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Comparative Analysis of Progressive Collapse Resisiting Capacity of Different Structural Systems

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Abstract- Progressive collapse is a disproportionate structural failure in which the localized loss of a critical load-carrying element can cause redistribution of forces, excessive deformation, and subsequent failure of adjacent structural members. An 11-storey regular reinforced-concrete commercial building was developed and analysed using SAP2000 under identical geometric, material, loading, and boundary conditions to ensure a consistent comparison. The Alternate Path Method (APM), following the GSA and UFC approaches adopted in the thesis, was employed by considering three sudden column-removal scenarios: corner-column removal, edge/mid-column removal, and interior-column removal. The structural response was evaluated in terms of vertical displacement, inter-storey drift, axial-force redistribution, bending and shear response, and overall structural stability. The results demonstrated a clear difference among the three structural systems. For the MRF, vertical displacement increased with storey height and reached approximately 0.16 in, with the second column-removal scenario producing the highest displacement response. In comparison, the Diagrid and Outrigger systems showed substantially lower displacement ranges, with their maximum responses occurring in Scenario 3. The MRF also exhibited the highest inter-storey drift, with the plotted response reaching approximately 8 in, whereas the Diagrid system showed a substantially lower drift response of approximately 2.5 in, and the Outrigger system exhibited the lowest drift response, reaching approximately 1.4 in. Axial-force redistribution increased from the upper storeys toward the lower storeys in all three systems. The MRF and Diagrid responses approached approximately 600 kip at the lower levels, whereas the Outrigger system showed a comparatively lower maximum axial-force response of approximately 400 kip. Among the removal cases, Scenario 3 generally produced the comparatively higher drift and axial-force response. Overall, the Diagrid System demonstrated the most favorable progressive-collapse performance, primarily because its triangulated perimeter configuration provides greater stiffness, redundancy, and efficient alternate load paths. The Outrigger System also demonstrated strong performance, particularly in controlling displacement and inter-storey drift through effective load transfer between the central core and perimeter columns. In contrast, the MRF exhibited the least favorable response, characterized by relatively higher deformation and drift.

Keywords— Progressive Collapse, Diagrid System and Outrigger System

I. INTRODUCTION

The rapid growth of urban populations, increasing land scarcity and the demand for efficient use of urban space have resulted in the widespread construction of high-rise buildings. As the height and complexity of buildings increase, structural engineers face greater challenges in ensuring adequate strength, stiffness, stability, ductility and robustness under both normal and abnormal loading conditions (S. K. Kunnath at, al., 2018). Conventional structural design generally focuses on anticipated gravity, wind and seismic actions; however, structures may also be exposed to accidental or abnormal events such as vehicle impact, explosions, fire, earthquakes, construction errors, or the sudden loss of a critical load-carrying member. Such localized damage can initiate a chain of failures in which loads are transferred to surrounding structural members, potentially resulting in disproportionate or progressive collapse. Research on reinforced-concrete structures has demonstrated that the response following column loss is governed not only by the capacity of individual members but also by the interaction and load-transfer mechanisms of the complete structural system (Z. J. Bunn at, al., 2021). Load redistribution, connection behavior, catenary action, membrane action, arching mechanisms and the availability of alternate load paths can significantly influence the residual capacity of a damaged structure. Numerical investigations have further demonstrated that the location of the removed column is an important factor because corner, edge and interior columns provide different levels of surrounding structural redundancy (O. Mohieldin at, al., 2025). The selection of the structural system is particularly important in high-rise buildings because different structural configurations provide different mechanisms for transferring gravity and lateral loads. The conventional Moment Resisting Frame (MRF) is one of the most widely used systems and primarily resists structural actions through beam-column frame action and moment-resisting connections. Its relatively simple configuration provides architectural flexibility and continuous framing; however, its progressive-collapse response depends strongly on the capacity of beam-column members and connections to redistribute forces following the loss of a vertical load-carrying member (M. M. Ali and K. S. Moon, 2007). Excessive deformation and drift may develop when the remaining frame does not possess sufficient stiffness or redundancy (V. C. Kamperidis, 2016). The Diagrid structural system has attracted considerable attention in high-rise construction because of its distinctive external diagonal configuration. The diagonal members form a triangulated structural network around the building perimeter and allow substantial portions of gravity and lateral loads to be transferred through axial forces (W. Shan, J. Liu, H. Qi, and J. Zhou, 2025). This configuration can increase global stiffness, reduce dependence on internal columns and provide multiple alternative load paths (C. Liu. at, al., 2018). Following localized member failure, the triangulated arrangement can facilitate redistribution of forces to surrounding members (M. Bagheripourasil and Y. Mohammadi, 2015). Consequently, the Diagrid system has the potential to provide greater structural redundancy and improved resistance to progressive collapse compared with conventional framing arrangements. Another important high-rise structural configuration is the Outrigger system, which consists of a central structural core connected to exterior columns through outrigger elements (S. Bianchi, 2020). Under normal loading, the outriggers engage the perimeter columns and improve the lateral stiffness and stability of the building (M. Hussaini, 2020). Following localized damage, the connection between the central core and exterior columns can provide additional routes for transferring forces away from the damaged region. This interaction between the core and perimeter structural elements can contribute to load redistribution, reduction of deformation and improved overall stability. The evaluation of progressive-collapse resistance requires an appropriate analytical procedure capable of representing localized damage and the subsequent response of the remaining structure (E. Asadi and H. Adeli, 2018). The Alternate Path Method (APM) is one of the commonly adopted approaches for progressive-collapse assessment (M. Heshmati and A. A. Aghakouchak, 2020). Under this method, a critical vertical load-carrying member is removed from the structural model and the resulting response of the remaining structure is evaluated. Previous research has indicated that the selected modelling strategy can substantially influence the predicted response of a structure following column loss (G. Nouri and M. R. Yosefzaei, 2020). The structural response following column removal is commonly evaluated using parameters such as vertical displacement, inter-storey drift, axial-force redistribution, bending moments, shear forces and overall stability (Y. Bao, J. A. Main and S.-Y. Noh, 2017). Vertical displacement provides an indication of the deformation caused by redistribution of gravity loads, while inter-storey drift reflects changes in structural stiffness and relative deformation between adjacent floors (A. Salmasi, at, al., 2020). Axial-force distribution is particularly important because it indicates how the load previously resisted by the removed column is transferred to the remaining load-carrying members. Increased internal forces and deformation near the damaged region may indicate a high level of demand and potential vulnerability to progressive failure (F. Kiakojouri, at, al., 2020). Several studies have investigated progressive-collapse behavior in reinforced-concrete frames and have demonstrated that structural configuration, damage location, redundancy and connection behavior have a major influence on collapse resistance (G. Angelucci, at, al., 2025). Research summarized in the thesis indicates that edge and corner column-removal cases can be critical because these locations generally have fewer surrounding members available to participate in load redistribution. Other investigations have shown that large-deformation mechanisms, including catenary and membrane action, may contribute to the resistance of damaged structures when adequate continuity and ductile detailing are available (O. A. Mohamed, at, al., 2006). However, the contribution of these mechanisms depends strongly on structural configuration, member detailing, material behavior and the adopted numerical modelling approach. For tall buildings, the interaction between structural configuration and progressive- collapse resistance remains an important area of research. Diagrid systems provide triangulated perimeter load paths, while Outrigger systems engage the central core and perimeter columns to improve stiffness and force transfer (H. Tavakoli and M. M. Afrapoli, 2018). Conventional MRF systems, in contrast, depend mainly on beam-column frame action (M. Botez at, al., 2016). Although these systems have been extensively studied for gravity, wind and seismic resistance, their comparative performance under identical progressive-collapse scenarios requires further investigation.

