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Determination of Progressive Collapse Resistance in RC Frame Buildings under Nonlinear Static and Pushdown Analysis

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Abstract-The certainty of the structure has always been considered vital to civil projects engineers. One of the mechanisms emphasized more recently is progressive collapse. It is a collapse in which a local break in the main structure will result in a successive failure in the next sections and finally a part or whole of the structure gets destroyed. This study, using the statute "GSA" (General Services Administration) and the software "SAP2000" has investigated the resistance of progressive collapse in RC frame buildings with medium ductility designed in very high risk seismic zone based on the statute "2800" in Iran and in two altitudes "5-storey" and "10-storey". Having been designed for constant loading, the buildings were analyzed by nonlinear static and Pushdown analysis applying side and corner column elimination. Based on the defined loadings in GSA and the bearing capacity diagrams of the structures, the resistance or the bearing capacity of the buildings designed in very high risk seismic zones has been acceptable. And also according to the results, the rise in height and floor numbers makes the buildings more resistant against the progressive collapse. Moreover, eliminating the side column outperforms eliminating the corner column resulting in more resistance.

Keywords- *Progressive Collapse Resistance, Nonlinear Static Analysis, Pushdown Analysis, RC Frame Building*

I. INTRODUCTION

Progressive collapse is defined as an extent of damage or collapse that is disproportionate to the magnitude of the initiating event. Since this definition focuses on the relative consequence or magnitude of the collapse rather than the manner in which it occurs, it is often referred to in the industry as "disproportionate" rather than "progressive" collapse [1]. Any flaw in the design or the structural elements implementation may cause the progressive collapse during explosive, fire or seismic loading. That's why such modeling has been a good challenge for researchers in the last two decades. This concern first arose due to the progressive collapse occurring in Ronan Point Building in 1968 and it was accelerated by the September 11 Catastrophe. Another incident was the Plasco 17-Storey steel building in 2017 where the fire in the upper floors hurt the main sections of the structure resulting in the total destruction.

One of the studies is the one by Tsai et al, working on concrete buildings resistant to earthquakes concluding that such buildings rarely experience progressive collapse [2]. Kim and Yu have conducted a research on RC frames in order to investigate the progressive collapse with the sudden elimination of the first floor column, using non-linear dynamic analysis, indicates that the structures not designed for seismic loading are so vulnerable to progressive collapse, while the ones designed accordingly are resistant against it [3]. Another study carried out by Marchis and Ioami, using dynamic analyses, a six-floor RC frame building in Romania has been investigated on progressive collapse designed for low-risk, medium-risk and high-risk seismic zones. It has been found out that the resistance rises with the increase of the lateral forces in the design [4]. Li and Sasani also drew a conclusion saying that both resistance and ductility are two crucial parameters in the building resistance against earthquakes and progressive collapse [5]. Abasnia and Yusefpour stated that the important factor in progressive collapse is the loading capacity, thus in all column elimination cases, high ductility results in more weakness than medium ductility [6].

II. RESEARCH GOAL

Many different committees have worked on progressive collapse and have upgraded their standards to tackle it. These committees include American Department of Defense (DOD), General Services Administration (GSA), and European Codes. In the present study, using the statute of GSA, the potential of progressive collapse in RC frame buildings located in very high risk seismic zone in Iran in two altitudes of 5 and 10-storey (two models) has been investigated. Having been designed with common loadings based on Iranian statutes, the buildings were analyzed according to different column elimination conditions using nonlinear static analysis followed by pushdown application to determine the ultimate resistance. And also, this study is trying to analyze the effect of the hazardous seismic zone and also of altitude on the progressive collapse resistance in RC frame buildings.

III. MODELING

This section talks about the modeling of the four buildings and the geometric characteristics of the buildings, the materials, loading, the hypotheses of analysis and designing, sections and the other parameters involved in the study. It is worth mentioning that to model the software "SAP2000 V.17.3.0" was used [7]. Tehran was picked as a representative for very high-risk zone. In this city two residential buildings with RC frame system and in two altitudes "5 and 10 floors" have analyzed and designed according to the regular plan shown in figure 1. The height of the floors is 3.2 meters, the ground type of the structure location is type III, gravity force resistance system is joist and block ceiling. For concrete with specifications of category C25, for longitudinal bars with specifications of category S400 and for confinement bars with specifications of category S340, has been used.

