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Numerical study on effect of integrity reinforcement on punching shear of flat plate

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Abstract. Reinforced concrete flat plates consist of slabs supported directly on columns. The absence of beams makes these systems attractive due to advantages such as economical formwork, shorter construction time, less total building height with more clear space and architectural flexibility. Punching shear failure is usually the governing failure mode of flat plate structures. Punching failure is brittle in nature which induces more vulnerability to this type of structure. To analyze the flat plate behavior under punching shear, twelve finite element models of flat plate on a column with different parameters have been developed and verified with experimental results. The maximum range of variation of punching stress, obtained numerically, is within 10% of the experimental results. Additional finite element models have been developed to analyze the influence of integrity reinforcement, clear cover and column reinforcement. Variation of clear cover influences the punching capacity of flat plate. Proposed finite element model can be a substitute to mechanical model to understand the influence of clear cover. Variation of slab thickness along with column reinforcement has noteworthy impact on punching capacity. From the study it has been noted that integrity reinforcement can increase the punching capacity as much as 19 percent in terms of force and 101 percent in terms of deformation.

Keywords: flat plate; punching shear; shear reinforcement; integrity reinforcement; column reinforcement

1. Introduction

Reinforced concrete flat plates consist of slabs supported directly on columns. The absence of beams makes these systems attractive due to advantages such as economical formwork, shorter construction time, less total building height with more clear space and architectural flexibility.

The greatest disadvantage of flat plate systems is the risk of brittle punching failure at the slab-column connection due to transfer of shear and unbalanced moment. Vertical loads acting on the floor system and moments transferred from the columns may create excessive shear stresses around the slab-column connection. Unbalanced moments naturally occur at corner and edge slab-column connections. Unbalanced moments may also occur at interior connections with unequal vertical loads on adjacent spans, or at any connection due to combined vertical and lateral forces as a result of wind effects or earthquake excitations. Punching of a flat plate is assumed to occur when the concrete compression strain at the column edge in the slab reaches a critical value that is considerably lower than the generally accepted ultimate compression strain 0.0035 (2005).

The model of Kinnunen and Nylander (1960) defines punching strength as a function of slab deformation. Other researchers adopted and further developed this approach. Muttoni (2008) describes the punching strength as a function of slab rotation. A Quadrilinear moment curvature relationship approach was adopted for calculation of slab response. Muttoni further developed Critical Shear Crack Theory (CSCT) similar to the model of Kinnunen and Nylander (1960), which is the basis of the fib Model Code (2010). It is noteworthy that most models are based on the theory of an axisymmetric slab. However, most punching test specimens were not axisymmetric and thus the validation of the model could not directly be performed.

Moeinaddin (2012) proposed a formula to calculate the punching shear stress of flat plates on the critical perimeter with good accuracy for a wide range of parameters such as slab thicknesses, tensile reinforcement ratios, amount of transverse reinforcement, and concrete compressive strengths. The main assumption of this method is that punching shear failure occurs due to the crushing of the critical concrete strut adjacent to the column. Moeinaddin gathered a large number of experimental results of slab test specimens, to evaluate the accuracy of the proposed formula, as well as the punching shear formulae in some of the internationally recognized standards such as ACI 318-05 (2005) and Eurocode2 (2004).

Lips and Muttoni (2012) examined influence of punching shear reinforcement on the flexural response of flat slabs. Lips and Muttoni performed an investigation on the flexural response of 16 full scale flat slab specimens with the aim to investigate the punching strength and rotation capacity of flat slabs with and without shear

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reinforcement. Ruiz and Muttoni (2009) performed analysis on applications of Critical Shear Crack Theory to punching of reinforced concrete slabs with transverse reinforcement. Mirzaei and Sasani (2011, 2013) performed extensive experimental and analytical study on post-punching behavior of reinforced concrete slabs. Ruiz F. M. *et al.* (2013) performed extensive experimental campaign related to the effect of integrity reinforcement to obtain physical explanations and a consistent design model for the load-carrying mechanisms and strength after punching failures. An analytical model was introduced by Micallef *et al.* (2014) on the basis of critical shear crack theory which can be applied to flat slabs subjected to impact loading. The findings of this model are useful for progressive collapse analysis and flat slab column connections subjected to impulsive axial load in the column.

Keyvani *et al.* (2013) proposed a new finite element modeling technique to simulate punching and post punching behavior of flat plates. The observation of the developed model was that punching strength is considerably enhanced by lateral restraining of the isolated slab which is attributed due to the formation of compressive membrane forces in the slab as a result of its tendency to grow in-plane since it deforms vertically. Kurtoğlu1a *et al.* (2016) performed the reliability analysis of design formulations derived for predicting the punching shear capacity of FRP-reinforced two-way slabs. By means of gene expression programming a new design code formulation was derived. The formulation was different from the existing ones since the slab length was introduced in the equation. Shuraim *et al.* (2016) reported punching shear behavior of reinforced concrete panels. The investigation was done experimentally and through finite element simulation with an aim to examine the punching shear of high strength concrete panels incorporating different types of aggregate.

Guandalini (2009) conducted experimental study on the punching behavior of flat plate with low reinforcement ratio. Fatema *et al.* (2016) later developed a finite element model (FEM) considering this criterion.

