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Original Research Article

INVESTIGATION OF THE OCCURRENCE OF PROGRESSIVE COLLAPSE IN HIGH-RISE STEEL BUILDINGS WITH DIFFERENT BRACED CONFIGURATIONS

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Abstract

The progressive collapse phenomenon refers to a chain of damages in a structure where all or a large part of the structure is destroyed by an initial local collapse in it, which can lead to very disastrous results. Therefore, the prevention of progressive collapse has become a necessary action in the design and analysis of buildings and it is vital to investigate this topic more accurately. This study aims to present a proposed pattern in the configuration of braces at the height of a high-rise steel building for reducing the probability of progressive collapse. In this regard, the vertical displacement of 18-story structure with four scenarios of column removal and five concentric bracing patterns

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including V, Inverted V, X, discontinuous X-bracing at height, and a combination of X-bracing in the side spans and discontinuous X-bracing at height in the middle spans are investigated and compared. In this study, the Alternative Path Method (APM) is used based on the GSA guideline for the analysis of progressive collapse. The results of this research showed that the use of X-bracing in the side spans and discontinuous X-bracing in the middle spans in nonlinear static and dynamic analyses performed better in reducing the probability of progressive collapse than other bracing configurations. Finally, it is recommended to use discontinuous X-bracing at the height that would place the bracings in one direction and providing alternative paths for force transferring in the structure.

Keywords: progressive collapse, nonlinear dynamic analysis, alternative path method (APM), concentric bracing, GSA guideline

1. INTRODUCTION

It is not more than fifty years since the term of progressive collapse entered into the structural design literature for the first time. In this half-century, three great events brought engineers' attention to this kind of failure. In the first event that occurred in 1968, the Ronan Point apartment building was ruined. In the second incident, the building of the Federal Reserve in Mauritius was destroyed due to the explosion of a bomb in 1995, and in the latest incident on 11 September 2001, two towers of the World Trade Center in New York were completely collapsed by the collision of two aircrafts. These three events may look different at first glimpse, but in fact, all three have a similarity which in the general case is the fact that the elimination of one or more of the original members has resulted in the destruction of all or a great part of the structure [1]. The failures of buildings that occurred in recent years have made the subject of progressive collapse very important. In fact, this type of failure is also called disproportionate failure. The localized failure of the structure can lead to the progressive collapse of the whole structure or a large part of it. Various factors can cause local failure and progressive collapse in the structures that, the most important of these factors include design or manufacturing error, fire, explosion, random overload, vehicle collision, bomb blast and etc [2]. During this half-century, various regulations and standards have tried to cover this issue, but most of them considered only qualitative terms and less offered practical solutions, but recently, regulations have been developed for the discussion of progressive collapse of structures, the most valid of which are (UFC, 2010) [3], (GSA, 2003) [4] and ASCE70-5 [5]. Any weakness in the design or implementation of structural elements, may develop a phenomenon of progressive collapse of structures during loading. Therefore, modeling buildings under progressive collapse has attracted the attention of many researchers in the two decades and some efforts have been made to develop analysis and design methods for this phenomenon. According to the significant importance of this type of failure in some structures, many researchers studied the causes of progressive collapse, behavior of structures or structural elements after the minor failure, structure improvement methods, case studies of the buildings and etc. Considering the increase of building construction and also the increased risk of abnormal loads, there is a demand for the study on this type of failure and collection of structural analysis and design basics against progressive collapse. One of the main elements in preventing progressive collapse is the use of various braces and their arrangement in the structure. The behavior of concentric braces in peripheral frames against progressive collapse has been investigated in this study, the results of their comparison present a new approach to select a concentric brace with appropriate performance against the vertical displacements in progressive collapse. One of the important items which has attracted the attention of researchers in this regard and investigated in this study is that, the structure should be designed in such a way as to absorb local failure and create a new way for load transfer. Only the removal of one key element is addressed in this technique, and the structure is examined to assess the effect of deleting this element. When a structural element is removed, the remaining structure must be stable enough to withstand the loads in that element over an extended length of time. This is known as the alternate path method (APM) [6].

In the following, the background of the study is presented. Powell compared linear static, nonlinear static, and nonlinear dynamical analyses in progressive collapse evaluation using APM. This research showed that the load factor 2 in static analysis produces much more conservative responses compared to dynamic analysis [7]. Kim and Dawoon evaluated the progressive collapse in 3 and 6-story steel frames with and without brace showed that, with an increasing number of spans, the connection effect of the structural members on the structural response is highly effective so that the responses are very different from the responses regardless of this effect. Also, increasing the number of stories has no effect on the responses [8]. Kim and Kim investigated the behavior of different types of bracing and compared their performance with the results of the designed moment frame with the same designed load in progressive collapse. According to the results of push-down analysis, most of the braced frames with the loss of the first fractured column due to the buckling of the frames and columns is gradually collapsing. Among the braced frames, the eight braced frames exhibit a more flexible behavior at the time of the progressive collapse [9]. Liu used APM to analyze a steel moment frame against progressive collapse, and then linear static, nonlinear static, and nonlinear dynamic analyses methods based on UFC Regulations criteria revealed that performing higher linear static analysis and the mass of the structural skeleton is higher in this case. Nonlinear static and nonlinear dynamic analysis approaches, on the other hand, result in a more affordable design that also includes a consideration of progressive collapse. Modeling and computer analysis, on the other hand, take more time in these investigations [10]. Gokul and

