



# SEISMIC DESIGN METHODOLOGY BASED ON PERFORMANCE OBJECTIVES FOR MASS-IRREGULAR RC STRUCTURES IN ELEVATION

Mohammed Hentri<sup>1</sup>, Mostefa Lallam<sup>2\*</sup> and Miloud Hemsas<sup>3</sup>

<sup>1, 2, 3</sup>Department of Civil Engineering, University of Mustapha Stambouli, Mamounia, 29000, Mascara, Algeria.

<sup>1</sup><https://orcid.org/0000-0001-6550-9949>, <sup>2</sup><https://orcid.org/0000-0002-0022-6646>, <sup>3</sup><https://orcid.org/0000-0002-7280-9322>

Email: [m.hentri@univ-mascara.dz](mailto:m.hentri@univ-mascara.dz), [m.lallam@univ-mascara.dz](mailto:m.lallam@univ-mascara.dz), [m.hemsas@univ-mascara.dz](mailto:m.hemsas@univ-mascara.dz)

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## ABSTRACT

Vertical irregularity in buildings often arises from architectural or functional requirements that lead to irregular mass distribution over different stories—such as open ground floors, setbacks, or changes in occupancy use. These irregularities can significantly affect seismic performance, making an accurate assessment essential for structural safety. This study presents a novel irregularity index that incorporates the interstory drift ratio into a performance-based framework for evaluating the seismic behaviour of ten-story reinforced concrete buildings with irregular mass distribution. Displacement-based adaptive pushover method is employed to analyse the response of vertically irregular structures under seismic loading. A detailed investigation is conducted focusing on key response parameters, including base shear versus roof displacement, interstory drift, and story-shear distribution, to identify the factors most critical to structural behaviour. The results highlight the influence of interstory drift on the seismic response of buildings with vertical mass irregularities. Based on these findings, a performance index is developed using the interstory drift ratio, which reflects sensitivity to variations in mass along the building height. This approach contributes to the broader understanding of how mass irregularity affects structural performance and offers an additional tool for evaluating seismic behaviour in irregular buildings.



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## I. INTRODUCTION

The seismic performance of buildings with vertical mass irregularities remains a key research focus, as such irregularities—often introduced for functional or aesthetic purposes—can significantly influence structural behaviour under dynamic loading. Although design codes such as RPA-99 [1], EC8 [2], and UBC [3] define irregularities primarily by differences in story properties, the impact of their location, rather than magnitude alone, is frequently overlooked [4], [5]. A common form of vertical irregularity is non-uniform mass distribution, which has been shown to significantly affect seismic response, as noted by Benaïed et al [6]. For instance, Al-Ali and Krawinkler [7] demonstrated that placing mass irregularity at the top of a ten-story building maximized drift, while Magliulo et al. [8] observed minimal impact. In contrast, Choi [9] and Aydin [10] reported severe effects, particularly in lower or upper stories, and Varadharajan et al. [11], [12]. Regular buildings generally show better seismic performance than irregular ones, which are often designed to meet diverse functional and commercial requirements.

Structural failure in irregular buildings typically initiates in zones of weakness caused by discontinuities in mass, stiffness, and strength along the vertical axis. Vertically irregular buildings are commonly classified into two categories: those with significant plan variations along the height, such as setback configurations and open ground stories, and those exhibiting abrupt changes in dynamic properties, including mass and lateral stiffness [13]. These irregularities may arise from varying story functions, concentrated mass in specific levels, or inconsistent story heights, with five primary layout types identified as particularly vulnerable [14]. Traditional codes rely on simplified approaches like Equivalent Static Lateral Force (ESLF) or Response Spectrum Method (RSM), which assume regularity and have proven inadequate for irregular structures. Nonlinear Response History Analysis (NRHA) provides accurate simulations, but they are computationally demanding.

Pushover-based nonlinear static procedures (NSP) are more practical but assume fundamental mode dominance—an issue in irregular high-rises where higher modes are significant. To address this, enhanced pushover methods have emerged. The Displacement-based Adaptive Pushover (DAP) method updates lateral loads based on dynamic characteristics, capturing higher mode effects and irregularities [15]. This study investigates how the location of vertical mass irregularities affects maximum structural response—focusing on adaptive capacity curves, inter-story drift, and story-shear distribution. On the other hand, while the irregularity index is an effective tool for assessing structural discontinuities that influence seismic performance, this paper proposes a new index aimed at enhancing that evaluation, as discussed by Rathnasiri et al. [16] and Nady et al. [17]. A 10-story regular frame will be analysed using OpenSEES [18] and the DAP method, preceded by a review of materials, framing systems, irregularity types, and seismic analysis techniques.