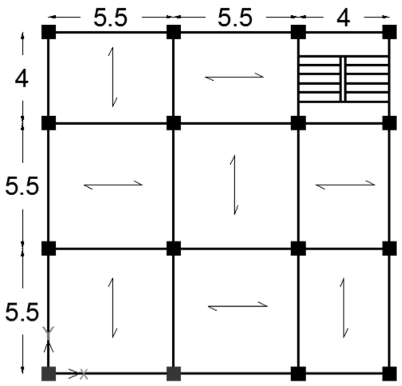

Figure 1. Buildings Plan (metric)

A. Gravity Loading

The sixth part of national building regulations of Iran is used for gravity loading [8]. The summary of gravity loading is presented in table I.

TABLE I. SUMMARY OF GRAVITY LOADING

Location	Dead Load (kgf/m^2)	Live Load (kgf/m^2)
Roof	580	150
Residential Floors	540	200
Staircase	570	500
Peripheral Wall	240	-
Parapet Wall	304	-
Partition Wall	-	100

B. Seismic Load

The seismic load has been calculated and applied based on the fourth version of Standard 2800 as the table II [9].

TABLE II. THE SEISMIC COEFFICIENTS

Number of story	Height	Period of time	Seismic coefficient (C)
5	16 m	0.7578 s	0.179
10	32 m	1.414 s	0.109

C. Analysis and Structure Design

To analyze the structures the equivalent static analysis has been used. To calculate the effective seismic weight, the dead load, partitioning and 20% of live load have been utilized. The lateral bearing system is intermediate reinforced concrete moment frame in both directions. The vertical earthquake load is applied to the entire structure. To design buildings and for load combinations, the ninth part of national building regulations of Iran and ACI-318 regulation have been used [10] & [11]. The sections of buildings are in tables III and IV.

TABLE III. SECTIONS OF 5-STOREY BUILDING

Story	Sections	
1	Column	55x55-16Φ25
	Beam	55x55
2	Column	50x50-12Φ25
	Beam	50x50
3	Column	45x45-12Φ25
	Beam	45x45
4	Column	45x45-12Φ22
	Beam	45x45
5	Column	40x40-8Φ22
	Beam	40x40
Dome roof	Column	35x35-8Φ16
	Beam	35x35

TABLE IV. SECTIONS OF 10-STOREY BUILDING

Story	Sections	
1	Column	70x70-24Φ28
	Beam	70x70
2	Column	70x70-20Φ25
	Beam	70x70
3	Column	60x60-20Φ25
	Beam	60x60
4	Column	60x60-16Φ25
	Beam	60x60
5	Column	55x55-16Φ25
	Beam	55x55
6	Column	55x55-12Φ25
	Beam	55x55
7	Column	50x50-12Φ25
	Beam	50x50
8	Column	50x50-8Φ25
	Beam	50x50
9	Column	45x45-8Φ22
	Beam	45x45
10	Column	40x40-8Φ22
	Beam	40x40
Dome roof	Column	35x35-8Φ16
	Beam	35x35

IV. Progressive Collapse Analysis

A. Nonlinear Static Analysis

The structure via alternate path method is analyzed by using 4 ways including linear and nonlinear static and dynamic methods. In this study, the non-linear static analysis was used.

This analysis was done based on GSA which the loading used in the progressive collapse level is different from the one in the design level. In column elimination, according to (1) uniform gravity loads is applied to all the structure. These loads include an increased gravity loads.

$$G_N = \Omega_N\, [1.2\, D + (0.5\, L \text{ or } 0.2\, S)] \tag{1}$$

In which G_N is the increased gravity loads for non-linear static analysis, Ω_N is the dynamic increase factor for calculating deformation-controlled and force-controlled actions for nonlinear static analysis, D is for the dead load, L is for the live load, and S is for the snow load. Based on GSA the dynamic increase factor for RC frame system is derived from (2).

$$\Omega_N = 1.04 + 0.45/(\theta_{pra}/\theta_y + 0.48) \tag{2}$$

In which θ_{pra} is the plastic rotation angle and θ_y is the yield rotation. It is to be said that the dynamic increase factor in the present study is 1.22.

