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STRUCTURAL INVESTIGATION OF HEIGHT - IRREGULAR- STEEL BRACED STRUCTURES AGAINST PROGRESSIVE COLLAPSE

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Abstract

Considering failure scenarios caused by a progressive collapse of structural systems subjected to special loadings such as explosion, impact, fire, design error and excessive unexpected loads is one of the main challenges that nowadays structural engineers encounter. Progressive collapse is defined as propagation of local failure of a structural member to other members that ultimately leads to failure of the whole structure or a portion of it. The effect of irregularities and the use of viscous damper in structural behavior of steel braced buildings against progressive collapse is the spotlight of this study. Three different steel buildings (5, 9 and 13 stories) with vertical irregularities are considered and analyzed with PERFORM 3D software. In the first part of this study, different scenarios for a sudden elimination of columns are modeled and the effect of irregularities on the pattern of collapse is studied. Then viscous dampers are used in the model to study whether they are able to prevent or mitigate the dynamic effects caused by the progressive collapse. The results show that the corner columns of the buildings are more sensitive than side columns. In addition, installing viscous dampers in the structure can improve its dynamic behavior to some extent.

Keywords: Irregular Steel Structure, Nonlinear Static Analysis, Nonlinear Dynamic Analysis, Viscous Damper, Progressive Collapse

1. Introduction

Over the past few decades, many structures have caused many financial losses and casualties due to terrorist attacks and inappropriate design. Progressive collapse is of the rare events in the United States or Western countries [1].

Nomenclatures

C	Damping Matrix
K	Stiffness Matrix
M	Mass Matrix
$r(t)$	External forces vector
$u(t)$	Displacement vector
$\dot{u}(t)$	Velocity vector
$\ddot{u}(t)$	Acceleration vector

This is because these events often occur in structures that are affected by abnormal loads and or their conditions are inappropriate in terms of integrity, plasticity, unspecified structure and fail to resist against the spread of damage [2]. Progressive collapse is the spread of local damage, from an initiating event from element to element, resulting eventually in the collapse of an entire structure or a disproportionately large part of it [3]. Moreover, natural hazards such as earthquakes can impose powerful lateral loads and stresses on structures and lead to the loss of one or more load bearing elements which might cause the destruction of a large part of structural elements [4]. The level of structural damage caused by earthquake is closely related to the capacity of the structure in absorption and dissipation of energy [5]. Structural safety has always been a key preoccupation for responsible for the design of civil engineering projects [4]. It should be noted that in recent decades, terrorist attacks particularly on the World Trade Center towers on September 11, 2001 have widely raised the issue of assessment of the potential progressive collapse of important structures and the structures that are in the design phase. Natural hazards such as earthquakes can impose powerful lateral loads and stresses to structures, and result in the loss of one or more load bearing elements that might cause the destruction of a large part of structural elements [6]. By observing the casualties and financial damage caused by such events several times in the past, the need to study and evaluate the potential of progressive collapse in the existing structures is highly felt in order to prevent the recurrence of such incidents [7].

This article aims to investigate the way of progressive collapse and to find out the position of eliminating critical columns in steel systems with simple frame and cross bracing. The structure is in an irregular height and the condition with and without damper will also be checked. In other words, in this structure by eliminating critical column, the structure behaviour against this loss will be examined. Furthermore, viscous damper will be used for the damaged area in order to overcome the problem of eliminating element. Viscous dampers play important role in energy dissipation and reducing structural responses [8]. Accordingly, the structure will be investigated in both regular and irregular height. In this study, three three-dimensional 5-, 9- and 13-story structures are used. Another objective is to provide appropriate solutions for engineers, companies, etc. for proper design against probable explosion.

2. Research Methodology

In order to model design a simple frame with cross bracing, ETABS software was used. Regulations used in this application for designing is Load and Resistance Factor Design (LRFD) method. Since the structures under study are at irregular height, according to standard No. 2800 [9], geometric irregularity in height has been used. It is noteworthy that this type of irregularity occurs when the horizontal dimensions of lateral load bearing system on each story are more than 130% of those in the adjacent stories. After that remodelling carried out in PERFORM-3D software [10] to do nonlinear analyses and assessment of their performance against progressive collapse. In this study, three models with three different heights in the form of 5-, 9- and 13-story are considered. Lateral load bearing system is a simple frame with cross bracing and gravity system is simple concrete slab with a thickness of 10 cm. Steel is typically used in the structures of chimneys, reservoirs, silos, pipelines, etc. [11]. Steel bracing system is a conventional and useful system in building industry [12]. The considered sections include IPE profiles for beams and BOX for columns and braces. The steel used in all beams and columns is ST37. Openings in all three models are variable in X and Y directions. The height of each story is considered to be 3 m.

