ANALYSIS OF FLAT SLABS STRENGTHENED BY REINFORCED CONCRETE OVERLAYS

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Abstract
The strengthening of flat concrete slabs using reinforced concrete overlays is an efficient method of increasing both the flexural stiffness and punching shear capacity of such slabs. The interface between the two concrete layers transmits a large amount of stress, so detailing of the interface is crucial to achieve an increase in resistance. The analysis introduced below compares the efficiency of different amount of shear studs and the effect of the dimensions of the overlaid concrete on punching shear capacity.

Keywords
Punching shear capacity, flat slab, concrete overlay, shear studs

1 INTRODUCTION

The experimental study consisted of the analysis of flat slabs strengthened by concrete overlays. A total of 5 experimental specimens were tested. Each of the tested specimens consisted of a reference flat slab with dimensions of 2.5 × 2.5 m and a thickness of 180 mm, and a concrete overlay with dimensions of 2.0 × 2.0 m (S_{4d}) or 1.4 × 1.4 m (S_{3d}) and a thickness of 60 mm. The concrete overlay dimensions represent a distance of 4*d* and 3*d* from the face of the column, where *d* is the effective depth of the strengthened slab with a concrete overlay. The 4*d* distance was determined to be twice the control perimeter of reference slab according to EC2 [1]. In order to reduce manual work during the application of the concrete overlay, a perimeter of 3*d* from the column face was also considered for comparison. The test specimens represent a flat slab supported by columns with circular cross section of 250 mm in diameter spaced approximately 7 m apart and zero bending moments at a distance of about 1.25 m from the centre of the slab. The load was applied to the slab by a hydraulic jack through a circular steel plate from the bottom of the slab. Eight steel bars were placed symmetrically around the perimeter of the slab to serve as supports. As a result, the amount of bending moments occurring at the edge of the slab was zero. With gradual loading, a critical shear crack developed from the bottom edge of the reference slab to the top edge of the concrete overlay, which resulted in the failure of the test specimens in punching shear. By cutting the test specimens, it was possible to perform an analysis of their failure.

2 METHODOLOGY

The experimental verification of the effectiveness of the strengthening by the concrete overlay involved five specimens that simulated a flat slab supported by a circular column and strengthened by a reinforced concrete overlay. The concrete overlay was realized up to a distance of three times the effective depth of the concrete overlay reinforcement in the case of variant S_{3d}, or up to a distance of four times the effective depth of the concrete overlay reinforcement for variant S_{4d}.

The interface between the concrete overlay and the reference flat slab was modified on all tested specimens by roughening the surface of the reference slab. Surface roughening was carried out using a TE-YX BT bushing head from Hilti. Using this method, a rough surface was achieved based on the definition laid out in EN-1992-1-1 [2]. This type of surface is created by raking the fresh concrete mixture or by exposing the aggregates within the concrete, the resulting grooves being at least 3 mm deep and a maximum distance of 40 mm from each other. The shear headed studs were inserted into pre-drilled holes with a depth of 110 mm; the holes were then injected by Hilti HIT-RE 500 V4 epoxy injection mortar and filled with the shear studs, where the depth of anchoring of the headed studs was 100 mm in the reference slab and 40 mm ($S_{3d.SD}$, $S_{4d.SD}$) in the concrete overlay. The shear headed studs were in the form of steel reinforcement (rebar) with a diameter of 10 mm, with the headed modification in the concrete overlay see Fig. 5. In the concrete-to-concrete interface of the reference slab and the concrete overlay of test specimen $S_{3d.SDR}$, the tensile reinforcement of the concrete overlay was bent at the ends and anchored to the reference slab in addition to the shear headed studs. This reinforcement was anchored into pre-drilled holes filled with epoxy injection mortar in a similar manner to the holes in $S_{3d.SD}$, $S_{4d.SD}$. The reference slab of test specimen $S_{4d.SB}$ was drilled through the entire thickness of the reference slab and headed shear bolts were used as shear connectors, which were screwed from the bottom surface and functioned as additional shear reinforcement. Test specimen $S_{4d.R}$ represents a strengthened slab using a concrete overlay without shear dowels. Relevant data about the tested specimens is given in Tab. 1. and Fig. 1.