B. Assign Plastic Hinges

For reinforced concrete (RC) flexural members, the plastic deformation is localized in a small zone namely the plastic hinge zone after the yielding of the member. Figure 2 is the definition of force-controlled and deformation-controlled actions, from ASCE 41 [12]. Based on GSA type 1 curve shown in figure 2 was used for the moment hinges of beams. In the curve, Q_y is for yield action (yield moment), Δ is for displacement (rotation), points 1 and 2, are for the nominal yield strength and ultimate strength, successively, and point 3 is for failure condition. Based on the values of regulations, modeling parameters are $a = 0.025$, $b = 0.03$ and $c = 0.2$.

To assign columns plastic hinges based on Specifications of FEMA, auto state of software including (P-M2-M3) degrees of freedom is used [13].

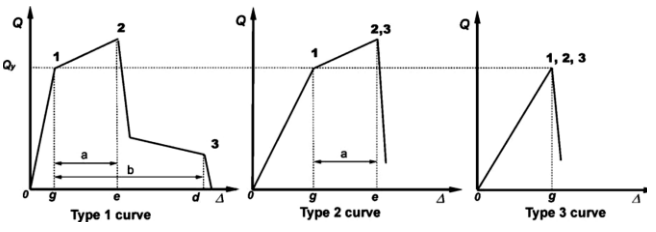

Figure 2. Definition of Force-Controlled and Deformation-Controlled Actions, from ASCE 41

C. Pushdown Analysis

To gain the ultimate resistance against progressive collapse, pushdown analysis needs to be done. Pushdown analysis on the damaged building is done in three ways including uniform pushdown, bay pushdown, and incremental dynamic pushdown.

The overload factors computed from these methods, together with the corresponding collapse modes, are proposed as measures of the robustness of the structural system against progressive collapse [14]. The result of the non-linear static analysis is shown through the diagram whose horizontal axis is for the displacement over the eliminated column and vertical axis is for overload factor. The overload factor is defined as the ratio of the applied load to the nominal load. The applied load is the load applied until the collapse and the nominal load is the one mentioned in the regulation. Equation (3) represents the load factor according to the loads defined in GSA guidelines.

$$\text{Load Factor} = \frac{P}{\Omega_N(1.2DL+0.5\,LL)} \tag{3}$$

In which P is the applied load, Ω_N is the dynamic increase factor, DL is the dead load and LL is the live load. Based on the GSA, two column elimination scenarios have been applied in the first floor of each building. The location of the columns elimination is shown in the figure 3.

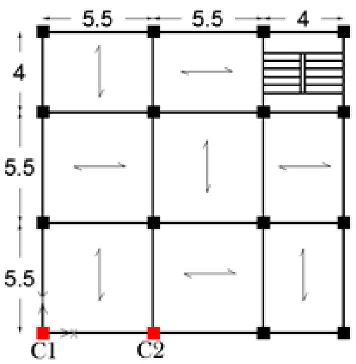

Figure 3. The Location of Columns Elimination in the First Floor Plan

V. Software Verification

To analyze progressive collapse, a software called "SAP2000V.17.3.0 has been used. To verify the authenticity of the results an experimental model accepted by Kokot et al has been utilized [15]. In this article, the problem of structural progressive collapse has been investigated using a real-scale reinforced concrete flat-slab frame building, which has survived collapse after two of its central columns had been physically destroyed.

Figure 4 shows the experimental model and the software. The diagram depicted in figure 5 shows the comparison between the results derived from the side column elimination. In the diagram of figure 5 made from dynamic analysis, the vertical axis is the movement above the eliminated column and the horizontal axis is the time of the movements. As it is seen a

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difference about 16% exists between the experimental and software result which is acceptable.

