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Seismic analysis of RC building frames with vertical mass and stiffness irregularities using adaptive pushover analysis

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Abstract: Irregular multistory buildings constitute a large part of modern urban infrastructure due to architectural aesthetics and functional requirements. In contrast, their behavior during recent major earthquakes indicated that severe structural damage was observed due to non-uniform distributions of mass, stiffness and strength either in plan or in elevation. Notably, abrupt changes in these quantities between adjacent stories are always associated with changes in the structural system along the height of the building. The present study investigates the inelastic response of RC buildings with mass and stiffness irregularities subjected to earthquake action. Thus, the displacement-based adaptive pushover method is used. This latter is motivated by the application of a lateral displacement pattern obtained by combining different mode shapes and updated incrementally at each analysis step. For this purpose, a ten-story regular frame structure is chosen and modified by incorporating vertical irregularities in various forms in order to estimate and quantify essential parameters' responses. The results obtained are discussed under the following headings: base shear forces, roof displacement, inter-story drift and story-shear distribution. With respect to the vertical mass and stiffness irregularities, it was noticed that the seismic response is more significantly influenced by stiffness irregularities compared to mass irregularities, which were found to have a slight impact on the seismic behavior of the building. It is also established that the simple procedure allows the evaluation of design forces and displacements in a more rational manner, in accordance with the current state of knowledge and modern trends in building codes. The results conclude, however, that the irregular structure cannot meet the seismic design requirements and must be constructed to minimize seismic effects.

Keywords: Seismic, adaptive pushover analysis, irregular structure, mass irregularity, stiffness irregularity.

1. Introduction

In the past, several major earthquakes have revealed many imperfections in buildings, leading to severe and sudden collapse. It became consequently quite clear that buildings of regular shape perform better in high earthquake areas. Some of them are heavily damaged due to the presence of vertical irregularities in various forms in elevation or in plan of the structure (Das & Nau, 2003; Dutta and Das, 2002; Caruso, Bento & Castro, 2018; Gunes et al., 2019).

Obviously, one of the common types of irregularity is the non-uniform distributions of mass, stiffness and strength, presented separately or in various combinations over the height of the structures. These vertical irregularities indeed have different impacts on behavioral seismic response. Practically speaking, a large amount of literatures has tackled this subject (Al-Ali & Krawinkler, 1998; Fragiadakis et al., 2006; Michalis et al., 2006; Özbayrak et al., 2021).

Despite the fact that analysis procedures for irregular multistory buildings are based on analytical and modal spectral analysis, the results exhibit that linear static procedures are insufficient in predicting the concentration of damage in structural members near the level of irregularity (Chang-Soo et al., 2021; Aboelhassan, 2021). Although Non-Linear Time History Analysis (NLTHA) has proven to be the most appropriate and reliable approach used to estimate this capacity, it tends to be too expensive computationally and too complex conceptually whenever used by practicing engineers (Aboelhassan, 2022). For practical application, a simplified procedure that is currently privileged for inelastic analysis is the nonlinear static pushover analysis (NSP), which combines the advantage of explicit treatment of yielding and inelastic deformations with the simplicity of static loading patterns (Aksoylu et al., 2020; Fajfar, 2000; FEMA-440, 2005; Hemsas et al., 2014; Tarabia et al., 2022; Çoşgun et al., 2022). Nevertheless, NSPs rely on the assumption that the response of a structure is controlled only by the fundamental mode. This assumption is not appropriate for irregular high-rise structures due to the contribution of higher vibration modes to the seismic responses. Accordingly, extensive research efforts have been devoted in recent years to developing enhanced nonlinear static (pushover) methods.

The latter takes into account the effects of higher modes and the influence of irregularities in the response of high-rise building structures. Among these methods, one can refer to the Modal Pushover Analysis (MPA) method, which incorporates the effects of higher modes (Chopra & Goel, 2002) as well as the extended N2-based method through the application of correction factors (Fajfar et al., 2005) and Eurocode-8 (2014). Incremental dynamic analysis (IDA) is also a parametric analysis method that has recently emerged in several different forms to more thoroughly examine structural performance under seismic loads. This approach involves subjecting a structural model to a set of ground motion records, each scaled to multiple levels of intensity, thus producing one (or more) curves of response parameterized versus intensity level (Gallegos et al., 2023). Furthermore, the unvarying shape of the applied loading vector stimulates the conventional (non-adaptive) pushover analysis, intending to conceal essential structural characteristics that lead to misleading results. These observations acknowledged the necessity for the development of recent methods such as displacement-based (adaptive) pushover analysis (DBAP). Thus, the applied lateral load is constantly updated, depending on the instantaneous dynamic features of the structure (Antoniou & Pinho, 2004).

The main objective of this particular research paper is to study the seismic response of vertically irregular structures using this advanced displacement-based adaptive pushover method (DBAP). In order to fulfill this purpose, a 10-story regular frame structure is chosen and modified by incorporating vertical mass and stiffness irregularities in various forms to estimate the response characteristics such as adaptive capacity curve, inter-story drift and story-shear distribution for this type of structures subjected to earthquake excitation.

2. Structural irregularities in buildings

In reality, many existing buildings were initially designed to be irregular to satisfy different functional or commercial requirements. To demonstrate, e.g., basements for commercial purposes are created by eliminating central columns as well as reducing beam and column sizes in the upper stories for functional usage. Recently, experimental and numerical studies proved that vertically irregular structures are unsafe and hazardous in seismic zones. Therefore, as far as possible, irregularities in a building must be avoided because of their unfavorable seismic behavior, as stated in almost all codes, such as the Algerian Seismic Code (RPA99, 2003). Noteworthy, when a building structure is subjected to lateral loads, the damage frequently initiates at the level of the structural weak zones present in the building systems. Obviously, many factors are at the origin of this structural weakness (or structural irregularity), which seriously affects the performance of buildings in the event of an earthquake.

Various types of irregularities appear in the buildings depending upon their location and scope; in contrast, they can be roughly classified into two basic groups: irregularities in plan and in elevation (Naresh et al., 2017). Irregularities in elevation that have significant physical discontinuities in a vertical direction include various types of structural irregularities, frequently encountered separately or in several combinations over the building height. These are Mass irregularity, Stiffness irregularity, Strength irregularity, vertical Geometric irregularity, and Discontinuity in capacity. The detailed classification of structural irregularity and Algerian code limits (RPA) is shown in Table 1.

The main framework of this paper is to study mainly the effect of Mass and Stiffness irregularities on the seismic response of a structure subjected to earthquake record.

