Parametric structural computational study of flat slabs under punching shear stress

Orlando M. L. Almeida[1], Leandro M. Trautwein[1], Thomaz E. T. Buttignol[1], Luiz C. Almeida[1]

[1]*School of Civil Engineering, Architecture and Urban Design, University of Campinas*
Saturnino de Brito 224, 13083-889, São Paulo, Brazil
orlandomlalmeida@gmail.com, leandromt@unicamp.br,
thomazb@unicamp.br, lca1955@unicamp.br

Abstract. The system composed of flat slabs and columns offers advantages compared to the traditional system of slab-beam system such as increased internal space and reduced formwork usage. This structural system has been the object of study over the last few decades due to the complexity of its structural behavior, particularly the punching shear phenomenon. It is a brittle failure mechanism that occurs in the slab-column connection, induced by high shear forces. Thereby, the study of punching shear is crucial due to structural sudden failure characteristic. Over the last decades, the relevance of parameters that influence the performance of flat slabs has been investigated, such as slab thickness, longitudinal reinforcement ratio and column size. The use of parametric computational analyses allows the use of optimization procedures to improve the efficiency of the system and further investigate the relevant parameters affecting punching shear. Therefore, this research employs three-dimensional parametric structural computational models to analyze the impact of slab thickness and column size in the phenomenon of punching shear. The models are based on a centrally located column in a slab panel measuring 250 x 250 mm. The space of solutions for the parameters under analysis are examined to find the optimal range for their use.

Keywords: reinforced concrete, flat slabs, parametric structural design, punching shear.

1 Introduction

Flat slab systems offer more agility of the construction as it reduces the number of formworks when compared to the slab-beam system. The system also provides comfort to the user due to its larger ceiling height and more flexibility.

According to Ferreira [1], although the system of flat slabs shows evident benefits, there are some characteristics that should be considered in the analysis. For example, the slabs displacement needs greater attention due to the decreased floor stiffness. Moreover, failure could occur due to punching shear, which is caused by high local shear stresses in the slab-column connection. It is the most critical aspect of the system once the punching failure can be propagated and induce the structure collapse.

According to Silva [2], the structural design and the definition of the element's dimensions are carried out by the engineer and evolves manual work, involving most of the times, poor visualization or incomplete control of the field of solution.

Côco Júnior [3] states that the use of algorithms can provide evident benefits to the workflow. It allows greater focus on processes due to the rationalization of certain work execution, transforming intuitive decisions into explicit logic rules. Moreover, Felippe [4] affirms that, due to advances in computer science, requirements for better efficiency of buildings boosted the development of simulation methods through generative, parametrization and optimization processes.

In agreement with that, Silva [5] states that the structural design process can be significantly enhanced by a real time digital model with input variable parameters, which increases the user interactivity and visualization of the possible solutions. These benefits were observed by Felippe [4], who states that visualizing the space of solutions during the analysis allows a better comprehension of the subject of study and improved work efficiency. According to Lucarelli [5], the use of these tools can provide greater effectiveness when solving engineering problems.

As stated by Wortmann [6], optimization processes based on simulations are able to define correlations between variables and performance goals. This process often reveals complex and non-linear relationships between the analyzed parameters. To this end, the structural analysis requires a digital model. According to Brown et al. [8], Grasshopper, a graphical algorithm integrated in Rhinoceros (a computer-aided design software), can be described as an environment for parametric designing tools (add-ons). It includes native add-on solvers for optimization, for example, Galapagos.

In accordance with Silva [2], the genetic algorithm Galapagos controls parameters for a specific optimization. By means of supplementary codes, the process data can be collected, allowing the generation of graphics for a correlation analysis. Grasshopper, although is not supposed to replace other tools, can assist usual building software, especially at the stages of the design concept.

Additionally, Felippe [4] observed great benefits of Grasshopper in the parametric simulation considering two hundred possible scenarios where the processing time decreased from 4 hours to 10 minutes. The author also states that even considering the complexity of the algorithm construction, the parametric simulation enabled the analysis of the space of possible solutions more efficiently compared to traditional methods.

Thus, this research is aimed to construct a parametric model for flat slabs to analyze the contribution of the slab thickness and column width on the punching shear capacity. An optimization procedure, using Galapagos, is performed to check the amount of concrete spent for each scenario.

2 Methodology

The parametric digital model was built on the Rhinoceros through the plug-in Grasshopper. The general workflow is as follows: initial data, geometry design, punching shear evaluation, optimization and finite element modeling.