## II. METHODOLOGY

### II.1 MATERIALS AND METHODS

This study evaluates the seismic performance of reinforced concrete (RC) moment-resisting frame buildings with vertical mass irregularities using nonlinear analysis techniques aligned with Algerian Seismic Regulations [1]. Both linear and nonlinear methods are permitted under these regulations for assessing existing structures. The Displacement-Based Adaptive Pushover (DBAP) method is employed to compare the seismic demand of regular and irregular structures. This method transforms the multi-degree-of-freedom system into an equivalent single-degree-of-freedom (SDOF) system subjected to the 1940 El Centro Earthquake accelerogram. In DBAP, the lateral load vector evolves during analysis to reflect the structure's dynamic properties. Modal characteristics are updated at each step via eigenvalue analysis and combined using the Square Root of the Sum of Squares (SRSS) rule [19]. Higher-mode effects are inherently captured due to the nonlinear response sensitivity of structures. Neglecting these contributions can lead to significant inaccuracies, as shown by Chopra and Goel [20] and Antoniou and Pinho [15]. A flowchart summarizing the DBAP procedure is presented in Figure. 1.

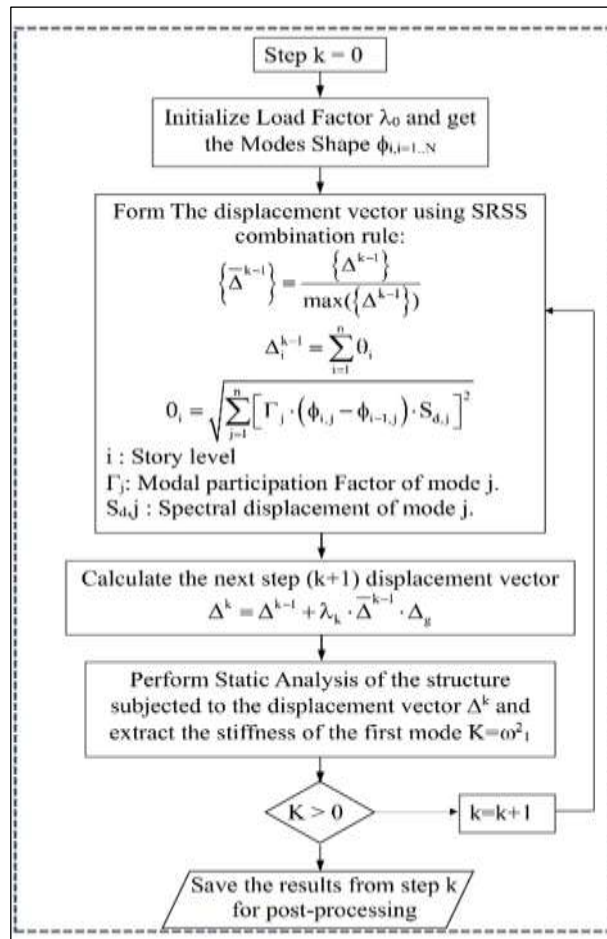


Figure 1: Flowchart of the modelling procedures using the Displacement Adaptive Pushover process.

Source: [18].

### III. DESCRIPTION OF STRUCTURAL MODELS

The reference structure is a 10-story RC frame with three bays (5 m each) and a standard floor height of 3.06 m. It features a symmetrical floor plan and was designed per NCAER [1] for seismic zone II.a with soft soil conditions (site class “1”). Dead and live loads are assigned as 600 kg/m² and 100 kg/m², respectively. Seismic mass at each floor combines full dead load and a fraction of the live load. The building is modelled in OpenSees [21], with fixed column bases and response evaluated in the x-direction. The fundamental period of the regular frame is 1.32 seconds, representing approximately 80% of the total mass, indicating a first-mode-dominated behaviour with sensitivity to higher modes. This model serves as the baseline for comparison with irregular configurations. Beam and column section details are provided in Table 1, and the structural layout is shown in Figure. 2

Table 1: Adopted the element's size.

| Elements     | Dimensions (cm <sup>2</sup> ) | Reinforcements (mm) |
|--------------|-------------------------------|---------------------|
| Beams Size   | 30x50                         | 10 $\phi$ 14        |
| Columns size | 50x50                         | 8 $\phi$ 14         |

Source: Authors, (2026).

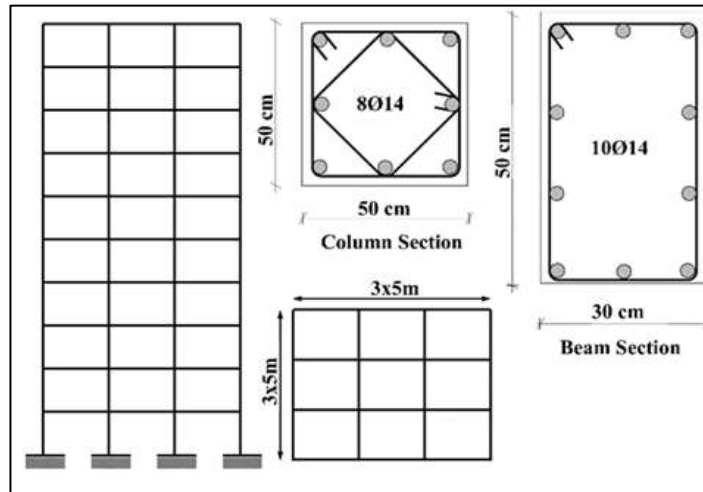


Figure 2: Elevation and plan of the reference 10-story building frame model.

