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Numerical Investigation on Progressive collapse Performance Analysis of Precast Reinforced Concrete Structures Subjected to Column Removal

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Abstract
Progressive collapse of a building occurs when a primary structural member fails and further failure propagate to the adjoining members, thus causing the collapse of the entire structure. The need to mitigate the impact of progressive collapse is necessary as it leads to catastrophic economic loss and causalities. Precast concrete construction is a well-known technology in which some standardized units which are manufactured in factories are used for fast construction. Precast concrete buildings are made of precast units that are bolted or connected together. Though the technology is developed many years ago but the implementation is not up the mark in our country. In the present study the performance of regular and irregular precast RC buildings subjected to progressive collapse is investigated. The impact of progressive collapse of the structure on column removal at different locations is studied by static progressive collapse analysis using SAP2000. The demand-capacity ratios of precast RC buildings are also evaluated.

Keywords: *Progressive collapse, precast RC structures, demand - capacity ratio.*

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I. INTRODUCTION

The precast reinforced concrete is easy to construct, requires less labor, time saving, durable, versatile, and had many uncertainties against the earthquake loading. As compared to conventional reinforced concrete these precast concrete systems are designed with appropriate levels of strength, ductility, stiffness, and energy dissipation characteristics. For precast structural system, the behavior of connections between the critical elements differs from conventional RC joints. Precast connections are semi rigid connections in nature, has good quality, provide speed and ease of erection. The structure consists of large units which are joined by special type of connections such as dowel bars, corbel connection, welded connection, billet connection whose function is to transmit compressive, sheer, tensile force and bending moment. The development of force distribution to immediate members due to failure of critical elements leads to collapse of the structure. The process can be considered as progressive collapse and it is also the localized damage of primary load bearing element by an abnormal event which leads to chain reaction of failures to nearby elements resulting in a partial or disproportionate collapse of the structure. Building must be designed to have enough robustness and protection against local damage during failure progression and no change has been made in design codes and regulation, such as the United States Department of Defense (DoD) or UFC, General Service Administration (GSA) and Eurocodes.

Significant amount of experimental studies on the progressive collapse of concrete frame structures have been performed. Sandy N yunna and B Feiliang Wang studied influence of the progressive collapse resistance of multistory reinforced concrete (RC) structures. Using bare and infill-wall RC frames. According to them, for column failure at corner and exterior locations, the infill walls are beneficial in the redistribution of loads after the failure of the column due to the increased collapse resistance of the RC building [19]. Shao-Bo Kang and Kang Hai Tan studied the behavior of precast concrete sub-assemblages in which significant catenary action developed in the beams under column removal scenarios, with pull-out failure of the bottom beam reinforcement in the joint [2]. Digesh D. Joshi Paresh V. Patel evaluated the demand capacity ratios of reinforced concrete for four and ten story frame structure as per GSA guidelines [12]. Kai Qian and Bing Li studied the effects of varying the types of slab-beam connections and beam-column joints on the progressive collapse performance of precast concrete structures. The arrived the failure modes and possible load resisting mechanisms of precast structures to resist progressive collapse [7]. N Hashim and J Agarwal investigate the Rotational Stiffness of Precast Beam-Column Connection using Finite Element Method. For modeling, a 3-dimensional beamcolumn connection with precast billet connection, categorized as semi-rigid connection with an appropriate stiffness (23,138kNm/rad) was used [18]. In the present study, an eight-story regular and ten story irregular structures with precast (PC) units is analyzed for progressive collapse. Linear and non-linear static analysis of the structure modeled in SAP2000 was carried out to find the DCR and Hinge formation.

