing a slip of 0.1mm by more than 10%; otherwise it is classified as brittle behaviour [6].

A diagram of failure modes with a visual depiction of coefficients *m* and *k* can be seen in Figure 2.

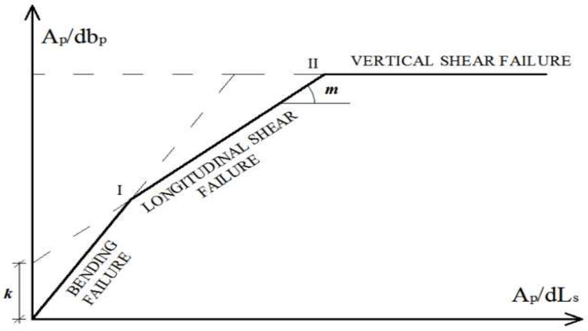

Fig. 2 Failure modes of composite slabs [5]

C. Small-scale tests

Small-scale tests were carried out to describe shear behaviour and the effect of embossments. Various setups are mentioned in the open literature, but they usually can be divided into two categories: those that require external lateral constraining forces to maintain the equilibrium of the specimens (Daniels' and Patrick's push-out tests) and those that do not need them (Porter's and Stark's test setups) [3].

The difference in the behaviour of laterally constrained and unconstrained steel sheeting can be seen in Figure 3. An example of an externally constrained test setup described in the literature is in Figure 4.

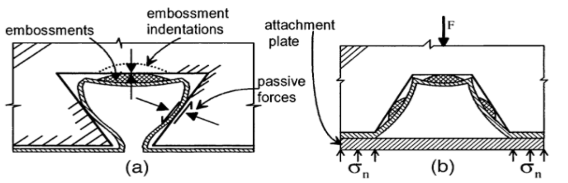

Fig. 3 Examples: an externally unconstrained sheet (a) and an externally constrained sheet (b) [3]

The lateral constraints prevent the steel sheet from separating from the concrete on the lower flanges of the sheet. Because of this, the steel sheet is forced into being deformed inside the rib, which influences the obtained load-slip dependence. From the nature of these tests it is obvious that they cannot include several other important factors, such as curvature due to bending or the ratio of shear span to effective depth. Small-scale tests cannot then be simply used instead of full-scale tests. A reasonable solution may be the combination of small-scale tests with finite element analysis. FE analysis can include the effects of bending and loadings regarding shear parameters obtained from the test. Crisinel and Marimon present a calculation method based on pull-out tests and three phases diagram in their paper [4]. They suggest several aspects for further analysis, such as the effect of shear strain distribution along the length of the slab, the effect of vertical separation between the profiled sheeting and the concrete slab, the reduction of mechanical connection strength due to elongation of the sheeting in bending, the generalisation of their method for use with other loading arrangements and its adaptation to a profile with brittle behaviour.

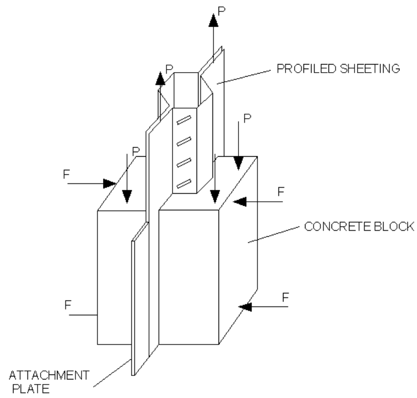

Fig. 4 Daniels' test setup [3].

III. Experimental Verification

Three kinds of laboratory experiments were performed in order to gain information about the real-life behaviour of this kind of slab. The first was vacuum loading using a special vacuum device. The other two were a four point bending test and a small-scale shear test. The casting of the specimens for vacuum loading and four-point bending was carried out without inner supports (Figure 5).

Fig. 5 Casting of specimens without inner supports

A. Vacuum loading

A specimen was placed on supports in a special device, and covered with plastic foil (Figure 7). Under the specimen there was a hermetically isolated space from which the air was sucked when the test began [7]. The pressure of the vacuum produced an ideally distributed area load on the slab surface. A measuring device was placed at the bottom of the slab for monitoring mutual sliding (Figure 6).