Source: Authors, (2026).

#### IV. MATERIAL MODELS FOR CONCRETE AND STEEL

All frame models use force-based multi-fiber beam-column elements in OpenSees [21]. Concrete fibers are assigned the Concrete01 material model, based on the modified Kent-Scott-Park formulation [22], which includes degraded linear unloading/reloading stiffness. Material properties are listed in Table 2, including compressive strength ( $f'_c$ ), crushing strength ( $f'_{cu}$ ), corresponding strains ( $\epsilon_{c0}$ ,  $\epsilon_{cu}$ ), and initial modulus ( $E_{c0}$ ) [23]. Steel reinforcement is modelled using the Steel02 bilinear kinematic hardening model. Parameters include yield strength ( $f_y$ ), elastic modulus ( $E_s$ ), strain-hardening ratio ( $b$ ), and cyclic behaviour coefficients ( $R_0$ ,  $CR_1$ ,  $CR_2$ ). Stress-strain behaviour for both materials is illustrated in Figure 3. Nonlinear displacement-controlled analysis is executed via Tcl scripting with adaptive solution algorithms. Further modelling details are available in the OpenSees documentation [21].

Table 2: Adopted the concrete element's size.

| Parameters                                            | Confined concrete | Unconfined concrete |
|-------------------------------------------------------|-------------------|---------------------|
| $f'_c$ [MPa]                                          | 54                | 45                  |
| Concrete strain at maximum strength, $\epsilon_{c0}$  | 0.002             | 0.002               |
| Concrete crushing strength, $f'_{cu}$ [MPa]           | 4                 | 9                   |
| Concrete strain at crushing strength, $\epsilon_{cu}$ | 10.8              | 0.0076              |

Source: Authors, (2026).

Table 3: Adopted the steel element's size.

| Strength, $f_y$ (MPa) | Initial stiffness, $E_s$ (MPa) | $b$  |
|-----------------------|--------------------------------|------|
| 450                   | 210000                         | 0.02 |

Source: Authors, (2026).

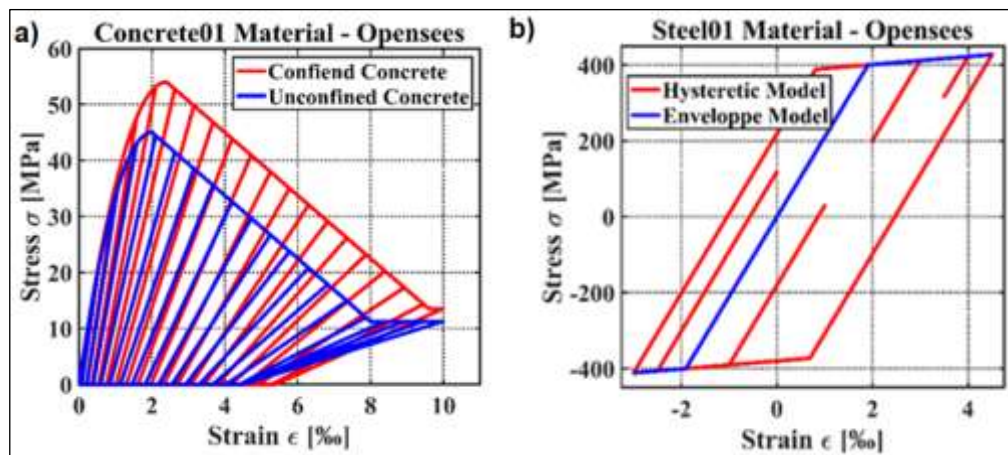


Figure 3: Typical hysteretic stress-strain relation of concrete01 and Steel02 models.

Source: Authors, (2026).

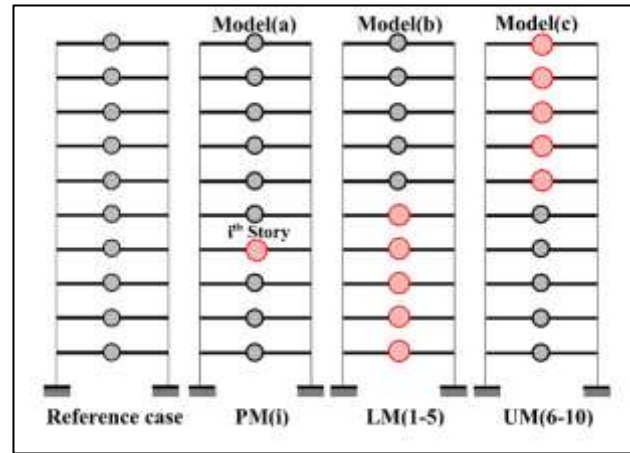


Figure 4: Building models with mass irregularity: particular mass (PM); Lower mass (LM) and upper mass (UM).  
Source: Authors, (2026).

