Earthquakes and Structures, *Vol. 18, No. 5 (2020)649-665*
DOI: https://doi.org/10.12989/eas.2020.18.5.649

Comparison of seismic progressive collapse distribution in low and mid rise RC buildings due to corner and edge columns removal

Somayyeh Karimiyan*

Department of Civil Engineering, Islamshahr Branch, Islamic Azad University, Islamshahr, Iran

(Received October 15, 2019, Revised January 30, 2020, Accepted March 1, 2020)

Abstract. One of the most important issues in structural systems is evaluation of the margin of safety in low and mid-rise buildings against the progressive collapse mechanism due to the earthquake loads. In this paper, modeling of collapse propagation in structural elements of RC frame buildings is evaluated by tracing down the collapse points in beam and column structural elements, one after another, under earthquake loads and the influence of column removal is investigated on how the collapse expansion in beam and column structural members. For this reason, progressive collapse phenomenon is studied in 3-story and 5-story intermediate moment resisting frame buildings due to the corner and edge column removal in presence of the earthquake loads. In this way, distribution and propagation of the collapse in progressive collapse mechanism is studied, from the first element of the structure to the collapse of a large part of the building with investigating and comparing the results of nonlinear time history analyses (NLTHA) in presence of two-component accelograms proposed by FEMA_P695. Evaluation of the results, including the statistical survey of the number and sequence of the collapsed points in process of the collapse distribution in structural system, show that the progressive collapse distribution are special and similar in low-rise and mid-rise RC buildings due to the simultaneous effects of the column removal and the earthquake loads and various patterns of the progressive collapse distribution are proposed and presented to predict the collapse propagation in structural elements of similar buildings. So, the results of collapse distribution patterns and comparing the values of collapse can be utilized to provide practical methods in codes and guidelines to enhance the structural resistance against the progressive collapse mechanism and eventually, the value of damage can be controlled and minimized in similar buildings.

Keywords: progressive collapse mechanism, collapse distribution, nonlinear time history analysis, intermediate moment resisting frame building

1. Introduction

Progressive collapse is a mechanism that a local, partial and primary damage occurs in one or more structural members due to any threat and inability of the other structural elements for redistribution of the over loads leads to the expansion of the failure in a large part or entire of the structure. In such a way that final collapse does not commensurate with the initial damage and subsequently, stability and continuity of the whole structure is eliminated. This phenomenon can be occurred due to any threat or loads such as bomb or gas explosion, impacts due to collision with a ship or air plane, earthquakes, fires and etc (Burnett 1975a, 1975b, Ellingwood and Leyendecker 1978, Somes 1973, McConnel and Kelly1983, Mays and Smith 1995, Bailey and Moore 2000a, Green and Wong 2001, Lyle *et al.* 2003, Hinman and Hammond 1997, Corley *et al.* 1998, Song *et al.* 2000). Natural incidents such as Northridge and Kobe earthquakes in 1994 and 1995, as well as abnormal events such as bombing in Murrah Federal Building in 1995 and the terrorist attacks at the World Trade Center towers, leads to the expansion of collapse in the structural members and eventually, progressive collapse mechanism in the structures, resulting in the huge casualties and macro economic impacts. Since then, progressive collapse phenomenon has been highly regarded by the researchers and scientists. The significance of this issue is to such an extent that in the past few years, topic of the design against the progressive collapse has been mentioned in many design codes and standards. Also, guidelines have been prepared, edited and revised several times in the current short time. For example, several methods has been proposed in UFC guideline such as Alternative load path (AP) method, Tie force (TF) method and Specific Local Resistance (SLR) method to increase the structural resistance against the progressive collapse mechanism. It can be said that the starting point for the study of progressive collapse phenomenon was the partial and step by step collapse in 22-story Ronan Point tower in 1968, which not only resulted in publication of numerous articles but led to the first stage of arrangement of codes, standards and guidelines to prevent progressive collapse in countries such as Britain, Canada and the United States (Griffith *et al.* 1968, Ferahian 1972, David *et al.* 2002)

Kaewkulchai and Williamson in 2004 presented a formulation for the use of fiber elements in structural modeling, as well as a procedure to analysis the progressive collapse mechanism in two-dimensional frames. In that study, the significance of dynamic redistribution of the

*Corresponding author, Assistant Professor
E-mail: s_karimiyan@iiau.ac.ir

http://www.techno-press.com/journals/was&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

loads due to the removal of the structural members was discussed and studied (Kaewkulchai and Williamson 2004).

Mohamed and Osama in 2006 compared the standards and codes in field of the progressive collapse mechanism. In that study, a variety of phenomena witch lead to the progressive collapse mechanism, loadings, analyses methods and the existing design instructions have been investigated (Osama and Mohamed 2006).

Vlassis and Anastasios in 2007 concluded that the structures should be designed in such a way that after initial failure, the structures remain stationary and stable in redistribution of the loads. Hence, principle issue in progressive collapse is the ultimate collapse mode which is more significance than the local initial collapse (Vlassis 2007).

In 2007, Starossek categorized the progressive collapse mechanism in 5 subjects in 4 categories. All types of progressive collapse mechanism in terms of path and direction of destruction, destruction process, destruction volume and how to start the destruction are:

Section type: in this category, because of the existence or creation the crack in a beam or column section, propagation of the crack occur due to the load transmission and lead to the collapse of the element.

Pancake type: in this case, due to downfall of the upper stories, a large amount of potential energy is converted into to the kinetic energy and is created a rigid vertical movement. Because of the influence of the impact and debris falling due to destruction of the upper stories, bearing elements of the lower stories are destructed and progressive collapse mechanism occurs. The best example of this kind of destruction is World Trade Center in New York. In this case, direction of damage is parallel to the progressive collapse phenomenon.

Domino type: In this case, the structural element rotate in rigid form, while overturning on to another element, also knocks to it. This impact is created due to conversion of the potential energy in to the kinetic energy, causing the overturning of the adjacent element and subsequently, the structural elements are located in the path of collapse. One of the most significant reasons for non-resistance of the elements in this type of collapse is slimming of the structural elements and lack of their inhibition.

Zipper type: this case of collapse is seen more in the design of cable bridges. For instance, the standard of Post Tension Institute (PTI) recommends that loading is considered as a "loss of cable" to prevent the progressive collapse mechanism and bridge instability is investigated due to the sudden failure of a cable. Thus, the torn cable force is instantaneously reached to the adjacent cables and consequently, this sudden increasing force cause to the progressive collapse mechanism in adjacent cables and ultimately, in the entire bridge.

The last type of progressive collapse is also called "compound progressive collapse", which is a combination of the above-mentioned progressive collapse mechanism (Starossek 2007).

In 2008, Zhongxian and Yanchao introduced direct simulation methods and the use of alternative paths as new and prevalent approaches to analysis the structures against the progressive collapse mechanism caused by the explosion loads. They examined the appropriateness, reliability and applicability of the mentioned methods (LI and Yanchao 2008).

In 2008, progressive collapse caused by the impact and explosion loads was investigated in reinforced concrete frame building and was concluded that between the direct modeling method and alternative path method, direct modeling method is more time-consuming and also, need the profound structural dynamic knowledge, collapse mechanic knowledge, material dynamic property and computation skills. Although, the alternative path method is relatively simpler, but has less accuracy. Also, another weakness of the alternative path method is to ignore the initial failure and non-zero initial conditions. In that study, with combination of both methods, a new method was proposed to remove the weakness of the alternative path method, although, this method is similar to the alternative path method, but comprehensive modeling such as direct method is not required. Therefore, it saves considerably time and memory. In addition, this new method provides a proper and reliable prediction of collapse expansion in comparison with the alternative path method (LI and Yanchao 2008, Xin Zheng *et al*. 2008).

In 2009, Alrudaini and Hadi used an alternative path method to evaluate the progressive collapse mechanism in a 10-story reinforced concrete building based on Australian code (AS3600). They used vertical cables which were connected to the ends of the beams in the existing buildings, and the cables which were embedded in the columns of new buildings, as the alternative paths. Then, using the nonlinear dynamic analyses according to GSA 2003 guideline, they concluded that the use of mentioned cables is useful and practical to resist against the progressive collapse mechanism (Thaer *et al*. 2009).

In 2011, progressive collapse mechanisms of symmetric and asymmetric buildings were studied due to the sudden column removal by designing several symmetric and asymmetric structural models, once with cores of bracing and again, with cores of reinforced concrete shear walls. The results of asymmetric models illustrated that varieties in resistance capacity of the progressive collapse depend on the location of removed columns. Progressive collapse potential in asymmetric buildings increases when the position of the removed column is in the asymmetric part of the building. Therefore, although the progressive collapse potential in asymmetric buildings is higher, but because of the cooperation and participation of other elements of structural system, it does not have significant difference in comparison with its symmetric type (Kim and Hong 2011).

In 2012, Gurley investigated the seismic resistance of structures to progressive collapse and also, the collapse mechanisms by comparing two-span mechanisms according to GSA guideline and the bending collapse mechanism due to the column removal caused by the explosion load. The results demonstrated that earthquake damages similar to the explosive loads could lead to the removal of the load bearing elements from the structural system. Therefore, the study of progressive collapse mechanism caused by the earthquake is very essential (Gurley 2012).

A large number of other researches have been conducted in field of the progressive collapse mechanism due to the column removal under explosion or impact loads (Bazant and Verdure 2007, Ibarra *et al*. 2005, Helmy *et al*. 2012, Qian and Li 2012, Mashhadiali and Kheyroddin 2013, Orton and Kirby 2013, Sagiroglu and Sasani 2013, Le and Xue 2013, Qian and Li 2013, Hafez *et al*. 2013, Tavakoli and Kiakojouri 2013, Lalkovski and Starossek 2013, UFC 2013, Lupoae 2013, Kim *et al*. 2013, Khandelwala *et al*. 2009, El-Tawil *et al*. 2007, Lew 2003, Karimiyan 2020), while, the progressive collapse due to the earthquake loads has been rarely studied.