3. Push Down Analysis

The sudden removal of a structural member has the same effect as the sudden application of the structural forces in those members in the opposite direction. The conventional nonlinear equivalent static approach (also termed "pushdown analysis") attempts to reproduce this effect examining the structure which has suffered the loss of one or more critical members under increasing gravity loads [13]. In describing this method it should be noted that the analysis is the same as pushover method which is used for lateral analyses. The nonlinear static procedure has become a new trend in structural analysis since it was first introduced [14]. In other words, this analysis is for obtaining static capacity of structure after the removal of column. In this method, first the desired column is removed in a static manner and then the opening affected by the eliminated column will be placed under loading bearing as mentioned in the abstract. Gravity loads with and without coefficients will gradually increase in 60 steps. By entering the load, the structure initially has a linear behaviour and then enters nonlinear area. Gravity load increases until one of the non-elastic members reaches the determined value in force-deformation curve or the structure become unstable and collapses. Each loading step is removed in correspondence with the displacement of vertical node on top of the column. In this section, the removal of different columns from the three mentioned structures will be reviewed and regular and irregular states will be compared and the results will be evaluated. The structure plan and elevation are shown as an example. Colored dots indicate eliminated positions. Figures 1 to 10 display plan and elevation of the structures and Figs. 11 to 28 display the results of the removal scenarios.

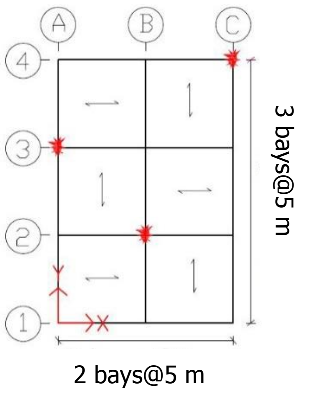


Fig. 1. Plan of 5-story building.

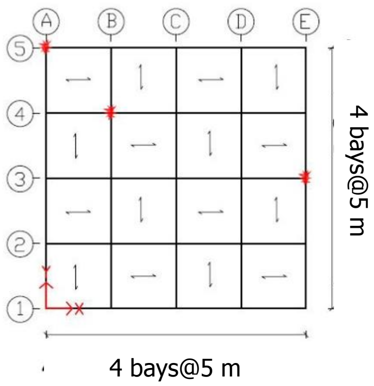


Fig. 2. Plan of 9-story building.

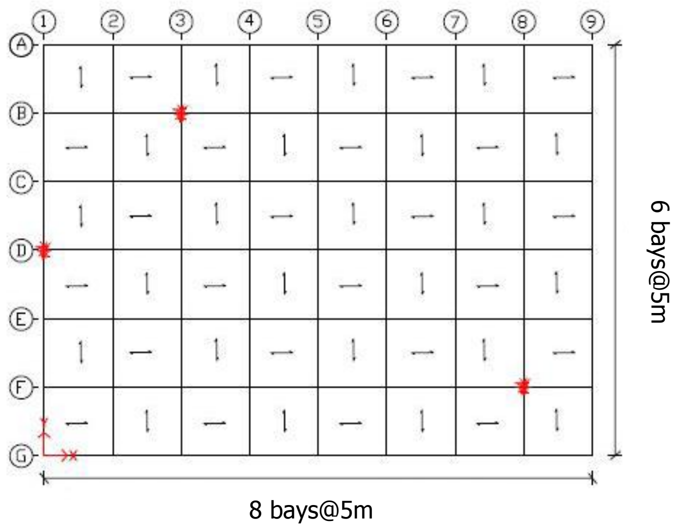
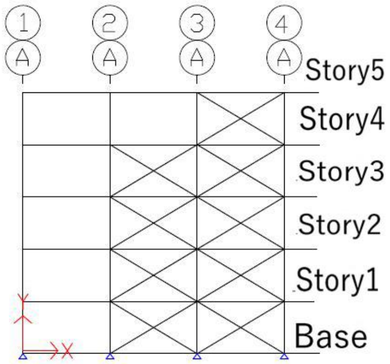


Fig. 3. Plan of 13-story building.



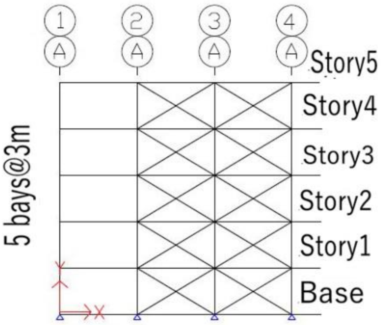


Fig. 4. Elevation of irregular structure.

Fig. 5. Elevation of regular structure.