II. BUILDING MODEL

2.1 GEOMETRY

The buildings were modeled in SAP2000. Precast, cast in-situ, partially precast RCC frame buildings with eight floors regular building structure and ten floors irregular building structure are modeled in accordance with ACI-318 specifications. The regular buildings are symmetrical in both longitudinal and transverse directions with four bays of span length 3.66 m. The ground floor height is 3.66 m whereas the other floor heights are 3.05 m with floor slab thickness as 100 mm. The plan and 3D view of the modeled regular building are shown in Figure 1. The compressive strength of concrete (f'c) is 17.24 MPa and the yield strength of reinforcing steels (fy) is 275.8 MPa for main bars and stirrups [19]. A precast building with irregular geometry is also studied. The irregularity in geometry is considered and the irregular structure is modeled as an H-shaped building. The plan and the 3D view of modeled irregular building are shown in Figure 2. The ground floor height is 3.66 m whereas the other floor heights are 3.05 m with floor slab thickness as 100 mm. The sectional properties for beams and columns are provided in Table 1 .All the columns and beams are modeled as frame elements, and the slabs are modeled as shell elements with end boundary condition of column as fixed. Flexural plastic hinges are assigned at both ends of the beams by adopting default hinge properties. The assigned plastic hinge models are activated only in nonlinear analysis procedures. For precast structure, billet connections are adopted for joints. The precast billet connection is classified as a low strength semi-rigid connection with a rotational stiffness of 23,138 k-Nm/rad shown in Figure 3[18]. The column removal considered in this study: corner column, middle column. There are four building models are considered for this study.

Model A: Regular RCC building
Model B: Regular PRECAST building
Model C: H SHAPED PRECAST building
Model D: Partially precast building

H shaped irregular structure is modeled as precast and partially precast. For partially precast structures, 1-5 floors of G+10 story building are modeled as cast in-situ RCC frame (Monolithic frame) and from 6-10 floors of G+10 story building are modeled as precast frame.

