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PUNCHING SHEAR RESISTANCE OF CONTINUOUS RC SLAB COMPARED TO EXPERIMENTAL SPECIMENS

Šarvaicová S.*, Borzovič V.**

Abstract: *This paper deals with the comparison of the shear resistance of the continuous flat slab compared to the isolated test specimens commonly used to determine shear resistance models. In both cases the shear resistance is determined on the basis of a non-linear analysis. The difference in results is due to the membrane forces and the possibility of redistribution of bending moments in the case of a continuous flat slab, which cannot occur in the case of isolated specimens. The work focuses on the flat slab with thickness of 200 mm supported by an elongated column (150 x 900 mm) and analyzing the influence of the ratio of adjacent slab span* l_x/l_y.

Keywords: Punching shear resistance, Flat slabs, Isolated test specimens, Membrane actions.

1. Introduction

Flat slab structures are among the most widespread structural solutions of buildings. From the design point of view, the connection of the local support and the slab is important. Concentrated shear stresses may be accompanied by brittle, sudden failure. That is why it attracts the attention of various scientific works. They are often focused on developing new ways of shear reinforcement (Mečár et. al., 2019) or refining and calibrating design models that often have an empirical character (Eurocode 2).

The experimental results on the basis of which the punching shear resistance of reinforced concrete flat slab were derived (Eurocode 2, Model Code 2010) were determined on isolated specimens. In these experiments, several aspects that affect the shear resistance could not be taken into account. It is mainly about considering the effect of membrane actions and redistribution of bending moments (Fig. 1). These effects can significantly increase the value of shear resistance. On the other hand, the shrinkage of concrete slightly reduces the shear resistance of continuous flat slab depending on the size of the longitudinal reinforcement ratio.

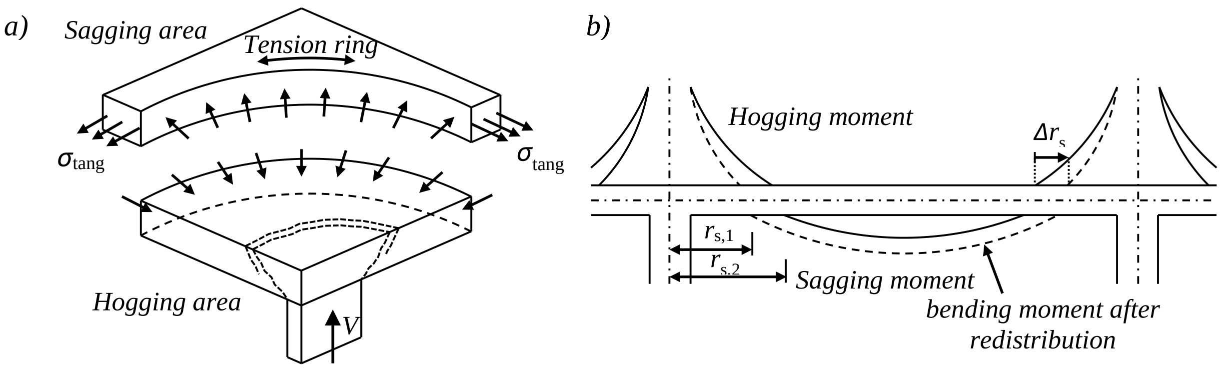

Fig. 1: a) Membrane action of continuous flat slab; b) redistribution of bending moments.

The beneficial effect of membrane action on continuous slabs (Belletti et. al., 2019), bridge deck slabs (Taylor el al., 2007) or steel fiber reinforced slabs (Di Prisco et al., 2016) was observed and analyzed by

* MSc. Simona Šarvaicová: Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11; 810 05, Bratislava; SK, simona.sarvaicova@stuba.sk

** Assoc. Prof. Viktor Borzovič: Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11; 810 05, Bratislava; SK, viktor.borzovic@stuba.sk

several methods. Membrane action can be evaluated by using rigid plastic approach, yield line methods or by finite element methods. Recently, it has been found (Belletti et. al., 2019) that the effect of membrane action can be up to 5 ÷ 30 % depending on the reinforcement ratio and slab geometry.