Karimiyan *et al*. in 2013, 2014, and 2015 were studied and compared the progressive collapse phenomenon in 3, 6, 9 and 12 story symmetric and asymmetric reinforced concrete buildings with mass eccentricity of 5%, 15% and 25% in presence of 2-components earthquake loads. The study of interstory dirifts, absorbed energy and the number of collapsed hinges in the structural elements indicate that progressive collapse potential in asymmetric buildings is more than its symmetric type (Karimiyan *et al*. 2015, Karimiyan *et al*. 2014, Karimiyan *et al*. 2013, Karimiyan *et al*. 2013, Karimiyan *et al*. 2015).

Alternative path method and the column removal scenario were introduced as an independent of treat method by Petrone *et al*. in 2016 for the basis of simulating, modeling and designing against the progressive collapse to model reinforced concrete buildings. Structural element modeling, material properties and gravity loading conditions are the cases which are very effective and decisive in the progressive collapse scenario, especially, in catenary action, when the column removal occurs in the lower stories of the buildings. They also proposed an energy-based method to investigate and identify collapse mechanism in the multi-story structures (Floriana *et al*. 2016).

Elshaer *et al*., in 2017 investigated UFC guideline to assess reinforced concrete structures in progressive collapse mechanism. They investigated the location and the level of removed column and also the type of loading in the structures which were constructed according to Egypt codes. The use of nonlinear dynamic analyses and applied elements method in three-dimensional structures in presence of the earthquake loads demonstrated that the structures which constructed according to Egypt codes would satisfy UFC guideline considerations with a confidence ratio of 1.97. They also stated that the removal of column during earthquake is more urgent and more critical than the removal of column only under gravity load (Ahmed *et al*. 2017).

In 2018, Amiri *et al*., evaluated the progressive collapse in the reinforced concrete buildings due to the sudden column removal. In this way, two dynamic amplification coefficients, called load increase coefficient and dynamic increase coefficient, were proposed in linear and nonlinear static analyses, respectively. They experimentally proposed a new formula to calculate the value of dynamic increase coefficient by studying the effect of the existing structural capacity on the amount of dynamic increase coefficient in the reinforced concrete structures. Then, this formula was examined in a series of three-dimensional reinforced concrete structures with various span length, stories numbers and different seismic resistance. The results indicated that the new formula is effective and efficient to predict tensions and deformations in members of RC structures after the column removal (Amiri *et al*. 2018).

In 2019, the effects of torsional irregularity and discontinuity in plane of resistant vertical elements against the lateral loading were investigated on progressive collapse potential of the steel special moment resisting frames which designed in different seismic sites. In order to assess the progressive collapse mechanism according to GSA 2013 guideline, an internal column and an external column were removed in 3-dimentional 3, 6 and 9-story models. The results of dynamic analyses showed that the structures which designed for high seismic risk areas had less progressive collapse potential. In the case of discontinuity in lateral load-bearing system, the structures which designed for low seismic risk areas according to GSA 2013 guideline were not resistant to the progressive collapse mechanism. While, the structures which designed for high seismic risk areas satisfied GSA 2013 guideline for resistance to progressive collapse mechanism (Yavari *et al*. 2019).

As observed in most recent studies, progressive collapse has only been studied due to the column removal under explosion or impact loads and in few studies, it has been investigated just under earthquake loads. Therefore, simultaneous effects of the earthquake load and also the column removal have not been investigated yet in the structures which have weak or defective columns in different parts of the structure. To follow above studies, in the present research, the progressive collapse mechanism of the structures have been studied in the low and mid-rise reinforced concrete buildings in presence of the earthquake loads after an edge or a corner column removal. Because, as we know, there are numerous buildings with weak or defective columns in different parts of the structure that may be resistant to gravity loads, but under earthquakes may result in irreparable damages to human and financial resources. Meanwhile, the study of progressive collapse mechanism in presence of the earthquake loads, after middle column removal is under study and will be presented in the future papers.

Despite of the vulnerability and collapse of the structures in the past, numerous studies have been carried out on the failure and destruction of the structures caused by seismic loads. However, optimal design and evaluation of collapse propagation and distribution in the beam and column structural elements, consecutively from the first element to the rupture and destruction of the entire structure, has not been studied, yet.

In the present study, the collapse distribution scenarios or alternately the expansion of collapse in beam and column structural elements is studied from the first element, one after another until the ending of the nonlinear dynamic analyses and ultimately, instability and entire collapse of the structure due to the earthquake loads and the column removal. Accordingly, 3 and 5-story reinforced concrete intermediate moment resisting frame buildings are considered. Then, after a removal of corner or edge column in the ground floor of the building according to UFC guideline, collapse distribution scenarios is investigated in members of the structures due to the earthquake loads. Distinction of the current research with the other previous studies is that in previous studies, traditionally, the level of collapse in the structures was considered a level which the first point of the structure would be at a damage or destruction. In other words, the failure of the first element of the structure was considered as the ultimate collapse of the structure, and the continuation of the collapse and how propagation of the collapse in the structural elements, consecutively, was not studied, yet. In this research, distribution of the collapse in the structural elements is investigated from the first element, one after another in beam and column structural elements until the ending of the nonlinear dynamic analyses or instability of the structures. It is noted that considered collapse criterion in the present study is the stage which a structural element exceeds the collapse prevention performance level according to Modified Ibarra-Medina-Krawinkler nonlinear model.

Therefore, it can be said that the innovations of the present research are:

• Modeling how expansion and distribution of the collapse from the starting point and then, evaluating the continuation and propagation of the collapse in the structural elements, one after another in the reinforced concrete intermediate moment resisting frame buildings due to simultaneous effects of the earthquake loads and column removal in three-dimensional state for the first time.

• Investigation of the influence of column removal variable in collapse distribution in reinforced concrete buildings in presence of the earthquake loads.

• Development of modeling and how to analyze the seismic progressive collapse mechanism.

• Propose Behavioral patterns of collapse distribution to predict collapse propagation in seismic progressive collapse mechanism due to the column removal in the similar structures.

• Estimation and comparison of the margin of safety in reinforced concrete structures due to the corner or edge column removal in the progressive collapse mechanism caused by the earthquake loads with comparing their vulnerability.

• Presentation and suggestion how to use the various available methods to determine new regulations in standards or guidelines to decrease the risk of the seismic progressive collapse due to the columns removal.

As we know, the majority of the administrative, commercial and residential buildings are made of intermediate moment resisting frames and evaluation of such buildings with intermediate moment frames is vital. For this reason, intermediate moment resisting frame structures were considered in the present research.

2. The sample study structures

In the present study, 3 and 5-story three-dimensional reinforced concrete intermediate moment resisting frame buildings with 3 spans in two horizontal directions, first designed according to ACI 2019 code and using Etabs software. The height of the stories is 4m, the length of the beams is 4.5m and the base shear coefficient is 0.13. Dead load and live load were considered 5.74 and 1.47 KN/m^2, respectively and also, Fc was considered 28 MPa. Then, designed structures were modeled in OPENSEES software to examine the progressive collapse mechanism. The reason for selecting the above mentioned specifications for the sample models is that the results of the present study can be generalized to a wide range of conventional buildings. Fig. 1 shows the 3D views of the studied sample buildings.

Thus, progressive collapse mechanism, distribution and expansion of the collapse from the first structural elements to the collapse of a large part of the structures are studied with comparing and evaluating the results of NLTHA after a corner or an edge column removal in presence of far field 2-component accelograms proposed by FEMA_P695 according to Table A-4C shown in Table 1.

It is worth to note that the influences of infills in the structural models are not considered in the present research. The reason for the use of Opensees software is that, there are numerous studies which have also been utilized Opensees software to evaluate and review the progressive collapse mechanism which corroborate the ability and sufficiency of this software to satisfy the requirements of the present research (FEMA P695 2009, Ibarra and Krawinkler 2004, Haselton and Deierlein 2007, Haselton *et al*. 2008, Haselton *et al*. 2009, Ibarra 2005, Lignos and Krawinkler 2012, Lignos and Krawinkler 2013, Zareian *et al*. 2009, Zareian *et al*. 2010).

As Modified Ibarra-Medina-Krawinkler Deterior ation Model is the only behavioral model which i s capable to model step-by-step collapse in the str uctural elements, sequentially in both steel and rei nforced concrete structures, to simulate the progres sive collapse mechanism in the structures, Modifie d Ibarra-Medina-Krawinkler Deterioration Model is used to model the concentrated plastic hinges in both ends of the elastic beam and column structur al elements (, FEMA P695 2009, Ibarra *et al*. 20 05, Ibarra and Krawinkler 2004, Haselton and Dei erlein 2007, Haselton *et al*. 2008).

Modified Ibarra-Medina-Krawinkler behavioral model has been calibrated according to the empirical relation ships which have been derived from the results of exte nsive RC experimental tests developed by Lignos and Krawinkler (ASCE 41, FEMA P695 2009, Ibarra *et al*. 2005, Ibarra and Krawinkler 2004, Haselton and Deier lein 2007, Haselton *et al*. 2008, Haselton *et al*. 2009, Ibarra 2005, Lignos and Krawinkler 2012, Lignos and Krawinkler 2013, Zareian *et al*. 2009, Zareian *et al*. 20 10). Accordingly, Modified Ibarra-Medina-Krawinkler D eterioration Model which was derived from the actual t est results is definitely a valid, proven and reliable mo del to model progressive collapse mechanism of the str uctures.