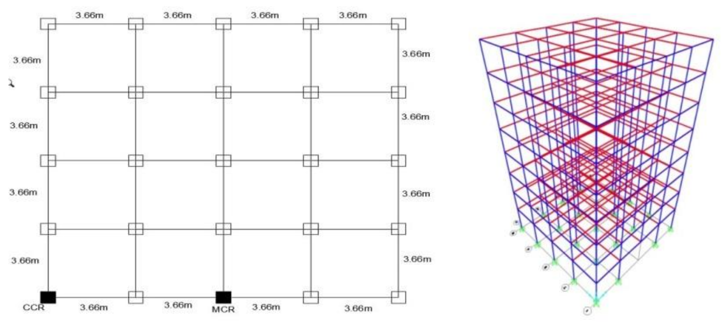

Figure 1: Plan and 3D view of the modeled regular precast building

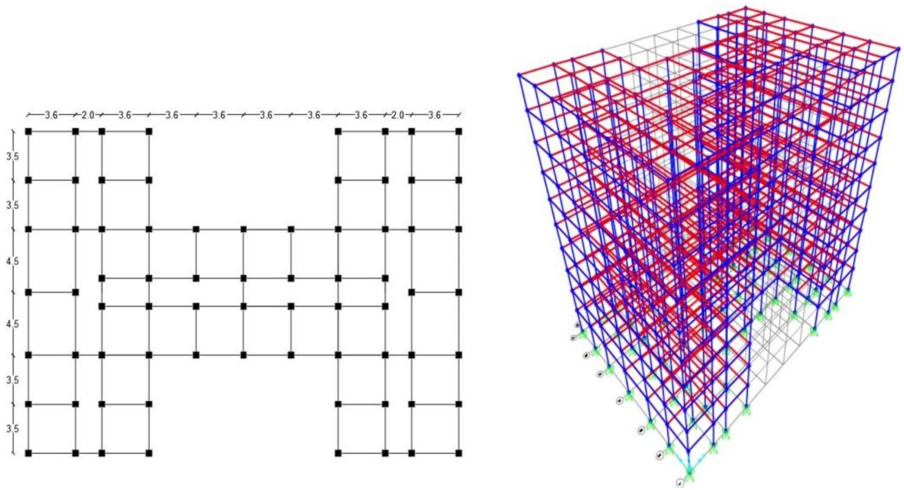

Figure2: (a)Plan and (b) 3D view of the H-shaped irregular precast building

Table 1: Sectional Properties of beams and columns

	Floor	Dimension (mm)
BEAM	1F-8F & 1F-10F	300x350
COLUMN	1F-8F & 1F-10F	400x400

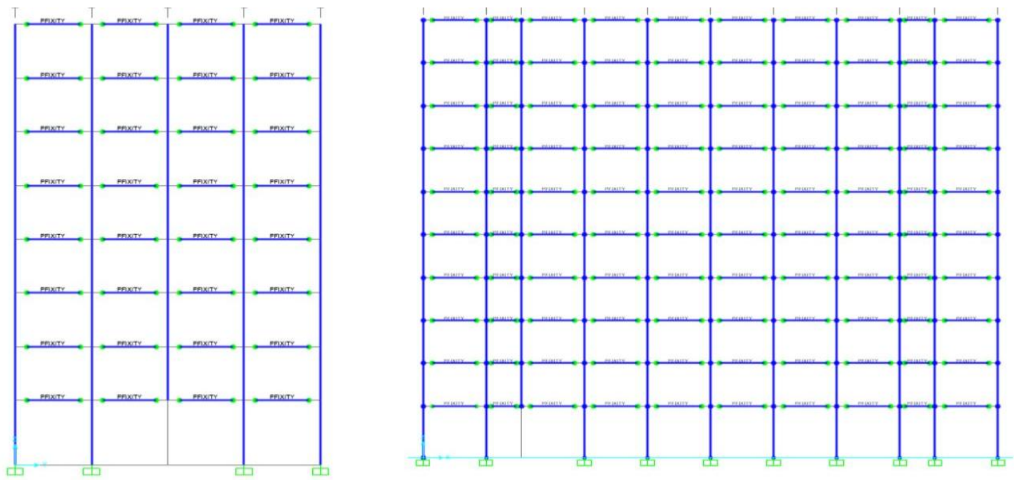

Figure 3: Precast frame

2.2 LOAD AND LOAD COMBINATIONS

As per GSA guidelines, that a load combination of full dead load (DL) and 0.25 times live load (LL) must be applied for analyzing the progressive collapse scenario. For regular building, in addition to the self-weight of the building, a dead load of 1kN/m² and live load of 2kN/m² are applied to all the stories. Wall load of 6.32kN/m is applied on the beams of the structure. In addition to irregular building, the dead load is assigned to all the members by software SAP2000 itself, a floor finish of 2kN/m² is applied as per IS 875 (Part 1):1987 and a live load of 4kN/m² is applied as per IS 875 (Part 2):1987. The load combination provided by GSA guidelines for linear static analysis is

$$2(DL + 0.25LL)$$

2.3 LOCATION OF COLUMN REMOVAL

As per GSA guidelines, two damaged cases are taken into account for the five model cases. The column removal is done to achieve the effect of progressive collapse in a building. The guidelines provided by the GSA are used to analysis a building for progressive collapse. The column removal cases taken for this study are:

(i) Middle Column Removal (MCR)

(iii) Corner column Removal (CCR)

III. PROGRESSIVE COLLAPSE ANALYSIS

3.1 LINEAR STATIC ANALYSIS

The linear static analysis is the simplest and easiest procedure, which is performed using an amplified combination of service loads, such as dead and live, applied statically.