2. Eurocode 2

The prediction according to EN 1992-1-1 was used to verify the punching shear resistance of specimens obtained by numerical methods. The shear resistance in flat slabs without shear reinforcement is ensured by several aspects. It mainly depends on the aggregate interlock in shear crack, compressed concrete area under neutral axis and longitudinal reinforcement. These facts are considered in the empiric formula which determines the punching shear resistance of a slab according to EC2.

$$V_{\mathrm{Rd,c}} = \frac{C_{\mathrm{Rk,c}}}{\gamma_{\mathrm{C}}} k \left(100\, \rho_{1} f_{\mathrm{ck}}\right)^{1/3} u_{1} d,$$

where: $C_{\mathrm{Rk,c}}$- empirical factor [MPa];

γ_{C} - partial safety factor, $\gamma_{\mathrm{C}} = 1.5$ [-];

k- the size factor, $k = 1 + (200\ [\mathrm{mm}]/d)^{0.5} \leq 2.0$ [-];

ρ_{l}- reinforcement ratio, $\rho = (\rho_{x}\rho_{y})^{0.5}$ [-];

f_{ck}- characteristic concrete compressive cylinder strength [MPa];

u_{1}- shear-resisting basic control perimeter at distance of $2d$ from the face of a column [mm];

d- effective depth [mm].

3. The non-linear analysis

The specimens were modeled in program Atena. The slab models consist of 3D elements using brick mesh. Because the analysis is time-consuming, only a quarter of the specimen was modeled using symmetry conditions. In the first step, an appropriate finite element mesh and the necessary number of iterations in one loading step were determined on the model of the experimental specimen. (Červenka el al., 2018) recommends using a mesh that corresponds to splitting the specimen into 4 to 6 elements along the slab thickness. Two types of brick mesh with side of 0.05 m (4 elements per slab thickness) and 0.04 m (5 elements) were chosen. Together six models of experimental isolated specimen were analyzed and the results are presented in the chapter 3.3.

3.1. Test specimens

The aim of this numerical analysis is to compare the punching shear resistance of isolated slabs and continuous flat slabs. Isolated slabs are loaded with concentrated forces and continuous slabs with uniform area load. Test specimens with thickness of 0.2 m are the subject of the analysis. The slab specimen has the dimensions 2.5 × 2.5 m (Fig. 2). It is supported by a column with rectangular cross-section dimension of 0.15 × 0.90 m, that means ratio $c_{\max} / c_{\min} = 6$. It represents planned experimental laboratory campaign. The specimen reaches maximum reinforcement ratio $\rho_{\mathrm{l}} = 1.26$ % using bars with 16 mm diameter spaced evenly by 100 mm in both directions in the area above the column. Otherwise it is reinforced with 10 mm bars spaced by 100 mm. The compression bottom face of the slab is reinforced with 10 mm bars spaced evenly by 200 mm and it is designed without transverse reinforcement. The nominal effective depth (d) was 159 mm.

3.2. Loading conditions

The experimental specimen models were loaded with concentrated forces as it is shown in Fig. 2c. Each load step means a force increase of 50 kN, that is 12.5 kN per modeled quarter of the specimen. Loading case XY represents a uniform load distribution that corresponds to the same 5.1 m span in both directions. Loading case X means the main load coming from the X direction (approximately two thirds of the total load), which corresponds to the spans of adjacent fields $l_{\mathrm{eff,x}} = 7.22$ m and $l_{\mathrm{eff,y}} = 3.6$ m. The opposite is the Loading case Y where two thirds of the load comes to the support from the Y direction.

