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EFFECT OF DIFFERENT VERTICAL STRUCTURAL IRREGULARITIES ON NONLINEAR RESPONSE OF REINFORCED CONCRETE BUILDINGS

FARKLI DÜŞEY DOĞRULTUDAKİ YAPISAL DÜZENSİZLİKLERİN BETONARME BİNALARIN DOĞRUSAL OLMAYAN DAVRANIŞINA ETKİSİ

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ABSTRACT

To achieve either some architectural view or functional utilization, many structures have been designed with some irregularity in plan or elevation. However, during the recent earthquakes, it has been noted that the presence of such irregularities can lead to structural damage in a single member or even the collapse of an entire building. In the current study, the seismic behavior of vertically irregular low-rise and medium-rise buildings was examined in comparison with the regular ones. As low- and medium-rise buildings, those with three and seven stories, respectively, and as types of vertical irregularities, stiffness/strength irregularity (missing beams or columns), mass irregularity, and vertical geometric irregularity due to setbacks were considered. For this purpose, analytical models of the two reference regular framed structures and thirty different irregular framed structures were developed, and their seismic behavior was evaluated using nonlinear finite element analysis. The effects of different irregularities on the seismic demand were discussed in terms of the variations in capacity curves, plastic hinge formations, and axial internal forces obtained in the columns. The results of the analysis indicate that, depending on the type of irregularity, buildings with irregularities, especially those with missing columns, become more vulnerable to seismic impacts.

Keywords: Capacity curves, nonlinear analysis; regular buildings; seismic response; vertical irregularity

ÖZET

Mimari görünüm veya işlevsel kullanım sebebiyle pek çok yapı yatayda ve düşeyde düzensizliklere sahip olarak tasarlanmaktadır. Ancak, son dönemde yaşanan depremler, yapılarda bu tür düzensizliklerin olması durumunda yapısal elemanlarda hasar oluşabileceği, hatta binada çökme meydana gelebileceğini göstermiştir. Bu çalışmada düşeyde düzensiz olan az ve orta katlı binaların sismik davranışları düşeyde düzenli binalarla karşılaştırmalı olarak incelenmiştir. Az ve orta katlı binalar olarak üç ve yedi katlı binalar düşünülmüştür. Düşey düzensizlikler olarak da kiriş veya kolon eksikliğinden kaynaklı düşeyde rijitlik ve dayanım düzensizliği, kütle düzensizliği ve düşeyde geometrik düzensizliği dikkate alınmıştır. Bu sebeple, referans olarak iki düzenli çerçeveli yapının ve otuz farklı düzensiz çerçeveli yapının analitik modelleri geliştirilmiş ve doğrusal olmayan sonlu elemanlar analizi kullanılarak sismik davranışları değerlendirilmiştir. Farklı düzensizliklerin sismik talep üzerindeki etkileri, kapasite eğrilerindeki değişimler, plastik mafsal oluşumları ve kolonlarda elde edilen eksenel iç kuvvetler açısından tartışılmıştır. Analiz sonuçları, düzensizlik türüne bağlı olarak, özellikle de kolonları düzensiz olan binaların sismik etkiler karşısında daha riskli hale geldiğini göstermektedir.

Anahtar Kelimeler: Kapasite eğrileri, doğrusal olmayan analiz, düzenli binalar, sismik tepki, dikey düzensizlik

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INTRODUCTION

Nowadays, irregular buildings are constructed widely around the world, especially in developed countries. That is simply due to the development of art and architecture. Architects take advantage of irregularity to enable them to express their thoughts openly. In addition, "form follows fiction," "form follows beauty," and form follows nature" are prominent doctrines that architects work based on. Irregularity provides architects with more opportunities to work freely based on the doctrines they prefer. Moreover, modern architecture presents a challenge in achieving both functional and artistic structures simultaneously. Thus, regular buildings are obstacles to designers. To construct buildings with optimal functionality and challenge the best projects that become a phenomenon, buildings must be irregular. Indeed, the role of civil engineers is more challenging in cases involving irregular buildings, especially in high-seismic zones. However, the ratio of irregularity and how it responds to seismic loads is specified by building codes (Soni and Mistry 2006).

When an earthquake occurs, the ground begins to shake, and the structures supported on it undergo this motion. The dynamic loads developed by an earthquake over the structures aren't external loads; however, the inertial influence is due to the motion of the supports. In this case, several factors contributing to the damage of the structures during earthquakes can be considered due to the irregularities (Kamath et al., 2014). According to current national and international codes, vertical irregularities are defined in details, for example, TBDY (2018) states three significant types of vertical irregularities, namely, strength irregularity between adjacent stories (weak story, whose lateral strength is lower than that of the above story), stiffness irregularity between adjacent stories (soft story, whose lateral stiffness is lower than that of the above or below story), and discontinuity of vertical elements of the structural system. In addition to these irregularities, ASCE/SEI 7 (2016), Eurocode 8 (2004), and IS 1893 (2016) also address two types of irregularities: mass irregularity and vertical geometric irregularity. It is worth noting that among codes, there may be discrepancies in the description and limitations of such vertical irregularities in structures.

In the literature, several studies have been conducted to evaluate the response of different types of vertical irregularity (Cassis and Cornejo 1996, Das and Nau 2003, Mezzi et al. 2004, Güler et al. 2008, Sadashiva et al. 2008, Kumar et al. 2012, Kara and Celep 2012, Akberuddin et al. 2013, Wasey et al. 2022, Raheem et al. 2024). For example, in the study of Cassis and Cornejo (1996), the nonlinear behavior of reinforced concrete (RC) buildings with irregularities in elevation was investigated. They determine the variation in strength and displacement capacity of buildings with and without irregularities. A brittle failure mode was observed in the structure, which had no infill wall over its elevation. Mezzi et al. (2004) conducted a numerical study to develop a technique for earthquake design of buildings, taking into account various factors that impact the building's seismic behavior. Based on the analysis of the results, they proposed a sample design procedure. Güler et al. (2008) studied the retrofitting of existing vertically irregular RC buildings based on seismic loading. For the numerical solution, SAP2000 and ZEUS-NL software were utilized. The retrofitted system was then analyzed for the performance assessment. The demand and capacity curves were plotted. It was reported that the existing irregular structure failed to meet the life-safety performance level, whereas the retrofitted one satisfied the required performance level. In the study by Sadashiva et al. (2008), which employed various nonlinear analysis methods, a simple procedure was proposed for considering structural irregularity limits in building design. Irregularity limits based on the inter-story drift response of the building as a result of mass irregularity were determined. Kumar et al. (2012) conducted a performance evaluation of RC buildings with vertical irregularities. For different seismic zones, the diverse dynamic affecting factors for the variation in base shear, period, and story displacement of buildings were computed and discussed comparatively. Akberuddin et al. (2013) performed a nonlinear static analysis of RC frames with vertical irregularity using ETABS software. It was observed that the irregularity in the building's elevation significantly reduced the structure's performance state. Wasey et al. (2022) investigated the performance of regular and irregular buildings equipped with base isolators, fluid viscous dampers, and shear walls. The optimum seismic control system was proposed based on the nonlinear time history analysis. It was found that the base-isolated and damped irregular buildings behaved more efficiently in diminishing the earthquake effect. In another recent study, Raheem et al. (2024) investigated the influence of pounding on the earthquake response of adjacent irregular buildings with a moment-resisting frame structural system and collinear alignment eccentricity. The results showed that low-rise buildings with eccentricity did not significantly influence inter-story drift demands. In contrast, pounding cases revealed decreased story drifts compared to non-pounding cases. Blasi et al. (2024) investigated the behavior of seismically designed and gravity load-designed irregular four-story RC buildings under earthquake loading. A model incorporating nonlinear flexural and shear behavior of the building was established, and a nonlinear incremental dynamic analysis was conducted. It was observed that the accelerations and displacements measured at the floor level were substantially influenced by the irregularity. In the study by Santos et al. (2024), the influence of vertical irregularities on reinforced concrete (RC) buildings was evaluated by Eurocode 8. The five-story moment-resisting frame structures, which exhibit vertical irregularity due to varying column heights and cross-sections, were analyzed, and it was found that the imposed irregularities in elevation have different influences on the seismic performance. It was also noted that more investigations on this issue were needed to permit their results to be more generalized. The susceptibility evaluation of vertically irregular medium-rise RC buildings with lead rubber bearings was investigated by Chavan and Mate (2025). They determined the acceleration, base shear, story displacement, story drift, and periods to assess the vulnerability response of the buildings. The inclusion of the lead rubber bearing diminished the rapid rise in the drift value where the stiffness irregularity existed. Aslani and Tehrani (2025) investigated the earthquake behavior and collapse capacity evaluation of dual eight- and twelve-story RC buildings with vertical irregularities in their shear walls. The irregularity was related to the lessening in the shear wall width. It was demonstrated that the current seismic code was ineffective in providing an accurate estimation of the earthquake response of RC shear wall buildings with such irregularities, and suggestions were provided for enhancing the existing seismic design provisions.

The studies above highlight the importance of vertical irregularity and the necessity of further analytical research to understand better the seismic response of buildings with different vertical irregularities as a powerful and safer alternative to seismic design. Within this context, apart from the above studies, this investigation addresses the effect of variation in type, degree, and location of vertical irregularity, along with their different distributions over the building elevation, on the seismic performance of the low-rise and medium-rise case studied RC buildings. In the selection of the type of the vertical irregularities, the ones mainly applied due to architectural purposes or for use of the building were taken into account and three different irregularities such as stiffness/strength irregularity due to discontinuous beams or columns, irregularity in mass, and geometric irregularity due to setback and various cases for each kind of vertical irregularity were considered. A total of thirty-two frame models were developed and analyzed to identify the critical irregularities for the studied structures. The variation in the capacity curve, plastic hinge formation, and axial internal force in the side and center columns of the structures was determined and compared for regular and irregular RC buildings.