Table 1. Definition of irregularity

	Type	Definition of irregularity
1	Vertical stiffness irregularity	Shall be considered to exist when the lateral stiffness of the SFRS in a story is less than 70% of the stiffness of any adjacent story, or less than 80% of the average stiffness of the three stories above or below.
2	Weight (mass) irregularity	Shall be considered to exist where the weight, Wi, of any story is more than 150 percent of the weight of an adjacent story.
3	Vertical geometric irregularity	Shall be considered to exist where the horizontal dimension of the SFRS in any story is more than 130 percent of that in an adjacent story.
4	In-plane discontinuity	An in-plane offset of a vertical lateral load-resisting element of the SFRS or a reduction in lateral stiffness of the resisting element in the story below.
5	Out-of-plane offsets	Discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements of the SFRS.
6	Discontinuity in capacity - weak story	A weak story is one in which the story shear strength is less than that in the story above. The story shear strength is the total strength of all seismic-resisting elements of the SFRS sharing the story shear for the direction under consideration.
7	Torsional sensitivity	To be considered when diaphragms are not flexible.
8	Non-orthogonal systems	Irregularity shall be considered to exist when the SFRS is not oriented along a set of orthogonal axes.

3. Reference regular building frame

This particular research paper aims to study the structural behavior of a reinforced concrete frame system composed uniquely of frames capable of carrying all the forces due to the vertical and horizontal loads. For this category, as per RPA99 regulation, the partition infill walls are considered non-structural elements and should not prevent the deformations of the frames (desolidarised or light infill or separation walls with connections not preventing the displacements of the frames). For the purpose of investigating the effect of selected vertical irregularities on the seismic responses of the building structures using DBAP method, an ordinary (regular) RC moment resisting frame was assumed as a reference structure without considering the effect of masonry infill panels on the response. Indeed, the structural frame ensures the bearing function, whereas the infill wall is not considered as a structural element and only serves to separate inner and outer space, filling up the boxes of the outer frames. The considered building frame is located in seismic zone II a (moderate seismicity) with soft soil conditions assigned to site class “1” as per Algerian Seismic Regulations (RPA99, 2003). This building represents the case of a three-bay, ten-story frame. The story heights are equal to 3.06 m throughout the frame, and the bays are 5 m. Figure 1 shows the configuration of the building frame. In addition, the dead and live loads were equal to 600 and 150 kg/m^2, respectively. The seismic mass at each floor level is equal to the full dead load plus an appropriate fraction of the live load.

In this work, one-directional seismic input is considered in the X-direction and no amplification is considered for torsional effects. The considered structures are regular in plan and elevation, which makes torsional effects negligible and the study of bi-direction seismic input is beyond the scope of this paper.

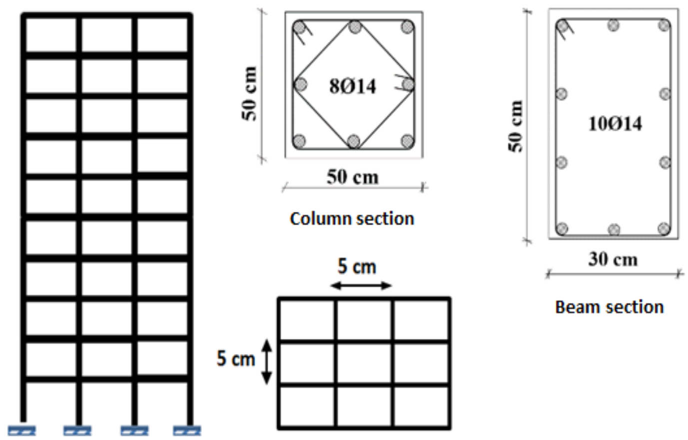


Figure 1. Elevation and plan of the reference 10-story building frame model.

Specifically, the attention has been focused on regular buildings with invariant horizontal stiffness throughout the height of the structure. The building model has a rectangular plan and a symmetric distribution of resisting systems. Figure 1 illustrates the model of the 10-story base-isolated building. This kind of idealization is based on the assumption that the floors are absolutely rigid and incompressible, thus transferring the floor displacement to all the columns equally. The RC building frame is modeled in OpenSees platform structural software (McKenna & Fenves, 2001). Details of the sections of the beams and columns are provided in Table 2. Also, the base of the structure (columns) is considered fixed as shown in Figure 1 and the response of the structure in the x-direction is considered. Hence, the fundamental period of the reference model is $T_1^* = 1.32$ s and accounts for approximately 80% of the total mass; it is essentially a first mode-dominated structure that still allows for a significant sensitivity to higher modes. This design will become the reference frame and serve as the basis for comparing all irregular systems.

Table 2. Detail of the beams and columns for the reference regular frame.

Elements	Dimensions (cm²)	Reinforcements
Beams	30x50	10ϕ14
Columns	50x50	8ϕ14

4. Material models for concrete and steel

The frame building models under analysis were developed using the object-oriented framework of OpenSees (Mazzoni et al., 2009; McKenna et al., 2010), in which the multi-fiber beam-based finite element is adopted (Figure 2). In this program, several material properties have been implemented that enable the simulation of structural RC elements.

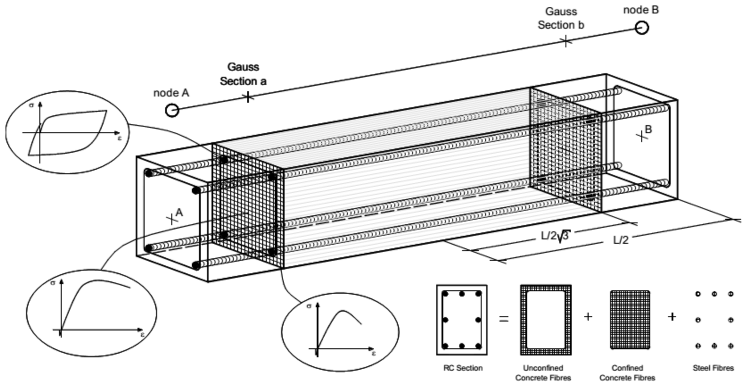


Figure 2. Discretization of a typical reinforced concrete cross-section.

In this study, the modified Kent-Scott-Park concrete model (Scott et al., 1982) is used for confined and unconfined concrete. This model, known as Concrete02, is available in the OpenSees software (Mazzoni et al., 2009). It has a parabolic curve until the maximum concrete stress, followed by a linear post-peak softening branch. The model also includes linear tension stiffening. The material properties of the model are described in Table 3, in which f'_c is the concrete compressive strength at 28 days, f'_{cu} and f_t are the concrete crushing strength and tensile strength of the concrete, respectively. ε_{c0} and ε_{cu} are the strains corresponding to the compressive strength, f'_c, and crushing strength, f'_{cu}, respectively. E_{c0} is the initial Young's modulus of concrete, and E_{ts} is the post-cracking modulus of concrete for the tension softening branch.

Table 3: Characteristics of concrete material model.

