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SHEAR EXPERIMENTS ON STRAIGHT REINFORCED CONCRETE SLABS

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As the existing bridge stock is aging, assessment of existing bridges becomes increasingly important. In the Netherlands, the shear capacity of reinforced concrete slab bridges is found to be insufficient. In particular, the shear and punching shear capacity of reinforced concrete slab bridges subjected to concentrated loads from the design tandem or truck is subject to discussion, as the shear behavior is situated in between one-way and two-way shear. Currently, an experimental program is being conducted at Delft University of Technology to determine the shear capacity of straight and skewed reinforced concrete slabs under point loads near to the support. This paper presents the results of the 25 tests conducted on six straight slabs of 5m × 2.5 m × 0.3 m subjected to a proof load testing loading protocol. The failure load and modes of the slabs are described in detail. Reinforced concrete slabs under concentrated loads can fail in shear, punching, and flexure, as well as a combination of these failure modes. The results of the experiments are compared to strength predictions obtained by using current design models and current methods for assessment. These experiments demonstrated that the Dutch guidelines, which are based on previous slab experiments, are an improvement as compared to the Eurocode for the assessment of existing reinforced concrete slab bridges. Ultimately, this work provides recommendations for bridge engineers tasked to assess reinforced concrete skewed slab bridges.

Keywords: Assessment, Effective width, Flexure, One-way shear, Punching, Size effect, Slab bridges, Two-way shear.

1 INTRODUCTION

In the Netherlands, a large number of bridges are reaching the end of their originally devised service life (Lantsoght *et al.* 2013a). Therefore, assessment of these bridges is becoming increasingly important. These bridges from the 1950s, 1960s and 1970s were designed with the capacity and load models of that era, and they are now faced with larger live loads. In addition, the capacity models have changed. For example, in the Netherlands, the simplified shear model from the old national code has been replaced by the Eurocode capacity model, which considers more variables and which can lead to lower calculated capacities for shear under certain combinations of parameters; such as commonly encountered in reinforced concrete slab bridges. As a result, the shear capacity of reinforced concrete slab bridges under the governing live load model is subject to discussion.

Two modes of shear failure can occur in reinforced concrete slabs under concentrated loads: one-way shear (also known as beam shear, or shear) and two-way shear (also known as punching).

One-way shear is typically checked on a section at a certain distance from the face of the load or from the support on a section, and is combined with a sectional analysis. Two-way shear is typically checked on a punching perimeter around the load. Both failure modes can occur in reinforced concrete slabs under concentrated loads (de Sousa *et al.* 2023). In addition, given the typical reinforcement ratios in reinforced concrete slab bridges, two-way flexure develops as well in the slabs, and in some cases yielding of the reinforcement can occur, which in turn influences the failure mode.

Between 2010-2012, a first series of slab experiments was carried out in the Stevin II Laboratory of Delft University of Technology (Lantsoght *et al.* 2013b). These experiments focused on loads close to the support, as this loading position was initially considered the most critical for shear. This research resulted in recommendations for the effective width for one-way shear in slabs, recommendations for the assessment of reinforced concrete slab bridges, insight in the influence of various parameters (concrete compressive strength, type of support, type of reinforcement, loading in the middle of the slab versus near the edge, influence of existing cracking, and effect of the combination of a line load and concentrated load) and resulted in the development of the Extended Strip Model (Lantsoght *et al.* 2017b).

Applying the knowledge from these past experiments resulted in the observation that the shear-critical position is further in the span for slabs. In addition, research efforts were geared towards the use of proof load testing for the assessment of reinforced concrete slab bridges (Lantsoght *et al.* 2017a). As such, it became necessary to test reinforced concrete slabs under concentrated loads in a cyclic manner, similar to the loading protocol used during proof load testing, to learn more about the capacity of reinforced concrete slab bridges under concentrated loads farther away from the support and to develop stop criteria for proof load testing of reinforced concrete slab bridges. This paper will report the outcomes and findings related to the capacity of reinforced concrete slabs under concentrated loads farther away from the support.

2 EXPERIMENTS

2.1 Experimental Setup

Figure 1 shows a top view of the test setup with a slab. The line supports are composed of a steel beam (HEM 340) equipped with seven load cells to measure the reaction forces. For the steel bearings, seven strips of steel with dimensions of 300 mm × 100 mm × 25 mm and seven pairs of plates of 300 mm × 300 mm × 20 mm were used. Three prestressing Dywidag bars were anchored to the laboratory floor to restrain the rotation and induce a bending moment over the continuous support. The bars were prestressed to 15 kN each at the beginning of every test, to compensate for the self-weight of the slab.

