Volume 45 Number 2
June - July 2018

ISSN 0970-0137

Journal of Structural Engineering

CSIR-Structural Engineering Research Centre
(Council of Scientific & Industrial Research)
Chennai, India

CSIR-SERC
ENGINEERING SUSTAINABLE STRUCTURES

JOURNAL OF STRUCTURAL ENGINEERING

NOTES TO CONTRIBUTORS

The Journal of Structural Engineering is an open forum on structural engineering and full-length papers and short communications relating to the field are always welcome. Prospective contributors may write for a copy of the 'Instructions to Authors' before submitting manuscripts or can directly download from the journal page of the website http:/www.serc.res.in.

Standards of acceptance of papers for publication in the Journal

1. The paper should be of value of interest to structural engineers. It should be a contribution to the advancement of knowledge in structural engineering.
2. The paper may be an original review of past practice, probe a new field of structural engineering activity, or report on results of research and development activities.
3. The paper should be a thought-provoking study that contributes to the planning, analysis, design, construction, or maintenance of structural engineering works.
4. The Short Communication papers should cover the topics: Details of experiment carried out as per the national/ international codes of practice (if available) and the experimental results, and/or new methodologies/ techniques developed in Structural Engineering. The number of pages (A4 size double spaced including tables, figures and/or any other illustrations) should not exceed eight. Every effort will be made to publish the short communications as early as possible.
5. The authors are encouraged to submit their papers electronically to any one of the editors with a copy to jose@serc.res.in, or, directly to jose@serc.res.in.
6. Editors have right to publish one paper out of turn.

Discussion

All technical matters appearing in the journal may be discussed, but the deadline given must be strictly met. Discussion should meet the policy of the journal and should be confined to the scope of the paper under discussion.

All enquires regarding subscription, change of address of subscribers, back numbers, reprints, etc., should be addressed to the Circulation Manager, Journal of Structural Engineering, CSIR-SERC, CSIR Campus, Taramani, Chennai – 600 113, India. All correspondence regarding contributions, discussions, and books for review should be addressed to the Editors.

The Journal is published once in two months from the CSIR-Structural Engineering Research Centre, Chennai. The publishers are not responsible for any statement made or any opinion expressed in the Journal. Permission is given to reprint any article after its publication in the Journal, provided due credit is given to the Journal and the authors, and, provided the copies are not intended for sale; however, prior information should be sent to the Editor for record.

Annual Subscription

Inland : ₹ 2000
Foreign : US $ 100

Journal of Structural Engineering

Volume 45 Number 2
June - July 2018

Contents

Typeset in LATEX and printed by
Sigma Publishing Services
No. 101B, 3rd Main Road, State Bank Colony
Nanganallur, Chennai - 600 061.
Phone: 044-65151910
Email: sigmapublishing17@gmail.com

ISSN 0970013-7

9 770970 013003

...al of Structural Engineering
...5, No. 2, June - July 2018 pp. 221-227

No. 45-T1

Parametric study on seismic behaviour of slab-column junctions in flat slab system subjected to punching shear

Vijaya Kumar Kandi*, Lute Venkat*,✉ and G. Papa Rao*

✉ Email: lutevenkat@gmail.com

*Department of Civil Engineering, Gayatri Vidya Parishad College of Engineering, Visakhapatnam - 530 048, INDIA.

