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VALIDATION OF PUNCHING SHEAR CAPACITY PREDICTIONS FOR FLAT SLABS WITH COARSE RECYCLED AGGREGATE CONCRETE

Tadeáš FECKO[1*], Ľudmila KORMOŠOVÁ[1]

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Abstract

This paper evaluates the experimentally determined punching shear capacities of slab-column connections without any shear reinforcement cast from coarse recycled concrete aggregate concrete (CRCAC). Three series of full-scale slab specimens, comprised of a total of six slabs, with reinforcement ratios of 0.52%, 1.23%, and 1.53%, were tested for their punching behaviour. In each series, one specimen was a reference slab, and the other slab was cast with a 100% replacement of the coarse natural aggregate with coarse recycled aggregate (CRA). During the tests, the slab rotations were recorded and used to calculate the punching shear resistance according to the Critical Shear Crack Theory (CSCT). The calculated punching shear resistances were compared with the experimentally measured values. The results show very good agreement between the experimentally measured and predicted punching shear capacities by CSCT and confirm the negligible effect of CRA on the punching shear behaviour of the slab-column connections tested.

Address

[1*] Slovak University of Technology in Bratislava, Faculty of Civil Engineering, Department of Concrete Structures and Bridges, Radlinského 11, 810 05 Bratislava, Slovakia

**** Corresponding author:*** tadeas.fecko@stuba.sk

Keywords

- punching,
- critical shear crack theory,
- coarse recycled aggregate,
- rotations of flat slabs.

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1 INTRODUCTION

The rapid construction and demolition of structures are generating an estimated 3 billion tonnes of construction and demolition waste (CDW) per year worldwide, and this amount continues to grow. The construction industry is responsible for around 30% of total waste, see (Purchase et al., 2022). The vast majority of this waste (often unsorted) ends up in landfills, which is unsustainable over the long term and can cause serious environmental damage. A substantial portion of CDW consists of concrete waste, which is partly deposited in a waste dump and partly processed into recycled aggregates (RA). Therefore, the reuse of RA in the production of structural concrete has become a prominent research topic in recent years. A very promising application of recycled aggregate concrete (RAC) is in the construction of flat slabs, which raises the need to investigate the effect of RA on the punching shear behaviour of slab-column connections. The research on the material showed that with an increasing amount of RA in concrete, the concrete's strength and mainly the modulus of elasticity decrease, while the concrete shrinkage increases. These effects are particularly significant when RA includes fine aggregates. Therefore, for structural purposes, a reasonable solution is the replacement of only coarse natural aggregate (CNA) by coarse recycled aggregates (CRA) in concrete.

The effect of CRA on the punching shear capacity has been discussed in several experimental studies, see below. They demonstrate that despite a decrease in the compressive strength and modulus of elasticity of the concrete, the presence of CRA in concrete does not have a significant effect on the punching shear strength, as noted in (Elsayed et al., 2021; Leelatanon et al., 2022; Ferreira et al., 2024; Reis et al., 2015). In some cases, CRA appeared to have a positive effect on the punching shear strength, see (Sahoo and Singh, 2021; Xiao et al., 2019).

The disadvantage of most experimental studies is in the small dimensions of the specimens, which were far from the dimensions of actual flat slabs. Therefore, an experimental program with slab specimens having dimensions comparable to actual slabs was prepared.

2 EXPERIMENTAL INVESTIGATION

The experimental program builds on research (Fecko et al., 2025) and includes testing of six full-scale flat slab specimens for the punching shear resistance. The slabs were divided into three series, with one reference slab in each series being cast from concrete without CRA and one slab with 100% replacement of CNA (57.4% of the total amount of aggregate). The differences among the individual series were due to the amount of flexural reinforcement. The third series, S3, also had a different support size. The punching shear tests were carried out on all the slab specimens at the Central Laboratory of STU in Bratislava.

2.1 Slab specimens

All the slab specimens had dimensions of 2.5 × 2.5 m and a thickness of 250 mm (see Fig. 1). Steel bars with a diameter of 12 mm and a spacing of 100 mm (ρ= 0.52%) were used for the slabs of the first series. In the second series, 20 mm diameter bars spaced at 125 mm (ρ= 1.23%) were used, while the third series was reinforced with 20 mm diameter bars spaced at 100 mm (ρ= 1.53%) (see Fig. 2).