II. RESEARCH METHODOLOGY

1. General Methodology

This study presents a comparative numerical investigation of the progressive collapse resistance of three high-rise reinforced concrete structural systems, namely the conventional Moment Resisting Frame (MRF), Diagrid system and Outrigger system. The primary objective is to evaluate and compare the ability of these structural configurations to maintain structural integrity and provide effective alternative load paths following the sudden loss of critical load-carrying members. For this purpose, an 11-storey reinforced concrete commercial building is selected as the reference structure and is modelled using SAP2000. To ensure a consistent and reliable comparison, the three structural systems are developed using the same building geometry, storey heights, material properties, loading criteria, support conditions and general modelling assumptions. The major difference among the models is therefore the structural configuration and its corresponding load-resisting mechanism. The structural models are subjected to the principal design loads, including dead load, live load, wind load and seismic load, in accordance with the adopted design provisions. Appropriate load combinations are considered to represent the critical design conditions of the building. After establishing the initial structural models and verifying their stability under the applied loading conditions, progressive collapse scenarios are introduced through the sudden removal of selected critical columns. The column-removal approach is based on the Alternate Path Method (APM), in which the structure is assumed to experience localized damage and the remaining structural members are required to redistribute the loads previously carried by the removed member. Three critical column-removal locations are investigated: corner column removal, edge or mid-column removal and interior column removal. These scenarios represent different levels of damage severity and allow the influence of column location on the progressive-collapse response to be evaluated. Following the removal of the critical columns, the structural response of each system is evaluated using several performance indicators. Vertical displacement is examined to determine the extent of deformation around the damaged region and the ability of the structure to control excessive downward movement. Inter-storey drift is evaluated to identify changes in lateral and vertical deformation patterns and to assess the overall stability of the building. Force redistribution is also investigated by examining the changes in internal forces carried by the adjacent structural members after column removal. Particular attention is given to bending moments and associated force demands because significant increases in these parameters may indicate the development of critical demand in members surrounding the damaged zone

2. Building Modelling and Structural Systems

An 11-storey regular reinforced concrete (RCC) commercial building is selected as the reference structure for the comparative analysis of progressive collapse resistance. The building is assumed to have a regular plan and elevation, with a typical storey height of 10 ft, while the ground or bottom storey is considered according to the adopted structural configuration. The structure is assumed to be located on Site Class B soil conditions, representing relatively stiff soil characteristics for the seismic analysis. The building consists of the primary structural components required to safely transfer gravity and lateral loads, including reinforced concrete beams, columns, floor slabs, central core elements, and lateral load-resisting members. The same overall building geometry, storey arrangement, material properties, loading conditions, support conditions, and modelling assumptions are maintained for all three structural systems so that the influence of the structural configuration on progressive collapse performance can be evaluated under comparable conditions. Three different structural systems are considered in this study: Moment Resisting Frame (MRF) as shown in figure 1, Diagrid as shown in figure 2 and Outrigger systems as shown in figure 3. The MRF represents a conventional reinforced concrete structural system in which beams and columns are connected through rigid or moment-resisting beam-column joints. The rigidity of these connections enables the frame to resist both gravity and lateral loads through the development of bending moments, shear forces, and axial forces within the structural members. The MRF provides a continuous load path between the floors and foundations; however, localized failure of an important column may result in significant load redistribution and increased deformation in adjacent beams and columns.

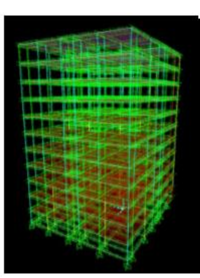
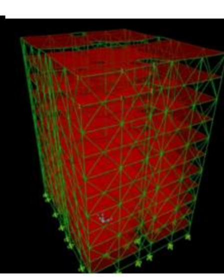
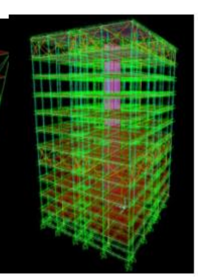




Figure 1: MRF structure Figure 2: Diagrid structure Figure 3: Outriggers structure