The loading plate is 200 mm × 200 mm and the load is applied with a speed of 0.04 mm/s. The load was applied in cycles of loading and unloading, as commonly used during proof load testing to reach the proof load in a safe way. The loading protocol was designed to represent a proof load test, using a limited number of cycles to various load levels linked to different performance requirements for bridges, and then cycled of loading to failure.

2.2 Specimens

The slabs that were tested in the laboratory are 1:2 scale models of reinforced concrete slab bridges. The reinforcement is designed so that both shear and flexural failures can be studied in the same specimen as a function of the position, and that scaling will not significantly influence the width and development of the cracks (Zarate Garnica and Lantsoght 2020).

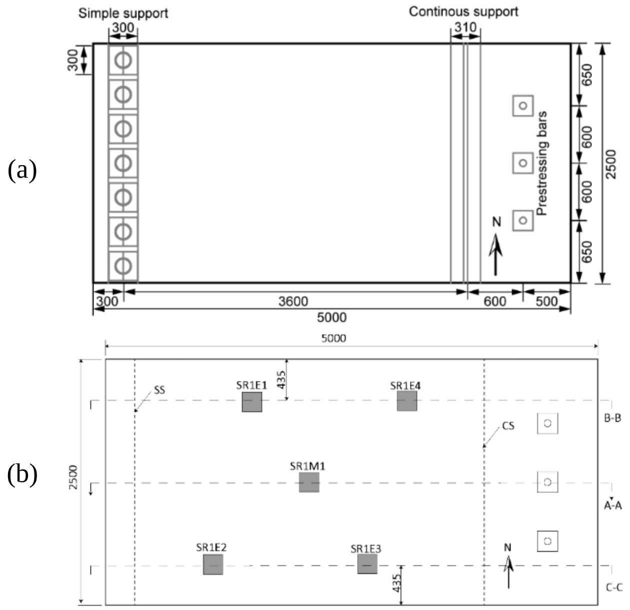

Figure 1. Top view of test setup: (a) showing layout of supports; (b) illustrating loading positions on SR1. All dimensions in [mm].

In the first series of experiments, six slabs were tested, four slabs reinforced with ribbed bars (B500 with a yield strength of 583 MPa and ultimate strength of 706 MPa, as tested in the laboratory) and two with plain bars (with a yield strength of 304 MPa and an ultimate strength of 442 MPa as tested in the laboratory on Ø25 mm bars). All slabs were cast using a B45 concrete mix, and the concrete cube compressive strength was determined at the age of testing the slabs. The thickness of the slabs is 300 mm, resulting in an effective depth of 265 mm for the slabs with ribbed bars and 262.5 mm for the slabs with plain bars. The slabs with ribbed bars had a reinforcement ratio of 0.99%, and the slabs with plain bars 2.02%.

The slabs were instrumented with 2D DIC, 3D DIC, acoustic emission sensors, LVDTs, lasers, and (in some cases) fiber optic sensors to fully capture the behavior during loading. Details of the experiments and sensors can be found in the measurement report (Zarate Garnica and Lantsoght 2021).

3 RESULTS AND ANALYSIS

3.1 Experimental Results

Table 1 summarizes the most important properties of the specimens and the results of the experiments. The following symbols are used in Table 1: f_{cucbe} the cube compressive strength of the concrete at the age of testing the slab, M/E testing in the middle of the width (M) or near the edge of the slab (E, at 435 mm), SS/CS testing near the simple (SS) or continuous (CS) support, *a/d* shear span to effective depth ratio, P_{max} the measured maximum load applied during the experiment, P_y the load at which yielding of the reinforcement was observed, V_{max} the resulting maximum sectional shear force, taking into account the externally applied load, the prestressing, and the self-weight of the slab, and "Mode" the observed failure mode: F (flexure), S (shear), and/or P (punching). The six slabs permitted for testing at various locations, so that 25 experiments were obtained in this first series of experiments, and permitted to study the effect of existing cracks on the behavior, failure modes, and stop criteria.

Table 1. Summary of experimental results.

