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PARAMETERS INFLUENCING THE BEHAVIOUR OF RC FLAT-SLABS UNDER COLUMN-LOSS SCENARIO

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ABSTRACT

Reinforced concrete (RC) structures, during their construction and operational phases, may be subjected to accidental loadings (e.g.; due to impact of a vehicle, removal of early formwork, etc.) which may cause damage to the supporting column. As a result, significant amount of forces needed to be redistributed to the remaining structural elements. If these structural elements do not provide sufficient resistance to these accidental redistributed forces generated due to the partial or the complete collapse of the column, they may initiate domino effect of slabs ultimately causing the progressive-collapse of the structure. In this investigation, a detailed non-linear finite element (FE) study has been conducted using finite element software, ABAQUS. The investigation aims to study the behaviour of the flat reinforced concrete (RC) slab due to column loss scenario and to identify the parameters which may influence its behaviour when subjected to accidental redistributed forces generated due to column loss. Based on the detailed parametric investigation, it was found that the concrete compressive-strength and thickness of the flat-slab play a significant role in redistributing the forces and ultimately resisting the domino effect by avoiding collapse of slab on to the another slab.

KEYWORDS: Reinforced-Concrete, Flat-Slab, Column-Loss, Finite-Element Analysis, Accidental Loading, Domino Effect.

المتغيرات المؤثرة على سلوك بلاطات الخرسانه المسلحه المسطحة لسيناريو فقدان الأعمدة

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الملخص

قد تتعرض الهياكل الخرسانية المسلحة، أثناء مرحلتي البناء والتشغيل، لأحمال عرضية (على سبيل المثال، بسبب تأثير مركبة، أو إزالة القوالب المؤقتة، وما إلى ذلك) مما قد يتسبب في تلف العمود الداعم. ونتيجة لذلك، كان لا بد من إعادة توزيع قدر كبير من القوى على العناصر الإنشائيه المتبقية. إذا لم توفر هذه العناصر الإنشائيه مقاومة كافية لهذه القوى العرضية المعاد توزيعها الناتجة عن الانهيار الجزئي أو الكامل للعمود، فإنها قد تبدأ تأثير الدومينو للبلاطات مما يؤدي في النهاية إلى الانهيار التدريجي للهيكل. في هذا البحث، أجريت دراسة تفصيلية للعناصر المحددة غير الخطية باستخدام برنامج العناصر المحددة (ABAQUS). يهدف هذا البحث إلى دراسة سلوك البلاطة الخرسانية المسلحة المسطحة نتيجة لسيناريو فقدان العمود وتحديد العوامل التي قد تؤثر على سلوكها عند تعرضها لقوى عرضية معاد توزيعها متولدة بسبب فقدان العمود. استناداً إلى التحقيق البارامتري التفصيلي، وجد أن مقاومة ضغط الخرسانه وسمك البلاطة المسطحة تلعب دوراً هاماً في إعادة توزيع القوى وفي نهاية المطاف مقاومة تأثير الدومينو عن طريق تجنب انهيار البلاطة على بلاطة أخرى.

الكلمات المفتاحية : الخرسانة المسلحة، البلاطة المسطحة، فقدان العمود، تحليل العناصر المحدودة، التحميل العرضي، تأثير الدومينو.

1. INTRODUCTION:

Due to design errors, human negligence and an accidental activity in the construction phase and the operating life span of the structure, the supporting columns may exhaust their load carrying capacity partially or completely which may result in the stability issues in the structure in general and more specifically in the slab. The behaviour of the reinforced concrete (RC) flat slabs became more vulnerable to the column loss scenario due to their inherent punching shear failure weakness. Therefore, the RC flat slabs should provide adequate resistance against the accidental redistributed forces generated due to the column loss scenario in order to avoid punching shear failure, initially, and ultimately resisting the progressive collapse of the structure due to the domino effect.

There are number of published investigations [Gardner *et al.* (2002), Pearson & Delatte (2003), Pearson & Delatte (2005), Schellhammer *et al.* (2012)] which aims on finding the causes of the premature structural collapse of the RC flat slabs during their operational or construction phase.