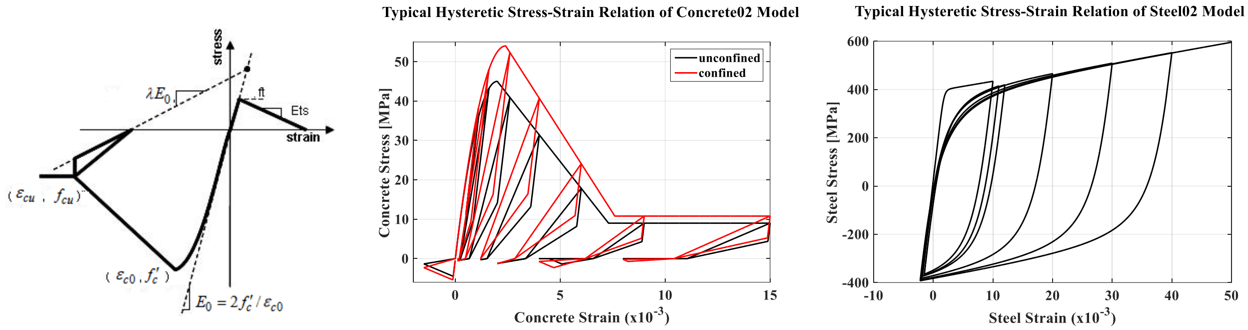
Material	Parameters	*Confined concrete*	*Unconfined concrete*
Concrete02	Concrete compressive strength at 28 days, f'_c [MPa]	45	54
	Concrete strain at maximum strength, ε_{c0}	0.0024	0.0020
	Concrete crushing strength, f'_{cu} [MPa]	10.8	9
	Concrete strain at crushing strength, ε_{cu}	0.0073	0.0076
	Ratio between unloading slope at ε_{cu} and initial slope, λ	0.2	0.2
	Tensile strength, f_t [MPa]	5.4	4.5
	Tension softening stiffness, E_{ts} [MPa]	2250	2250

Reinforcing steel bars in RC sections is modeled using a bilinear kinematic hardening model defined by Steel02 material in OpenSees (Mazzoni et al., 2009). Table 4 summarizes the characteristics of the computed properties of the material model (Steel02), in which, f_y is the yield strength, E_s is the initial elastic stiffness, b is the strain-hardening ratio, R_0 is a constant between 10 and 20, and C_{R1} and C_{R2} are coefficients.

Table 4. Characteristics of steel material model.

	Yield strength, f_y (MPa)	*Initial stiffness, E_s* (MPa)	b	R_0	C_{R1}	C_{R2}
Steel02	400	210000	0.02	20	0.925	0.15

Figure 3 shows the stress-strain relationship of the concrete and steel material models. A displacement control with an adaptive solution algorithm is developed using the Tcl code in the OpenSees to run the nonlinear analysis. Further details of the model parameters, equations and implementation are available in the OpenSees package (OpenSees, 2011).



(a) (b) (c)

Figure 3. Typical hysteretic stress-strain relation of concrete model: (a) General stress-stain model; (b) Computed properties for concrete02 and (c) Steel02 material model.

These two models have taken into account the nonlinearity of materials. Geometric nonlinearities (such as P-delta effects) are not considered, since no attempt was made to account for these effects in the design through the aforementioned adaptive pushover analysis.

5. Frames with irregular configurations

A regular building structure having basic quantities of mass, stiffness and strength uniformly distributed through its height behaves in a common way.

Practically, an unlimited number of vertically irregular designs can be obtained through the selection of different parameters and varying their distribution, separately or in combinations, over the height of the proposed benchmark frame building. Following the process of selecting irregularity, only two types of vertical irregularities are planned: mass (MF) and stiffness (SF) irregularities, modified for a particular or multiple stories along the building height. It can be noted that higher modal contributions are implicitly included within the adaptive DBAP process. This is due to the nonlinear behavior of the structures, which is sensitive to the higher-modal contributions. Importantly, the ignorance of these higher modes would result in an inaccurate representation of the seismic response parameters (Chopra & Goel, 2002) and (Antoniou & Pinho, 2004).

In the cases considered, the story properties are modified by increasing or decreasing the properties of all members of the story (beams and columns), by a wide range of modification factors (MF) or (SF). In fact, the modification factor is equal to the ratio of the modified quantity of the irregular case to that of the reference case at floor level. Each of the two types of irregularities considered was applied to each of the ten stories of the frame. As explicitly mentioned, since the period of the reference frame is influenced by varying the stiffness of one or more stories, the stiffnesses of all stories were scaled identically (for each irregular model) by the same amount in order to reach the targeted first mode period, as suggested by FEMA (2018).

6. Proposed methodology

Different methods for assessing seismic structural performance have been proposed alongside and as part of the development of performance-based earthquake engineering. As mentioned above, the conventional pushover method utilizes a predefined, generally triangular or uniform lateral load pattern to push the structure. However, in the adaptive pushover technique, which is entirely feasible, the lateral load model is a variable vector during analysis. It is updated at each step to take into account the current dynamic properties of the structure. This is an Eigen value problem that must be resolved before each step. Moreover, modal forms are combined using the SRSS rule to obtain the lateral load pattern (Hentri et al., 2018). The seismic demands for both regular (reference) and irregular structures are evaluated thanks to Displacement Based Adaptive Pushover (DBAP) analysis, in which the corresponding equivalent single degree of freedom system is subjected to a ground motion record and the seismic demands are evaluated. The selected earthquake ground motion used in this research is generated from the real accelerogram recorded during the 1940 El-Centro Earthquake (Figure 4). This record was appropriately scaled to cover the entire range of structural responses, from elasticity to global dynamic instability. Details of the DBAP method are presented in (Hentri et al., 2018) research.

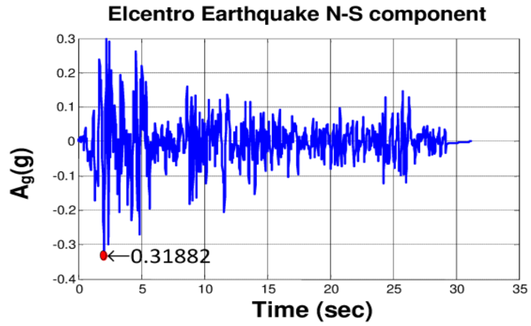


Figure 4. Ground Acceleration of N-S Component of El-Centro Earthquake.

7. Effects of vertical irregularities

Accurately, the effects of mass and stiffness irregularities on nonlinear demands are assessed in the present paper by evaluating roof displacement demands (adaptive capacity curves) and the distribution of story demands over the height of the structure.

7.1. Cases with irregular mass distribution

The mass modification factor (MF) is a parameter that represents the amount of modification in the mass distribution of the reference case. This modification factor, which equals the ratio of the modified mass of the irregular case to the mass of the reference case at a story level, is chosen between 0.25 and 4 and applied either to one floor or to a series of floors. Attention is paid to evaluating the effects of the location of mass irregularities at the floor levels of the structure. Figure 5 shows the cases with irregular mass distribution (MM) compared to the original mass distribution of the reference case at the floor levels, according to the following locations:

- Model (a) with mass modification factors MF(n) of 0.25, 0.5, 2.0 and 4.0 (stories 1 to 10);
- Model (b) in which the mass of the lower half of the structure is adjusted with modification factors MF of 0.25, 0.5, 2.0 and 4.0.
- Model (c) in which the mass of the upper half of the structure is adjusted with mass modification factors MF of 0.25, 0.5, 2.0 and 4.0.