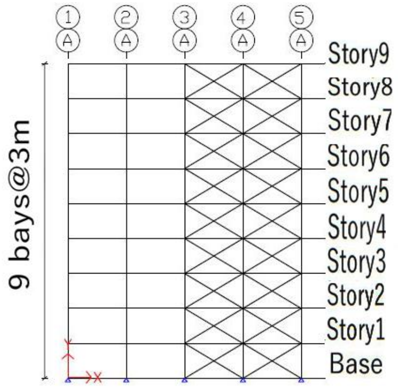


Fig. 6. Elevation of irregular structure.

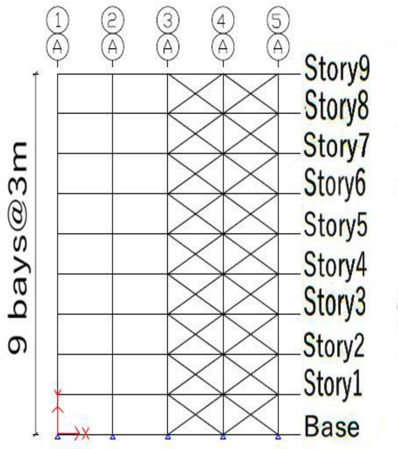


Fig. 7. Elevation of regular structure.

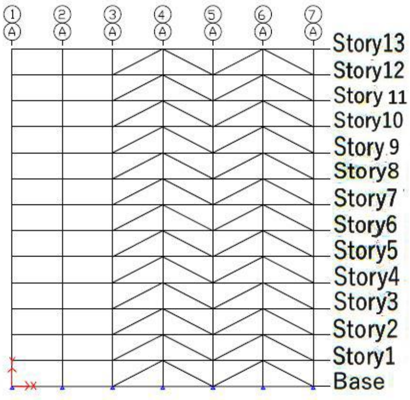


Fig. 8. Elevation of regular structure.

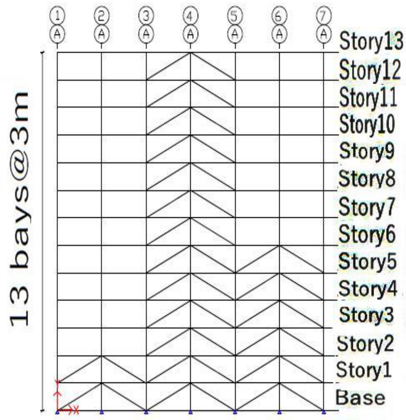


Fig. 9. Elevation of irregular structure.

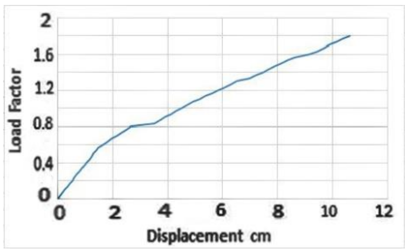


Fig. 10. Omission of C4 column (Irregular 5-st).

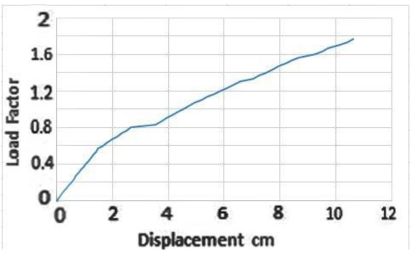


Fig. 11. Omission of C4 column (Regular 5-st).

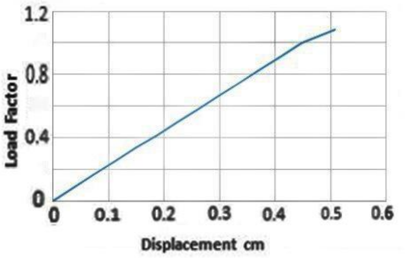


Fig. 12. Omission of A3 column (Irregular 5-st).

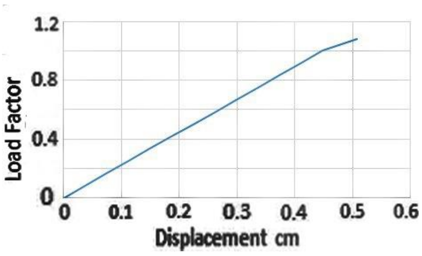


Fig. 13. Omission of A3 column (Regular 5-st).

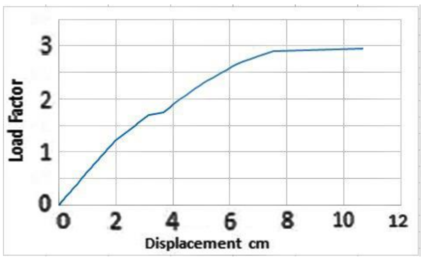


Fig. 14. Omission of B2 column (Irregular 5-st).

