Advances in the research on the shear capacity of one-way bridge slabs under concentrated loads

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Summary

The research on the shear capacity of bridge deck slabs has gathered much attention on the assessment of bridge deck slabs as the normative codes have adopted more conservative expressions of capacity and heavier design loads. While advances in this topic were attained in the last decades, different interpretations of the test results and solutions have been proposed, varying the level of sophistication of the method. This paper proposes to discuss the most significant advances in the research related to the shear capacity of one-way slabs under concentrated loads in light of the different proposed methods and results described in the literature. Besides that, this paper showcases a summary of the Brazilian developments in this field.

1 INTRODUCTION

The shear capacity of bridge deck slabs has raised concern in several countries, as many bridges designed between 1970 and 1980 are reaching the end of their designed service life. To extend the service life of such bridges, they need to be assessed against the most updated design codes. However, the current design codes use heavier design loads than in the past and more conservative expressions of shear capacity. As a result, many bridges were rated as critical in shear, despite no distress signal, when using quick scan assessment approaches [1].

This paper proposes to discuss the main available approaches to evaluate the shear capacity of bridge deck slabs based on the most recent publications in this field. In practice, the paper also discusses some of the Brazilian researcher's developments in this field, including analytical, numerical, and experimental investigations.

2 HOW THE PROBLEM IS INVESTIGATED

Some challenges appear when evaluating the shear capacity of such structures. In practice, these structural members are thick and are loaded by a combination of several concentrated loads. Therefore, testing these structures on a full scale would be uneconomical and unfeasible in most cases (Figure 1a). Based on that, the problem is frequently addressed in reduced-scaled slabs using only a single concentrated load (Figure 1b), assuming that this load replaces the whole design truck on a global scale or that it represents reasonably well the effect of one of the wheels on a local scale.

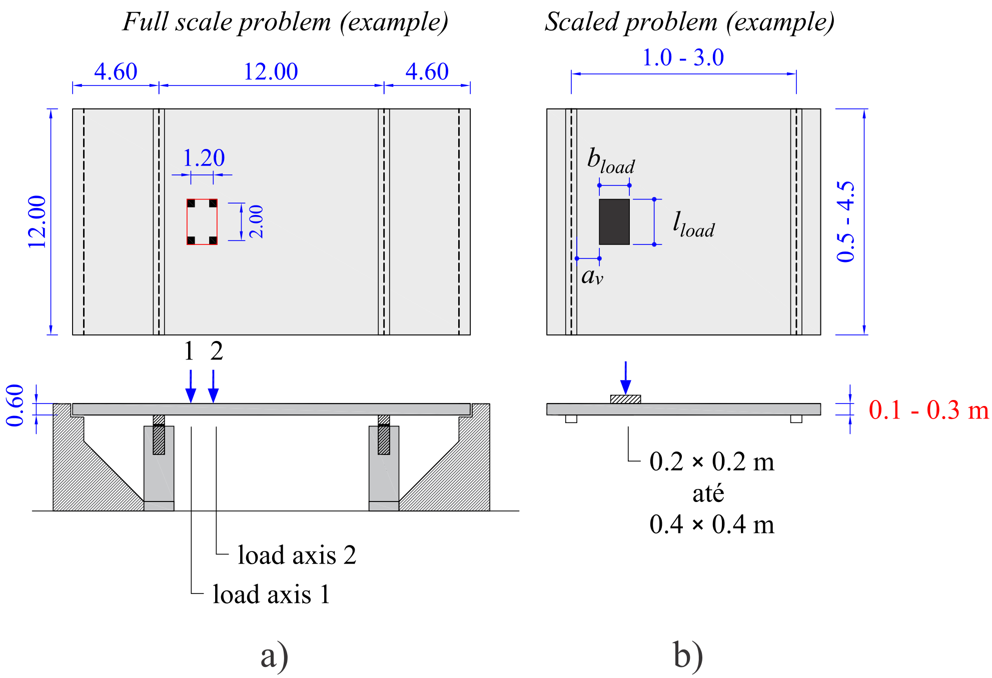


Fig. 1 a) Example of one-way slabs under concentrated loads in solid slabs bridges in full scale; b) example of reduced-scale one-way slab typically tested at a laboratory (Dimensions in m).

