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Numerical prediction of punching behavior of RC slabs using 3D non-linear FE analysis

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ABSTRACT: This study was conducted by carrying out nonlinear FE analysis of RC slabs subjected to punching failure, using three-dimensional (3D) continuum elements. The influence of several modelling choices for concrete material were investigated by comparing results such as load-carrying capacity, load-deflection response and crack pattern from the FE analyses with available experimental data. The analyses of the tested slabs show possibility to accurately predict the load-carrying capacity and realistically simulate the behavior of slabs using the proposed method.

1 INTRODUCTION

The existing infrastructure represents a substantial part of the societal assets and existing bridges represent a huge capital that need to be well administrated. Bridge deck slabs are among the most exposed bridge parts and are often critical for punching failure (SB-ICA, 2007). This failure mode is associated with the local introduction of concentrated loads such as columns or wheel loads. It is brittle and therefore undesirable. In addition, punching is one of the most difficult design problem in structural concrete (CEB-FIP, 2001). Consequently, it is important to examine if the current assessment and analysis methods are appropriate. Nonlinear finite element analysis (FEA) has been proved to be an enhanced method to evaluate the punching capacity of Reinforced Concrete (RC) slabs with high level of accuracy (SB-LRA, 2007). However, even though nonlinear FEA has been used increasingly for the assessment of existing structures, building codes do not provide specific guidance on how to perform these analyses. Therefore, the overall aim of this study is to investigate how accurate the response of slabs can be predicted with nonlinear finite element analysis, and how the modelling choices might influence the analysis results. Moreover, these should complement more general guidelines already available in literature such as Fib (CEB-FIP, 2001), Fib (CEB-FIP, 2008) and Hendriks *et al.* (2012).

In the previous years, several numerical investigations were carried out to apply the finite element method (FEM) to predict punching behaviour of slabs. Among these, studies with 2D models has been conducted, e.g. Menetry *et al.* (1997) and Hallgren (1996). A separate application was investigated by those who implement layered shell elements which take into account an out-of-plane shear response and allow implementation of three-dimensional constitutive models, e.g. Polak (2005). Compared to 2D element models, a 3D element model offer higher flexibility and accuracy in the modelling of out-of-plane behavior of reinforced concrete structures and generally lead to more realistic results (Plos *et al,* 2015). 3D numerical analyses of punching failure of slabs can be found in e.g. Ozbolt & Vocke (2000), Zheng *et al.* (2009) Amir (2014) and Eder *et al.* (2010).

For the application of FEM for RC structure, a large number of constitutive models to describe the behavior, including cracking of concrete, has been developed. Among those, the models based on the theory of plasticity and continuum fracture mechanics along with smeared crack approach have been widely used. The FE analyses carried out in this study were compared to tests to investigate the influence of different material models as well as modelling choices on results regarding load-carrying capacity and structural behavior. The load-deflection relation and crack pattern from FE analysis have been compared with corresponding experimental data from Guandilini & Muttoni (2004, 2009).

2 DESCRIPTION OF EXPERIMENTS

Guandilini & Muttoni (2004, 2009) carried out a series of tests on slabs at EPFL in Lausanne; see Figure 1. The aim of these tests was to investigate the behavior of slabs failing in punching shear with different reinforcement ratios. The size of the specimens and the compressive strength of concrete were also varied to investigate their effect on punching shear capacity. The test series consisted of eleven reinforced concrete slabs representing internal slab-column connections without transverse reinforcement.

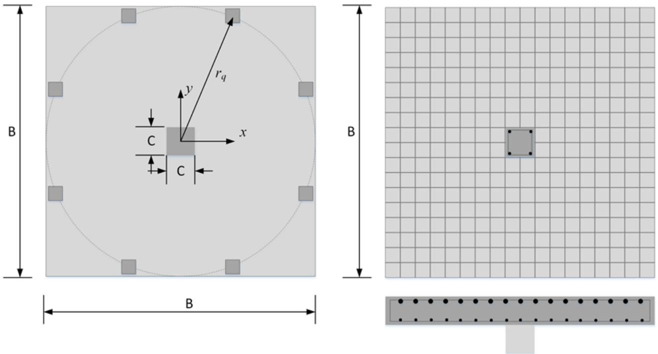

Figure 1: The dimensions and rebar layout of a "full-size" experimental slab, from Guandilini & Muttoni (2009).