Fig. 5 Configuration of the measuring device for monitoring sliding on the interface between the concrete and the steel sheet

Fig. 6 Vacuum loading. Configuration of the measuring devices for monitoring slab deflection

B. Four-point bending test

During this research, steel-concrete slabs were also investigated by four-point bending. The methods used are described directly in EC4 [6]. The test setup is shown in Figure 7. As a first step the two specimens were tested statically in order to set the parameters of cyclic loading for the rest of the specimens. Then, the other specimens were tested by cyclic loading.

After the cyclic load had been maintained for 5000 load cycles, an increasing static load was applied until the structure collapsed [8].

Fig. 7 Four-point bending. Configuration of the test setup

The following figure (Fig. 8) shows a load deformation diagram of a specimen under cyclic loading.

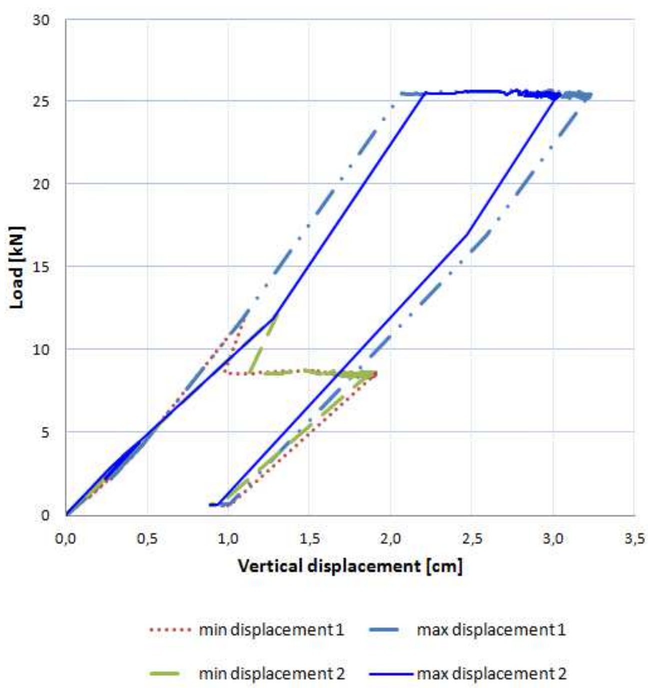

Fig. 8 Load deformation diagram

C. Comparison of vacuum loading and four-point bending

The following figure (Fig. 9) shows a comparison of the load-displacement curves of specimens loaded with vacuum loading with that of specimens subjected to four-point bending statically after cycling.

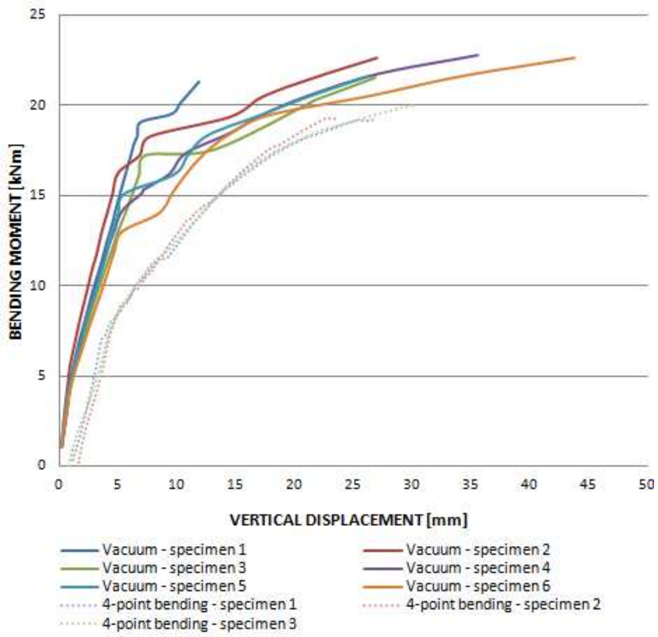

Fig. 9 Load deformation diagram of the results of vacuum loading and four-point bending tests

Maximum individual bending moments acting on the specimens for six specimens loaded with vacuum loading and for three specimens loaded with four-point bending are compared in Figure 10.