Received: 07 August 2017; Accepted: 28 December 2017

As the construction activities are going on everywhere, there will be space crunch, staggered column orientation and irregular geometry. Construction of huge structures has been generated to overcome these difficulties by introducing flat slabs which make beams invisible, lesser dead weight, increased speed of construction and enlarges floor area. It is simple to construct and enhances the clear height. These structures contain large vertical forces and bending moment in zone of support. In 1905 American Engineer Turner employed the concrete floor slabs without beams (called flat plates or flat slabs) and used diagonal and orthogonal pattern of reinforcing bars. This was the beginning of flat-slab construction. However the past and recent failures of flat slab structures have underlined the need for reviewing the construction practices and current design, especially the construction of flat slab system in high seismic regions. Kuang and Morley[1] studied punching shear behavior of restrained reinforced concrete flat slabs and concluded that edge and corner restraint has significant effect on punching load of slabs. In two-way shear failure or punching failure, the diagonal tension cracks will occur along a pyramid or truncated cone passing through the critical sections. Sagaseta[2] depicted that the punching shear strength of flat slabs at rectangular columns can be lower than the equivalent square columns with a similar length of the control perimeter. The reduction in punching shear capacity due to the concentration of shear forces near the corners of square and rectangular columns with the side length of column to depth of slab ratio greater than three depends on the bending deflections of the column geometry and slab. Many flat plate structures have been collapsing in the mode of punching failure especially during earthquakes. Osman, et.al[3] discussed the exterior slab column connection subjected to an unbalanced moment produced by the lateral as well as gravity load in the non-linear analysis method. It was concluded that the exterior slab-column connection more susceptible to punching shear failure. Unlike interior panels, the exterior panel is not in a fixed manner due to torsional effects which are induced by unbalanced moments and results in lifting up of corner and edge connections of slab inducing reduction of stiffness of slab. Therefore the punching shear failure in flat slab system has greater significance and effective solutions to avoid punching shear failure are of great importance. John and David[4] stated that the punching shear strength of an interior slab-column connection increases as the column aspect ratio (shorter side of column/longer side of column) increases. The shear stress resistance of slab-column connection decreases as column side length to slab depth ratio increases. Tuan[5] reported that the high strength concrete improves the punching shear strength by delivering the higher forces through slab-column connection. Many of design procedures are based on normal strength of concrete. Therefore, it is necessary to use of high strength concrete. Based on extensive experimental and analytical studies, it is intended to prescribe the design guide lines for safe construction of flat slab structure in high seismic zones. Priya, et, al.[6] carried out analytical model for flat slab column connection subjected to lateral load in order to verify the connection behavior for the given detailing.

Kashliwal and Dasgupta[7] worked on finite element model of flat slab and column connection under seismic loading and studied the influence of various parameters on punching shear. Hosahalli and Aktan[8] investigated the weakness of exterior flat slab-column connection during extreme seismic condition. Based on the literature, it is concluded that the flat slab –column connection is critical zone for punching shear. Hence, in this study number of parameters influencing the punching shear capacity at the slab-column connection under lateral load is considered.

A typical six storey (*G*+5) residential type open ground reinforced concrete flat slab is considered. The non-linear static pushover analysis was performed for which non linear model for concrete is taken. This process is repeated for various column aspect ratios, depth to span ratio and influence of drop on punching shear stresses are being studied. This study particularly emphasized on the predicted mode of failure and punching shear capacity. The different modes of failure were based on structural response i.e., deflection, crack pattern and stresses in steel and concrete which agree with analytical observations. Parametric study using non-linear pushover analysis was performed to carry out the strength and distribution of internal forces developing at the corner and interior slab-column junctions.

Structural modeling

In this study, six storey (*G*+5) residential type open ground reinforced concrete building with flat plate system is taken. Analysis has been carried out using ETABS software. The structural properties and external load details are mentioned in Table 1. Plan and elevation of the structure along with dimensions are shown in Figs. 1 and 2.

Analysis methodology

In order to study non-linear behaviour of building, pushover analysis is carried out. It is a step wise non-linear static procedure primarily used to govern the response of a structure at every individual step. It is a non linear and static procedure in which the magnitude of structural loading increased incrementally with a certain pre-defined pattern accordingly. With the increase in magnitude of structural loading, failure modes and weak links are found. It involves two steps: (i) the response of the structure is governed under vertical or gravity loads only (*DL* + *LL*) and (ii) Then the structure is displaced in the direction of lateral load.