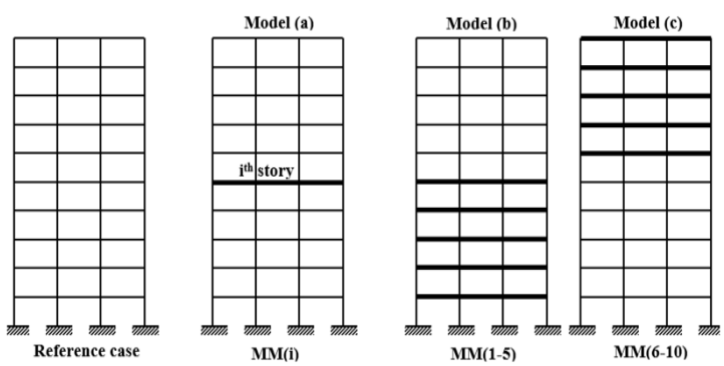


Figure 5. Cases with irregular mass distribution to the original mass distribution of the reference case.

The inelastic responses of cases with mass irregularities compared to the reference case are investigated here. Base/story shear and inter-story drift are the basic seismic parameters that control the change in the inelastic responses of the structure.

In the first model (a), the irregularity occurs only at one floor, but the location is varied from the lower level to the top "cases MF(1–n)". The subsequent observations are graphically made to illustrate the effects of varying the location of the irregularity. Note that varying the mass at a single floor by a modification factor of 0.25, 0.5, 2.0 and 4.0 generally does not have significant effects on all the nonlinear responses. It means that it will not noticeably reduce the collapse resistance of the moment frame models, provided that the lateral system is proportioned to satisfy the seismic demands (which often increase due to the presence of the irregularity). Figure 6 initially illustrates adaptive capacity curves for the reference case structure, including the effects of vertical irregularities at the locations cited above. Maximum base shear is highest in the regular frame (932 kN for a displacement of 78 cm). In all irregular cases, base shear is greatest when top story has a light-mass MF of 0.5 (for instance), and then in fluctuation change for the other stories wherever the location of the irregularity is. However, the cases with heavy mass (MF=2 or 4) have an opposite effect and the response provides the inverse behavior.

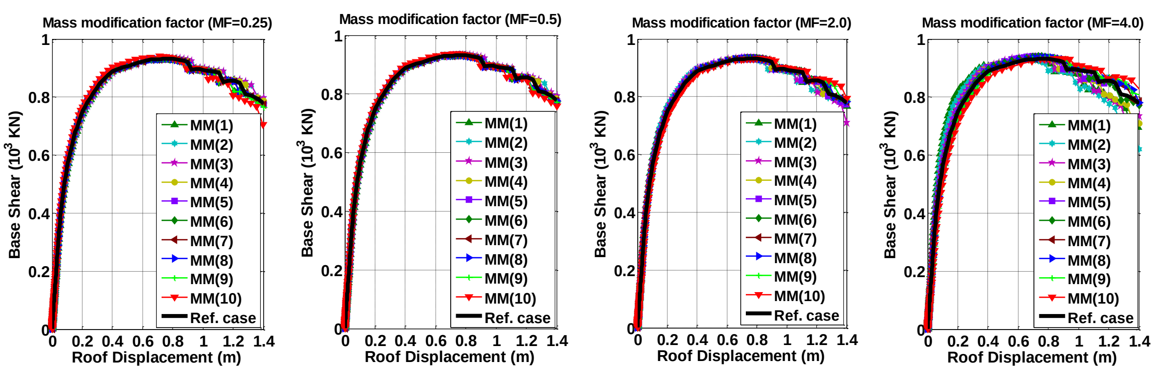


Figure 6. Adaptive capacity curves for the reference case and all irregularity cases related to Model (a).

In order to have a better assessment of this type of irregular structure, the inter-story drift ratio has to be evaluated on a floor-by-floor basis rather than considering the maximum. From Figure 7, it is illustrated that the cases with a light mass MF (0.25, 0.5) have an influence on the inter-story drift demand depending on the location of the story irregularity. The inter-story drift increases at all floors, with an excessive increase at the 2nd, 3rd, and 4th floors for the first, 2nd and 3rd story irregularity locations due to altering the modes of vibration and fundamental period of the structure, exhibiting a reduction in stiffness. However, the cases with heavy mass MF (2, 4) have an opposite effect, and the response provides the inverse behavior.

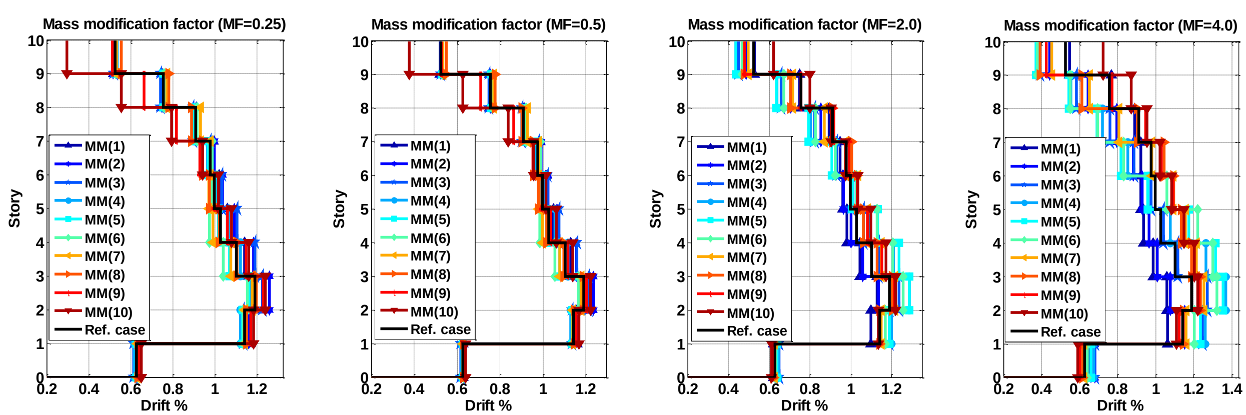


Figure 7. Inter-story drift ratio for the reference case and all irregularity cases related to Model (a).

The similar pattern of story shears is obtained (Figure 8); the normalized story shears do not differ noticeably from the reference case. Consequently, the highest value is obtained in the second story for all irregular cases, while moderate change is expected at mid-height, followed by quick decreases in the upper half of the structure. For the cases with mass modification of MF = 4.0 (extreme value), the normalized shears are slightly higher at the top floor as compared to the reference case due to the contributions of higher modes.