2.1 Initial data and geometry design

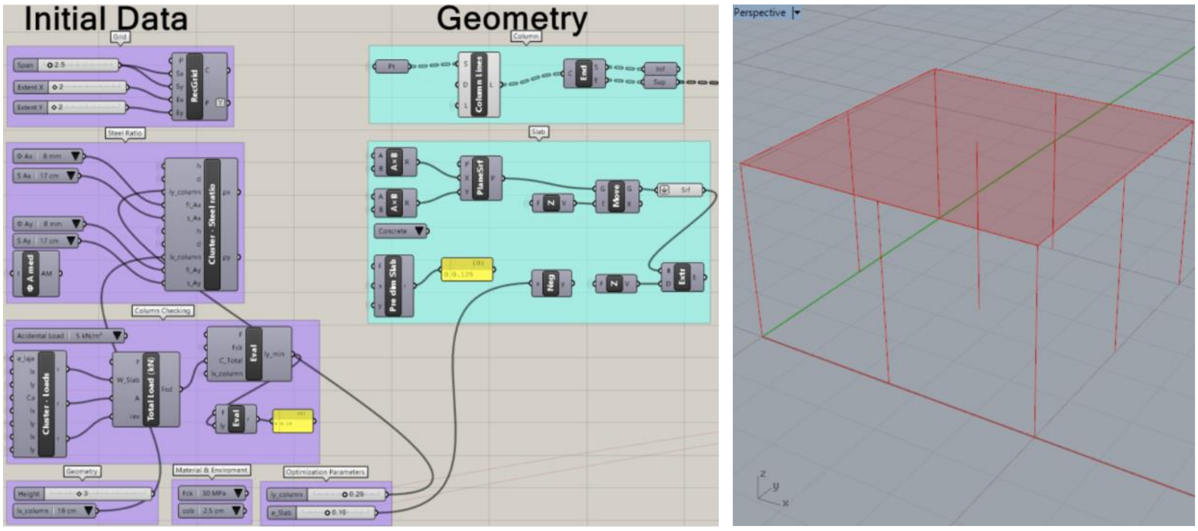
The geometric parameters, materials properties and loads applied are defined in the digital model. The model was composed by a grid of columns and the flat slab. The object of study is the central column of the grid and the slab influence area above it. The main model properties are shown in Tab. 1.

Table 1. Initial Data

Material & Loads		Geometry & Dimensions	
f_{ck}	30 MPa	Ceiling Height	3,0 m
Live load	5 kN/m²	Span	2,5 m
Ceramic floor	1 kN/m²	l_x (column)	19 cm
Φ As	8 mm	l_y (column)	19 cm - 40 cm
S As	17 cm	e (slab)	7 cm - 15 cm

All parameters were fixed, except the column width in y direction (l_y) and the slab thickness (e), which vary as shown in the Tab. 1 and are going to be discussed latter. The steel ratio was considered the same both x and y direction.

Then, the geometries were created based on the initial data. It is composed of vertical lines to represent the columns and a surface to represent the slab. The Grasshopper general layout and the geometry on Rhinoceros can be observed on Fig. 1.



a. b.

Figure 1. Initial data and geometry: a. Grasshopper, b. Rhinoceros

2.2 Punching shear evaluation

The main goal of the study is to understand the tendency of the combination of slab thickness and column dimensions in order to mitigate the volume of concrete. The dimensions must achieve the punching requirements [9]. The shear strength in the boundaries C and C' was evaluated according to the ABNT NBR 6118 (2014). The boundaries of C and C' are shown in Fig 2.

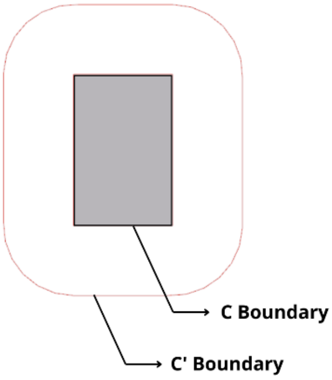


Figure 2. Boundaries C and C'

The analyzed column is in the center of the slab. Therefore, there is no bending moment caused by eccentricity.