To validate this research, it should be said that Mo dified Ibarra-Medina-Krawinkler behavioral curve has al ready been utilized in progressive collapse mechanism

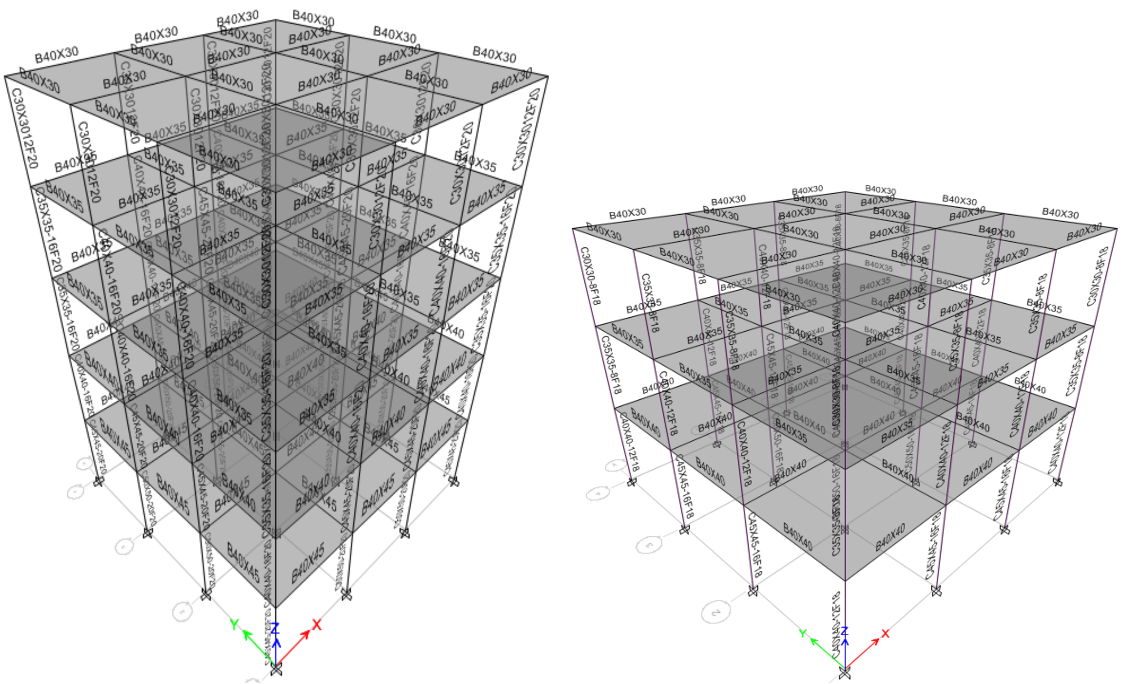

Fig.1 3-dimensional views of the studied sample buildings

Table 1 Far-Field Records used in the study proposed by FEMA_P695 (FEMA P695 2009)

ID No.	PEER-NGA Record Information				Recorded Motions	
	Record Seq. No.	Lowest Freq (Hz.)	File Names – Horizontal Records		PGA *max* (g)	PGV *max* (cm/s.)
			Compotent 1	Component 2		
1	953	0.25	NORTHR/MRL009	NORTHR/MRL279	0.52	63
2	960	0.13	NORTHR/LOS000	NORTHR/LOS270	0.48	45
3	1602	0.06	DUZCE/BOL000	DUZCE/BOL090	0.82	62
4	1787	0.04	HECTOR/HEC000	HECTOR/HEC090	0.34	42
5	169	0.06	IMPVLL/H-DLT262	IMPVLL/H-DLT352	0.35	33
6	174	0.25	IMPVALL/H-E11140	IMPVALL/H-E11230	0.38	42
7	1111	0.13	KOBE/NIS000	KOBE/NIS090	0.51	37
8	1116	0.13	KOBE/NIS000	KOBE/SHI090	0.24	38
9	1158	0.24	KOCAELI/DZC180	KOCAELI/DZC270	0.36	59
10	1148	0.09	KOCAELI/ARC000	KOCAELI/ARC090	0.22	40
11	900	0.07	LANDERS/YER270	LANDERS/YER360	0.24	52
12	848	0.13	LANDERS/CLW-LN	LANDERS/CLW-TR	0.42	42
13	752	0.13	LOMAP/CAP000	LOMAP/CAP090	0.53	35
14	767	0.13	LOMAP/G0300	LOMAP/G03090	0.56	45
15	1633	0.13	MANJIL/ABBAR-L	MANJIL/ABBAR-T	0.51	54
16	721	0.13	SUPERST/B-ICC000	SUPERST/B-ICC090	0.36	46
17	725	0.25	SUPERST/B-POE270	SUPERST/B-POE360	0.45	36
18	829	0.07	CAPEMEND/ROI270	CAPEMEND/ROI360	0.55	44
19	1244	0.05	CHICHI/CHY101-E	CHICHI/CHY101-N	0.44	115
20	1485	0.05	CHICHI/TCU045-E	CHICHI/TCU045-N	0.51	39
21	68	0.25	SFERN/PEL090	SFERN/PEL180	0.21	19
22	125	0.13	FRIULI/A-TMZ000	FRIULI/A-TMZ270	0.35	31

of 2D structures by the creators of abovementioned hysteresis curve (Haselton and Deierlein 2007, Haselton *et al*. 2009, Haselton *et al*. 2009). The present study has been inspired by the previous 2D researches. Based on that, in this paper the analyses have been extended in 3D structures. In other words, the assumptions and conditions considered by previous researchers in 2D structures are now generalized to 3D buildings.

This nonlinear behavioral model is capable to model the strain-softening behavior associated with concrete crushing, rebar buckling and fracture or bond failure [52]. The reason for the use of concentrated plastic

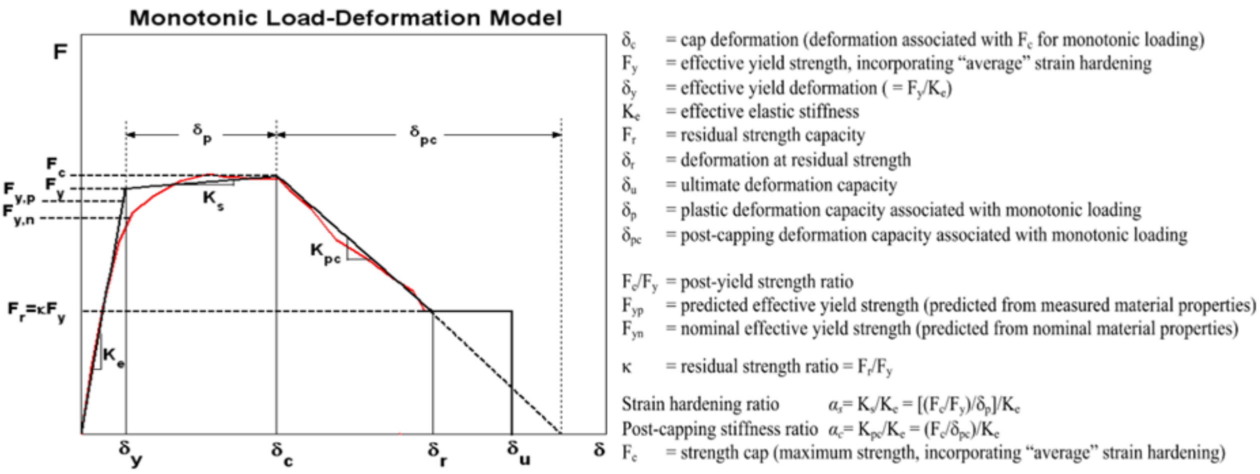

Fig. 2 Backbone curve of modified Ibarra-Medina-Krawinkler nonlinear model in the present study (Ibarra and Kawinkler 2004, Lignos *et al*. 2008, Haselton *et al*. 2009, Ibarra 2005, Lignos and Krawinkler 2012m Krawinkler *et al*. 2009)

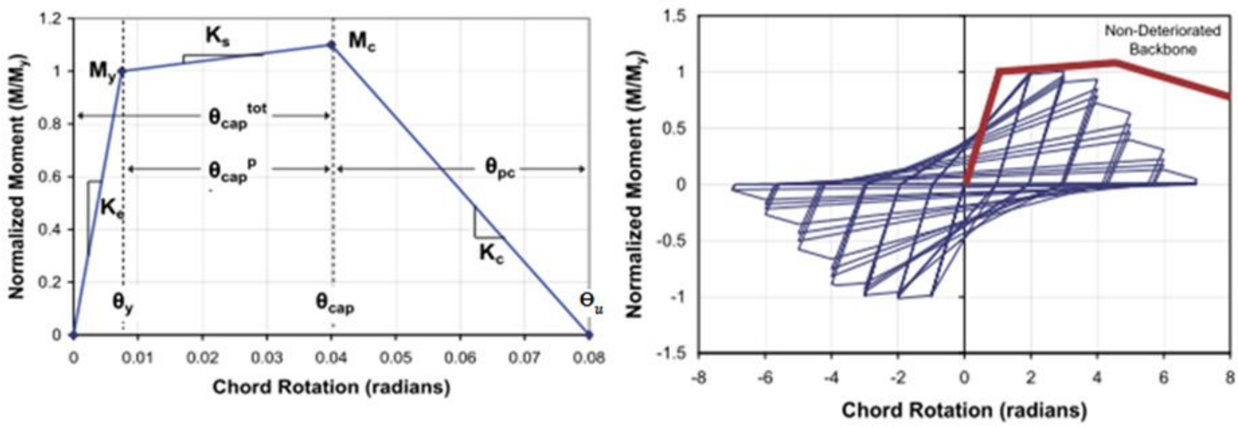

Fig. 3 Monotonic and hysereisis behavior of modified Ibarra-Medina-Krawinkler nonlinear model in the present study (Ibarra *et al*. 2005, Zareian *et al*. 2009, Zareian and Medina 2010, Haselton and Deierlein 2007, Haselton *et al*. 2008)

hinges, instead of fiber elements is that the fiber elements are not able to simulate strain-softening related to rebar buckling. Hence, the flexural collapse of reinforced concrete frames cannot be reliably simulated (FEMA P695 2009, Ibarra *et al*. 2005, Ibarra and Krawinkler 2004, Haselton *et al*. 2008). Figs. 2 and 3 illustrate Modified Ibarra-Medina-Krawinkler nonlinear model.