Although much progress has been made in the field based on the testing of reduced-scale slabs, some drawbacks appear: (i) the size effect in shear existing on full-scale slabs cannot be considered at the laboratory tests, and (ii) the accuracy of most approaches developed from single loaded slabs cannot be directly validated for slabs under a combination of concentrated loads.

3 ANALYTICAL BASED APPROACHES TO ASSESSMENT

The more straightforward and most traditional approach to evaluating the shear capacity of such slabs is to calculate a slab strip over which the shear force can be distributed b_{eff}, also known as effective shear width (Figure 2a). Based on this distribution length, the nominal shear demand v_E (shear force per unit length) can be determined in the control section as:

$$v_E = \frac{V_E}{b_{eff}} \tag{1}$$

Alternatively, someone can assume that the effective shear width is the slab strip that contributes effectively to the shear capacity and multiply the nominal shear capacity v_R by the effective shear width b_{eff}:

$$V_R = v_R \cdot b_{eff} \tag{2}$$

In this case, the shear demand V_E and resistance V_R may be compared in force units.

Another aspect that was improved in the understanding of the shear capacity of slabs is the similarity with the beam regarding the arching action. While in the past it was not clear if members of lower thicknesses could benefit from arching action, nowadays it is well accepted that for members with a ratio $a_v/d_l \leq 2$, the arching action significantly improves the shear capacity of the slabs. Because of this, the enhanced shear capacity $v_{R,enhanced}$ can be calculated as:

$$v_{R,enhanced} = v_R \cdot \mu_1 \tag{3}$$

$$\mu_1 = \frac{2d_l}{a_v} \begin{cases} \geq 1 \\ \leq 4 \end{cases} \tag{4}$$

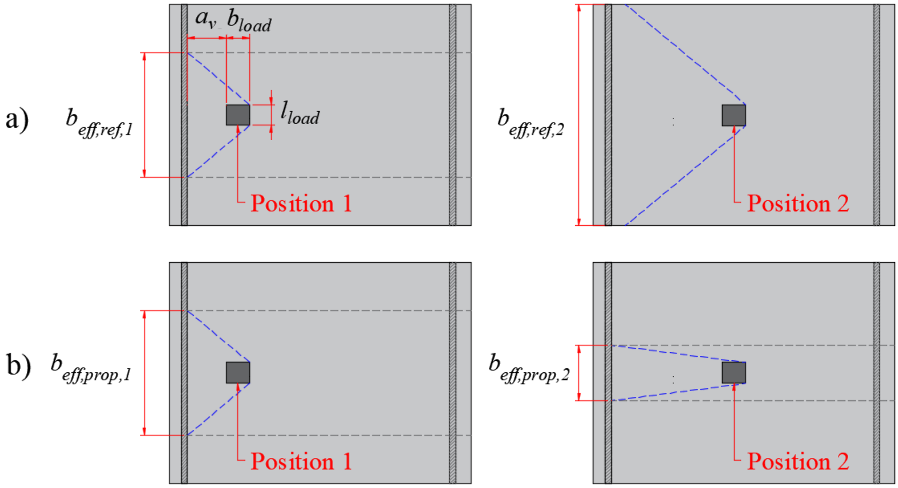


Fig. 2 a) most traditional effective shear width model based on a fixed spreading angle [2]; b) proposed effective shear width approach by the authors in [3].

There are many analytical approaches to calculate the effective shear width. Nevertheless, the most traditional is based on the assumption of a horizontal loading spreading from the back edges of the loaded area towards the support with a fixed angle of 45º, such as in Figure 2a. Despite this approach providing reasonable accuracy for the predictions of shear capacity for loads close to the support [4], it may overestimate the shear capacity for loads far away from the support, which typically fails by punching or a mixed mode between shear and punching [3]. This occurs because the predicted effective shear width increases as the distance between the load and the support increases (Figure 2a). Because of this, the authors proposed an effective shear width model that decreases the predicted effective shear width as the distance between the load and the support increases (Figure 2b), providing excellent accuracy levels for different shear models [3,5,6]. For simply supported slabs, the effective shear width b_{eff} is calculated as :