Mahmoud (2015) proposed three-dimensional FEM using Ansys 10 computer software, to carry out the nonlinear analysis of 16 flat-slab models with and without punching shear reinforcement. Solid 65 element was used to simulate the behavior of concrete. Solid 65 element uses the Smeared Crack constitutive model of concrete. Smeared Crack constitutive model requires that the linear elastic material model be used to define elastic properties (2009). As a result, there is a great extent of variation between the numerical result and experimental result.

In this context, Concrete Damage Plasticity Model (CDPM) has been adopted in this study in order to predict structural response of flat plates more accurately. CDPM uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete.

There is a lack of study on the effect of clear cover, reinforcement ratio, column reinforcement and integrity reinforcement on punching capacity of flat plates. A 3D FE model of a flat plate interior connection has been developed in this study to explore the effects of these parameters on the punching behavior of flat plates.

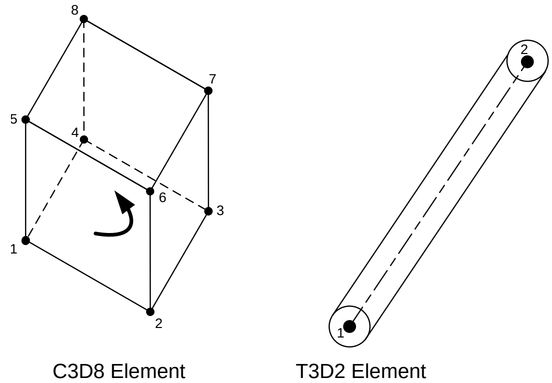


Fig. 1 Elements used in model development

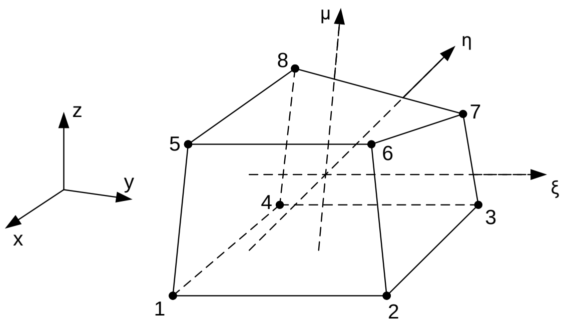


Fig. 2 Hexahedral element used in model development

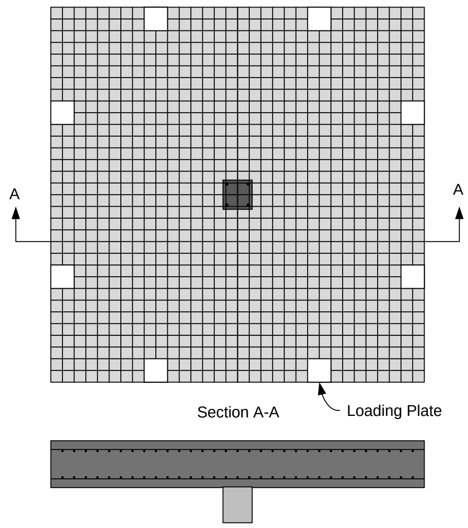
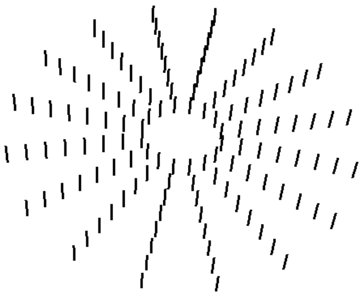


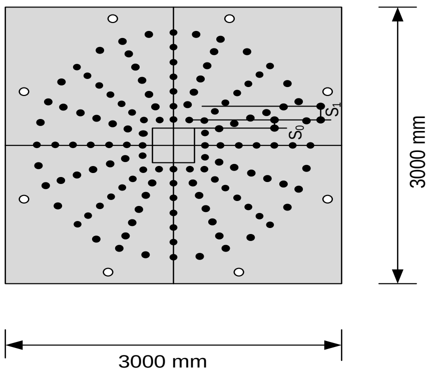
Fig. 3 Typical layout of flexure reinforcement

2. Model development

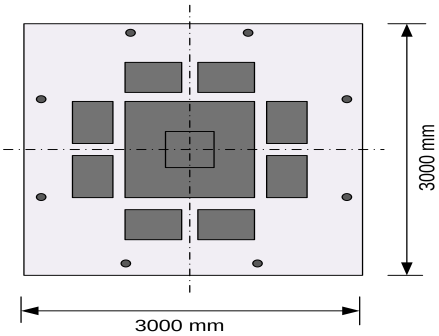
Using ABAQUS (2009) a complete 3D finite element model of a flat plate interior connection has been developed in this study to investigate the punching behavior of a reinforced flat plate. Due to symmetry and simplicity an interior column along with half of a slab panel in all direction is modeled in this study. The geometry of a model is described by elements and their nodes. Slab is modeled by using a three dimensional eight noded continuum solid element (C3D8) and the reinforcement is modeled using truss element (T3D2) as shown in Fig. 1. Continuum solid element (C3D8) is a quadrilateral hexahedron element. The



