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Finite Element Prediction on the Post-Punching Behavior of Slab-Column Connections

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Abstract. The post-punching behavior of slab-column connections with the employment of engineered cementitious composite (ECC) material was investigated. Two specimen models were modeled and simulated in the finite element program to predict the limit of punching shear resistance and post-punching shear behavior due to lateral load. The first specimen was constructed using regular concrete as the control specimen. The second specimen was built with ECC material at the local thickening at drop panel area and regular concrete at the rest of the members. ECC material was selected due to its superior performance with high tensile strain of more than 2% through multiple micro-cracking with width of less than 80 μm. The results highlighted an improvement of shear capacity and post-punching behavior at the second specimen. Furthermore, compressive damage of post-crushing response on the second specimen also indicated less crushing phenomenon at the critical perimeter than that of the first specimen.

Introduction

The effect of high gravity shear ratio and severe earthquake loading have indicated a number of catastrophic failures in flat slab structures [1]. As the slab member carries the uniform shear force and unbalanced moment at the critical area, the punching shear failure may occur when the adjacent slab-column connection is overloaded [2]. Hence, in the extreme condition, the collapse of the top floor to the bottom floor will propagate the progressive collapse of the building.

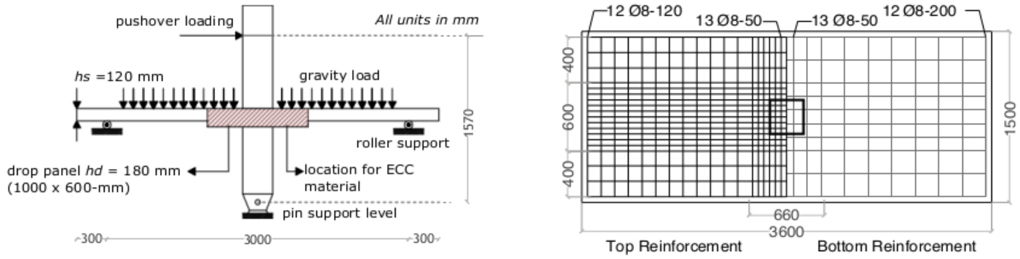
Many tests have been conducted both in laboratory experiments and numerical analyses to provide more information to prevent the progressive collapses in flat slab structures. For instance, the use of closed stirrup and shear stud [3], post-tensioned system on the slab (Kang et.al., 2008), shear capitals and drop panel [4], or steel fiber [5]. However, the previous tests have not been able to trigger the change in any design codes. Thus, the need for more investigations is imperative.

The use of drop panel as local thickening is adopted in this study to assure the additional shear capacity at the critical perimeter [6]. The new class of cementitious material with high tensile strain capacity of more than 2% is also used in this study. Also known as ECC, engineered cementitious composite material exhibits strain hardening behavior through multiple micro-cracking [7]. Besides that, the compressive strength of ECC material is typical with regular concrete with less post-crushing behavior [8].

This paper presents the finite element prediction of the post-punching behavior of interior slab-column connections using ECC material. Finite element simulation is chosen to give an insight of punching shear behavior due to the acting loads. In this paper, finite element program ABAQUS is used with damage plasticity model for both of regular concrete and ECC material. The suggested increase of response is justified by numerical results.

Specimen Model

The experimental work of isolated interior slab-column connection specimen model with shear reinforcement was taken from previous study conducted by [9]. Subsequently, the specimen was developed and verified through numerical analysis using regular concrete [10]. The results showed the good agreement from experimental work and numerical analysis.



(a) (b)

Fig. 1 Schematic drawing of the specimen. (a) Geometry and loading form, (b) reinforcement layout.

Based on the previous study, a further analysis can be performed to understand the post-punching behavior of flat slab structure. As seen in Fig. 1, the slab dimension of the specimen was 3600 x 1500 x 120-mm with cover in both top and bottom layers was 20 mm. For the flexural reinforcement for top and bottom of slab, D8-mm bars were used. The reinforcement configuration for top and bottom slab were set dissimilar. The square column of 300 x 300-mm with height of 1570 mm beyond the top and bottom faces of the slab was used. The longitudinal deform bars 12D13-mm and transversal bars D6-mm with 50 mm space were used for the column. Table 1 summarized the material properties of the model.

Table 1. Material properties of the specimen model.