TABLE 1

STRUCTURAL PROPERTIES

Column size = 600mm × 450mm	Size of drop= 2500mm × 2500mm
Overall depth of the slab (*D*) = 300mm	Thickness of drop = 80mm
Effective depth of the slab (*d*) = 270mm	Panel size = 6000mm × 8000mm
Live load on the roof floor = 1.75kN/m^2	Live load on the remaining floors =3.5kN/m^2
Dead load = 7.5kN/m^2	Zone factor = IV
Grade of concrete = M25	Grade of steel = HYSD bars 415
Total gravity load on the roof floor of slab = 9.25kN/m^2	Total gravity load on the remaining floors of slab = 11kN/m^2

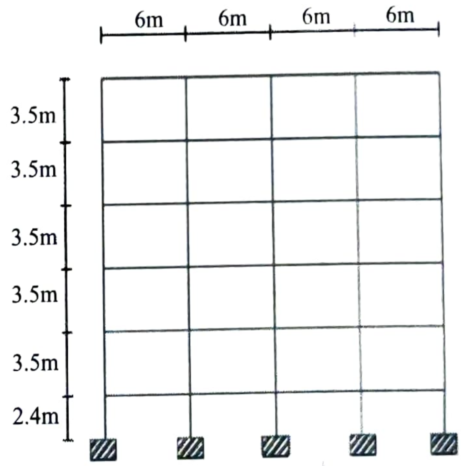


Fig. 1 Sectional elevation of the building

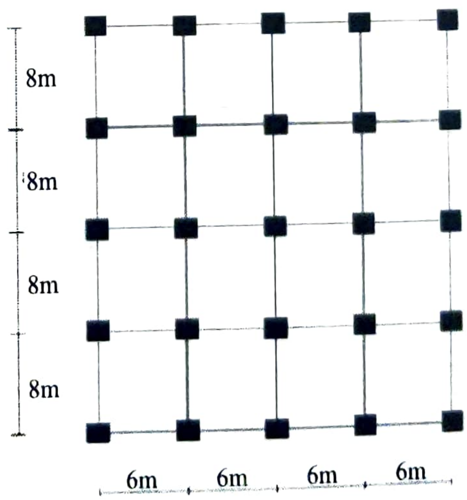


Fig. 2 Plan of the building

imary steps involved in pushover analysis

placement control: It is attempted to examine the tility of the structure. Displacement control monitors behavior of moments, hinges and base reactions etc. h respect to lateral drift. In this study, displacement trol pushover analysis is carried out using software ABS program. On performing pushover analysis, behavior of slab-column connections punching ear capacity is monitored at every step.

orce control: It is undertaken to estimate up to what level of forces the structures behaves elastically. Once the structure reaches the plastic state, then the force control pushover analysis will fails as the load carrying capacity of the structure becomes constant. Force control pushover analysis is performed in case of linear analysis because to monitor the behavior beyond plastic phase, displacement control pushover analysis is used.

RESULTS AND DISCUSSION

The parameters influencing the punching shear strength of flat slab system are column aspect ratio, concrete strength, depth to span ratio, flexural reinforcement, gravity loading, shear reinforcement and the presence of drop. In the present study, the parameters taken for investigation of the behavior of punching shear strength are column aspect ratio, depth to span ratio and presence and absence of drop. The response of the 3rd storey i.e., intermediate floor is being considered. The results and discussions are obtained for intermediate and corner slab-column junctions of the building. The shear stress (τ_v) of the flat slab-column connection is normalized with respect to the design shear capacity of the connection ($\tau_c = 0.25\sqrt{(f_{ck})}$). And the displacement (Δ) values of the building are established with respect to the height of building (H_b) which is known as lateral drift ratio also.