3. Alternate Path Method and Column Removal Scenarios

The Alternate Path Method (APM) is adopted in this study to evaluate and compare the progressive collapse resistance of the Moment Resisting Frame (MRF), Diagrid, and Outrigger structural systems. The APM is based on the assumption that a localized structural failure, such as the sudden loss of a critical load-carrying column, may occur due to accidental or extreme loading events. Following the removal of the damaged member, the gravity loads previously supported by that member must be redistributed to the surrounding beams, columns, slabs and other load-resisting components. The ability of the remaining structural system to accommodate these additional demands and establish alternative load paths is used as an indication of its robustness and resistance to progressive collapse. In the present study, critical columns are removed individually from the numerical models to simulate localized structural damage. The sudden removal of a column represents a severe but localized damage condition and allows the post-damage behaviour of the building to be examined. The column removal is carried out after establishing the initial equilibrium condition of the structure under the specified gravity loading. The response of the structure immediately after column removal is then evaluated to determine how effectively the remaining members redistribute the additional gravity loads. Particular attention is given to the deformation and force demands that develop in the members surrounding the removed column because these areas are expected to experience significant increases in structural demand. Three critical column-removal scenarios are considered to represent different locations of local damage within the building. In the first scenario column removed from top floor as given in figure 4, second scenario column removed from center floor as given in figure 5, third scenario column removed from bottom floor as given in figure 6, a corner column is removed, representing damage at the building perimeter where the availability of alternative load paths may be comparatively limited. In the second scenario, a mid or edge column is removed, representing localized damage along the exterior portion of the structural frame.

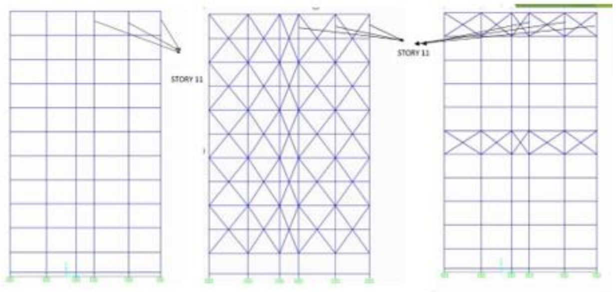


Figure 4: Column Removal Scenario 1 at top floor of Building

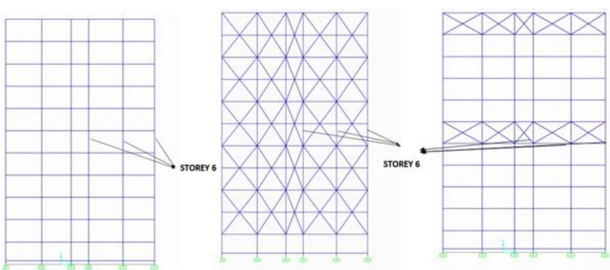


Figure 5: Column Removal Scenario 2 at center of Building

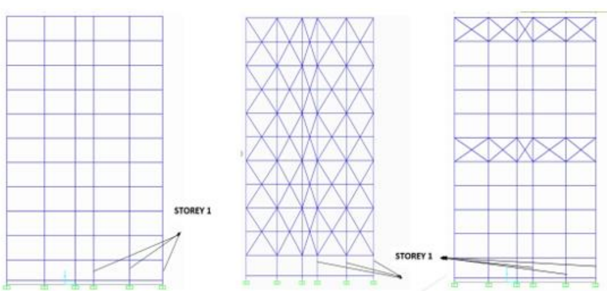


Figure 6: Column Removal Scenario 3 at Bottom of Building

III. RESULTS AND DISCUSSION

1. General Results

he results of the progressive collapse analysis demonstrate that the structural configuration has a significant influence on the behavior and resistance of high-rise reinforced concrete buildings following the sudden removal of critical load-carrying columns. The MRF system generally exhibited the highest structural deformation and inter-storey drift, indicating comparatively lower stiffness and limited alternate load-path capability. The vertical displacement increased toward the upper storeys, while the most critical response was generally associated with the more severe column-removal scenarios. In contrast, the Diagrid system demonstrated improved structural performance because its external diagonal members provided additional stiffness, redundancy and efficient load-transfer paths. The triangulated configuration enabled the structure to redistribute loads more effectively following local column loss and consequently reduced the overall deformation response. The Outrigger system also demonstrated favorable behavior, particularly in controlling structural displacement and inter-storey drift. The connection between the central structural system and perimeter columns through the outrigger mechanism facilitated more effective load redistribution and enhanced the overall stability of the building.

The axial-force results showed a progressive increase in force demand from the upper storeys toward the lower storeys and plinth level. After column removal, the redistribution of forces increased the demand on neighboring structural members, with the interior-column removal case generally producing comparatively higher axial-force responses. The MRF and Diagrid systems showed axial-force distributions extending to approximately 600 kip, whereas the Outrigger system showed a comparatively lower range of approximately 400 kip. The comparative displacement results also indicated that the MRF produced the largest response, while the Diagrid and Outrigger systems maintained comparatively lower deformation levels. Similarly, the MRF exhibited the highest inter-storey drift, whereas the Outrigger system provided the lowest drift response. Overall, the results indicate that the Diagrid system provided the most favorable overall progressive-collapse resistance, owing to its high stiffness, redundancy, and efficient alternate load paths, while the Outrigger system ranked second and demonstrated particularly effective control of displacement and drift. The MRF system showed the least favorable performance among the three systems. These findings emphasize the importance of structural configuration and efficient load-transfer mechanisms in improving the robustness and resilience of high-rise buildings subjected to sudden local structural damage.

2. Structural Response After Column Removal

The structural response of the Moment Resisting Frame (MRF), Diagrid, and Outrigger systems was evaluated after the sudden removal of critical columns using the Alternate Path Method (APM). Three column-removal scenarios were considered, representing corner, mid/edge, and interior column removal conditions. The removal of a critical column caused the gravity loads carried by the removed member to redistribute to the surrounding beams, slabs, columns, and other load-resisting members. Consequently, increases in internal forces, vertical displacement, inter-storey drift, and stress concentrations were observed around the damaged region. Figure 7 illustrate the structural response of the MRF system for the three column-removal scenarios, figure 8 present the corresponding responses of the Diagrid system. The diagonal perimeter members provide an additional load-transfer mechanism around the building perimeter and figure 9 show the structural response of the Outrigger system under the three removal scenarios.