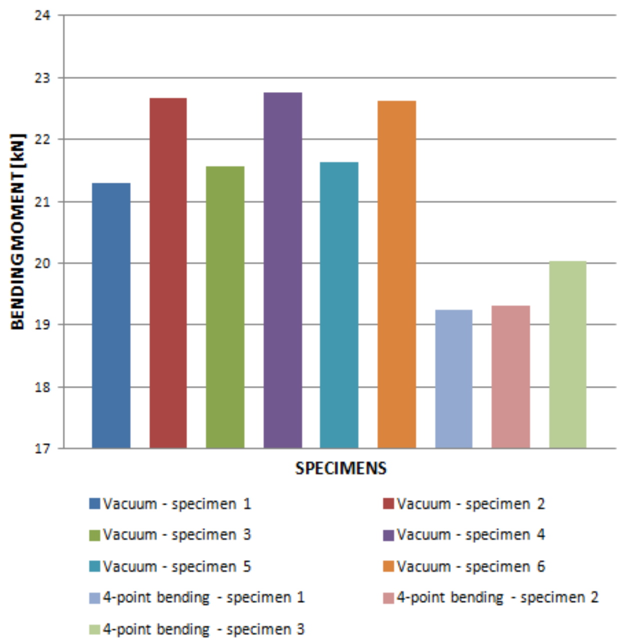

Fig. 10 Bending moments

D.Small scale tests

The test setup used for the small-scale tests carried out in the authors' laboratory (Fig. 11) is similar to Daniels' test setup (Fig. 4). Specimens with overlapping steel sheeting were fixed with bolts to a thick base plate. A vertical force was applied on the upper surface of the concrete to simulate the effect of a vertical load on a whole slab subjected to bending. Different magnitudes of vertical load were applied. Horizontal shear force was applied on the vertical surface of the concrete from the side using bolts. The concrete part of the specimen was then pushed away from the steel sheet, which was in tension.

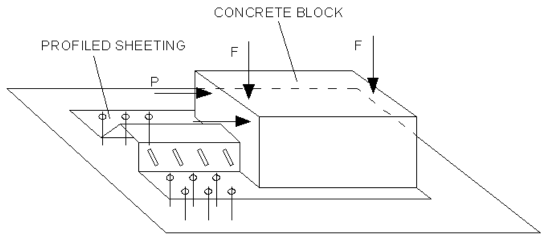

Fig. 11 Schematic diagram of the performed small-scale test

The test assembly can be seen in Fig. 13. The base plate was welded to a massive steel cross section. A cantilever was welded at the end of the massive cross section to serve as a support for the horizontal press. A thick steel rod transmitted the load to distributing layers (a steel plate and plywood plates).

The vertical press was held by four screwed rods welded to the base plate. It was necessary to allow the free horizontal movement of the concrete part. To achieve this, a group of cylinders was inserted between the distributing steel plates under the press (Fig. 14).

The dimensions of the concrete part of the specimens were 414 mm x 200 mm; the height of the specimens was 110 mm and the length of the steel sheets was 330 mm (Figure 12). 12 specimens were tested in two series. The first series of 6 specimens was tested with a vertical load of 1.9 kN and the second series of 6 was with a vertical load of 3.9 kN.

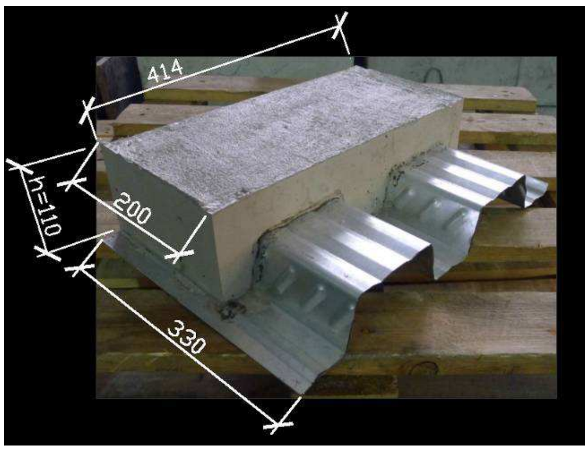

Fig. 12 Specimen dimensions.