Gardner *et al.* [Gardner *et al.* (2002)] investigated the causes of premature collapse of 5-story Sampoong departmental store, located in Seoul - South Korea, which consists of a flat plate supported by rigid shear wall type structure. The building was in a region that was neither vulnerable to extreme weather nor to any seismic faults. Based on detailed examination, in general, the investigation revealed number of design errors, construction faults and poor-quality construction and building control management. It was found that the collapse of the structure was initiated due to the failure of column. More specifically, the reduction in the cross-sectional dimensions of the columns supporting the fifth floor was executed during its construction phase without considering any design remedies which resulted in decrease in its load carrying capacity. Furthermore, the change in the use of the fifth floor from its initial design as roller-skating ring into a restaurant significantly resulted in an increased dead and live load of up to 35%. The investigation further revealed that the effective depth of slab in the negative moment region was reduced from 410mm to 360mm and the diameters of column supporting the fifth floor were 600mm instead of the designed diameter of 800mm. In addition to the change of column sizes and usage purpose, it was also found that the construction was carried out using concrete having nominal compressive strength of 18MPa instead of design compressive strength of 21MPa.

Schellhammer et *al.* [Schellhammer *et al.* (2012)], investigated the causes that result in the collapse of Skyline Plaza, at Bailey's crossroads, Virginia, during its construction phase. The plaza consists of 26 residential stories having 4 stories reserved for basement and a parking garage and was constructed using light weight concrete having compressive strength of 20.7MPa for constructing floor slab (flat slab having uniform thickness), whereas, normal weight concrete having compressive strengths of 34.5MPa, 27.6MPa & 20.7MPa for constructing columns. Based on the investigation, it was found that the collapse initiated from 24th floor when the slab collapsed and fell on 23rd floor slab which resulted in the collapse of the floor due to punching shear and as a result ultimately causing the failure of whole structure due to the domino action. The collapse of slabs resulted in tearing of a structure into two parts separated by 18m distance. Based on the findings of the investigation, it was observed that the factors resulted in the collapse of the structure include the poor form work condition, early removal of shores, below the 23rd floor slab, low strength of concrete used in the supporting area of 23rd floor and the pace of construction.

Based on the experimental studies conducted on studying the behaviour of the RC flat slab subjected to the column loss scenario and the investigations carried out to examine the causes which resulted in the premature failure of the structure during its operational stage and construction phase, it can be concluded that in addition to the design errors and human negligence parameters such as concrete compressive-strength, placement of steel and alternative load paths to adjust forces due to column loss play an important role in avoiding initiation of the progressive collapse. Therefore, this detailed parametric investigation has been carried out to study the influence of different parameters on the behavior of flat-slab due to column loss scenario. For this purpose, non-linear finite element (FE) analyses have been carried out using finite element software ABAQUS [ABAQUS (2013)].

2. NUMERICAL INVESTIGATION

To study the behavior of RC flat slab under column loss scenario, a numerical investigation was carried out using Finite Element software ABAQUS [ABAQUS (2013)]. For this purpose, firstly experimental results of Russel *et al.* [Russell (2015)] were used for the validation of non-linear finite element (FE) analyses which was then followed by the detailed parametric investigation studying the influence of various parameters on the behaviour of the flat slab due to the column loss scenario.