Daniel investigated the behavior of steel moment frames with two cross-braced and V-braced systems with four spans and six spans with 20-story to identify the vulnerability of structures to progressive collapse. The simulation results obtained by comparing modal analysis, period, cumulative load mass contribution ratio, and linear static analysis in bracing and non-bracing states showed that if the number of spans increased, the resistance of the structure to progressive collapse increases due to the redistribution of forces in the failing member [11]. Salmasi and Sheidaii used the nonlinear static alternate route technique to assess the strength of dual steel moment frames furnished with a range of eccentric bracings against progressive collapse. Six-story building examples were created using a steel frame and a dual steel moment system, as well as three distinct forms of bracing. The consequences of abruptly removing columns from different floors of these structures were investigated. These tests revealed that twin steel moment frames with eccentric bracings displayed generally satisfactory strength against progressive collapse [12]. Kang and Kim also investigated the effects of various foundation connection details on the impact performance of a steel column. The results demonstrated that the reinforcement plots had an effect in minimizing the damages [13]. Then there are probabilistic studies, which have recently gained favor. The probabilistic investigations include Javidan et al. evaluations of the dependability and fragility curves of a three-story steel moment-resisting frame (SMRF) in weak and strong axis directions, as well as a comparison of the results between artificial neural network (ANN) and finite element analysis. The results showed that ANN's accuracy is considerable and satisfactory [14]. Santos et al. recently published the results of a numerical study of SMRF structures exposed to vehicle impact loadings. The results revealed that car impact tests produced more structural responses and substantial damage, especially at high collision velocities, than the column removal approach using APM [15]. Khizab et al. investigated the behavior of moment-resisting frame structures subjected to blast loading with and without a steel plate shear wall in two scenarios: in-plane and out-of-plane frames. In the scenario "in-plane blast loading," a steel plate shear wall dual system outperforms a moment-resisting frame, according to the study's conclusions. Due to the propagation of the blast loading, it restricted the progressive collapse potential in the scenario "out-of-plane blast loading." [16]. Sadeghi et al. assessed the dependability of the aforementioned structure under severe vehicle impact loadings using Monte Carlo Simulation (MCS). To reduce computational costs, meta-model methods such as Kriging, Polynomial Response Surface Methodology (PRSM), and Artificial Neural Network (ANN) are employed, and their efficiency is assessed. The findings indicated that random parameters such vehicle mass and velocity, as well as the yield strength of the materials used, were the most beneficial in determining failure probability. Kriging, as opposed to MCS, can forecast failure probability with the least amount of error, sample

quantity, and computer processing time. [17]. Wang and Wang presented a simple theoretical approach for assessing progressive collapse resistance during the design stage. Finally, for multi-story and high-rise structures, the potentially largest tributary area of each column under the progressive collapse scenario is presented, taking into consideration column instability under the excessively distributed gravity load [18]. Furthermore, Sadeghi et al. studied the collapse capacity and endurance length of an SMRF structure with a corner damaged column exposed to vehicle impact under seismic records [19].
In this study, as a novelty, the behavior of concentric braces with different configurations in the perimeter of a high-rise steel building against progressive collapse has been investigated. The results of comparing their vertical displacement are a new approach. To select a concentric bracing configuration is proposed that has good performance against progressive collapse. One of the important cases that have attracted the attention of researchers in this regard and in this research is that the structure is designed to be able to absorb the local damage and a new route to transfer loads is to be created. In this method, only the removal of a main and critical element is examined and the structure is analyzed statically and dynamically to determine the effect of removing this element.

2. MODELING PROCEDURE

In this research, the performance of braced frames exposed to the sudden removal of a column was studied by utilizing SAP 2000 software and nonlinear static and dynamic analyses. The GSA Code [4] was utilized for analysis. According to the rules for nonlinear static analysis and the method of nonlinear static analysis to evaluate the structural performance of buildings against progressive collapse, the reinforcing coefficient in the load composition as indicated in the loading pattern in Fig. 1 is 2. It is used with a progressive rise in vertical displacement at the position of the deleted column. This approach is useful for assessing the structure's elastic range and failure. Before removing the column, the axial force operating on it is computed, and the column is replaced by the point force corresponding to the axial force of the member, as illustrated in Fig. 2. The analyzed frames in this study are extracted from a three-dimensional model with 5 spans with a width of 5 m in each direction with a double-sided slab roof with a thickness of 15 cm with soil type II, the relative seismic risk is very high and the coefficient of importance is considered moderate. Dead load equal to 6.3 kN/m^2 for stories and 6.6 kN/m^2 for roof, live load of stories based on office application equal to 2.5 kN/m^2 and live load is considered 1.5 kN/m^2 for roof. The partition load in the stories is 1.2 kN/m^2 and the linear load of the perimeter walls in the stories is 8 kN/m and for the roof is 3 kN/m according to Fig. 1 (a). In the following, dead loads of stories and roof are considered 18.25 kN and 16.5 kN, respectively. The live loads of stories and roof are 6.25 kN and 3.75 kN, respectively. According to Fig. 2 (b), all the above loads are calculated as a load combination of DL+0.25 LL on the frame.

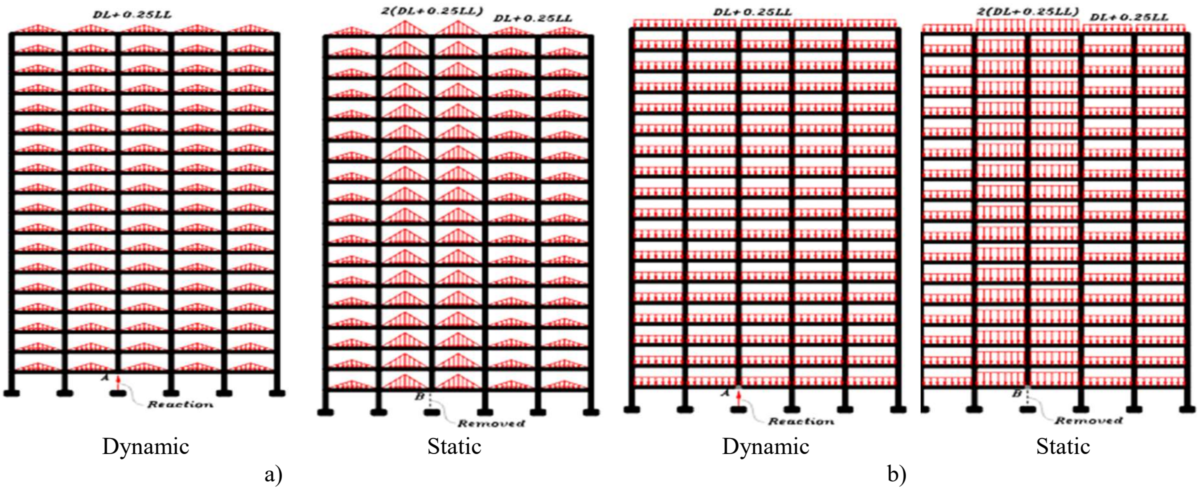


Fig. 1. Modeling procedure of dead and live loading in dynamic and static states

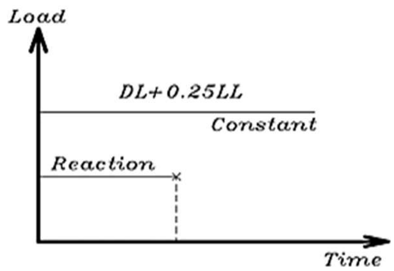


Fig. 2. Nonlinear dynamic loading in terms of force – time

2.1. Modeling verification

To demonstrate modeling capability in SAP2000 software, a 9-story SAC frame has been selected [20]. Fig. 3 shows the dimensions of this structure. According to Fig. 4, the SAC structure is modelled in SAP2000 software and the beam and column sections, all of which are of type W, are marked on each member.