## V. FRAMES WITH IRREGULAR MASS DISTRIBUTION

Mass irregularity is introduced by modifying the seismic mass at specific stories. A regular structure assumes uniform mass, stiffness, and strength, while irregular structures feature abrupt variations. These variations affect lateral inertial forces and ductility, leading to complex dynamic behavior. Three irregular configurations are studied:

- PM Model: Mass irregularity in a particular story
- LM Model: Mass irregularity in the lower half of the structure
- UM Model: Mass irregularity in the upper half of the structure

Mass Modification Factors (MF) ranging from 0.25 to 4.0 are applied to one or multiple stories. Structural member stiffness within modified stories is adjusted proportionally using MF values. To maintain consistency in dynamic properties, story stiffness is scaled to match the target first-mode period, following FEMA guidelines [24]. The irregular model configurations are shown in Figure 4, and their descriptions are tabulated in Table 4.

Table 4: Description of mass irregularities for the investigated models.

| Model        | Location of Irregularity | Model                   |
|--------------|--------------------------|-------------------------|
| Model(i) PM  | 1–10                     | 0.25, 0.5, 2.0, and 4.0 |
| Model(ii) LM | 1–5                      | 0.25, 0.5, 2.0, and 4.0 |
| Model(ii) UM | 6–10                     | 0.25, 0.5, 2.0, and 4.0 |

Source: Authors, (2026).

## VI. NUMERICAL STUDY AND RESULTS

This section explains the effects of the location of mass irregularity on the seismic response of various irregular structural models. Using the parameters listed in Table 5, the models are simulated in OpenSEES finite element software. The inelastic responses of cases exhibiting mass irregularities are analysed and compared with the reference regular model. The resulting outputs include the fundamental period, base and story shear forces, maximum roof displacement, and inter-story drift. Two models of irregularity variations are considered. In the first model, the irregularity occurs at one story but the location (denoted by IL) is varied (level at which the irregularity starts). In the second model IL is kept constant, and the fraction of the total height over which the irregularity extends is varied (EI = 0.1, 0.2, or 0.5).

### VI.1 FUNDAMENTAL PERIOD FOR STRUCTURAL IRREGULARITY MODELS

Figure 5 illustrates how altering the mass on a single floor—when the irregularity spans 10% of the structure's height—significantly impacts the fundamental period. As the irregularity level increases (MF > 1), the fundamental period also rises.

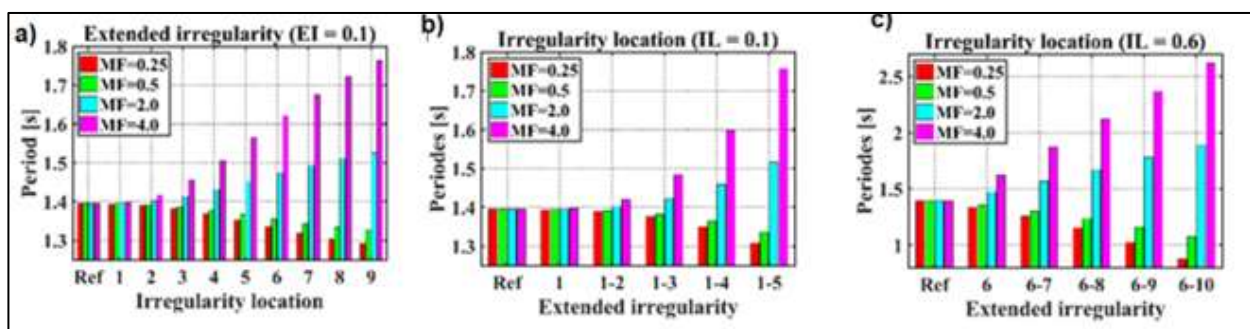


Figure 5: Change in fundamental period with mass irregularity.  
Source: Authors, (2026).

## VI.2 DUCTILITY FOR DIFFERENT STRUCTURAL IRREGULARITY MODELS

Furthermore, mass irregularity in top stories of the building models leads to higher ductility factors, especially when extending over 10% of the height ( $EI = 0.1$ ) with an  $MF > 1$ , as shown in Figure. 6(a).

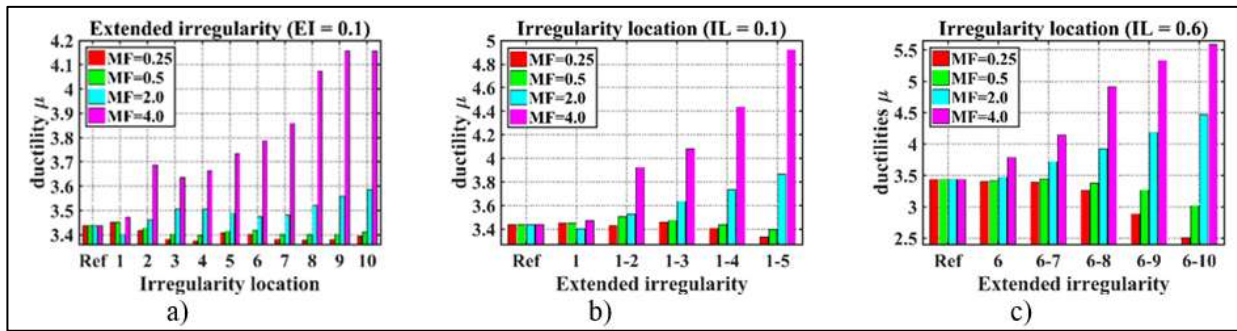


Figure 6: Change in fundamental period with mass irregularity.

