
# Membrane action in reinforced concrete flat slabs

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## ABSTRACT

Membrane action can be considered as a defense mechanism of the progressive collapse of a reinforced concrete flat plate system. The compressive forces strengthen and stiffen the slab allowing it to fail at a much higher load. Then, the slab snaps through and the large deflections create a tensile membrane where the reinforcement resists loading resulting to a secondary mechanism capable to resist a progressive collapse. The study presents nonlinear finite element analysis (FEA) of an interior slab-column connection using shell elements and the rebar layer definition for reinforcement. Concrete is simulated with the concrete damaged plasticity model offered in ABAQUS software. The compressive membrane action effect is accounted using different boundary conditions to restrain against in-plane motions. The results provide valuable information on the membrane action mechanism in a slab-column structure and offer a simple and applicable model that can be considered for parametric studies on different type of slab-column connections.

Keywords: concrete slabs, membrane action, finite element analysis, continuous slabs.

## INTRODUCTION

Punching shear is a failure mode observed in slab-column connections within concrete structures and can cause immense damage in the event of its occurrence [1]. Compressive membrane action is the development of internal stresses within slabs when horizontal restraint is provided. Membrane action provides a significant increase in the resistance against punching shear which can play an important role in the prevention of such failure. Two important aspects should be highlighted. Firstly, the current design provisions against punching shear are strictly empirical based on experimental data and tend to be conservative in nature. Secondly, there is a lack of incorporation of the resistance-increasing effect of membrane action within structural design codes. In this research, nonlinear finite element analysis (FEA) on the effect of compressive membrane action on punching shear by varying the size of the specimen using shell elements are considered. This is done using the commercial finite element analysis software ABAQUS via the Concrete Damaged Plasticity Model embedded within it.

In the analysis of structures, finite element modelling can be more economical and time efficient than physical testing depending on the complexity of the models. In addition to the ability of varying parameters and boundary conditions, stress distributions, force paths, propagation of failure and other valuable information can be determined more readily. An interior slab-column connection without shear reinforcement, hereby referred to as SB1, and based on previous works [2] is modelled to examine the membrane action effect on the punching shear resistance. FEA is performed on one-quarter of SB1 due to the symmetry offered by its geometric shape. The material properties of the concrete slab and reinforcement used within ABAQUS are presented in Table 1 and Table 2, respectively. The values of the material parameters are considered based on previous research [2]. In total, three slabs are examined under displacement control analysis until failure: the control specimen SB1 and the two continuous slabs. The dimensions and the loading of the control slab SB1 are shown in Figure 1.

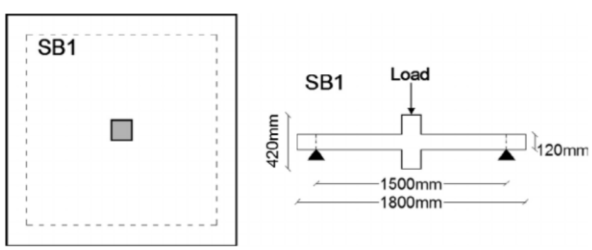


*Figure 1: Schematic drawing of the isolated interior slab-column connection SB1.*

*Table 1: Material properties and plasticity parameters of concrete used in ABAQUS for the analysis of SB1.*

| Parameter | Value |
|---|---|
| $f_c'$ [MPa] | 44 |
| $f_t'$ [MPa] | 2.2 |
| $G_f$ [N/mm] | 0.082 |
| $E_c$ [MPa] | 36,483 |
| $\nu$ | 0.2 |
| *Dilation angle,* $\psi$ [degrees] | 40 |
| $\varepsilon$ | 0.1 |
| $\sigma_{b0}/\sigma_{c0}$ | 1.16 |
| $K_c$ | 0.667 |
| $\mu$ | 0 |

*Table 2: Material properties of steel reinforcement.*

| Parameter | Value |
|---|---|
| $E_s$ [MPa] | 200,000 |
| $\nu$ | 0.3 |
| $f_y$ [MPa] | 455 |

## CONTINUOUS MODELS IN FEA

Finite element analysis of SB1 is performed using the Concrete Damaged Plasticity Model in ABAQUS. One-quarter of SB1 is modelled using homogenous shell elements and its dimensions are 750 x 750 x 120 mm. Steel reinforcement is modeled with the rebar layer definition both within the top and bottom portion of the slab oriented along both the perpendicular and parallel directions. The slab is meshed using S4R elements which are four-noded doubly curved thick shells with reduced integration, hourglass control and finite membrane strains. The approximate global size of the meshed elements is equal to 20 mm.