Effect of depth to span ratio

Depth to span ratio (D/L) is varied by changing the thickness of depth of flat slab for the constant span. Punching shear strength of the corner as well as interior junctions is obtained with the varying depth to span ratio of flat slab for a particular grade of concrete, loads and column aspect ratio. For the analysis, the different depths to span ratios taken are:

(i) $D/L = 0.10$; (ii) $D/L = 0.08$; (iii) $D/L = 0.07$ (iv) $D/L = 0.05$; (v) $D/L = 0.03$

The shear stress distribution in the flat-slab system for various depth to span ratios is obtained after performing the non linear static pushover analysis using ETABS 2015. From the obtained stress diagram (Figs. 9 and10), it is observed that the area of flat plate around the edge and corner column positions become very critical because of high punching shear stresses. As the loading is on only two sides of the column, the induced unbalanced moment produces additional torsional moments.

Interior slab- column junctions

The slab dimensions considered this study are same but varying depth of the slab. It is observed that there is significant effect on nominal punching shear stress. The general trend of the punching shear is presented in Fig. 3. It indicates that with increase in depth to span ratio (D/L), nominal shear stress decreases and punching shear strength increases. With the increased thickness of slab depth, the local and brittle nature of shear failure diminishes because of higher shear resistance of concrete. The slope of lower depth to span flat plate remains nearly same. From Fig. 3 it is also observed that the shear capacity of connection is found to highest for $D/L = 0.03$ with 3.104 τ_c equals to 3.88 N/mm2 and less value is obtained for $D/L = 0.10$ with 0.626 τ_c equals to 0.7825 N/mm2. Beyond the peak shear strength phase, the flat plate structure with higher depth to span ratios shows abrupt failure in shear with brittle mode of failure because thicker depth of slab has lower rotation capacity and allows them to fail in brittle only. Post peak strength of slab-column connections with lower values of D/L ratio is found to degrade gradually. The depth to span ratio 0.07 is found to be critical D/L ratio. A dimensionless parameter N_{dr} is defined as $(D/L)/0.07$, which is mathematically equals to $N_{dr} = 14.28\ (D/L)$. If N_{dr} is less than one, mode of punching shear failure is ductile and if N_{dr} greater than one, it is brittle. For lower D/L ratios, connections preceded by larger rotations because of thinner depth of slab leading to ductile failure of the connection. For higher D/L ratios, slabs fail in brittle because the compressive stress exceeds the compressive strength of concrete, then portion of the slab near slab-column connection was crushed. Accordingly higher depth of slab enhances the stiffness and lowers the deflections. In Fig. 3, it is shown that the lateral drift ratio increases with decrease in D/L ratio because of larger rotations and unbalanced moments. For $D/L = 0.10$, the peak lateral drift is 0.476% and for $D/L = 0.03$, it is 1.135%. Irrespective of the depth to span ratio, the elastic drift limit is likely to be more than 0.4% of the height of the building, which is more than the prescribed limit by IS: 1893-2002[9].

Corner slab-column connection

The general trend of the graph (Fig. 4) depicts that with increase in D/L ratio, the punching shear capacity is increased. The corner slab-column connections confined to limited width on either sides of the column, which are susceptible to higher torsional moments. The punching shear stress of the corner slab-column connection is found to be highest for $D/L = 0.03$ equals to 7.368 τ_c and the least value was observed for $D/L = 0.10$ equals to 2.936 τ_c.