MODEL DEFINITION

The study focuses on low-rise and medium-rise structures that are chosen to symbolize both regular and irregular buildings. The nonlinear analysis method was selected to determine the behavior of regular and irregular building models under seismic effects. For this purpose, the structural analysis program of SAP 2000 (2011) was employed. As a low-rise building, a three-story framed structure (G+2) was considered, whereas a medium-rise seven-story framed structure (G+6) was also considered. Several types of irregularities that may occur in the buildings, such as mass irregularities, vertical geometry irregularities (setbacks), and stiffness/strength irregularities with missing beams and columns, were investigated.

As reference buildings, typical reinforced concrete frames with a height of three meters and four bays with a span length of four meters in each direction were considered. The concrete strength of the buildings was 30 MPa, and the steel yield strength was 420 MPa. The columns were mainly 30x40 cm and 30x55 cm, reinforced using 1.2% reinforcement in the low-rise and medium-rise buildings, respectively. The beams were mainly 35x55 cm in size, while the beams supporting the missing columns were 35x70 cm. The depth of the slab was 15 cm. The dead load and live load for the building were taken as 5.5 and 5.0 kN/m^2, respectively. ASCE/SEI 7 (2016) was used to determine the loads acting through the buildings, assuming the building is used as a commercial building. For both low-rise and medium-rise buildings, a total of 32 models were generated, representing both regular and irregular building forms. Each irregular structure model was configured to examine which one most significantly influences the structure's reaction to seismic forces. The floor plan and 3D model of the low- and medium-rise regular buildings, considered as reference structures, are given in Figures 1 and 2. The elevation views of the low- and medium-rise irregular frames, which exhibit strength and stiffness irregularities due to missing beams, are presented in Figures 3 and 4, respectively. Additionally, the elevation views of the three-story and seven-story framed structures, which exhibit strength/stiffness irregularities formed by missing columns, are displayed in Figures 5 and 6, respectively. The locations of the missing beams and columns were selected from the bottom, middle, and top story levels of the buildings to illustrate their effects. For this, example cases were selected. In the low-rise structure, the absence of beams in the first and second stories was considered. In the medium-rise structure, the absence of beams was considered in the first, fourth, and sixth stories. Single and double missing column cases in the first and third stories of the low-rise buildings, as well as in the first, fourth, and seventh stories of the medium-rise buildings, were taken into account. The investigated three-story and seven-story structures, which exhibit mass irregularity and vertical geometric irregularity (setbacks), are presented in Figures 7 through 10. In the cases of mass irregularity exemplified, for the low-rise and medium-rise buildings, the masses at the first and third floor levels were increased. In contrast, the masses at the first, third, fifth, and seventh floor levels were increased by four times the masses at the other floor levels. As seen from these figures, the low-rise buildings with strength/stiffness irregularity caused by a missing beam are denoted as BL, whereas the medium-rise ones are indicated as BM. Similarly, low-rise irregular buildings with strength or stiffness irregularity due to missing columns are denoted as CL, while CM indicates medium-rise ones. For buildings with mass irregularity, ML and MM are used to indicate the low- and medium-rise frames, respectively. On the other hand, irregular buildings with setbacks (vertical geometric irregularity) are represented by SL and SM for the three-story and seven-story structures, respectively.

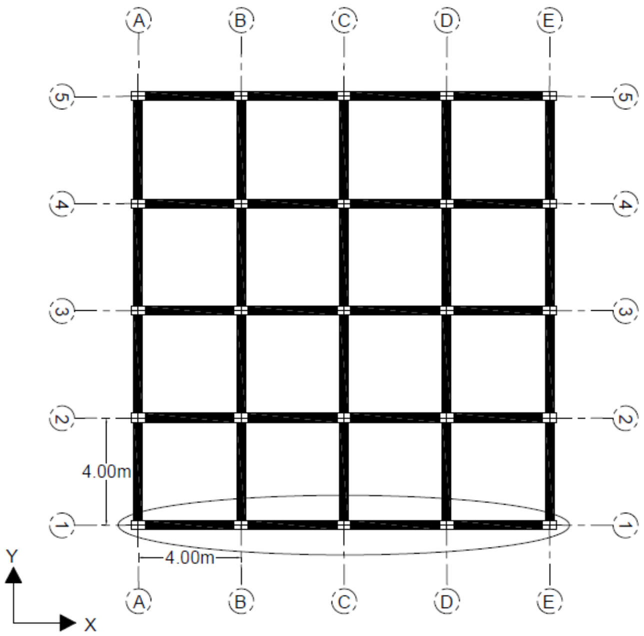


Figure 1. Floor Plan of Regular Buildings

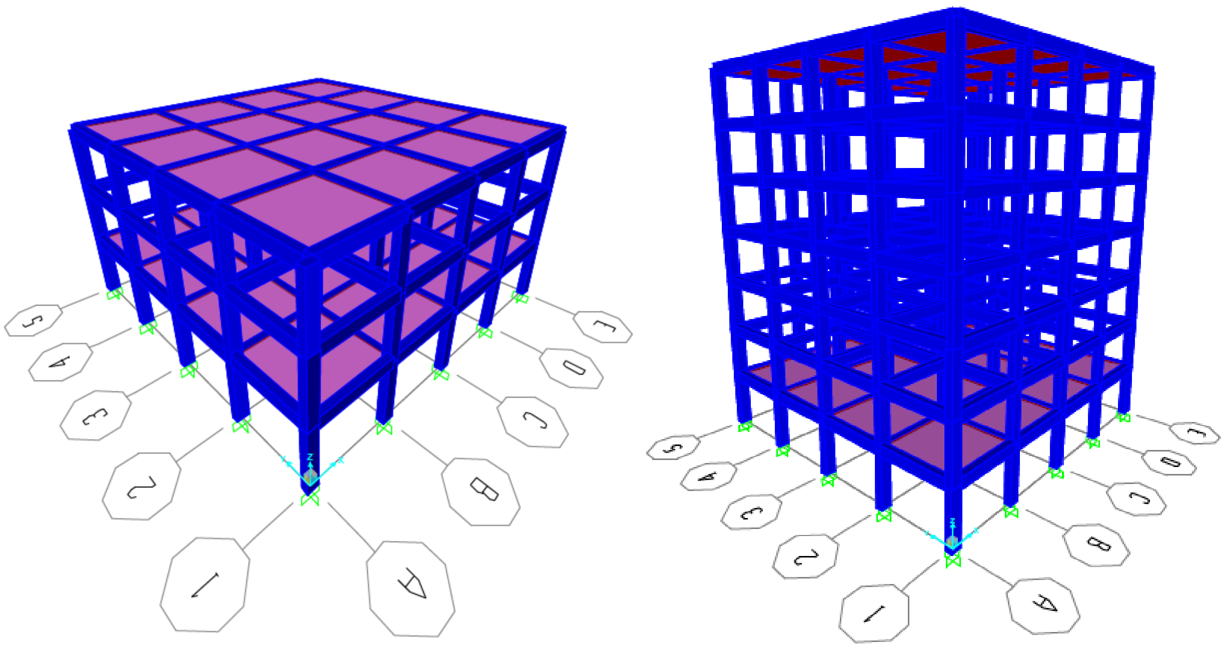


Figure 2. 3D Model of Low and Medium-Rise Regular Buildings

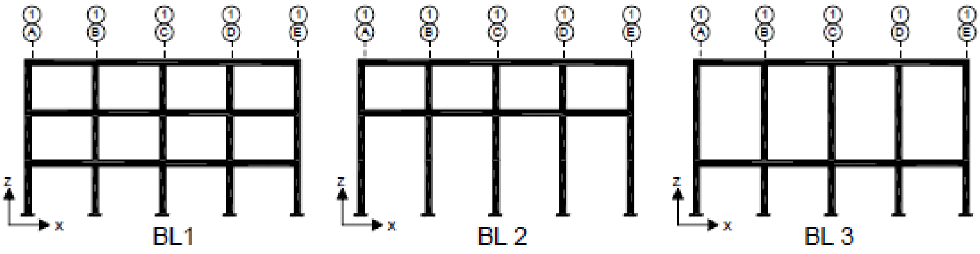


Figure 3. Low-Rise Frames with Strength/Stiffness Irregularity (Missing Beam)

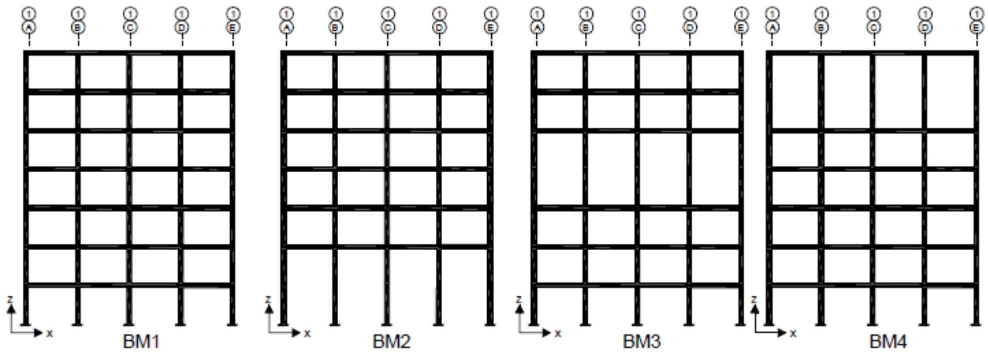


Figure 4. Medium-Rise Frames with Strength/Stiffness Irregularity (Missing Beam)