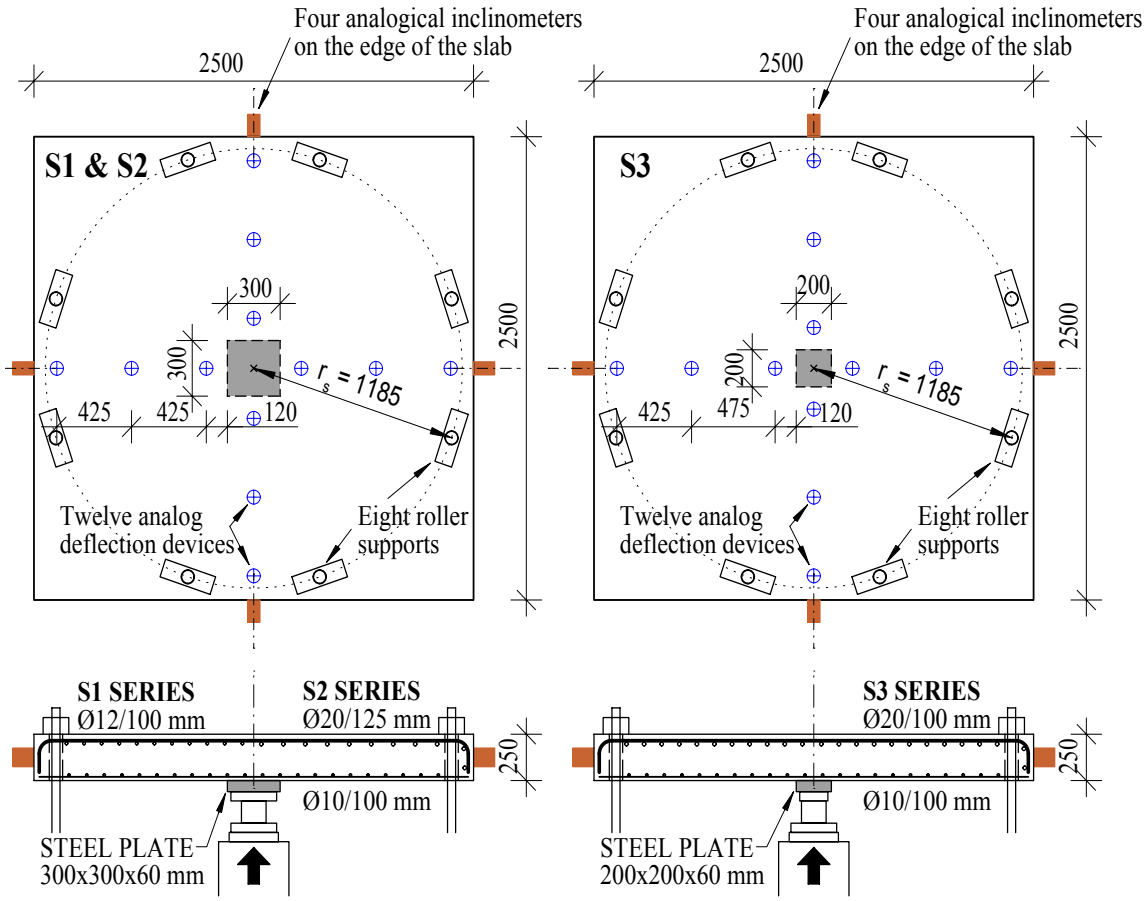


Fig. 1 *Dimensions and the reinforcement of the slab specimens and measuring devices: S1 and S2 series (left) and S3 series (right)*

For the 12 mm diameter steel bars, a concrete cover of 20 mm was considered, whereas a cover of 25 mm was designed for the bars with a diameter of 20 mm. However, this value was difficult to ensure because the specimens were cast with the main tensile reinforcement at the upper surface (as in practice); therefore, the reinforcement cover and the average effective depth differ slightly (see Tab. 2). The slabs were without any shear reinforcement.



Fig. 2 *Slab specimens prepared for casting: S1.0 (left), S2.0 (middle), and S3.0 (right)*

2.2 Mechanical properties of the concrete

The concrete used to produce all the specimens had the same composition; the only difference was the amount of CRA with a 4/16 mm fraction (see Tab. 1). The more environmentally friendly cement CEM II/A-LL 42.5 R was used, due to the presence of limestone in this product.

The material properties were determined from tests of the concrete cylinders and cubes (concrete strength) and prisms (modulus of elasticity) that were produced during the casting of each slab specimen. These properties were determined at the same time that the slabs were tested, due to the relatively short period between casting and testing (approximately 35 days). Reinforcing steel B500B was used. The measured properties of the concrete and steel reinforcement are presented in Tab. 1.

Tab. 1 *Mechanical properties of materials*

	Concrete					Steel reinforcement		
Slab	CRA substitution rate	ρ_c	$f_{cm,cyl}$	$f_{cm,cube}$	E_{cm}	φ	f_{ym}	f_{tm}
		[kg/m³]	[MPa]	[MPa]	[GPa]	[mm]	[MPa]	[MPa]
S1.0	0%	2389	39.6	51.3	38.8	12	601	728
S1.2	100%	2248	33.4	44.3	29.1			
S2.0	0%	2286	30.8	37.0	34.5	20	545	633
S2.2	100%	2241	33.7	46.5	29.3			
S3.0	0%	2302	35.8	47.2	36.7			
S3.2	100%	2209	35.9	47.0	31.2			
Average	0%	2326	35.4	45.2	36.7			
	100%	2233	34.3	45.9	29.9			

When comparing the above mechanical properties, Tab. 1 shows that, in some cases, the concrete cube and cylinder strengths increased, while in others they decreased. In specimen S2.0, an unknown defect occurred during the mixing of the concrete, which resulted in poorer mechanical properties of the concrete. According to the data in Tab. 1, CRCA did not have a clear effect on the strength of the concrete. However, CRCA reduced the modulus of elasticity by an average of 18.5%.