For further investigation, the figure of the first three output modes of the SAC structure shows that it fits very well with the main structure. The main reason for choosing modal analysis for verification is that modal analysis indicates the dynamic behavior of the structure and the appropriate match between the vibration modes obtained in SAP2000 software with the SAC structure indicates correct modeling and proper mass assignment and precise definition of modal behavior. Fig. 5 shows the modal analysis output in SAP2000 software.

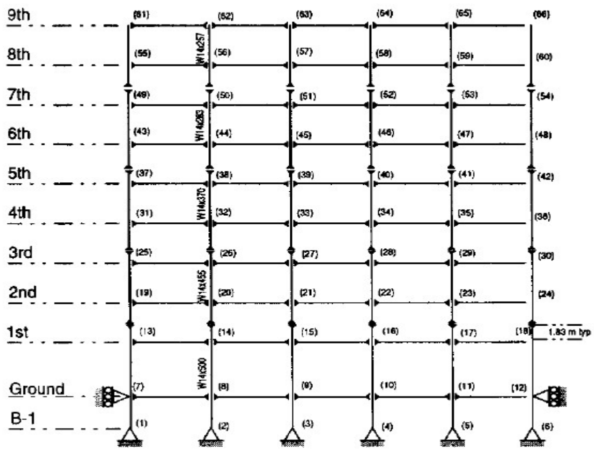


Fig. 3. Configuration of the SAC frame [20]

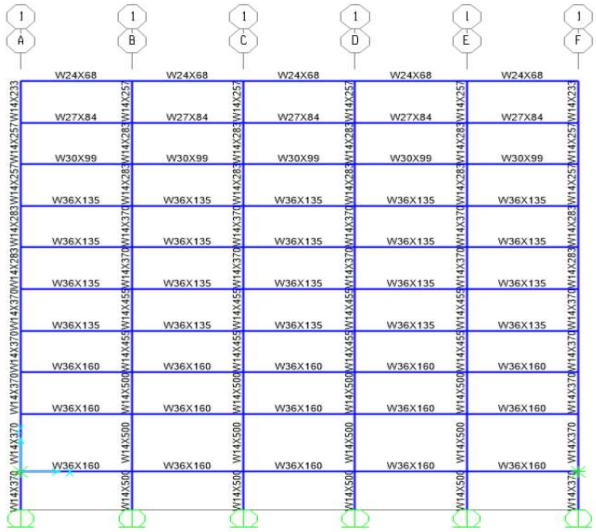


Fig. 4. Modeling of SAC frame in SAP 2000 software

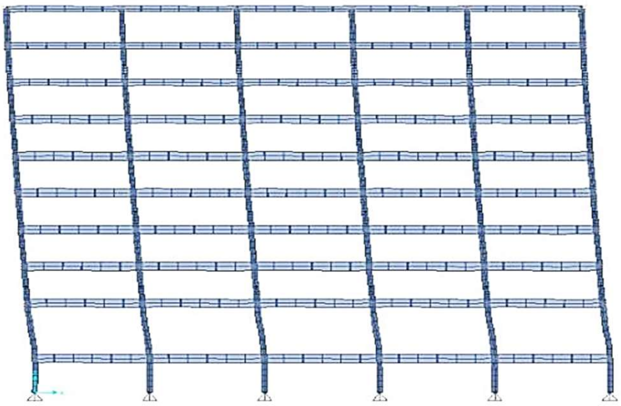


Fig. 5. The 1st vibration mode of the modelled frame

For further investigation, according to Fig. 6 (a) and (b), the three elementary modes based on the displacement of the roof of the present study with the reference paper [20] are shown and the accuracy of the results is evaluated. Finally, the modeling procedure is verified.

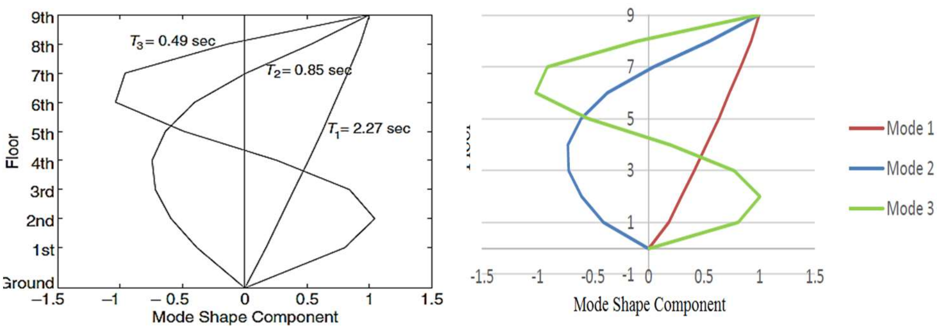


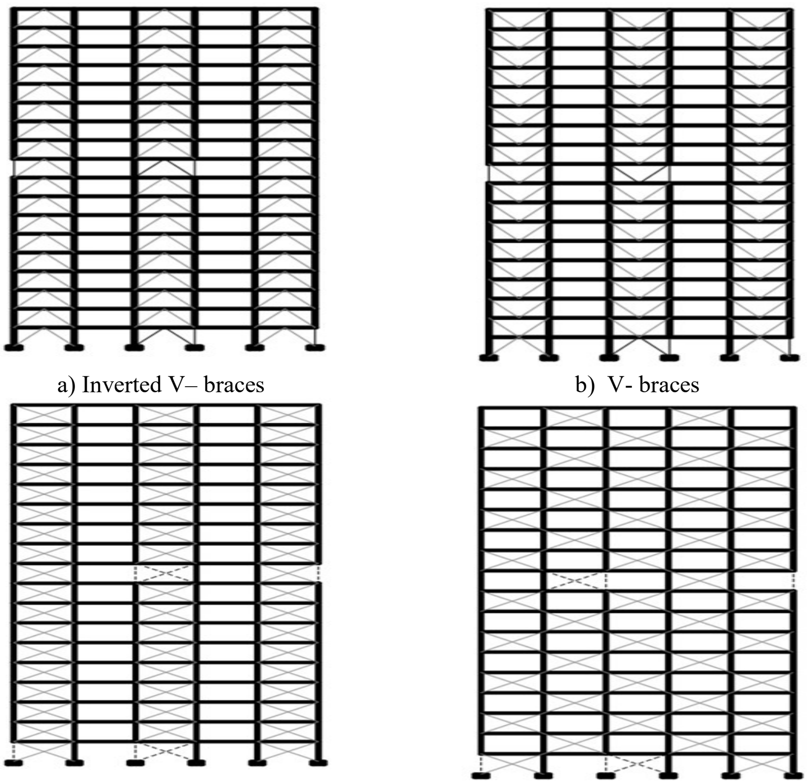
Fig. 6. The vibration modes: a) the reference study [20], b) the present study