Regular Concrete		**ECC Material**		**Yield Strength of Reinforcement**		
Compressive Strength (MPa)	Tensile Strength (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Slab (MPa)	Column (MPa)	Stirrup (MPa)
46.21	3.79	48.7	4.5	321.5	390.74	354.77

Finite Element Analysis

The slab and column members were discretized with eight-node hexahedral brick elements using reduced integration, which is known as C3D8R in ABAQUS. Elasto-plastic truss elements were applied as the reinforcement bars to neglect the bond-slip between concrete and reinforcement. The embedded technique was also used as the connectivity between concrete nodes and reinforcement nodes to create the perfect bond [11].

In the numerical simulations two cases of slab-column models were considered; the first specimen (SCC-1) was modeled using regular concrete for all elements. Furthermore, the second specimen (SCC-2) was built with two distinct concrete materials i.e. ECC material and regular concrete. ECC material was placed only at the local thickening area, where the rest of the volume was filled in with regular concrete.

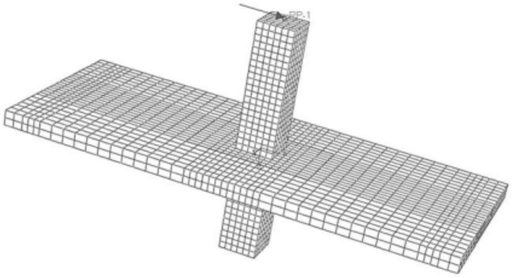


Fig. 2 Finite element mesh of the specimen model.

In ABAQUS, gravity load in the form of self-weight was given by introducing gravitational acceleration of 9.81 m/sec^2. In addition, the superimposed dead load and live load were simulated as pressure loads. After the gravity loads were attached on the surface of the model, the pushover load at the column tip as shown in Fig. 1*a* was subsequently applied under displacement control method. Fig. 2 illustrated the simulated specimen.

Concrete Damage Plasticity (CDP) Model

CDP model adopts the concepts of isotropic elasticity in combination with isotropic compressive and tensile damaged plasticity to represent the inelastic behavior of concrete and stiffness degradation [12]. CDP model assumes two main failure mechanisms i.e. the compressive crushing and tensile cracking. In this paper, the input material parameters of CDP was based on the previous study conducted by [10]. Fig. 3 shows the compressive and tensile behavior curves for regular concrete and ECC material.

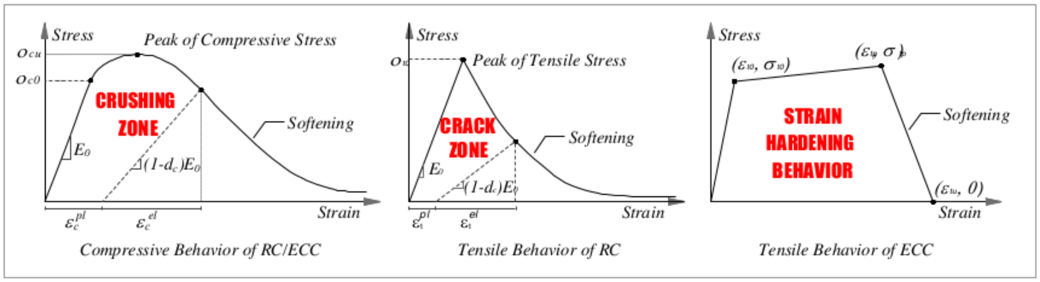


Fig. 3 CDP model for compression and tension

Differ from regular concrete, the tensile stress-strain behavior of ECC material is identified by three distinct characteristics; linear elastic response, strain hardening response, and tension softening response. However, the compressive stress-strain response for ECC material is assumed to be quite similar with conventional concrete. Thus, the approximate formula to determine the compressive behavior for conventional concrete can be used in ECC material.

Results and Discussion

The complete shear-displacement response of all specimens and the summary of key load stages during the simulation are provided in Fig. 4 and Table 2. The overall condition indicated that SCC-2 referred the improvement behavior compared to SCC-1.

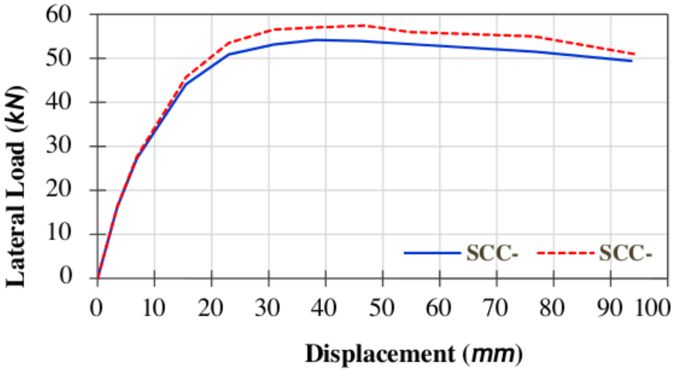


Fig. 4 Load-displacement response of specimens.