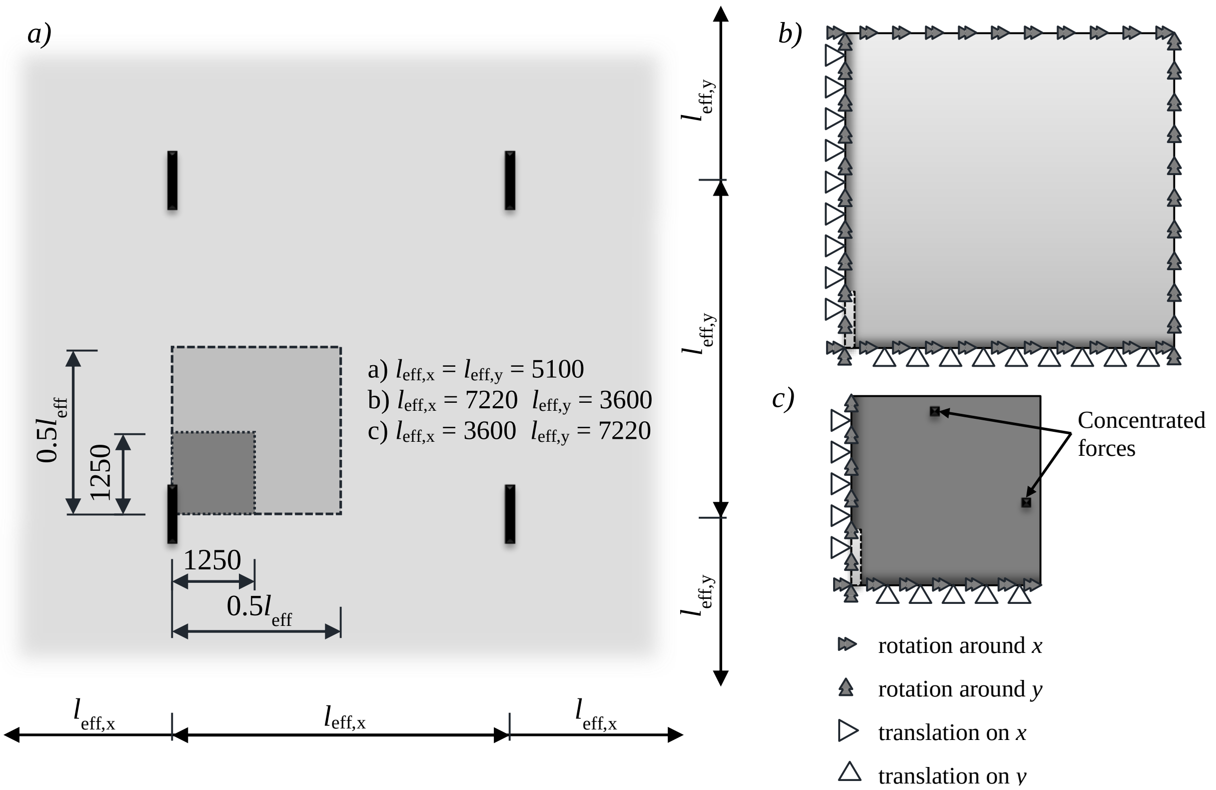

Fig. 2: a) Geometry of isolated and continuous slab models; b) boundary conditions of continuous flat slab; c) boundary conditions of isolated slabs.

Models which represents the whole quarter of a span of continuous flat slab were loaded by area load with value $f_d = 1.92$ kN/m^2. By multiplying this value by the loading area of the support, an equivalent force of 50 kN per one loading step is obtained as in previous models.

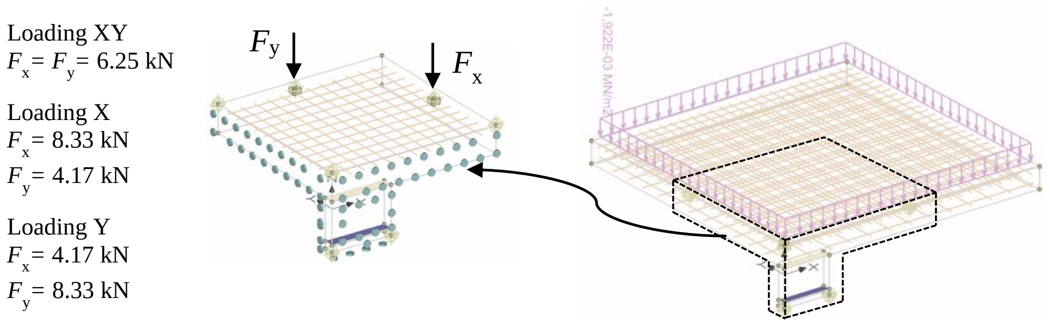

Fig. 3: a) Loading conditions of isolated and continuous flat slab.