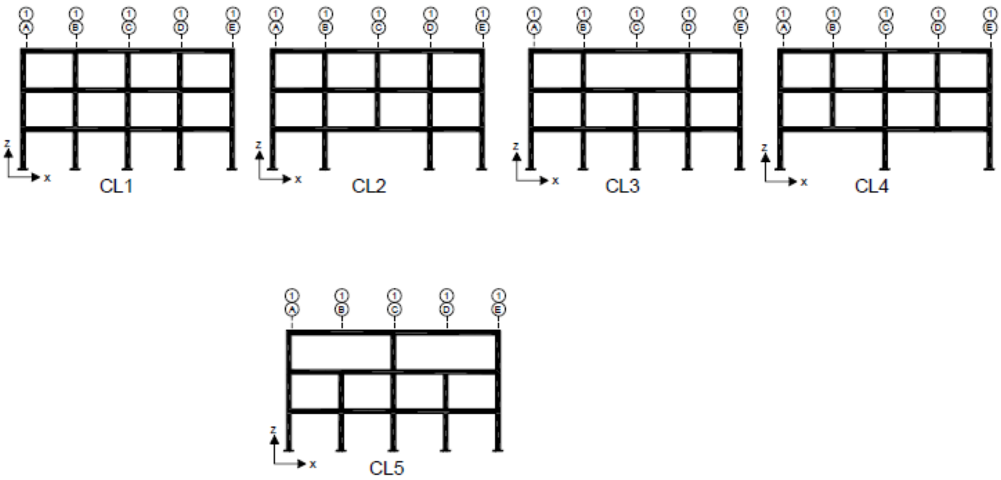


Figure 5. Low-Rise Frames with Strength/Stiffness Irregularity (Missing Column)

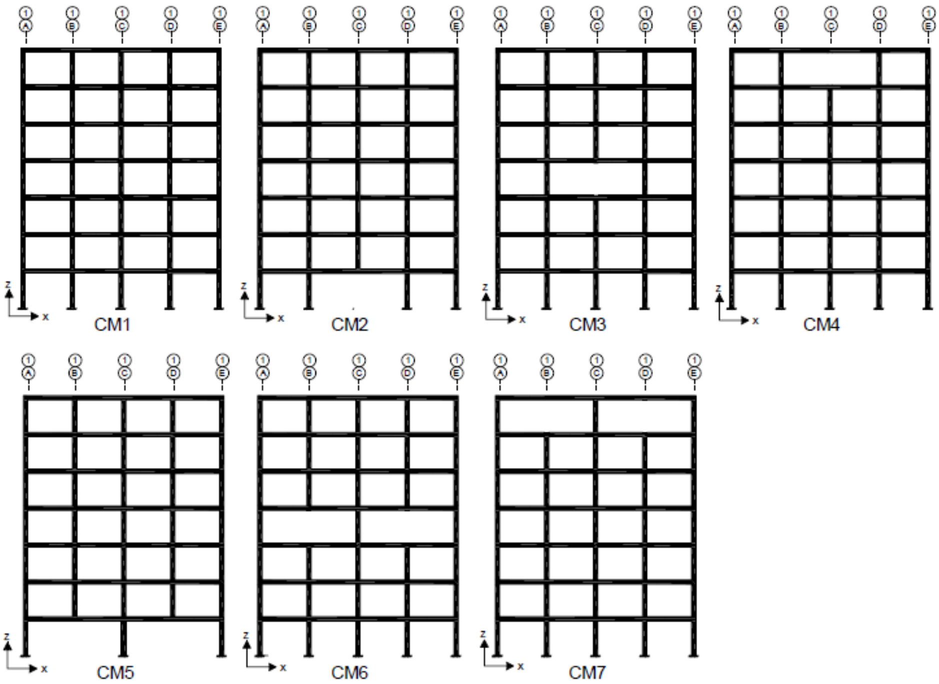


Figure 6. Medium-Rise Frames with Strength/Stiffness Irregularity (Missing Column)