2.2. The studied frames

In this study, five steel models of the hybrid moment bracing system type and four column removal scenarios have been considered which are presented in Tab. 1. The removal location of the columns and braces have been identified by dotted lines. The sections used in the models have been standard sections of the SAP software according to Tab. 2, and the compression and plastic hinges are calculated automatically by the program.

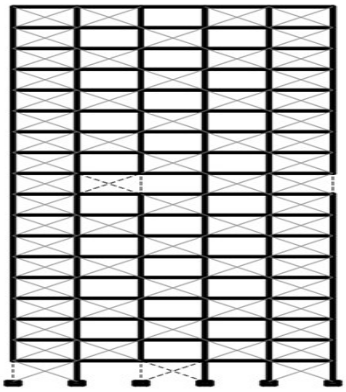
- Model (a): Based on Fig. 7 (a), a diagonal concentric bracing has been used. Therefore, the layout has been done in the peripheral environment of the structure according to the research.

- Model (b): Based on Fig. 7 (b), a V-shaped concentric bracing is used.
- Model (c): Based on Fig. 7 (c), an X-shaped concentric bracing is used.
- Model (d): As shown in Fig. 7 (d), a cross-shaped concentric bracing with a different arrangement at different spans and discontinuously has been in height. In Model (d), as you can see in Fig. 7 (d), it has been attempted to provide a path for the forces to move and the use of the APM method with one in-between layout of braces and by placing the braces in one direction. The movement direction of the forces in the braces is from one point diagonally from one side of the structure to the other, that this case in samples a, b, c follows a short path over the length of a brace.
- Model (e): Based on Fig. 7 (e), the combination of patterns (c) and (d) is used.



a) Inverted V– braces b) V- braces

c) X– braces d) XX– braces



e) XXX– braces

Fig. 7. Braced configurations of the prototype model

Table 1. Introduction of removal column scenarios in this study

Scenario	Removal column
1	Side column of 1st story
2	Middle column and brace of 1st story
3	Side column of 10th story
4	Middle column and brace of 10th story

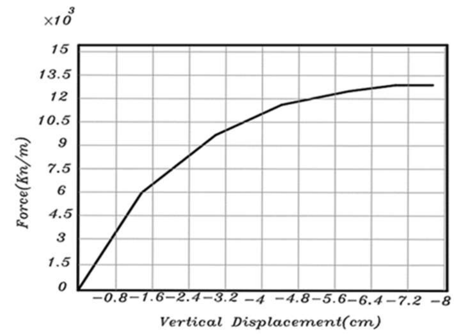
Table 2. The designed sections of studied models

Model	Element	Story 1-5	Story 5-10	Story 11-14	Story 15-17	Story 18
a	Column	BOX200*200*20	BOX140*140*20	BOX120*120*20	BOX100*100*20	BOX90*90*20
	Beam	IPE240	IPE240	IPE220	IPE200	IPE200
	Brace	BOX80*80*8	BOX80*80*8	BOX80*80*8	BOX80*80*8	BOX80*80*8
b	Column	BOX200*200*20	BOX140*140*20	BOX120*120*20	BOX100*100*20	BOX90*90*20
	Beam	IPE240	IPE240	IPE220	IPE200	IPE200
	Brace	BOX80*80*8	BOX80*80*8	BOX80*80*8	BOX80*80*8	BOX80*80*8
c	Column	BOX320*160*20	BOX200*200*20	BOX140*140*20	BOX120*120*8	BOX100*100*10
	Beam	IPE300	IPE300	IPE280	IPE260	IPE240
	Brace	BOX100*100*10	BOX100*100*10	BOX100*100*10	BOX80*80*8	BOX80*80*8
d	Column	BOX320*160*20	BOX200*200*20	BOX140*140*20	BOX120*120*8	BOX100*100*10
	Beam	IPE240	IPE240	IPE220	IPE200	IPE200
	Brace	BOX100*100*10	BOX100*100*10	BOX100*100*10	BOX80*80*8	BOX80*80*8
e	Column	BOX320*160*20	BOX100*100*10	BOX140*140*20	BOX120*120*8	BOX100*100*10
	Beam	IPE280	IPE260	IPE240	IPE220	IPE200
	Brace	BOX100*100*10	BOX80*80*8	BOX80*80*8	BOX80*80*8	BOX80*80*8

3. RESULTS

3.1. Nonlinear static analysis

The following procedure is used to perform nonlinear static analysis in the vertical direction: a) Under continual loads on the building, a static analysis is performed to identify the internal forces to be removed. B) The model has been changed by removing the load-bearing part and substituting permanent loads on the structure for the internal forces at the removed element's end. C) A single force is delivered in a vertical direction to the removed element's end. This force is gradually and steadily raised until the specified control point moves to the intended goal displacement or the structure breaks. Nonlinear static analysis with starting conditions (to sustain the stresses produced by the structure's permanent loading) in the controlled mode by displacement was employed for this aim. The influence of P- is also taken into account in this research. Following analysis, the curve (axial force - vertical displacement) of the removed element's higher node is retrieved. A quantity is known as the "load factor" is derived by dividing the axial force of this curve by the axial force measured in the previous stage (the force that the removed element resisted under constant loads). If the load factor parameter is near to one, it suggests a rise in the progressive collapse potential owing to the removal of the load-bearing part, and if it is less than one, it indicates a progressive collapse in the structure due to removal. The element is load-bearing. The load combination 2 (DL+0.25LL) is eliminated in the column bays for vertical nonlinear incremental static analysis, and the DL+0.25LL load combination is utilized in the other bays, according to GSA code. After eliminating the desired column and applying the GSA code loading compositions, the structure is examined under increasing gravity loads in nonlinear static analysis. The results of the vertical incremental nonlinear static analysis are force-displacement curves. Based on these curves, the values of the total capacity of the structure before and after the removal of the relevant column can be obtained. The vertical displacement in nonlinear static analysis is shown in Figs. 8 to 11. According to the results, it is clear that Pattern (e) has less displacement in the studied scenarios. Based on Figs. 12 to 15, the formation of plastic hinges in nonlinear static analysis is presented for scenarios 1 to 4.