The C boundary stresses were checked following the eq. (1):

$$\tau_{Rd2} = 0.27\left(1-\frac{f_{ck}}{250}\right)f_{cd} \geq \frac{F_{Sd}}{u_C.d} = \tau_{Sd}. \tag{1}$$

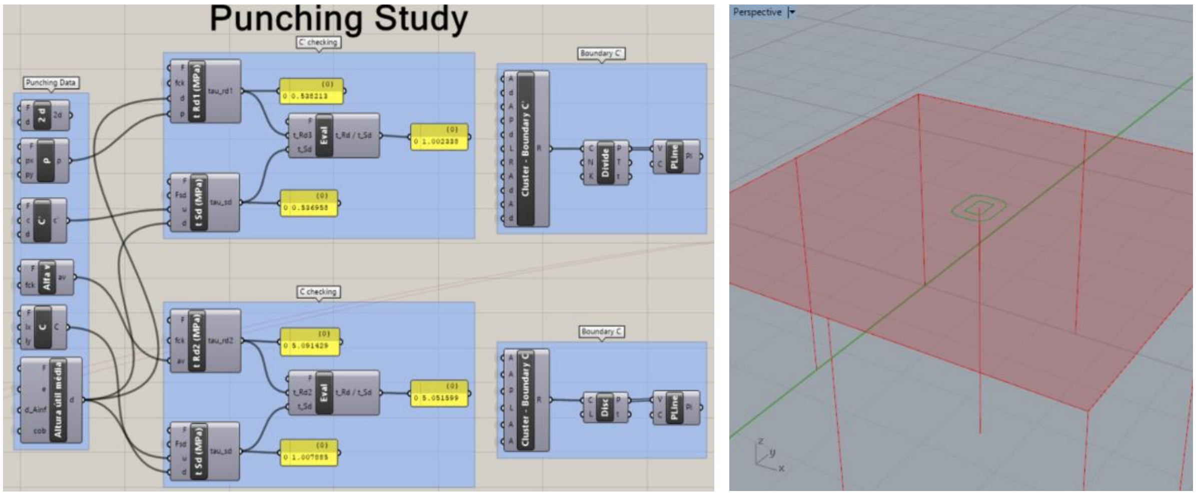
Where: τ_{Rd2} and τ_{Sd} represent, respectively, the shear stress capacity and the applied shear stress; u_c describes the perimeter of the C boundary.

The C' boundary shear capacity was evaluated according to the eq. (2):

$$\tau_{Rd1} = 0.13\left(1+\frac{20}{d}\right)(100\,\rho\, f_{cd}) \geq \frac{F_{Sd}}{u_{C'}.d} = \tau_{Sd}. \tag{2}$$

Where: d describes the slab's usable height; ρ is the average of steel ratio in the x and y directions along a specified perimeter.

The punching evaluation was performed through the ratio of the shear stress strength and applied stresses. The algorithm for punching analysis is shown in Fig. 3.



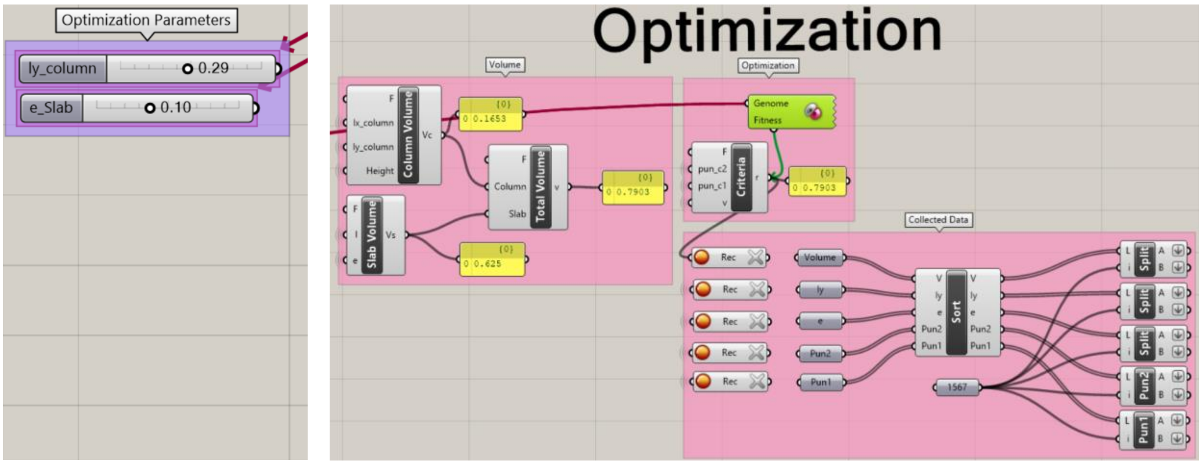
a. b.