3.2NON-LINEAR STATIC ANALYSIS

For progressive collapse analysis, a nonlinear static analysis method implies a stepwise increase of amplified vertical loads, until maximum amplified loads are attained or until the structure collapses. This means that in most cases vertical pushover analysis would be load controlled. Nonlinear static analysis procedure is limited to structures where dynamic behavior patterns can be easily and intuitively identified.

3.3ACCEPTANCE CRITERIA

The GSA specifies different assessment criteria for linear and nonlinear analysis procedures. For linear static procedure, the progressive collapse potential of a structure is assessed by checking the demand capacity ratio (DCR) of each structural member as indicated in Eq.

$$\text{DCR} = \frac{Q_{UD}}{Q_{CE}}$$

Q_{UD} = Demand determined in member or connection (moment, axial force, shear, and possible combined forces)

Q_{CE} = Expected ultimate capacity of the member and connection (moment, axial force, shear and possible combined forces)

For the building having a regular structural configuration, the DCR of the primary structural components should be less than 2 to avoid failure and for building having an irregular structural configuration, the DCR of the primary structural components should be less than 1.5 to avoid failure.

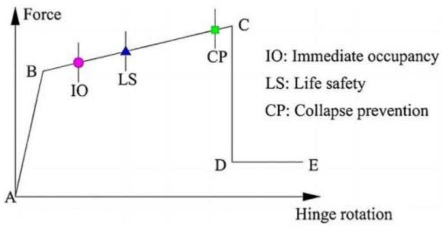

Figure 4: Force rotation relationship

For nonlinear analysis procedures, the damage levels of members are assessed by various performance levels of plastic hinges i.e. Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) as described in Figure 4. It is recommended in the GSA guidelines that the performance level of plastic hinges should not exceed Collapse Prevention (CP) otherwise structural members are considered severely failed.