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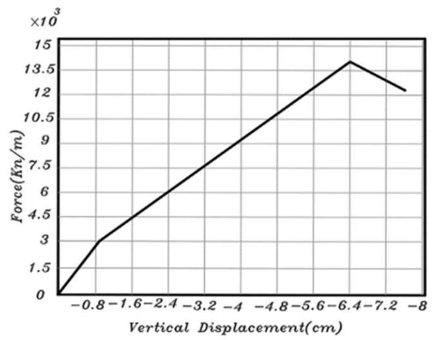

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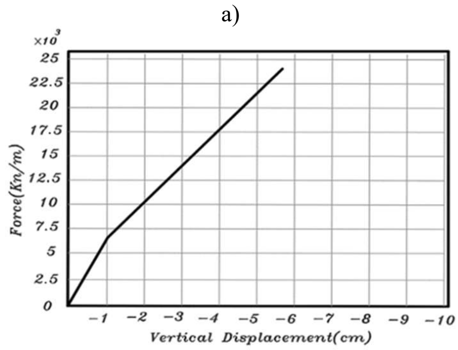

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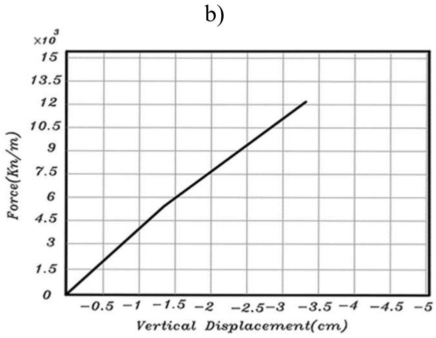

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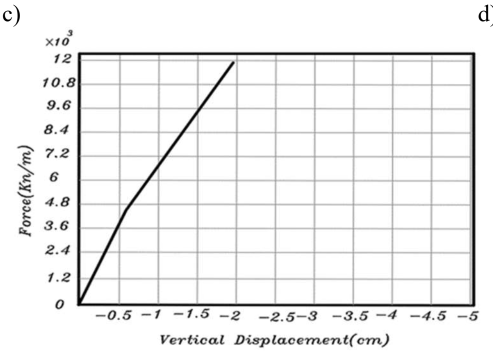


e)

Fig. 8. Vertical displacement in nonlinear static analysis of models considered in Scenario 1 (removal of side column of 1st story)

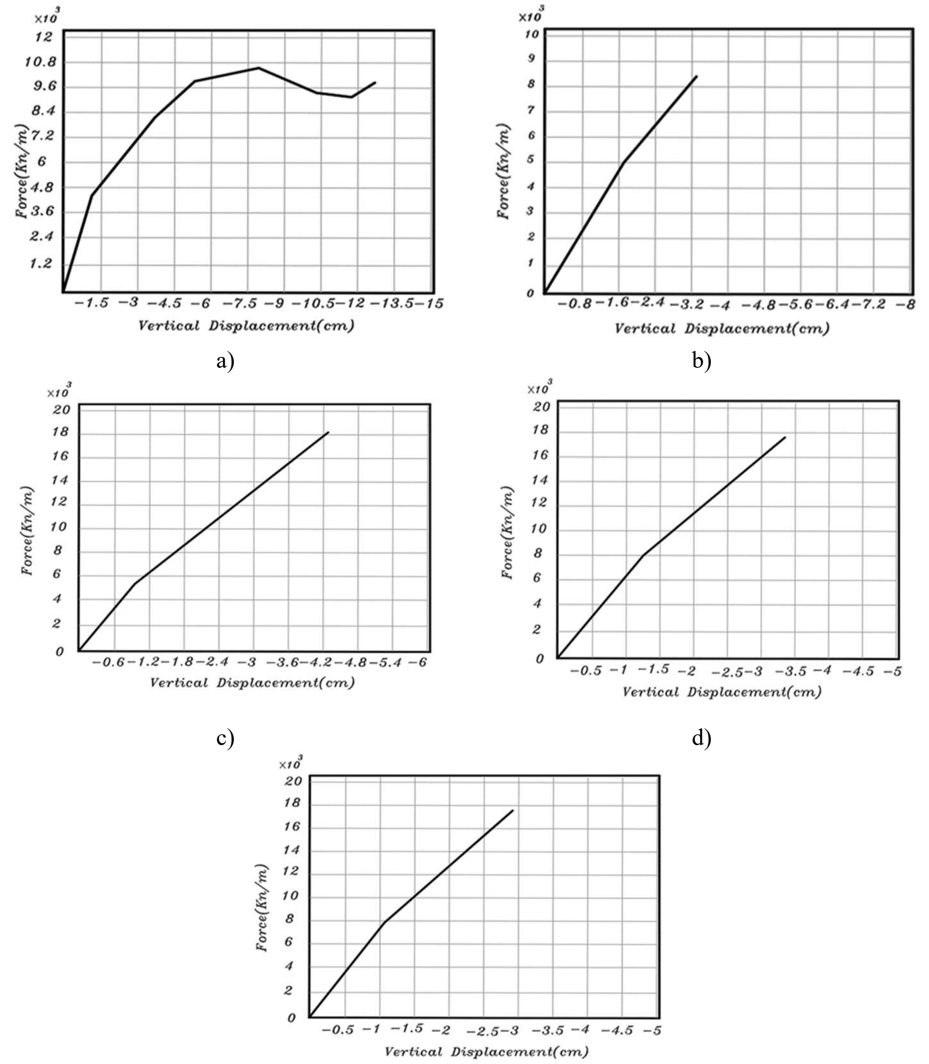
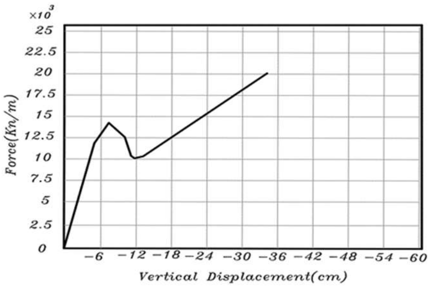
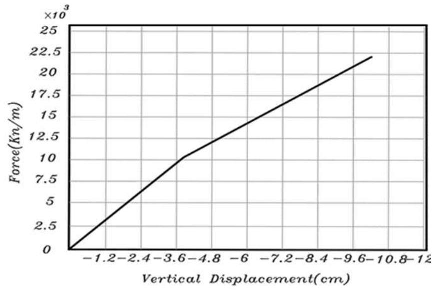