In the second model (b), once the irregularity occurs in the lower half of the structure with mass modification factors MF (1–5) of 0.5, 2.0, and 4.0, the same arguments can be made but with an opposite effect. Further, the response provides larger drifts in the lower stories (Figure 9).

According to the model (c), the irregularity occurs in the upper half of the structure with mass modification factors MF (6–10) of 0.5, 2.0, and 4.0; the effect of change in the total mass is less significant on the maximum base shear (Figure 9). In addition, inter-story drift and story-shear profiles change gradually over the building height. As can be seen, an increase is observed at the lower floors, and then a moderate variation at mid-height is expected, followed by rapid decreases in the upper half of the structure.

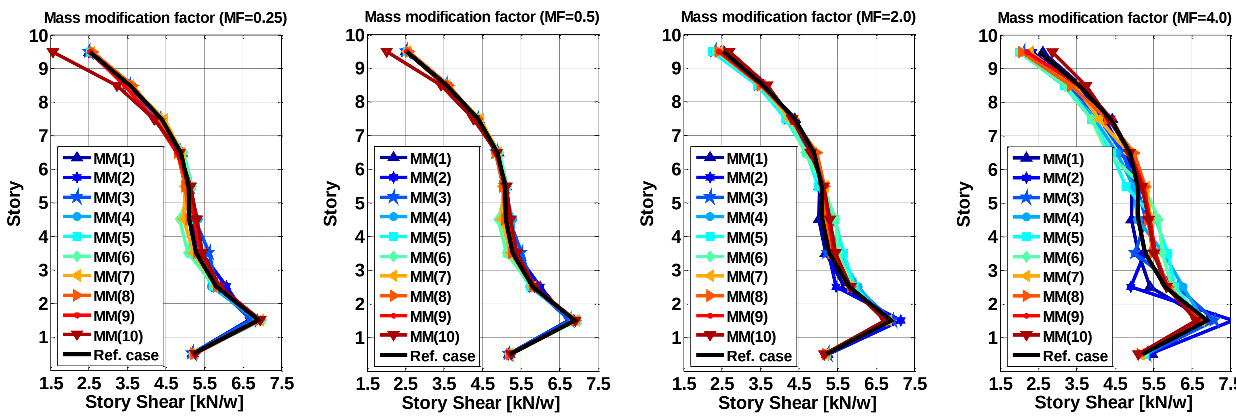
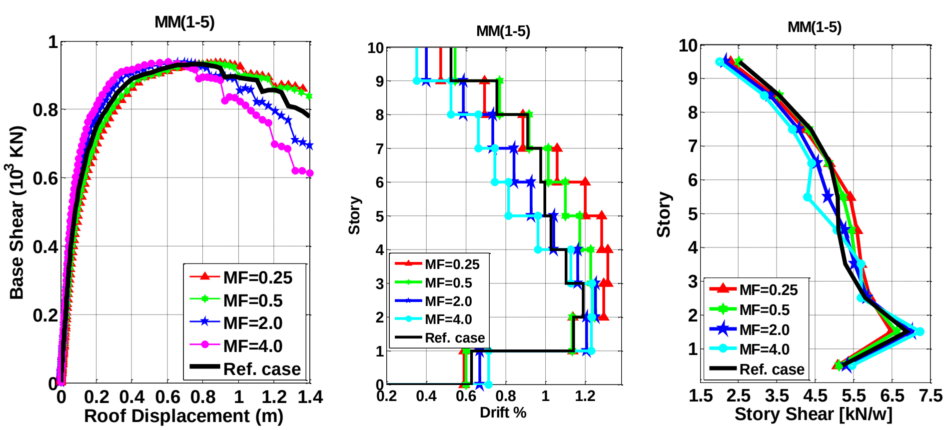


Figure 8. Story-shear for the reference case and all irregularity cases related to model (a).



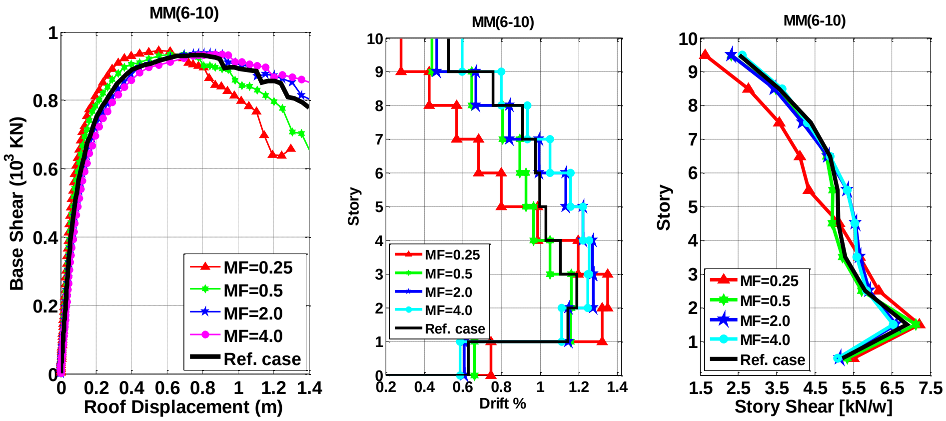


Figure 9. Story-shear for the reference case and all irregularity cases related to model (a).

Furthermore, Figure 10(a) shows the variation of base shear demands for irregular cases normalized by the base shear demand for the reference case. It is plotted against variations in location of mass irregularity for the cases with mass modifications MF (1–10) of 0.25, 0.5, 2.0, and 4. Indeed, the base shear demand does not show large variations with changes in the level of the same mass irregularity (it does not exceed at most 2%). Whereas, when the mass irregularity is located on the first floor, the ratio of base shear (irregular case over reference case) is greater than one, due almost entirely to the influence of higher vibration modes besides the great effect of mass increasing. Yet, the effect of mass fluctuates as the irregularity moves to higher floors. For the extreme case of a "heavy" story with MF = 4, the base shear does not change significantly compared to the reference case. Exceptionally, the 1st and 2nd stories are respectively large due to the fact that these stories are too rigid by developing greater inertial forces than the others.

Likewise, Figure 10 (b) presents afterward the variation of normalized base shear with the level of mass irregularity, which extends over more than one level, starting with the first floor. It is seen that the level of irregularity has no major effect on the abrupt increase in the normalized base shear. In case MF (l–5)*4, for instance, the ratio of the base shear of this case to the reference case is 1.05 (5%). This difference is primarily due to the change in the basic dynamic characteristics of the structure as well as to the effect of the number and length of the bays, which have an influence on the fundamental frequency of the building system.