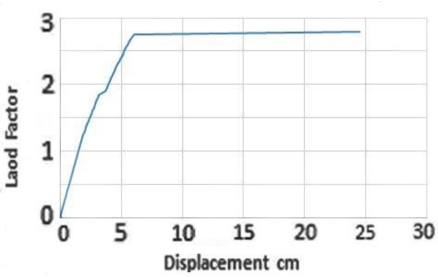


Fig. 15. Omission of B2 column (Regular 5-st).

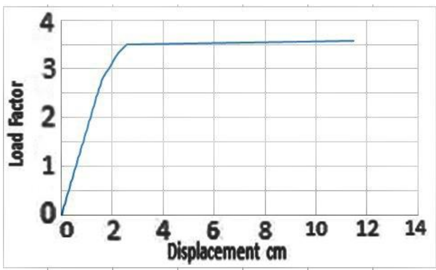


Fig. 16. Omission of A5 column (Irregular 9-st).

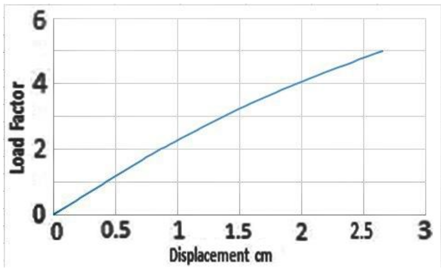


Fig. 17. Omission of A5 column (Regular 9-st).

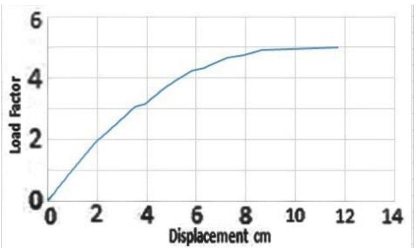


Fig. 18. Omission of B4 column (Irregular 9-st).

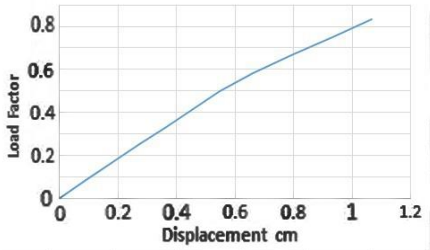


Fig. 19. Omission of B4 column (Regular 9-st).

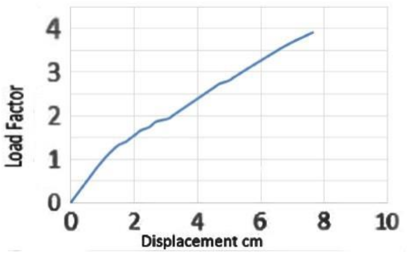


Fig. 20. Omission of E3 column (Irregular 9-st).

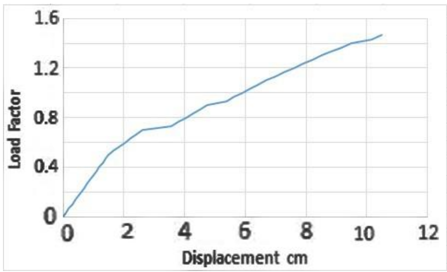


Fig. 21. Omission of E3 column (Regular 9-st).

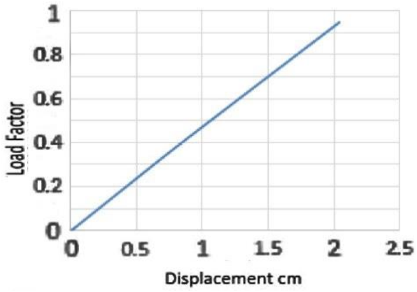


Fig. 22. Omission of F8 column (Irregular 13-st).

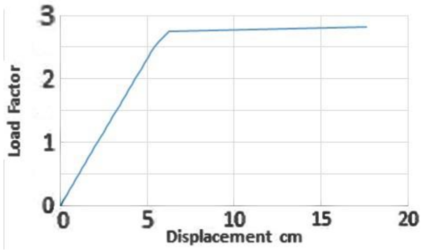


Fig. 23. Omission of F8 column (Regular 13-st).

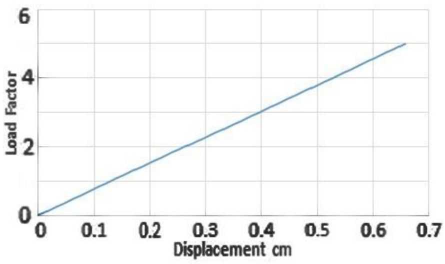


Fig. 24. Omission of B3 column (Irregular 13-st).