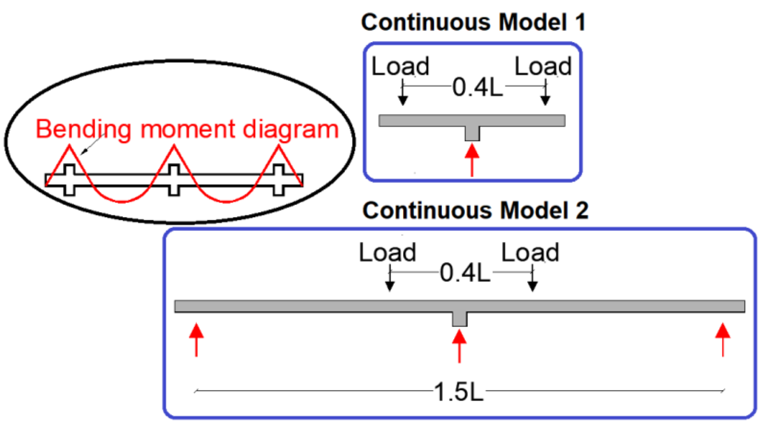


*Figure 2: Continuous models.*

Two scenarios are examined for the continuous slabs. Continuous Model 1has restrained supports with both horizontal and vertical restraints (pinned supports) at the locations of the lines of the contra-flexure in order to provide lateral restraints and simulate the continuous scenario. The lateral restraints are applied not only at the bottom of the slab but also at the whole height of the slab. Continuous Model 2 is considered with dimensions (1.6L=6,000 mm) and simple supports at distance 0.4L=1,500 mm and at 1.5L=5,625 mm, where L denotes the center-to-center span of the slabs (L=3,750 mm). That model is based on the bending moment diagram of a floor system simulating the zero moments with the support conditions. The two continuous models are shown in Figure 2. Both continuous models were previously examined using 3D solid elements for concrete and embedded truss elements for the reinforcement [3]. This study examines the same continuous models using shell elements with the objective to reduce the computational time needed to run an analysis of bigger specimens such as the Continuous Model 2 or future simulations that will consider the whole floor system.

## LOAD-DISPLACEMENT CURVES AND CRACKING

Figure 3 presents the numerical results of the analyzed slabs in terms of load and midspan displacement. Both continuous models and the isolated simply supported slab (FEA and test) are shown. The comparison between test and FEA results for the simply supported slab seem to be in good agreement. The continuous models that represent the continuity, show an increase in the failure load compared to the test and the FEA results of the conventional slab. The ultimate load of the continuous model 1 is increased by approximately 50% and the ultimate load of the continuous model 2 is increased by approximately 60%, both compared to the numerical results of the isolated simply supported slab. The developed crack patterns of the analyzed continuous slabs at failure are presented in Figures 5 and 6. The continuous slabs appear the cracking concentrated around the column and it does not spread to the edges, as it happens on the isolated simply supported slab (Figure 4). This can be explained by considering the in-plane constraining that leads to lower crack widths and thus to larger punching shear capacity.