(a) 3-D arrangement of corrugated stud



(b) Corrugated stud



(c) Continuous stirrup

Fig. 4 Arrangement of stirrups in the model

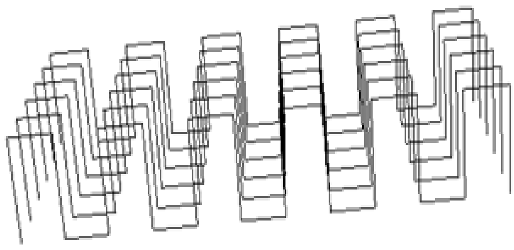
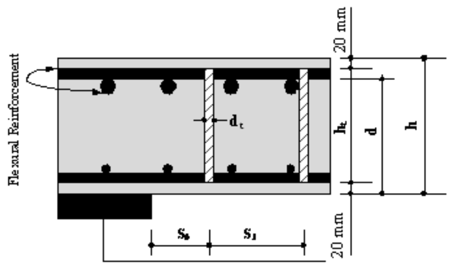


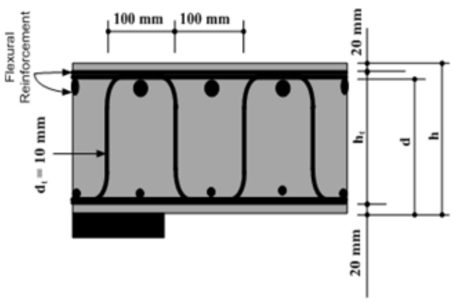
Fig. 5 Isometric view of continuous stirrup

Table 1 Main parameters used for model development in correlation to the experiment of Lips *et al.* (2012)

Model	h (m)	C (m)	d (m)	f_c (Mpa)	ρ, %	f_y (Mpa)	ρ_t, %	f_{yt}(Mpa)	System
PL1	0.25	0.13×0.13	0.193	36.2	1.63	583	0	0	None
PF1	0.25	0.13×0.13	0.209	31.1	1.5	583	0.79	536	Stirrups
PV1	0.25	0.26×0.26	0.21	34	1.5	709	0	0	None
PL7	0.25	0.26×0.26	0.197	35.9	1.59	583	0.93	519	Studs
PF2	0.25	0.26×0.26	0.208	30.4	1.51	583	0.79	536	Stirrups
PL3	0.25	0.52×0.52	0.197	36.5	1.59	583	0	0	None
PL8	0.25	0.52×0.52	0.2	36	1.57	583	0.85	519	Studs
PF3	0.25	0.52×0.52	0.209	37.1	1.5	583	0.79	536	Stirrups
PL4	0.32	0.34×0.34	0.267	30.5	1.58	531 ø20 580 ø26	0	0	None
PL9	0.32	0.34×0.34	0.266	32.1	1.59	531 ø20 580 ø26	0.93	516	Studs
PF4	0.32	0.34×0.34	0.274	37.4	1.54	531 ø20 580 ø26	0.79	550	Stirrups
PL5	0.4	0.44×0.44	0.353	31.9	1.5	580	0	0	None
PF5	0.4	0.44×0.44	0.354	33.4	1.5	580	0.79	550	Stirrups



(a) Corrugated studs



(b) Cages of continuous stirrups

Fig. 6 Details of shear reinforcements

corresponding generalization of a quadrilateral is a hexahedron, also known in the finite element literature as brick (Fig. 2). A hexahedron is topologically equivalent to the shape of a cube. The element contains eight corners, twelve edges or sides, and six faces. Each node has three degrees of freedom (Displacements, Rotations and Temperature) (2009). Many researchers have extensively used this three-dimensional solid element in their FE models. Appropriate natural coordinate system is introduced for this type of element. The natural coordinates are called ξ, η and μ, and are called isoparametric hexahedral coordinates or simply natural coordinates (Fig. 2).

Truss elements are used to model reinforcement that can carry only tensile or compressive loads. They have no resistance to bending. The truss element as shown in Fig. 2 is T3D2 element and has been used to model all types of reinforcements.

The length of the panel and the dimensions of the column varied according to the purpose. Typical layout of flexure reinforcement is shown in Fig. 3. The arrangements and types of punching shear reinforcements are shown in the Figs. 4 and 5.

Table 1 shows the essential parameters used for the model development. Each model is 3×3 m in dimension. Approximately 1.5% flexural reinforcement ratio is