Fig. 9. Vertical displacement in nonlinear static analysis of models considered in Scenario 2 (removal of middle column and brace of 1st story)



a)



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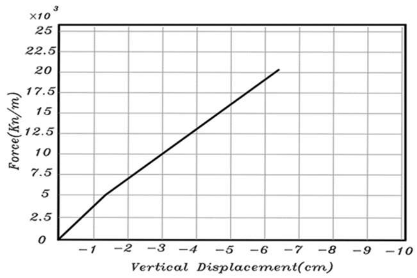

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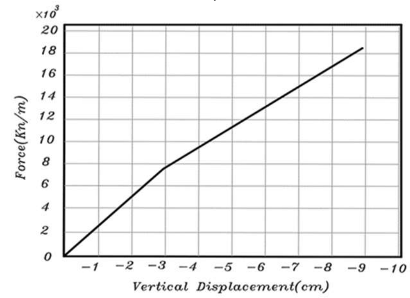

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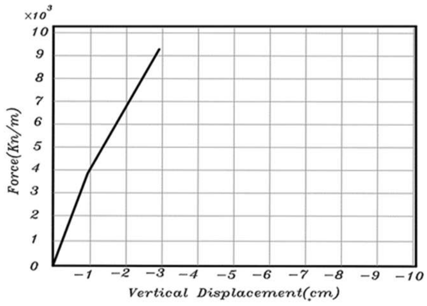
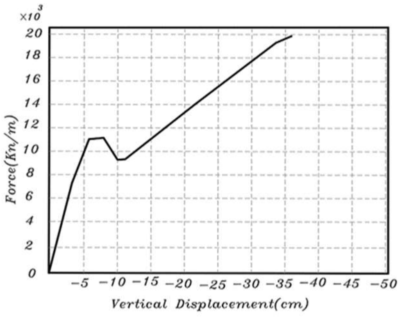


e)

Fig. 10. Vertical displacement in nonlinear static analysis of models considered in Scenario 3 (removal of side column of 10th story)



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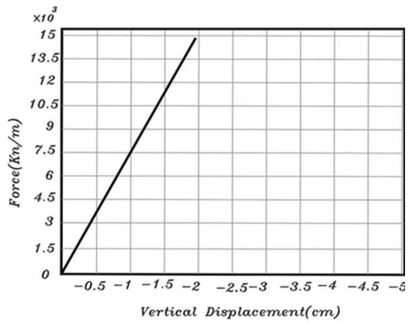

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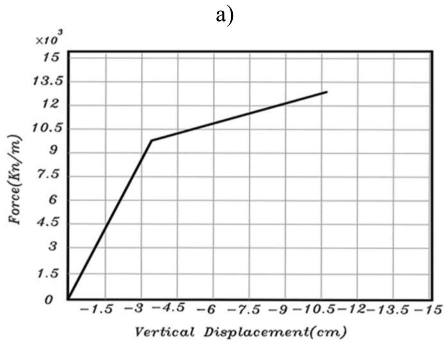

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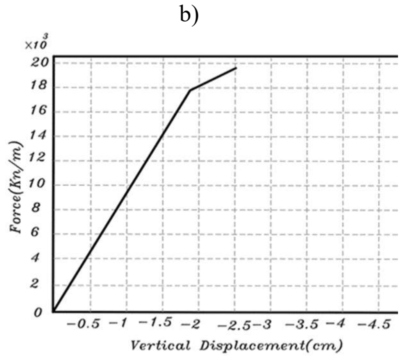

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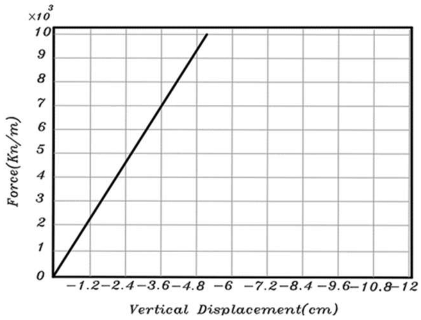
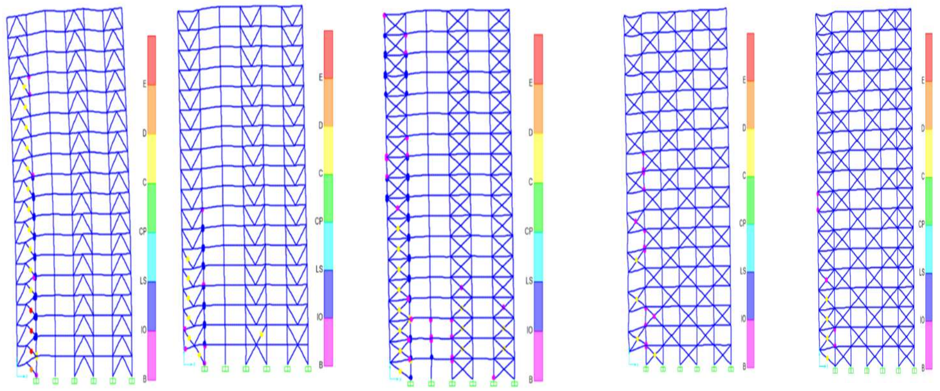


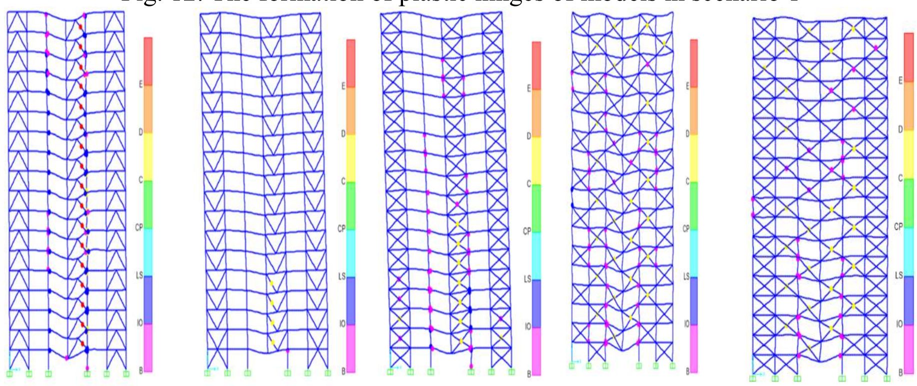
e)

