Civil Engineering Infrastructures Journal 2021, 54(1): 181-194
DOI: 10.22059/ceij.2020.291570.1624

TECHNICAL NOTE

A Review on Progressive Collapse of Reinforced Concrete Flat Slab Structures

Silpa, G.[1] **and Yamini Sreevalli, I.**[2]*

[1] Ph.D. Candidate, Research Scholar, School of Mechanical and Building Sciences, Vellore Institute of Technology, Chennai, India.
[2] Associate Professor, School of Mechanical and Building Sciences, Vellore Institute of Technology, Chennai, India.

Received: 29 Oct. 2019; Revised: 07 Sep. 2020; Accepted: 12 Sep. 2020

ABSTRACT: The reinforced concrete flat slab structures are highly susceptible to punching shear failure. This occurs due to the transferring of shear force and due to the bending moment between the slab and the column. The initial local failure and the following redistribution of load can lead to punching failure of the slab in the adjacent column locations. This issue can collapse an entire building or a huge portion of a structure. Hence, an alternate load path method is necessary for preventing the catastrophic failure of the buildings. Compared to the moment frame buildings, flat slab buildings are more prone to the progressive collapse. Thus, the designing of flat plate structures demands more attention and study. Due to higher construction costs and limitations in the test set up, the researchers have adopted scale down structures for the experimental studies. The progressive collapse behavior of the prototype structures is usually analyzed using both analytical and numerical simulations. This paper discusses the existing researchers on the analytical study, experimental study, and numerical simulations of flat slab structures along with various load resisting mechanisms to mitigate progressive collapse. Further, various strengthening techniques available in the literature for the flat slab structures have been discussed. A parametric study and comparison of different strengthening techniques are also performed in this work.

Keywords: Flat Slab, Load Carrying Mechanisms, Progressive Collapse, Punching Shear, Strengthening Technique.

1. Introduction

The reinforced concrete flat slab structure comprises of slabs with or without drop panels, which is directly supported on the columns with or without flared column heads. Flat slab structures without drop panels are called as flat plate structures. The flat slab structures are generally used in industrial and residential buildings. Simple formwork, less construction cost, ease of installation, higher flexibility in interior layout, ease of future renovation, and larger clear space are the major advantages of the flat plate buildings. The increased freedom in architectural design will also help to minimize the cost of maintenance and construction. Despite these advantages, the

* Corresponding author E-mail: yaminisreevalli.i@vit.ac.in

flat slab structures are highly susceptible to punching shear failure because of the concentrated shear force and bending moment near the slab-column connections. Hence, it is desirable to redistribute the gravity load initially carried by the failed slab column connection to the neighboring locations. This additional load may cause punching shear failures in those locations. The progressive collapse of the whole structure occurs as a result of an inadequate load-carrying mechanism (Rezaie et al., 2018). Compared to the moment frame structures, the flat slab structures are more prone to progressive collapse. This occurs as there is no beam to redistribute the load, which is previously supported by the lost column. The schematic sketch of the horizontally propagating punching shear failure is shown in Figure 1.

One of the most disastrous events that happened due to the failure of punching shear of the flat plates is the collision of the Sampoong Department Store in South Korea during the year 1995. Around 500 people were killed in this tragedy. Another event is the collapse of the Pipers Row car park in Wolverhampton in 1997 (Zahrai et al., 2014). The collapse of these structures occurred due to low punching shear capacity, poor quality of the materials used and weak reinforcement detailing. Thus, a thorough knowledge of the progressive collapse mechanism is essential for rational and safe designs. To prevent the progressive collapse triggered due to local failure, the design and detailing of the slab has to be done carefully. Adequate design and detailing of the slab helps to establish the secondary load-carrying mechanism after the foremost failure. The appropriately anchored continuous reinforcement bars help to develop the tensile membrane action after the initial failure of the slab. The final collapse of the structure will occur due to the rupture of the reinforcement (Mitchell et al., 1984).

In this paper, it is explained the various analytical, experimental and numerical studies for assessing the progressive collapse of flat slab buildings. The various load-carrying mechanisms and strengthening techniques available in the literature to mitigate progressive collapses are also discussed. A comparison of the existing strengthening techniques is also presented in this work. This study deals only with ductile gravity resistant flat slab structures.

2. Analytical Study

Mitchell et al. (1984) analytically investigated the progressive collapse response of the RC slab under simply supported and fixed boundary conditions. This is the only paper that discusses the analytical study of the progressive collapse of flat slab models. In this work, the authors described an analytical model and proposed an iterative method to find out the tensile membrane action of the slab. They also developed a non-linear computer program for analyzing the slab’s post-failure response. This computer coding can foresee the tensile membrane action of the slab having various boundary conditions. They emphasized the importance of the properly anchored bottom reinforcement. Figure 2 demonstrates the distinct variation in the post-failure response of the slab-column joints. In the slab-column connection with no bottom reinforcement, the reinforcement at the upper part rips out after the punching shear failure and loses its load-carrying capacity. This negligible post punching resistance results in the collapse of the flat slab. The post punching resistance exists in the slab-column connection having well-anchored bottom reinforcement. This is due to the dowel and tensile membrane actions. The properly anchored and the continuous reinforcement will hang off the damaged slab, as the tensile membrane action develops in the bar. With analytical and available experimental analyses, they explained the design and the detailing recommendations for the flat plate and flat slab.