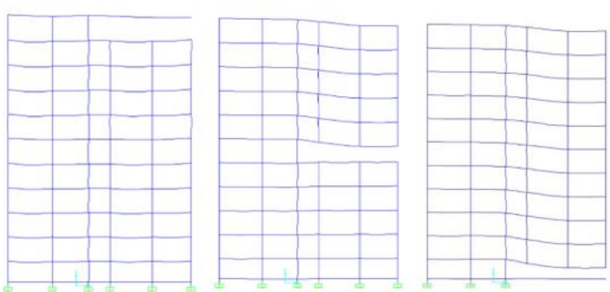


Figure 7: MRF Column Removal Scenarios at Bottom Floor, Center Floor and Top Floor

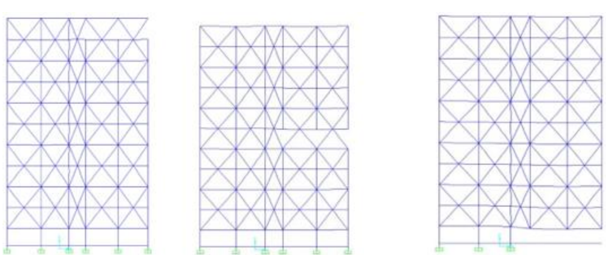


Figure 8: Diagrid system Column Removal Scenarios at Bottom Floor, Center Floor and Top Floor

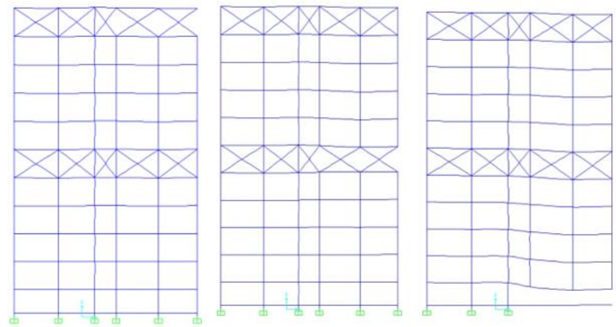


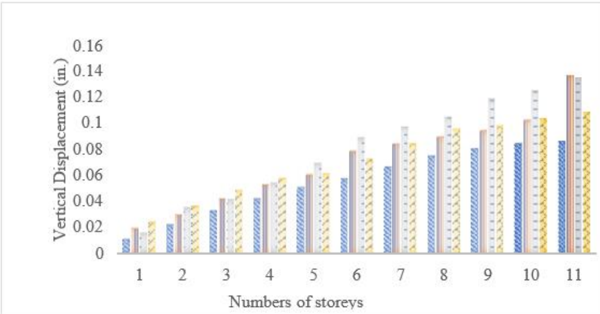
Figure 9: Outrigger system Column Removal Scenarios at Bottom Floor, Center Floor and Top Floor.

3. Vertical Displacement, Storey Drift and Axial Force Distribution

Vertical displacement

The figure 10 presents the vertical displacement response of the structural system before column removal and under three different column-removal scenarios for the 11-storey building. The vertical displacement generally increases with increasing storey level, indicating that the upper storeys experience greater deformation than the lower storeys. Before column removal, the displacement increases gradually from approximately 0.01 in at the first storey to about 0.085 in at the eleventh storey. This progressive increase is associated with the greater accumulated deformation of the upper portion of the building. After column removal, the displacement increases in all three scenarios, confirming that the sudden loss of a load-carrying column causes redistribution of gravity loads to the surrounding structural members. At the lower storeys, the difference between the pre-removal and post-removal conditions is relatively small; however, the difference becomes more pronounced at the upper storeys. This indicates that the structural disturbance produced by column removal affects the overall load-transfer mechanism and results in increased deformation throughout the building. Among the three removal cases, the 2nd scenario produces the highest vertical displacement over most of the storey levels. The displacement reaches approximately 0.12 in at Storey 9, 0.125 in at Storey 10, and about 0.135 in at Storey 11. The 1st scenario generally produces a lower response, although its displacement becomes significant at the upper storeys, reaching approximately 0.136 in at Storey

11. The 3rd scenario also causes an increase in displacement, with the maximum value of approximately 0.108 in at Storey 11.



.Figure 10: Presents the vertical displacement response of the MRF structural system

The figure 11 illustrates the vertical displacement response of the Diagrid structural system before column removal and after the application of three different column-removal scenarios over the 11-storey building. The results show a clear increasing trend in vertical displacement with increasing storey height. This indicates that the upper storeys undergo greater deformation than the lower storeys due to the cumulative effect of structural deformation and redistribution of gravity loads. Before column removal, the vertical displacement increases gradually from approximately 0.01 in at Storey 1 to about 0.09 in at Storey 11. After the removal of a critical column, the displacement increases compared with the original condition, demonstrating the effect of load redistribution on the remaining structural members. The increase becomes more noticeable at the upper storeys, where the structural deformation is comparatively larger. Among the three column-removal scenarios, the 3rd scenario generally produces the highest vertical displacement, particularly at the upper storeys. Its displacement reaches approximately 0.095 in at Storey 11. The 2nd scenario also produces a relatively high response, reaching approximately 0.09 in, while the 1st scenario generally remains lower than the other two removal cases. The difference between the scenarios is relatively small at the lower storeys but becomes more evident as the storey height increases.

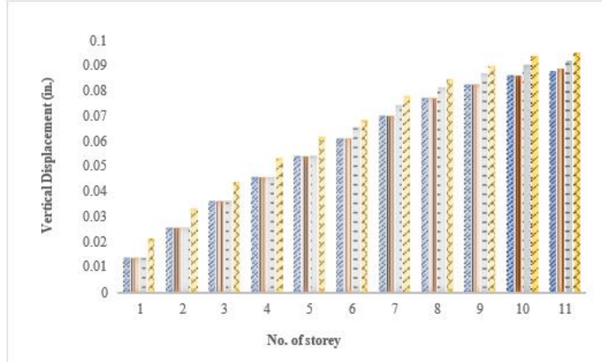


Figure 11: illustrates the vertical displacement response of the Diagrid structural system

The figure 12 shows that the Outrigger vertical displacement response demonstrates a gradual increase in displacement as the storey level increases. The plotted vertical-displacement scale extends from 0.00 to 0.10 in, indicating that the overall deformation remains relatively small compared with the MRF system, whose plotted response extends to approximately 0.16 in. The lower storeys experience comparatively smaller vertical movements, whereas displacement becomes more pronounced toward the upper storeys. Among the three column-removal conditions, Scenario 3 produces the highest displacement response, indicating that interior-column removal has the greatest influence on the vertical deformation of the Outrigger system. The improved displacement control can be attributed to the interaction between the central core, outrigger elements, and perimeter columns. Following column removal, the gravity loads that were previously carried by the damaged column are redistributed through the remaining structural members. The outrigger mechanism assists this redistribution by mobilizing the perimeter columns and transferring forces between the core and exterior structural system. Consequently, the building is able to maintain greater stiffness and stability after localized damage. The relatively low displacement response therefore indicates that the Outrigger system has an effective alternative load-transfer mechanism and better deformation control than the conventional MRF.