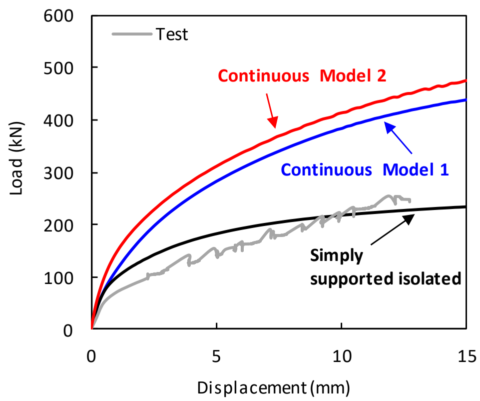


*Figure 3: Load-displacement curves of analyzed slabs.*

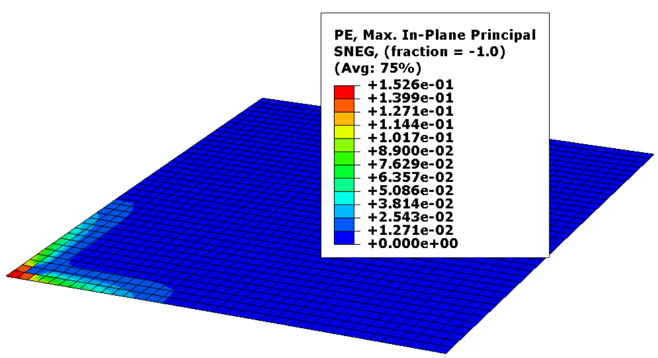


*Figure 4: Cracking of isolated simply supported slab.*

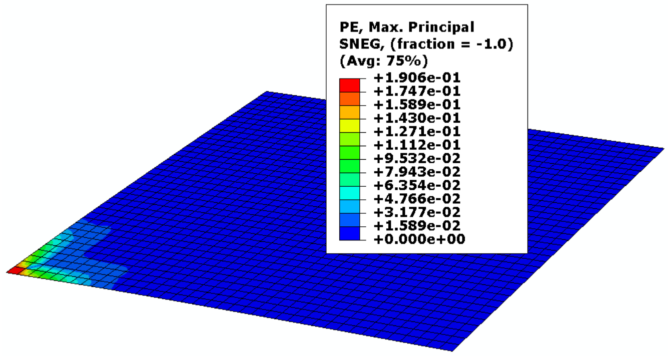


*Figure 5: Cracking of Continuous Model 1.*

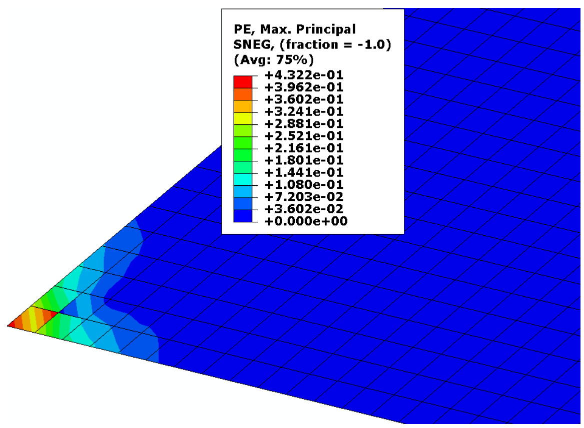


*Figure 6: Cracking of Continuous Model 2.*

## CONCLUSIONS

FEA can be effectively used to examine the compressive membrane action effect, since experimental research on continuous slabs can be considered as time consuming and expensive. Proper calibration of FEA should be done in advance, and then parametric studies can follow. The calibrated concrete damaged plasticity model in ABAQUS predicts accurately the responses of the continuous and isolated slabs. This study can provide the following conclusions:

1. Shell elements with the rebar layer definition can be considered to model the response of reinforced concrete slabs. The results for the conventional simply supported isolated slab were close to the experimental results. This great agreement between test and numerical results combined by the reduced computational time needed when shell elements are used, make the proposed models in this study an important suggestion for future studies.
2. The results of the continuous model 1 with the lateral restraints combined with the simple supports at the edges in the isolated specimen SB1 show an increase in the punching strength 50%, while the continuous model 2 with the simple supports and with dimensions 1.5L present an increase in the punching strength by about 60%. Thus, the two continuous models show quite similar increase of the punching shear load due to continuity.
3. Due to the membrane action effect, the continuous models of the slabs show smaller crack widths and the crack patterns are concentrated around the area of the column and they are not spread to the edges of the slabs.

Future studies will aim to investigate the punching shear capacity of the whole floor system and compare its response with the results obtained from the continuous models presented in this study.

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