2.3 Test setup

During the testing, the load was applied upward by a hydraulic jack through a steel plate (300 × 300 mm for the S1 and S2 series and 200 × 200 mm for the S3 series), which represented the column of a flat slab. The change in the size of the column for the S3 series was chosen to assure the punching shear failure. The slab was anchored to a strong laboratory floor using eight 42 mm Dywidag bars with a spherical element and a steel plate, which created a hinge restraint on the top of the slab. The deformation was measured using LVDT sensors located both beneath and on the top surface of the slab. In addition, the deformations were monitored using twelve analog deflection gauges and photogrammetry. However, the deformation measurements are not the subject of this article.

The slab rotations were measured on each of the four sides of the slab using manual inclinometers (see Fig. 3). At a level of 50 kN, which approximately corresponds to the self-weight of the slab, the specimen was leveled and stabilized. Therefore, the rotation curves (in Fig. 5) start at 50 kN.

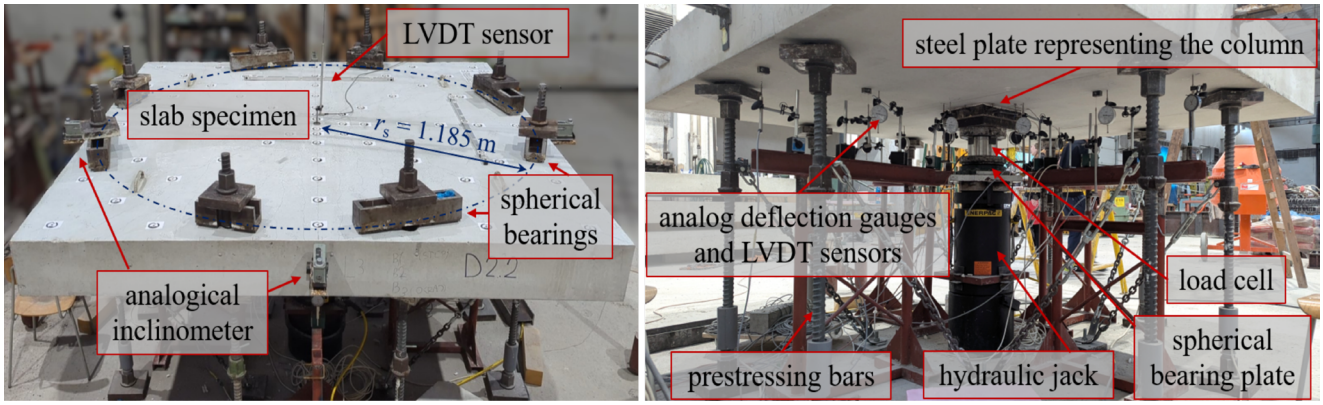


Fig. 3 *Test setup*
The distance between the column's axis and the line of the contraflexure of the radial bending moments was r_s = 1.185 m for every slab specimen in this test setup.

3 RESULTS OF THE EXPERIMENTS

All the slabs failed in punching, as shown in Fig. 4. Tab. 2 summarizes the punching shear resistance and rotations for the individual specimens. The slabs of the first series had a lower stiffness than those of the second series due to a lower flexural reinforcement ratio; therefore, they exhibited greater specimen rotations, which resulted in lower punching capacities.

