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ONE-WAY SLABS IN TRANSITION BETWEEN ONE-WAY SHEAR AND PUNCHING: EXPERIMENTS AND RECENT INSIGHTS FOR EVALUATION

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Bridge deck slabs are members on which one-way reinforced concrete slabs are found frequently loaded by concentrated loads. Although the one-way shear failure mechanism has gathered more attention in the past years, both one-way shear and two-way shear mechanisms may be critical for such loading conditions. This paper addressed the ultimate capacity of thin one-way reinforced concrete slabs subjected to concentrated loads and yielding of the flexural reinforcement. In practice, the test setup studied was devised to represent short-span rural bridges frequently found in Brazil. The experimental program included 12 tests performed on 6 slabs applying the concentrated loads at varied positions. All tests started to fail by punching shear. Nevertheless, both one-way shear and punching shear cracks were observed at ultimate states after shear redistribution. The reinforcement yielding followed by excessive flexural cracking hampered the arching action activation for loads closer to the support. The comparison of experimental and calculated resistances using standard code-based expressions suggests that improvements in unitary shear capacity could be supported as a result of slabs' transverse load distribution capacity. Alternatively, increasing the effective shear width can help estimate one-way shear capacity for loads near to the support.

Keywords: Concentrated loads, Effective shear width, Reinforced concrete, Arching action, Shear redistribution.

1 INTRODUCTION

The road network infrastructure is getting older, and the service life of many bridges and box culverts is reaching the design value of 50 years. Besides, the demands on these structures have increased in the last decades. Consequently, it is frequently required to investigate if slabs designed for a past design load support the new and heavier loads. In this context, many European solid slab bridges were rated as critical in shear capacity assessments even though no distress signal could be detected under inspection (Lantsoght *et al.* 2013, de Sousa *et al.* 2021).

In the last decade, several studies conducted on this topic revealed that commonly used approaches could lead to overly conservative estimations of the shear capacity of slabs under concentrated loads. For instance, Henze *et al.* (2020) observed that the unitary shear capacity v_R in one-way shear assessments could be increased to consider the favorable effect of transverse load distribution in one-way slabs under concentrated loads. In his approach, the unitary shear demand v_E to be compared with the unitary shear capacity should be determined based on the use of linear elastic finite element analyses (LEFEA). Using a different approach, de Sousa *et al.* (2021)

concluded that the effective shear width b_{eff} could be increased close to the support to consider the enhanced transverse distribution of slabs under concentrated loads. In this approach, b_{eff} is the length that shall be multiplied by a given unitary shear capacity v_R to determine the one-way shear capacity V_R (in force units).

The presented studies provide important contributions to assessing one-way slabs under concentrated loads. Nevertheless, they addressed only over-reinforced slabs designed to achieve shear failures without reinforcement yielding. Therefore, it is not clear if the main conclusions drawn from these studies apply to slabs subjected to possible reinforcement yielding or excessive flexural cracking at failure.

The aim of this study is to describe a series of experiments that were carried out on spanning slabs subjected to concentrated loads, where both shear and punching shear failure mechanisms were observed, along with yielding of reinforcement. Besides, this paper describes a comparison between experimental and calculated resistances using LEFEA to determine the unitary shear demand and also based on the approach using the effective shear width concept.

2 APPROACHES TO ASSESS THE ONE-WAY SHEAR CAPACITY

Two approaches were tested in this study to evaluate the one-way shear capacity of one-way slabs under concentrated loads close to the support. In both approaches, partial safety factors were removed. Approach I is a fully analytical and based on the concept of an effective shear width, on which an even distribution of shear demand and shear resistances along the control section for verification can be assumed. The shear demand V_{test} was determined at the average distance between the support and the load ($a_v/2$). The shear capacity V_R was calculated by multiplying the unitary shear capacity v_R (calculated according to the EN 1992-1-1:2005 (CEN 2005)) by the effective shear width b_{eff} (calculated based on the load position - Figure 1a). The factor $C_{R,c,test}$ was assumed to equal 0.15 based on Lantsoght *et al.* (2015), and arching action was considered by multiplying the unitary shear capacity by $1/\beta_{EC}$ to consider the favorable effect of direct load transfer to the support when $a_v \leq 2d_l$.