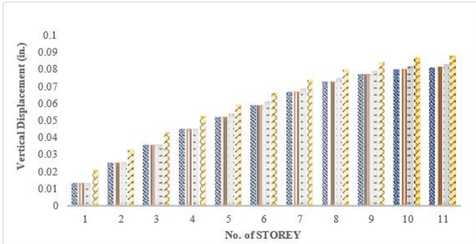


Figure 12: shows that the Outrigger vertical displacement response

Story Drift

Figure 13 presents the story drift response of the Moment Resisting Frame (MRF) under different column-removal scenarios. The story drift shows a clear increasing trend toward the upper storeys, while comparatively lower values are observed at the lower storeys. For discussion purposes, the drift may be considered approximately 2.0 in at the lower storeys, 4.0 in at the middle storeys, and 7.0–8.0 in at the upper storeys. The structure without column removal exhibits the lowest drift, indicating its normal and stable load-carrying condition. After column removal, the drift increases because the sudden loss of a vertical load-carrying member forces the surrounding beams and columns to redistribute the gravity loads through alternate load paths. Among the removal cases, Scenario 3 produces the highest story drift, approximately 8.0 in at the upper levels, followed by the other column-removal scenarios. The higher drift at the upper storeys indicates greater flexibility of the MRF and reduced lateral stiffness in comparison with more efficient structural systems. The increasing drift toward the top of the building also demonstrates that deformation becomes more pronounced as the height of the structure increases.

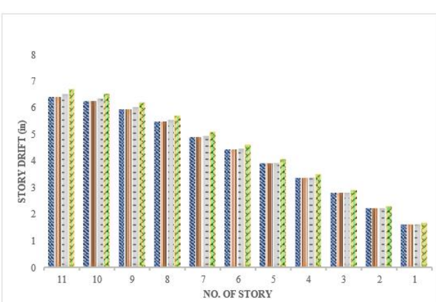


Figure 13: story drift response of the Moment Resisting Frame (MRF)

Figure 14 presents the story drift response of the Diagrid structural system under different column-removal scenarios. The results indicate that story drift generally increases toward the upper storeys, while comparatively smaller drift values are observed at the lower levels. For representative discussion, the story drift may be considered approximately 0.75 in at the lower storeys, 1.50 in at the middle storeys, and 2.50–3.00 in at the upper storeys. The structure without column removal shows the lowest drift, confirming the stable behavior of the intact Diagrid system. Following column removal, the drift increases due to redistribution of gravity loads through the surrounding structural members. Among the considered cases, Scenario 3 produces the highest story drift, reaching approximately 3.0 in at the upper storeys, whereas Scenarios 1 and 2 exhibit comparatively lower drift values. The relatively small magnitude of drift demonstrates the high lateral stiffness and effective load-distribution capability of the Diagrid system. The diagonal perimeter members form a triangulated structural arrangement that efficiently transfers forces and limits excessive deformation following local column loss. Compared with the MRF system, the Diagrid exhibits substantially lower story drift, indicating improved structural rigidity and greater resistance to progressive collapse.

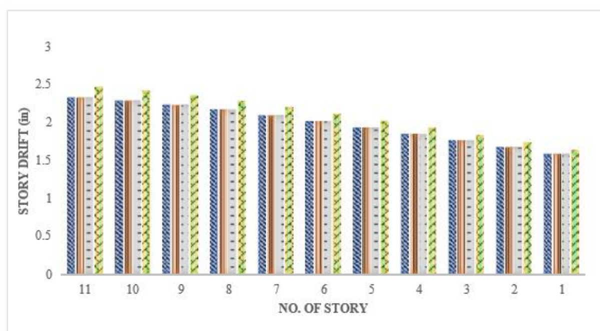


Figure 14: Presents the story drift response of the Diagrid structural system

Figure 15 presents the story drift response of the Outrigger structural system under different column-removal scenarios. The results show that story drift generally increases toward the upper storeys, whereas relatively smaller values are observed at the lower levels. For representative discussion, the story drift may be considered approximately 0.30 in at the lower storeys, 0.70 in at the middle storeys, and 1.20–1.40 in at the upper storeys. The intact structure without column removal exhibits the minimum story drift, demonstrating its stable structural response under normal loading conditions. After column removal, the story drift increases because the gravity loads carried by the removed column are redistributed to adjacent structural members. Among the different removal scenarios, Scenario 3 produces the maximum story drift, reaching approximately 1.4 in at the upper storeys, while Scenarios 1 and 2 show comparatively lower values. The relatively small drift values indicate that the Outrigger system provides effective control of structural deformation after local damage. The outrigger mechanism improves the interaction between the central structural core and perimeter columns, thereby increasing the overall stiffness and providing an efficient alternate load path. Compared with the MRF system, the Outrigger system exhibits considerably lower story drift, while its drift response is also comparable to that of the Diagrid system. Therefore, the results demonstrate that the Outrigger system has a strong capability to control inter-storey deformation and enhance progressive-collapse resistance, particularly under critical column-removal conditions.