The columns were casted to the slab, with a side dimension *c* slightly larger than the thickness *h* of the slabs. The dimensions of the tested specimens were of three types: "full-size" specimens (PG1, PG2b, PG4, PG5, PG10 and PG11), "double-size" specimen (PG3) and "half-size" specimens (PG6, PG7, PG8 and PG9). Table 1 shows the main parameters and characteristics of each specimen. The full-size specimens were loaded through eight concentrated forces acting on the perimeter of the specimen; the load was introduced using four hydraulic jacks placed underneath the laboratory strong floor. During the punching test, the load was increased at a constant speed up to failure. For all specimens, the final failure mode was punching shear, with a clearly delimited punching cone.

Table 1: Dimensions and material properties of test series, from Guandilini & Muttoni (2009).

Specimen dimension [m]		Concrete			Reinforcing steel			
		d [m]	f_c [MPa]	d_g [mm]	Reinforcement	ρ [%]	f_y [MPa]	f_u [MPa]
Full size 3×3×0.25	PG1	0.21	27.6	16	Ø 20 s100	1.5%	573	656
	PG2b		40.5		Ø 10s150	0.25%	552	612
	PG4		32.2	4	Ø 10s150	0.25%	541	603
	PG5		29.3		Ø 10s115	0.33%	555	659
	PG10		28.5	16	Ø 10s115	0.33%	577	648
	PG11		31.5		Ø16/18s145	0.75%	570	684
Double size 6×6×0.5	PG3	0.456	32.4		Ø 16s135	0.33%	520	607
Half size 1.5×1.5×0.125	PG6	0.096	34.7		Ø 14s110	1.5%	526	607
	PG7	0.1			Ø 10s105	0.75%	550	623
	PG8	0.117			Ø 8s155	0.28%	525	586
	PG9	0.117			Ø 8s196	0.22%	525	586

3 NUMERICAL MODELLING

The finite element software DIANA 9.5 (2014) was used to model the slabs, using a 3D tetrahedron 4-node element model, as displayed in Figure 2. Due to symmetry and to reduce the computation time, only a quarter of the slab was included in the FE model. The loading steel plates were included and interface elements were used between the concrete and steel plates to describe the friction. The translation of all nodes at the symmetry faces were fixed in the perpendicular direction. The load was applied as a prescribed vertical displacement to the center node at the bottom surface of the column. To model the distributed load from the hydraulic jack, all the nodes on bottom surface of the column were tied to the center node so that they had the same vertical deflection. An incremental static analysis was performed using specified increment sizes. Each increment was equivalent to a vertical displacement of 0.1 mm until the deflection became 3 mm. After that, the increments were increased to 1 mm to save computation time. The analyses were carried out using a regular Newton-Raphson iteration method based on force and energy convergence criteria, with a tolerance of 0.01.

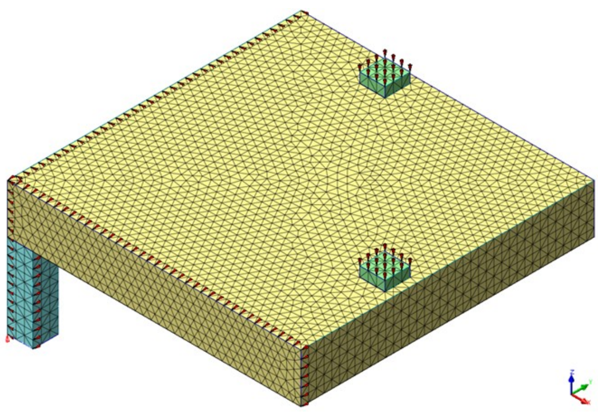

Figure 2: FE model of a quarter of slab PG2b.