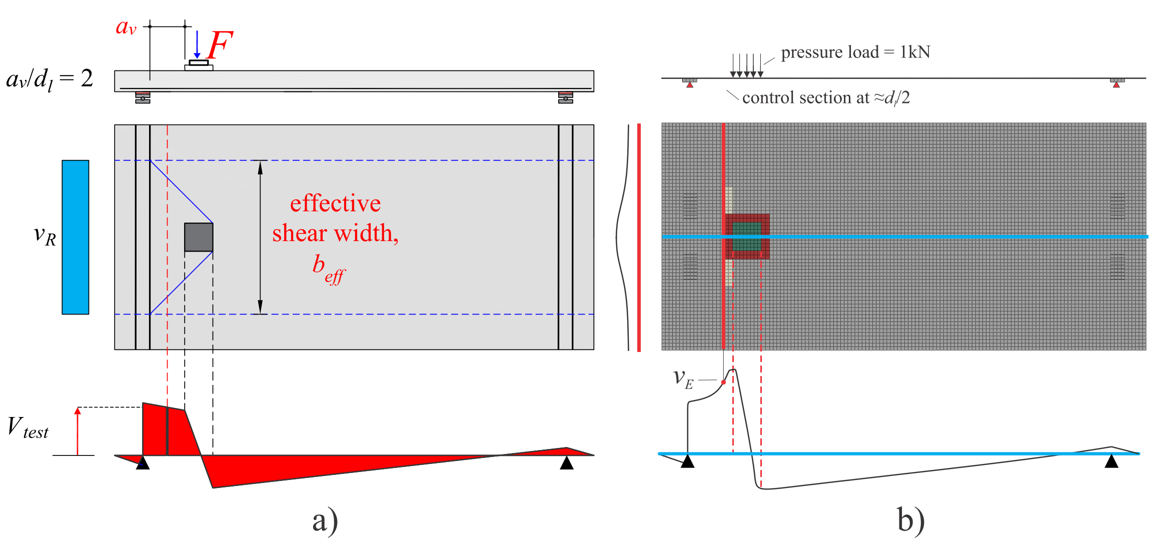
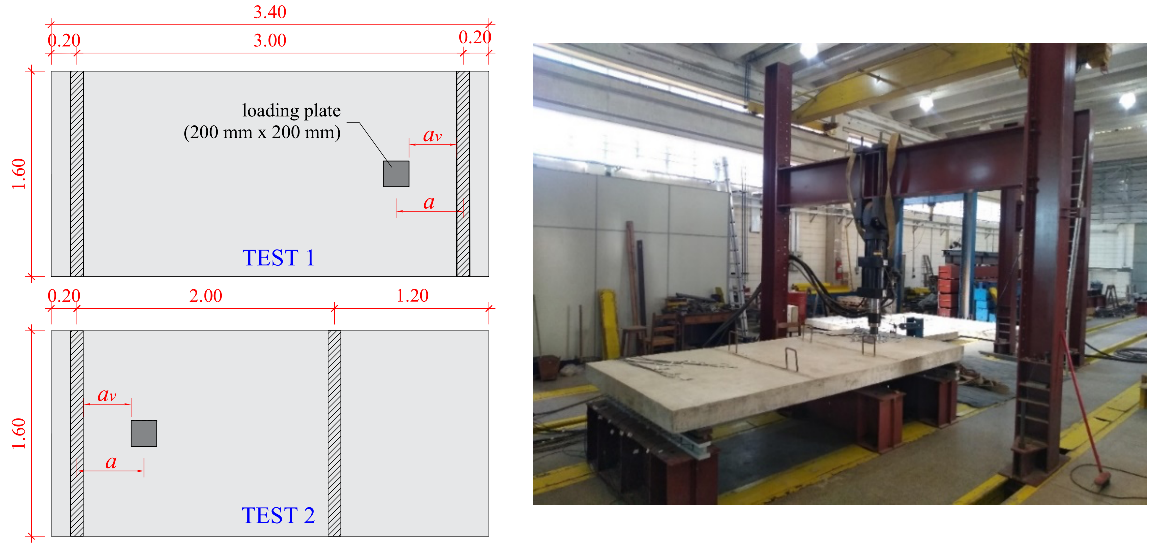


Figure 1. Approaches to assess the one-way shear capacity of the slabs: a) analytical approach based on the effective shear width concept; b) LEFEA approach.