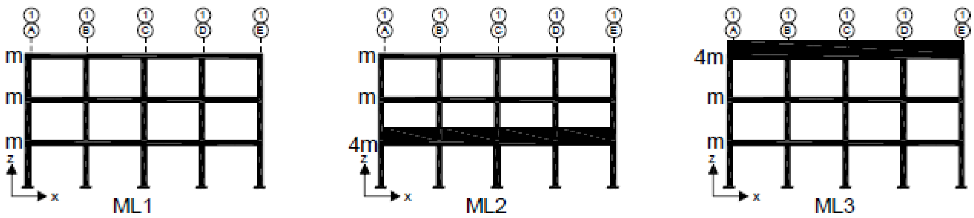


Figure 7. Low-Rise Frames with Mass Irregularity

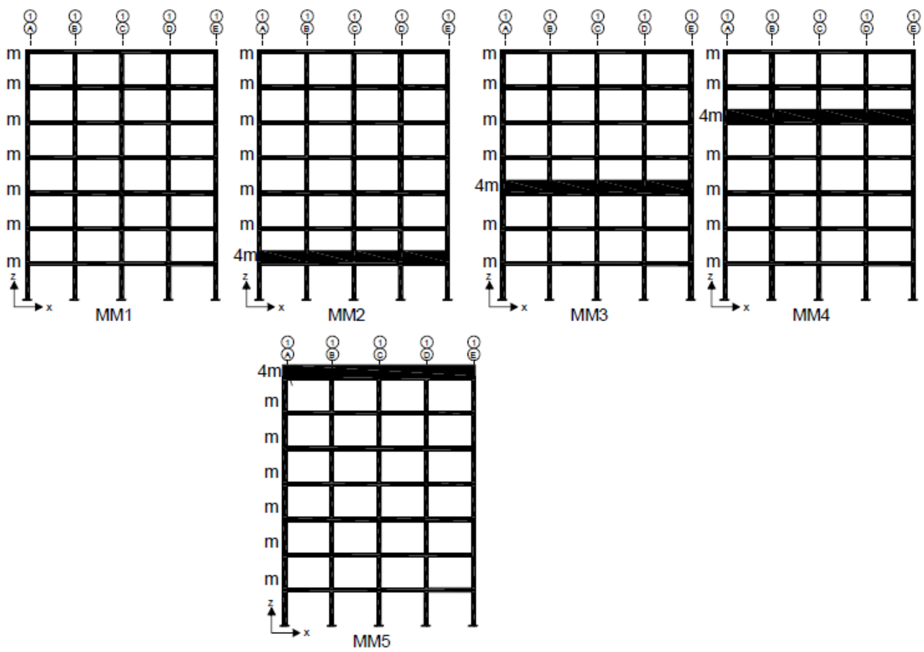


Figure 8. Medium-Rise Frames with Mass Irregularity

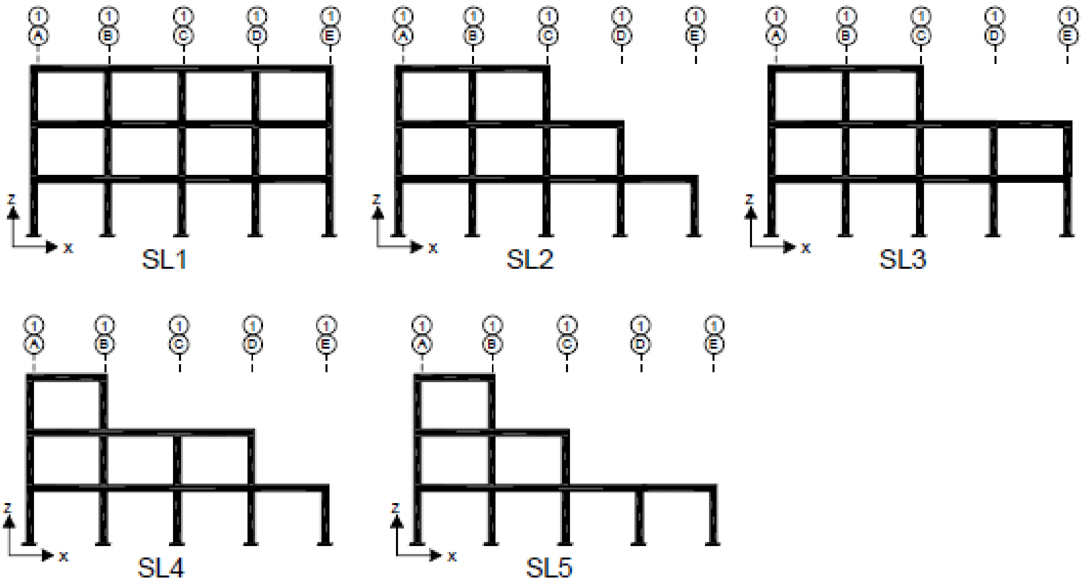


Figure 9. Low-Rise Vertical Geometric Irregular Setback Frames

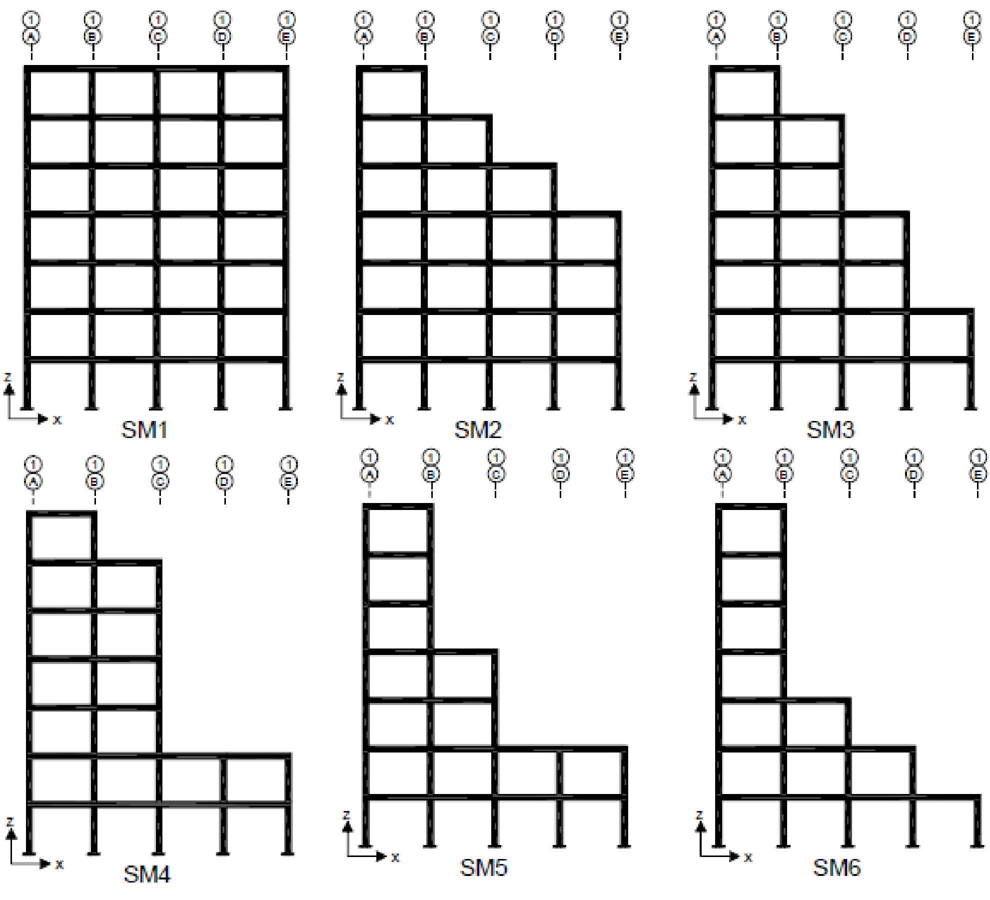


Figure 10. Medium-Rise Vertical Geometric Irregular Setback Frames

NONLINEAR ANALYSIS METHOD

To determine the effect of vertical irregularity on the seismic demand of the studied RC frames, a nonlinear pushover analysis was conducted using the SAP 2000 finite element program. This analysis is a preferred method for evaluating the seismic response of low- to medium-rise buildings. In this method, by exposing a structure to a pattern of monotonically increasing lateral forces, the inertial forces and displacement demands that the structure would experience when subjected to ground shaking can be simulated. In this study, firstly, gravity loading was applied, and then, based on the first mode of the building, lateral loads were imposed and incrementally increased up to failure.

In addition to the elastic behavior, the plastic behavior of the structural members was considered for the occurrence at possible specific locations defined as plastic hinges in the analytical models. Thus, elastic behavior occurs across the length of the structural members, whereas the hinges defined in the model specifically and separately, completely deform beyond the elastic limit. The integration of plastic strain and plastic curvature, which occurred within a specific hinge length, typically at the order of member depth, represented the inelastic behavior. A chain of hinges was developed to describe the plasticity dispersed along the member length. Additionally, different hinges were defined at the same member based on the types of internal forces that occur on these members. Plasticity was associated with moment-rotation for torsion and bending, while it was related to force-displacement behaviors for axial and shear forces. In this study, hysteretic relations of plastic hinges, as defined according to FEMA 356 (2000), were used at both ends of the column and beam components to account for nonlinearity. Axial force and biaxial moment hinges (PMM) were taken into consideration for the column members, while flexural moment hinges (M3) were taken into consideration for the beams.

Another crucial aspect in the nonlinear static analysis that is utilized to consider the ductility of the structural components comes from the correct and detailed definition of the material models. When modeling beam and column elements, their actions are governed by deformation; the simplified force-deformation model depicted in Figure 11 was utilized (Barros et al., 2014; Bento et al., 2004). The load-deformation curve's initial line, indicated as AB, shows a linear response for a structural member, reaching its yield capacity at point B. The following part of the curve, BC, indicates some hardening capacity for the member, having typically low inclination, ranging from 0% to 10% of the elastic part's slope AB value. The CD part shows the decrease in resistive ability, while the DE part denotes the plasticization. For both primary (P) and secondary (S) structural members, the criteria for acceptable deformation could be determined as given in Figure 11. As seen in the figure, three performance levels were defined: immediate occupancy (IO) for the structure's utility and serviceability, life safety (LS) for life preservation, and collapse prevention (CP). These were defined according to FEMA-356 (2000).

As mentioned above, the nonlinear behavior, defined by the plastic hinge characteristics of the structural elements, was taken into account based on the component type and failure mechanism, as outlined in FEMA 356 (2000). In the pushover analysis, firstly, constant gravity loads are applied and kept on the structure. Secondly, the lateral loads were used based on an assumed pattern determined in general according to the first mode of vibration. Due to the increased lateral loads, the structural members could behave beyond the elastic range, and the observed elastic and inelastic deformations also progressed. A total base shear versus roof level displacement curve, also known as a capacity curve, was obtained. This curve illustrates the loss of rigidity, the potential early failure, and the deformation demand expected under seismic effects. (Fardis et al., 2015). Therefore, from the analysis, the nonlinear behavior in terms of plastic rotation observed in the structural members under progressively increasing lateral loads was evaluated, and the capacity curves of regular and irregular frame buildings with different types of vertical irregularities were obtained.

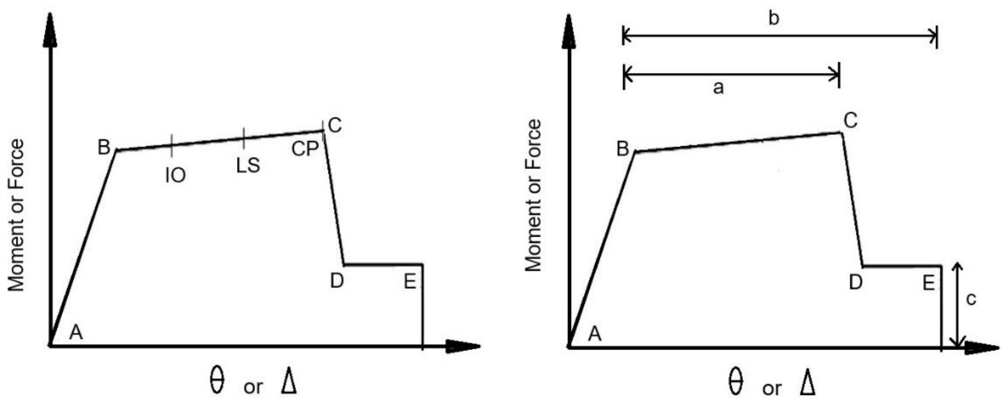
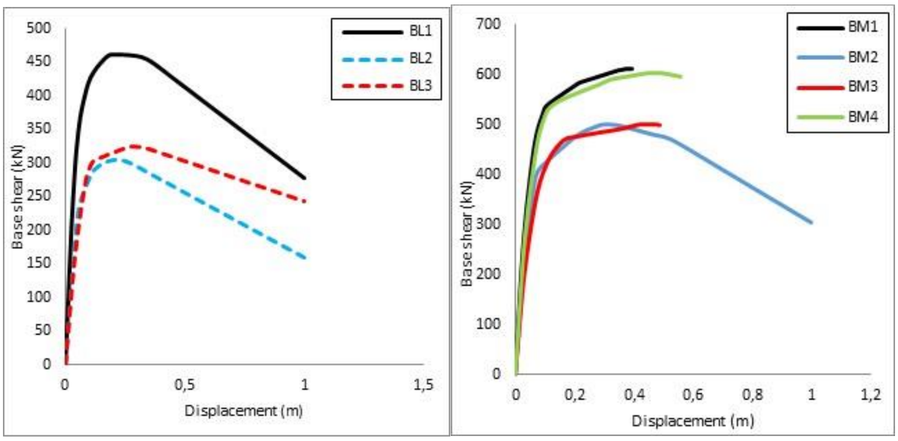


Figure 11. Inelastic Behavior Model Used for the Structural Elements (FEMA 356, 2000)

RESULTS AND DISCUSSION

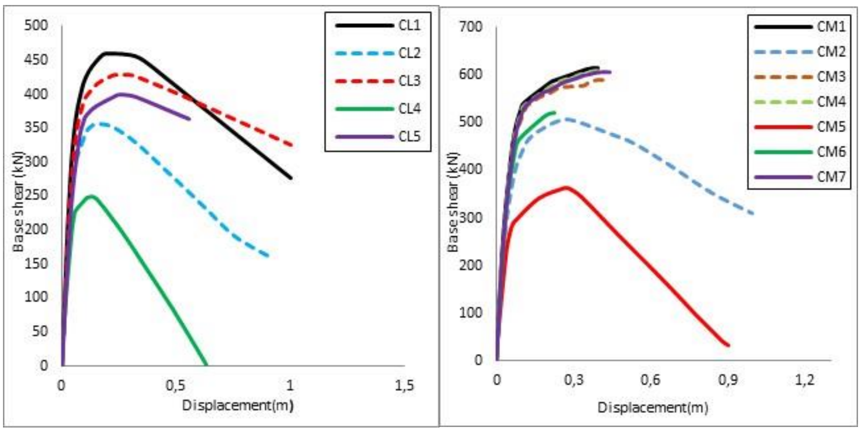
In the current study, low-rise and medium-rise buildings having vertical irregularities such as irregularity in mass, geometry (setbacks), strength/stiffness; totally 32 different cases were analyzed by the application of nonlinear static analysis methodology and the results of the analyses were compared to elaborate the impacts of various kinds of vertical irregularities on the seismic behavior of the case studied buildings.