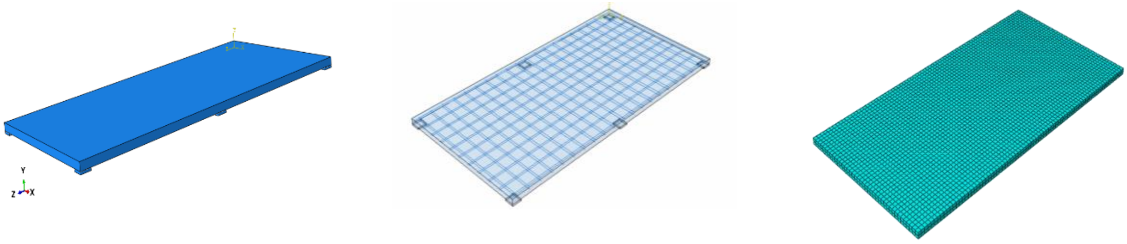
3. TEST SETUP

The behavior of the RC flat slab due to the column loss scenario has been experimentally investigated by Russel *et al.* [Russell (2015)]. For this purpose, a sample of flat slab having cross-section dimensions of 4100mm x 2100mm and a thickness of 80mm was used. The slab was reinforced with 6mm-diameter bars, in its both directions and both bottom and top faces, with 200mm center to center spacing. Furthermore, in order to account for the effect of hogging moment, 6mm-diameter bars were also used at the internal supports. The specimens were supported using rigid steel plates having a cross-section of 135mm x 135mm and a depth of 25mm.

4. VALIDATION OF THE NON-LINEAR FE ANALYSIS

Similar to the experimental test setup defined in section 3, an RC flat slab having cross-section dimensions of 4100mm x 2100mm and a depth of 80mm supported using fully fixed steel rigid plates was modelled in ABAQUS [ABAQUS (2013)] as shown in Fig. 1. The slab was meshed using 8 noded linear brick 3D solid elements each having a size of 52.5mm x 52.5mm x 52.5mm (see Fig. 1).

In order to define the behavior of concrete in FE analysis, an already available concrete damage plasticity model (CDPM) in ABAQUS [ABAQUS (2013)] was used. In publication [Russell (2015)] stress-strain curves of concrete under tension and compression from which slabs casted were not provided; therefore, similar stress-strain relationship under uniaxial tension and compression was used. In order to define the material behavior of the steel reinforcing bars under uniaxial tension in the FE model, classical metal plasticity model [ABAQUS (2013)] was used. The non-linear static FE analysis was carried out in three different steps. In step-1, the load of 3kPa was applied on the surface of slab similar to the experimental test setup; whereas, in step-2 bottom left column (see **Error! Reference source not found.**) was removed, which was then followed by next step (step-3) in which load was increased till failure of the specimen occurred.



(a) (b) (c)

Fig. 1. (a) FE Model, (b) Reinforcement and (c) Mesh Layout used for the Slab.

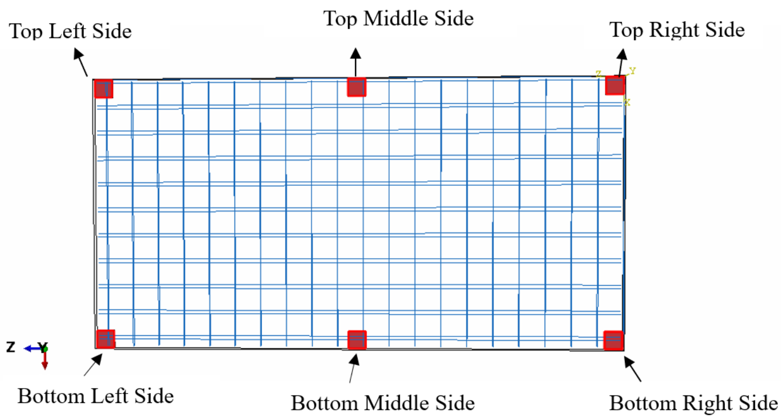


Fig. 2. Schematic Representation of Locations of Columns [Russell (2015)].

Table 1. Comparison of Support Reactions Observed Experimentally and Exhibited Numerically

	APPLIED LOAD (KN)					
Column Location	**Step 1 (Pre-Loading)**		**Step 2 (Column Removal)**		**Step 3 (Post-Column Removal)**	
	FE	Experimental	FE	Experimental	FE	Experimental
Top Left	5.2	5.5	8.17	-	15.4	-
Top Middle	13.8	14.2	13.13	-	18.47	-
Top Right	5.19	5	4.96	-	8.38	-
Bottom Left	5.2	5.15	0	-	0	-
Bottom Middle	13.8	14.2	16.96	-	25.28	-
Bottom Right	5.2	5.3	4.84	-	8.56	

Error! Reference source not found. gives the comparison of the support reactions observed experimentally and that exhibited using FE analysis. Good agreement was observed for support reactions observed experimentally and exhibited numerically. Based on the FE analysis, it was observed that once the column was removed significant amount of force redistribution occurred. It was also observed that the top left and bottom middle column (see **Error! Reference source not found.**) carried maximum amount of support reactions after the removal of the load. This may be attributed to the fact that these two columns are adjacent to the removed column.