$$b_{eff,prop} = b_{eff,ref} \cdot \mu_2 \tag{5}$$

$$b_{eff,ref} = l_{load} + 2 \cdot \left(a_v + b_{load}\right) \tag{6}$$

$$\mu_2 = 1,46 - 0,14 \cdot a_v / d_l \tag{7}$$

In practice, the approach based on the effective shear width is used more in a preliminary assessment of the whole bridge stock, and, hence, it is reasonable that this approach has a higher level of conservatism. Nevertheless, when some bridge is classified as deficient on shear based on a preliminary classification, which uses a most conservative approach, a most refined and less conservative approach can be used, such as the ones involving finite element analyses, which will be described below.

4 SIMPLIFIED FINITE ELEMENT ANALYSES

Simplified finite element analyses for assessment can be defined as applying shell elements to simulate the slab and considering linear elastic material properties for concrete (Figure 3). The main advantage of such approaches is that the spatial distribution of shear forces and bending moments can be measured [7]. Hence, the most critical regions can be determined more straightforwardly. Besides, the uneven distribution of shear forces and bending moments at the considered control sections can be evaluated.

In Natário et al. [8], the unitary shear capacity v_R was determined based on the Critical Shear Crack Theory (CSCT) expressions. Therefore, the measured shear forces v_E and bending moments m_E at the control section of the finite element models for a given load were used as input in the expressions of shear capacity. In Henze et al. [7], the shear capacity is determined based on the code expressions from Eurocode but considering the improved transverse load distribution capacity from slabs by using $C_{R,c,test}$

= 0.35. In this approach, the shear force $v_{E,test}$ caused by the concentrated loads shall be measured at the distance of $d_l/2$ from the loaded area.

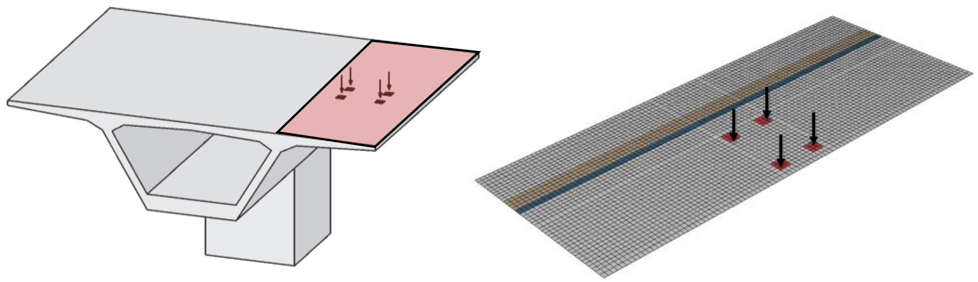


Fig. 3 a) Cantilever slab from a concrete box girder section under a combination of concentrated loads (adapted from [2]); b) cantilever slab simulated using shell finite elements.

5 ADVANCED FINITE ELEMENT ANALYSES

Advanced finite element analyses for assessment can be considered those that simulate the slab using solid or three-dimensional finite elements and consider the non-linear stress-strain behaviour of concrete (mainly) and steel (Figure 4a). One of the main advantages of such approaches is that the ultimate capacity is determined directly in the numerical model. Besides, the governing failure mechanism of the structure (shear, punching, flexure, or a mixed mode between them) can also be determined based on the evaluation of the cracking pattern and steel strains (Figure 4b).

Figure 4 shows one of the results of the simulations performed by the authors in de Sousa et al. [9]. Between the main contributions from this study, we evaluated the impact of different modelling choices related to the Concrete Damaged Plasticity Model (CDPM) in the predictions of capacity and failure mechanisms.