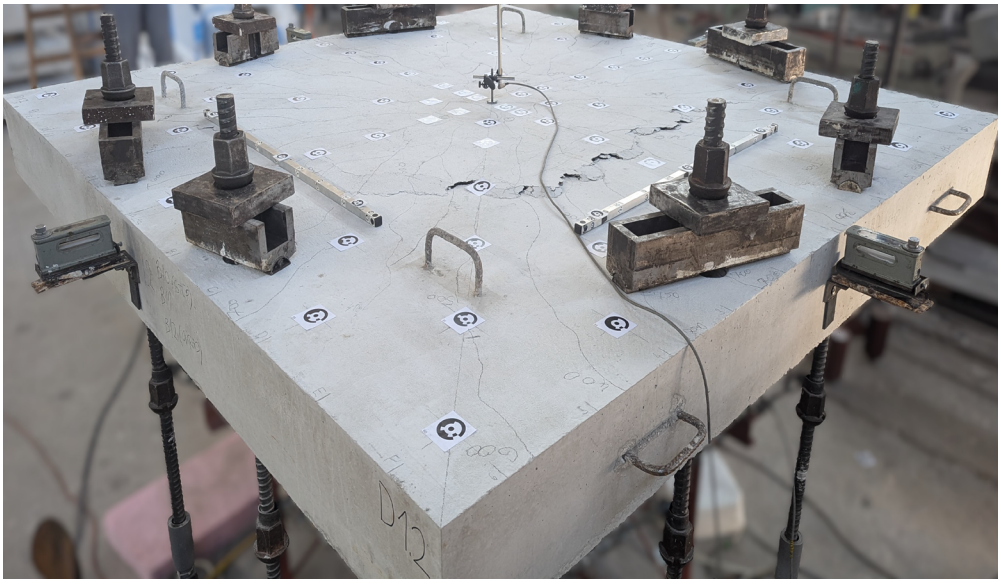


Fig. 4 *Slab S1.2 after failure*

Despite the higher reinforcement ratio, the slabs of the third series S3 achieved lower punching shear resistances due to the smaller column size. The change in the normalized punching shear resistance of all the slabs is described in (Fecko et al., 2025).

Tab. 2 *Results of the experiments of the punching shear resistance of the flat slabs*

Slab	d	ρ	f_{cm}	$V_{R.test}$	$\psi_{inclin,avg}$	$\psi_{def.g,avg}$
	[mm]	[%]	[MPa]	[kN]	[mm/m]	[mm/m]
S1.0	210	0.539	39.6	839	15.6	14.7
S1.2	213	0.531	33.4	847	13.3	13.1
S2.0	202	1.244	30.8	1000	10.0	11.0
S2.2	202	1.250	33.7	1035	9.5	10.3
S3.0	200	1.571	35.8	856	6.7	5.9
S3.2	199	1.579	35.9	905	7.2	6.6

The rotations of the slabs were obtained from inclinometer measurements and from the evaluation of the analog deflection gauges as the difference in the deflection of two adjacent points at a distance of 120 and 545 mm (in the case of series S1 and S2) and at a distance of 120 and 595 mm (in the case of the S3 series) from the face of the column (see Fig. 1). The rotation values were measured in load increments of approximately 50 - 100 kN each; therefore, the values at the failure load were determined by extrapolation. The last rotation measurement was a maximum of 1 loading step (approximately 50 kN) for all the slabs before failure. The rotations of specimen S2.2 for inclinometer L2 are reported only up to 400 kN due to a malfunction of the inclinometer. The load-rotation relationships are shown in Fig. 5.

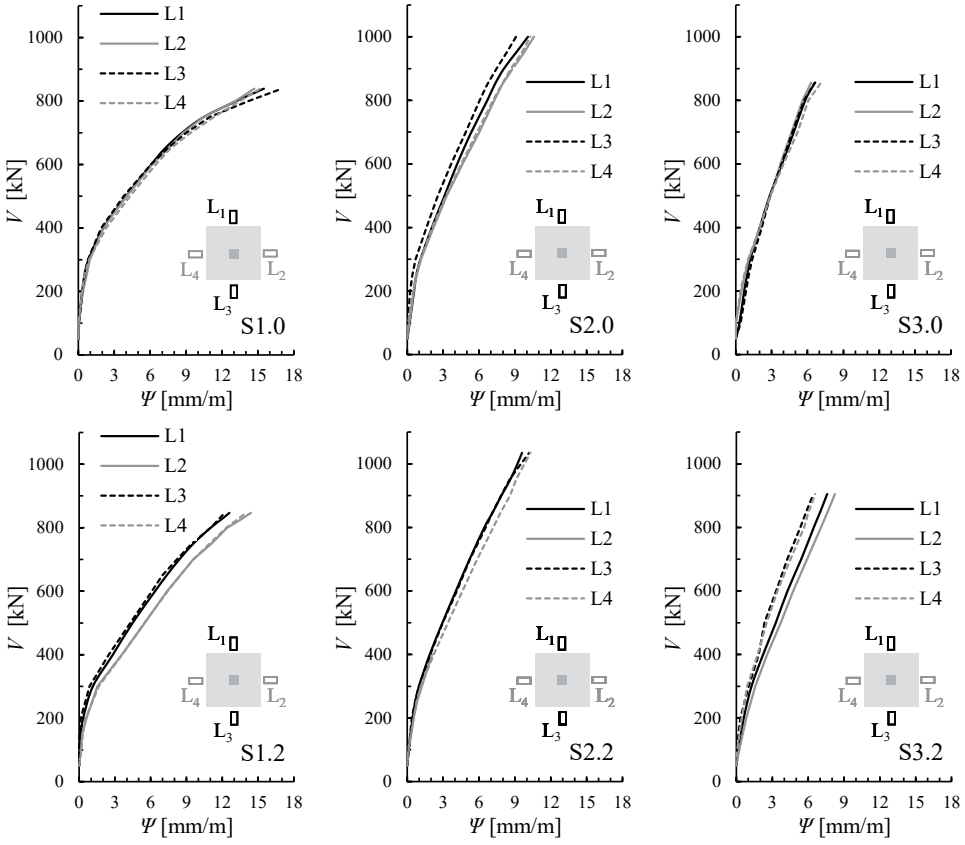


Fig. 5 *Load-rotation curves measured by inclinometers in four directions (inclinometers L1 and L3 are in the direction of the higher stiffness of the slab)*

The curves of the specimen rotations versus the increasing load reflect the different stiffnesses of the specimens due to the varying reinforcement ratios. The largest rotations were achieved by the slabs of the first series S1, which had the lowest reinforcement ratio; they reached approximately 14 mm/m. Conversely, the lowest rotations were recorded for the slabs of the third series S3, with values of approximately 6 mm/m according to the analogical inclinometers. The inclinometers showed very similar rotation values in all the directions measured.