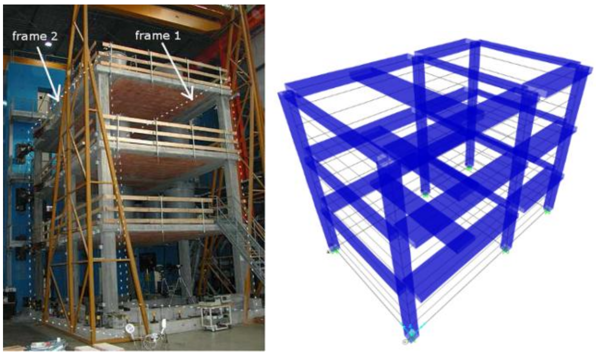


Figure 4. Experimental and Software Models

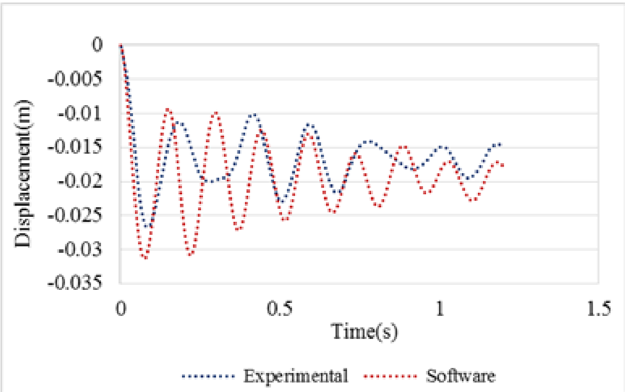
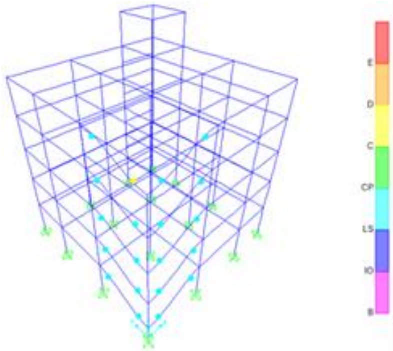


Figure 5. Diagram of Dynamic Analysis of Column Elimination in Experimental and Software Models

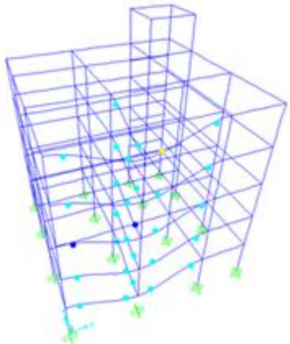
VI. RESULTS

A. Plastic Hinges Formation

The mechanism of plastic hinges formation in nonlinear static analysis and different column elimination conditions in the buildings designed in very high seismic zones in 5 and 10 floor heights is analyzed and shown in figures 4 and 5. Also, performance levels are "IO" (Immediate Occupancy), "LS" (Life Safety), "CP" (Collapse Prevention) and The "E" point is for ultimate failure. As depicted in figures 4 and 5 the collapse begins in the upper floors meaning that the plastic hinges are first formed in the upper floors and then reach their final resistance. Moreover, most of the hinges are formed in the beams surrounding the bays of the eliminated column and are often in the range of the collapse prevention level.

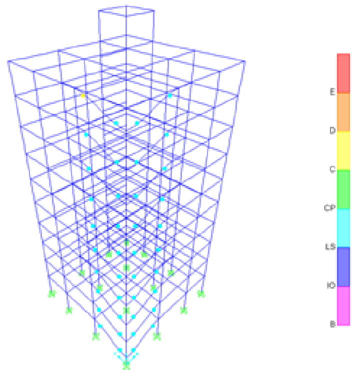


(a)



(b)

Figure 6. Plastic Hinges Formation of 5-Storey Building. a) Corner Column Elimination. b) Side Column Elimination