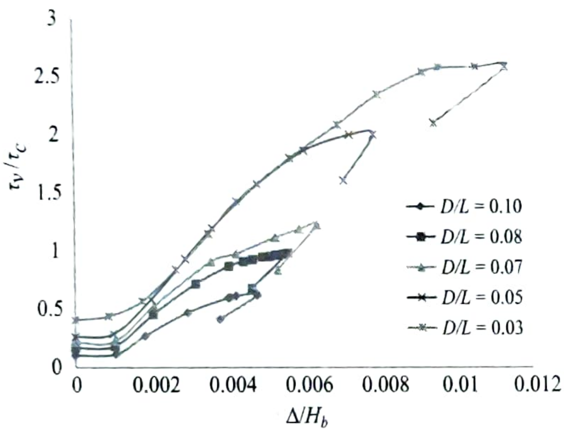


Fig. 3 Effect of D/L on punching shear for interior slab-column junction

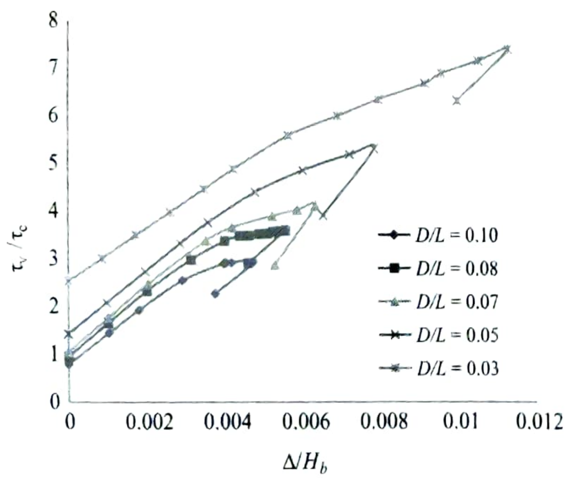


Fig. 4 Effect of D/L on punching shear for corner slab-column junction

Effect of column aspect ratio

Aspect ratio (β) is equals to the ratio of longer side of the column to the shorter side of the column. For a given grade of concrete, fixed span and thickness of plate, the influence of aspect ratio on punching shear is studied. The variation in aspect ratio is obtained by varying the width of the column but the depth of column in the direction of pushover is kept same. The various aspect ratios taken are:

size of column = 600mm × 600mm; $\beta = 1$;
size of column = 600mm × 530mm; $\beta = 1.14$
size of column = 600mm × 450mm; $\beta = 1.33$
size of column = 600mm × 400mm; $\beta = 1.5$
size of column = 600mm × 300mm; $\beta = 2$

Interior and corner slab-column junctions

With an increase in the column aspect ratio (β), the punching shear strength around the slab-column connection decreases till the peak shear strength is reached and beyond the peak strength the trend reverses. Beyond the peak shear strength, the shear strength of slab-column connection having lower aspect ratio falls steeply compare to the connections having larger aspect ratio. The peak occurs at higher values of lateral drift ratio with an increase in the column aspect ratio because transverse moments are confined to limited width on either sides of the column due to reduced column dimension. Slab-column connections with higher aspect ratios ($\beta = 1.5$ and 2) appears to be more ductile in comparison to the connections with lower values aspect ratio ($\beta = 1$ and 1.14) is depicted in Figs. 5 and 6. The maximum shear capacity is obtained in a lateral drift range of 0.7-0.9% for both junctions. The shear capacity varies linearly up to a lateral drift of about 0.55% before the shear capacity curves goes into non-linear zone.

For β=1, the interior column shows punching shear capacity four times more than corner column. The code IS1893:2002[9] (part1) prescribed drift limit of 0.4% underestimates the actual behavior because the code follows only elastic concrete behavior. And the additional strength due to material non-linearity of concrete doesn't take into account in resisting punching shear. The peak shear strength is found to be higher in case of corner connections compare to interior connections due to torsional stiffness and unbalanced moment. The column aspect ratio didn't tell about ode of failure i.e., either brittle or ductile, because it lated to the depth of slab. And the lateral drift range is me for both interior and corner junctions and shows riation in punching shear capacity only. From Figs. 3 d 5, it is clear that the punching shear stress remains near up to some initial deflection and then it abruptly ses in interior slab-column junctions compare to xterior slab-column junctions. This is because of nterior junctions possess more rigidity and does not subject to lateral load primarily.