Tab. 1 Parameters of tested specimens.

	Concrete overlay			Interface	Reference slab		
	Dimensions m	Thickness mm	Reinforcement	Shear connector	Dimensions m	Thickness mm	Reinforcement
$S_{3d.SD}$	*1.4 × 1.4*			*dowels*			
$S_{3d.SDR}$	*1.4 × 1.4*			*dowels + reinforcement*			
$S_{4d.R}$	*2 × 2*	*60*	*2Ø10/100*	*-*	*2.5 × 2.5*	*180*	*Ø16/100*
$S_{4d.SD}$	*2 × 2*			*dowels*			
$S_{4d.SB}$	*2 × 2*			*shear bolts*			

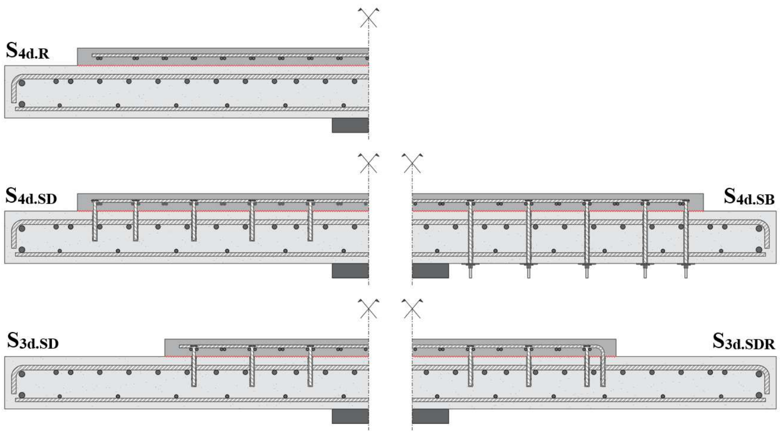

Fig. 1 Scheme of the tested specimens.

Preparation of the tested specimens

The preparation of the concrete overlay was carried out in several phases. In the first phase, it was necessary to avoid drilling holes in positions occupied by the existing longitudinal rebar in the reference slab. The assessment of the location of the longitudinal rebar was performed by a Bosch D-tect 150 magnetic scanner and the main axes were drawn on the reference slab see Fig. 2.

Fig. 2 Mapping of existing rebar by a magnetic scanner.

In the second phase, holes for the application of shear connectors were drilled. This phase was not performed on specimen $S_{4d.R}$, the interface of which does not contain shear connectors. For specimens $S_{3d.\,SD}$ and $S_{3d.SDR}$ 48 holes were drilled with a depth of 110 mm and a diameter of 12 mm. The mutual distance of the drilled holes was 200 mm (approximately *d*, where *d* is the effective depth of the reinforcement in the concrete overlay, see Fig. 3 right). In addition, the concrete overlay of the $S_{3d.SDR}$ specimen was also anchored through the bent reinforcement into the reference slab. Anchoring of the longitudinal reinforcement was performed at the edge of the concrete overlay in 52 drilled holes. Specimen $S_{4d.SD}$ contained 120 drilled holes with a depth of 110 mm and a diameter of 12 mm see Fig. 3 left. The reference slab (specimen $S_{4d.SB}$) also contained 120 drilled holes, which were in this case drilled through the entire thickness of the reference slab.

Fig. 3 Drilling holes in specimen S_{4d} (left) and S_{3d} (right).

The third phase was the roughening of the surface of the reference slab. The interface between the reference slab and the concrete overlay was roughened over the whole contact area. To obtain the required rough surface, a Hilti TE-YX BT bushing head was used to expose the aggregates. This technology of chipping with the bushing head allowed the surface of the reference slab to be roughened, which is recommended for concrete-to-concrete bonding see Fig. 4. The interfaces of all five of the specimens were modified by roughening.