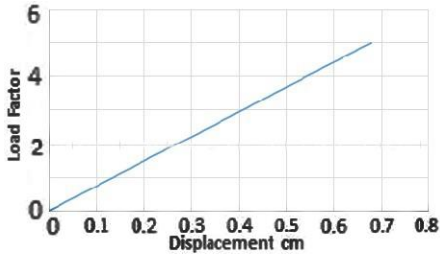


Fig. 25. Omission of B3 column (Regular 13-st).

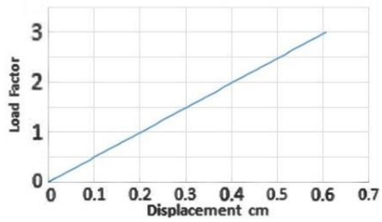


Fig. 26. Omission of D1 column (Irregular 13-st).

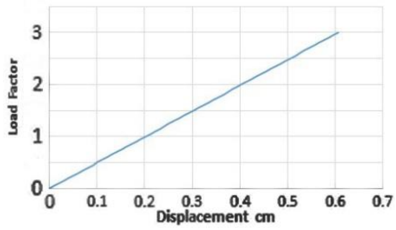


Fig. 27. Omission of D1 column (Regular 13-st).

4. Nonlinear Dynamic Analysis

Nonlinear dynamic analysis is one of the most accurate methods in comparison with other type of analysis [15]. In this method, solving the differential equation of dynamic equilibrium of motion (Eq. 1) is actually the main goal.

$$K\,u(t) + C\,\dot{u}(t) + M\,\ddot{u}(t) = r(t) \tag{1}$$

Where: M, C, K are mass, damping and stiffness matrixes, respectively. r(t) is external force vector. $u, \dot{u}$ and $\ddot{u}$ are the acceleration, velocity and displacement vectors, respectively [15, 16]. The procedure used in this study is a dynamic simulation of sudden removal of columns under different scenarios of progressive collapse. To simulate this phenomenon according to the Regulations of Public Service Department, interior simulated forces are removed after a period of time, so that the internal forces before removal are calculated under the initial analysis of loading combination of dead load plus a quarter of live load, then the desired column is removed and replaced with a concentrated load in the nodes above it. For simulation in Perform program, sudden removal of a function must be defined as Fig. 28. Figure 29 displays force-time function introduced to the software.

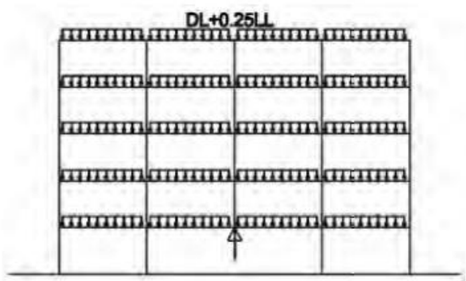


Fig. 28. Load pattern for dynamic analysis by GSA.

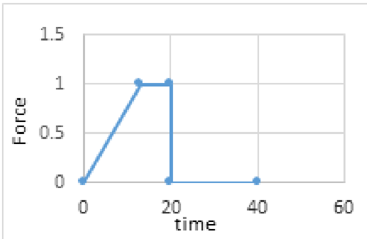


Fig. 29. Force-Time function introduced for software.

In Fig. 29, force reaches from zero to its maximum value within 13 minutes and then it is allowed to remain stable for 7 seconds (until 20 seconds). Then the column is removed suddenly in 0.1 second and the analysis will continue for 20 seconds (until 40 seconds). After the displacement analysis in time, the node above the eliminated column will be examined. In this part of the analysis will be reviewed for the first story columns in three 5-story, 9-story, and 13-story structures. Removal scenarios and the results from each structure are given below. Figures 31 to 33 show the removal scenarios and Figs. 34 to 49 show the results of elimination.

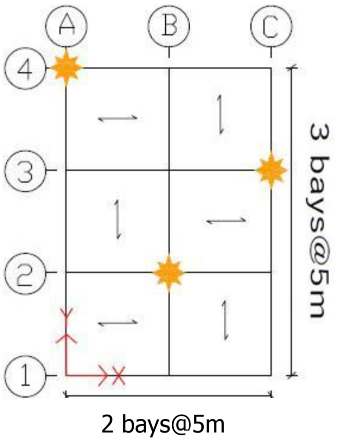


Fig. 30. Position of omitted column (5-st).

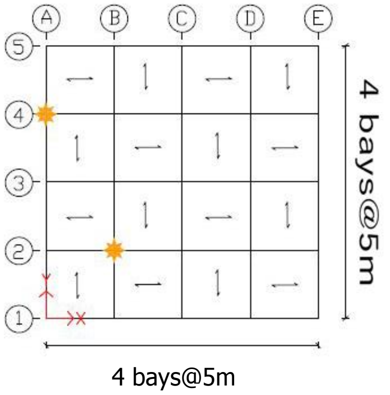


Fig. 31. Position of omitted column (9-st).