As mentioned before, the criterion to model the progressive collapse in the structures is collapse prevention performance level in structural elements. Thus, according to Fig. 2, the parameter κ must be equal to value of zero to satisfy this issue. In other words, according to Fig. 3, the value of bending resistance corresponds to the value of θ_u is zero. This means that by considering the value of zero for the parameter κ, during the NLTHA, when the resistance of a beam or column element reaches to value of zero, at the same time as convergence of computations and continuing the analysis, the structural element will automatically removed from the structure and time history analysis is continued in the residual structure, without the aforementioned element, till the next point resistance in the beam or column structural elements reaches to the value of zero and is automatically removed from the residual structure. This process continues in the structure till the structure is completely collapsed. Therefore, the collapse index defined for per structural element is θ_u according to Modified Ibarra-Medina-Krawinkler behavioral model. This means that during the NLTHA, when the value of θ in each concentrated plastic hinge exceeds its corresponding value of θ_u , it means that the bending resistance value of that hinge is equal to zero and the related element is automatically removed from the residual structural system. θ_u for each concentrated plastic hinge is calculated according to the relationships associate with Modified Medina-Ibarra-Krawinkler curve. It is noted that two concentrated plastic hinges has been defined at both ends of each elastic beam and column structural element.

Then, NLTHA was performed in 3 and 5-story reinforced concrete buildings, once due to a corner column removal and again due to an edge column removal in presence of 22 far-field ground motion records proposed in FEMA_P695. The ground motion records

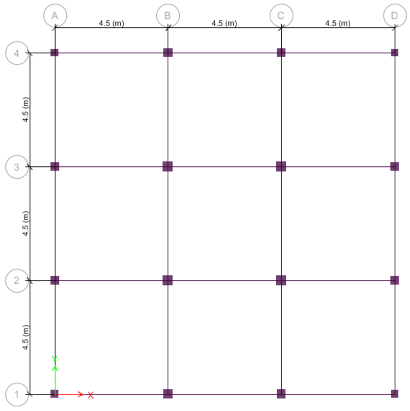

Fig 4. Locations of the corner column and the edge column considered in the present study

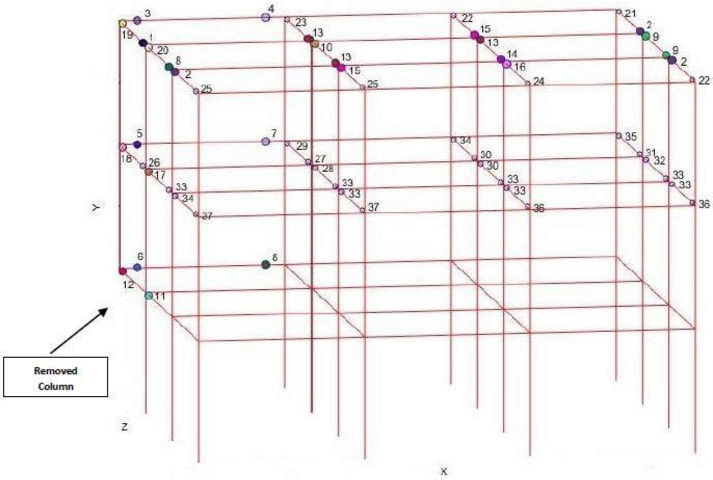

Fig. 5 Distribution of collapse in 3-story building in presence of earthquake record #169

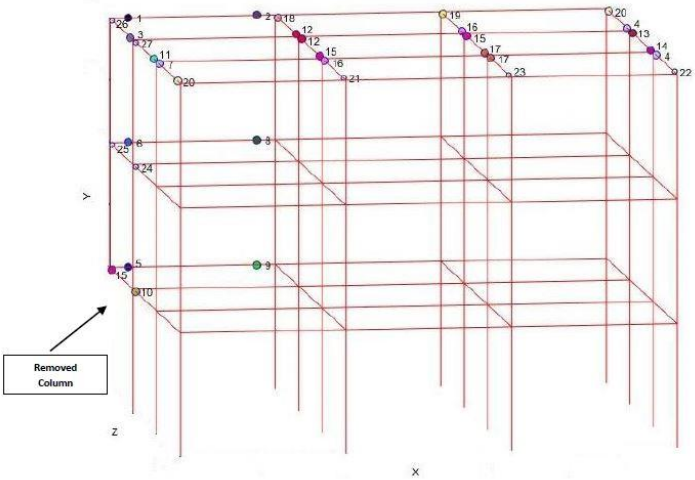

Fig 6. Distribution of collapse in 3-story building in presence of earthquake record #725

suggested in FEMA_P695 have extensive been studied to evaluate the collapse mechanism and have been reco mmended by this reference to use the earthquakes in r esearches relevant to the collapse mechanism. The reas on for the use far-field earthquakes is that these record s are more applicable and also, have also been utilized in the reference articles that are the basis of the prese nt study.

Meanwhile, since the purpose of the present study i s to investigate the collapse mechanism in the structure s and as collapse prevention performance level is the c riterion to analysis the progressive collapse mechanism,

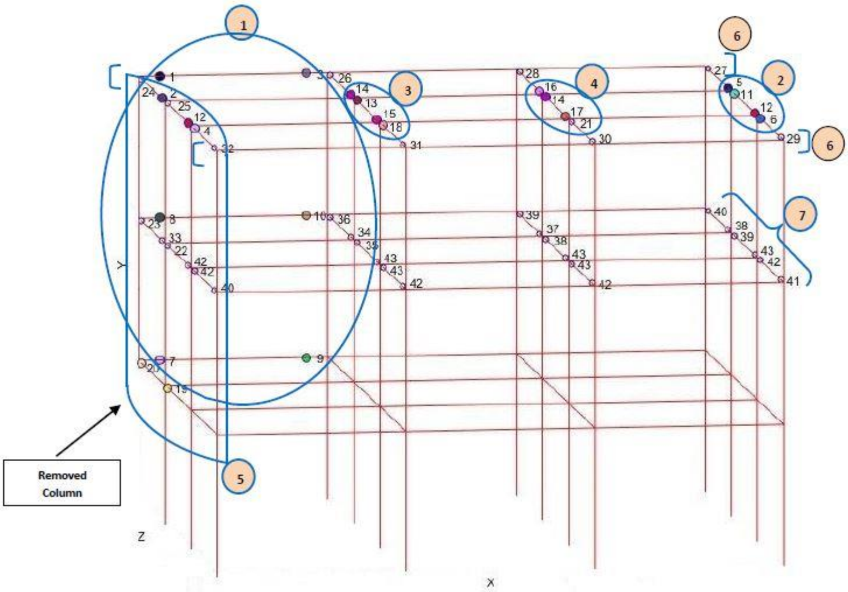

Fig 7. Distribution of collapse in 3-story building in presence of earthquake record #721

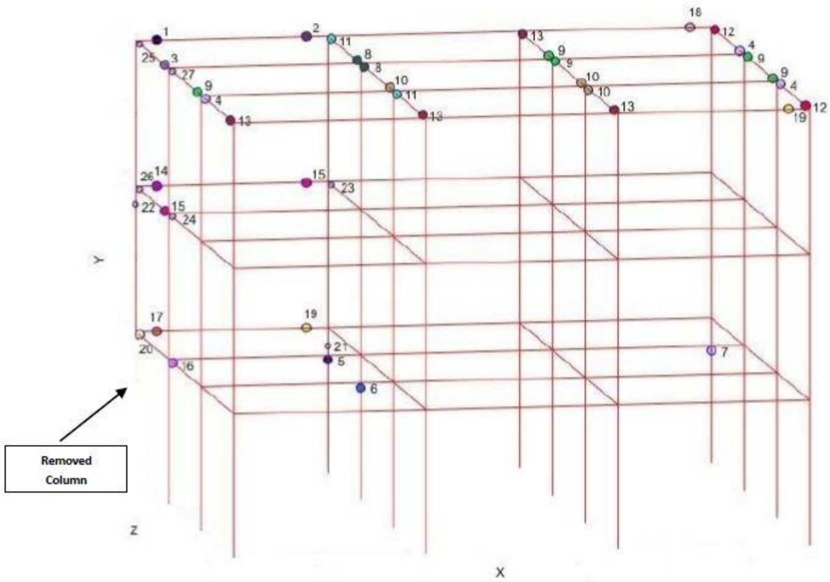

Fig 8. Distribution of collapse in 3-story building in presence of earthquake record #125

to exert a drastic effect of the earthquake loads which increases the probability of collapse in structures, PGA value of the earthquakes has been scaled in PGA level of 1 g to 2.5 g, using incremental dynamic analyses. The PGA value of above accelerograms has been step by step increased to result in formation of the plastic concentrated hinges in the beam and column elements which, in the sense of causing collapse in the structural elements and subsequently, the structures become unstable.

3. Collapse distribution

In order to study the propagation and distribution process of the collapse, one after another in beam and column structural elements of the structures in field of progressive collapse mechanism, after removing a corner column, in 3-story and 5-story buildings, NLTHA was performed using the proposed earthquakes in FEMA_P695 and the sequence of collapse was investigated in the structural members or in other words, the collapse scenario in beam and column elements was studied. The same process was repeated once again, after an edge column removal in 3-story and 5-story buildings and the expansion of collapse was investigated, sequentially. The sequence of collapse from the first beam or column element was followed, one after another, in the structural system and continued till the structure becomes unstable or the time history analysis is completed. Fig. 4 illustrates the locations of the corner and the edge columns considered in the present study.

3.1 Collapse distribution in 3-story building due to the corner column removal in presence of the earthquake loads

As noted before, to evaluate the collapse distribution in progressive collapse mechanism, after corner column removal in 3-story reinforced concrete building, the sequence of collapse was followed in beam and column elements of the structure during NLTHA. In other words, collapse scenarios were investigated in mentioned structure. Accordingly, Results of the observed collapse propagations demonstrated that there are two patterns of the collapse distribution in 3-story reinforced concrete building due to the corner column removal.

3.2 The first pattern of collapse distribution in 3-story building due to corner column removal in presence of earthquake loads

For an instance, Figs. 5 and 6 show that how the collapse is distributed in 3 story RC building in presence of the earthquake records # 160 and #725, respectively. It is worth to mention that the numbers in the following Figs indicates the order and sequence of collapsed hinges in beam and column structural elements.