Fig. 11. Vertical displacement in nonlinear static analysis of models considered in Scenario 4 (removal of middle column and brace of 10^{th} story)



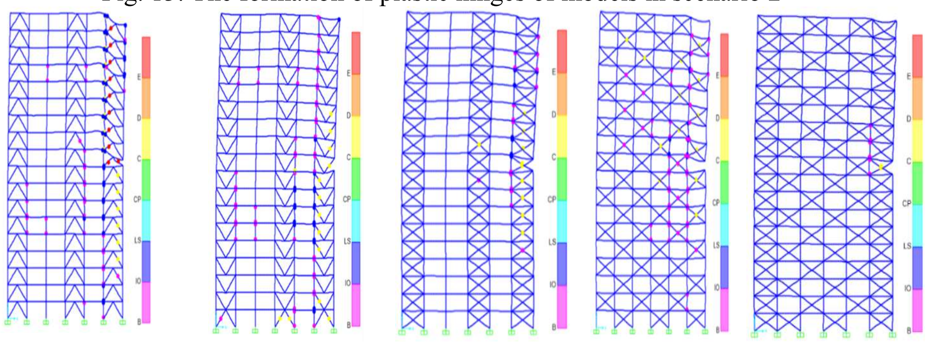
a) b) c) d) e)

Fig. 12. The formation of plastic hinges of models in scenario 1



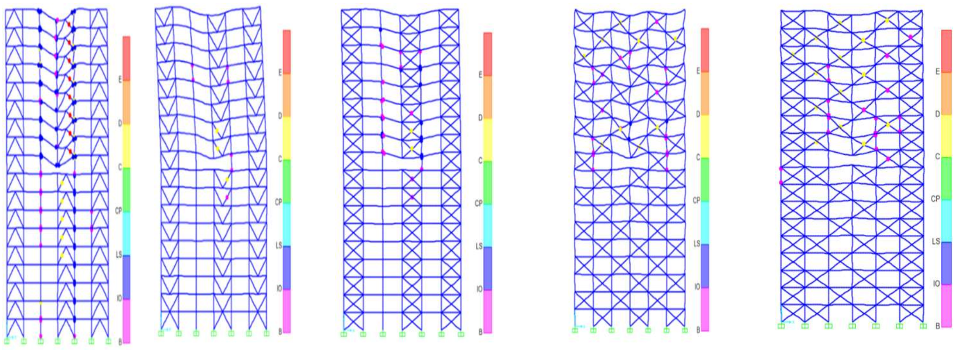
a) b) c) d) e)

Fig. 13. The formation of plastic hinges of models in scenario 2



a) b) c) d) e)

Fig. 14. The formation of plastic hinges of models in scenario 3

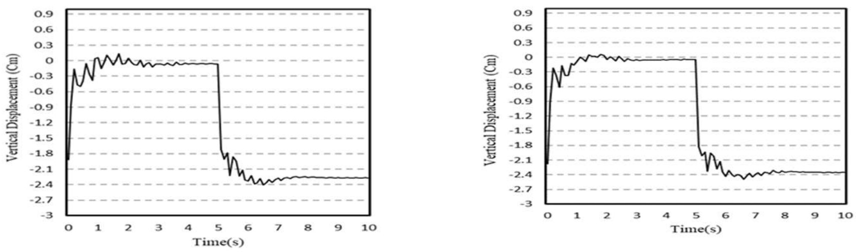


a) b) c) d) e)

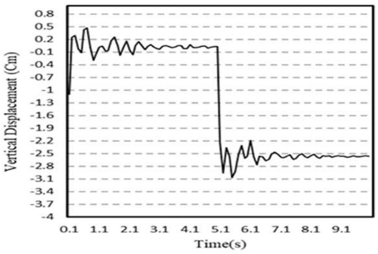
Fig. 15. The formation of plastic hinges of models in scenario 4

3.2. Nonlinear dynamic analysis

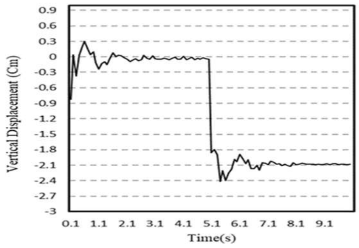
For dynamic analysis, the axial force acting on the member is calculated before removal. The member is then replaced with a point load. To simulate the phenomenon of sudden removal of the member, gravity, lateral loads and member forces are applied to the structure simultaneously and gradually over a period of 10 seconds. In the 10th second, the total gravitational and lateral loads of the structure enter it. The force that should have been applied to the structure instead of the member to simulate the effect of the member has also reached its final value. At this point, the specimen acts as an undamaged structure. Now, after 5 seconds, the member force is removed at once to simulate a sudden failure while the gravitational and lateral loads are still on the structure. The vertical displacements in the nonlinear dynamic state are shown in Figs. 16 to 19. Scenarios 1 and 2 performed better.



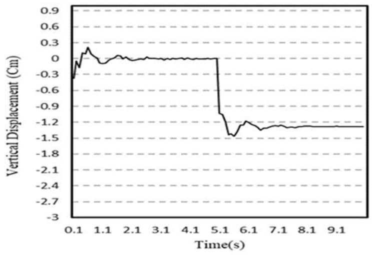
a) b)



c)

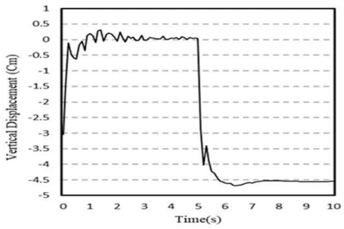


d)

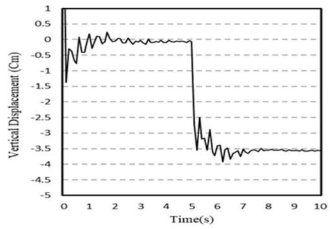


e)

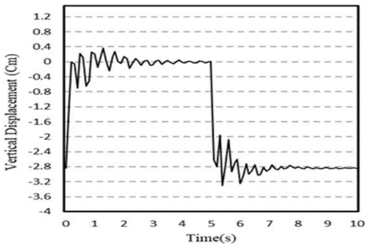
Fig. 16. Vertical displacement in nonlinear dynamic analysis of models considered in Scenario 1 (removal of side column of 1st story)