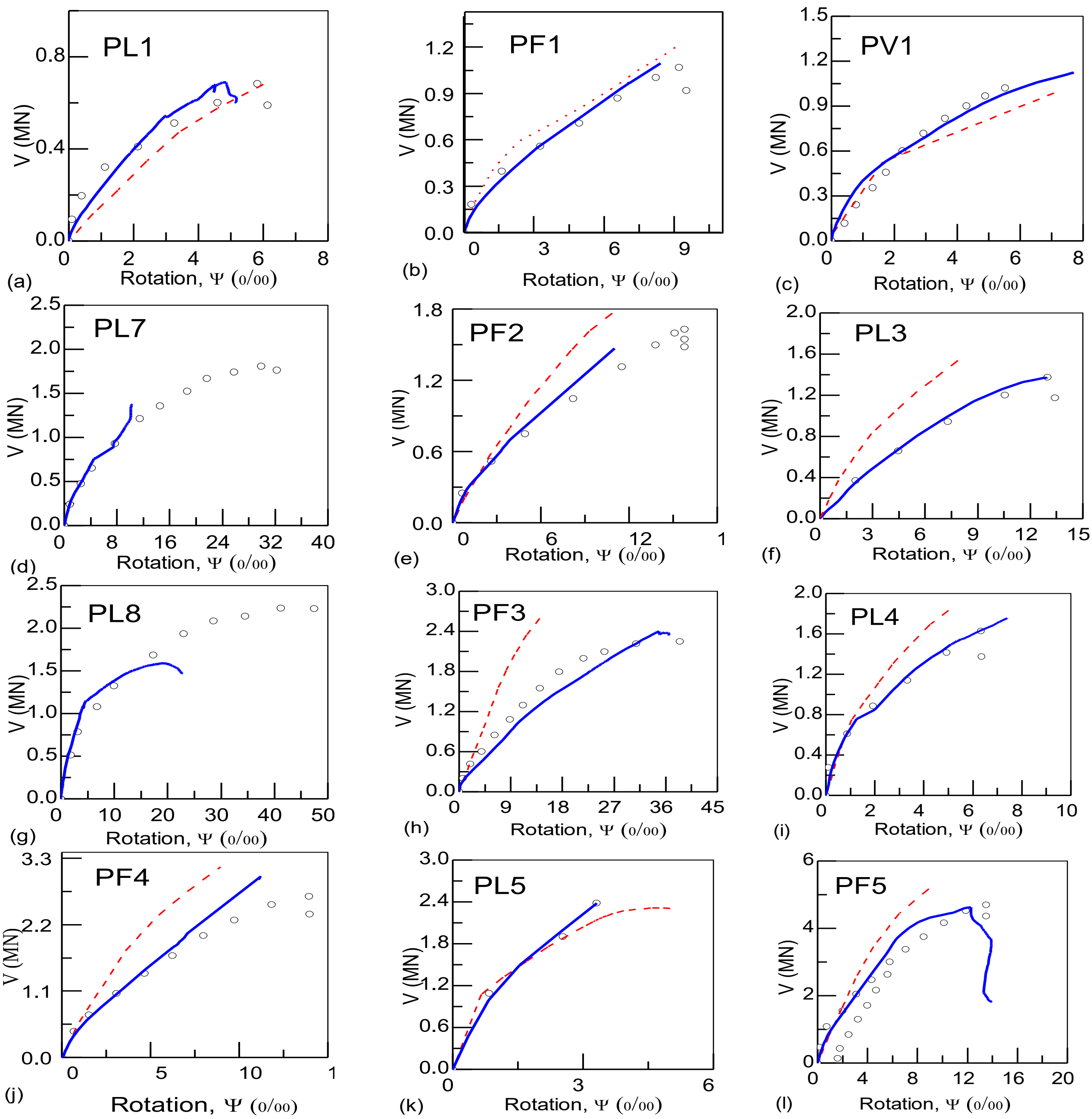


Fig. 7 Verification of the FE model with experimental model of Lips *et al.* (2012). (Symbol (circle), dashed line and straight lines represent experimental data, numerical data of Mahmoud (2015) and numerical data of the present model respectively)

maintained in all the models. The reinforcement laid in such a fashion that they are orthogonal and parallel to the slab edges. Fig. 4 depicts the typical model developed for the parametric study with stirrup. Figs. 6(a)-(b) illustrates the details of shear reinforcement systems. In this study, flat plates under three categories were verified with experimental results. Column size and slab thickness were varied for verification purpose. Then the amount of shear reinforcement was varied. The essential details are shown in Table 1. The shear studs are modeled without the anchoring plate at the top and bottom. Studs are arranged radially having constant spacing between studs of a radius according to European practice. The cages of continuous stirrups are bent bars of 10 mm dia. The spacing between each of the stirrups was kept constant 100 mm, leading to a constant shear reinforcement ratio. A 1200×1200 mm cage was placed at the center of the slab surrounded by eight smaller cages with dimensions 600×600 mm to prevent a failure at the outer perimeter of the shear reinforced area. Table 2 shows the parameters of the continuous stirrups for each model. The loads were applied at eight loading plates as shown in Fig. 3.

3. Validation of the analytical model

Results obtained from the proposed numerical models were verified with the experimental results of Lips *et al.*

Table 2 Parameters used for cages of continuous stirrup Lips *et al.* (2012)

Specimen	d_t, mm	s_t, mm	ρ_t, %	h_t, mm
PF1-PF3	10	100	0.79	200
PF4	10	100	0.79	270
PF5	10	100	0.79	345