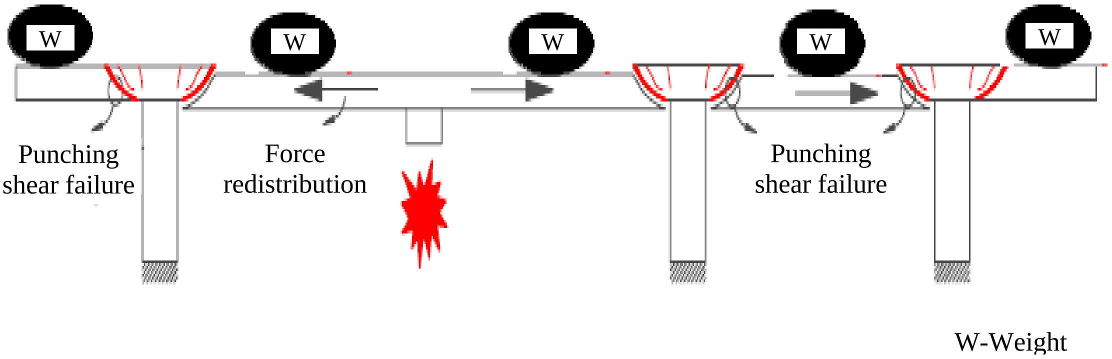
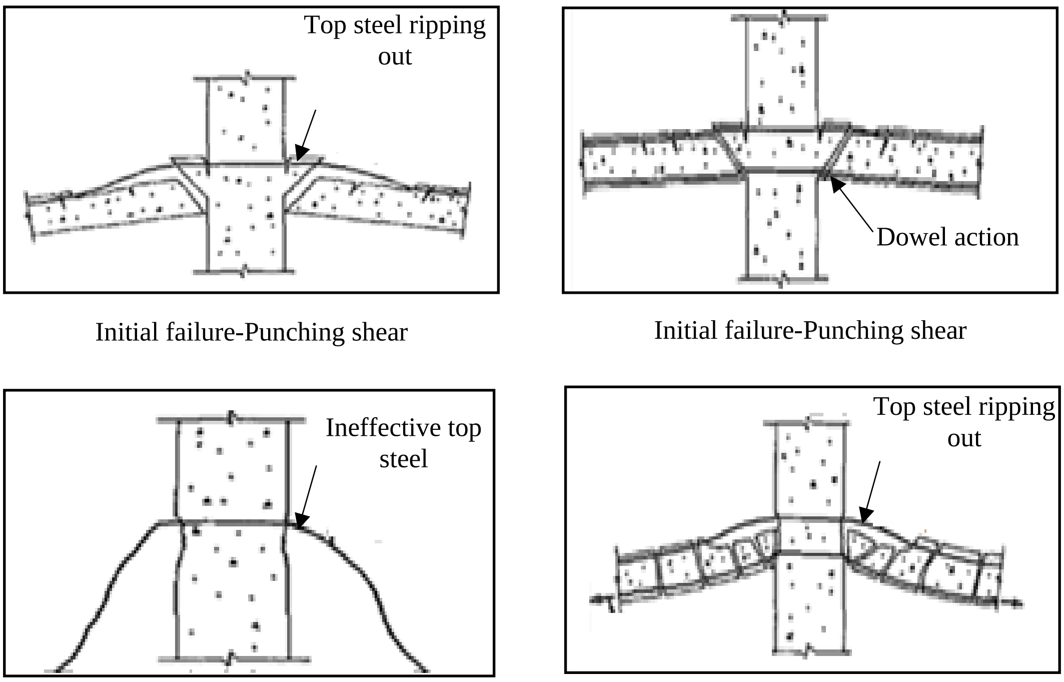


Fig. 1. Propagation of punching shear failure (Mitchell et al., 1984)



Final state- Total collapse
(a) Without Continuous Bottom bar

Final state- Total collapse
(b) With Continuous Bottom Bars

Fig. 2. Function of bottom reinforcement (Mitchell et al., 1984)

3. Experimental Study

Qian et al. (2013) carried out the static analysis to determine the progressive collapse resistance of flat plates and flat slabs. They used a specimen with a dimension of 3100×3100×70 mm with and without drop panels. A drop panel thickness of 40 mm is used in their experiment. They followed a scale of 1:3 for their experiment. The investigation is conducted to determine the performance of the structure after corner column loss. They also analyzed the effect of the slab reinforcement. The experimental set up is demonstrated in Figure 3.

The design axial force is taken as 15.9 kN. The reinforcement detailing of the slab is given in Table 1. The slab is loaded equivalent to a deflection, which is approximately six times the thickness of the slab. They described different performance levels, such as the appearance of the first flexural crack, the initial yield point of the slab reinforcement, the first peak capacity, and the tensile membrane action.

The authors observed that the drop panel increases the moment capacity of the slab-column connection and shifted the critical section to the edge of the drop panel. The first yield point, first peak capacity and the maximum tensile membrane action of the specimen increase with the increase of reinforcement ratio. The first peak-carrying capacities of FS1, FS2, and FS3 are increased compared to FP1, FP2, and FP3, by 124.7%, 87.5% and 61.6% respectively.

Yi et al. (2014) conducted a quasi-static test to analyze the functioning of a reinforced flat plate structure after the abrupt loss of the column. They considered the removal of interior, corner and exterior columns on a model. The authors designed and constructed a flat plate of thickness 90 mm with a scale of 1:2.34. As it is difficult to record the dynamic data for a concise duration, they adopted the quasi-static test. As per the General Services Administration (GSA) recommendation, the design load of the specimen is 10.25 kN/m^2. Initially, the specimen is subjected to uniform loading up to two times the design load (i.e. 20.5 kN/m^2). The structure is able to withstand this applied load. Finally, a point load with a rising magnitude is applied to the internal column location. The resistance of this point load will be the residual capacity of the structure. After the loss of the column, a sudden increment in the displacement is observed for a comparatively lower load.

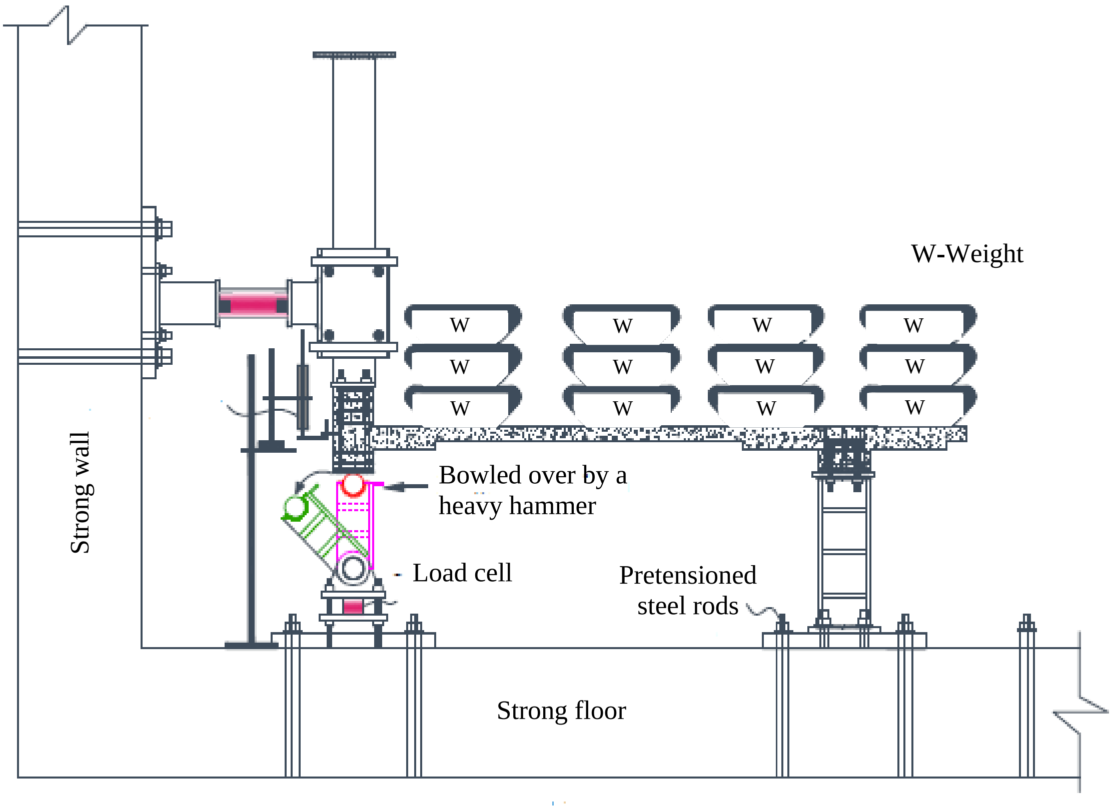


Fig. 3. Experimental set up (Qian et al, 2013)