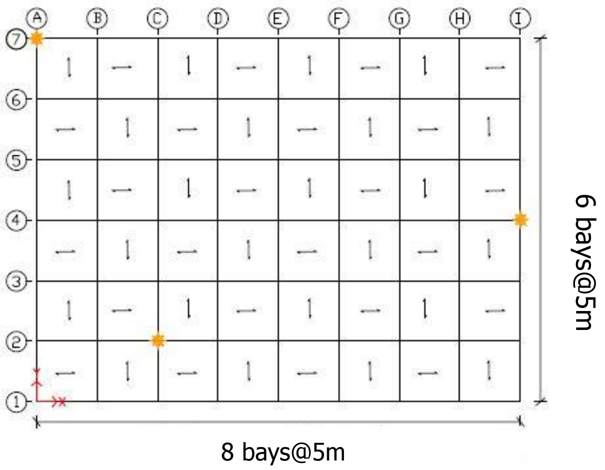


Fig. 32. Position of omitted column (13-st)

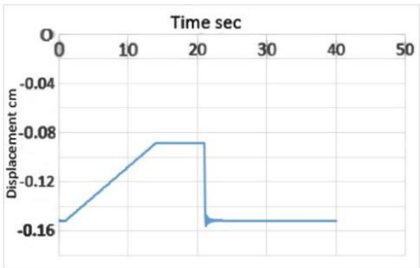


Fig. 33. Omission of C3 column (Irregular 5-st).

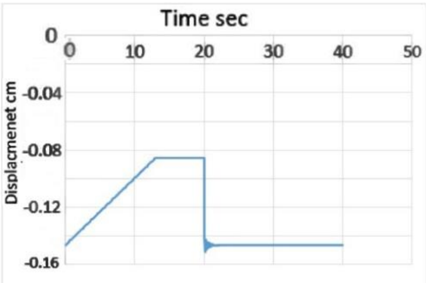


Fig. 34. Omission of C3 column (Regular 5-s).

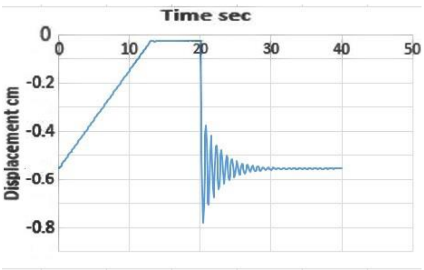


Fig. 35. Omission of B2 column (Irregular 5-st).

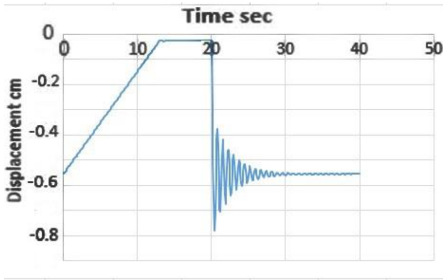


Fig. 36. Omission of B2 column (Regular 5-st).

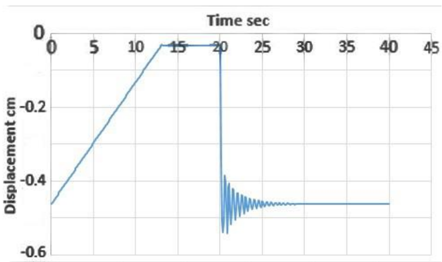


Fig. 37. Omission of A4 column (Irregular 5-st).

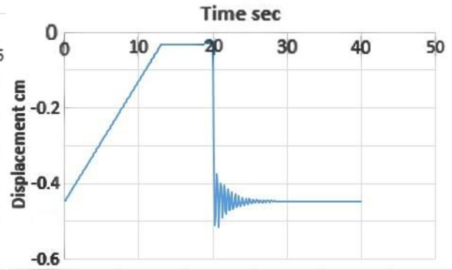


Fig. 38. Omission of A4 column (Regular 5-st).

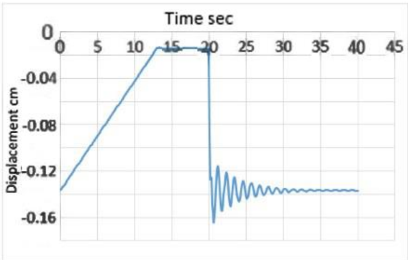


Fig. 39. Omission of A4 column (Irregular 9-st).

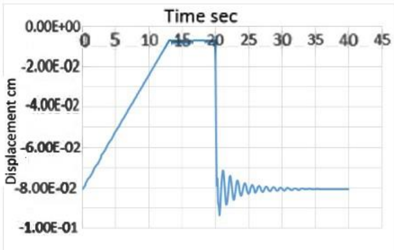


Fig. 40. Omission of A4 column (Regular 9-st).