As Fig. 5 shows the starting point of the collapse is occurred at the top of the removed corner column in the third ceiling (concentrated hinge no. 1). Then the collapse is continued in x-directional beams above the removed column at the third, second and first ceilings (concentrated hinges 2, 3, 4, 5, 6, 7 and 8) and it is transmitted to z-directional beams of the right border of the third ceiling (concentrated hinge no. 9). In following, collapse is distributed in z-directional beams of the left inner frame in the same third ceiling (concentrated hinges 10, 13 and 15) and after that, it is propagated in z-directional beams of the right inner frame (concentrated hinges 13, 14, 15 and 16) and then it is transferred to beams of the z-directional frame above the removed column (concentrated hinges 17, 18, 19 and 20). Subsequently, hinges are formed in the peripheral connections of z-directional beams of the third ceiling (concentrated hinges 21, 22, 23, 24 and 25) and finally it ends up in z-directional beams of the second ceiling (concentrated hinges 26 to 37).

According to Fig. 6, the failure initiation point is exactly formed above the removed corner column of the third ceiling (hinge no. 1). Then the failure is continued on the upper beams of the removed column in two directions X and Z on the third ceiling (hinges 2 and 3) and then it is transmitted to z-directional beams of the right peripheral edge of the third ceiling (hinge no. 4). Then the collapse is distributed in the x-directional beams above the removed column in the second and the first ceilings (hinges 5, 6, 8 and 9) and afterward it is spread in the z-directional beams above the removed column (hinges 10 and 11) and in the left side inner frame of the third ceiling (hinge no. 12). Thereafter, the collapse is formed in the z-directional beams of the two half-right frames of the same ceiling (hinges 13, 14, 15, 16 and 17) and after distribution in z-directional beams of the right side inner frame, it ends up with propagation in marginal connections of z-directional beams of the third ceiling and finally the second ceiling (hinges 18 to 27).

The same process was repeated for the other earthquakes recommended in FEMA_P695 guideline, and the sequence of the plastic hinges occurrence or, in other words, step by step failure of the beam and column elements were investigated according to the collapse criterion recommended by Modified Ibara-Medina-Krawinkler curve in the 3-story RC building. For a better and more accurate understanding of the order of formed critical collapse hinges and subsequently the sequence of the collapse in beam and column elements, the 3-dimensional Figs. of the other earthquake records, such as above Figs., were plotted and compared. It was observed that the fracture distribution follows a special and similar trend in 3-story buildings, in such a way that it is possible to predict the same collapse distribution scenarios in beam and column structural elements of other similar buildings. In other words, collapse distributions are similar and independent of earthquakes, as well as the collapse initiation points and the subsequent critical members due to the numerous earthquake records. Results demonstrated that there are two patterns of collapse distribution in 3-story RC buildings. Based on the obtained results and observations of about 65% of earthquake records, if we want to summarize how the collapse is distributed in similar buildings as the first pattern, the collapse distribution scenario in 3-story building is shown in Fig. 7 as an instance in presence of the earthquake records# 721.

As Fig. 7 shows, the collapse is exactly begun from above the removed column in the third ceiling (hinge no. 1) Then the spread of the collapse is continued in the upper beams of the removed column in both directions X and Z in the third ceiling (hinges 2, 3 and 4) and then it is propagated in z-directional beams of the right boundary in the third floor (hinges 5 and 6). After that, the collapse is distributed in x-directional beams, above the removed column, in the second and the first ceilings, respectively (hinges 7, 8, 9 and 10) and in following, it is propagated in perimeter z-directional beams of the right margin (hinges 11 and 12) and also, in the left side inner frame of the third floor (hinges 13, 14 and 15). The expansion of the collapse is continued in z-directional beams of the right side inner frame (hinges 16 and 17). Then, it is transmitted to z-directional beams above the removed column (hinges 19, 20, 22, 23, 24 and 25) and after distribution in marginal connections of z-directional beams of the third floor (hinges 26 to 32), it ends up in all z-directional beams of the second ceiling (hinges 33 to 42).

3.3 The second pattern of collapse distribution in 3-story building due to corner column removal in presence of earthquake loads

Fig. 8 illustrates the second pattern of the collapse distribution in 3 story RC building.

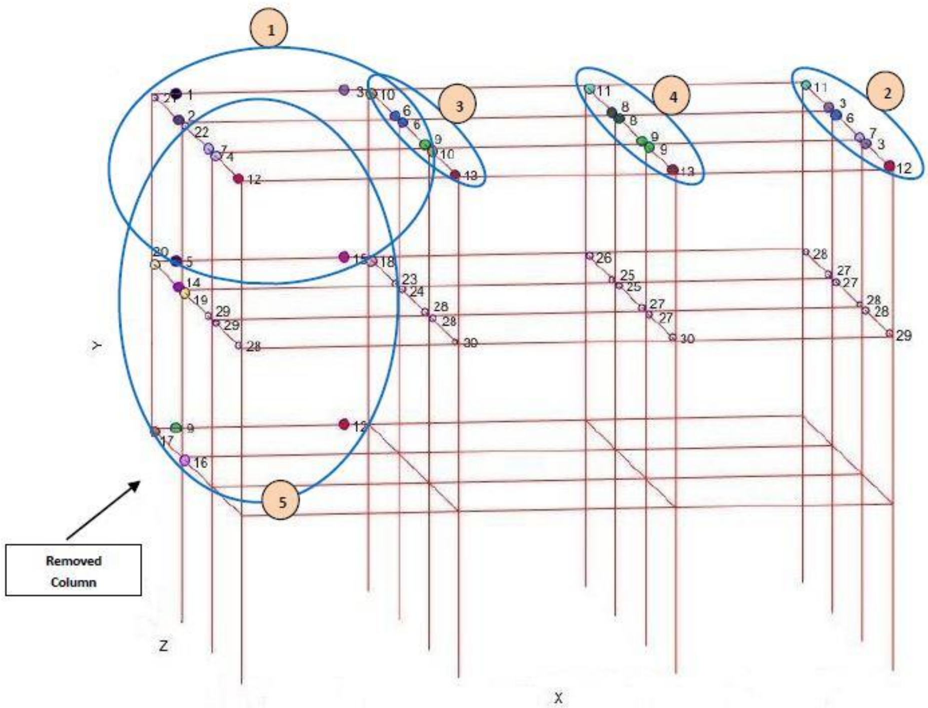

Fig 9. Distribution of collapse in 3-story building in presence of earthquake record #1633

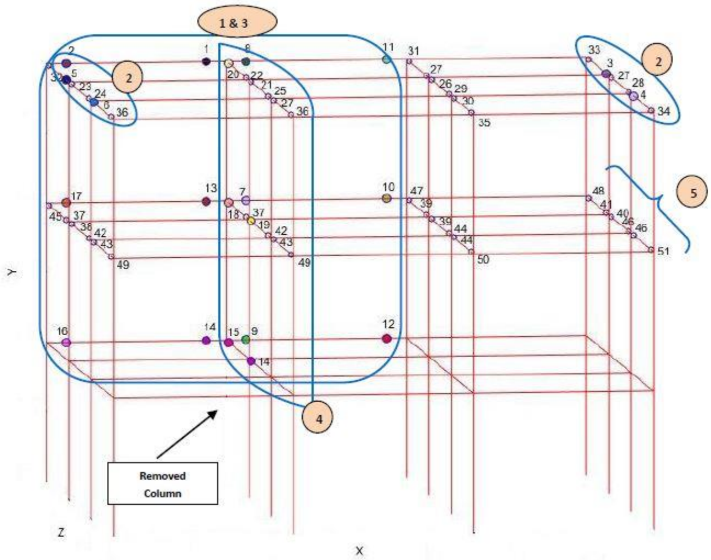

Fig 10. Distribution of collapse in 3-story building in presence of earthquake record #169

As Fig. 8 shows collapse is exactly started from above the removed column in the third ceiling (hinge no. 1). Then it is propagated in upper beams of the removed column in both X and Z directions (hinges 2, 3 and 4) and after that, it is transferred to z-directional beams of the right side border in the third story (hinge no. 4). In the following, collapse is distributed in z-directional beams of the left side inner frame of the third ceiling (hinges 8, 10, 11 and 13) and afterwards, it is transmitted to z-directional beams of the right side inner frame in the same ceiling (hinges 9, 10 and 13) and eventually, it ends up with distribution in the two side frames above the removed column in both X and Z directions (hinges 14, 15, 16, 17, 19, 20, 21, 22, 24, 25 and 26).

As the result, second pattern of the collapse distribution is shown in figure 9 due to earthquake record #1633. This type of the collapse distribution pattern includes approximately 15% of the results in 3-story building without a corner column.

As Fig. 11 shows, collapse is exactly started at the

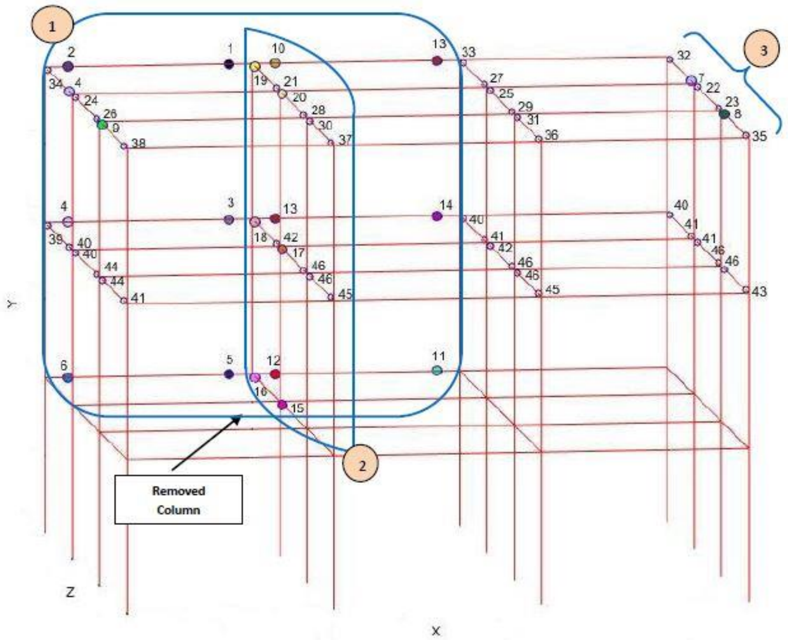

Fig 11. Distribution of collapse in 3-story building in presence of earthquake record #721

top of the removed column in the third ceiling (hinge no. 1). Then it is distributed in x-directional beams above the removed column in the third, second, and the first ceilings (hinges 2, 3, 4, 5, 6, 10, 11, 12, 13 and 14). Afterwards, it is transferred to z-directional beams of the inner frame including the removed column (hinges 15 to 21). Then, it ends up in the rest of the z-directional beams of the third ceiling (hinges 22 to 38) and finally, in beams of the second story (hinges 39 to 45). According to the Fig. 15, the focus of the collapse is more above the removed column in left area of the structure. Also, in comparison between the collapse occurrence in beams and columns, more collapses are distributed in the beams and lastly, it is observed that direction of the collapse is from top to bottom of the structure.