Fig. 3 shows the deformed profile of the slab before and after the removal of bottom left column (see **Error! Reference source not found.**). As can be seen from Fig. 3, that whole slab reacted to the applied load before column was removed; however, after the removal of the column the deformation became localized toward the slab removal zone. It was also observed that the deformation increased significantly due to the column loss having its maximum impact in the column removal zone (see Fig. 3 (a) and (b)). It was also observed that once the column was removed the forces travel towards the adjacent supporting columns of the slab, thus, if the structure is located in the accidental impact prone area, the adjacent column should provide sufficient resistance to these accidental forces.

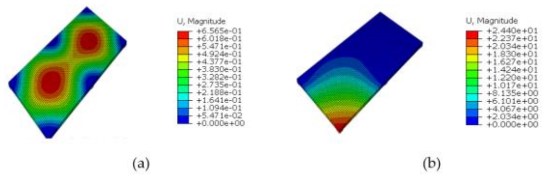
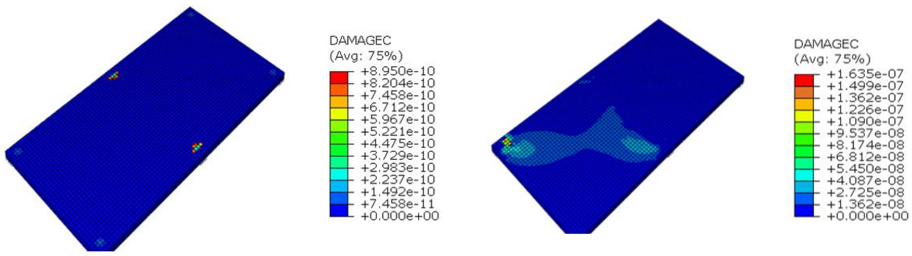


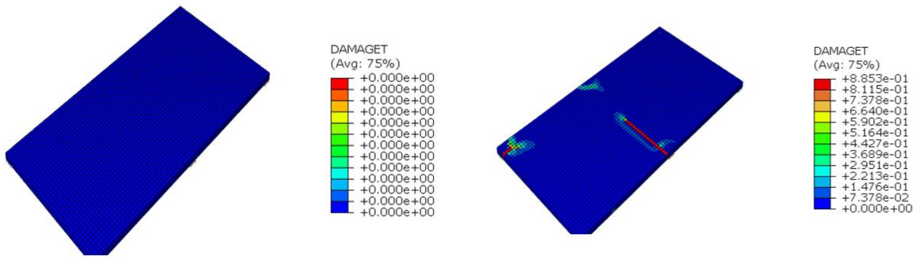
Fig. 3. Deformed Profile of the Slab (a) Before Column Removal and (b) After Column Removal.

Fig. 4 and Fig. 5 show the damage caused to the slab in terms of compression crushing and tensile cracking respectively. It was observed that no significant damage was caused to the concrete of the slab both before and after column removal as the damage parameters d_c and d_t which varies between 0 (no damage) to 1 (completely damaged) were observed to be significantly less than 1 (see Fig. 4 and Fig. 5). Based on this, it can be concluded that the column removal scenario the stresses in concrete do not increase significantly which may be attributed to the fact that the slab moves as a whole body in the column removal zone, thus focus should be to avoid this movement by providing significant resistance in the adjacent supporting columns of the slab in the column removal zone.



(a) (b)

Fig. 4. Damage Caused to the Slab in Terms of Compression Crushing (a) Before Column Removal and (b) After Column Removal.