IV. RESULT AND DISCUSSION

The linear static analysis and non-linear static analysis on the regular and irregular building, regular and irregular precast building and irregular partially precast building were done. The results are obtained in terms of DCR value and vertical displacements are as discussed below.

4.1 LINEAR STATIC ANALYSIS

Eight story regular and ten story irregular cast in-situ, precast and partially precast structure is studied for linear static analysis to assess the potential for progressive collapse. Linear static analysis is performed by applying the GSA load combination on the column removed building. DCR values of the beams are calculated as per acceptance criteria.

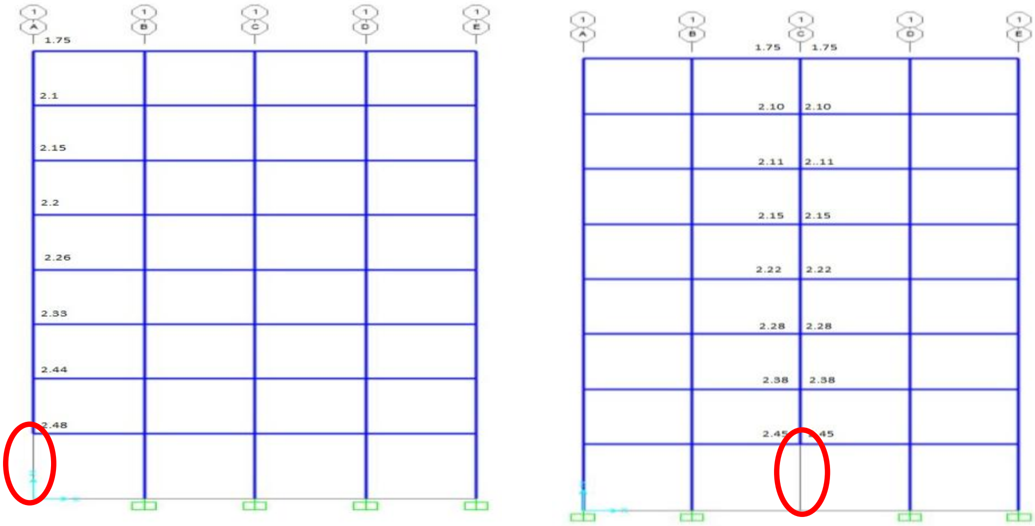

Figure 5: DCR value for regular precast building for CCR and MCR

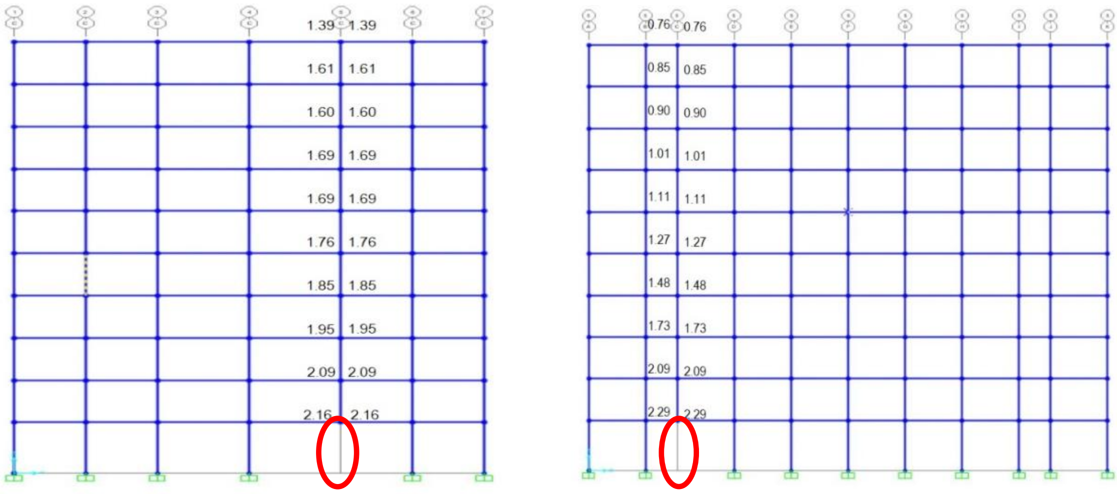

Figure 6: DCR value for irregular precast building for CCR and MCR

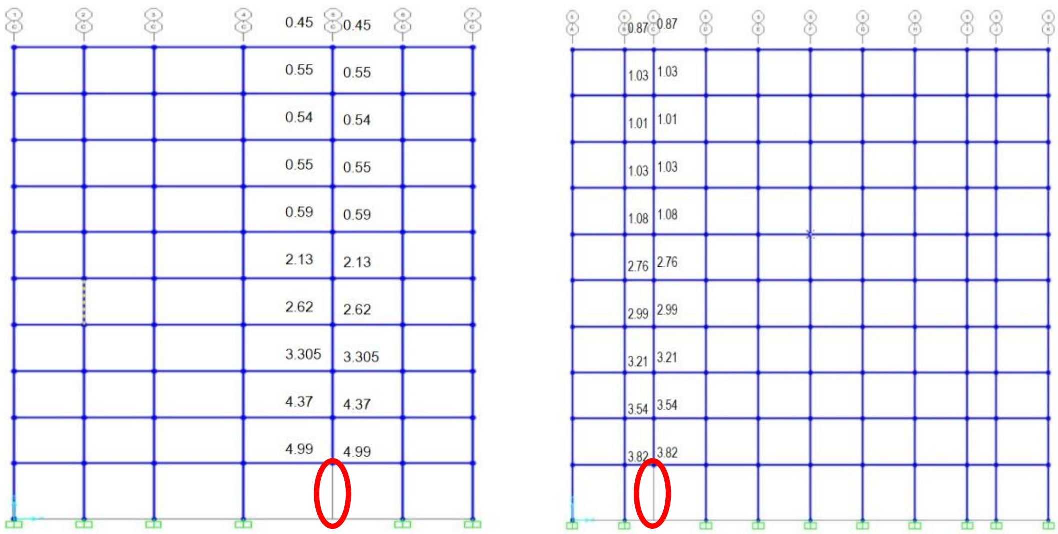

Figure 7: DCR value for irregular partially precast building for CCR and MCR

The results of linear static analysis are summarized in the Table 2. The downward displacements at the removal point and the maximum values of DCR and the number of stories collapsed (DCR>2) are listed.

Table 2: Summary of the DCR and displacement due to CCR and MCR

Structure	Damage case	Maximum DCR	Displacement (mm)	No of stories collapsed (DCR>2)
RC	CCR	3.27	12.9	7
	MCR	3.55	12	7
PC	CCR	2.48	24.4	7
	MCR	2.45	22	7
PC- H shaped building	CCR	2.16	22	2
	MCR	2.29	12	2
Cast in-situ H shaped	CCR	3.35	13.3	6
	MCR	4.65	9.8	4
H building with 1-5 floor cast-in-situ and 6-10 PC frames	CCR	3.82	14.8	5
	MCR	4.99	10.2	5