Table 1. Reinforcement details of slab subjected to static loading (Qian et al., 2013)

Test	**Top reinforcement details**		**Bottom reinforcement details**		**Drop panel reinforcement (mm)**
	Column strip (mm)	**Middle strip (mm)**	**Column strip (mm)**	**Middle strip (mm)**	
FP1	R6 @ 125 c/c	R6 @ 250 c/c	R6 @ 250 c/c	R6 @ 250 c/c	Nil
FP2	R6 @ 60 c/c	R6 @ 125 c/c	R6 @ 125 c/c	R6 @ 125 c/c	Nil
FP3	R6 @ 35 c/c	R6 @ 70 c/c	R6 @ 70 c/c	R6 @ 70 c/c	Nil
FS1	R6 @ 125 c/c	R6 @ 250 c/c	R6 @ 250 c/c	R6 @ 250 c/c	R6 @ 70 c/c
FS2	R6 @ 60 c/c	R6 @125 c/c	R6 @125 c/c	R6 @125 c/c	R6 @ 70 c/c
FS3	R6 @ 35 c/c	R6 @ 70 c/c	R6 @ 70 c/c	R6 @ 70 c/c	R6 @ 70 c/c

R6: Plain reinforcing bar with 6 mm diameter; FP: Flat plate; FS: Flat slab

Punching shear failure occurred when the concentrated force is 113 kN. Further, they also tested the exterior and corner column removal scenarios. The authors pointed out that the compressive membrane actions and the tensile membrane actions are the major load carrying mechanisms for flat plate structures. The compressive membrane action is developed due to the lateral in-plane motion of the slab. Initially, the edges of the plate will move to the outer side and then move towards the inner side. The tendency to move outward is partially resisted by the lateral stiffness of the columns. This leads to the formation of compressive membrane action. This compressive action enhances the flexural strength of the flat plate structure. Further increase of vertical displacement causes the plate edges to move inward. This indicates the transformation of the load-carrying mechanism from compressive to tensile membrane action. The correlation between horizontal and vertical displacement is shown in Figure 4.

Tensile membrane action is developed due to well anchored and continuous longitudinal reinforcement. The authors pointed out that the side and corner span are more susceptible to damage due to the corner column. These results provide valuable insights into nonlinear behavior. Peng et al. (2016) analyzed the punching and post punching behavior of the internal flat slab structure subjected to internal column loss. They used the specimen with dimensions of 6100×6100×140 mm and with a scale of 0.76. They investigated the effect of the slab reinforcement ratio and the lateral restraint at the slab boundary. The reinforcement details, boundary conditions and test outcomes are given in Table 2. The authors conducted the test with and without the hook for the tensile reinforcement.

The authors found that the slab with a high reinforcement ratio has 30% more punching strength compared to the slab with a low reinforcement ratio. The punching strength in the restrained slab is 7.1% higher compared to the unrestrained slab with a reinforcement ratio of 1%. Similarly, the punching strength in the restrained slab is 4.5% higher compared to the unrestrained slab with a reinforcement ratio of 0.64%. Even though the slabs have a discontinuous bottom bar, the post punching strength is about 80% of punching strength in the slab with tensile reinforcement and hook. This is due to anchored tensile bars. The slab column connection without anchoring hook has only 55.5 % punching strength.

Xue et al. (2018) performed the static test on two identical 1/3 scaled RC flat-plate specimens with dimension 2000×2000×90 mm. The experiment is carried out for an interior column loss case. Initially, a uniformly distributed load of magnitude 5 kP is applied on the slab. An incremental concentrated load is applied on the slab near the lost column location. They studied the collapse-resistant behavior and the redistribution of the load in the structure. They observed that over 90% of the applied load is carried to the nearby columns. The three distinct load-carrying mechanisms developed in the slab are flexural action, tensile membrane action and combined action of one-way catenary and dowel actions. The different failure modes are illustrated in Figure 5.

Flexural action occurs after the preliminary set of cracks occurs on the face of the plate. Further, the circumferential crack ring and the bottom radial crack band will be developed.

Table 2. Specimen properties and results (Peng et al., 2016)

Test	**Reinforcement ratio (%)**	**Boundary condition**	**Punching strength P_S (kN)**	**Post punching load capacity P_R (kN)**	**P_R/P_S (%)**
1	1	Unrestrained	308	256	83.3
2	0.64	Unrestrained	231	184	79.4
3	1	Restrained	329	246	74.7
4	0.64	Restrained	242	214	88.3
5	0.64 (No hook)	Restrained	253	141	55.5

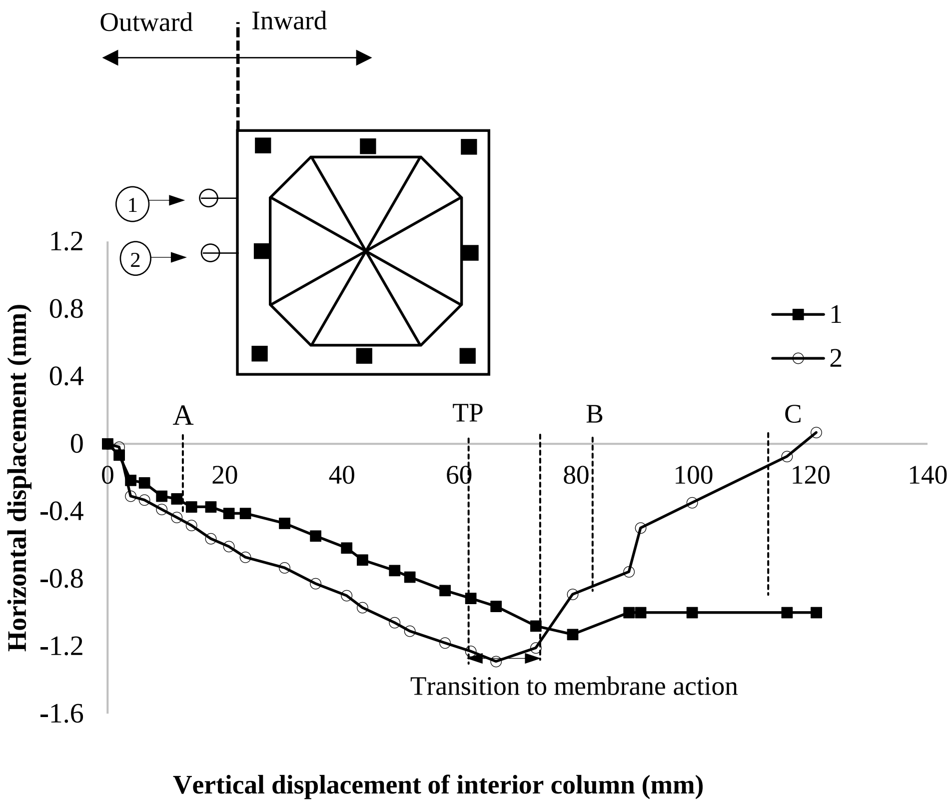


Fig. 4. Relationship between horizontal and vertical displacement (Yi et al., 2014)