Pushover curves for the frames with strength and stiffness irregularities due to missing beams are illustrated in Figure 12. As seen from this figure, the regular frame BL1's maximum base shear was approximately 450 kN, whereas for the irregular buildings BL2 and BL3, this value reached approximately 300 kN and 325 kN, respectively. When medium-rise structures were compared, the regular frame BM1 had a base shear up to about 620 kN, whereas the irregular frames BM2, BM3, and BM4 had base shears reaching up to 520, 500, and 600 kN, respectively. Additionally, the behavior in stiffness seemed to be similar to that of the base shear, which means that the regular 3-story and 7-story frames, namely BL1 and BM1, had greater stiffness than the irregular frames. As seen in Figure 12, the low-rise and medium-rise case studied frames had nearly equal strength and stiffness up to 200 kN and 350 kN, respectively. After those points, differences among the case study frames become evident, which comes from the differences in the nonlinear behavior of the frames. Additionally, due to the missing beam located in a lower story, in BL2 and BM2, the frames' strength and stiffness are significantly lower than those found in BL3 and BM3, which have missing beams in the upper stories.



(a) (b)

Figure 12. Capacity Curves of Case Studied a) 3-Story and b) 7-Story Buildings Having Strength and Stiffness Irregularity Due to Discontinuous Beams

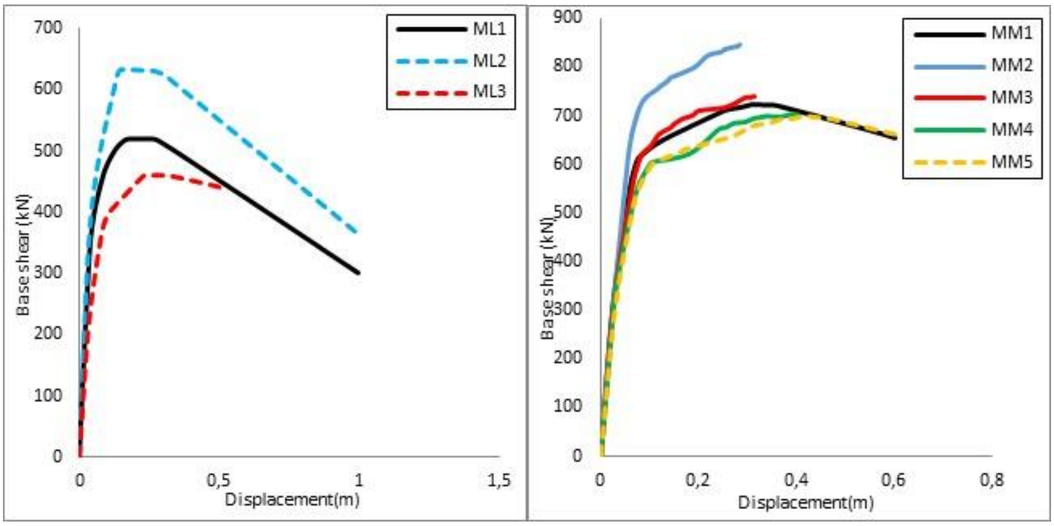


(a) (b)

Figure 13. Capacity Curves of Case Studied a) 3-Story and b) 7-Story Buildings Having Strength and Stiffness Irregularity Due to Discontinuous Columns

Figure 13 displays the lateral load carrying capacity of the frames with strength and stiffness irregularity because of the discontinuous column cases, similar to the previous strength and stiffness irregularity because of the missing beam cases, it was revealed that the base shear capacity of regular frames CL1 and CM1 were higher than that of the irregular frames.

Figure 14 illustrates the lateral load-carrying capacity of the case study mass irregularity frames. As realized from the figure, the base shear capacity of the irregular low-rise frame having mass irregularity, as in the case of ML2, is greater than that of the regular and the other irregular cases in mass. On the other hand, among the medium-rise frames having mass irregularity, the lateral load capacity of MM2 and MM3 irregular frames is higher than that of the regular and the other irregular cases in mass. It was noted that the peak base shear occurred in the low-rise buildings designated as ML2, which was approximately 630 kN; in contrast, for medium-rise buildings, it was observed in MM2, which was about 850 kN. It is worth noting that for cases MM2 and MM3, after the peak capacity for the base shear was reached, the frames also lost their deformation capacity. On the other hand, among the medium-rise frames, MM1, MM4, and MM5, which are the case-study frames, the low-rise frames, ML2 and ML3, display a more ductile behavior.



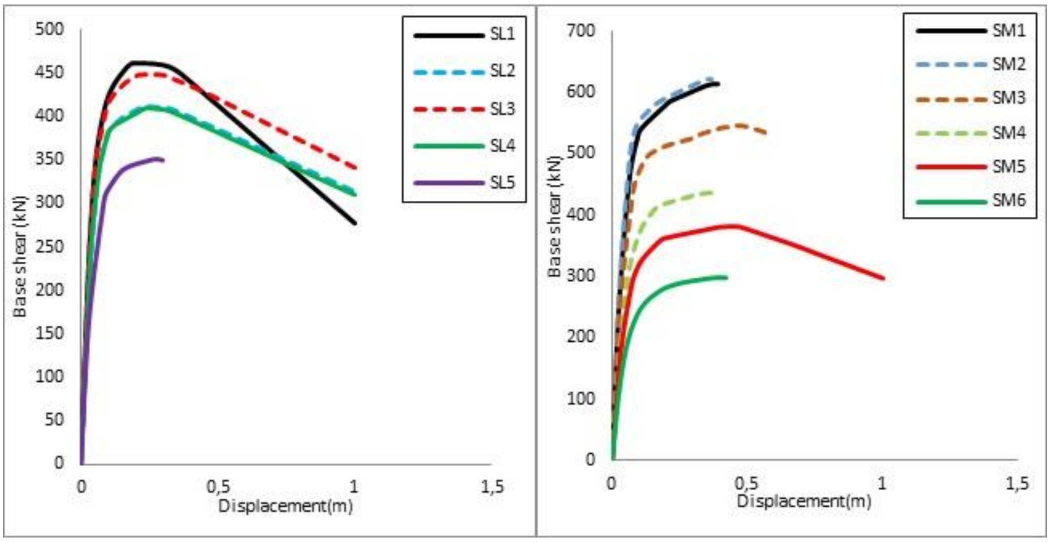
(a) (b)

Figure 14. Capacity Curves of Case Studied a) 3-Story and b) 7-Story Buildings Having Mass Irregularity

Figure 15 demonstrates that for the vertical geometric irregularity-setback frames, the stiffness values for all cases are relatively close to each other until the base shear reaches 200 kN and 150 kN for the 3-story and 7-story frames, respectively. After considering these points, the variation in stiffness and the difference in their nonlinear behavior become obvious. The regular cases generally had a greater load capacity than the irregular ones, except for the cases of SM2 and SL3, which were almost the same as the regular ones. Among the frames with vertical geometry irregularity, as the ratio of the setback increases, both the lateral load-carrying capacity and the stiffness of the frames decrease, indicating that SL5 and SM6 had the lowest lateral load capacity among the low- and medium-rise frames, respectively.

For all case study buildings, the nonlinear behavior observed at the end of the pushover analysis is presented in Figures 16 to 23, which show the deformed shapes and plastic hinges formed during the last step of the pushover analysis, based on the FEMA 356 performance limit state definition. It is worthy to note that in these figures, there isn't plastic deformation till point B, where the hinge comes to the yield point, point C indicates the ultimate capacity, point D shows the residual strength and point E denotes the peak displacement capacity of the hinge afterward getting the total failure (Pambhar, 2012). At each deformation step of the pushover analysis, the location of the hinges and their plastic rotation in the elements, as well as the performance limit state of the hinges defined based on FEMA 356, which are IO, LS, and CP, can be identified by color alteration.

The distribution of plastic hinges in the final stage for the three-story buildings, BL1, BL2, and BL3, is shown in Figure 16. The graphic shows that in the situations of BL1 and BL3, the building reaches a collapsed state not only in the columns but also in the beams. Nevertheless, in the case of BL2, it only reaches a collapsed state in the columns. Only the first-floor beams came to the collapse point in instance BL1, while both the first and second-story columns went to the same point. However, in the case of BL3, the column and beam elements at that story receive a collapse prevention level since the second-story beam elements have not been available. In other situations, because the second-floor beams support a relatively normal load, they are at the Immediate Occupancy performance level. The regular building reached a state of collapse due to the formation of nonlinear behavior in the first and second-story columns, as well as the first-story beams, which had the most significant capacity among all. In the irregular building BL2, with the absence of the first-story beams, it was observed that the building reached its capacity with the formation of the hinges in the columns of the first and second stories. In the case of BL3, a behavior closer to the regular one, characterized by nonlinear behavior at the first-story beams, was observed. However, due to the missing beams, the nonlinear behavior shifted to the third-story columns.