3.1 *Material model for concrete*

The analyses were performed with different material models for concrete. A Total Strain (TS) rotating crack model (TNO, 2014) which is implemented in

DIANA was selected as reference model since it has been proven able to predict the structural behaviour of slabs accurately (Plos *et al.*, 2015) & (Shu *et al,* 2014). For comparison with the FE results, a Total Strain (TS) fixed crack model with various shear retention factors was also used.

3.2 *Reference model*

In the reference model, the TS rotating crack model with crack band approach was used. In this approach, the crack width w is related to the crack strain ε_{cr} perpendicular to the crack via a characteristic length - the crack band width h_b. The reinforcement is modelled assuming complete interaction with the surrounding concrete; consequently, the crack band width equal to the mean crack distance. Figure 3 (top) shows the tensile property of concrete according to Hordijk *et al.* (1985), used for the reference model. The behavior of concrete in compression was described according to Thorenfeldt *et al.* (1987). When the stress-strain relationship is used in numerical analyses, the localization of deformations in compressive failure needs to be taken into account. The compression softening behavior is related to the boundary conditions and size of the specimen in the material tests. Consequently, as the stress-strain relation has been calibrated by measurements in compression tests on 300 mm long cylinders, the softening branch needs to be modified for the concrete element size used in the FE model (2013); see Figure 3 (bottom), in which X indicates original strain. The fracture energy was calculated according to MC1990 (2013) and the influence of lateral confinement was taken into account according to Selby & Vecchio (1997).

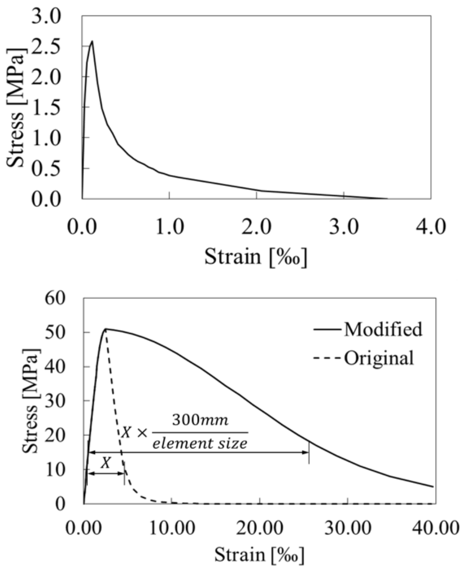

Figure 3: Tensile and compressive input of concrete for the reference model

3.3 *Alternative modelling choices*

In order to evaluate the influence of variable modelling choices, parameters possibly influencing the shear behavior were investigated. Modelling parameters such as mesh sensitivity, lateral confinement, and fracture energy were varied and the structural response was compared with the reference model. The influence of using a stress-strain relation in tension according to the modified compression field theory (MCFT) by Collins & Mitchell (1986) was also studied since it attempts to take into account the concrete contribution in shear, i.e. friction, aggregate interlocking and dowel action. In the comparative analyses with the TS fixed crack model, parameters such as the shear retention factor was varied with constant values (β = 0.01, 0.1, 0.25), an aggregate size based function (see Equation 1, d_{agg} = aggregate size, ε_n = total strain, h = crack band width) and the Maekawa shear model (1989).

$$\beta = 1 - \left(\frac{2}{d_{agg}}\right)\varepsilon_n h \qquad (1)$$

4 RESULTS AND DISCUSSION

4.1 *Mesh sensitivity*

The size of finite elements, i.e., mesh density, has effect on the results of analysis. A mesh size study was performed for specimen PG2b for three different mesh sizes with 5, 6 and 7 layers of elements through the slab thickness; see Figure 4 (top). The study confirmed that a mesh with 7 layers was fine