Source: Authors, (2026).

## VII. CASES WITH IRREGULAR MASS DISTRIBUTIONS AND ADJUSTED STIFFNESS

To eliminate the effects of period variations on the response, all structures are adjusted to have the same elastic first-mode period. This permits a rational comparison of the irregular cases with the reference case, according to the proposal of Al-Ali and Krawinkler [6]. Story demands are established according to the cases cited below, as shown in Figure. 4. This adjustment in story stiffness distribution for cases with mass irregularities will be reflected in the establishment of story demands for each irregular building model, as the base shear force (adaptive capacity curves), inter-story drift, and story-shear.

### VII.1 STORY DEMANDS FOR THE FIRST MODEL (I)

In model (i), irregularity is limited to one story, shifting vertically from bottom to top (case MF(1–n)). This model integrates adjusted stiffness through scenarios with mass irregularities. Graphical results reveal that the position of mass irregularity has minimal impact on base shear. Likewise, reducing the mass factor at a single floor ( $MF < 1$ ) generally does not alter nonlinear responses significantly. Even when MF is doubled ( $MF = 2.0$ ), sensitivity remains low. These findings suggest that such mass variations do not substantially compromise collapse resistance, provided the lateral system accommodates the increased seismic demand. As shown in Figure. 7, when  $MF < 1$ , inter-story drift demand varies with the irregularity's location—drift increases in lower stories, except at the first and top levels, where it decreases due to changes in vibration modes and the fundamental period, indicating reduced stiffness. In contrast, for  $MF > 1$ , drift behavior reverses: although overall demand remains comparable, upper stories experience significantly higher drift when their mass is increased.

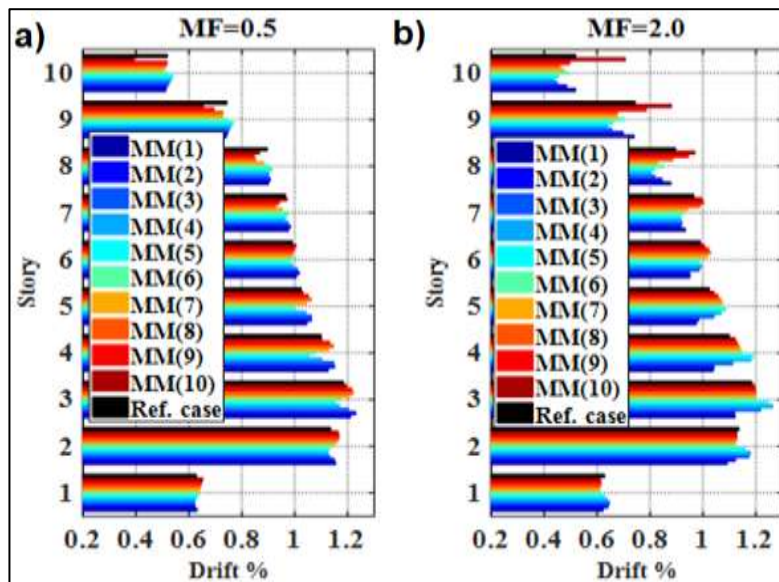


Figure 7: Inter-story drift ratio for the reference case and all irregularity cases related to Model (i).

Source: Authors, (2026).

### VII.2 STORY DEMANDS FOR THE SECOND MODEL (II)

In this case, Figure. 8 illustrates that when irregularity arises in the lower half of the edifice with mass modification factors MF(1–5) from 0.25 to 4.0, similar but opposite behavior leads to larger drifts in the lower stories. Furthermore, Figure. 9 plainly demonstrates that the base shear force is higher in buildings with mass irregularity in the bottom floors (LM model) than in those with irregularities in the middle or top stories (MS and TS models).

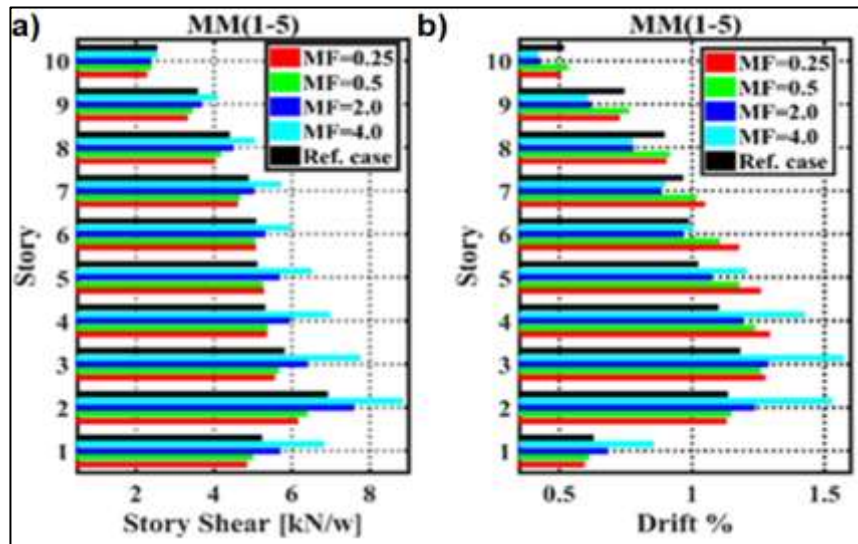


Figure 8: Story demands for the second model (ii).