3.7 Results of the collapse distribution in 3-story RC building due to an edge column removal in presence of earth quake loads

The evaluation of the results from the NLTHA indicates that the collapse distribution due to the simultaneous effects of the edge column removal and the earthquake loads is specific, similar, repetitive process and independent of the earthquake records, in such a way that, this process can be used to predict the collapse distribution in beams and columns, one after another, and ultimately to reduce the progressive collapse potential of the similar buildings.

Findings also indicate that in 100% of the results, the concentration of collapse is more in the eliminated column area. In other words, the critical elements of the structure are in the upper part and around the defective column, in left side frames in 3-story building. Therefore, the structural elements around and above the defective column, especially the structural members in upper part of the structure, should be prioritized to reinforce such structures and to increase the structural resistance against the progressive collapse mechanism technical approaches provided in UFC guideline can be used to reinforce the critical structural elements.

Other results show that in 76% of the analyses, distribution of the collapse is from top to bottom of the structure, because due to design considerations, geometry and dimensions of the sections in lower members of the structure are stronger than upper members. So, direction of the collapse distribution is vertically from the third ceiling to the lower part of the structure. In this regard, this issue can be utilized to provide regulations in guidelines and codes to strengthen the similar structure against the progressive collapse. For example, alternative path method can be useful as a practical approach.

The results also show that the collapse initiation points and the critical members are repetitive in the structural system. Another finding of the present study, accounting about 88% of the results, is the large number of the collapse occurrences in beams in comparison with the columns, especially in the early stages of structural collapse. This is due to the weak beam-strong column issue, which leads to overtake the most collapse events in beams in comparison with the columns. Therefore, reinforcement of beam elements should be prioritized to increase structural resistance to progressive collapse mechanism.

Consequently, above results can be used in design stage of similar structures. UFC guideline and other researches have provided solutions such as alternative path method, tie force method, and specific local resistance method, etc to improve and increase the structural resistance to progressive collapse mechanism. Combination of mentioned resources and results of the present study can be used to decrease progressive collapse potential of the similar structures.

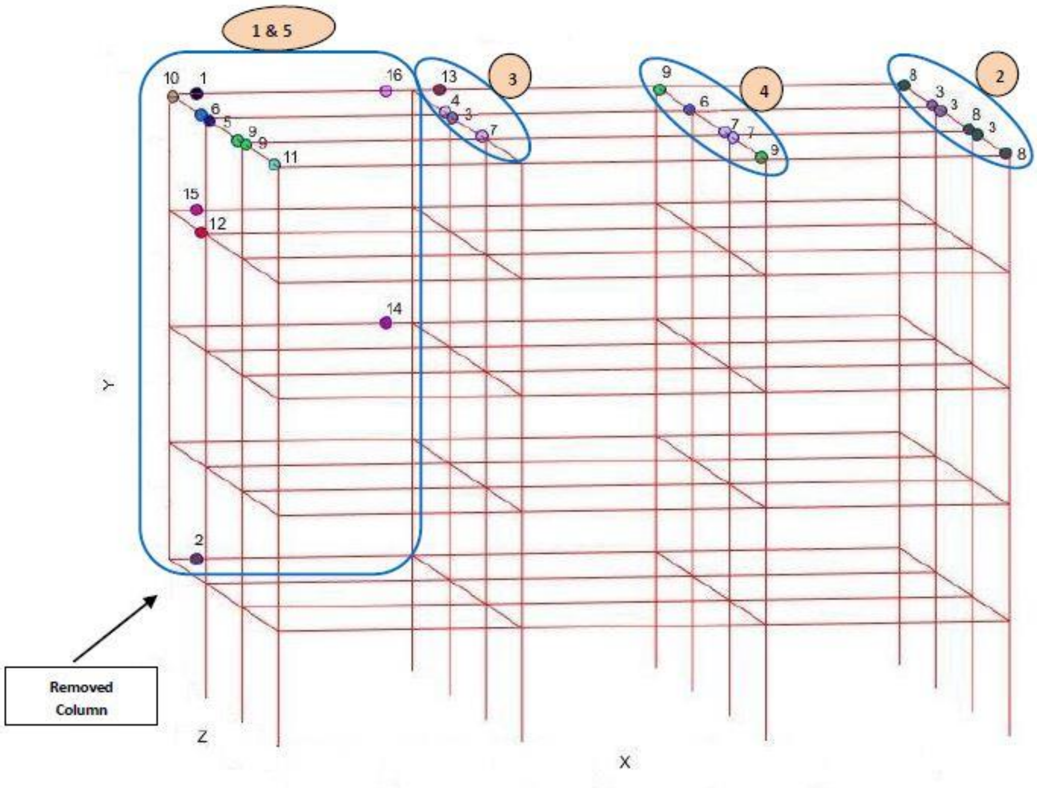

Fig 12. Distribution of collapse in 5-story building in presence of earthquake record #125

3.8 Collapse distribution in 5-story RC building due to the corner column removal in presence of earth quake loads:

Similar to what already has been carried out, to investigate the collapse distribution in progressive collapse mechanism, the corner column in 5-story RC building was removed and NLTHA were performed. The collapse scenario was investigated by studying the sequence of collapsed hinges in beams and column elements. The results of the collapse distribution in this structure show that scattering of the results are higher in 5-story structure and about 45% of the results show one pattern of the collapse distribution, which is presented in Fig. 12 due to earthquake record #125.

3.9 Pattern of Collapse distribution in 5-story RC building due to the corner column removal in presence of earth quake loads

As Fig. 12 shows, the collapse initiation point is in the beam above the removed column in the fifth ceiling. Also, concentration of the collapse is more in the upper region of the removed column. In comparison between the beams and columns, collapse distribution is more in the beams and direction of the collapse distribution is from the fifth ceiling, the upper part of the structure, to the lower part of the structure. It is worth to mention that, due to the corner column removal, pattern of the collapse distribution in 5-story building is approximately similar to the second pattern of the collapse distribution in 3-story building.

3.10 Collapse distribution in 5-story RC building due to the edge column removal in presence of earth quake loads

In the following, the edge column was removed in 5-story RC building and NLTHA were performed. Then the sequence of the collapsed hinges in the structural elements was investigated to present the pattern of collapse distribution. The results of collapse distribution in this structure indicate that due to simultaneous effects of the earthquake loads and the edge column removal, scattering of the results in 5-story structure are greater and in about 54% of the results, there is one pattern of collapse distribution, shown in Fig. 13 due to earthquake record #1244.

3.11 Pattern of Collapse distribution in 5-story RC building due to the edge column removal in presence of earth quake loads:

According to Fig. 13, the greater concentration of c ollapse is in upper part of the removed column and th e starting point of the collapse is mostly in the beam elements. Most of the collapse distribution is in the be am elements and direction of the collapse distribution i s from top to bottom of the structure. Fig. 13 shows t hat, due to the edge column removal, pattern of the co llapse distribution in 5-story building is approximately t he combination of the first and the second patterns of

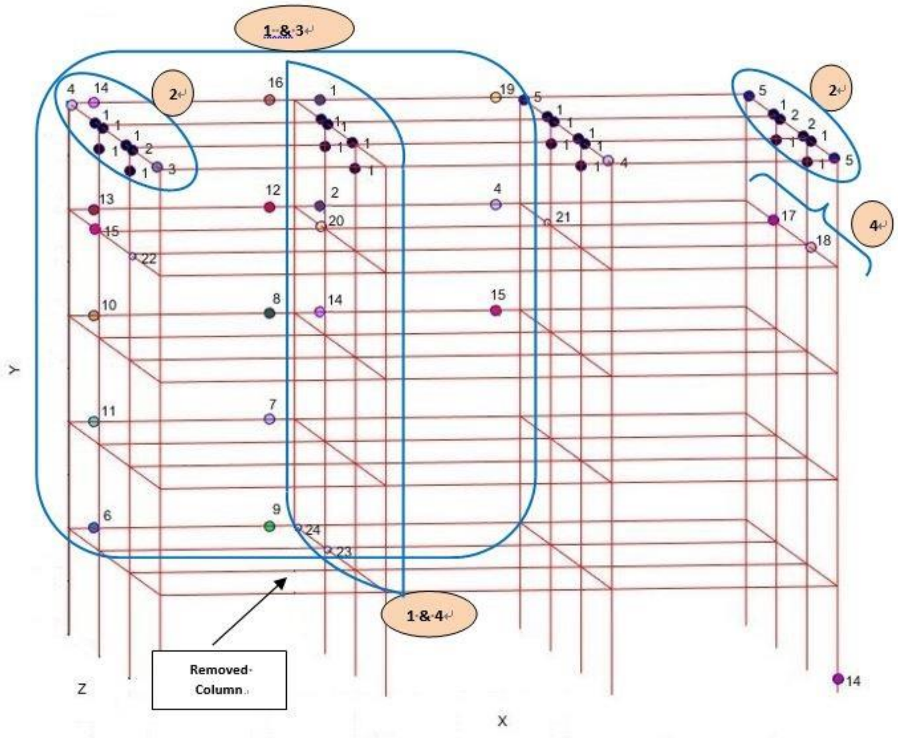

Fig. 13 Distribution of collapse in 5-story building in presence of earthquake record #1244

the collapse distributions in 3-story building.