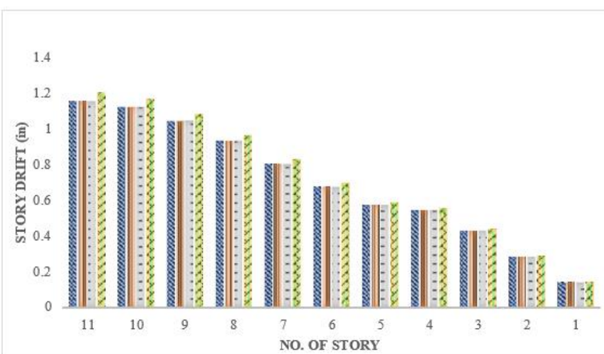


Figure 15: Presents the story drift response of the Outrigger structural system

Axial Force Distribution

Figure 16 illustrates the axial force distribution in the Moment Resisting Frame (MRF) under different column-removal scenarios. The results show that the axial force generally increases toward the lower storeys because the columns at the lower levels carry the accumulated gravity loads from the floors above. For representative discussion, the axial force may be considered approximately 150 kip at the upper storeys, 350 kip at the middle storeys, and 550–600 kip at the lower storeys. The intact structure without column removal exhibits the normal axial-force distribution, whereas the removal of a column causes redistribution of the load to the adjacent columns. Among the considered scenarios, Scenario 3 produces comparatively higher axial forces, approaching approximately 600 kip at the lower levels, indicating a greater demand on the remaining load-carrying members. The increase in axial force after column removal demonstrates the development of alternate load paths within the MRF. The lower-storey columns are particularly critical because they receive the combined effect of loads transferred from the upper floors. Although the redistribution mechanism allows the structure to continue carrying the applied loads, the increased axial demand may increase the vulnerability of the remaining columns under severe local damage.

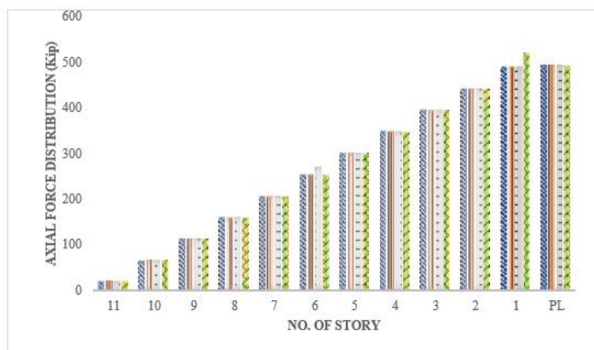


Figure 16: Illustrates the axial force distribution in the Moment Resisting Frame (MRF)

Figure 17 presents the axial force distribution in the Diagrid structural system under different column-removal scenarios. The results demonstrate that the axial force generally increases toward the lower storeys, as the lower structural members carry the accumulated gravity loads transferred from the upper floors. For representative discussion, the axial force may be considered approximately 150 kip at the upper storeys, 350 kip at the middle storeys, and 550–600 kip at the lower storeys. The structure without column removal shows the normal axial-force distribution, while the removal of a critical column causes the surrounding members to accommodate additional load through alternate load paths. Among the considered cases, Scenario 3 produces comparatively higher axial-force demand, approaching approximately 600 kip at the lower levels. The high axial-force capacity and efficient redistribution are attributed to the triangulated arrangement of the Diagrid members, which enables gravity and lateral loads to be transferred efficiently through the external diagonal structural system. The increase in axial force toward the lower storeys is expected because these members support the combined loads from multiple floors above. Despite the increase in force following column removal, the Diagrid system demonstrates an effective load-redistribution mechanism and maintains structural stability.

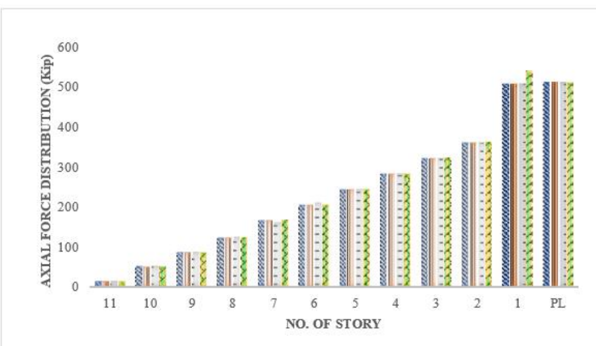


Figure 17: presents the axial force distribution in the Diagrid structural system

The figure 18 presents the axial force distribution in the Outrigger structural system under different column-removal scenarios. The results indicate that the axial force generally increases toward the lower storeys because the lower-level columns carry the accumulated gravity loads transferred from the upper floors. For representative discussion, the axial force may be considered approximately 100 kip at the upper storeys, 220 kip at the middle storeys, and 350–400 kip at the lower storeys. The intact structure without column removal shows the normal axial-force distribution, whereas the removal of a critical column causes the surrounding members to redistribute the applied loads through alternate load paths. Among the considered cases, Scenario 3 produces the comparatively highest axial-force demand, reaching approximately 400 kip at the lower levels. The relatively lower axial-force values compared with the MRF and Diagrid systems indicate the effective load-transfer mechanism of the Outrigger system. The outrigger members establish an efficient interaction between the central core and perimeter columns, allowing the redistributed gravity loads to be shared among a larger number of structural members. As a result, excessive force concentration in individual members is reduced. The axial force increases progressively toward the lower storeys because these members support the cumulative load from the floors above.

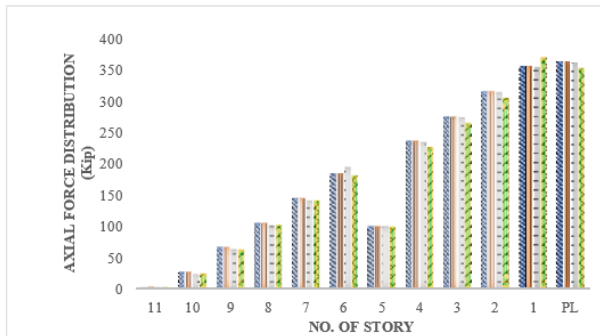


Figure 18: Presents the axial force distribution in the Outrigger structural system

The graph indicates that axial force distribution increases progressively from the upper storeys to the lower levels. Scenario 3 shows relatively higher axial force values, while the maximum force occurs at the lower storeys and plinth level.