The second approach (approach II), was based on the use of LEFEA to estimate the unitary shear demand $v_{E,test}$ at the control section $d_l/2$, as suggested in Henze *et al.* (2020). In this case, the tested concentrated load at failure F_{test} was multiplied by the unitary shear demand estimated for a concentrated load equal 1 kN. The numerical models used shell elements to simulate the slab and solid elements to represent the support. An interface with free lifting was applied between the support and the slabs. Further details on the numerical modeling can be consulted elsewhere (de Sousa *et al.* 2023b). The unitary shear capacity v_R was calculated using $C_{R,c,test} = 0.35$ based on Henze *et al.* (2020), which assumes an enhanced unitary shear capacity due to transversal load redistribution. No arching action was considered for loads close to the support in this method.

3 EXPERIMENTAL PROGRAM

The experimental program was conducted at the University of São Paulo (São Carlos School of Engineering). In total, 12 tests were performed on six slabs (two tests per slab). The size of the slabs was 3.4 m × 1.6 m in plan, and the thickness equaled 0.15 m (Figure 2). The geometry of the slabs simulates short-span rural bridges frequently found in Brazil in a simplified test setup, using only one concentrated load as in other publications.



a) b)

Figure 2. a) Test layout with the geometry of the specimens and; b) picture of the test setup. Dimensions in m.

The span length was from 3 m in the first test to 2 m in the second test for each slab, which allowed for isolating the most damaged region from the first test.

The other parameters that were varied in the tests were (i) the ratio a_v/d_l (where a_v is the clear shear span and d_l is the effective depth towards the longitudinal reinforcement); (ii) and the longitudinal reinforcement ratio ρ_l, which varied between 0.99% and 1.32%. The reinforcement ratio in the transverse direction ρ_t was fixed at 0.44%. Bars of 12.5 mm and 8.0 mm were applied in the longitudinal and transverse direction, respectively, spaced each 100 mm. A concrete cover of 20 mm was used for all slabs.

The concrete properties varied between the first group of slabs (L1 to L3) and the second group (L4 to L5). The compressive strength of concrete measured on cylinders (100 mm × 200 mm) $f_{c,cyl}$

was 22.0 MPa to the first group and 28.3 MPa to the second group. The concrete splitting tensile strength $f_{ct,sp}$, measured on diametral compression tests was 2.36 MPa in the first group and 2.63 MPa in the second group. Coarse aggregates of a maximum size of 19 mm were used in the concrete mix. The yield strength of the 12.5 mm and 8.0 mm bars were 514 and 513 MPa, respectively. Table 1 summarizes the main information about concrete properties, reinforcement ratio, load position and span length for each test. Letters N and S indicate the first and second tests for each slab. Along the experimental program, the following data were analyzed: (i) the evolution of rebar strains in the spanning and transverse directions near the load, (ii) slab deflection at the bottom side of the loaded area, (iii) applied load with the displacement-controlled jack, (iv) distribution of support reactions on the instrumented aluminum beam close to the load and (v) cracking pattern after failure. In this study only the results of the ultimate loads and cracking pattern will be discussed. Further details on the other parameters measured can be consulted elsewhere (de Sousa *et al.* 2023a).