Despite its higher modulus of elasticity, slab S1.0 exhibited larger rotations at failure than did slab S1.2, which was caused by the yielding of a large amount of the flexural reinforcement. In the remaining series, the slabs made with CNA and CRCA achieved similar rotations upon failure.

4 CRITICAL SHEAR CRACK THEORY (CSCT) AND MODEL CODE 2010

The Critical Shear Crack Theory (CSCT) is a mechanical model used for predicting the punching shear capacity of slab-column connections. The theory is based on the assumption that a critical shear crack develops near a column. The punching resistance is then provided by two primary mechanisms, i.e., the aggregate interlocking along the faces of the critical shear crack and the tensile strength of the concrete. Aggregate interlocking is highly dependent on the friction within the critical crack. This friction is governed by two main factors, i.e., slab rotation ψ and the maximum aggregate size $d_{g,max.}$ In slab rotation ψ, as the slab rotates, the crack widens, which reduces friction. Therefore, the friction and punching shear strength are inversely proportional to the slab rotation. In relation to the maximum aggregate size $d_{g,max,}$ with the larger aggregate size, the roughness of the interlocking surface increases, and thus directly influences the capacity for friction.

The relationship between the punching shear capacity $V_{R,c}$ (calculated according to formula (1) below ψ and the rotation ψ of the slab at the critical shear crack is given by the failure criterion. Muttoni (Muttoni and Ruiz, 2008) defined a hyperbolic failure criterion, which is expressed by the formula (2).

$$V_{R,c} = k_\psi \sqrt{f_c}\, b_0\, d_v \tag{1}$$

$$k_\psi = \frac{0.75}{1 + 15 \cdot \frac{\psi\, d}{d_g + 16}} = \frac{1}{1.333 + 0.625\, k_{dg}\, \psi\, d} \leq 0.6 \tag{2}$$

To enhance the reliability of the design model, the failure criterion (2) was later modified to use the 5% fractile, yielding formula (3), as described in Muttoni and Ruiz (2012). The Model Code 2010 model then adopted this criterion through the design formula (4).

$$k_\psi = \frac{1}{1.5 + 0.9 \cdot k_{dg}\, \psi\, d} \leq 0.6 \tag{3}$$

$$V_{Rd,c} = k_\psi \frac{\sqrt{f_{ck}}}{\gamma_C} b_0 d_v \tag{4}$$

where:

d_v is the effective depth of the slab for shear, usually $d_v = d$

b_0 length of the control perimeter at a distance $d_v/2$ from a column's periphery

k_{dg} factor accounting for the effect of the maximum aggregate size $d_{g,max}$ [mm], $k_{dg} = 32/(16 + d_{g,max})$