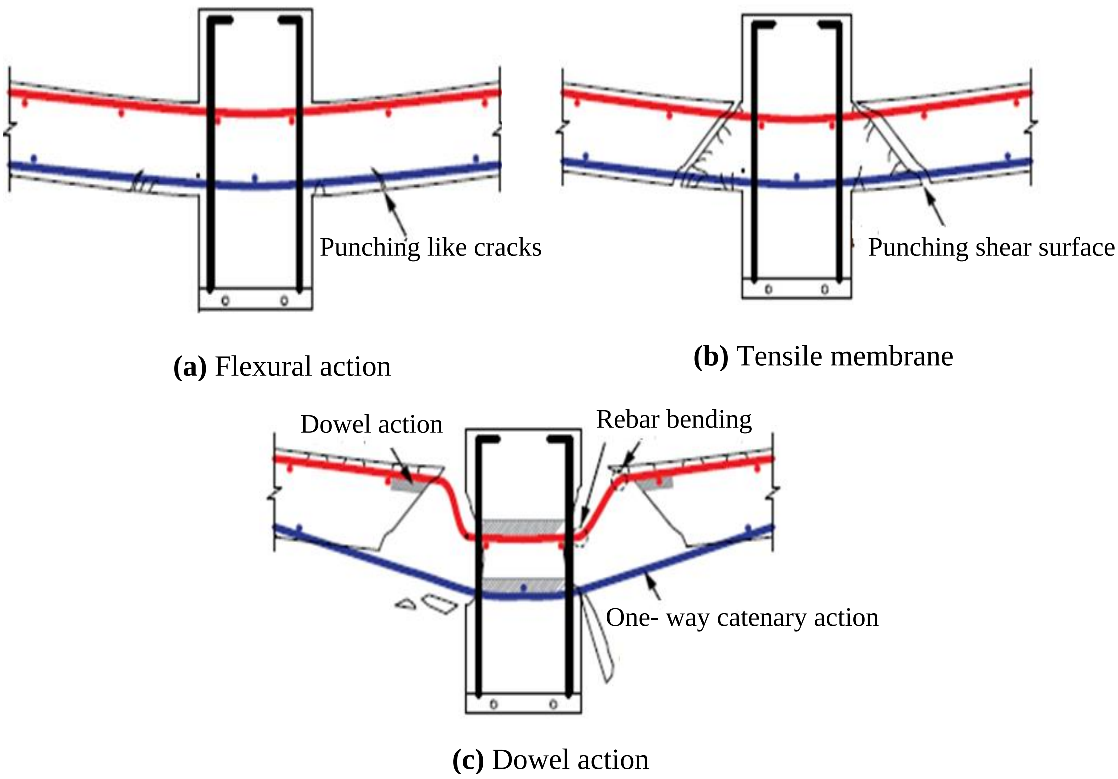


Fig. 5. Failure modes (Xue et al., 2018)

After a further increase in loading, the specimen will exhibit global yielding. Thereafter, the plastic hinges will be formed along the crack. The flexural action will be dominant along with the in-plane forces during this stage. When the subsequent increase of load reaches the ultimate flexural capacity, the punching shear failure happens, and the applied load suddenly drops down. The load is mainly resisted by tensile membrane action after punching shear failure. Here, the applied load is resisted by a steel net. When the load reaches post ultimate capacity, the top reinforcement bars and some of the integrity bars undergo confined bending near the interior column. In this stage, the load drops down further and is partly opposed by the other integrity bar in the tensile area. Moreover, the dowel actions of the locally bent reinforcement bars will also help to resist the load.

Ma et al. (2019) performed the quasi-static tests on a 1/3 scaled RC flat plate substructures. They used the specimen with a dimension of 4575×4575×90 mm. Here they conducted the experiments by removing the corner column. In this experiment, two edges of the slab are reinforced with torsional strips and the specimen is tested two times. In the first case, they removed one of the corner columns and applied a uniformly distributed load on the panel which is next to that column. The applied load was raised until the failure of the slab occurs. In this case, the slab edges which are adjacent to the lost column are reinforced with torsional strips. In the second case, they removed the corner column which is located diagonally opposite to the first lost column. Similar to the first test, the uniformly distributed load is applied till the failure of the slab. In this case, the slab edges which are adjacent to the discarded column have a 500 mm overhang from the column center and have no torsional strips. The flexural action is the significant load-carrying mechanism in both tests. As a result of the full depth flexural cracks, the load-bearing capacity is lost in the first case. In the second case, a combination of flexural, dowel and tensile membrane is observed. The occurrence of punching shear failure is prevented in the slab panel reinforced with torsional strips. The presence of overhangs around the removed corner column will also resist the load. The addition of torsional strip and overhang reduces the risk of progressive collapse in flat plate models.

Qian et al. (2014) carried out a test on 1:3 scaled flat-slab structures with a dimension of 3100×3100×70 mm. The thickness of the drop panel is 40 mm. They investigated the dynamic load redistribution capacity after the abrupt loss of the corner column. Two integrity reinforcements are provided in each direction and they are passed through the column reinforcement cage. A parametric study considering the effect of drop panel, design service load and the effect of reinforcement ratio are carried out using nonlinear finite element software LS DYNA. The variations of the flat slab reinforcement are shown in Table 3.

From the analysis, the authors observed the factors responsible for the failure of flat-slab and flat plate structures. They showed that the flexural damage is accountable for the failure of flat-slab structures. However, the punching shear failure is responsible for the failure of flat plate structures. For flat slab structures, the displacement response decreases significantly with the increase in the slab reinforcement ratio. For flat plate structures, the reinforcement ratio has a low impact on the displacement response. The impact of the reinforcement ratio on the flat slab and flat plate structure is shown in Figure 6.

Russel et al. (2015) experimentally investigated the dynamic behavior of the scaled flat slab structure for various column removal conditions. For carrying out the dynamic tests, temporary support is constructed as vertical steel bars between the two steel plates. The bottom steel plate is fixed on a load cell, and the steel rollers help the support to move rapidly. The column removal mechanism is illustrated in Figure 7. They used a specimen of dimension 4100×2100×80 mm. Experiments were carried out by removing the corner column, penultimate edge, and middle column. They tested 1:3 scale reinforced concrete flat slabs by considering the dynamic and nonlinear effects. The bottom and top reinforcement ratio of 0.18% and 0.21% is added to the interior supports in the column strip to fulfill the conditions for the hogging moment. Further, the authors studied the effect of continuous reinforcement through the column. They compared the static and dynamic test results by using various levels of loadings. The different loading levels are listed in Table 4. The authors observed that in the dynamic case, the peak rise in displacements is about 50% higher than that of the static case, due to the inertial effects.