Figure 3. Punching check and boundary: a. Grasshopper, b. Rhinoceros

2.3 Optimization

After the punching evaluation, the optimization process was carried out. Two parameters for the optimization were selected: the column width in y direction and the slab thickness. The parameters were optimized with respect of the concrete volume of the column/slab influence area. The punching evaluation considers both perimeters and separate the acceptable results from the unacceptable results. The filter allowed to link the unacceptable results to the cause of the failure, that is, due to the C boundary or C' boundary.

The optimization was performed using the Grasshopper add-on Galapagos. The parameters were analyzed with respect of punching and concrete volume efficiency. The optimization step is shown in Fig. 4.



a. b.

Figure 4. Optimization process a. Parameters, b. Criteria

The collected data was imported on Origin Lab for the analysis. In parallel, a finite element model was developed using the Grasshopper add-on Karamba 3D. The model consisted, respectively, of beam and shell elements for the columns and slab. The software performed a linear analysis and the displacement on the slabs and maximum stresses on the columns were observed.

3 Results

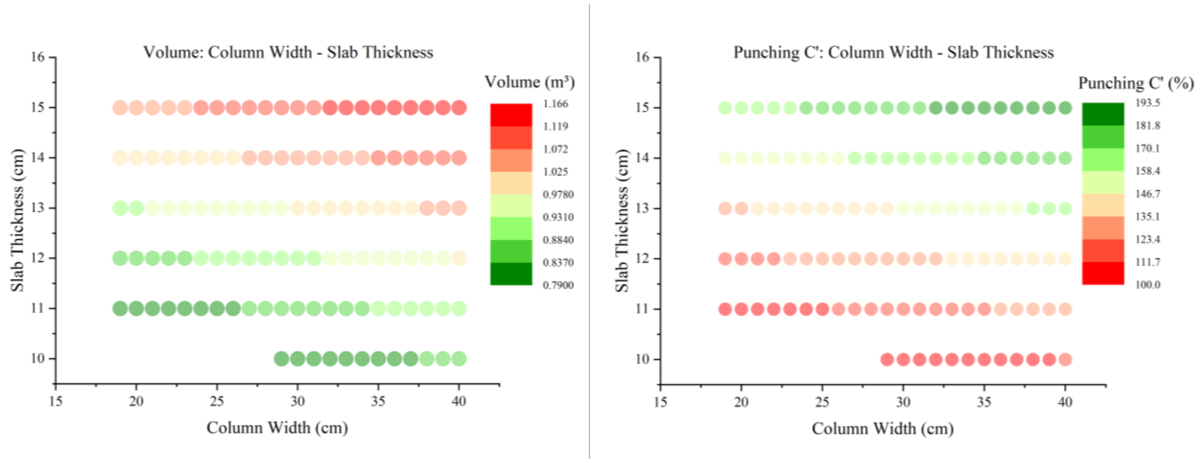
The flat slab optimization, considering the conditions previously mentioned, calculated the concrete volume efficiency ranking, as shown in Tab. 2.

Table 2. Optimization best results

Column Width cm	Slab Thickness cm	Concrete Volume m³	Punching C' %
29,0	10,0	0,7903	100,2
19,0	11,0	0,7958	103,7
30,0	10,0	0,7960	101,3
20,0	11,0	0,8015	104,9
31,0	10,0	0,8017	102,5

It was observed, after the data analysis, that the punching over the C boundary was on the safe side. Therefore, the results consider only the C' boundary. The slab column configuration has multiple options for the most economic results. These possibilities allow the selection of the structure dimensions under different constrains, considering the work conditions. The distribution of the parameters and the concrete volume does not seem to be predictable due to the complexity of the punching shear phenomenon. The results of the analyses ensures the relevance of the computational tools to assist in solving problems of this nature.

The colormap diagram for the volume and punching efficiency can be observed on the Fig. 5.



a. b.

Figure 5. Parameters Efficiency a. Volume, b. Puncture

The data only includes accepted configurations. The minimum punching factor is close to 100%, which is very good from an efficiency perspective. However, higher percentages indicate the system shear strength has a higher load capacity. Analyzing the volume efficiency, the data indicates that there is a relation between the column width and the slab thickness. The pattern shows the best system efficiency is achieved when the diagram values move from top to bottom and from right to left. Furthermore, the punching efficiency shows that the slabs with less than 10 centimeters thickness fail under the applied shear stresses.

The Karamba 3D modeling for the optimum configuration is shown in Fig 6.