3.12 Results of the collapse distribution in 5-story RC building due to the corner and edge columns removal in presence of earth quake loads:

Results of the NLTHA due to the other earthquake records show that similar to the results of 3-story building, distributions of the collapse are similar, specific, repetitive and independent of the earthquake records and can be utilized in the other similar structures to predict the collapse distribution through the structural members, consecutively, and subsequently to provide criteria and measures to reinforce the similar structures against the progressive collapse mechanism.

Results also indicate that in 63% of the analyses, concentration of the collapse is in the upper part of the removed column and the critical elements of the structure are mostly in upper regions and around the weak or defective column. Therefore, to reinforce similar structures, the structural elements around the weak or defective column, especially the members of the upper part of the structure, should be prioritized for retrofitting. In this regard, proposed methods in UFC guideline can be useful to increase the structural resistance against the progressive collapse.

Other results show that in about 59% of the analyses, direction of the collapse distribution is from top to bottom of the structure, which can also be used to provide criteria and regulations in codes and guidelines to increase the structural resistance against the progressive collapse. For example, alternative path method for load redistribution is suggested as a practical and usable method.

Results also show that in 5-story buildings, collapse initiation points and the critical members are similar and repetitive in the structural systems and the number of collapsed hinges in beams is higher than the columns, especially in early stages of the structural collapse. As indicated before, it is due to the effect of weak beam-strong column which leads to overtake the collapse occurrence in beam elements in comparison with the columns. Therefore, further reinforcement of the beam elements should be prioritized to increase the structural resistance in progressive collapse mechanism.

Other results indicate that in 5-story building, in 68% of the analyses, in comparison with the beam and column elements, the starting points of the collapse are in the beam elements, indicating that the beam elements are more important for increasing the structural resistance in progressive collapse. Consequently, aforementioned results can be used in the design and retrofitting of the structures in field of the progressive collapse mechanism.

The results of the present study, in combination with the other existing researches, such as the presented methods in UFC, can be used to provide regulations to increase the structural resistance against the progressive collapse mechanism.

4. Comparison of collapse intensity in 3-story and 5-story buildings due to corner and edge columns removal

To evaluate the collapse intensity in 3-story building in presence of the earthquake loads, the number of collapsed hinges in the structural members was compared due to the

Table 2 Number of collapsed hinges in 3-story RC building due to corner and edge columns removal in presence of the earthquakes

The Number of Recorded Earthquakes	The Number of Collapsed Hinges		The Number of Recorded Earthquakes	The Number of Collapsed Hinges	
	Due to Corner Column Removal	Due to Edge Column Removal		Due to Corner Column Removal	Due to Edge Column Removal
953	154	161	721	56	62
960	19	23	725	34	52
1602	71	129	829	13	18
1787	76	136	1244	34	161
169	56	62	1485	105	113
174	240	40	68	87	99
1111	44	100	125	43	144
1116	31	116	848	240	151
1158	210	240	752	240	85
1148	44	100	767	240	83
900	119	0	1633	56	42

corner and edge columns removal. Table 2 shows the number of collapsed hinges in 3-story building due to removal of the corner and edge columns.

Table 2 shows that, in 3-story RC intermediate moment resisting frame building, in equal loading and structural conditions, the rate of the collapse in the structure due to the edge column removal is about 72% greater than the corner column removal. In another time history analyses, the resonance phenomenon is the reason for the larger collapse rate due to the corner column removal.

The same process was also investigated in 5-story RC building and it was found that with the same structural and loading conditions, in about 63% of the results, the collapse rate due to the edge column removal is greater than that of the corner column removal. Therefore, it can be concluded that in progressive collapse mechanism of low-rise and mid-rise RC intermediate moment resisting frame buildings, due to simultaneous effects of the column removal and the earthquake loads, the collapse rate due to the edge column removal is greater than that of the corner column removal. Therefore, the edge column is more significant than the corner column to design or retrofit against the progressive collapse mechanism and this issue can be taken into account in codes and guidelines.

5. Conclusions

- Collapse distributions due to the simultaneous effects of the column removal and the earthquake loads are specific, similar, and repetitive process, So that, these trends can be used to predict and present patterns of the collapse distribution in progressive collapse mechanism of the similar structures.
- Process of the collapse distribution caused by the simultaneous effects of the column removal and the earthquake loads is independent of earthquake records.
- In about 90% of the results, the values of collapse in beam elements are higher than the columns, especially, in early stages of the structural collapse. Therefore, in order to increase the structural resistance to the progressive collapse mechanism, design and retrofit of the beam elements should be prioritized. This issue can be taken to consideration in codes or guidelines to provide some measures and criteria in structural designs and retrofitting processes.
- In about 80% of analyses, the collapse initiation points and critical members are similar, special and repetitive in the structural system.
- In about 80% of nonlinear analyses, in comparison between the beam and column elements, the starting collapse point is in the beam elements, not in columns, indicating the greater significance of the beam elements to enhance the structural resistance to the progressive collapse mechanism. This process can be incorporated into the standards and design codes.
- In about 98% of the results, concentration and extension of the collapse is higher in upper regions of the removed column. In other words, critical structural elements are in upper parts and around the removed column. Therefore, in similar structures, the structural elements around the defective column, especially the members of the upper part of the structures, should be prioritized to design and retrofit against the progressive collapse mechanism.
- In about 81% of the results, the path and direction of the collapse distribution is vertically, from top to bottom of the structure. So, alternative path method and other technical procedures can be utilized to reduce the progressive collapse potential in stages of design or retrofitting the structures.
- Two behavioral patterns of the collapse distribution has been presented to predict the path and direction of the progressive collapse in 3-story RC intermediate moment resisting frame buildings due to the simultaneous effects of the corner column removal and the earthquake loads in the present article.
- To predict the progressive collapse distribution in 3-story RC intermediate moment resisting frame buildings due to simultaneous effects of the edge column removal and the earthquake loads, two behavioral patterns of the collapse distribution has been proposed and presented in the present article.
- In 5-story RC intermediate moment resisting frame

buildings, due to simultaneous effects of the corner column removal and the earthquake loads, a behavioral pattern of the collapse distribution has been proposed and presented to predict the scenario of the progressive collapse distribution in the present article.

• A behavioral pattern of collapse distribution in 5-story RC intermediate moment resisting frame buildings, due to simultaneous effects of the edge column removal and the earthquake loads has been proposed and presented in the present article.

• To prevent the progressive collapse occurrence during the stages of design or retrofitting of the structures, behavioral patterns of the collapse distribution presented in the present study can be used to provide technical procedures and regulations in codes or guidelines for the similar buildings.

• Behavioral patterns of the collapse distribution in low-rise and mid-rise RC structures depend on the location of the removed column.

• The behavioral patterns of the collapse distribution are approximately similar in low-rise and mid-rise buildings due to the corner or edge column removal, although, scattering of the results is more in the mid-rise buildings.

• Results of the NLTHA in 3-story and 5-story buildings indicate that the number of collapsed hinges in buildings with the edge column removal is greater than the number of collapsed hinges in buildings with the corner column removal. In other words, due to simultaneous effects of the earthquake loads and column removal, progressive collapse potential of the structures with defective edge column is greater than those of the structures with defective corner column, which can be considered as an important criterion in process of the structural retrofitting.

References

Ahmed, Elshaer., Hatem, Mostafa. and Hamed, Salem. (2017), “Progressive collapse assessment of multistory reinforced concrete structures subjected to seismic actions”, *KSCE J. Civil Eng*., **21**(1), 184-194.

Alrudaini, Thaer., Muhammad, N. and Hadi, S. (2009), “A new design to prevent progressive collapse of reinforced concrete building”, *In The 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference*.

American Society of Civil Engineers (2007), “Seismic rehabilitation of existing buildings (ASCE/SEI 41-06)”, Rehabilitation Requirements.

Amiri, Setareh., Saffari, Hamed. and Mashhadi, Javad. (2018), “Assessment of dynamic increase factor for progressive collapse analysis of RC structures”, *Eng. Fail. Anal*., **84**, 300-310.

Applied Technology Council and United States. Federal Emergency Management Agency (2009), “Quantification of building seismic performance factors”, US Department of Homeland Security, FEMA.

Bailey, C.G. and Moore, D.B. (2000a), “The structural behavior of steel frames with composite floor slabs subject to rire, Part I: Theory”, *Struct. Eng*., **78**(11), 19-27.

Bazant, Z.P. and Verdure, M. (2007), “Mechanics of progressive collapse: Learning from world trade center and building demolitions”, *J. Eng. Mech.*, **133**(3), 308-319. https://doi.org/10.1061/(ASCE)0733-9399(2007)133:3(308).

Burnett, E.F.P. (1975), “Abnormal loading and building safety”, Special Publication, **48**, 141-190.

Burnett, E.F.P. (1975a), “The avoidance of progressive collapse: regulatory approaches to the problem”, NBS-GCR 75-48, US Department of Commerce, National Bureau of Standards, Washington, DC, USA, October.

Corley, W.G., Mlakar, P.F., Sozen, M.A. and Thornton, C.H. (1998), “The Oklahoma City bombing: Summary and recommendations for multihazard mitigation”, *J. Perform. Construct. Facilit*, **12**(3), 100-112.

El-Tawil, S., Khandelwal, K., Kunnath, S., and Lew, H-S., (2007). “Macro models for progressive collapse analysis of steel moment frame buildings.” *Proc. Structures Congress.* Long Beach, CA.

Ellingwood, B. and Leyendecker, E.V. (1978), “Approaches for design against progressive collapse”, *J. Struct. Div*, **104**(3), 413-423.

Green, M. and Wong, Y. (2001) “Value of the Full Scale Cardington Fire Tests to the Structural Engineer”, *In the Proceedings of the Structures Congress & Exposition. ASCE*, Washington, D.C., U.S.A.

Griffith, H., Pugsley, A. and Saunders, O. (1968), “Report of the inquiry into collapse of flats of Ronan point”, Canning Town, London, England.

Gurley, C. (2012), “Progressive collapse and earthquake resistance”, *Struct. Des. Constr. ASCE*, **13**(1), 19-23. https://doi.org/10.1061/(ASCE)1084-0680(2008)13:1(19).