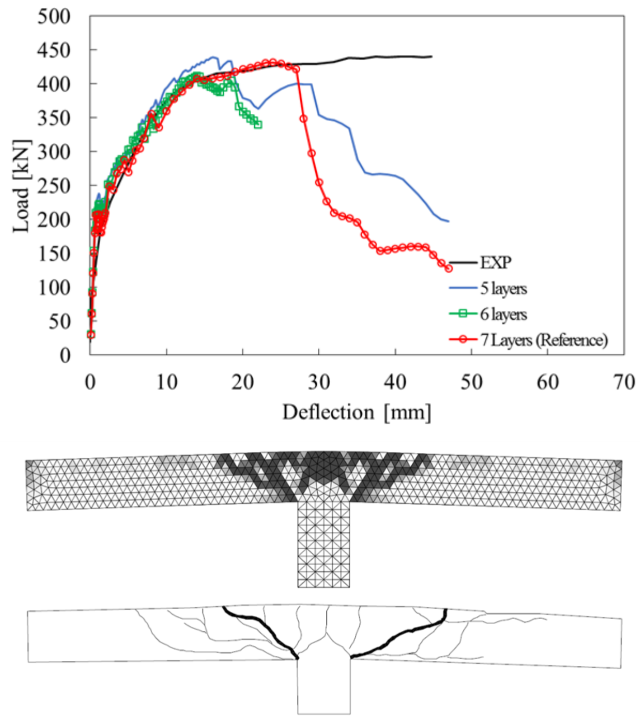

Figure 4: Mesh sensitivity analysis for PG2b (top) and crack pattern from the reference FE analysis (principal tensile strains, middle) and the experiment (bottom)

enough and a further refinement did not bring a significant improvement. Therefore, the model with 7 layers through the thickness was used in the following analyses (reference model). The crack pattern and failure mode obtained from the model with 7 layers of elements is also in a good agreement with experimental result; see Figure 4 (middle and bottom).

4.2 *Modelling choices for material behavior in FE models*

The alternative modelling choices for the TS rotating crack model included alternative fracture energy according to MC2010 (CEB-FIP, 2013), stress-strain relation according to the MCFT by Collins and Mitchell (1986) and excluding of the confinement model by Selby & Vecchio (1997). The results of analyses with these three modelling choices were compared with the reference analysis as well as with experimental results;

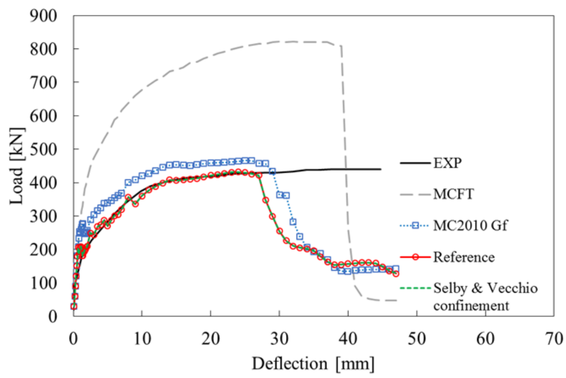

Figure 5: The results of analyses using TS rotating crack model with different modelling choices

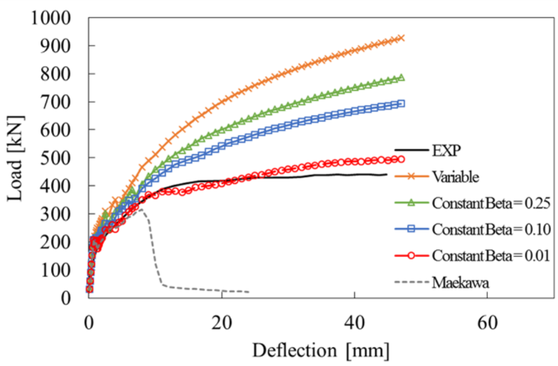

Figure 6: The results of analyses using the TS fixed crack model with different modelling choices

see Figure 5. It was observed the confinement model by Selby & Vecchio (1997) only has very minor change to the load-deflection response of the slab. The fracture energy was calculated as 142N/m according to MC2010 (CEB-FIP, 2013) instead of 80 N/m according to MC1990 (CEB-FIP, 1993), leading to an increase of 8% on the load carrying capacity. The tensile model from MCFT obviously has significant influence on the results since the load carrying capacity increased by 91%.