Peng et al. (2017) carried out a dynamic collapse test on the single-story reinforced concrete flat-plate structure. The dimension of the structure is 6100×5570×88.9 mm, with a scale of 1:2.5. The test specimen used here represents the earlier flat-plate building, which is designed without integrity reinforcement bars. The test is conducted for the immediate removal of an exterior column. They experimented thrice with various gravity loads. They applied a load of 4.83 kN/m^2, 17.18 kN/m^2, and 9.86 kN/m^2 in the three cases, respectively. In the first test, they observed some damage, but the complete failure of the specimen did not happen. In the second test, the specimen is likely to undergo punching shear problems in the adjacent column locations. In the third test, punching failure happened at the adjacent slab column connection. They concluded that when the gravity load applied is higher than 42% of the factored design load capacity (22 kN/m^2), then the flat plate building without integrity reinforcement will be under the threat of progressive collapse. After the punching shear failure, some of the discontinuous bottom reinforcements are stripped out, and some are fractured as shown in Figure 8. The experimental results indicate that the post-punching resistance is restricted in the slab-column connection without the bottom reinforcement.

Peng et al. (2018) also conducted an experimental study for the interior column removal scenario. They used the same specimen with different thicknesses. The thickness of the specimen slab is 71mm. They applied a load of 7.33 kN/m^2. They explained that if the gravity load applied is higher than 34 % of intact flexural capacity, then the flat plate structure will be under the threat of collapse. From these results, it is concluded that the loss of an internal slab-column connection can initiate the progressive collapse.

Table 3. Reinforcement details of the slab subjected to dynamic loading (Qian et al., 2014)

Test	**Top reinforcement** Column strip (mm)	**Top reinforcement** Middle strip (mm)	**Bottom reinforcement** Column strip (mm)	**Bottom reinforcement** Middle strip (mm)	**Axial force in the column (kN)**
FS1	R6@125	R6@250	R6@250	R6@250	-15.9
FS2	R6@ 60	R6@125	R6@125	R6@125	-15.9
FS2a	R6@60	R6@125	R6@125	R6@125	-19.2
FS3	R@35	R6@70	R6@70	R6@70	-15.9
FS3a	R6@35	R6@70	R6@70	R6@70	-27.8

Table 4. Loading level (Russel et al., 2015)

Column removal location	**Loading level kN/m^2**
Corner	3, 6.8, 7.7
Penultimate with continuous reinforcement	2.5, 5.6
Penultimate column with reduced reinforcement	2.3, 5.7
Middle	3.1, 6.7, 8.5

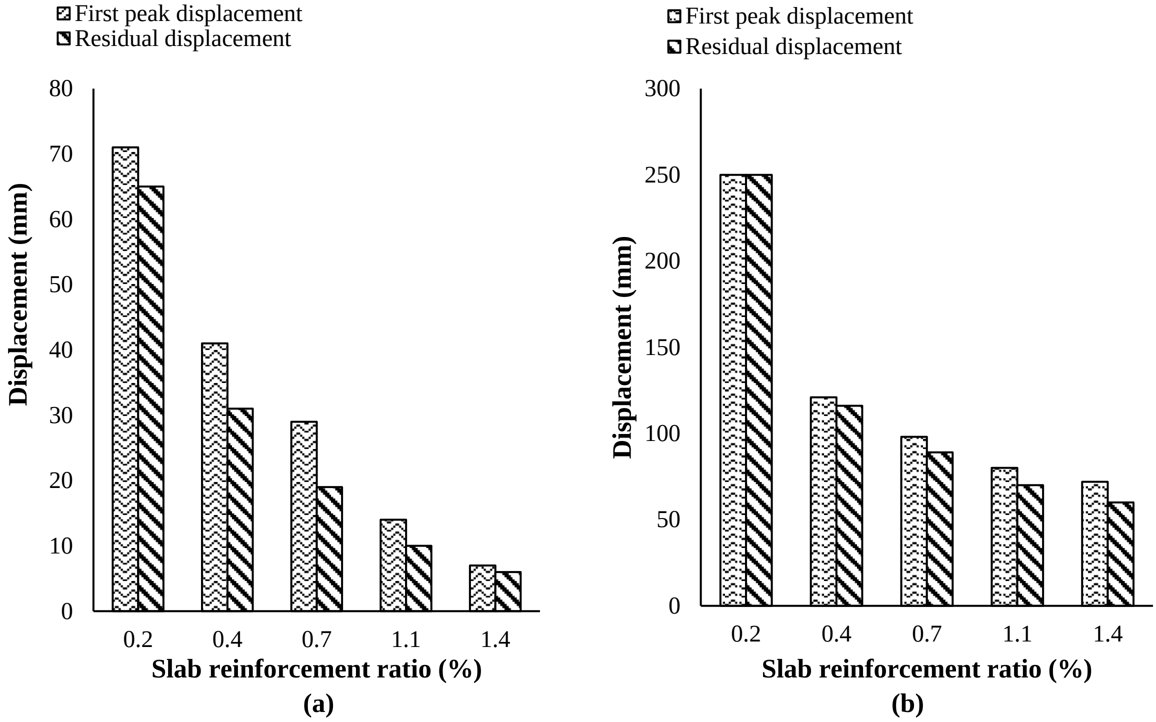


Fig. 6. Effect of reinforcement ratio: a) Flat slab structure and; b) Flat plate structure

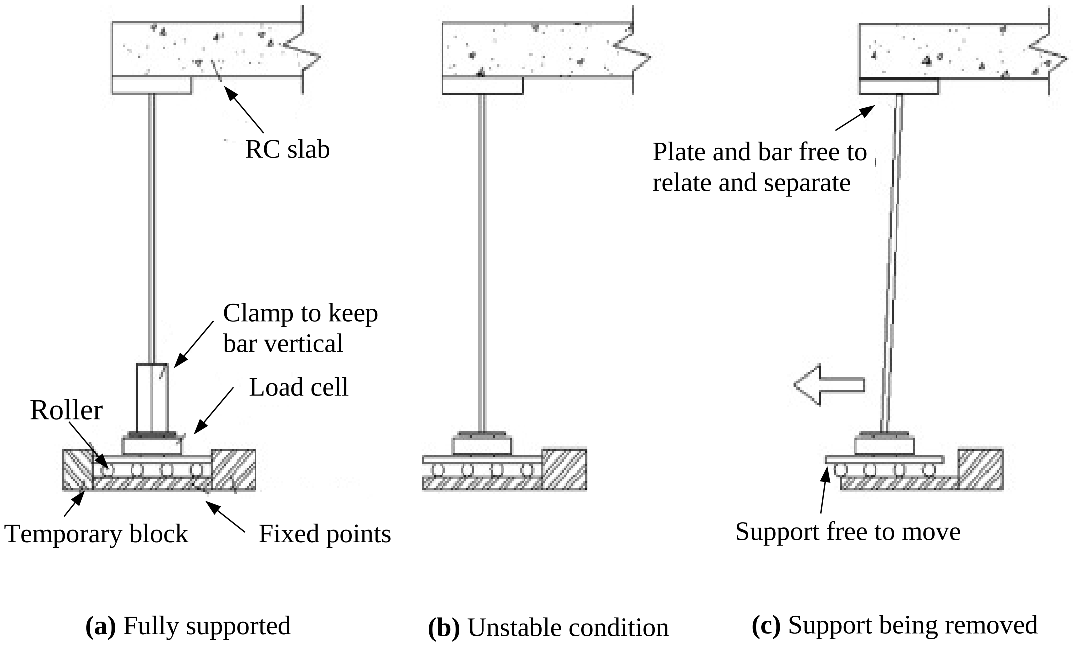


Fig. 7. The mechanism of the loss of the column (Russel et al., 2015)