Hafez, Islam., Khalil, Ahmed. and Mourad, Sherif A. (2013), “Alternate path method analysis of RC structures using applied element method”, *Int. J. Protect. Struct.*, **4**(1), 45-64.

Haselton, C.B. and Deierlein, G.G. (2007), “Assessment seismic collapse safety of modern reinforced concrete moment frame building”, The John A. Blume Earthquake Engineering Center, Stanford University.

Haselton, C.B. and Pacific Earthquake Engineering Research Center. (2008), “Beam-column element model calibrated for predicting flexural response leading to global collapse of RC frame buildings”, Pacific Earthq. Eng. Research Center.

Haselton, C.B., Liel, A.B. and Deierlein, G.G. (2009), “Simulating structural collapse due to earthquakes: Model idealization”, *In the Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Greece.

Helmy, Huda., Salem, Hamed. and Mourad, Sherif. (2012), “Progressive collapse assessment of framed reinforced concrete structures according to UFC guidelines for alternative path method”, *Eng. Struct.*, **42**, 127-141.

Hinman, E.E. and Hammond, D.J. (1997), “Lessons from the Oklahoma City bombing: Defensive design techniques”, Amer. Soc. Civil Eng., https://doi.org/10.1061/9780784402177.

Ibarra, L.F. (2005), “Global collapse of frame structures under seismic excitations”, Ph.D. Dissertation. Stanford Univ.

Ibarra, L.F. and Krawinkler, H. (2004), “Global collapse of deteriorating MDOF Systems”, *The Procedeeings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada, August.

Ibarra, L.F., Medina, R.A. and Krawinkler, H. (2005), “Hysteretic models that incorporate strength and stiffness deterioration”, *J. Earthq. Eng. Struct. Dyn.*, **34**, 1489-1511. https://doi.org/10.1002/eqe.495.

Kaewkulchai, G. and Williamson, E.B. (2004), “Beam element formulation and solution procedure for dynamic progressive collapse analysis”, *Comput. Struct*., **82**(7-8), 639-651. https://doi.org/10.1016/j.compstruc.2003.12.001.

Kai, Q. and Bing, L. (2013), “Experimental study of drop panel effects on response of reinforced concrete flat slabs after loss of corner column".

Karimiyan, S. (2020). "Collapse distribution scenario in seismic progressive collapse of RC buildings caused by internal column elimination", *Iran. J. Sci. Technol., Transactions Civil Eng.*, 1-12.

Karimiyan, S., Husseinzadeh Kashan, A. and Karimiyan, M. (2014), "Progressive collapse vulnerability in 6-Story RC symmetric and asymmetric buildings under earthquake loads", *Earthq. Struct.*, **6**(5),473-494. https://doi.org/10.12989/eas.2014.6.5.473.

Karimiyan, S., Moghadam, A.S. and Vetr, M.G. (2013), "Seismic progressive collapse assessment of 3-story RC moment resisting buildings with diferent levels of eccentricity in plan", *Earthq. Struct.*, **5**(3), 277-296. https://doi.org/10.12989/eas.2013.5.3.277.

Karimiyan, S., Moghadam, A.S., Husseinzadeh, Kashan, A. and Karimiyan, M. (2015), "Progressive collapse evaluation of RC symmetric and asymmetric mid-rise and tall buildings under earthquake loads", *Int. J. Civil Eng.*, **13**, 30-44.

Karimiyan, S., Moghadam, A.S., Karimiyan, M. and Husseinzadeh Kashan, A. (2013), "Seismic collapse propagation in 6-story RC regular and irregular buildings", *Earthq. Struct.*, **5**(6),753-779. https://doi.org/10.12989/eas.2013.5.6.753.

Karimiyan, S., Moghadam, A.S., Kashan, A. H. and Karimiyan, M. (2017), "Evaluation of collapse distribution in three-story RC moment-resisting asymmetric buildings due to earthquake loads", *Int. J. Civil Eng.*, **15**(5), 809-825. https://doi.org/10.1007/s40999-017-0197-4**.**

Khandelwal, K., El-Tawil, S. and Sadek, F. (2009), "Progressive collapse analysis of seismically designed steel braced frames", J. Construct. Steel Res., **65**(3), 699-708. https://doi.org/10.1016/j.jcsr.2008.02.007.

Kim, H.S., Ahn, J.G. and Ahn, H.S. (2013), "Numerical simulation of progressive collapse for a reinforced concrete building", *World Academy Sci. Eng. Technol.*, **76**.

Kim, J. and Hong, S. (2011), "Progressive collapse performance of irregular buildings", *Struct. Des. Tall Spec. Build.*, **20**(6), 721-734. https://doi.org/10.1002/tal.575.

Krawinkler, H., Zareian, F., Lignos, D.G., and Ibarra, L.F. (2009), "Prediction of collapse of structures under earthquake excitations", *In Proceedings of the 2nd international conference on computational methods in structural dynamics and earthquake engineering.*

Lalkovski, N. and Starossek, U. (2013), "Pancake-type collapse-energy absorption mechanisms and their influence on the final outcome".

Le, J. and Xue, B. (2013), "Probabilistic analysis of vulnerability of reinforced concrete buildings against progressive collapse", *Struct. Congress, **2013***, 20-31. https://doi.org/10.1061/9780784412848.003.

Lew, H-S. (2003), "Best practices guidelines for mitigation of building progressive collapse", National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A. 20899-8611.

Li, Z. and Shi, Y. (2008), "Methods for progressive collapse analysis of building structures under blast and impact loads", *Transactions Tianjin Univ.*, **14**(5), 329-339.

Lignos, D. and Krawinkler, H. (2012), "Sidesway collapse of deteriorating structural systems under seismic excitations", The John A. Blume Earthquake Engineering Center, Stanford University.

Lignos, D.G. and Krawinkler, H. (2013), "Development and utilization of structural component databases for performance-based earthquake engineering", *J. Struct. Eng.*, **139**(8), 1382-1394. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000646.

Lignos, D.G., Zareian, F. and Krawinkler, H. (2008), "Reliability of a 4-story steel moment-resisting frame against collapse due to seismic excitations", *In Structures Congress 2008: Crossing Borders*.

Lu, X. Z., Li, Y., Ye, L.P., Ma, Y.F. and Liang, Y. (2008), "Study on the design methods to resist progressive collapse for building structures", *The Proceedings of 10th International Symposium on Structural Engineering for Young Experts.*

Lupoae, M., Baciu, C. and Constantin, D. (2013), "Theoretical and experimental research on progressive collapse of RC frame buildings", *Urbanism Arhitectura Constructii*, **4**(3).

Lyle, J., Wainwright, F., Izatt, C. and Hadden, D. (2003), "Aircraft Impacts and Explosions in Buildings", *Ove. Arup. Partners.*, London, U.K.

Mashhadiali, N. and Kheyroddin, A. (2014), "Progressive collapse assessment of new hexagrid structural system for tall buildings", *Struct. Des. Tall Spec. Build.*, **23**(12), 947-961. https://doi.org/10.1002/tal.1097.

Mays, G.C. and Smith, P.D. (1995), "Blast effects on Buildings", Thomas Telford, London. U.K.

Orton, S. and Kirby, J. (2014), "Dynamic response of a RC frame under column removal", *J. Perform. Constr. Facil.*, **28**(4), 04014010. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000464.

Osama, A. and Mohamed, P.E. (2006), "Progressive collapse of structures: annotated bibliography and comparison of codes and standards", *J. Perform. Construt. Facilit.*, **20**(4), 418-425. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:4(418).

Petrone, F., Shan, L. and Kunnath, S.K. (2016), "Modeling of RC frame buildings for progressive collapse analysis", *Int. J. Concrete Struct. Mat.*, **10**(1), 1-13. https://doi.org/10.1007/s4006m9-016-0126-y.

Qian, K. and Li, B. (2013), "Performance of three-dimensional reinforced concrete beam-column substructures under loss of a corner column scenario", *J. Struct. Eng.*, **139**(4), 584-594. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000630.

Sagiroglu, S. and Sasani, M. (2014), "Progressive collapse resisting mechanisms of reinforced concrete structures and effects of initial damage locations", *J. Struct. Eng.*, **140**(3). https://doi.org/10.1061/(ASCE)ST.1943-541X.0000854.

Somes, N.F. (1973), "Abnormal loading on buildings and progressive collapse", *Build. Sci. Series*, **46**, National Bureau of Standards, Washington, D.C.

Song, L., Izzuddin, B.A., Elnashai, A.S. and Dowling, P.J. (2000), "An integrated adaptive environment for fire and explosion analysis of steel frames - Part I: analytical models", *J. Construct. Steel Res.*, **53**(1), 63-85. https://doi.org/10.1016/S0143-974X(99)00040-1.

Starossek, U. (2007), "Typology of progressive collapse", *Eng. Struct.*, **29**, 2302-2307. https://doi.org/10.1016/j.engstruct.2006.11.025.

Tavakoli, H.R. and Kiakojouri, F. (2013), "Numerical study of progressive collapse in framed structures: A new approach for dynamic column removal", *IJE TRANSACTIONS* A: Basics, **26**(7), 685-692.

Unified Facilities Criteria (2013), "Design of buildings to resist progressive collapse", *Including Change 2*.

Vlassis, A.G. (2007), "Progressive collapse assessment of tall buildings", Doctoral Dissertation, University of London.

Yavari, H., Ghobadi, M.S. and Yakhchalian, M. (2019), "Progressive collapse potential of different types of irregular buildings located in diverse seismic sites", *Heliyon*, **5**(1), e01137.

Zareian F., Lignos D.G. and Krawinkler H. (2009), "Quantification of modeling uncertainties for collapse assessment of structural systems under seismic excitations", *COMPDYN 2009, ECCOMAS 15 Thematic Conference on, Computational Methods in Structural Dynamics and Earthquake Engineering*, Greece.

Zareian, F. and Medina R.A. (2010). "Practical method for proper modeling of structural damping in inelastic plane structural systems", *J. Comput. Struct*., **88**(1-2), 45-53. https://doi.org/10.1016/j.compstruc.2009.08.001.

AT