(a) (b)

Figure 15. Pushover Curves of Case Studied a) 3-Story and b) 7-Story Frames Having Vertical Geometry Irregularity-Setback

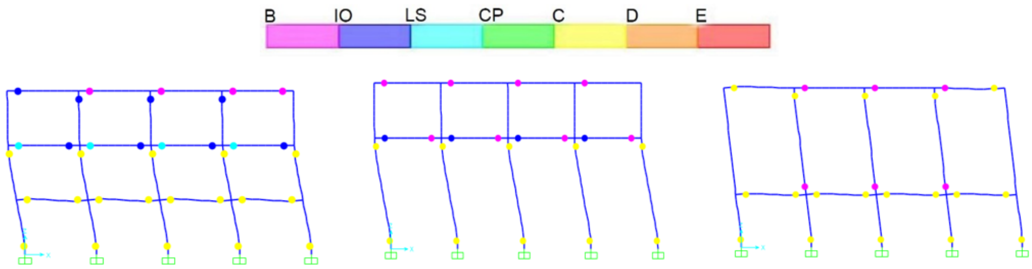


Figure 16. Plastic Hinge Formation for Low-Rise Frames with Strength/Stiffness Irregularity Due to Missing Beam

Based on the outcomes displayed in Figure 17, except for BM2, where the first-story beams do not exist, the beams of the first three stories reached failure. In all the case study buildings, some or all of the ground floor columns reached a state of collapse, while for BM, three more columns on the third floor also reached a state of collapse. Since the fourth floor's beams have been removed, the columns must support a greater load than in the regular case, which results in a higher deformation demand for them. However, the structure is not significantly impacted by the removal of the beams on the sixth story. Additionally, the higher floor beams and columns have an immediate occupancy limit state, are in a safe condition, or have just reached yield.

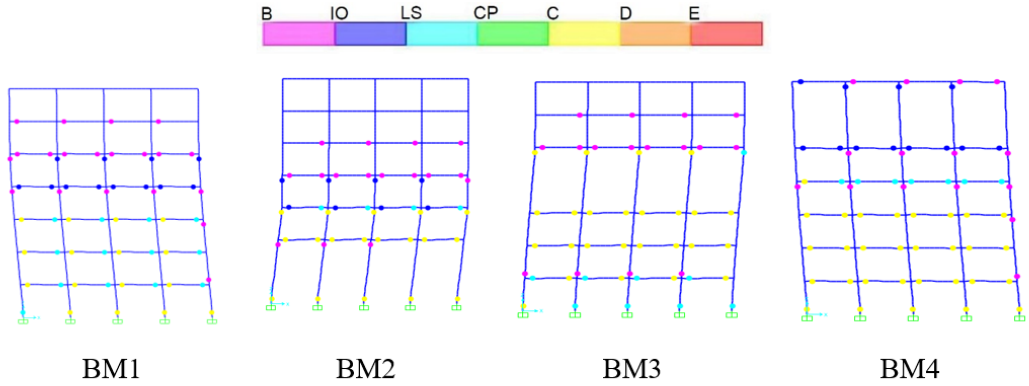


Figure 17. Plastic Hinge Formation for Medium-Rise Frames with Strength/Stiffness Irregularity Due to Missing Beam

In the case of the ground story, beam elements achieve their maximum deformation capacity. CL4 is the worst scenario, as indicated by the formation of plastic hinges, as shown in Figure 18. This occurs as a result of the removal of ground-level columns, which necessitates that beams transfer their weight to nearby columns, and existing columns must carry a greater amount of lateral loads. Additionally, as a result, the collapse prevention state is seen for every column on that floor. Although the beam elements adjacent to the missing column undergo the maximum deformation, the irregular frame CL2 poses fewer risks compared to the irregular frame CL4. There are varying amounts at various locations, ranging from the yield point to collapse prevention performance states, in the remaining CL1, CL3, and CL5 cases.

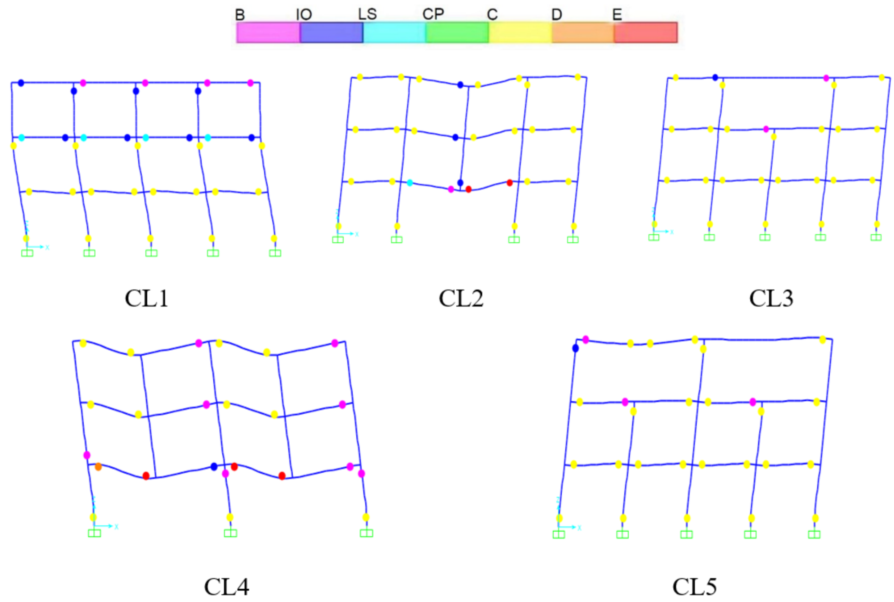


Figure 18. Plastic Hinge Formation for Low-Rise Frames with Strength/Stiffness Irregularity Due to Missing Column

As observed in Figure 19, the removal of ground floor columns in the irregular building of CM5 requires the beam elements to transfer their loads to the neighboring columns, which are then subjected to a greater amount of both gravity and lateral loads. In addition to this, since the ground floor beams reach their maximum displacement capacity at many points and the collapse level was reached by the columns on that floor, among the irregular buildings with missing columns, CM5 becomes the worst-case scenario. Although the beams adjacent to the discontinuous column achieve the ultimate capacity for displacement, the irregular case CM2 appears to be better than the irregular case CM5, as it requires a smaller number of points to reach failure. Different performance levels, ranging from yield to collapse prevention states at various locations within the structural members, were observed in other irregularly designed case study buildings, designated as CM1, CM3, CM6, and CM7.

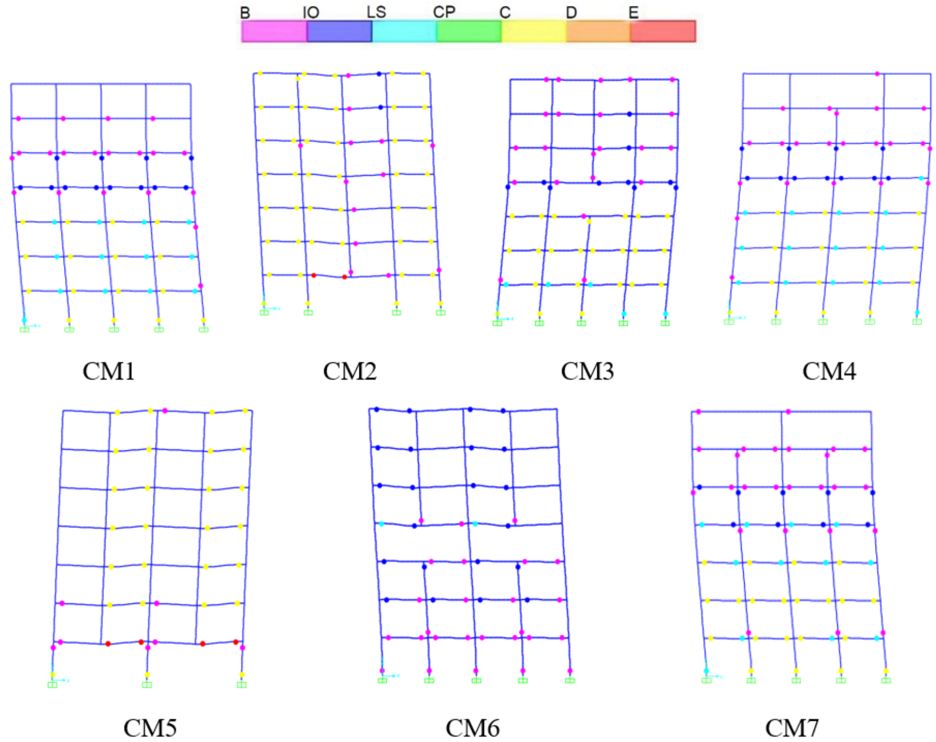


Figure 19. Plastic Hinge Formation for Medium-Rise Frames with Strength/Stiffness Irregularity Due to Missing Column

Figure 20 reveals that there is little difference in the failure behavior of the ML1 and ML2 buildings, indicating that the greater mass at the first floor has a slight effect on the deformed shape at the final stage. However, when a greater mass was applied on the second floor, its impact was evident throughout the entire structure, as indicated by a larger number of members; nearly every floor's columns and beams reached a state of collapse prevention.