Fig. 4 Roughening the surface of the reference slab specimen.

The fourth phase involves the reinforcement of the concrete overlay with shear connectors and the injection of epoxy mortar. Shear headed connectors were inserted into pre-drilled holes, which were then filled in with the epoxy injection mortar using a Hilti HDE 500-22 battery-powered epoxy anchor dispenser. To achieve the required depth of the anchored shear headed studs, a supporting structure was used Fig. 5.

Fig. 5 Injecting shear headed connectors.

After the epoxy hardened, the longitudinal reinforcement of the concrete overlay was tied. Minimal concrete cover was achieved by using reinforcement of reduced diameter (a pair of 10 mm bars) with a spacing of 100 mm in each direction Fig. 6. Longitudinal reinforcement in the form of straight steel rebars was used in the concrete overlays, except for the reinforcement of specimen $S_{3d.SDR}$, where the steel rebars were bent at the ends and used for additional anchoring see Fig. 6 right. The anchoring of the longitudinal reinforcement near the ends of the concrete overlay was carried out according to the increase in the anchor length up to the distance of the basic control perimeter considered in 2*d*. The anchored reinforcement also served as a shear connector that acted against the lifting phenomenon at the edges of the concrete overlay and prevented the interface crack from opening.

Fig. 6 Reinforcement of specimens $S_{4d,SD}$ (left) and $S_{3d,SDR}$ (right).

The fifth and last phase of preparation was the casting of the concrete overlays see Fig. 7. After the hardening of the concrete overlays (approximately 28 days), the specimens were prepared for experimental testing. For a better understanding of the behaviour of the tested specimens, several strain gauges were installed on the longitudinal reinforcement and also shear headed studs and shear headed bolts.

Fig. 7 Casting a layer of concrete overlay.

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Five specimens were strengthened by concrete overlays and consequently loaded to failure mode. All of the tested specimens are illustrated in Fig. 1. Specimen $S_{4d,SB}$ contains headed shear bolts which were screwed from the bottom face of the slab by hexagonal nuts through steel pads.

Test setup

Before strengthening, the reference slab specimens were pre-loaded to 50% of the resistance of the non-strengthened original flat slab to simulate a real structure with a history of loading. After strengthening, the specimens were loaded from the centre through a steel plate of circular shape below the slab up to failure.

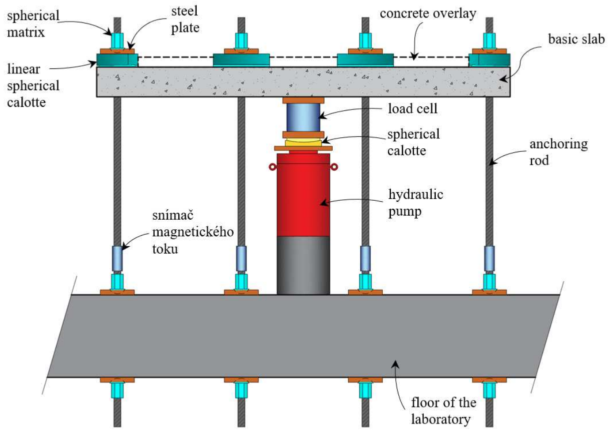

Fig. 8 Test setup used for the experimental programme, conceptual (left) and real setup (right).

The placement of eight steel supporting bars symmetrically around the perimeter of the slab successfully restricted the number of bending moments in that region to zero. The test setup is illustrated in Fig. 8.

Vertical displacements were measured by linear variable differential transformer sensors (LVDT) on the bottom face of the slab and one LVDT sensor on the top of the concrete overlay at the centre of the experimental specimen. Plunger dial indicators were also used on the bottom face for measuring vertical displacements. Strain gauges were applied to the bottom of the reference flat slab on the concrete surface and also to the longitudinal reinforcement and shear connectors. The LVDT sensors, strain gauges and hydraulic pump were attached to a QuantumX data-logger and monitored by Catman software. Loading and data measurement were performed gradually in steps of 50 kN.