4. Displacement Comparison of Structural Systems

Figure 19 compares the story displacement response of the Moment Resisting Frame (MRF), Diagrid and Outrigger structural systems under the considered column-removal scenarios. The results clearly demonstrate that the MRF experiences the greatest displacement, whereas the Diagrid and Outrigger systems provide considerably better control of structural deformation. For representative comparison, the displacement of the MRF may be considered approximately 0.16 in at the upper storeys, compared with approximately 0.10 in for the Diagrid and 0.09 in for the Outrigger system. At the lower storeys, the corresponding displacement values are relatively small, approximately 0.03 in for MRF, 0.02 in for Diagrid, and 0.02 in for Outrigger.

The greater displacement of the MRF is associated with its comparatively lower lateral stiffness and less efficient load redistribution following column removal. In contrast, the Diagrid system exhibits lower displacement because its triangulated perimeter members provide high structural stiffness and efficient load transfer. The Outrigger system also demonstrates effective displacement control by transferring forces between the central core and perimeter columns.

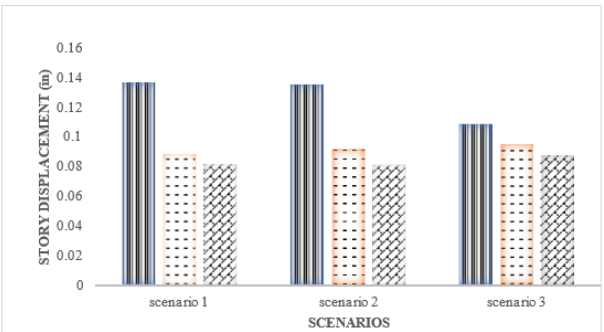


Figure 19: compares the story displacement response of the Moment Resisting Frame (MRF), Diagrid and Outrigger structural systems

4. Story Drift Comparison of Structural Systems

The figure 20 presents a comparison of story drift among the Moment Resisting Frame (MRF), Diagrid and Outrigger structural systems under the considered column-removal scenarios. The results show a significant difference in the deformation response of the three structural systems. The MRF exhibits the highest story drift, with a representative maximum value of approximately 8.0 in at the upper storeys. In comparison, the Diagrid system shows a substantially lower maximum drift of approximately 3.0 in, while the Outrigger system provides the lowest drift, with a maximum value of approximately 1.4 in. At the lower storeys, the drift values are considerably smaller, approximately 2.0 in for MRF, 0.8 in for Diagrid, and 0.4 in for Outrigger. The higher drift of the MRF is attributed to its comparatively lower structural stiffness and greater flexibility, particularly after the sudden removal of a critical column. The Diagrid system reduces story drift through its triangulated perimeter configuration, which provides enhanced stiffness and efficient load redistribution. The Outrigger system demonstrates the most effective drift control because the outrigger mechanism improves interaction between the central core and perimeter columns and facilitates efficient transfer of forces.

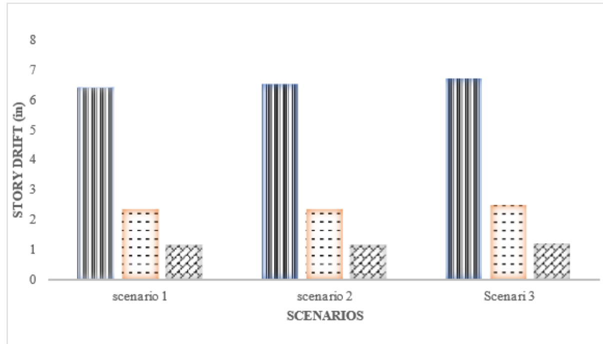


Figure 20: presents a comparison of story drift among the Moment Resisting Frame (MRF), Diagrid and Outrigger structural systems

The Figure 21 presents a comparison of the axial force distribution in the Moment Resisting Frame (MRF), Diagrid, and Outrigger structural systems under the considered column-removal scenarios. The results show that the axial force generally increases toward the lower storeys because the lower-level structural members carry the accumulated gravity loads transferred from the floors above. The Diagrid system exhibits the highest axial force demand, with a representative maximum value of approximately 600 kip at the lower storeys. The MRF also reaches an axial force of approximately 600 kip, whereas the Outrigger system shows comparatively lower axial-force demand, with a maximum of approximately 400 kip. At the middle levels, representative axial forces may be considered approximately 350 kip for MRF, 350 kip for Diagrid, and 220 kip for Outrigger, while at the upper levels the values are approximately 150 kip, 150 kip, and 100 kip, respectively. The higher axial forces in the Diagrid are associated with its efficient triangulated perimeter system, through which a significant portion of the structural loads is transferred through the diagonal members. The MRF distributes gravity loads primarily through its conventional beam-column system, resulting in substantial axial demand in the lower columns. In contrast, the Outrigger system provides comparatively lower axial-force concentration because the outrigger mechanism facilitates load sharing between the central core and perimeter columns.

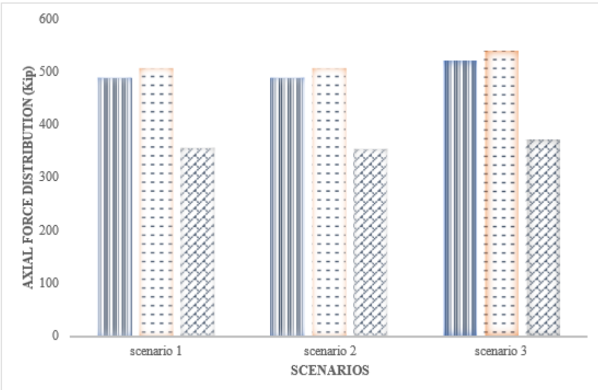


Figure 21: presents a comparison of the axial force distribution in the Moment Resisting Frame (MRF), Diagrid and Outrigger structural systems