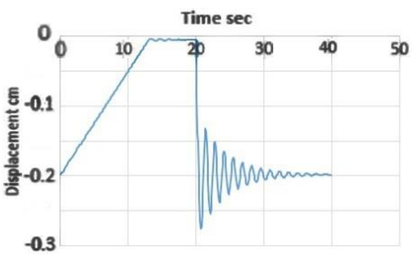


Fig. 41. Omission of B2 column (Irregular 9-st).

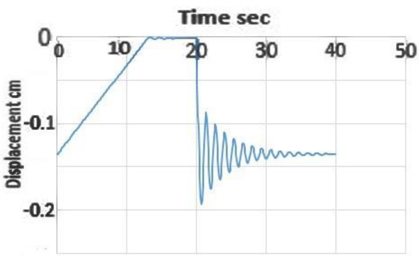


Fig. 42. Omission of B2 column (Regular 9-st).

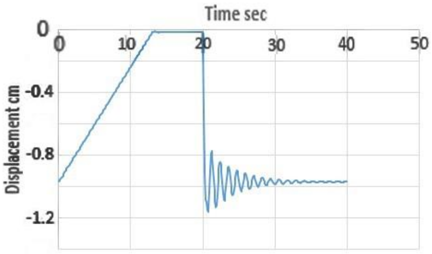


Fig. 43. Omission of A1 column (Irregular 13-st).

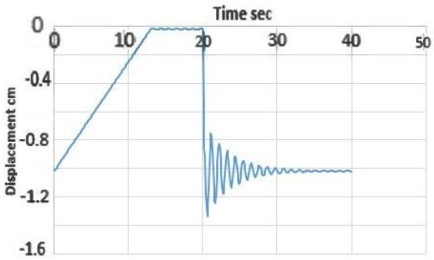


Fig. 44. Omission of A1 column (Regular 13-st).

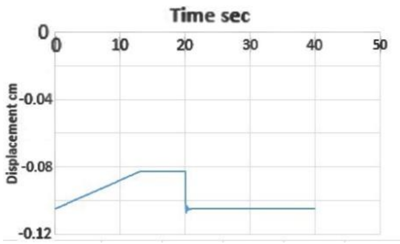


Fig. 45. Omission of D9 column (Irregular 13-st).

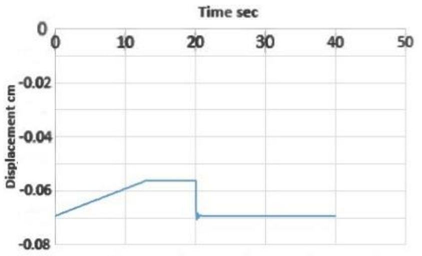


Fig. 46. Omission of D9 column (Regular 13-st).

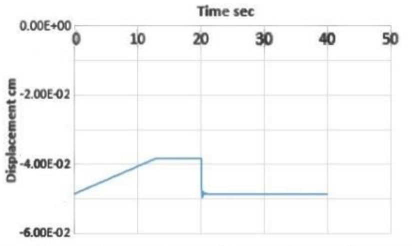


Fig. 47. Omission of F3 column (Irregular 13-st).

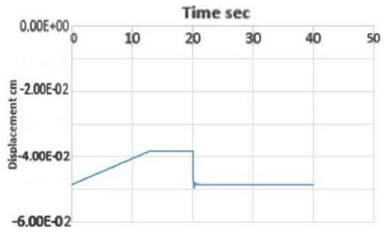


Fig. 48. Omission of F3 column (Regular 13-st).

5. Comparing Shape Modes With and Without Dampers for 9-Story Structures

In this section, non-linear dynamic responses of 9-story structures will be compared with each other in both regular and irregular modes with and without dampers. In other words, each structure will be examined individually. A viscoelastic material has both elastic and viscous components. Pure elastic materials do not lose energy under dynamic loadings. However, a viscoelastic material loses energy when loaded and unloaded [17]. Figures 49 and 50 display the removal scenarios and Figs. 51 to 54 show the results of those scenarios.

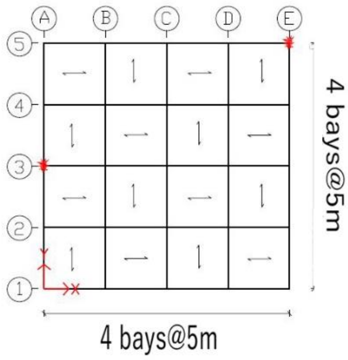


Fig. 49. Position of omitted column (Irregular 9-st).