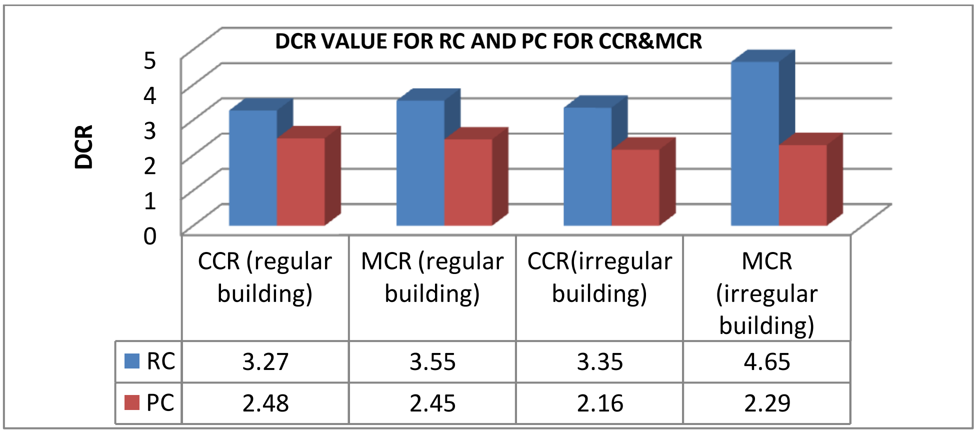

Figure 8: Maximum DCR value for CCR and MCR of regular and irregular buildings

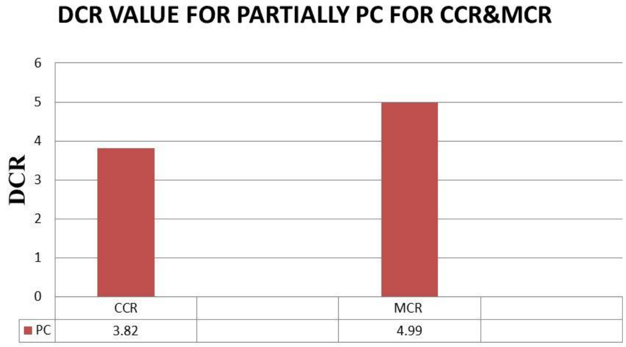

Figure 9: Maximum DCR value for CCR and MCR of partially precast building

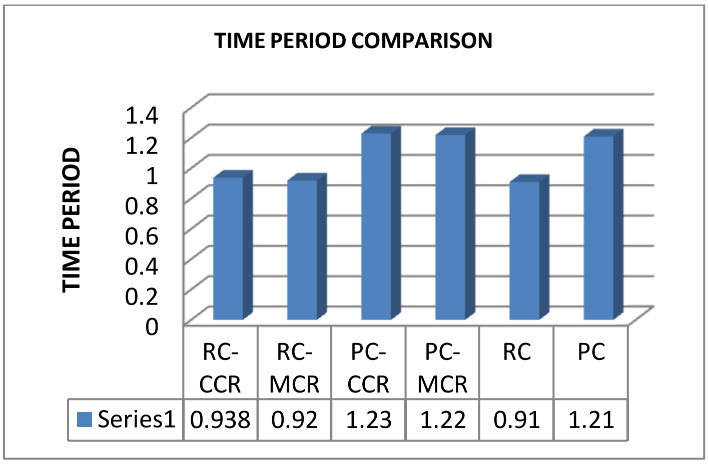

Figure 10: Comparison of time period for the building models

4.2 NON-LINEAR STATIC ANALYSIS

Nonlinear static analysis is performed by following a load-controlled procedure to examine the residual capacity of the buildings. In the load-controlled procedure, loading is initiated from zero and a stepwise increase of gravity load is applied to the column removed building until the full GSA load combination is achieved. The load displacement response is tabulated in Table 3 and graphical representation is shown in Figure 11.

Table 3: Load Displacement response

Structure	Damage case	IO hinge		LS hinge		Time period
		Displacement	Base force (kN)	Displacement	Base force (kN)	sec
RC	RC-CCR	10	29419	42	54941	0.938
	RC-MCR	9.1	26679	40	73636	0.92
PC	PC-CCR	19	29214	57	57337	1.23
	PC-MCR	18	28337	53	62094	1.22

For regular cast in-situ and precast structures, non-linear static analysis is performed and the formation of hinges as per the hinges assigned for the beams is shown in Figure 12. The relation curve between the displacement base force relation of cast in-situ RC and PC structure subjected to MCR & CCR