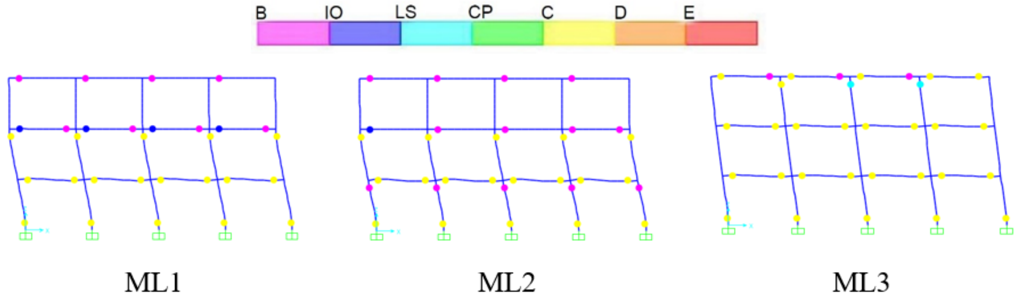


Figure 20. Plastic Hinge Formation for Low-Rise Frames with Strength/Stiffness Irregularity Due to Mass Irregularity

For medium-rise buildings similar to low-rise ones, many of the beam and column members beneath the greater mass were subjected to collapse prevention. At the same time, some were also required to meet life safety performance standards, as shown in Figure 21. On the other hand, for the beam and column members above the heavy mass level, generally yield and immediate occupancy states were experienced, indicating that the excessive weight has a slight impact on the structural parts above. Figures 22 and 23 illustrate the variation in the distribution of plastic hinges for regular and irregular buildings with vertical geometry-setback, respectively, for 3-story and 7-story buildings. Based on these figures, it was noted that the uneven geometry primarily affects the beam elements rather than the column elements. Most of the beams achieve a collapse prevention level in the irregular buildings, except for SL5 and SM4, which have fewer beams in the collapse prevention limit state.

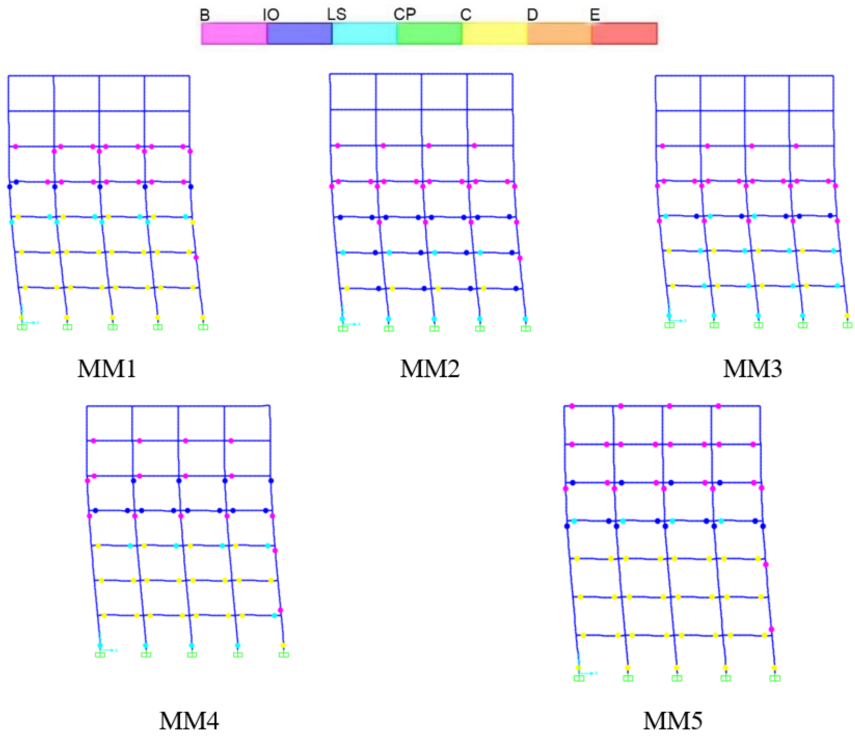


Figure 21. Plastic Hinge Formation for Medium-Rise Frames with Mass Irregularity

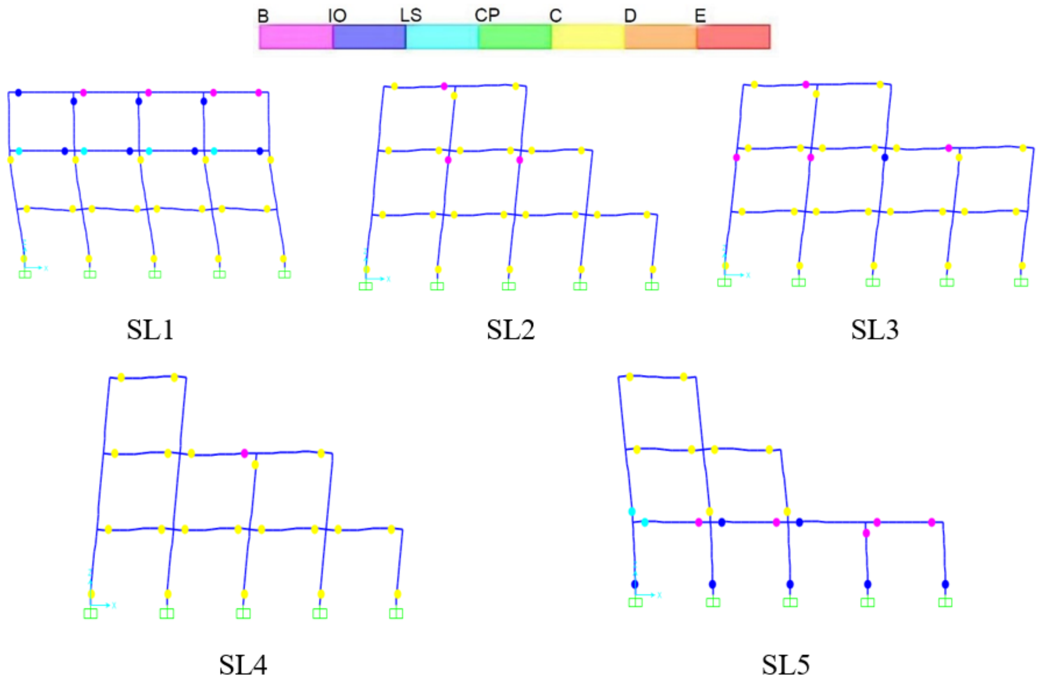


Figure 22. Plastic Hinge Formation for Low-Rise Frames Having Vertical Geometry Irregularity Due to Setback

For the strength and stiffness of irregular buildings with missing columns, the variation of axial force in the columns was investigated. For this purpose, the axial internal forces in the central and side columns of three- and seven-story irregular reinforced concrete (RC) buildings were compared. These values were taken from the nonlinear static analysis results. According to the findings presented in Figure 24(a), for the case studied, the absence of a middle column has almost no effect on the axial force of the side column for buildings of CL2 and CL3. It was observed that the axial force in the side columns of the CL1, CL2, and CL3 case studied buildings varied from approximately 230 kN to 80 kN from the first through the third story. Since the side column in CL4 had to support the axial force of the discontinuous column, the axial internal force in that column peaked on the first floor. Furthermore, among the other investigated buildings in CL5, the axial force value in the side column is the greatest on the third floor, as the missing column is located on that floor. Figure 24(b) reveals that in CL2 and CL3, the middle column axial forces were lower than the usual frame axial internal forces due to the absence of the column. However, since the middle column should support the missing columns' axial force, the axial internal force was recorded as the maximum in CL4 and CL5 situations. In CL4, once the discontinuous column was on the first story, the axial force increased quickly from the third to the first floor column; however, in CL5, once the missing column was on the third story, the axial internal force rose slightly as compared to CL4. In CL2, in the first story, the column axial force was zero because there was no column on the first floor of the building. Since there wasn't a column to support the force, it was evident that the first floor's axial force, like in CL2, was observed to be zero.