The modelling choices for the TS fixed crack model included different constant shear retention factors, aggregate size based shear retention factor and Maekawa shear model (1989). The results of the analyses with these modelling choices were compared with experimental results and displayed in figure 6. It was observed that only the model with constant $\beta = 0.01$ provides a reasonable results whereas higher β values, including the aggregate size based, overestimate the load carrying capacity. The Maekawa model (1989), on the other hand, underestimated the load carrying capacity considerably.

4.3 *Results of analyses for all experiments of the test series*

Based on the analyses above, the FE model with the TS rotating crack model and the modelling choices of the reference model (section 3.2) was judged to be a reliable method to simulate the structural behavior of slabs subjected to punching failure. Consequently, this method was selected for the analyses of the experiments of the punching test series by Guandilini & Muttoni (2004). The load carrying capacity according to the analyses is tabulated and compared with the experimental results and simplified results according to EC2 (EN 1992-1-1, 2004), in Table 2. The results show that the proposed reference model is able to predict punching capacity rather accurately, with a smaller coefficient of variation (0.13).

Table 2: Comparison between FEA results, EC2 results and experiment results

Specimens	$V_{R.EXP}$ [kN]	$V_{R.FEA}$ [kN]	$V_{R.EC2}$ [kN]	$\frac{V_{R.EXP}}{V_{R.FEA}}$	$\frac{V_{R.EXP}}{V_{R.EC2}}$
PG1	1023	755	950	1.35	1.61
PG2b	440	431	594	1.02	1.11
PG3	2153	1910	2347	1.13	1.38
PG4	408	423	550	0.96	1.11
PG5	550	498	585	1.10	1.41
PG6	238	232	223	1.03	1.60
PG7	241	192	189	1.26	1.91
PG8	140	144	179	0.97	1.17
PG9	115	118	165	0.97	1.05
PG10	540	496	580	1.09	1.40
PG11	763	586	787	1.30	1.45
Average				1.10	1.38
Coefficient of variation				0.12	0.18

5 CONCLUSIONS

By comparing the results of the FE analyses with experiment, it is concluded that the reference model was capable of predicting the punching capacity and crack pattern with good accuracy. Through the parameter study, the results show that the capacity predicted by FE analysis was significantly affected by modelling choices. For the TS rotating crack model, the fracture energy was an important influencing factor. In addition, using the stress-strain relation according to the modified compression field theory (MCFT) leads to overestimation of the punching capacity even though it was proven to be useful for simulating shear panel tests (Collins & Mitchell, 1986). For the TS fixed crack model, the punching capacity was affected by the shear retention considerably. Consequently, the modelling choices of the reference model could be recommended as a reliable modelling method for RC slabs subjected to punching failure.

6 REFERENCES

Amir, S. (2014). *Compressive membrane action in prestressed concrete deck slabs*. PhD Thesis. Delft University of Technology, Delft.

CEB-FIP. (1993). *fib Model Code for Concrete Structures 1990*. Lausanne.

CEB-FIP. (2001). *fib Bulletin No. 12: Punching of structural concrete slabs*. Lausanne.

CEB-FIP. (2008). *fib Bulletin No. 45: Practitioners' guide to finite element modelling of reinforced concrete structures*. Lausanne, Switzerland.

CEB-FIP. (2013). *fib Model Code for Concrete Structures 2010*. Lausanne.

Cornelissen, H. a W., Hordijk, D. a., & Reinhardt, H. W. (1985). Experimental Determination of Crack Softening Characteristics of Normalweight and Lightweight Concrete. *Heron*, *31*(2), 45–56.