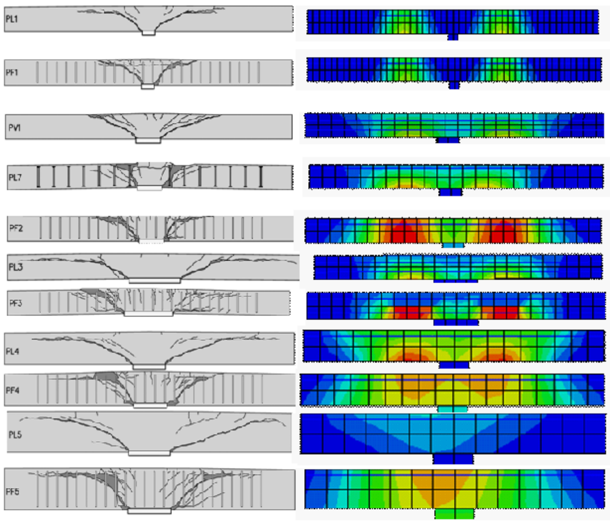


Fig. 8 Proposed and experimental cracking patterns after punching failure in correlation with experimental model of Lips *et al.* (2012)

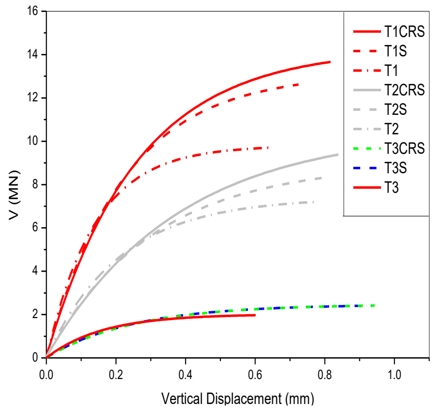


Fig. 9 Influence of slab thickness along with column reinforcement and punching reinforcement

(2012). Different finite element models with varying column size, slab thickness and punching reinforcement were developed and compared with the experimental results. The comparisons of the proposed and experimental results are shown in Figs. 7(a)-(l). Graphical presentation of the comparisons shows very good agreement between the proposed finite element model and experimental model.

Fig. 7(d) and Fig. 7(g) shows FE model results which consist of stud type of punching reinforcement without base plate. However, stud type of punching reinforcement with base plate was used in the experimental specimen. Present FE model failed to carry further load at a level far below the strength of experimental model. This is due to the fact that the studs used in the FE model are without top and bottom

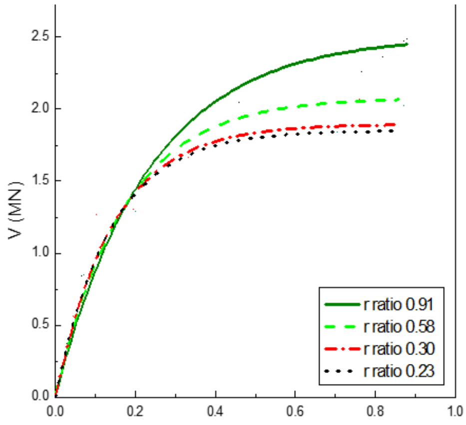


Fig. 10 Influence of reinforcement ratio

Table 3 Details of FE models for assessing influence of slab thickness, column reinforcement and punching reinforcement

Specimen	Slab Thickness	Description of the specimen
T1CRS	600 mm	With column reinforcement and punching reinforcement
T1S	600 mm	With punching reinforcement
T1	600 mm	Without column reinforcement and punching reinforcement
T2CRS	400 mm	With column reinforcement and punching reinforcement
T2S	400 mm	With punching reinforcement
T2	400 mm	Without column reinforcement and punching reinforcement
T3CRS	200 mm	With column reinforcement and punching reinforcement
T3S	200 mm	With punching reinforcement
T3	200 mm	Without column reinforcement and punching reinforcement

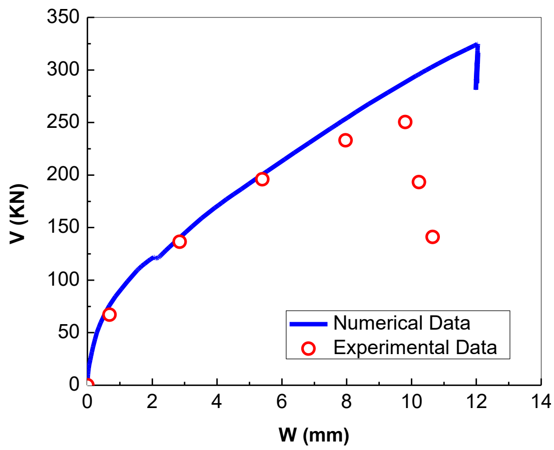


Fig. 11 Comparison of FEM results with experimental observations of Fernandez *et al.* (2013) for flat plate with integrity reinforcement

base plate. Based on the comparison it can be concluded that base plate of stud type of reinforcement contributes a significant role in carrying punching load. The proposed PL7 finite element model can attain 60 percent and PL8 finite element model can attain 70 percent of the strength of experimental model. Fig. 8 depicts the cracking pattern of the proposed and mechanical model. Location of strain localization matches with the crack pattern. Steep