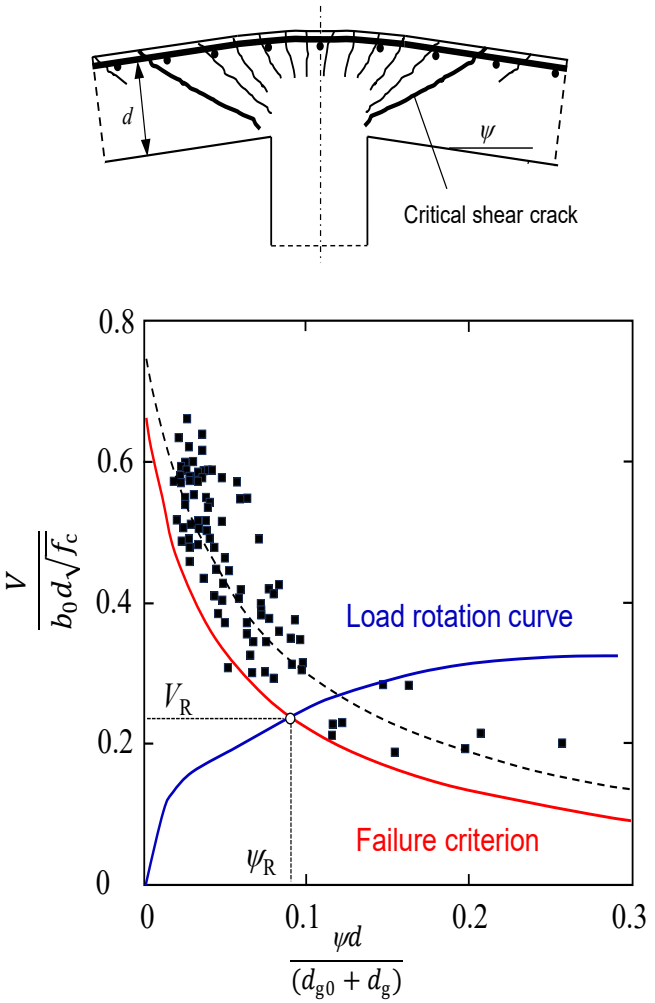


Fig. 6 *Critical Shear Crack Theory: critical shear crack on the flat slab (top) and the experimental results describing the failure criterion (Muttoni and Ruiz, 2008)*

Methods for the assessment of ψ are provided in Model Code 2010 (Fédération internationale du béton (fib), Model Code 2010 - final draft, 2012), and depend on the levels of approximation (LoA). Model Code 2010 determines the rotation of the slab (from a concrete load) at four levels of approximation, according to the required level of accuracy. In the first three levels of approximation, the rotation is determined by relation (5). Depend on the LoA, the relation (5) could be expressed as relation (6-8) listed in Tab. 3. This relation is based on a non-linear parabolic law. For LoA IV, a non-linear analysis must be used to determine ψ .

$$\psi = k_m \frac{r_s}{d} \frac{f_{yd}}{E_s} \left(\frac{m_{Sd}}{m_{Rd}}\right)^{1.5} \quad (5)$$

where:

- r_s is the distance measured from the axis of the column to the line of the contraflexure of the radial bending moments
- k_m factor depending on the level of approximation
- f_{yd} yield strength of the main flexural reinforcement
- m_{Rd} average design bending capacity of a slab per unit length
- m_{Sd} average design bending moments per unit length.

Tab. 3 *Determining slab rotation according to Model Code 2010 (MC10)*

Higher accuracy ↓ ↓ ↓	LoA I	$\psi = 1.5 \cdot \frac{r_s}{d} \frac{f_{yd}}{E_s} (1)^{1.5}$	(6)	lowest degree of accuracy, ratio m_{Sd} / m_{Rd} is considered as 1.0
	LoA II	$\psi = 1.5 \cdot \frac{r_s}{d} \frac{f_{yd}}{E_s} \left(\frac{m_{Sd}}{m_{Rd}}\right)^{1.5}$	(7)	$m_{Sd} = V_{Ed}/8$ (for axi-symmetric conditions)
	LoA III	$\psi = 1.2 \cdot \frac{r_s}{d} \frac{f_{yd}}{E_s} \left(\frac{m_{Sd}}{m_{Rd}}\right)^{1.5}$	(8)	linear elastic analysis can be used to determine r_s and m_{Sd}
	LoA IV	from non-linear analysis		highest degree of accuracy, non-linear analysis accounting for cracking and tension stiffening is used

5 PREDICTIONS OF THE PUNCHING SHEAR RESISTANCE

Two calculations were performed for both models. In the first approach, the punching capacities were calculated using experimentally measured rotations. The second approach was based on rotations determined using formula (8). LoA III was chosen for a higher degree of accuracy and, as a simplification, the design bending moments were the design bending moments were calculated as $m_{Sd} = V_{Rd}/8$; the evaluation was carried out with partial factor $\gamma_C = 1.0$.

Tab. 4 presents the rotations at failure of all the slabs obtained experimentally and those calculated in the predictions. It is apparent that the experimentally measured rotations were generally higher than those predicted by the CSCT and MC10.

Tab. 4 *Experimentally measured rotations (average of four directions) and predicted slab rotations at failure*

Slab	ψ [mm/m]			
	Inclinometers	Analog def. gauges	CSCT	MC10
S1.0	15.6	14.7	12.9	10.5
S1.2	13.3	13.1	12.0	9.8
S2.0	10.0	11.0	6.5	5.3
S2.2	9.5	10.3	6.7	5.5
S3.0	6.7	5.9	4.4	3.6
S3.2	7.2	6.6	4.5	3.7

Tab. 5 summarizes the results of the punching shear resistance obtained from the experiment and the predicted resistances according to CSCT and MC10. The safety of the results is verified by comparing the punching shear resistance from the experiments with the resistance calculated using the rotations measured in the tests and the rotations predicted.