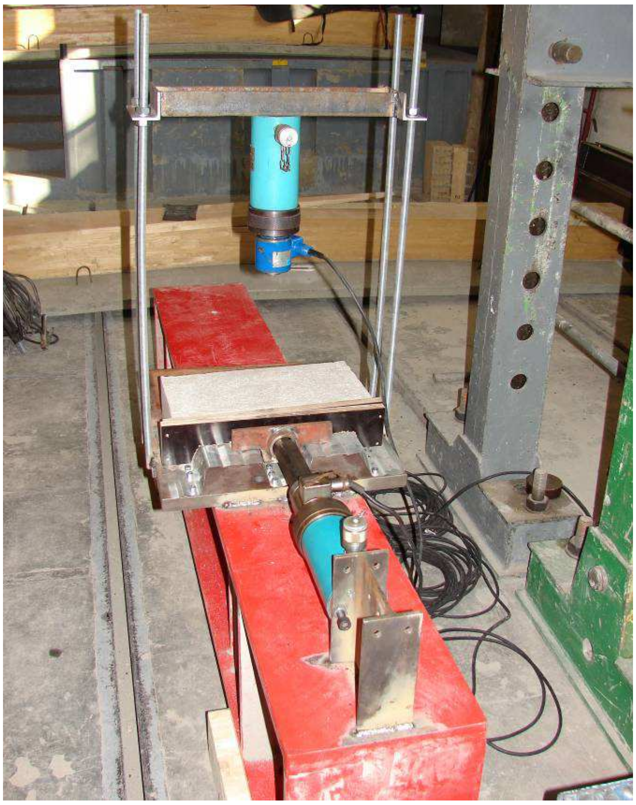

Fig. 13 Test assembly for the small-scale tests

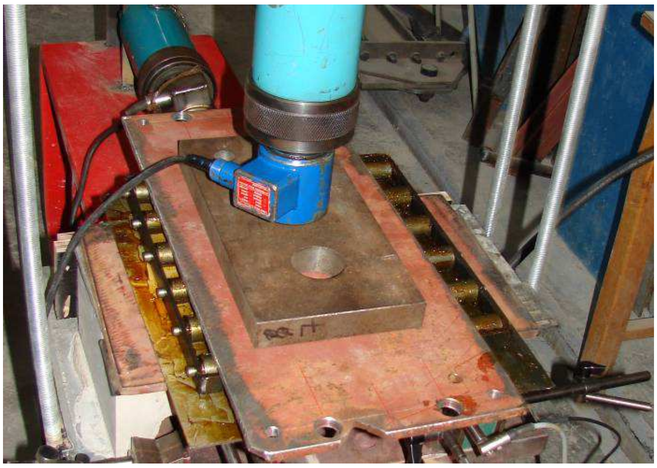

Fig. 14 Group of cylinders allowing the horizontal movement of the concrete part

Two pairs of measuring devices were placed on both sides of the specimens to record any rotation that might occur. One pair measured longitudinal slip between the steel sheet and the concrete slab, while the second pair measured mutual slip between the base plate and the bolted steel sheet. The magnitudes of both vertical and horizontal forces were also recorded.

The load-slip dependencies of both series of tests can be seen in Figure 15 and Figure 16. The displayed curves are polynomial regressions of the 6th degree; the original values are only shown for two of the curves (in green and blue) to document their accordance with the regression curves.

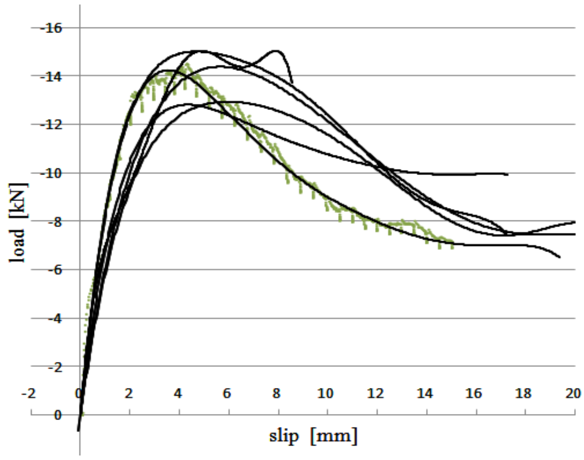

Fig. 15 Load-slip diagram of the regression curves from the first series of tests.

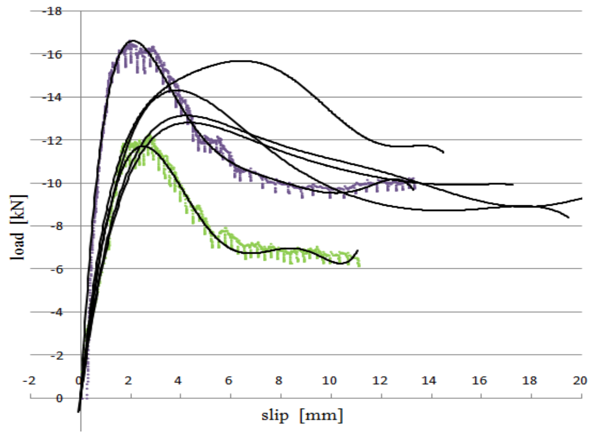

Fig. 16 Load-slip diagram of the regression curves from the second series of tests.