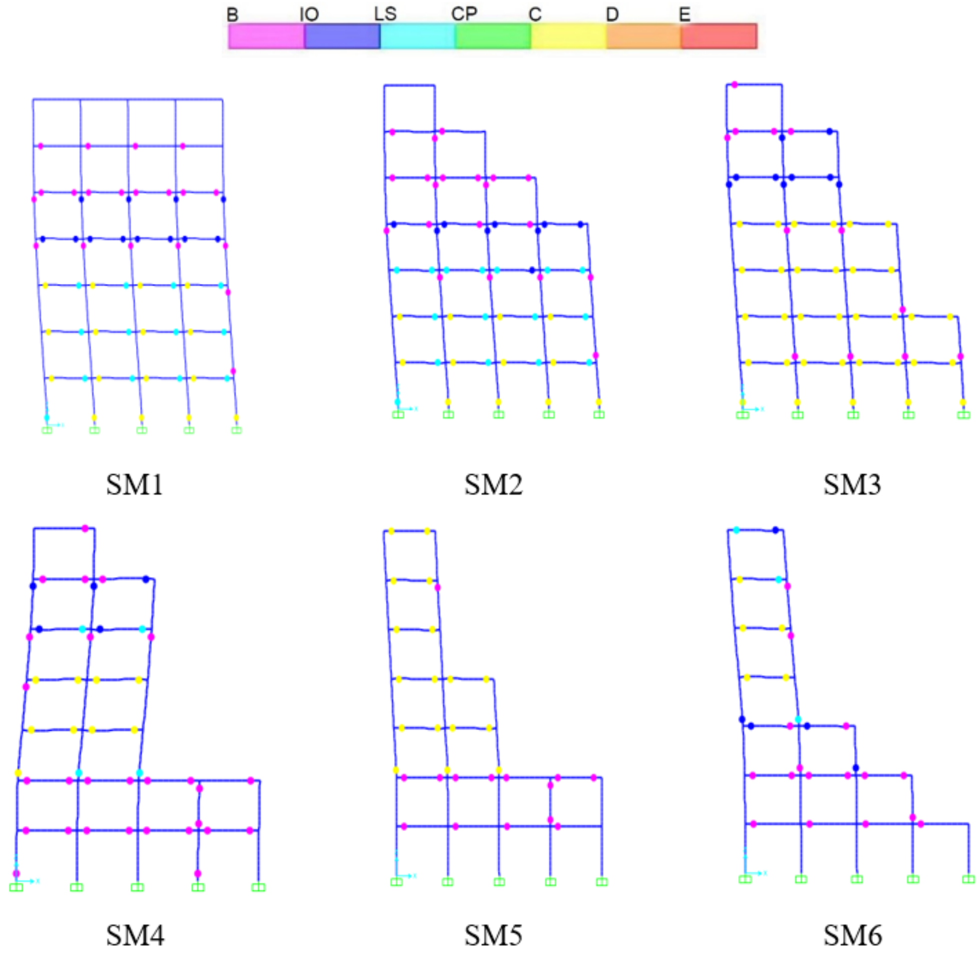
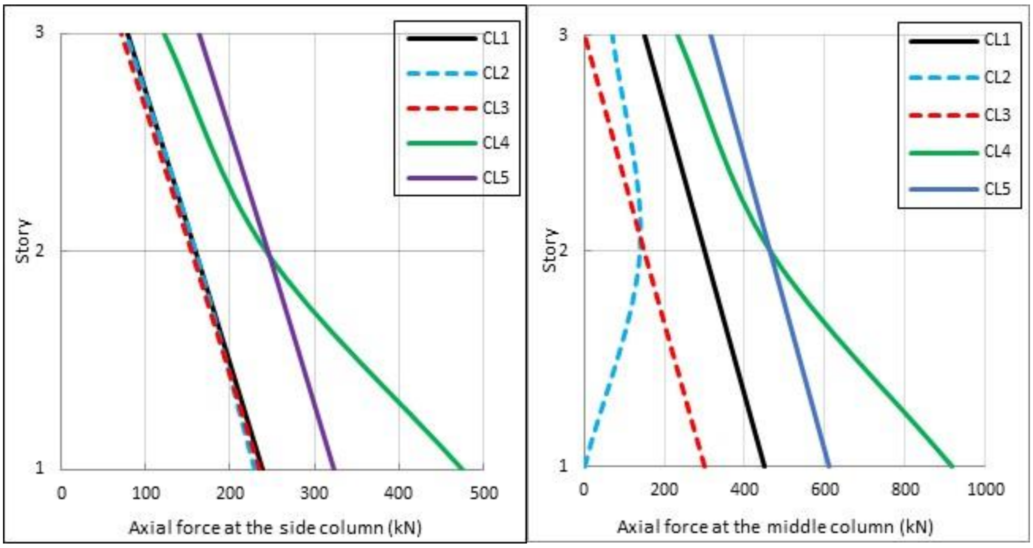


Figure 23. Plastic Hinge Formation for Medium-Rise Frames Having Vertical Geometry Irregularity Due to Setback

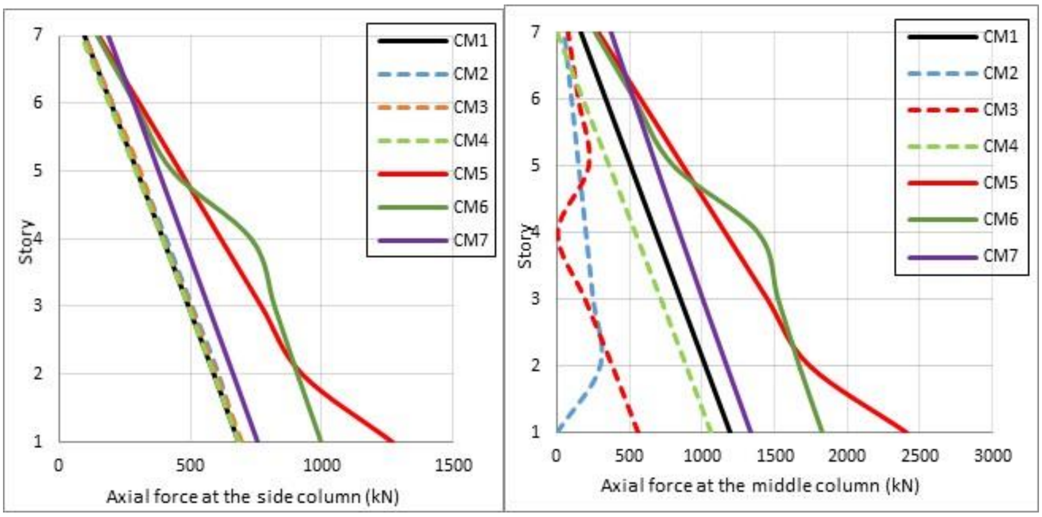
In the case of CM2, CM3, and CM4, the middle missing column didn't alter the side column axial force as shown in Figure 25(a). It was noted that the axial force applied to the side columns did not affect the middle one. Thus, from the seventh to the first level, for instance, the axial force for the case of CM1, CM2, CM3, and CM4 dropped linearly. Since the side column on the first floor should support the missing columns' axial force, it reached its maximum in the irregular frame CM5 once the discontinuous column was not the middle one. Furthermore, the axial force grew linearly from the third floor to the first floor, but it was larger when the missing column was in the middle column on the fourth floor. The axial force positively varied from the seventh story to the first story if the discontinuous column was in the middle.



(a) side column (b) middle column

Figure 24. Plotting of Axial Forces at the Side and Middle Columns of the 3-Story Frame with a Missing Column

Since there wasn't a column to support the force, it was clear from the result curves given in Figure 25(b) that the internal axial forces of the cases CM3 on the third level and CM2 on the first floor were zero. For the scenario of CM7, where the missing column was in the center of the seventh floor, the axial force grew directly from the seventh story to the first story column; whereas, for scenario CM5, where the discontinuous column was in the first story, the axial force increased quickly. Additionally, when there was a discontinuous column in the middle of CM2, CM3, and CM4, the internal axial force of the middle column was lower than that of the usual frame. However, as the intermediate column should transmit the axial force of the missing columns, the axial force was the maximum in the other irregular frames, namely, CM5, CM6, and CM7.



(a) side column (b) middle column

Figure 25. Plotting of Axial Forces at the Side and Middle Columns of the 7-Story Frame with a Missing Column

CONCLUSIONS

The seismic response of reinforced concrete (RC) buildings with varying vertical irregularities was investigated. From the findings of this investigation, the following conclusions could be obtained:

- It was observed that in the presence of vertical irregularity, the seismic response of both low-rise and medium-rise RC buildings was negatively influenced. However, the degree of this effect depended mainly on the type of vertical irregularity existing in the structures.

- The vertical irregularity and the corresponding base shear capacity of the building had a reverse relationship. The base shear of the building generally diminished when the degree of irregularity increased. Accordingly, the lateral seismic capacity of the building is reduced. This issue needs to be considered in the design of structures with irregular elevations.
- The seismic demand of the building was observed to be related to the existence of vertical regularity. The strength and displacement capacity of irregular buildings was observed to be considerably different from that of regular ones. The type and degree of irregularity that occurred in the building are the primary focus of this response.
- The energy absorption capacity of irregular buildings was mainly lower than that of the regular ones, especially for low-rise cases with the strength/stiffness irregularity due to the missing beam and column.
- It was pointed out that both low-rise and medium-rise buildings with the strength/stiffness irregularity (missing column) yielded adverse results as compared to the buildings with other types of vertical irregularities of strength and stiffness due to missing beam, mass, and geometry due to setbacks.
- For most cases, the stiffness and strength of low-rise and medium-rise regular buildings were considerably higher than that of irregular buildings, irrespective of the type of vertical irregularity.
- For the case of strength and stiffness irregularity in buildings due to missing columns, the absence of columns in the buildings had a vital effect, irrespective of the number of stories of the buildings. Moreover, the location of the missing columns, especially from which story they were removed, influenced the axial force distribution in the other column members and also the plastic hinge formations observed in these irregular buildings.

RECOMMENDATIONS FOR FUTURE RESEARCH

In this study, the results of nonlinear static analysis, focusing on the differences between regular and vertically irregular buildings, were investigated. The vertical irregularities, strength/stiffness irregularities due to missing columns and beams, irregularities in mass, and geometric setbacks were considered. The effect of varying the location of vertical irregularity over the building height was considered. Thus, based on different types of vertical irregularities, their varying degrees and distributions, a total of thirty-two buildings were examined comparatively. However, as a further research, to be able to draw more general conclusions, considering different seismic demands and different soil conditions, performance points for each type of building could be determined; their performance states at these performance points could be comparatively analyzed, the types of the buildings, the variation in the location of the irregularities, could be increased. By using earthquake accelerations determined for various seismic demands, time-history analysis could be conducted.

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