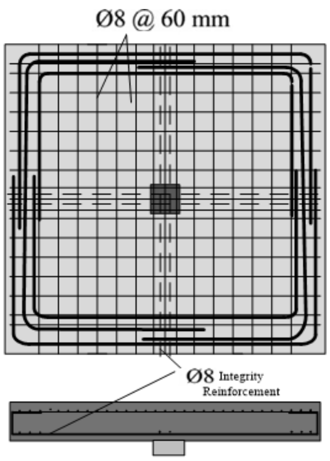


Fig. 12 Typical Layout of model for verification of integrity reinforcement

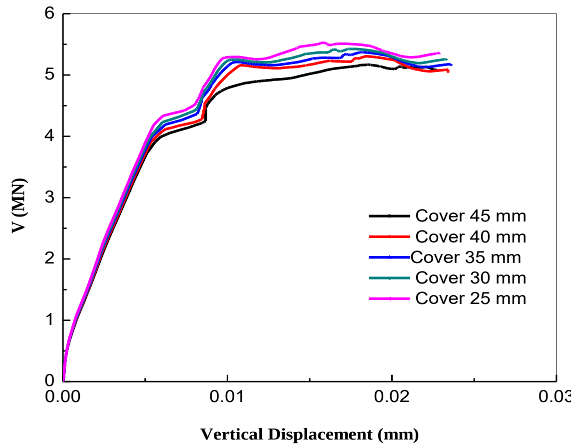


Fig. 15 Influence of clear cover

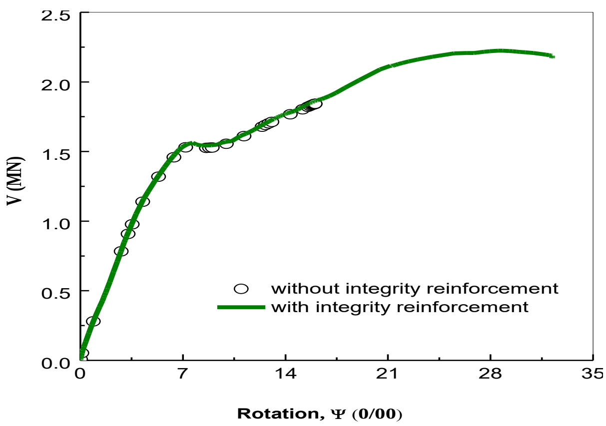


Fig. 13 Influence of integrity reinforcement

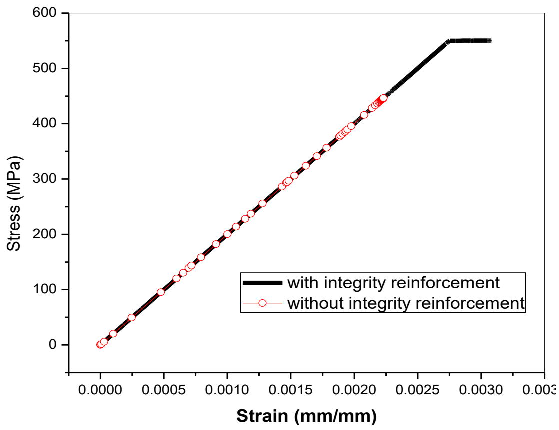


Fig. 14 Stress strain curve of column strip reinforcement

inclination of the failure surface occurs for members with large amounts of shear reinforcement. Figs. 7(i)-(j) show a comparatively large variation (approximately 30 percent) between experimental data and numerical data. The cause is attributed to the distribution of flexural reinforcement arrangement of two different types of steel in experimental setup. In Fig. 7(l) there is a loading unloading phase in experimental setup which is absent in the numerical simulation. However, the skeleton curve is in good agreement with the experimental curve.

4. Parametric study

From literature review it has been known that integrity reinforcement, column reinforcement, reinforcement ratio and clear cover exhibit important role in carrying punching load. To acquire a clear understanding of these parameters a parametric study has been carried out. Nine FE models have been developed to assess punching capacity for varying slab thickness along with column and punching reinforcement. Details of the developed FE models are shown in Table 3. Results obtained from the FE analysis are presented in Fig. 9. Increase in slab thickness increases the punching strength and ductility. If column reinforcement is incorporated in the same model it has its influence upon punching capacity. Additionally, it can be observed that for small slab thickness inclusion of column reinforcement increases ductility only.

The influence of reinforcement ratio is presented in Fig. 10. Significant variation is observed in ultimate stage of loading. In case of increase in reinforcement ratio from 0.23 to 0.91 (296%) the punching capacity increases 19 percent. As the change in reinforcement ratio from 0.23 to 0.3 is very low the change in punching capacity is very low too. Additionally, ductility decreases 6 percent due to increase with the increase in reinforcement ratio from 0.23 to 0.91 (296%). This is fact due to the failure of concrete with over reinforcement ratio. This is fact due to the failure of concrete with over reinforcement ratio.

Integrity reinforcement has marked effect on punching behaviour of flat plate. Fernandez *et al.* (2013) experimentally investigated the effect of integrity reinforcement upon punching capacity of flat plate. Finite element model has been developed in this study and results have been compared with the experimental results of Fernandez *et al.* (2013) as shown in Fig. 11. Layout of the model used for verification purpose is shown in Fig. 12.