3.3. Test results

In general, models with dense finite element mesh get more accurate results. For both mesh divisions, three evaluations were made with various number of iterations. The Fig. 4a shows that the results do not differ significantly when the iteration number increases above sixty. This model also demonstrates the closest match of the shear resistance value to evaluation according to EC2 model and therefore models with sixty iterations per one loading step and brick mesh with a side of 0.04 m will be considered in numerical analysis.

Fig. 4b shows the relationship of the increasing loading force on displacement measured in the distance 1.2 m from the column center in order to compare isolated and self-confined continuous models. The self-confined slabs achieve 37 ÷ 43 % higher punching shear resistance than isolated slabs. There are several factors which influence the value of punching shear resistance of the slabs. Mainly, these effects are moments redistribution and membrane actions which are not considered in the isolated models. It is difficult to discern what share the individual effects have on the punching shear resistance.

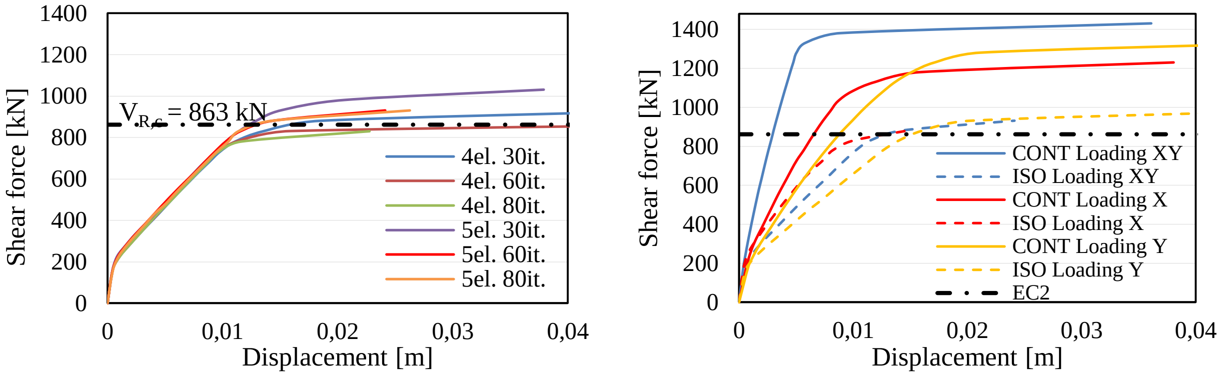

Fig. 4: a) The dependence of the increasing force on displacement measured on isolated models; b) the comparison of the dependence of the increasing force on displacement between isolated and self-confined models.

Tab. 1: Punching shear resistances obtained from Atena.

	$V_{R,c,EC}$ [kN]	$V_{R,ATENA}$ [kN]		$V_{R,c,CONT}$ / $V_{R,c,ISO}$ [-]
		Isolated slab model $V_{R,c,ISO}$	Continuous flat slab $V_{R,c,CONT}$	
Loading XY	863	930	1380	1.48
Loading X		880	1180	1.34
Loading Y		930	1330*	1.43
Note: * bending failure occurred in continuous slab				

4. Conclusions

This article deals with the influence of various factors on the punching shear resistance of the flat slabs. The most important influencing factors are the redistribution of bending moments and membrane actions. In real conditions the effect of membrane actions is reduced by shrinkage, but this was not the subject of this analysis due to the fact that it is a comparison with experimental specimens. Based on non-linear analysis, the following conclusions were made:

1. The effect of membrane action was confirmed and it reaches up to 34 ÷ 48 % beneficial influence.
2. The magnitude of influence of the membrane action could not be confirmed in Loading case Y, as the continuous slab led to bending failure.

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