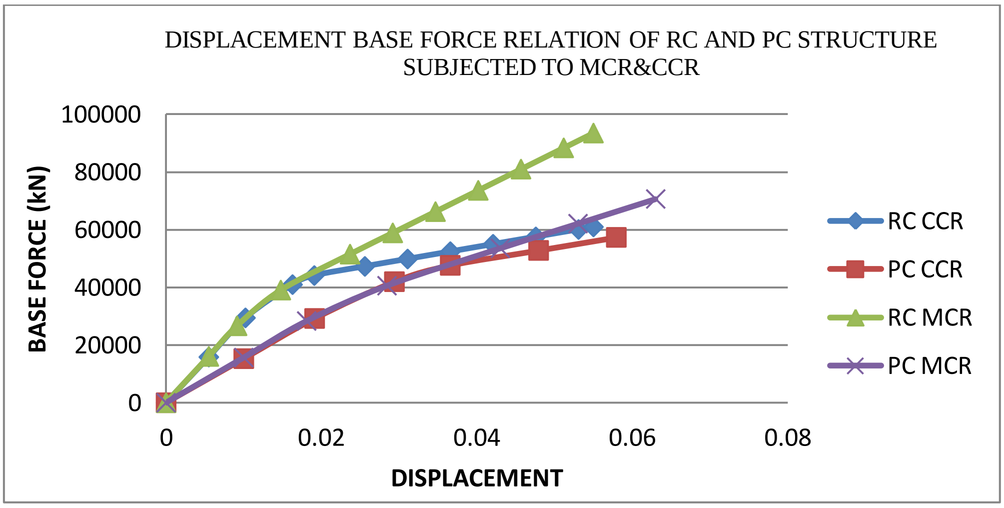

Figure 11: Base force versus displacement curve

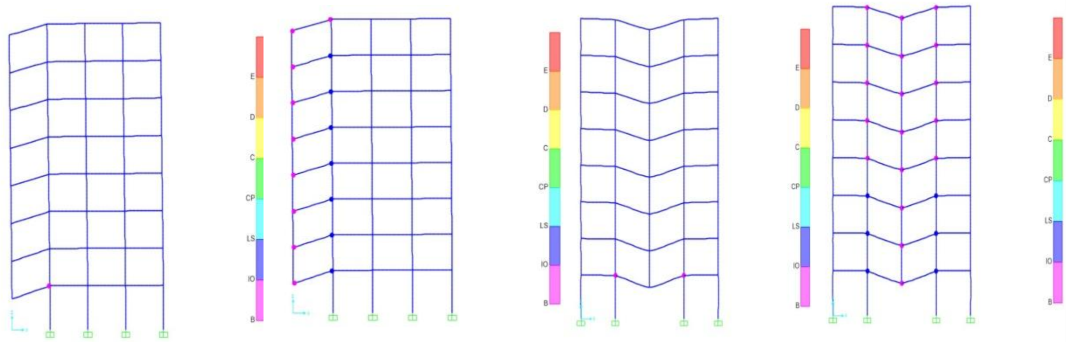

Figure 12: Hinge formation for corner & middle column removal of regular building

The immediate occupancy and life safety is demonstrated in Figure 12. Analysis is performed for each case of column failure. The hinge formation pattern for various displacement levels are observed for all the cases of column removal in the building. Displacement in mm at the point above the column failure is also shown in Table 3 for the hinge formation. It can be clearly observed that first hinge forms at the location where demand capacity ratio is maximum. Further progress of hinge formation occurs with sections having higher values of demand capacity ratio

V. CONCLUSION

Progressive collapse performance analysis of regular and irregular precast multi-stored buildings is done in the present study. From the bending moment details, the DCR values for each beam on different column removal cases are calculated. The vertical displacement and time period relation are also studied. The results obtained are summarized below.

- The adjacent beam of the removed column shows the maximum DCR value.
- The maximum DCR values obtained from progressive analysis for CCR and MCR cases of precast buildings are 2.48 and 2.45 respectively, whereas the maximum DCR value obtained for CCR and MCR cases of regular cast in-situ buildings are 3.27 and 3.55 respectively. The DCR values for the stories up to 7 floors are greater than the acceptance criteria limitation of DCR value (DCR>2) as per the GSA guidelines.
- From the static analysis, the DCR values of beams in the upper floors above the column removed floor is more for cast in-situ RCC regular frame compared to precast frame.
- For irregular H-shaped precast building, the maximum DCR values obtained are 2.16 and 2.29 for CCR and MCR cases respectively. But cast in-situ buildings shows maximum DCR values as 3.35 and 4.65, which are higher than the corresponding values of precast building.
- Irregular H- shaped buildings with partially precast (cast in-situ frame for 1-5 floors and precast frame for 6-10 floors), the DCR values for CCR and MCR cases are 3.82 and 4.99 respectively.
- Comparing the three types of structures under progressive analysis with respect to the DCR values of the members, comparatively a better performance is observed for irregular H-shaped fully precast structure.
- The vertical displacements for the both damage cases are 14. 8mm and 10.2 mm and the number of story collapsed is approximately 5 floors (DCR>2)
- Hinge formation starts from the location having maximum demand capacity ratio, and hence there is a high possibility of member components collapse during column failure scenario.
- It reveals that the middle column removal case as per the GSA guidelines is the critical location of column removal.
- The time period and displacement are more for precast building compared to cast in-situ frames.
- To prevent progressive collapse, the expected ultimate BM capacity of the members and connections, which shows higher values of DCR, should be increased to attain DCR value less than two.
- In general, structures designed and detailed with an adequate level of continuity, redundancy, and ductility can develop alternative load paths following the loss of an individual member and prevent progressive collapse.

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