(a) (b)

Fig. 5. Damage Caused to the Slab in Terms of Tensile Cracking (a) Before Column Removal and (b) After Column Removal.

5. PARAMETRIC STUDY

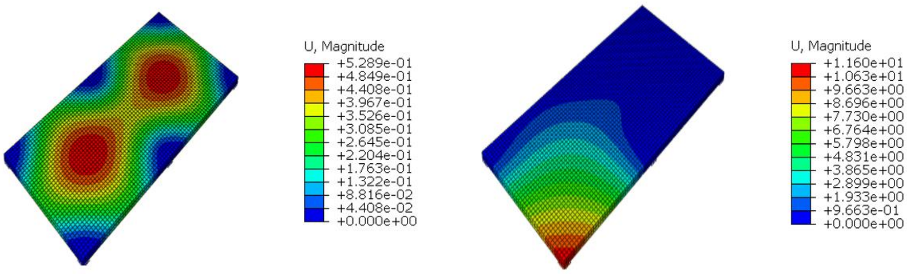
A range of parameters can potentially influence the behavior of reinforced concrete slab under column loss scenario. A parametric investigation is carried out herein to study the influence of these parameters on the behavior of RC flat slab exhibited under column loss scenario. The parameters considered in this study are (i) concrete compressive strength (f_c') from which slab is made and (ii) depth of the reinforced concrete slab (h).

5.1 Influence of Strength of Concrete

To investigate the influence of concrete compressive strength on the behavior of reinforced concrete flat slab under column loss scenario, slabs with three different concrete strengths were used. The same FE model as described in section 4 was used for investigating the behavior of RC flat slab under the column loss scenario for following case studies:

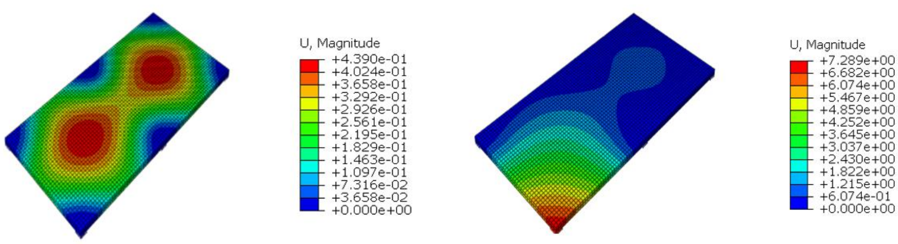
i. Case study - C26: RC flat slab made with concrete having f_c' = 26MPa
ii. Case study - C40: RC flat slab made with concrete having f_c' = 40MPa
iii. Case study - C60: RC flat slab made with concrete having f_c' = 60MPa
iv. Case study - C80: RC flat slab made with concrete having f_c' = 80MPa

Fig. 6 to Fig. 8 shows the deformed profile for the case of RC flat slab investigated made with different concrete compressive strengths. In general, it was observed that with the increase in the concrete compressive strength the deformation exhibited by slab during both before and after column removal scenarios decreases significantly (see Fig. 3 and Fig. 6 to Fig. 8). As observed in section 4, the deformation localized to the column removal zone once column is removed and the damage caused to the concrete of slab both in terms of compression crushing and tensile cracking was observed to be insignificant.



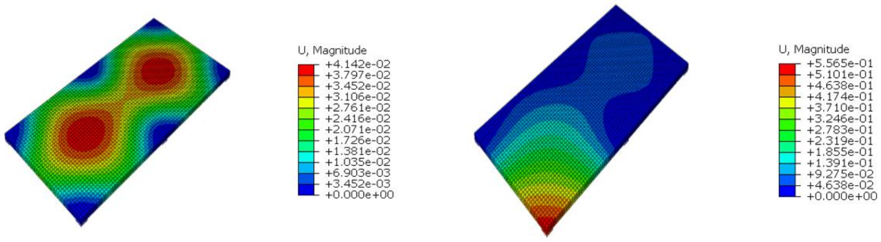
(a) (b)

Fig. 6. Deformed Profile of the Slab used in Case Study-C40 (a) Before Column Removal and (b) After Column Removal.