4. Numerical Simulation

The progressive collapse capacity of the RC flat plates is barely analyzed using the Finite Element Method (FEM). The main reason for this is the complexity in modelling the punching shear failure and load-carrying mechanisms. Keyvani et al. (2013) numerically analyzed a single-story flat-plate model, subjected to interior column removal. The Finite Element model is developed in ABAQUS to analyze the behavior of the flat plates during and after the punching shear failure. The FEM is verified against an available experiment done by Mirzaei et al. (2008). The slab with the dimension of 1500×1500×125 mm is used in this numerical analysis. They used a concrete damaged plasticity model for modeling the concrete. They analyzed the response of flat plate structure by considering and not considering the impact of compressive membrane force. Compressive membrane force can increase the load-carrying capacity of about 17% and 34% in multi-panel flat slab structure and fully restrained isolated slab structure, respectively. The punching strength of the flat slab structure will be underestimated if the compressive membrane force is ignored. This analysis illustrates that the compressive membrane action could be properly simulated by giving partial lateral restraints to the slab-column connections.

Qian et al. (2014) conducted a numerical analysis using nonlinear Finite Element software LS DYNA. They investigated the dynamic load-redistribution capacity of the flat-slab with a dimension of 3100×3100×70 mm. The structure is exposed to the sudden removal of a corner column. They studied the effect of the drop panel, reinforcement ratio and service load. The Concrete Damage Rel-3 model available in the LS-DYNA software is used for modeling the concrete, and the Plastic Kinematic model is applied for modeling the reinforcement.

Liu et al. (2015) created a macro model for the slab-column connections. They used this model for performing analysis on the reinforced concrete flat plate structure. They considered the in-plane, flexural, torsional and shear behavior for the modeling. This model uses the connector and shell elements for simulating the complex behavior of flat slabs. The shell element is employed for simulating the flexural response and to determine the redistribution of the load. The connector is used for modeling the transfer of internal force between the column and slab. Here, they used the finite element package ABAQUS (2010) for numerical analysis. The schematic sketch of the macro model of the flat plate is represented in Figure 9. To attain the equal progressive collapse-resistant capacity, the dynamically removed columns require a greater degree of structural redundancy compared to a quasi-static column removal application.

Liu et al. (2015) analyzed the progressive collapse resistance of a multi-story reinforced concrete flat-plate structure which is not having the shear or structural integrity reinforcement. They used a macro modeling approach. In their experiment, they considered two loading scenarios which are the rapid elimination of the internal and external columns. They observed that a flat-plate structure without continuous bottom reinforcement is extremely susceptible to progressive collapse. Thus, a greater possibility of the progressive collapse is present in the structure subjected to exterior column loss. Pang et al. (2017) also performed the numerical analysis using the macro modeling approach which was developed by Liu et al. (2015). They validated the effectiveness of the deformation-based punching failure on the macro model.

5. Strengthening Techniques

RC flat plates are highly susceptible to progressive collapse as there is no beam for redistributing the axial force previously supported by the removed columns. Hence, it is important to analyze the performance of various methods for improving the capability of the flat slabs to mitigate the collapse. A few researchers have studied the reliable strengthening techniques to mitigate the progressive collapse of flat plate models. Qian et al. (2013) studied the strengthening effect of carbon fiber reinforced polymer (CFRP) laminates on the flat plate structure. Figure 10 shows the plan view of the flat plate strengthened with CFRP laminates. They tested flat plate with and without strengthening fiber. The authors observed severe flexural cracks in the failure mode of the plate without strengthening fiber. They upgraded the flexural strength by incorporating CFRP.

The resistance capacity of the specimen will increase after the debonding and delamination of the CFRP laminates. This occurs because of the tensile membrane action dominated in the large displacement stage.

Qian et al. (2014) further studied the strengthening effect of glass fiber reinforced polymer (GFRP) laminates on the flat slab structure. Figure 11 shows the flat plate strengthened by GFRP laminates. They used four specimens which are strengthened by GFRP strips, and three specimens without the strengthening. They observed that the GFRP laminates enhanced the flexural resistance and initial stiffness of flat slab structures. But, the post-failure resistance and deformation capacity of the structure is not improved. This is due to the debonding of the GFRP strips in the large displacement stage. The debonding will happen even when the well-designed fiber anchors are used. The GFRP has a larger deformation capacity compared to CFRP.

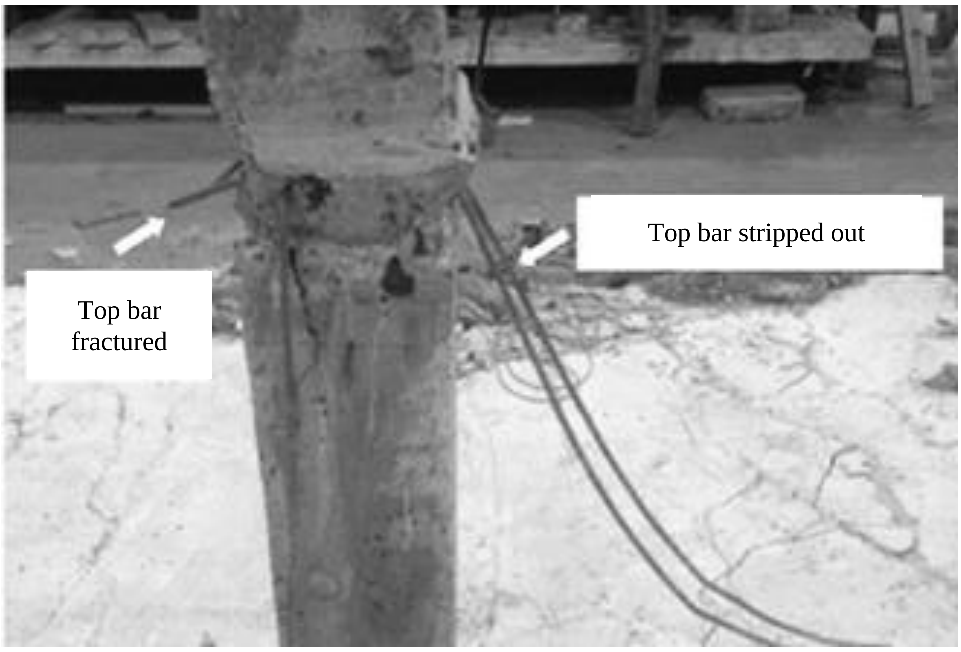


Fig. 8. Post punching shear failure pattern (Peng et al., 2017)