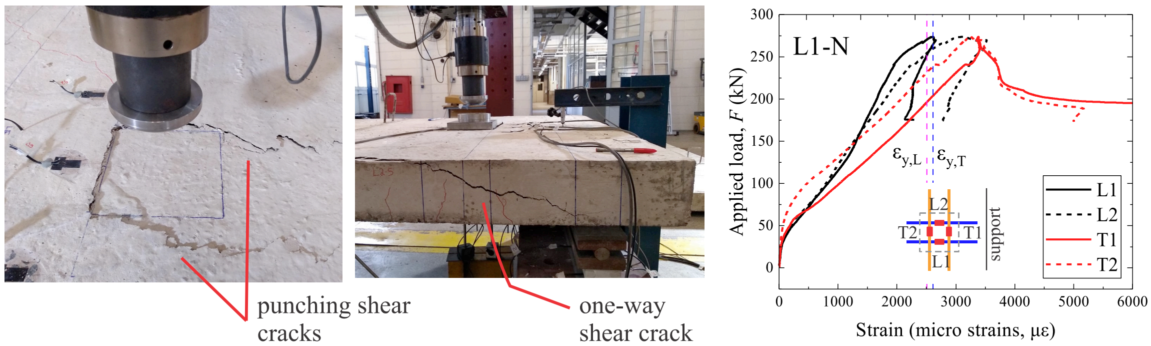
Table 1. Material properties, reinforcement ratio, and load layout of slabs L1 to L6. The coefficient of variation is denoted by the number in parentheses.

Test	$f_{c,cyl}$ (MPa)	$f_{ct,sp}$ (MPa)	ρ_l (%)	ρ_t (%)	a_v/d_l [-]	a/d_l [-]	l_{span} (m)
L1-N	22.0 (12.0%)	2.36 (11.0%)	0.99	0.44	1.00	2.21	3
L1-S					1.00	2.21	2
L2-N					2.00	3.21	3
L2-S					2.00	3.21	2
L3-N					3.00	4.21	3
L3-S					3.00	4.21	2
L4-N	28.3 (10.6%)	2.63 (12.6%)	1.32	0.44	1.00	2.21	3
L4-S					1.00	2.21	2
L5-N					2.00	3.21	3
L5-S					2.00	3.21	2
L6-N					3.00	4.21	3
L6-S					3.00	4.21	2

4 TEST RESULTS AND PREDICTIONS

Figure 3 illustrates the cracking pattern for most of the slabs (10/12). After the development of punching shear failure near the load (Figure 3a) and significant shear redistribution, most slabs developed a one-way shear failure similar to wide beams, which were apparent on the slab side (Figure 3b). This shear redistribution was also detected by the evolution of tensile strains at the longitudinal and transverse reinforcement located around the load (Figure 3c). In practice, when the slabs developed the first failure mechanism by punching, the tensile strains at the longitudinal reinforcement stopped increasing (L1 and L2 in Figure 3c), while the elongation at the transverse rebar (T1 and T2 in Figure 3c) kept increasing. This indicates that the load moved from the shear span axis to the lateral sides of the load plate, which posteriorly activated a one-way shear failure.

Table 2 shows the experimental and predicted ultimate resistances using different approaches. The effective shear width method (approach I) was applied in columns #6 to #7, while in columns #8 to #10, LEFEA was applied together with recommendations from Henze *et al.* (2020) (approach II).



a) b) c)

Figure 3. a) First failure mechanism (punching shear); b) second failure mechanism (one-way shear); c) strain evolution of longitudinal and transverse rebars around the load during the tests.

Table 2. Comparison between tested and predicted resistances using one-way shear expressions based on effective shear width concepts and LEFEA.

#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Test	l_{span} (m)	a_v/d_l (-)	F_{test} (kN)	V_{test} (kN)	V_R (kN)	$\frac{V_{test}}{V_R}$	$v_{E,test}$ (kN/m)	v_R (kN/m)	$\frac{v_{E,test}}{v_{R,Henze}}$
L1-N	**3**	1	273.5	256.4	188.9	1.46	195.0	166.0	1.17
L2-N	**3**	2	282.1	252.3	125.0	2.22	201.1	166.0	1.21
L3-N	**3**	3	275.4	234.7	161.3	1.69	196.3	166.0	1.18
L1-S	**2**	1	332.1	294.5	198.9	1.67	223.1	166.0	1.34
L2-S	**2**	2	270.4	224.1	135.4	1.97	181.6	166.0	1.09
L3-S	**2**	3	253.9	194.9	180.3	1.40	170.6	166.0	1.03
L4-N	**3**	1	351.5	327.3	227.0	1.56	250.6	198.7	1.26
L5-N	**3**	2	321.6	286.5	150.8	2.11	229.2	198.7	1.15
L6-N	**3**	3	267.0	227.8	194.5	1.37	190.3	198.7	0.96
L4-S	**2**	1	374.1	330.8	239.0	1.57	251.3	198.7	1.26
L5-S	**2**	2	296.3	244.9	163.3	1.80	199.0	198.7	1.00
L6-S	**2**	3	314.8	239.9	217.4	1.44	211.5	198.7	1.06
					AVG	1.69		AVG	1.14
					COV	16.8%		COV	10.3%