Source: Authors, (2026).

### VII.3 STORY DEMANDS FOR THE THIRD MODEL (III)

For Model (iii), an irregularity is concentrated in the upper half of the structure, characterized by mass modification factors (MF) varying significantly from 0.25 to 4.0. This structural alteration results in a smooth, progressive change in both inter-story drift and story-shear profiles across the building's vertical extent. Figure. 9 illustrates that the base shear force peaks in models where mass irregularity is located in the lower stories. Conversely, it reaches its minimum in the upper stories, exhibits a moderate shift around mid-height, and then declines sharply in the upper half of the structure.

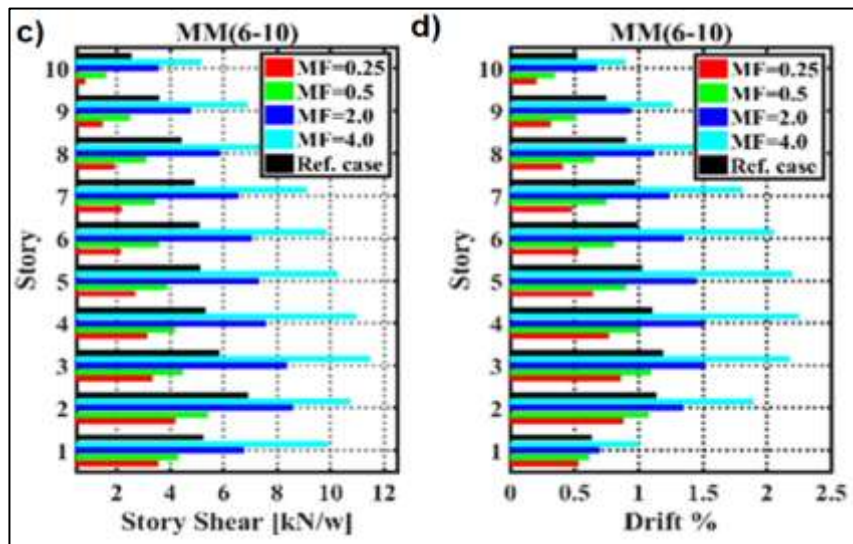


Figure 9: Story demands for the third model (iii).

Source: Authors, (2026).

Figure 10(a) presents the normalized base shear demands for irregular configurations as a function of mass irregularity location. The analysis indicates that varying the vertical level of a given mass irregularity yields only a marginal increase (approximately 2%) in base shear demand. However, when the mass irregularity is situated on the first floor, the normalized base shear is significantly greater than unity, which can be attributed to the contribution of higher modes and the pronounced effect of the increased mass. Nonetheless, the influence of the mass fluctuates as the irregularity ascends the structure. In the extreme scenario of a heavy story with  $MF = 4$ , the base shear demonstrates no substantial deviation from the regular case. It is particularly noteworthy that the first and second stories experience comparably larger base shear demands due to the development of greater inertial forces within these specific stories. The base shear demand does not appear large difference by changing the level of the same mass irregularity when values of  $MF < 1$  is assigned to lower stories. The normalized base shear is slightly greater than one when the mass irregularity is located on the first floor. This is due to higher mode influence and the significant increase in mass. Conversely, the mass effect intensifies as the irregularity moves to higher stories. For instance, with a heavy story ( $MF = 4$ ), the base shear changes considerably from the regular case. In particular, the upper floors are larger because they develop greater inertial forces than the other floors. As shown in Figure. 10(b), the normalized base shear varies with mass irregularity that extends more than one level, beginning at the first floor. Interestingly, the specific level of irregularity does not have a major impact on the sharp increase in normalized base shear.

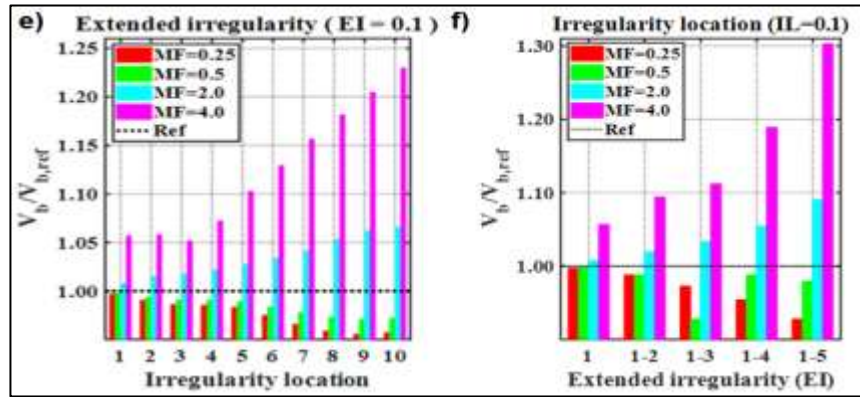


Figure 10: Variation of normalized base shear demands with the location and extended mass irregularity.  
Source: Authors, (2026).