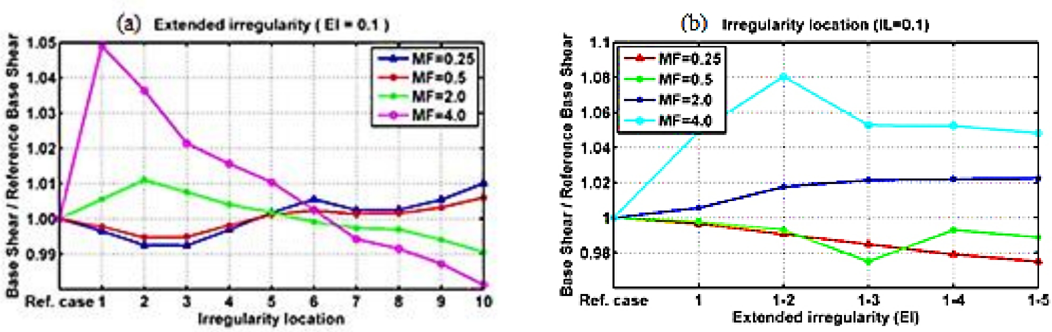


Figure 10. Variation of normalized base shear demands with the location and extended mass irregularity.

7.2. Case with irregular stiffness distribution

Cases with stiffness irregularities (MK) are created by changing the stiffness distribution of the reference case while keeping the same mass distribution as the reference model. Therefore, the stiffness modification factor SF, which represents the amount of modification in the stiffness distribution of the reference case, is varied for each irregular case by the same amount in order to reach the targeted first mode period of vibration (1.32 s). This refers technically to the definition of a soft/weak story building.

To illustrate, MK (5)*0.5 (for instance) represents a case with a "soft" story at mid-height. This case is created by modifying the stiffness of the fifth story of the reference case by a factor of 0.5 also changing the absolute values of all story stiffness to reach a first mode period value of 1.32s. Figure 11 represents irregular stiffness distributions compared to the stiffness distributions of the reference case. This change in story stiffness will be reflected in capacity curves, inter-story drift and inter-story shear.

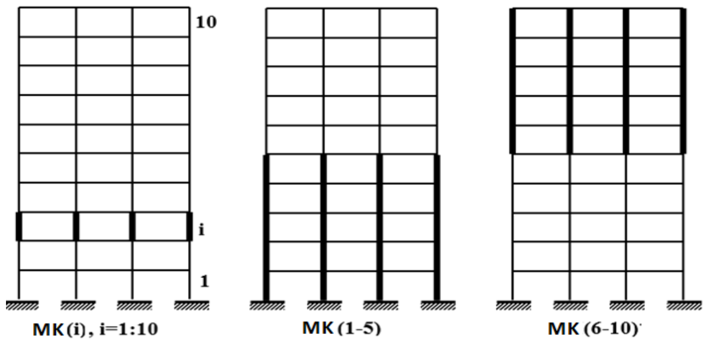
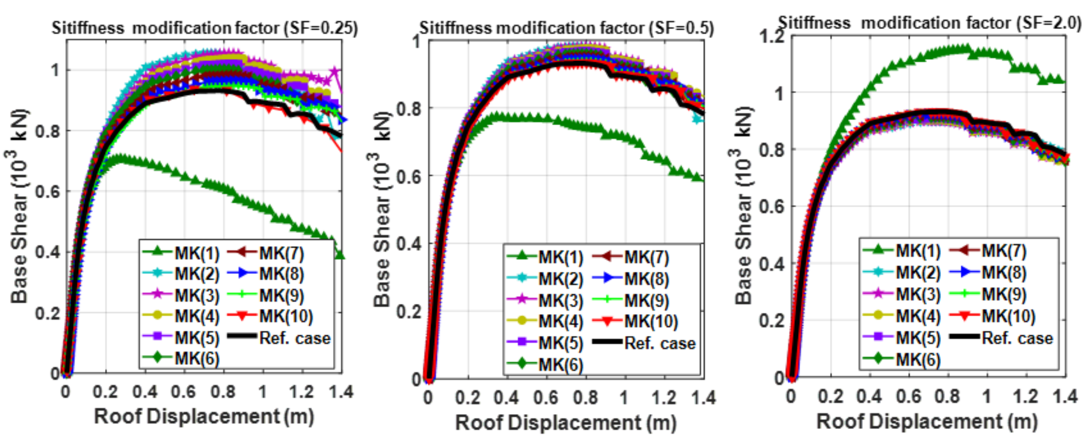


Figure 11. Cases with irregular stiffness distribution to the stiffness distribution of the reference case.

The following observations arise from studying the effects of stiffness irregularities on the nonlinear response by varying the location of the irregularity (Figure 12). Accordingly, the effect on the adaptive capacity curves by introducing a stiffness irregularity with a modification factor of SF = 0.25, 0.5, 2 and 4.0 at one story only for each irregular case is moderately increased as compared to the regular reference frame (the difference is less than 5%). Maximum base shear is captured for a displacement value of 75 cm for almost every case except for SF(1) = 0.25 and 0.5, and it is shown that the soft story happened on this floor.

Importantly, reducing the stiffness of the first story (SF(1) = 0.25 and 0.5) causes the story to considerably deform rapidly into the nonlinear range; hence, ductility capacity substantially decreases. Also, maximum base shear is captured for a lower displacement value (30 cm) in comparison with the reference regular frame (75 cm). Generally, the capacity demand (MK(1)) is considerably less than the other stories (MK(2–10)). However, increasing the stiffness of the first story (SF(1) = 2 and 4.0) causes a reversed behavior.

According to the model (b) with MK (1–5), the capacity curves with a constant initial stiffness (Figure 12) are characterized by having a decreasing strength when the stiffness modification factor is less than one (SF<1). Although, a reverse behavior is observed for the model (c) with MK(6-10) where the strength decreases when the stiffness modification factor is greater than one (SF>1).