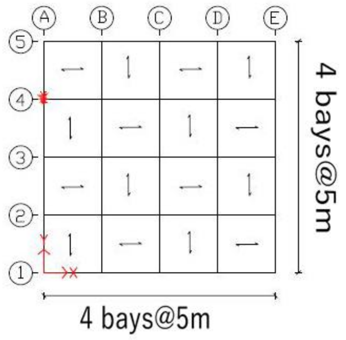


Fig. 50. Position of omitted column (Regular 9-st).

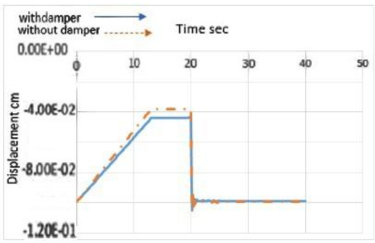


Fig. 51. Omission of A3 column (Irregular 9-st).

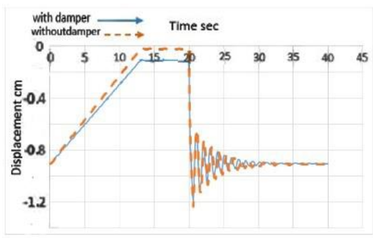


Fig. 52. Omission of E5 column (Irregular 9-st).

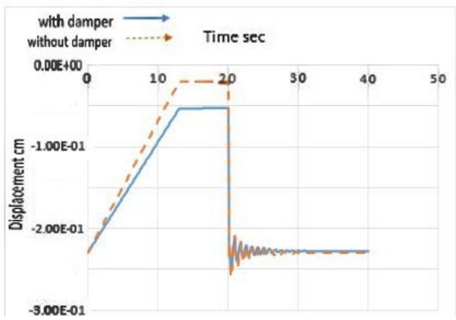


Fig. 53. Omission of A4 column (Regular 9-st).

6. Discussion and Conclusion

Before proceeding to the conclusion, it is noted that there are some limitations and assumptions while processing the analyses, such as: a. not considering the effect of infill, b. elastoplastic behavior with strain hardening for steel material, c. direct integration dynamic procedure with Newmark method and, d. the uncertainties for the removal of column and other members. In the following, the main points derived from this study are noted concisely:

- In pushover analysis, columns such as the columns of 13-story structure except F8 have not entered nonlinear stage regularly which might be due to the brace and high lateral stiffness or large amount of profiles beside the removed column or local effects of the structure which causes a part of the structure to collapse and the other part not to enter nonlinear phase. The different failure mechanisms in different scenarios are due to low uncertainty of the structure to prevent nonlinear act of the structure; in other words, the radius of local distribution is limited and stress is distributed in a limited part of the structure; therefore, it will continue to have elastic behavior.

  In relation to 5-story structure, it must be said that C4 and A3 columns have acted the same in both structures, but column B2 in irregular structure as well as 9-story structure were the same, except column A5 in 9-story structure that the regular structure has performed better which could be due to different stiffness of regular and irregular structures, so that due to the decrease and increase of braces the sections have changed. Moreover, if the removal scenarios are changed another conclusion might be possible and in the research, the total structure response is considered to be equivalent to the behavior of an average node and if the entire structure behaviors (behaviors of all free degrees) are compared, better response and behavior will be obtained by the regular structure.

- Using nonlinear dynamic analysis and according to the figures displayed previously, the starting point is the displacement resulting from static response and after that equivalent load of column enters the structure for 13 seconds to achieve its maximum value and then it is kept constant for 7 seconds until the system reaches equilibrium and finally it is suddenly removed in the 20th second. Then the structure oscillates around its static equilibrium position with a domain that reduces continuously and gradually it is converged and fixed with the static response that is developed under initial gravity loading. In relation to dynamic analysis of 5-story structure it should be said that regular structure with less displacement acts better than irregular structure except column B which has acted the same in both structures. In 9-story structure, regular structure had the best response as well. Column A1 in irregular structure and column D9 in regular structure created generated the best response, but column F3 in both structures behaved the same. In other words, in nonlinear dynamic analysis of 5-story structure it should be noted that highest displacement belongs to the removal of internal columns of the structure and then the corner columns are more critical. Side columns of the structure had less displacement than two previous modes; therefore, by eliminating interior columns the structure has become more vulnerable and has shown more critical behavior. Considering nonlinear dynamic analysis of 13-story structure it can be said that corner columns are more vulnerable and then side columns and finally interior columns, but these conditions are not true for 9-story structure.

- In Fig. 51, the existence of a damper has no significant effect on structure response, but in column E2 in Fig. 52, the structure response in a state with a damper has reduced as much as 5% with the sudden removal of column and the maximum response per cycle of oscillation reduces until reaching to alternative equilibrium. For regular structure, the presence of a damper for column A4 is effective as much as 2%; therefore, it can be said that the effect of damper is mainly on the corner columns.

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