(a) (b)

Fig. 7. Deformed Profile of the Slab used in Case Study-C60 (a) Before Column Removal and (b) After Column Removal.



(a) (b)

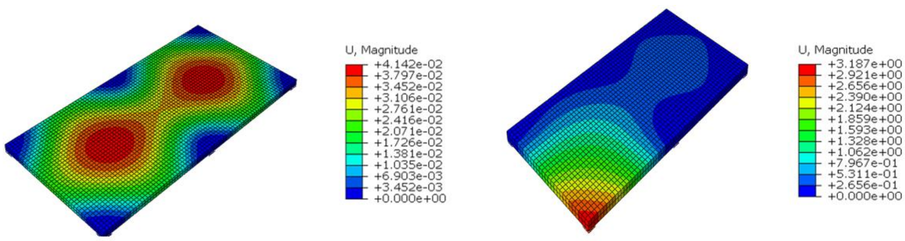
Fig. 8. Deformed Profile of the Slab used in Case Study-C80 (a) Before Column Removal and (b) After Column Removal.

5.2 Influence of Thickness of Slab

To investigate the influence of thickness (h) on the behavior of RC flat slab under column loss scenario, slabs with three different thicknesses were used. The same FE model as used in section 4 was used for investigating the behavior of RC flat slab under the column loss scenario having thicknesses of 80mm, 125mm and 160mm as follow:

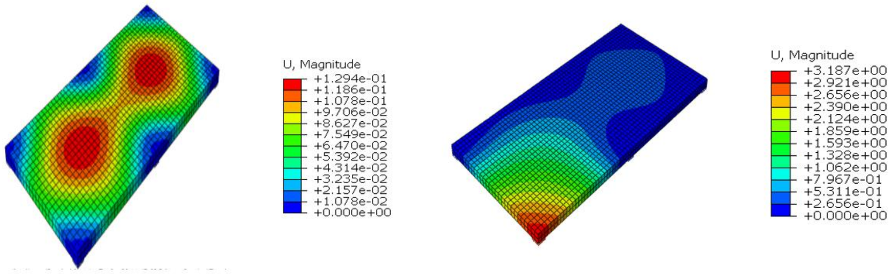
i. Case study - C80 : h = 80mm
ii. Case study - C125 : h = 125mm
iii. Case study - C160 : h = 160mm

Fig. 9 and Fig. 10 show the deformed profile of the RC flat slab having different thicknesses. In general, it was observed that with the increase in the thickness of the slab the deformation exhibited by slab during both before and after column removal scenarios decreases significantly (see Fig. 3, Fig. 9 and Fig. 10). It is important to note that the slabs used in this investigation have concrete compressive strength of 26MPa and as observed in section 4, the deformation increases significantly once column is removed, however, with increasing thicknesses of the slab the deformation decreases significantly even with low strength concrete (see Fig. 3, Fig. 9 and Fig. 10). Thus, it can be concluded that deformation in the slab can be significantly reduced even with low strength concrete by increasing the depth of the slab which benefit in lowering the chances of the complete or partial progressive collapse of the structure.



(a) (b)

Fig. 9. Deformed Profile of Slab having Thickness of 125mm (Case Study-C125) (a) Before Column Removal and (b) After Column Removal.



(a) (b)

Fig. 10. Deformed Profile of Slab having Thickness of 160mm (Case Study-C160) (a) Before Column Removal and (b) After Column Removal.

CONCLUSIONS

This numerical study focused on investigating the behaviour of the RC flat slab under column loss scenario. In general, it was observed that due to the column loss, the forces travel towards the adjacent supporting columns of the flat slab; thus, if the structure is located in the accidental impact prone area, the adjacent column should provide sufficient resistance to these accidental forces. Furthermore, based on the detailed parametric investigation, it was found that the concrete compressive-strength and thickness of flat-slab significantly reduced the deformation exhibited by the slab in the case of loss of column which can ultimately reduce the chances of partial or complete progressive collapse of the structure.

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