Influence of integrity reinforcement upon the punching capacity of flat plate is presented in Fig. 13. Integrity reinforcement increases the capacity up to 19 percent and the ductility in terms of rotation is increased by 101 percent as shown in Fig. 13. Effect of integrity reinforcement on stress strain curve of column strip reinforcement is shown in Fig. 14. From this figure it is observed that the presence of integrity reinforcement ensures the ductile failure since

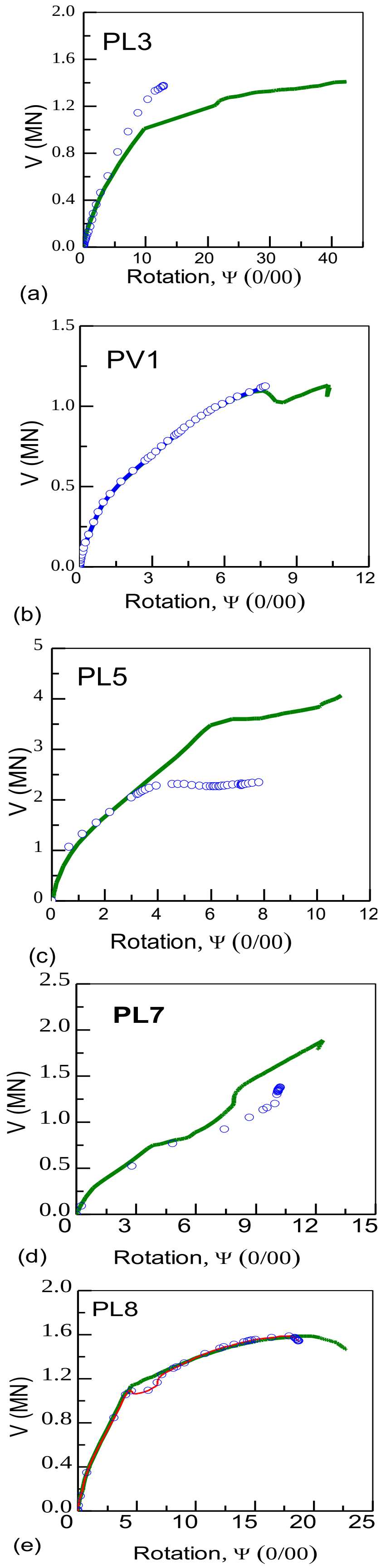


Fig. 16 Influence of column reinforcement. Symbol and straight line represents numerical data without column reinforcement and numerical data with column reinforcement respectively

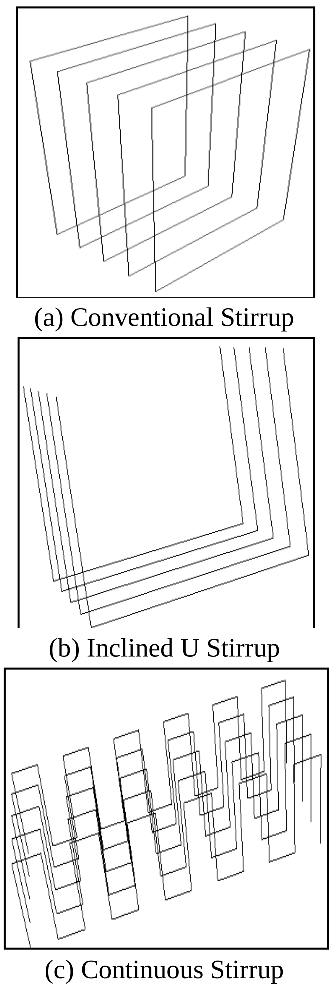


Fig. 17 Different types of shear reinforcement used for numerical simulations

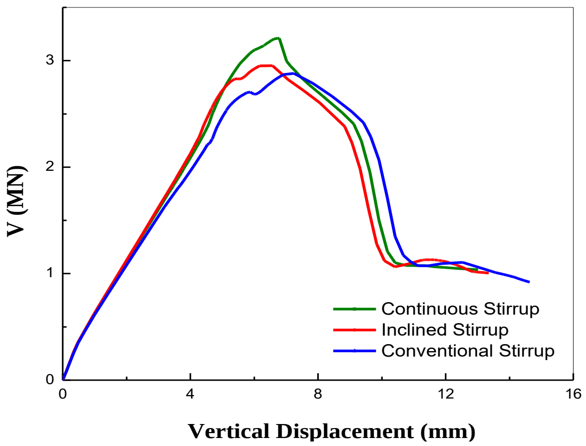


Fig. 18 Influence of different types of stirrup

the column strip reinforcement is in a stage of yielding during failure. As the clear cover increases the thickness of inbound concrete decreases consequently the capacity of slab decreases. This fact is reflected in Fig. 15. To quantify the effect of column reinforcement same amount of column reinforcements are provided in the PV1, PL3, PL5, PL7 and PL8 model. Inclusion of column reinforcement increases the punching capacity as well as ductility in terms of rotation for relatively thicker specimen as depicted in Figs. 16 (a)-(e). As the column size is higher in PL3 and PL8 the amount of column reinforcement ratio for these cases are smaller and the amount of increase in punching strength is very small. However, the ductility is increased in PL3 at a higher percentage than PL8 as transverse reinforcements are absent in PL3 model and thus the inclusion of column reinforcement contributes significantly in terms of ductility. Both punching capacity and ductility are increased significantly in case of PL7 and PL5. Different types of stirrups as shown in Fig. 17 are used to perform a comparative study. From Fig. 18 it can be concluded that continuous stirrup can provide higher punching strength. At the same time, it can also be mentioned that conventional stirrups show increased ductility. The model with cages of continuous stirrup has a capacity of 3210.7 KN which is 12 percent higher than the conventional stirrup.