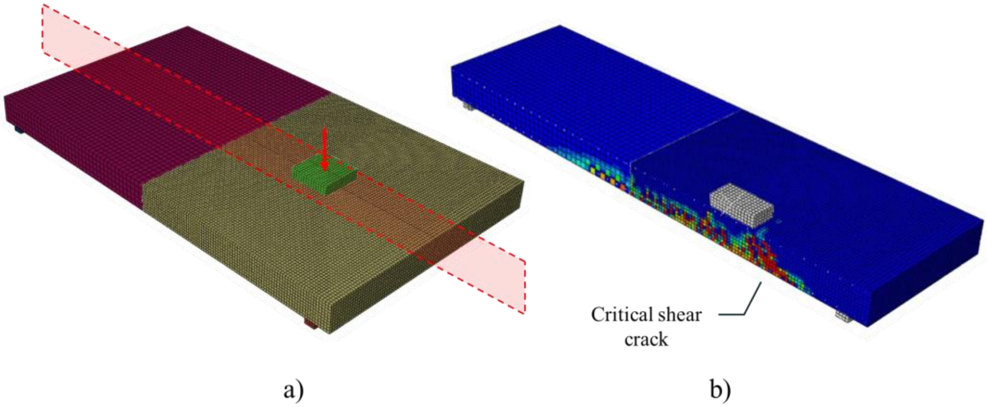


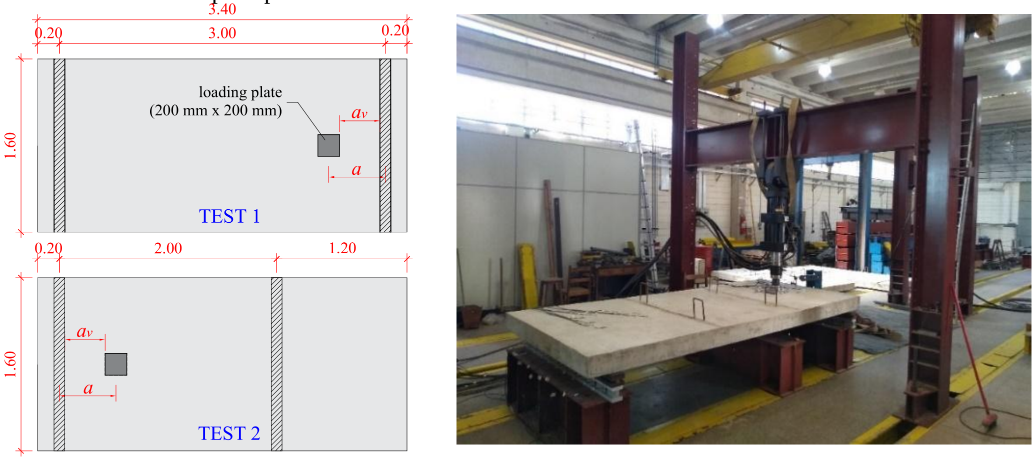
Fig. 4 a) Numerical models of a one-way slab under concentrated load using three-dimensional solid elements (C3D8R) and considering non-linear material behavior; b) cut-view at failure load showing the critical shear crack.

Despite the high amount of information that can be prospected from the numerical models, the number of input parameters in these numerical models is also large. Besides, the results of the numerical simulations are frequently highly sensitive to the input parameters considered in the simulations and, hence, the accuracy of the predictions request experience of the users.

In this paper, the modeling options considered in the non-linear finite element analyses are equal to those considered in Sousa et al. [9], which simulated simply supported slabs under concentrated loads with varied load positions and slab widths. Therefore, the stress-strain behavior under compression and fracture energy G_f were modeled according to the expressions from *fib* Model Code 2010 [10]. The tensile stress-strain behavior was modeled using Hordijk's model [11]. The damage evolution laws in compression and tension were described according to the models from Birtel and Mark [12] and Alfarah et al. [13].

6 EXPERIMENTAL TESTS CONDUCTED IN BRAZIL

The experimental program was carried out in the São Carlos School of Engineering at the University of São Paulo. Six slabs underwent a total of 12 tests, with two tests conducted on each slab. In the plan, the slabs measured 3.4 m by 1.6 m, and their thickness was 0.15 m (Figure 5). In a simplified test scenario, the slabs' design mimics short-span rural bridges commonly seen in Brazil, with a single concentrated load as in prior publications.



a) b)

Fig. 5 Test layout with the geometry of the specimens and; b) picture of the test setup. Dimensions in m. Adapted from [14].