Test name	$f_{c,cube}$ (MPa)	M/E	SS/CS	*a/d*	P_{max} (kN)	P_y (kN)	V_{max} (kN)	Mode
SR1M1	58.73	M		6.79	1125	860		F-P
SR1E1	59.17	E	SS	4.53	701	701		F
SR1E2	59.31	E	SS	3.02	726		572	S
SR1E3	59.67	E	CS	4.53	624		484	S
SR1E3-2	60.05	E	CS	4.53	746		562	S
SR1E4	59.90	E	CS	3.02	694		601	S
SR2M1	60.47	M		6.79	900	900		F
SR2M2	60.27	M	SS	4.53	1036	1036		F
SR2M3	60.19	M	SS	3.02	1187		911	S-P
SR2M4	59.85	M	CS	4.53	1044		772	S-P
SR3M1	65.65	M	SS	3.02	1141		862	S
SR3M2	65.58	M	CS	4.53	1149		858	S
SR4E1	64.72	E	SS	3.02	1048		807	S
SR4E2	64.94	E	CS	4.53	880		665	S
SR4E3	65.08	E	CS	4.53	816		619	S
SR4E4	65.32	E	SS	3.02	735	735	583	F
SP1M1	61.58	M		6.86	950	950		F
SP1M2	61.96	M	SS	4.57	1150	1150		F
SP1M3	62.08	M	SS	3.05	1135		886	S
SP1E1	62.27	E	CS	4.57	863	863		F
SP1E2	62.38	E	CS	3.05	800		675	S
SP1E3	62.44	E	CS	3.05	951		796	S
SP2M1	62.59	M	SS	3.05	1291		1007	S
SP2E1	62.70	E	CS	3.05	993		826	S
SP2E2	62.61	E	CS	3.05	899		755	S

3.2 Comparison to Design Codes and Methods

The maximum loads in the experiments are compared to various codes and analytical models, see Table 2. The methods used for comparison are Regan’s method (Regan 1982), the Extended Strip Model (Lantsoght *et al*. 2017b), the current Eurocode (considering the governing failure model between shear and flexure) (CEN 2011), the Dutch guidelines (“RBK”) for the assessment of existing bridges (Rijkswaterstaat 2013), the upcoming Eurocode (CEN 2021), and the Critical Shear Displacement Theory (Yang *et al.* 2016). In addition, for comparison the results using a nonlinear finite element model (DIANA) are include: both for the case where each experiment is considered separately (NLFEA) as well as for the case in which phased analysis is used to replicate the sequence of testing on a slab. For the rows indicated with an *, only the shear experiments are compared to the analytically determined shear capacities.

Table 2. Summary of comparison between tested and predicted values, with average value (AVG) and coefficient of variation (COV).

Method	**Compares**	**AVG**	**COV**
Regan's method	P_{max}	0.92	14.7%
Extended Strip Model	P_{max}	1.39	18.6%
Eurocode 2	V_{max}, M_{span}	1.33	24.6%
RBK	V_{max}, M_{span}	1.13	21.5%
New Eurocode*	V_{max}	1.30	18.7%
Critical Shear Displacement Theory*	V_{max}	1.09	15.6%
NLFEA	P_{max}	0.95	11%
NLFEA-PA	P_{max}	1.05	15%

*: Results using comparison between experiments with a shear failure and analytical model only

With the Eurocode and Dutch approaches as well as with the Critical Shear Displacement Theory, the shear capacity of the slabs is determined using the effective width based on a 45-degree horizontal load spreading from the far side of the load to the face of the support, as used in engineering practice in France. The Eurocode approach predicted the correct failure mode for 21 out of 25 experiments. The Dutch approach predicted the correct failure mode for 22 out of 25 experiments. From the comparison between experiments and calculated capacities, we can observe that Regan's method, which is a modified punching model for slabs under concentrated loads close to the support, is slightly unconservative but gives a low coefficient of variation. The Extended Strip Model is on the conservative side, as expected for a lower-bound plasticity-based approach, and has a low coefficient of variation considering the simplicity of application of the model. The Dutch guidelines are slightly better than the Eurocode, as these guidelines have incorporated the insights of the previous research on slabs. The Critical Shear Displacement Theory and the new Eurocode formula give a reasonable prediction of the shear capacity of the slabs, with the CSDT giving more accurate results. The nonlinear finite element models are quite accurate, but the gain in accuracy may be considered small as compared to the added complexity and computational time and effort.

Based on the experimental results, following recommendations for practice can be formulated:

- The French load spreading method can be used for loads farther away from the support.
- The Dutch guidelines are safe for applications to the assessment of existing bridges.
- Both shear and flexural capacity should be considered in an assessment, and the governing failure mode should be determined as a function of various loading positions that can be applied on a slab bridge.

Future research will extend this series of experiments by considering skewed slabs, to validate the stop criteria for proof load testing on skewed slab bridges, and to evaluate the capacity of skewed slab bridges (and the effective width that should be applied).

4 SUMMARY AND CONCLUSIONS

This paper reports on 25 experiments on six reinforced concrete slabs, representing reinforced concrete slab bridges. These experiments serve to improve the assessment of existing reinforced concrete slab bridge. The following main conclusions can be drawn:

- Reinforced concrete slabs under concentrated loads can fail in shear, punching, and flexure, as well as a combination of these failure modes.
- These experiments demonstrated that the Dutch guidelines, which are based on previous slab experiments, are an improvement as compared to the Eurocode for the assessment of existing reinforced concrete slab bridges.
- The Critical Shear Displacement Theory leads to the most accurate predictions of the shear capacity.

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