For example, with MF (1–5) \* 4, the base shear ratio to the reference case is 1.05 (a 5% increase) and 1.3 (a 30% increase). This disparity is mainly due to alterations in the structure's fundamental dynamic characteristics and the effect of the number and length of bays, both of which influence the building system's fundamental frequency.

## VIII. QUANTIFICATIONS OF IRREGULARITY AND DEVELOPMENT OF THE IRREGULARITY INDEX

Although limits of mass irregularity have been defined by different codes of practice but quantification of irregularity mass in terms of a parameter has not yet been perfectly defined. Although building codes define threshold limits to identify mass irregularities, current design regulations cannot quantify their severity based on dynamic structural characteristics. The results demonstrate that the location of mass irregularity significantly influences critical response parameters, including fundamental period, base shear, story-shear distribution, roof displacement, and maximum inter-story drift. Therefore, the present subsection aims to quantify the degree of mass irregularity in reinforced concrete (RC) buildings using a proposed Irregularity Index (Ir) that depends on the dynamic characteristics, magnitude, and location of the irregularity. The proposed Irregularity Index (Ir) can help to identify the different degrees of mass irregularity based on its extent and location within the building.

### VIII.1 PROPOSED IRREGULARITY INDEX

The Irregularity Index (Ir) quantifies the structural irregularity of mass-irregular reinforced concrete (RC) buildings by dividing their maximum inter-story drift at the performance point by that of a corresponding regular RC building, as specified in Equation (1). This index effectively captures the extent of irregularity across various elevation levels in mass-irregular RC structures. An Ir value of zero indicates no mass irregularity, while higher positive values reflect increasing irregularity and lower positive values indicate decreasing deviation from regularity relative to the reference building. The maximum inter-story drift corresponding to the performance point is computed for both the irregular and regular RC buildings, thanks to displacement-based adaptive pushover analysis.

$$I_r = \frac{\sqrt{\sum_{i=1}^{n_{modes}} Drift_i^2}}{\sqrt{\sum_{i=1}^{n_{modes}} Drift_{ref,i}^2}} \quad (1)$$

After calculating the proposed irregularity index for different irregular models mentioned above, the relationship between the variations in location and levels of mass irregularity and the proposed irregularity index is illustrated in Figure. 11 and Figure. 12. It can be observed that: In the case of mass irregularity in a single story (Model (i)), the proposed irregularity index, shown in Figure. 11, increases in the lower half of the structure when MF > 1 relative to those of the stories when MF < 1. The opposite trend is observed in the upper half stories. The proposed irregularity index was maximum when the mass irregularity persisted in the fourth story (MF > 1), while it was minimum when the mass irregularity persisted in the top story. In the case when MF < 1, the proposed irregularity index was maximum when the mass irregularity persisted in the second story, while it was minimum when the mass irregularity persisted in the sixth story.

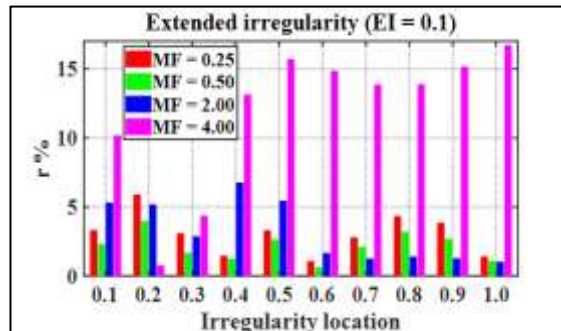


Figure 11: Variation of the proposed irregularity index with the irregularity location.  
Source: Authors, (2026).

In the case of extended irregularity ( $MF < 1$ ), the proposed irregularity index, according to Figure. 12(a), reach the top values when the irregularity extents over the first three stories and the first four stories, whereas, for  $MF > 1$ , the proposed index, according to Figure. 12(b), reach the top value when the irregularity extents over the upper five stories.

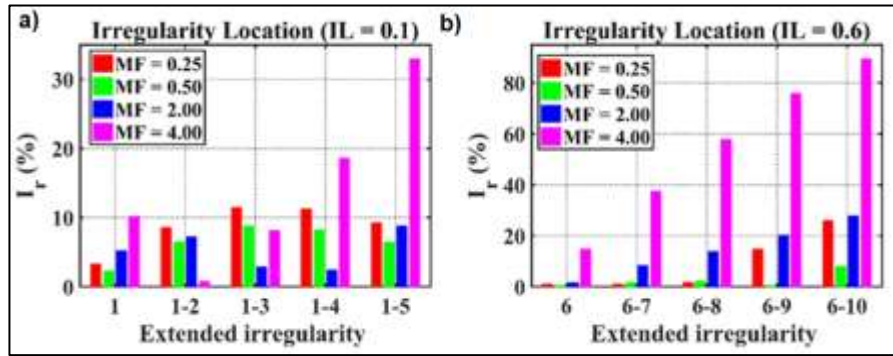


Figure 12: Variation of normalized base shear demands with the location and extended mass irregularity.  
Source: Authors, (2026).