Tab. 5 *Comparison of the experimental and predicted results*

Slab	$V_{R,test}$ [kN]	$V_{R,pred}$ [kN] ($V_{R,test}$ / $V_{R,pred}$)					
		$k_{\psi.CSCT,} \psi_{inclin.}$	$k_{\psi.CSCT,} \psi_{def.g.}$	$k_{\psi.CSCT,} \psi_{CSCT}$	$k_{\psi.MC10,} \psi_{inclin.}$	$k_{\psi.MC10,} \psi_{def.g.}$	$k_{\psi.MC10,} \psi_{MC10}$
S1.0	839	727 (1.15)	753 (1.11)	811 (1.03)	552 (1.52)	574 (1.46)	705 (1.19)
S1.2	847	741 (1.14)	748 (1.13)	785 (1.08)	568 (1.49)	574 (1.48)	683 (1.24)
S2.0	1000	792 (1.26)	755 (1.32)	956 (1.05)	620 (1.61)	588 (1.70)	835 (1.20)

Slab	$V_{R,test}$ [kN]	$V_{R,pred}$ [kN] ($V_{R,test}$ / $V_{R,pred}$)					
		$k_{\psi.CSCT}$, $\psi_{inclin.}$	$k_{\psi.CSCT}$, $\psi_{def.g.}$	$k_{\psi.CSCT}$, ψ_{CSCT}	$k_{\psi.MC10}$, $\psi_{inclin.}$	$k_{\psi.MC10}$, $\psi_{def.g.}$	$k_{\psi.MC10}$, ψ_{MC10}
S2.2	1035	849 (1.22)	849 (1.22)	987 (1.05)	667 (1.55)	638 (1.62)	862 (1.20)
S3.0	856	787 (1.09)	825 (1.04)	904 (0.95)	632 (1.36)	667 (1.28)	792 (1.08)
S3.2	905	762 (1.19)	789 (1.15)	899 (1.01)	609 (1.49)	633 (1.43)	788 (1.15)
Mean		1.18	1.17	1.03	1.50	1.50	1.18
Stand. deviation		0.061	0.105	0.045	0.083	0.148	0.055
CoV		0.052	0.090	0.044	0.055	0.099	0.047

The best agreement between the experimental and predicted punching shear resistances was achieved by predictions based on the CSCT with the rotations calculated at an average ratio $V_{R,test}/V_{R,pred}$ of 1.03 and the lowest CoV = 0.044. The remaining predictions of the punching shear resistance based on CSCT, with the rotations measured, showed a higher margin of safety at the 1.17 level. Furthermore, level. Furthermore, for Model Code 2010, the predictions using the slab rotations calculated, with an average value of 1.18 and a low coefficient of variance (CoV = 0.047), were closest to the experiments. The least accurate predictions were those based on Model Code 2010 with the rotations measured at 1.50. Comparisons of the results in Tab. 5 are shown in Fig. 7.

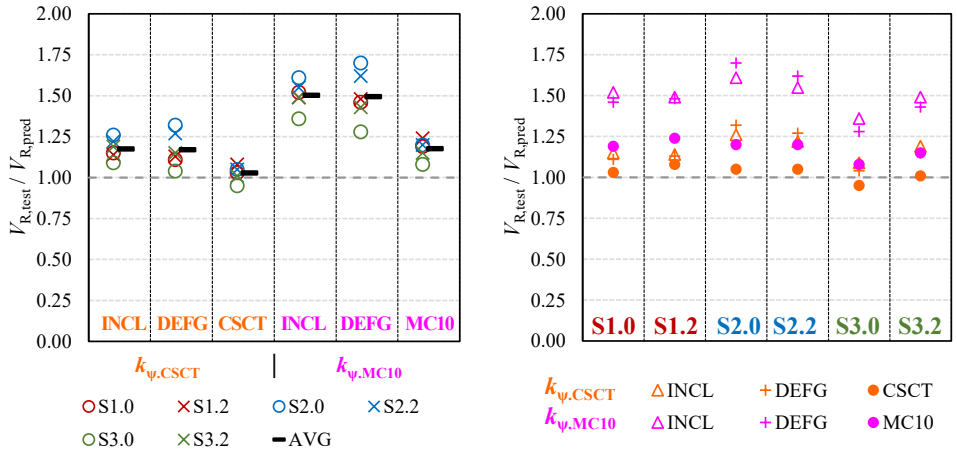


Fig. 7 *Comparison of the prediction results from Tab. 5 according to: the rotations considered (left) and the individual slabs (right); INCL – analogical inclinometers, DEFG – analog deflection gauges*

When comparing the ratio $V_{R,test}/V_{R,pred}$ for the individual slabs, it cannot be clearly concluded that the slabs from CNA achieved a more accurate prediction. Therefore, the analyses confirmed the applicability of the CSCT and MC10 models for predicting the punching resistance of slab-column connections cast from concrete with CRCA. The results presented are in accordance with the conclusions drawn by (Fecko et al., 2025).