Table 2. Load-carrying capacity of both specimens.

Designation	Specimen SCC-1		Specimen SCC-1	
	Shear Force (kN)	Displacement (mm)	Shear Force (kN)	Displacement (mm)
Punching Shear	54.20	38.80	57.50	46.80
Post-punching Shear	49.40	93.60	51.00	94.20

The typical behavior of all specimens highlighted that the slab experienced membrane action, as the peak lateral load at punching failure was followed by a decrease in shear value along with the increase in displacement. Subsequently, the loading continued after punching shear failure to predict the behavior of specimen in post-punching condition.

Shear Stress Analysis. The finite element results of the punching shear failure behavior were compared with the predictions based on the equation specified in [13] section 11.12.2.1. The smallest nominal shear strength of concrete is given in Eq. 1.

$$v_c = \frac{1}{3}\sqrt{f_c^{'}} \tag{1}$$

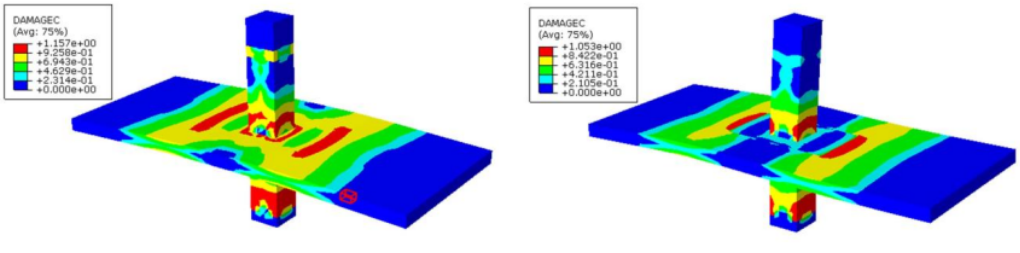
where, the value of 1.0 for shear ratio between ultimate shear stress (v_u) and nominal shear stress (v_c) indicates that the connection is on the verge of punching shear failure. If the ratio is greater than 1.0, the punching shear failure occurs. Based on the finite element simulation, the results of shear stress acting on concrete are summarized in Table 3.

Table 3. The prediction of shear stress distribution of specimen.

Case	Status	Ultimate Stress (v_u) (MPa)	Nominal Stress (v_c) (MPa)	Shear Ratio (v_u/v_c)	Prediction of Visual Behavior
SCC-1	Punching	2.11	2.24	0.94	Cracks develop and punching shear failure is imminent
	Post-punching	4.4	2.24	1.96	Punching shear failure occurs (concrete crush and top slab rebar may rip out)
SCC-2	Punching	1.56	2.30	0.68	Small cracks develop and punching shear failure is not imminent
	Post-punching	3.14	2.30	1.36	Punching shear failure and structural cracks may develop

Post-crushing Behavior. The concrete damage for all specimens can be visualized in ABAQUS. Continuum mechanics model succeeded to predict the crushing of concrete (compression damage) at the last displacement. Total damage occurs when the ratio between undamaged and damage stress is 1.0, where it is marked by the red contours in ABAQUS.

Fig. 5 presents the post-crushing response of specimen due to the damage of concrete at the last step. Based on the simulation, it is evident that SCC-2 has less crushing phenomena in compression than that of SCC-1. The compression damage ratio on the slab near column is still less than 1.0. It is due to the role of ECC material that has superior performance to prevent the severe damage. Fibers have been assessed as the best admixture to create the pseudo strain hardening behavior and multiple micro-cracking phenomenon on the ECC material. Thus, the insignificant failure may occur on the specimen.



(a) (b)

Fig. 5 Post-crushing behavior of specimens. (a) Specimen SCC-1, (b) Specimen SCC-2

Conclusion

In this paper, a nonlinear analysis of slab-column connections with different material was performed using ABAQUS program. Based on the numerical results, the following conclusion are drawn:

1. It is proven from numerical simulation that the use of ECC material can upgrade the shear capacity of specimen.
2. The shear stress ratio of SCC-2 at the first punching phenomena is almost two times less than of SCC-1.
3. The punching failure of specimen using ECC material only cause small cracks and the post-punching behavior does not cause the catastrophic damage.
4. Temporary results can be made that the prediction generated the feasibility of ECC material to upgrade the structural performance.

Acknowledgement

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