Eder, M. A., Vollum, R. L., Elghazouli, a. Y., & Abdel-Fattah, T. (2010). Modelling and experimental assessment of punching shear in flat slabs with shearheads. *Engineering Structures*, *32*(12), 3911–3924. doi:10.1016/j.engstruct.2010.09.004

EN 1992-1-1. (2004). *Eurocode 2: Design of concrete structures - part 1-1: General rules and rules for buildings.* Brussels, Belgium: CEN European Committee for Standardization.

Guandalini, S., Burdet, O. L., & Muttoni, A. (2009). Punching tests of slabs with low reinforcement ratios. *ACI Structural Journal*, 87–95.

Guandalini, S., & Muttoni, A. (2004). *Symmetrical Punching Tests on Slabs without Transverse Reinforcement*. Doctoral Thesis, Lausanne, Switland.

Hallgren, M. (1996). *Punching shear capacity of reinforced high-strength concrete slabs*. *ProQuest Dissertations and Theses*. Doctoral Thesis, Kungliga Tekniska Hogskolan, Stockholm, Sweden.

Hendriks, M. A. N., den Uijl, J. A., de Boer, A., Feenstr, P. H., Belletti, B., & Damoni, C. (2012). *Guidelines for nonlinear finite element analysis of concrete structures.* (1st ed.). Delft: Rijkswaterstaat Centre for Infrastructure.

Li, B., Maekawa, K., & Okamura, H. (1989). Contact density model for stress transfer across cracks in concrete. *Journal of the Faculty of Engineering, the University of Tokyo*, *XL*(1).

Menétrey, P., Walther, R., Zimmermann, T., Willam, K. J., & Regan, P. E. (1997). Simulation of Punching Failure in Reinforced-Concrete Structures. *Journal of Structural Engineering*, *123*(5), 652–659. doi:10.1061/(ASCE)0733-9445(1997)123:5(652)

Ozbolt, J., Vocke, H., & Eligehausen, R. (2000). Three-dimensional numerical analysis of punching failure. *Trita-BKN. Bulletin*, *57*, 65–74.

Plos, M., Shu, J., Zandi, K., & Lundgren, K. (2015). A Multi-level Structural Assessment Proposal For REinforced Concrete Bridge Deck Slabs. *Structure and Infrastructure Engineering*, (submitted).

Polak, M. A. (2005). Shell finite element analysis of RC plates supported on columns for punching shear and flexure. *Engineering Computations*, *22*(4), 409–428. doi:10.1108/02644400510598750

SB-ICA. (2007). *Guideline for Inspection and Condition Assessment*. Sustainable bridges: Report.

SB-LRA. (2007). *Guideline for Load and Resistance Assessment of Existing European Railway Bridges*. Sustainable Bridges: Report.

Selby, R. G., & Vecchio, F. J. (1997). A constitutive model for analysis of reinforced concrete solids. *Canadian Journal of Civil Engineering*, *24*(3), 460–470. doi:10.1139/cjce-24-3-460

Shu, J., Fall, D., Plos, M., Zandi, K., & Lundgren, K. (2014). Development of modelling strategies for two-way RC slabs. *Engineering Structures*, *101*, 439–449.

Thorenfeldt, E., Tomaszewicz, A., and Jensen, J. J. (1987). Mechanical properties of high-strength concrete and applications in design. In *In Proc. Symp. Utilization of High-Strength Concrete*.

TNO. (2014). *Diana finite element analysis, User's Manual -- Release 9.5*. TNO DIANA BV.

Vecchio, F. J., & Collins, M. P. (1986). The modified compression field theory for reinforced concrete elements subjected to shear. *ACI Journal*, *83*(22), 219–231.

Zandi Hanjari, K., Kettil, P., & Lundgren, K. (2013). Modeling the Structural Behavior of Frost-damaged Reinforced Concrete Structures. *Structure and Infrastructure Engineering*, *9*(5), 416–431.

Zheng, Y., Robinson, D., Taylor, S., & Cleland, D. (2009). Finite element investigation of the structural behaviour of deck slabs in composite bridges. *Engineering Structures*, *31*(8), 1762–1776. doi:10.1016/j.engstruct.2009.02.047