Table 2 shows that even using factors related to arching action β for forces applied near the support, the ratio V_{test}/V_R was overly conservative (AVG = 1.69 and COV = 16.8%). On the other hand, using LEFEA to estimate the shear demand $v_{E,test}$ and the recommendations from Henze *et al.* (2020) to compute the unitary shear capacity v_R, the relation between experimental and calculated resistances $v_{E,test}/\ v_R$ achieved an enhanced level of accuracy (AVG = 1.14 and COV = 10.3%).

5 CONCLUSIONS

This study investigated the level of accuracy of different approaches to assess the one-way shear capacity of one-way slabs under concentrated loads close to the support. Different from previous investigations, reinforcement yielding took place at failure. The results show even after yielding of the flexural reinforcement, thin slabs may develop significant shear redistribution. In this study, the shear redistribution around the load activated a one-way shear failure mechanism after local punching shear. Besides, it was shown that using traditional rules from the literature based on the effective shear width concepts can result in excessive conservative predictions of shear capacity, even considering the favorable effect of arching action in the capacity. In practice, this occurs mainly because it is necessary to consider the enhanced shear resistance due to shear redistribution capacity transversely. Using the proposed approach from Henze *et al.* (2020), based on the combination of LEFEA and enhanced $C_{Rc,test}$, the forecasts of one-way shear resistance fitted better the test results ($v_{E,test}/v_{R,Henze}$ with AVG = 1.14 and COV = 10.3% compared to V_{test}/V_R with AVG = 1.69 and COV = 16.8%). This occurs mainly because the LEFEA allows considering a more realistic distribution of shear forces over the shear critical regions. Besides that, the enhanced value of $C_{Rc,test}$ enables consideration of the favorable effect of shear redistribution of slabs. Regarding the experimental program, it was found that, even after reinforcement yield and large flexural cracking around the load, the slabs still developed a large capacity of shear redistribution at failure. This shear redistribution allowed the slabs to develop a shear failure similar to wide beams at the slab sides after a first punching shear failure mechanism.

Acknowledgments

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References

CEN, *EN 1992-1-1:2005: Eurocode 2: Design of Concrete Structures -Part 1-1: General Rules and Rules for Buildings*, Comité Européen de Normalisation, Brussels, Belgium, 2005.

de Sousa, A. M. D., Lantsoght, E. O. L., and El Debs, M. K., *Failure Mechanism of One-Way Slabs under Concentrated Loads after Local Reinforcement Yielding*, Engineering Structures, Elsevier, 291, 116396, September, 2023a.

de Sousa, A. M. D., Lantsoght, E. O. L., Setiawan, A., and El Debs, M. K., *Shear and Punching Capacity Predictions for Slabs under Concentrated Loads Aided by LEFEA*, ACI Special Publication, American Concrete Institute, 357, 100–122, April, 2023b.

de Sousa, A. M. D., Lantsoght, E. O. L., Yang, Y., and El Debs, M. K., *Extended CSDT Model for Shear Capacity Assessments of Bridge Deck Slabs*, Engineering Structures, Elsevier, 234, 111897, May, 2021.

Henze, L., Rombach, G. A., and Harter, M., *New Approach for Shear Design of Reinforced Concrete Slabs under Concentrated Loads Based on Tests and Statistical Analysis*, Engineering Structures, Elsevier, 219, 110795, September, 2020.

Lantsoght, E. O. L., van der Veen, C., de Boer, A., and Walraven, J., *Proposal for the Extension of the Eurocode Shear Formula for One-Way Slabs under Concentrated Loads*, Engineering Structures, Elsevier, 95, 16–24, July, 2015.

Lantsoght, E. O. L., van der Veen, C., and Walraven, J. C., *Shear in One-Way Slabs under Concentrated Load Close to Support*, ACI Structural Journal, American Concrete Institute, 110(2), 275–284, March, 2013.