6 CONCLUSION

The article presents the results from the experimental tests on three series of full-scale flat-slab specimens cast with concrete containing coarse natural aggregate (CNA) and with a 100% replacement of CNA by coarse recycled concrete aggregate (CRCA). The punching shear resistance test results are compared with the predictions. The main conclusions of this article are as follows:

- The experimentally determined material properties of the concrete confirmed the effect of CRA on the modulus of elasticity, i.e., across all the series, the lowest modulus of elasticity was obtained for the concrete with a 100% replacement of CNA.
- The experimental tests confirmed the applicability of models based on the CSCT for predicting the punching shear capacity of the slab-column connections cast from the concrete containing CRCA.
- The predictions of the punching shear capacity using critical shear crack theory (CSCT) confirmed the negligible effect of the CRCA on the punching shear resistance when both experimentally measured and predicted rotations were used. However, more experiments are required to confirm this conclusion.
- The most accurate results were obtained with the original CSCT model using a hyperbolic failure criterion and rotations calculated when CoV = 0.044, with a mean value of 1.03.
- The punching shear resistances according to MC10 showed a higher level of safety than CSCT for the slabs made of concrete with both CNA and CRCA, with a mean value of 1.18; the CoV = 0.047.
- In this experimental program, using experimentally measured slab rotations yields more conservative punching shear resistance results than using the rotations predicted.

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AI tools were used for language editing/ grammar improvement; the authors retain full responsibility for the content.

REFERENCES

ELSAYED, MAHMOUD; TAYEH, BASSAM A.; MOHAMED, MAI; ELYMANY, MAGDY AND MANSI, AHMED H. Punching shear behaviour of RC flat slabs incorporating recycled coarse aggregates and crumb rubber. Journal of Building Engineering, vol. 44 (2021), 103363. Available at: https://doi.org/10.1016/j.jobe.2021.103363

FECKO, TADEÁŠ; KORMOŠOVÁ, ĽUDMILA; RAMOS, ANTÓNIO P. AND HALVONIK, JAROSLAV. Punching shear behaviour of full-scale slab-column connections cast from concrete with coarse recycled aggregate. Engineering Structures, vol. 345 (2025), 121460. Available at: https://doi.org/10.1016/j.engstruct.2025.121460

FÉDÉRATION INTERNATIONALE DU BÉTON (FIB), *Model Code 2010 - Final draft, Vol. 1 (2012), Bulletin 65, Lausanne, Switzerland. DOI: doi.org/10.35789/fib.BULL.0065*

FERREIRA, MAURICIO P.; DAMASCENO, IANA I. R.; PEREIRA FILHO, MANOEL J. M.; LIMA NETO, AARÃO F.; OLIVEIRA, MARCOS H. AND RIBEIRO JÚNIOR, JAYRON A. *Effect of recycled concrete aggregates on the punching strength of slab-column connections without shear reinforcement.* Journal of Building Engineering, vol. 95 (2024), 110174. Available at: https://doi.org/10.1016/j.jobe.2024.110174

LEELATANON, SATJAPAN; IMJAI, THANONGASAK; SETKIT, MONTHAIN; GARCIA, REYES AND KIM, BOKSUN. *Punching Shear Capacity of Recycled Aggregate Concrete Slabs. Buildings, vol. 12(10) (2022), 1584. Available at: https://doi.org/10.3390/buildings12101584*

MUTTONI, AURELIO AND RUIZ, MIGUEL F. *Shear Strength of Members without Transverse Reinforcement as Function of Critical Shear Crack Width.* ACI Structural Journal, vol. 105 (2008), pp. 163-172. DOI: 10.14359/19731

MUTTONI, AURELIO AND RUIZ, MIGUEL F. *The levels-of-approximation approach in MC 2010: applications to punching shear provisions.* Structural Concrete, Ernst & Sohn, Germany, vol. 13 (2012), No. 1, pp. 32-41. Available at: https://doi.org/10.1002/suco.201100032

PURCHASE, CALLUN KEITH; AL ZULAYQ, DHAFER MANNA; O'BRIEN, BIO TALAKATOA; KOWALEWSKI, MATTHEW JOSEPH; BERENJIAN, AYDIN; TARIGHALESLAMI, AMIR HOSSEIN AND SEIFAN, MOSTAFA. *Circular Economy of Construction and Demolition Waste: A Literature Review on Lessons, Challenges, and Benefits.* Materials. vol. 15 (2022), no. 1. Available at: https://doi.org/10.3390/ma15010076

REIS, NUNO; DE BRITO, JORGE; CORREIA, JOÃO R. AND ARRUDA, MÁRIO R. T. *Punching behaviour of concrete slabs incorporating coarse recycled concrete aggregates.* Engineering Structures, vol. 100 (2015), pp. 238-248. Available at: https://doi.org/10.1016/j.engstruct.2015.06.011

SAHOO, SAUMYARANJAN AND SINGH, BHUPINDER. *Punching shear capacity of recycled-aggregate concrete slab-column connections.* Journal of Building Engineering, vol. 41 (2021). Available at: https://doi.org/10.1016/j.jobe.2021.102430

XIAO, JIANZHUANG; WANG, WAN; ZHOU, ZHENGJIU; TAWANA, MATHEWS M *Punching shear behavior of recycled aggregate concrete slabs with and without steel fibres.* Frontiers of Structural and Civil Engineering, vol. 13 (2019), pp. 725-740. Available at: https://doi.org/10.1007/s11709-018-0510-6