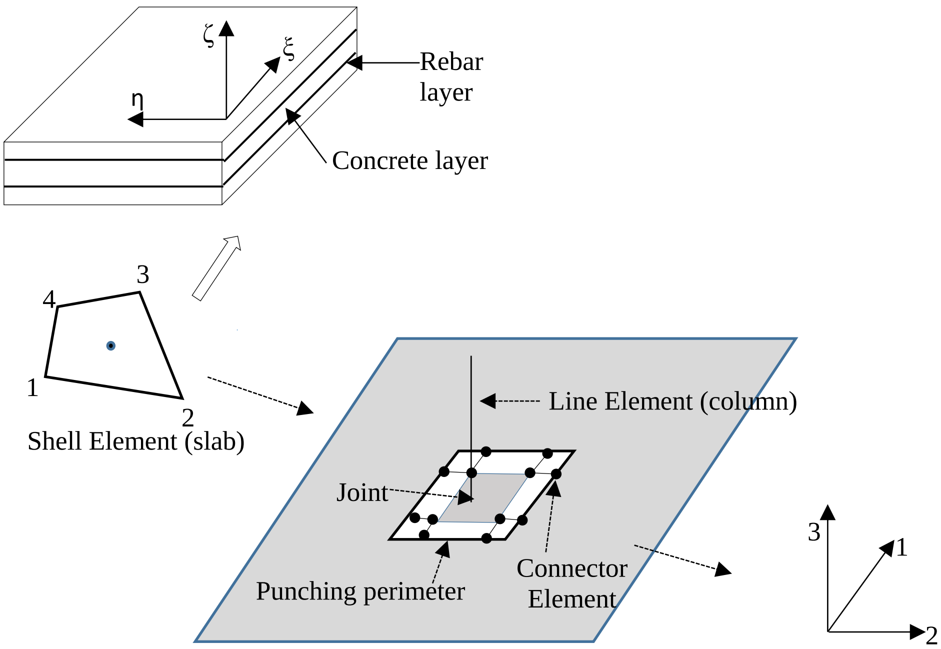


Fig. 9. Schematic sketch macro model for flat plate

The comparison of the effect of drop panel, reinforcement and CFRP on first peak capacity, and the maximum tensile membrane action is presented in Figure 12. The reinforcement details are given in Table 5. From this, it is clear that the increase in the reinforcement ratio will increase the first peak capacity and the maximum tensile membrane action. The tensile membrane action produced in the flat slab is more than that in the flat plate. This is due to the effect of the drop panel. The flat plate structure can be strengthened by using CFRP laminates. For the low reinforcement ratio, CFRP laminates can increase the peak capacity of the flat plate by about 111.76%.

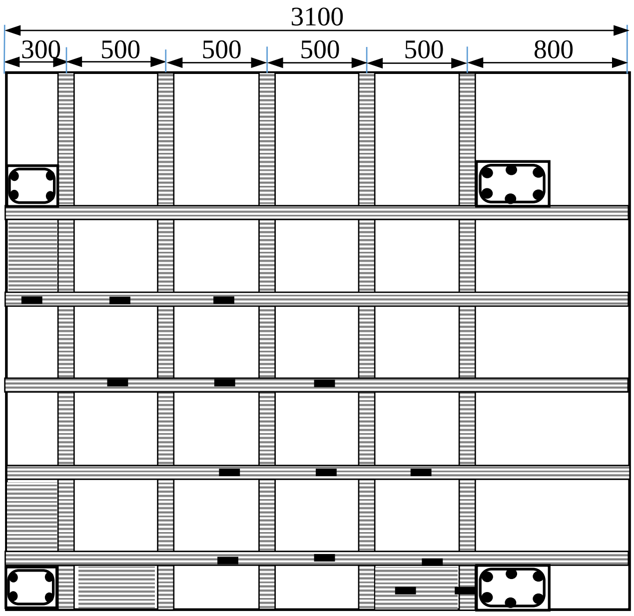


Fig. 10. Plan view flat plate strengthened with CFRP (Qian et al., 2013)

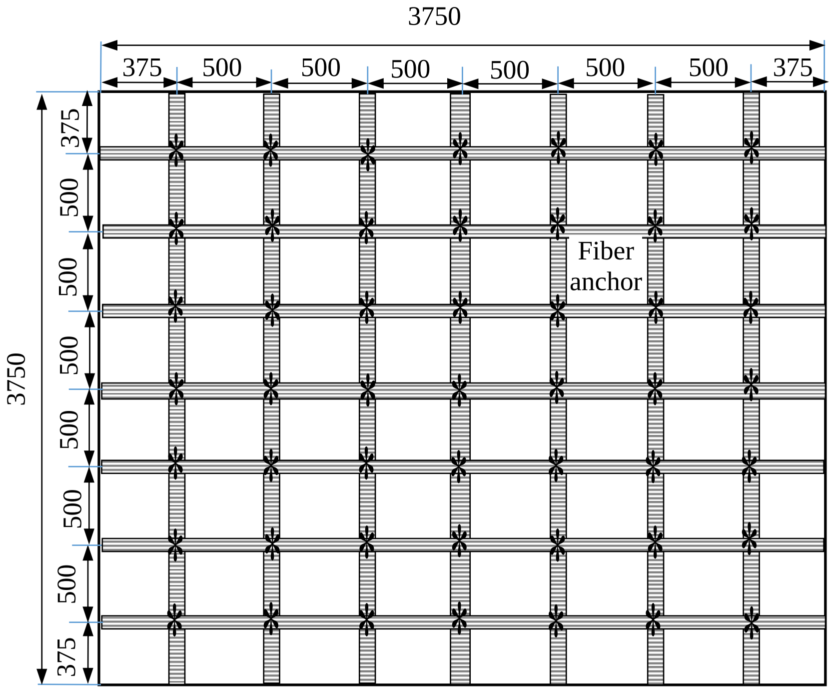


Fig. 11. Plan view of flat plate strengthened with GFRP (Qian et al., 2014)