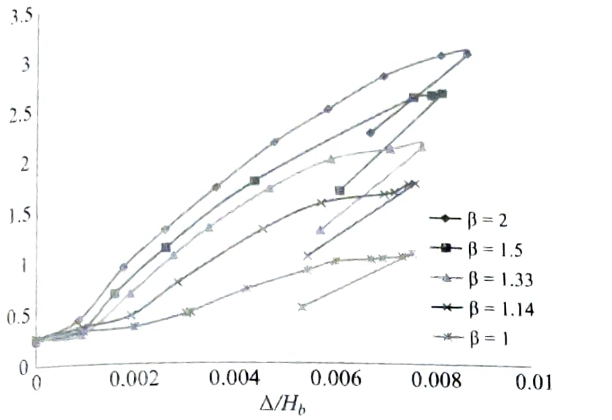


Fig. 5 Effect of β on punching shear for interior slab-column junction

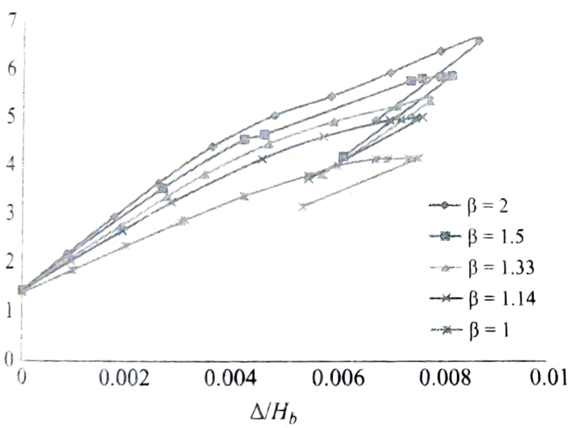


Fig. 6 Effect of β on punching shear for corner slab-column junction

Influence of drop on punching shear and stress pattern

As the flat slabs directly rests on the columns, high magnitude of bending moment and shear force develops at the face of the column. Therefore the columns may likely to punch the slab. To sustain these stresses, the slab is thickened near slab-column connection. When a flat plate structure is subjected to lateral loading, the mechanism of transfer of moments from a slab to the columns is very complex and gives rise to unbalanced moments. These unbalanced moments produce shear and torsion at the slab-column joints and transferred into column leading to excessive cracking and reduction in stiffness of connections. Influence of the drop is plotted in Figs. 7 and 8, it is observed that with provision of drop, the punching shear capacity drastically increases and deflections are reduced. The maximum peak stress observed for exterior column of flat plate without drop model is 4.56 times γ_c and whereas the flat plate with drop model is 1.768 times γ_c. The peak stress for interior column of flat plate without drop model is 1.68 times γ_c and that for with drop is 0.568 times γ_c. From the graphs (Figs. 7 and 8), it is observed that to counteract punching shear failure, the interior column connections of a building should be of flat-plate type and exterior column connections are of flat plate with drop type is more effective and economical compare to flat-plate with perimeter beams structure. Beyond peak strength, the punching shear capacity decreases gradually for flat plate with drop model and falls steeply for without drop model. Therefore flat plate with drop structure shows more stiffness, lesser deflection, reduction in negative bending moment and decrease in shear stress. Flat plate with drop is more preferred in high seismic regions. In Fig. 7, it is shown that the flat slab with drop model has deflection 1.44 times less and punching shear capacity 2.97 times more in comparison to without drop model. Flat plate with perimeter beams shows more rigidity and punching shear capacity in initial stage because of beam-column action. But at later stage it reduces drastically due to slab-column action of interior columns.