The results of both series are very similar. The higher vertical force influenced the obtained shear force only slightly. This is probably caused by differences in behaviour between the small scale specimens used in these tests and whole-span slabs. With small specimens the loaded part of the concrete tends to lift up on the loaded side, which is not possible in the case of the whole slab.

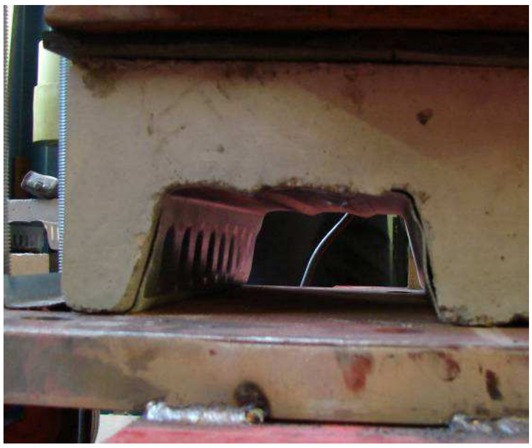

Fig. 17 Test specimen after unloading

The deformed sheeting inside the rib after the test (as illustrated in Figure 3) is observed only on the sides of the specimens opposite the press (Figure 17).

The obtained dependencies will be used to adjust shear characteristics in numerical models of small-scale specimens (Figure 18). These characteristics can be then used for models of whole-span slabs, since direct adjustment of such models is very difficult.

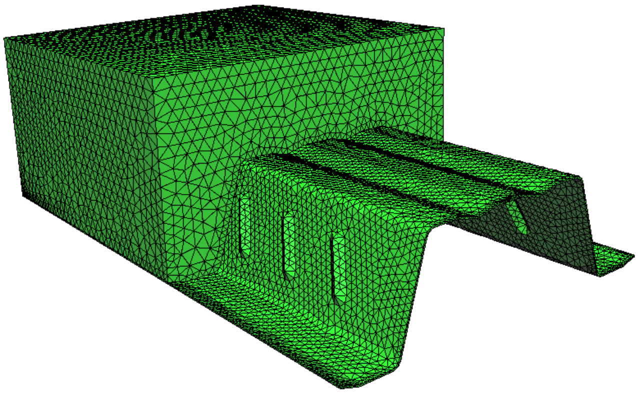

Fig. 18 Numerical model of a small-scale specimen

E. Comparison of four-point bending and small scale tests

TABLE I
LONGITUDINAL SHEAR FORCE

EXPERIMENTAL METHOD	SPECIMEN NUMBER	FORCE [kN]	SLIP [mm]
4-POINT BENDING static after cycling	1	45.06	2.064
	2	45.25	1.795
	3	47.04	2.484
SMALL SCALE TEST	1	15.78	5.348
	2	16.07	4.697
	3	14.52	4.259
	4	13.44	4.178
	5	15.41	5.713
	6	13.32	7.109
	7	12.28	2.666
	8	15.12	3.644
	9	13.36	5.169
	10	16.66	1.925
	11	13.44	4.178
	12	16.35	4.598

The forces of the four-point bending test are recalculated for the same number of embossments (same layout area) as in the case of the small-scale specimens. Shear distribution is constant in the shear span. Direct comparison with vacuum loading is not possible, since the horizontal shear has linear distribution.

IV. CONCLUSION

Regarding the results from the three test methods discussed here the following conclusions were reached:

The bending resistance of the specimens during vacuum loading is higher than of four-point bending. The shape of the vertical deflection curve of the continuous uniform load is more uniform in compare to that arising during four-point bending.

Longitudinal shear force is constant over the shear span in the four-point bending tests, so the results of this method can be easily compared with those from small-scale testing. The significant differences observed when making this comparison are probably caused by differences between the methods used, the different boundary conditions of the concrete part, and imperfections in the test setup of the small scale tests (i.e. the load on the face of the concrete tends to lift up the concrete, the positioning of the loads). These factors probably explain also the negligible differences in load-slip behaviour for various magnitudes of vertical load.

The results from these experiments regarding small scale tests will be used in further research to adjust numerical models of small-scale specimens and of models dealing with the whole spans of slabs.

ACKNOWLEDGMENT

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