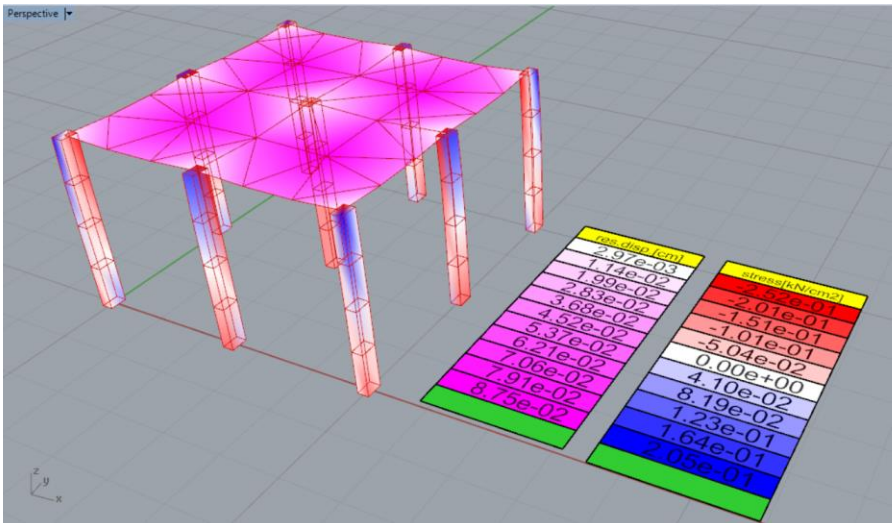


Figure 6. Karamba 3D Optimized Structure

As mentioned by Ferreira [1], the displacement should be closely observed. For the selected configuration, the displacement was very small compared to the stablished limit in ABNT [9]. The design code recommends, for a 2.5 meter span, an equivalent displacement of 1 cm, while the maximum displacement observed is 0.0875 cm.

4 Conclusions

Considering the range of the parameters analyzed, the results for the slab structural analysis were not obvious. As shown in Tab. 2, the column width, slab thickness and the punching factor does not follow a clear pattern related to the concrete volume. This indicates that it is unlikely to achieve the best results without testing different scenarios. Thus, the optimization procedure can improve the structure efficiency.

The parametric generation has positive impact on the process control by the user, as it facilitates the user learning on the process. The parametric algorithm enhances significantly the work production, since any modification of the model is made very quickly and with real time visualization.

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] M. de P. Ferreira, Punção em lajes lisas de concreto armado com armaduras de cisalhamento e momentos desbalanceados, Universidade de Brasília, 2010.
[2] F.T. da Silva, Modelo paramétrico de pórticos em concreto armado com dimensionamento otimizado: uma proposta de ferramenta de projeto para as fases iniciais de concepção estrutural, Ambiente Construído, 2018. 193–210. https://doi.org/10.1590/s1678-86212018000100216.
[3] V.H. Côco Júnior, G. Celani, Algoritmização do projeto arquitetônico em BIM: uma aplicação na indústria de banheiros pré-fabricados, Gestão & Tecnologia de Projetos, 2021. https://doi.org/10.11606/gtp.v16i2.181038.
[4] A.R. Felippe, L.N. Moraes, R.W. Fonseca, F.O.R. Pereira, Modelagem paramétrica para simulação do desempenho da iluminação natural e termo-energético da edificação, in: XIX Congresso Da Sociedade Ibero-Americana de Gráfica Digital (SIGRADI), 2015.
[5] F.T. da Silva, Concepção estrutural integrada à arquitetura auxiliada pela inteligência artificial, Gestão & Tecnologia de Projetos, 2022. https://doi.org/10.11606/gtp.v17i3.185781.

[6] C. de C. Lucarelli, J.C. Carlo, A.C.P. Martínez, Parameterization and solar radiation simulation for optimization of a modular canopy, PARC Pesquisa Em Arquitetura e Construção, 2019. https://doi.org/10.20396/parc.v10i0.8653371.
[7] T. Wortmann, OPOSSUM Introducing and Evaluating a Model-based Optimization Tool for Grasshopper, in: Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), 2017.
[8] N.C. Brown, V. Jusiega, C.T. Mueller, Implementing data-driven parametric building design with a flexible toolbox, Autom Constr, 2020. https://doi.org/10.1016/j.autcon.2020.103252.
[9] Brazilian Association of Technical Standards – ABNT (Associação Brasileira de Normas Técnicas), NBR 6118 - Projeto de estruturas de concreto - Procedimento, 2014.