5. Conclusions

Twelve finite element models have been developed and verified with the experimental setup of Lips *et al.* On the basis of the numerical simulation and experimentally available data, it can be concluded that the developed numerical model along with the material property can be used for analyzing flat plate where experimental setup is unavailable and expensive. Integrity reinforcement can be used to substantially increase the punching capacity as observed from the numerical data. Numerical simulation shows that provision of integrity reinforcement increases 19 percent of punching capacity and 101 percent of ductility. Developed numerical model can be used to quantify the influence of reinforcement ratio up on the behavior of flat plate. Variation of clear cover influences the punching capacity of flat plate. Developed finite element model can be a substitute to mechanical model to understand the influence of clear cover. Variation of slab thickness along with column reinforcement has noteworthy impact on punching capacity which is shown in Fig. 7. Increase in slab thickness increases the punching strength and ductility. Based on the comparison it can be concluded that base plate of stud type reinforcement contributes a significant role in carrying punching load. The developed finite element model with stud type transverse reinforcement without base plate can attain only 60 to 70 percent of the strength of mechanical model with stud along with base plate. To analyze the effect of column reinforcement same amount of column reinforcements is provided in the PV1, PL3, PL5, PL7 and PL8 model. Inclusion of column reinforcement increases the punching capacity as well as ductility. Cages of continuous stirrup provide higher punching strength than conventional stirrup and inclined stirrup. Inclined stirrup also provides a significant punching strength and hence can be used for retrofitting purpose.

References

Abaqus 6.9 (2009), *Abaqus Analysis User's Manual*, DassaultSystèmesSimulia Corp., Providence, Rhode Island, U.S.A.

Abaqus 6.9 (2009), *Abaqus Analysis User's Manual*, DassaultSystèmesSimulia Corp., Providence, Rhode Island, U.S.A.

ACI 318-05 (2005), *Building Code Requirements for Structural Concrete*, American Concrete Institute, Farmington Hills, Michigan, U.S.A.

Eurocode 2 (2004), *Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings*, European Committee for Standardization (CEN), Brussels, Belgium.

Fib (2010), *International Federation for Structural Concrete*, Comité Euro-International and Federation for Prestressing, Lausanne, Switzerland.

Guandalini, S., Burdet, O. and Muttoni, A. (2009), "Punching tests of slabs with low reinforcement ratios", *ACI Structural J.*, **106**(1), 87-95.

Keyvani, L., Sasani, M. and Mirzaei, Y. (2014), "Compressive membrane action in progressive collapse resistance of RC flat plates", *Eng. Struct.*, **59**, 554-564.

Kinnunen, S. and Nylander, H. (1960), Punching of Concrete Slabs without Reinforcement", Royal Institute of Technology, Stockholm, Sweden.

Kurtoğlula, A.E., Cevik, A., Albegmprli, H.M., Gülşan, M.E. and Bilgehanld, M. (2016), "Reliability-based modeling of punching shear capacity of FRP-reinforced two-way slabs", *Comput. Concrete*, **17**(1), 0-20.

Lips, S., Ruiz, F.M. and Muttoni, A. (2012), "Experimental investigation on punching strength and deformation capacity of shear-reinforced slabs", *ACI Struct. J.*, **109**, 889-900.

Mahmoud, A.M. (2015), "Finite element implementation of punching shear behaviors in shear-reinforced flat slabs", *Ain Sham. Eng. J.*, **6**(3), 735-754.

Mirzaei, Y. and Sasani, M. (2011), "Punching shear failure in progressive collapse analysis", *Struct. Congr.*, 2941-2950.

Mirzaei, Y. and Sasani, M. (2013), "Progressive collapse resistance of flat slab-modeling post punching behavior", *Comput. Concrete*, **12**(3), 351-375.

Micallef, K., Sagaseta, J., Fernández, R.M. and Muttoni, A. (2014), "Assessing punching shear failure in reinforced concrete at slabs subjected to localized impact loading", *J. Imp. Eng.*, **71**, 17-33.

Moeinaddin, F. (2012), "Concentric punching shear strength of reinforced concrete flat plates", M.Sc. Dissertation, Swinburne University of Technology, Melbourne, Australia.

Muttoni, A. (2008), "Punching shear strength of reinforced concrete slabs without transverse reinforcement", *ACI Struct. J.*, **105**(4), 440-450.

Ruiz, F.M. and Muttoni, A. (2009), "Applications of the critical shear crack theory to punching of R/C slabs with transverse reinforcement", *ACI Struct. J.*, **106**(4), 485-494.

Ruiz, F.M., Mirzaei, Y. and Muttoni, A. (2013), "Post-punching behavior of flat slabs", *ACI Struct. J.*, **110**(5), 801-812.

Shuraim, A.B., Aslam, F., Hussain, R.R. and Alhozaimy, A.M. (2016), "Analysis of punching shear in high strength RC panels-experiments, comparison with codes and FEM results", *Comput. Concrete*, **17**(6), 739-760.

Zahura, F.T. and Ahsan, R. (2016), "Numerical simulation of punching shear of flat plates with low reinforcement", *J. Civil Environ. Struct. Constr. Architect. Eng.*, **10**(7), 883-886.

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