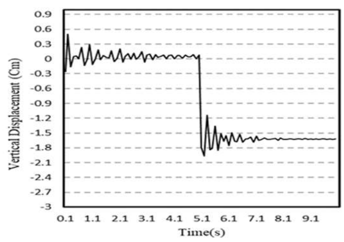
a)



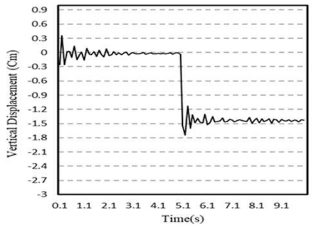
b)



c)

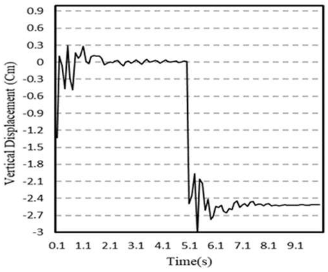


d)

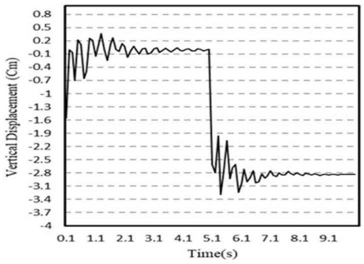


e)

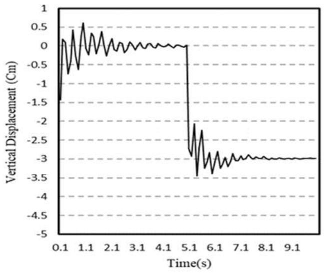
Fig. 17. Vertical displacement in nonlinear dynamic analysis of models considered in Scenario 2 (removal of middle column and brace of 1st story)



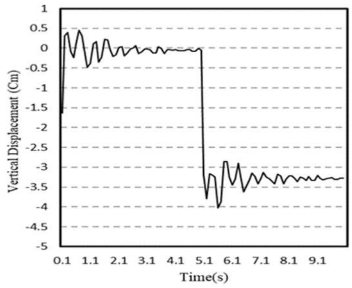
a)



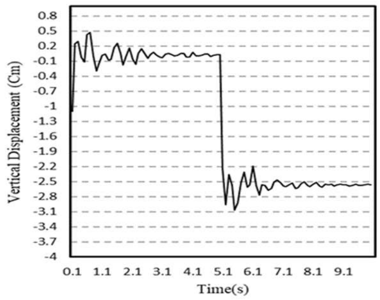
b)



c)



d)



e)

Fig. 18. Vertical displacement in nonlinear static analysis of models considered in Scenario 3 (removal of side column of 10th story)

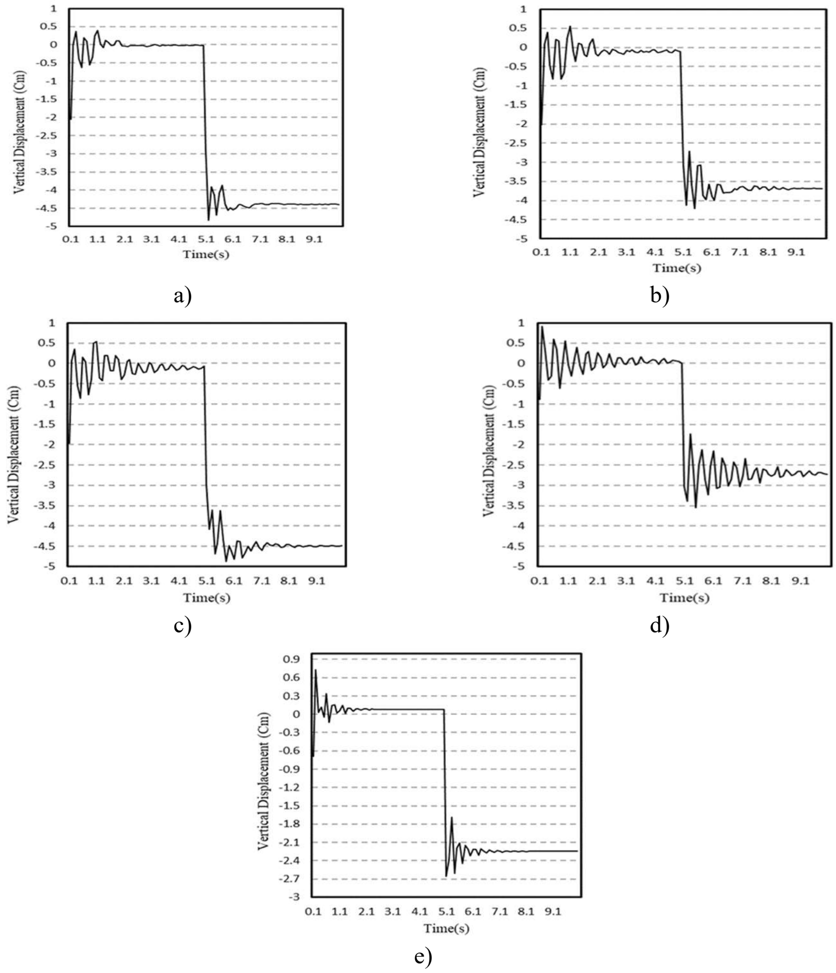


Fig. 19. Vertical displacement in nonlinear dynamic analysis of models considered in Scenario 4 (removal of middle column and brace of 10th story)

4. CONCLUSIONS

In this study, the effect of concentric brace configuration on high-rise steel structure with 18-story and a moment frame system with a concentric bracing under four removal scenarios in the first and tenth stories was numerically investigated. SAP 2000 software was used for modeling and analysis. Results of nonlinear static and dynamic analyses showed that displacement of cross braces was less effective in progressive collapse than the other concentric braced configurations inside spans and, also the cross braces in an uneven height at the middle spans because of the braces being positioned in a diagonal direction in the structure has moved the forces over more framed sections and affected more hinges and this causes that the vertical displacement of the node whose column is removed is lower. After examining the first four models, the 5th model, which is a combination of model number (c) and (d), was proposed to be at the side spans of the continuous cross braces (model c) and in the middle spans of the discontinuous cross braces (model d) was used. Comparison of the results showed that the vertical displacement of Model (e) in the progressive collapse was less than other models and has had better performance. Also, in this study, it has been recognized as a suitable model.

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