IV. CONCLUSION

The present study evaluated the progressive-collapse performance of three high-rise structural systems, namely the Moment Resisting Frame (MRF), Diagrid and Outrigger systems, using the Alternate Path Method (APM) under different column-removal scenarios. The results demonstrate that the removal of a critical column significantly influences the displacement, story drift, and axial-force response of the remaining structural members. The MRF exhibited the greatest vertical displacement and story drift, indicating comparatively lower stiffness and greater deformation following local column loss. The maximum representative story displacement of the MRF was approximately 0.16 in, while its story drift reached approximately 8.0 in. The Diagrid system showed improved deformation control, with representative maximum displacement and story-drift values of approximately 0.10 in and 3.0 in, respectively, due to its triangulated perimeter configuration and efficient load redistribution. The Outrigger system demonstrated the most effective control of story drift, with a representative maximum displacement of approximately 0.09 in and story drift of approximately 1.4 in. The axial-force results further showed that axial demand generally increases toward the lower storeys in all structural systems because these members carry the accumulated gravity loads from the upper floors. The MRF and Diagrid systems developed axial forces approaching approximately 600 kip, whereas the Outrigger system exhibited a comparatively lower maximum axial force of approximately 400 kip. The higher axial force in the Diagrid reflects efficient transfer of loads through its diagonal structural members, while the lower axial demand in the Outrigger indicates effective load sharing between the central core and perimeter columns. Overall, the comparative assessment indicates that the MRF provides the least favorable response, whereas the Diagrid and Outrigger systems provide superior deformation control and alternate load-path development. The Diagrid can be considered highly effective in terms of stiffness, redundancy, and efficient load redistribution, while the Outrigger provides particularly strong control of displacement and story drift. Therefore, both Diagrid and Outrigger structural systems demonstrate better potential for mitigating progressive-collapse effects than the conventional MRF system.

REFERENCES

1. S. K. Kunnath, Y. Bao, and S. El-Tawil, "Advances in computational simulation of gravity-induced disproportionate collapse of RC frame buildings," J. Struct. Eng., vol. 144, no. 2, p. 3117003, 2018.
2. Z. J. Bunn, J. L. Wyatt, J. N. Burns, B. Riser, K. P. Arnett, and M. G. Oesterle, "Leveraging DoD Relationships and Interests to Improve Undergraduate Education and Enhance the Structural Engineering Profession," in 2021 ASEE Virtual Annual Conference Content Access, 2021.
3. O. Mohieldin, M. Jadallah, C. Cicos, F. Mehdi, S. Sağıroğlu, and A. Doğangün, "Evaluating progressive collapse in multi-story buildings: Influence of slabs and building height," Adv. Struct. Eng., p. 13694332251383308, 2025.
4. M. M. Ali and K. S. Moon, "Structural developments in tall buildings: current trends and future prospects," Archit. Sci. Rev., vol. 50, no. 3, pp. 205–223, 2007.
5. V. C. Kamperidis, "Novel damage-free self-centering column base connection for earthquake-resilient steel buildings," 2016, University of Warwick.

6. W. Shan, J. Liu, H. Qi, and J. Zhou, "Intelligent optimization method for complex supertall inclined CFT frame-core tube-outrigger truss structures," Struct. Multidiscip. Optim., vol. 68, no. 11, p. 233, 2025.
7. C. Liu, Q. Li, Z. Lu, and H. Wu, "A review of the diagrid structural system for tall buildings," Struct. Des. Tall Spec. Build., vol. 27, no. 4, p. e1445, 2018.
8. M. Bagheripourasil and Y. Mohammadi, "Comparison between alternative load path method and a direct applying blast loading method in assessment of the progressive collapse," J. Rehabil. Civ. Eng., vol. 3, no. 2, pp. 1–15, 2015.
9. S. Bianchi, "Multi-performance evaluation of traditional and low-damage non-structural components," 2020.
10. M. Hussaini, "A Review paper on seismic pareformance of high-rise building using bracing, diagrid and outrigger system," Int. J. Eng. Res., vol. 9, no. 06, pp. 1148–1150, 2020.
11. E. Asadi and H. Adeli, "Nonlinear behavior and design of mid-to high-rise diagrid structures in seismic regions," Eng. J., vol. 55, no. 3, pp. 161–180, 2018.
12. M. Heshmati and A. A. Aghakouchak, "Collapse analysis of regular and irregular tall steel moment frames under fire loading," Struct. Des. Tall Spec. Build., vol. 29, no. 3, p. e1696, 2020.
13. G. Nouri and M. R. Yosefzaei, "Effect of Mass Irregularity on the Progressive Collapse Potential of Steel Moment Frames," in Seismic Behaviour and Design of Irregular and Complex Civil Structures III, Springer, 2020, pp. 349–360.
14. Y. Bao, J. A. Main, and S.-Y. Noh, "Evaluation of structural robustness against column loss: Methodology and application to RC frame buildings," J. Struct. Eng., vol. 143, no. 8, p. 4017066, 2017.
15. A. Salmasi, M. R. Sheidaii, M. Saghaie Sahebalzaman, and S. Tariverdilo, "Effect of fully restrained beam-to-column connection on the progressive collapse strength of steel moment frames," Adv. Struct. Eng., vol. 23, no. 8, pp. 1656–1668, 2020.
16. F. Kiakojouri, M. R. Sheidaii, V. De Biagi, and B. Chiaia, "Progressive collapse assessment of steel moment-resisting frames using static-and dynamic-incremental analyses," J. Perform. Constr. Facil., vol. 34, no. 3, p. 4020025, 2020.
17. G. Angelucci, E. Cecca, and F. Mollaioli, "Parametric Analysis of Outrigger Systems for High-Rise Buildings with Different Geometric Shapes," Appl. Sci., vol. 15, no. 10, p. 5643, 2025.
18. O. A. Mohamed, "Progressive collapse of structures: annotated bibliography and comparison of codes and standards," J. Perform. Constr. Facil., vol. 20, no. 4, pp. 418–425, 2006.
19. H. Tavakoli and M. M. Afrapoli, "Robustness analysis of steel structures with various lateral load resisting systems under the seismic progressive collapse," Eng. Fail. Anal., vol. 83, pp. 88–101, 2018.
20. M. Botez, L. Bredean, and A. M. Ioani, "Improving the accuracy of progressive collapse risk assessment: Efficiency and contribution of supplementary progressive collapse resisting mechanisms," Comput. Struct., vol. 174, pp. 54–65, 2016.