To allow each slab to be used in two tests, the span length for each slab changed from 3 meters in the first test to 2 meters in the second test. The second test was performed on the inverted side of the slabs, and the most damaged side was isolated by decreasing the span length between the supports.

The key details regarding each test's concrete characteristics, reinforcing ratio, load location, and span length are compiled in Table 1. Each slab's first and second tests are denoted by the letters N and S. In Table 1, $f_{c,cyl}$ is the concrete compressive strength measured on cylinder specimens at the testing age, $f_{ct,sp}$ is the concrete splitting tensile strength measured on diametral compression tests, ρ_l and ρ_t are the longitudinal and transverse reinforcement ratios, respectively, a_v/d_l is the shear slenderness parameter 1 (where a_v is the clear shear span between the load and the support and d_l is the effective depth of the longitudinal reinforcement) ; a/d_l is the shear slenderness parameter 2 (where « a » is the shear span or distance between axes of load and support); l_{span} is the span length in the test, F_{test} is the applied concentrated load at failure in the test and V_{test} is the shear force measured at failure (related to F_{test}). Further details on the other parameters measured can be consulted elsewhere [15].

Unlike most publications in this field, the slabs were designed to allow reinforcement yielding at failure. Therefore, the slabs' failure mechanism combined flexure and shear mechanisms.

Between the main contributions from the experimental program, we may highlight (i) the identification of the combined failure mechanism between shear, punching and flexure in most cases tested, (ii) the significant shear redistribution at failure measured by tracking the reinforcement strains evolution and also by the cracking patter at the tests. In practice, a punching shear took place around the load as the first failure mechanism in the tests, mainly at the frontal side of the load. Nevertheless, the shear redistributed from the central axis to the lateral sides, which allowed a one-way shear failure at the slab sides after certain deformation of the slabs.

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)	F_{test} (kN)	V_{test} (kN)
L1-N	22.0 (12.0%)	2.36 (11.0%)	0.99	0.44	1.00	2.21	3	273.5	256.4
L1-S					1.00	2.21	2	332.1	294.5
L2-N					2.00	3.21	3	282.1	252.3
L2-S					2.00	3.21	2	270.4	224.1
L3-N					3.00	4.21	3	275.4	234.7
L3-S					3.00	4.21	2	253.9	194.9
L4-N	28.3 (10.6%)	2.63 (12.6%)	1.32	0.44	1.00	2.21	3	351.5	327.3
L4-S					1.00	2.21	2	374.1	330.8
L5-N					2.00	3.21	3	321.6	286.5
L5-S					2.00	3.21	2	296.3	244.9
L6-N					3.00	4.21	3	267.0	227.8
L6-S					3.00	4.21	2	314.8	239.9

7 COMPARISON BETWEEN TESTED AND PREDICTED RESISTANCES

Table 2 shows a comparison between tested and predicted resistances for the tests conducted in Brazil using different approaches: (i) fully analytical, using the EN 1992-1-1:2005 [16] to calculate the unitary shear capacity v_R and considering or not arching action, (ii) using LEFEA to predict the unitary shear demand $v_{E,test}$ and $C_{Rdc,test}$ = 0,35 such as suggested by Henze et al. [7] (no arching action was considered in these calculations) and (iii) using non-linear finite element analyses NLFEA following the recommendations from [9]. In the analytical approach, two approaches were tested: (i) in the reference approach $V_{R,ref}$ (column #6), the effective shear width was calculated as in Figure 2a and arching action was not considered and (ii) in the proposed calculations, $V_{R,prop}$ (column #7), the effective shear width was calculated as proposed by the authors in Sousa et al. [6] (Figure 2b) and arching action was considered by multiplying the unitary shear capacity by $1/\beta_{EC}$.

Table 2 shows that using the proposed recommendations for calculating the effective shear width b_{eff} and arching action, the analytical predictions of shear capacity improve and still provide conservative predictions. The ratio between tested and predicted resistances $V_{test}/V_{R,ref}$, using the traditional b_{eff} and not including arching action, showed an average value of 2.21 with a coefficient of variation equal to 33.3%. On the other hand, the ratio $V_{test}/V_{R,prop}$ showed an average value of 1.44 with a coefficient of variation equal to 17.8%.