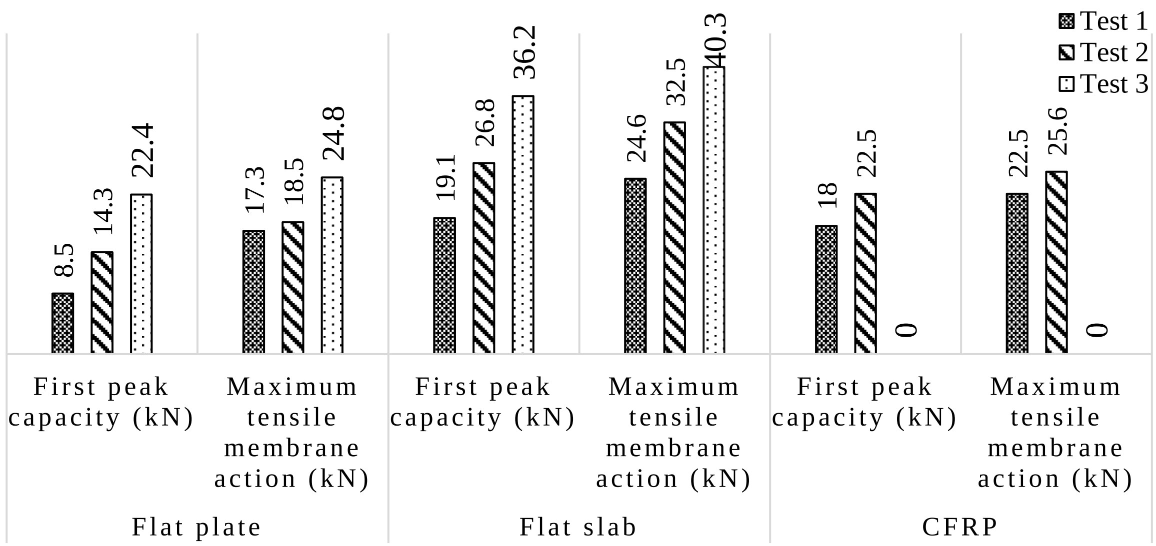


Fig. 12. Comparison of different parameter values

Table 5. Reinforcement details

Test	Slab top layer reinforcing bar		Slab bottom layer reinforcing bar	
	Column Strip (mm)	**Middle strip (mm)**	**Column strip (mm)**	**Middle strip (mm)**
1	R6 at 125	R6 at 250	R6 at 250	R6 at 250
2	R6 at 60	R6 at 125	R6 at 125	R6 at 125
3	R6 at 35	R6 at 70	R6 at 70	R6 at 70

6. Summary

The flat slab structure is highly susceptible to punching shear failure due to the heavily concentrated shear force and due to the bending moment in the vicinity of the slab-column connections. Hence, it is important to redistribute the gravity load, which is initially resisted by the failed slab column connection to the neighboring locations. This additional load can develop punching shear failures in those areas. Catastrophic failure of the structure may occur due to an inadequate load-carrying mechanism to carry the extra redistributed load. The flexural action in the slab will carry the load before the occurrence of the punching failure. After the occurrence of the punching shear failure, the load is normally resisted by the tensile membrane action, dowel action, and the catenary action of the reinforcement.

The analytical study of flat slab structures is described only in a single work. In this study, the authors described an analytical model and proposed a method to find out the tensile membrane action of the slab. They also explained the design and detailing recommendations for the flat slab. The majority of the experimental studies used a static loading method without considering the dynamic effect. Only a few researchers have examined the dynamic effects. The response of flat slab considering dynamic effects is quite different from that of static loading case. In the dynamic case, the peak rise in the displacements is about 50% higher than that of the static case, due to the inertial effects.

Numerical simulation of the progressive collapse of flat slab structures is also addressed in this review. The researchers have used Finite Element software such as LS DYNA and ABAQUS for the analysis. Two papers have mentioned the strengthening technique of flat slab structures. They have used Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) for laminating the flat slabs. These polymers can increase the first peak capacity and maximum tensile membrane action.

7. References

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

Liu, J., Tian, Y., Orton, S.L. and Said, A.M. (2015). "Resistance of flat-plate buildings against progressive collapse. I: Modeling of slab-column connections", *Journal of Structural Engineering*, 141(12), 04015053.

Liu, J., Tian, Y. and Orton, S.L. (2015). "Resistance of flat-plate buildings against progressive collapse, II: System response", *Journal of Structural Engineering*, 141(12), 04015054.

Ma, F., Gilbert, B.P., Guan, H., Xue, H., Lu, X. and Li, Y. (2019). "Experimental study on the progressive collapse behavior of RC flat plate substructures subjected to corner column removal scenarios", *Engineering Structures*, 180, 728-741.

Mirzaei, Y. and Muttoni, A. (2008). "Tests of the post-punching behavior of the reinforced concrete flat slabs", PhD Thesis, IS-BETON.

Mitchell, D. and Cook, W.D. (1984). "Preventing progressive collapse of slab structures", *Journal of Structural Engineering*, 110(7), 1513-1532.

Peng, Z., Orton, S.L., Liu, J. and Tian, Y. (2016). "Effects of in-plane restraint on progression of collapse in flat-plate structures", *Journal of Performance of Constructed Facilities*, 31(3), 04016112.

Peng, Z., Orton, S.L., Liu, J. and Tian, Y. (2017). "Experimental study of dynamic progressive collapse in flat-plate buildings subjected to exterior column removal", Journal *of Structural Engineering*, 143(9), 04017125.

Qian, K. and Li, B. (2012). "Strengthening and retrofitting of RC flat slabs to mitigate progressive collapse by externally bonded CFRP laminates", *Journal of Composites for Construction*, 17(4), 554-565.

Qian, K. and Li, B. (2013). "Experimental study of drop panel effects on response of reinforced concrete flat slabs after loss of corner column", *ACI structural journal*, 110(2), 319-329.

Qian, K. and Li, B. (2014). "Dynamic disproportionate collapse in flat-slab structures", *Journal of Performance of Constructed Facilities*, 29(5), B4014005.

Qian, K. and Li, B. (2014). "Strengthening of multi bay reinforced concrete flat slabs to mitigate progressive collapse", *Journal of Structural Engineering*, 141(6), 04014154.

Rezaie, F., Fakhradini, S. M. and Ghahremannejad, M. (2018). "Numerical evaluation of progressive collapse potential in reinforced concrete buildings with various floor plans due to single column removal", *Civil Engineering Infrastructures Journal*, 51(2), 405-424.

Russell, J.M., Owen, J.S. and Hajirasouliha, I. (2015). "Experimental investigation on the dynamic response of RC flat slabs after a sudden column loss", *Engineering Structures,* 99, 28-41.

Xue, H., Gilbert, B.P., Guan, H., Lu, X., Li, Y., Ma, F. and Tian, Y. (2018). "Load transfer and Ccollapse resistance of RC flat plates under interior column removal scenario", *Journal of Structural Engineering*, 144(7), 04018087.

Yi, W.J., Zhang, F.Z. and Kunnath, S.K. (2014). "Progressive collapse performance of RC flat plate frame structures", *Journal of Structural Engineering*, 140(9), 04014048.

Zahrai, S.M. and Ezoddin, A.R. (2014). "Numerical study of progressive collapse in intermediate moment resisting reinforced concrete frame due to column removal", *Civil Engineering Infrastructures Journal*, 47(1), 71-88.