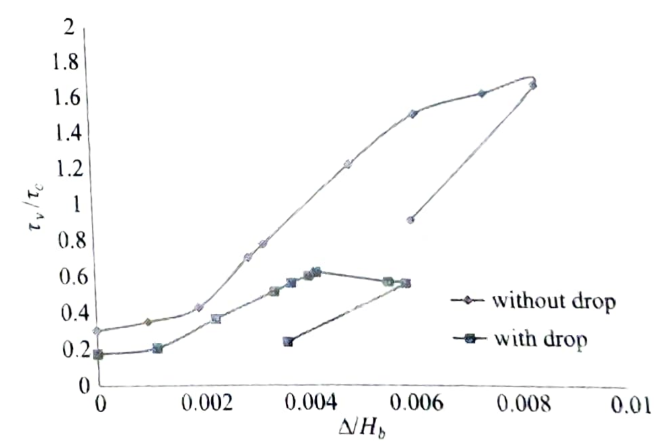


Fig. 7 Effect of drop on punching shear for interior slab-column junction

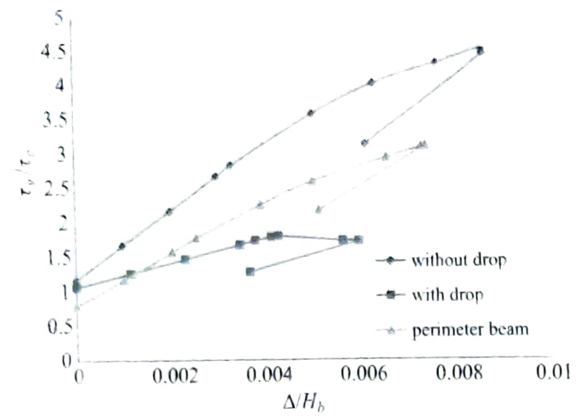
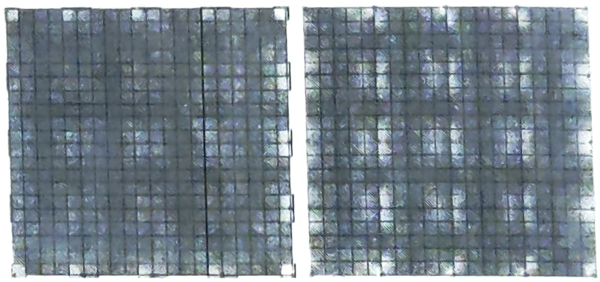


Fig. 8 Effect of drop on punching shear for corner slab-column junction

Stress pattern

When the load is applied on the slab, the first crack to form around the perimeter of loaded area is roughly a circular crack due to the negative bending moment in the radial direction. Due to negative bending moment, radial cracks are developed in the circumferential direction and they extend from perimeter. After a significant increment in load, tangential cracks form around the loaded area at a certain distance from the column face. At the same time shear or inclined cracks form on the truncated surface. The critical section of the slab for shear and moment are both at or close to the periphery of the loaded area and hence it is expected that moment shear interaction would occur. This moment-shear interaction complicates the classification of mode of failure at the connections. Once the shear strength of slab is reached, the punching shear failure takes place along a truncated cone developed by the diagonal tension cracks around the column. At compressed surface, the strain in concrete reaches their highest values and the strains in radial direction decreases rapidly with increase in distance from the column. For the circular columns of circular slab, the tangential strain always to be higher than radial strain and the radial strain around the column often decreases before failure and also sometimes changes from compression to tension. The distribution of strains at the rectangular column face shows concentration of stress at corner.

The Figs. 9(a) and 9(b) indicates that the punching shear stress is high at the corner than interior slab-column junctions in both models. This is because of primary susceptible of lateral load, torsional dissimilarities around the corner slab-column junction. This concentration of stress basically increases with larger rectangular or square column but is absent in slabs with round or circular column. The shear stress at various locations i.e., interior, edge and corner slab-column junctions of flat slab are summarized in Table 2 for gravity and gravity plus push conditions after performing the non-linear static pushover analysis.