Using the LEFEA and following the recommendations from Henze et al. [7], the ratio between tested and predicted resistances showed the best level of accuracy (column #12), with an average ratio $v_{E,test}/v_{R,Henze}$ equal to 1.14 with a coefficient of variation of 10.3%. In practice, this level of accuracy is similar to the one reached by Natário et al. [8], but it does not include iterative calculations to determine the shear resistance v_R.

The NLFEA is the most refined approach to predicting the ultimate capacity. Nevertheless, in this example, the level of accuracy in the predictions (column #13) reached using this approach was similar to that based on fully analytical calculations. The average ratio between tested and predicted resistances F_{test}/F_{NLFEA} was 1.40, with a coefficient of variation of 11.7%. In practice, this may be attributed to the fact that the numerical models were not calibrated for the tested slabs, as the modeling choices were those recommended by Sousa et al. [9]. Therefore, this study highlights that the level of accuracy of the NLFEA is sensitive to the modeling choices and that the use of material properties calibrated to other concrete or other tests may not be fully representative of the tested slabs.

Table 2 - Comparison between tested and predicted resistances using (i) fully analytical approaches, (ii) LEFEA to calculate $v_{E,test}$ and (iii) using NLFA.

#1	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
Test	F_{test} (kN)	V_{test} (kN)	$V_{R,ref}$ (kN)	$\frac{V_{test}}{V_{R,ref}}$	$V_{R,prop}$ (kN)	$\frac{V_{test}}{V_{R,prop}}$	$v_{E,test}$ (kN/m)	v_R (kN/m)	$\frac{v_{E,test}}{v_{R,Henze}}$	$\frac{F_{test}}{F_{NLFEA}}$
L1-N	273.5	256.4	87.9	2.92	230.7	1.10	195.0	166.0	1.17	1.39
L2-N	282.1	252.3	113.6	2.22	132.7	1.88	201.1	166.0	1.21	1.64
L3-N	275.4	234.7	139.3	1.69	142.6	1.64	196.3	166.0	1.18	1.35
L1-S	332.1	294.5	87.9	3.35	230.7	1.26	223.1	166.0	1.34	1.24
L2-S	270.4	224.1	113.6	1.97	132.7	1.67	181.6	166.0	1.09	1.54
L3-S	253.9	194.9	139.3	1.40	142.6	1.36	170.6	166.0	1.03	1.25
L4-N	351.5	327.3	105.2	3.11	276.1	1.17	250.6	198.7	1.26	1.54
L5-N	321.6	286.5	136.0	2.11	158.8	1.79	229.2	198.7	1.15	1.25
L6-N	267.0	227.8	166.7	1.37	170.7	1.33	190.3	198.7	0.96	1.57
L4-S	374.1	330.8	105.2	3.14	276.1	1.18	251.3	198.7	1.26	1.61
L5-S	296.3	244.9	136.0	1.80	158.8	1.53	199.0	198.7	1.00	1.19
L6-S	314.8	239.9	166.7	1.44	170.7	1.40	211.5	198.7	1.06	1.29
			AVG	2.21		1.44		AVG	1.14	1.40
			COV	33.3%		17.8%		COV	10.3%	11.7%

8 CONCLUSIONS

The paper discusses different approaches for the evaluation of the shear capacity of one-way slabs under concentrated loads, a representative loading case from bridges. Besides, it discusses Brazilian developments in this field regarding analytical, numerical, and experimental investigations. From the presented results, the following conclusions can be drawn:

- Analytical-based approaches can be considered an adequate way to reach quick predictions of the shear capacity as they provide quick and conservative predictions of shear capacity. Nevertheless, a better evaluation of the effective shear width such as proposed by Sousa et al. [6] and considering arching action are important to avoid overly conservative predictions of shear capacity
- Linear elastic finite element analyses, such as those recommended by Henze et al. [7], provide excellent levels of precision in the predictions of shear capacity compared to analytical-based approaches. In this study, besides, they provided the best predictions when compared to NLFEA.
- Non-linear finite element analyses have a level of precision that is very sensitive to the material input parameters. In this study, the use of the same modeling choices validated for another experimental program in [9] for the tests conducted in Brazil did not provide the same level of accuracy. In this case, the level of accuracy was almost the same reached using only analytical-based calculations.