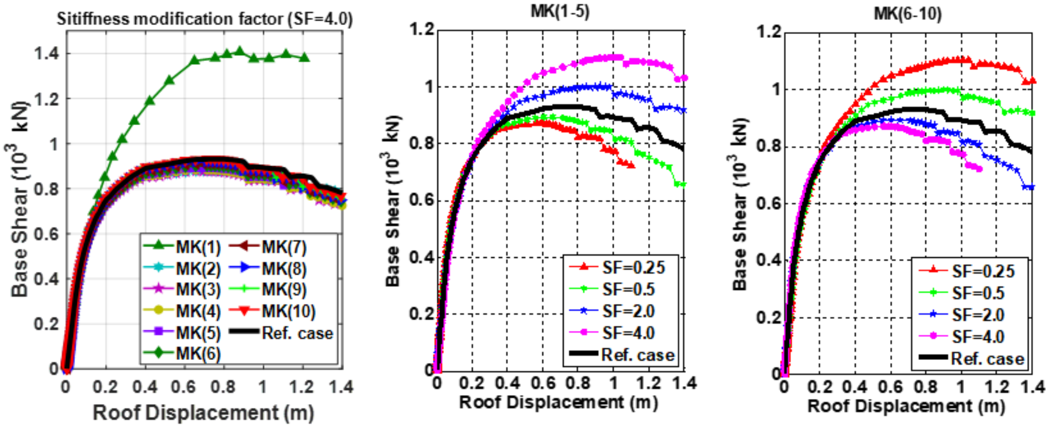
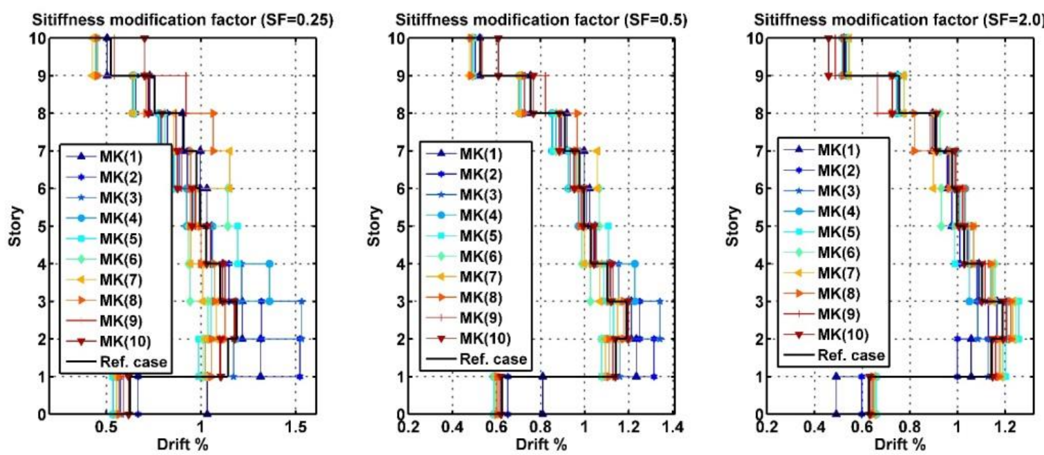


Figure 12. Adaptive capacity curves for the reference case and all stiffness irregularity cases.

For a good understanding of the effects of irregularities in different locations along the height, each of the locations mentioned earlier is separately studied. As observed in Figure 13, in the cases of model (a) with MK(1)*0.25 and MK(1)*0.5, reducing the stiffness of the first story in the edifice increases the first story drift by up to 1.2 times that of the regular reference frame. Furthermore, the inter-story drift increases to a better extent at adjacent stories (second, third, and fourth stories). On the other hand, reducing the stiffness of a story causes its drift to moderately increase compared to the regular reference frame, and vice versa.

Referring to Figure 13, decreasing the stiffness at the lower half stories of model (b) with SF = 0.25 and 0.5 relatively increases inter-story drifts at the lower half stories, but it has the opposite effect on the upper story drifts. However, increasing the stiffness at the lower half stories (cases with SF = 2 and 4) relatively decreases drifts at the lower stories but has an opposite effect on the upper story drifts, and vice versa for the cases of model (c) where SF = 2 and 4.



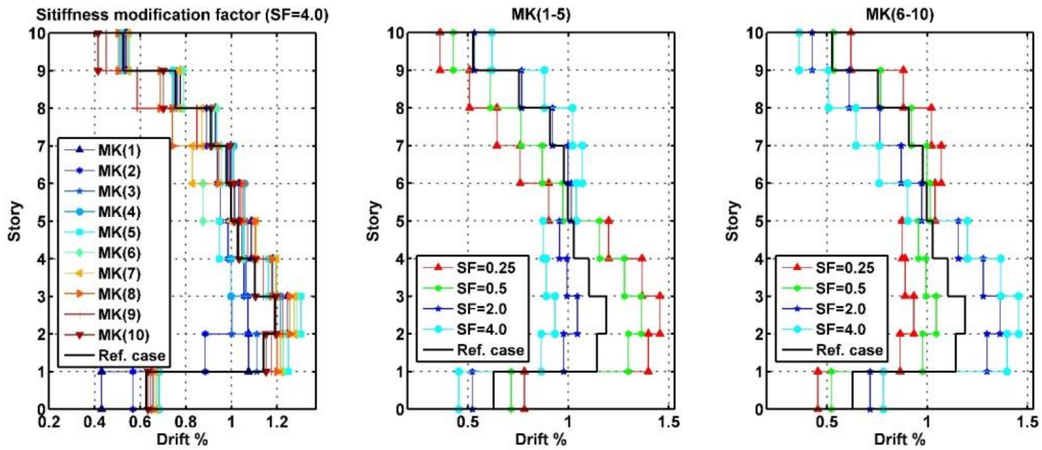
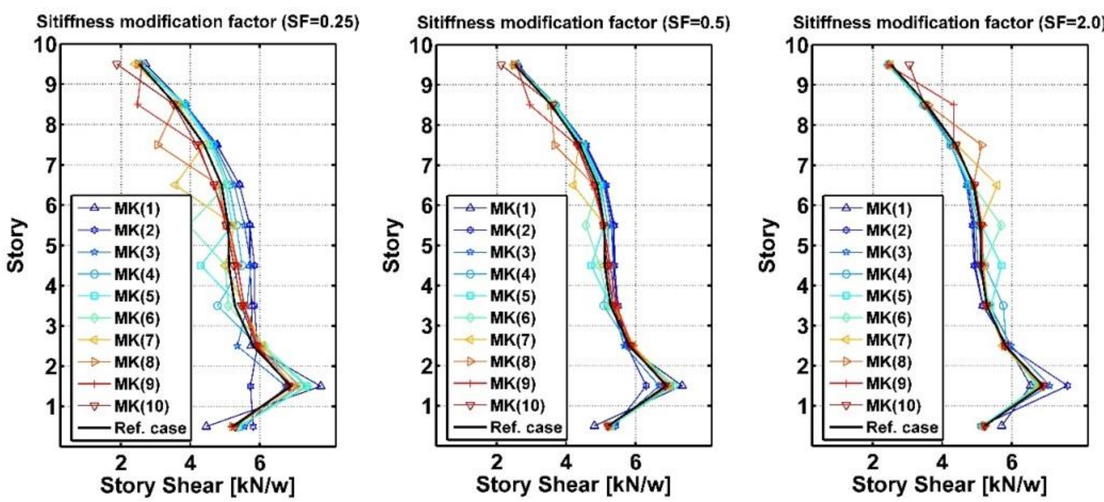


Figure 13. Inter-story drift ratio for the reference case and all irregular cases stiffness irregularity.

Moreover, as shown in Figure 14, the decrease in stiffness in one or several stories of the regular frame influences the story shear of the lower stories significantly in the 2nd story and least in the 10th story. It is seen that the location of the irregularity has a major contribution to the abrupt change in the story shear of that particular story. It means that when the ith story is irregular, the story shear of that particular ith story suddenly changes rather than that of the regular frame. These findings result in a flexible floor and, hence, a dangerous column mechanism (floor mechanism). Alternatively, the increase in stiffness in one or several stories results in quite the opposite behavior.