3 RESULTS

After strengthening, a significant increase in the shear resistance of all tested specimens was achieved. Specimen S_{REF} was a non-strengthened slab (reference slab). From Tab. 2 it can be observed that the punching shear capacity of a strengthened slab with a concrete overlay can be more than double that of reference slab S_{REF}. The provision of a concrete overlay only on the upper surface of the slab and the use of headed shear bolts can lead to an increase in punching shear capacity of about 65%. Additionally, higher stiffness was achieved for all tested specimens strengthened by a concrete overlay. Values for the maximum load applied and the deflection of the centre of the specimen are presented in Tab. 2.

Tab. 2 Shear resistance and deflection of the tested specimens.

	Failure load kN	**Deflection** mm
$S_{3d.SD}$	637.8	16.63
$S_{3d.SDR}$	*687.0*	*12.88*
$S_{4d.R}$	673.7	17.34
$S_{4d.SD}$	*703.5*	*18.54*
$S_{4d.SB}$	*900.9*	*23.59*
S_{REF}	*428.4*	*15.11*

4 DISCUSSION

On the S_{4d} test specimens with shear connectors, it is possible to observe punching through the concrete overlay. The stresses arose in the reference slab and were transferred to the concrete overlay, which conditioned the slope of the critical shear crack and provided increased punching shear capacity to the tested specimens. By analysing the cross-sections of the test specimens, it is possible to observe the deflection of the slope of the critical shear crack at the location of the shear connectors. The test specimen $S_{4d.R}$, which did not contain shear connectors, failed via debonding of the concrete-to-concrete interface and the subsequent formation of a longitudinal crack in that interface. In this case, the concrete overlay debonded because the concrete-to-concrete interface without shear connectors was unable to transfer the applied amount of stress from the reference slab to the concrete overlay. Debonding occurred when the interface could not resist any more deformation. A similar phenomenon was described in several works by Hugo Fernandes [3] and Daphne Rocha [4].

Test specimens S_{3d} show the dimensions of the concrete overlay were insufficient, as a critical shear crack evolved below the surface of the concrete overlay. Based on the cross-section sawcut, it is possible to observe the significant deflection of the critical shear crack in the reference slab, but the insufficient dimensions of the concrete overlay caused the appearance of this crack in the edge of the concrete overlay and the subsequent failure of the test specimen.

5 CONCLUSION

When observing the test results, it is possible to conclude that when the shear studs or bolts were used, even in the case of high shear stresses at the concrete-to-concrete interface, the surfaces of the specimens were not debonded, and in any case, the punching shear resistance of the slab was increased compared to the punching shear resistance of the tested specimens without strengthening (S_{REF}). It is possible to claim that the strengthened specimens behave almost monolithically, which can also be determined based on the development of a critical shear crack.

The failure mode of the test specimens S_{4d} is accompanied by the formation of a failure surface, which delimits a typical punching shear cone arising during shear failure. The greatest punching shear resistance was achieved by the test specimen $S_{4d.SB}$, where headed shear bolts were used as shear connectors that also functioned as additional shear reinforcement. The lowest punching shear resistance was achieved by the test specimen $S_{3d.SD}$, with concrete overlay dimensions of 1.4 × 1.4 m and headed shear studs used as shear connectors.

The test specimens S_{3d} show that the dimensions of the concrete overlay were insufficient due to the shape and slope of the failure surface. The failure was accompanied by the formation of a shear cone, which was a symptom of the insufficient resistance of the non-strengthened slab immediately behind the concrete overlay. The test specimens $S_{3d.SD}$ and $S_{3d.SDR}$ behaved almost identically during loading and failure, below the surface of the tensile reinforcement of the concrete overlay in specimen $S_{3d.SDR}$ was anchored to the reference slab at the ends. Specimen $S_{3d.SDR}$ was designed to prevent the lifting phenomenon from occurring at the concrete overlay edges mentioned in recommendation [5].

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