Acknowledgements

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References

[1] Lantsoght EOL, van der Veen C, Walraven J, de Boer A. Recommendations for the Shear Assessment of Reinforced Concrete Slab Bridges from Experiments. Structural Engineering International 2013;23:418–26. https://doi.org/10.2749/101686613X13627347100239.

[2] Lantsoght EOL, van der Veen C, Walraven JC. Shear in one-way slabs under concentrated load close to support. ACI Struct J 2013;110:275–84. https://doi.org/10.14359/51684407.

[3] de Sousa AMD, Lantsoght EOL, El Debs MK. Transition between Shear and Punching in Reinforced Concrete Slabs: Review and Predictions with ACI Code Expressions. ACI Struct J 2023;120. https://doi.org/10.14359/51738350.

[4] de Sousa AMD, Lantsoght EOL, Yang Y, El Debs MK. Extended CSDT model for shear capacity assessments of bridge deck slabs. Eng Struct 2021;234. https://doi.org/10.1016/j.engstruct.2021.111897.

[5] Sousa AMD de, Lantsoght EOL, Araújo D de L, Prado LP, El Debs MK. Recommendations to assess the shear and punching capacity of one-way slabs under concentrated loads according to the ABNT NBR 6118:2014. Revista IBRACON de Estruturas e Materiais 2023;16:e16308. https://doi.org/10.1590/S1983-41952023000300008.

[6] de Sousa AMD, Lantsoght EOL, El Debs MK. Shear and Punching Capacity Predictions for One-Way Slabs under Concentrated Loads Considering the Transition between Failure Mechanisms. Buildings 2023;13. https://doi.org/10.3390/buildings13020434.

[7] Henze L, Rombach GA, Harter M. New approach for shear design of reinforced concrete slabs under concentrated loads based on tests and statistical analysis. Eng Struct 2020;219:110795. https://doi.org/10.1016/j.engstruct.2020.110795.

[8] Natário F, Fernández Ruiz M, Muttoni A. Shear strength of RC slabs under concentrated loads near clamped linear supports. Eng Struct 2014;76:10–23. https://doi.org/10.1016/j.engstruct.2014.06.036.

[9] de Sousa AMD, Lantsoght EOL, Genikomsou AS, Prado LP, El Debs MK. NLFEA of one-way slabs in transition between shear and punching: Recommendations for modeling. Eng Struct 2023;293:116617. https://doi.org/10.1016/j.engstruct.2023.116617.

[10] Fédération Internationale du Béton (fib). fib Model Code for Concrete Structures 2010. vol. 1–2. Lausanne, Switzerland: Ernst & Sohn - fédération internationale du béton, Bulletin 65; 2012.

[11] Hordijk DA. Tensile and tensile fatigue behaviour of concrete — experiments, modelling and analyses. Heron 1992;37:3–79.

[12] Birtel V, Mark P. Parameterised Finite Element Modelling of RC Beam Shear Failure. Abaqus User's Conference, 2006, p. 95–108.

[13] Alfarah B, López-Almansa F, Oller S. New methodology for calculating damage variables evolution in Plastic Damage Model for RC structures. Eng Struct 2017;132:70–86. https://doi.org/10.1016/j.engstruct.2016.11.022.

[14] de Sousa AMD, Lantsoght EOL, El Debs MK. One-way slabs in transition between one-way shear and punching: experiments and recent insights for evaluation. Proceedings of International Structural Engineering and Construction 2024;11. https://doi.org/10.14455/ISEC.2024.11(1).STR-10.

[15] de Sousa AMD, Lantsoght EOL, El Debs MK. Failure mechanism of one-way slabs under concentrated loads after local reinforcement yielding. Eng Struct 2023;291:116396. https://doi.org/10.1016/j.engstruct.2023.116396.

[16] CEN. EN 1992-1-1: Eurocode 2: Design of concrete structures -Part 1-1: General rules and rules for buildings, EN 1992-1-1:2005 2005.