Notably, as is apparent from Figure 14, increasing the stiffness at the lower-half stories (MK (1–5)*2 and 4) relatively influences story shear at the lower stories but has a minor effect on the upper stories. The Figure demonstrates that decreasing the stiffness at the upper-half stories (MK (6–10)*0.5) has an opposite effect compared to the first cases and that the top stories are slightly influenced by this kind of irregularity, with the stiffness severely decreasing at the top of the 10-story frame.



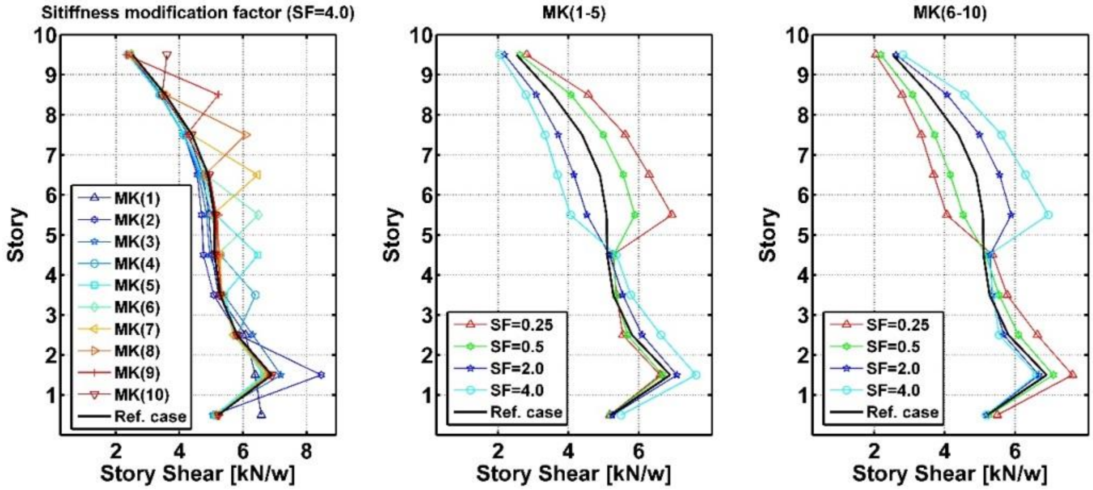


Figure 14. Story-shear for the reference case and all irregular cases stiffness irregularity.

On the other hand, modifying the stiffness of a story slightly changes the normalized base shear in comparison with the reference frame. For the extreme case of a "stiff" story with SF = 4, as noticed in Figure 15(a), the normalized base shear does not change significantly from the reference case except for the first story, which is greater than one (matching 25 %); that explains the increasing capacity demand (see Figure 12). For the cases with stiffness modification factors of SF = 0.25 (case of a "soft" story at the bottom), the irregularity has opposite effects on the base shear value. The base shear significantly converges to that of the reference case from the 7th story to the top.

Figure 15(b) illustrates the change in the normalized base shear demand once the irregularity increases along the height of the structure with stiffness modification factors SF (1–5) of 0.25, 0.5, 2.0, and 4.0. For an excessive value (case MK(1)*4, for instance), the normalized base shear increases by 26% as compared to the reference case, and for case MK(l)*0.25, the base shear decreases by 15%.

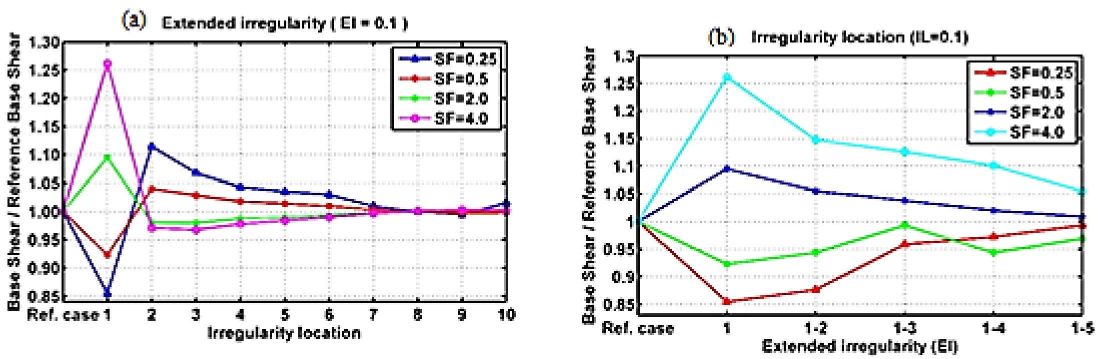


Figure 15. Variation of normalized base shear with the extended and location of stiffness irregularity.

8. Conclusions and comments

To sum up, the effects of vertical mass and stiffness irregularities on the seismic response of building structures are investigated in the current research paper. The intended objectives are to improve our understanding of the behavior of structures with vertical mass and stiffness irregularities and quantify their effects on seismic demands. An advanced procedure for estimating global demands and the distribution of story demands along the height of the structure (base shear-roof displacement, inter-story drift and story-shear distribution) of irregular RC buildings is assessed thanks to adaptive pushover analysis. The ground motion recorded on rock soils during the 1940 El-Centro Earthquake is used in the analyses. In this study, a reference case structure is utilized, and cases that represent irregular structures are identified by modifying the distributions of mass and stiffness of the reference case. Building structures are represented by two-dimensional, three-bay, ten-story frame MDOF models. The following are the conclusions drawn from this part of the study:

1. Mass irregularities (with modification factors of MF = 0.25 to 2.0) show relatively small effects on all the nonlinear responses (story drift and story shear demands). Indeed, the changes in the distribution of story drift over the height due to mass irregularities are, on average, less than the variations in the distribution of these demands for the reference case. A mass increase at the top has a relatively larger effect on roof drift and inter-story drifts than an increase at mid-height or at the base;
2. The study found that the presence of mass irregularities, soft/weak story irregularities, and lateral capacity demand generally do not significantly reduce the collapse resistance of moment frame buildings, provided that the lateral system is proportioned to satisfy the seismic demands (which often increase due to the presence of the irregularity).
3. Stiffness irregularities (with modification factors of SF = 0.25 to 2.0) show comparatively significant effects on story shear demands but larger effects on capacity and story drift demands. Modifying the stiffness of one story slightly changes the normalized base shear in comparison with the reference frame. The effects are amplified for cases with large stiffness modification factors (extreme case with SF = 4);
4. Story-shear demands at the lower-half stories are not very sensitive to the increasing of either mass or stiffness irregularities, but have a minor effect on the upper stories. However, the decreasing of the mass or stiffness at the upper-half stories has the opposite effect compared to the first cases;
5. Finally, more research needs to be carried out in order to assess the effects of vertical irregularities with other conditions and mechanisms (e.g., effects of strength irregularities, combined irregularities, Soil-structure interaction, and structures with in-plan irregularities). Recognizing the merits and limitations of existing methodologies, the displacement-based adaptive pushover method (DBAP) procedure developed herein might indicate that revisions to the current Algerian seismic design regulations ("RPA99, 2003") might be necessary in order to prevent excessive amplifications of seismic demands.

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