(a) (b)

(c)

Fig. 9 (a) Shear stress didtribution in with drop model; (b) shear stress didtribution in without drop model; (c) intensity of stress in MPa

CONCLUSIONS

Non-linear static pushover analysis of flat plate structure was performed to study the influence of

TABLE 2

VARIATION OF SHEAR STRESS (τ_v) in N/mm² AT DIFFERENT JUNCTIONS UNDER GRAVITY AND SEISMIC LOADING

Slab-column junction	With drop			Without drop		
	Gravity	Gravity + push		Gravity	Gravity + push	
	maximum	Ultimate point	Breaking point	maximum	Ultimate point	Breaking point
Interior	0.21	0.72	0.27	0.35	1.02	0.74
Exterior	0.44	1.15	0.79	0.8	1.45	1.01
Corner	1.15	2.22	1.64	1.72	2.47	1.93

rameters like column aspect ratio, depth to span ratio d drop dimensions on the punching shear capacity the corner and intermediate slab-column junctions. e salient conclusions drawn from non-linear static lysis are as follows:

- Compared to flat-plate building, the flat-plate with drop structure enhances the punching shear capacity 2.579 times more and shows 1.44 times lesser deflections and more stiffness. In a higher seismic regions, the flat plate with drop is more effective and shows 1.791 times more punching shear strength compare to the flat plate with perimeter beams.
- With the increase in depth to span ratio, the punching shear capacity is increased for both intermediate and corner junctions. Higher this ratio, the structures behave brittle mode of failure because the thicker plate has lower rotation capacity. When this ratio is low it indicates ductile nature. Punching shear failure abruptly occurs in brittle mode only.
- With the increase in column aspect ratio, the punching shear strength of slab-column junction decreases for both interior and corner junctions. Higher this ratio, columns appears to be more ductile compare to low aspect ratio because these columns are confined to limited width on either sides of the column.
- If depth to span ratio is less than 0.07, then mode of punching shear failure is brittle and if depth to span ratio is greater than 0.07, it is ductile mode of failure.
- IS1893:2002[9] prescribed elastic drift limit of 0.4% which underestimates the actual behavior, because IS code follows elastic concrete behavior doesn't considering additional strength due to material non-linearity of concrete in resisting punching shear.

REFERENCES

1. Kuang, J.S. and Morley, T.C., "Punching shear behaviour of restrained reinforced concrete slabs" *ACI Struct. Jl.*, Vol. 89, 1993, pp 13–19.
2. Sagaseta, J., Tassinari, L., Fernandez Ruiz, M. and Muttoni, A., "Punching of flat slabs supported on rectangular columns", *Engg. Structs.* (Elsevier), Vol. 77, 2014, pp 17–33.
3. Osman, M., Marzouk, H. and Helmy, S., "Behavior of High-Strength Lightweight Concrete Slabs under Punching Loads", *ACI Struct. Jl.*, Vol. 97, 2007, pp 492–498.
4. John, L. and David, M., "Punching shear behavior of slabs with varying span-depth ratios", *ACI Struct. Jl.*, Vol. 87, 2012, pp 507–511.
5. Tuan, N.D., "Punching shear resistance of high-strength concrete slabs", *Elect. Jol. of Struct. Engg.*, Vol. 1, 2001, pp 52–61.
6. Priya, M., Greeshma, S. and Suganya, K.N., "Finite Element Analysis of slab-column joint under lateral loading", *Asian Jl. of Civ. Engg.*, Vol. 16(2), 2015, pp 291–300.
7. Kashliwal, A. and Dasgupta, K., "Parametric study on seismic behaviour of exterior reinforced concrete flat plate column connection", *Proc. of 15th World Con. on Earthquake Engg.*, Lisbon, Portugal, 2012.
8. Hosahalli, S.R. and Aktan, A.E., "Seismic vulnerability of flat slab- core buildings", *Jl. of Struct. Engg.* (ASCE), Vol. 120 (2), 1994, pp 339–359.
9. IS 1893:2002 (Part1), *Indian standard criteria for Earthquake resistant design of structures - part1: General provisions and buildings*, Bureau of Indian Standards, New Delhi.

(Discussion on this article must reach the editor before November 30, 2018)