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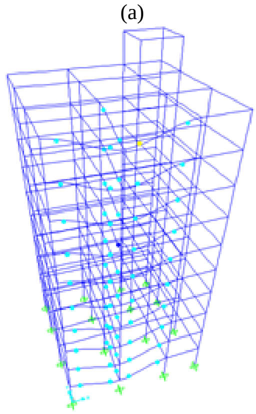
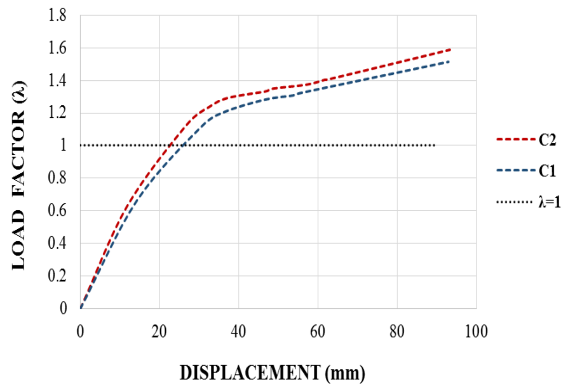


(b)

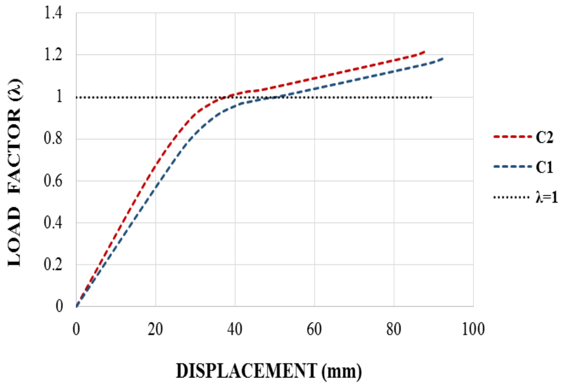
Figure 7. Plastic Hinges Formation of 10-Storey Building. a) Corner Column Elimination. b) Side Column Elimination

B. Nonlinear Static Analysis Diagrams

The results of the nonlinear static analysis are shown through the diagram whose horizontal axis is for the displacement over the eliminated column and vertical axis is for overload factor. In the uniform pushdown case (UP), gravity loads on the entire damaged structure are increased proportionally within a nonlinear static analysis framework until the system collapses. An UP analysis will lead to a collapse state corresponding to failure of the weakest part of the damaged structure and failure may occur outside the damaged bays. If the load factor is bigger than 1, according to GSA, the structure can tackle progressive collapse and is also able to redistribute the forces caused by the eliminated column. But if it is smaller than 1, the building cannot stand the column elimination and will not able to redistribute the forces. In the following, based on the diagrams shown in the figure 6 the bearing capacity of the structure, the effect of the building height and the effect of the eliminated column position on the progressive collapse resistance of the buildings has been discussed.



(a)



(b)

Figure 8. Diagrams of Nonlinear Static Analysis for Corner (C1) and Side (C2) Columns Elimination . a) 10-Storey Building. b) 5-Storey Building

According to the diagrams depicted in figure 6, the buildings enjoy acceptable residence. For the 10-storey building the resistance due to corner column elimination is about 51% and due to side column elimination is around 58%. This resistance for the 5-storey building is 18 and 21% respectively. Based on the diagrams, the 10-storey building is more resistant than the 5-storey one. For instance, the 10-storey building has 37% more resistance than the 5-storey one under the side column elimination.

Moreover, it has been concluded that the buildings have more resistance against the side column elimination than against the corner column elimination. For example, in the 10-storey building, the resistance against the side column elimination is 7% more than against the corner column elimination. This is 3% for the 5-storey building.

VII. CONCLUSION

In this study according to the GSA guidelines, how to determine the progressive collapse resistance of RC frame buildings under non-linear static and pushdown analysis was investigated.

This study concluded that the buildings designed in very high-risk seismic zones are appropriately resistant and of course their performance against progressive collapse will be acceptable. It has to be said that the regulations of the buildings in high-risk seismic zones against earthquakes impose a bigger lateral loads on the structures in order to increase the resistance.

With the rise in the height, the structure, due to more elements and uncertain degree increase is better at distributing the forces caused by the column elimination.

It has been concluded that the buildings are more resistant against side column elimination than corner column elimination. Because of the more uncertain degree, side and middle columns have more load substitution paths.

It has been witnessed that the collapse begins in the upper floors and the plastic hinges are first formed in the upper floors and then reach the ultimate resistance.

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