## VIII.2 THE PROPOSED INDEX AND PREVIOUS INDICES

To verify the performance of the proposed irregularity index, a comparison of the results is provided with those calculated using the indices proposed by Sarkar et al. [25], as expressed in equation (2), and by Varadharajan, et al. [12], as expressed in equation (3), based on dynamic properties.

$$\eta = \frac{\Gamma_1}{\Gamma_{ref,1}} \quad (2)$$

$$\lambda_r = \sum_{i=1}^{nnmodes} \frac{\omega_r}{\omega_{ref,r}} \quad (3)$$

Where  $\omega_i$  denotes the natural frequency of the  $i$ -th mode,  $\Gamma_1$  represents the coefficient of the contribution of the first mode, and the subscript "ref" refers to the reference regular model.

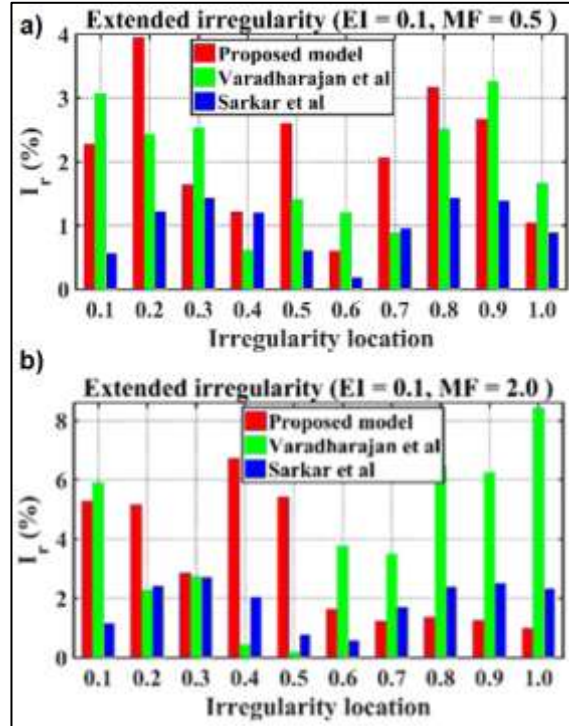


Figure 13: Comparison of the proposed index with the model index of Varadharajan, et al. [12] and Sarkar, et al. [25].  
Source: Authors, (2026).

According to the Irregularity Index ( $I_r$ ) proposed by Varadharajan, et al. [12], the degree of irregularity increases with the elevation of the mass irregular floors in all the single variation location, as illustrated in Figure. 13, and extended floor mass irregularity, as illustrated in Figure. 14 and Figure. 15. Furthermore, this Irregularity Index decreases with the increasing number of mass irregular floors at the same elevation in the RC building.

Hence, the Irregularity Index introduced by Varadharajan effectively measures mass irregularity in RC structures by analysing elevation characteristics. Consequently, the Irregularity Index ( $I_r$ ) proposed by Sarkar, et al. [25] proves insufficient in accurately evaluating mass irregularity concerning elevation distribution in reinforced concrete buildings.

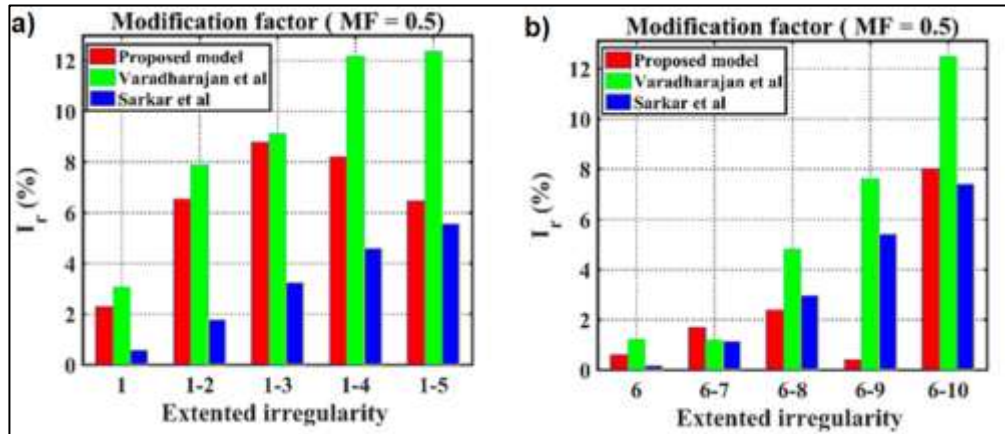


Figure 14: Comparison of the proposed index with the model index of Varadharajan et al and Sarkar et al for MF=0.5.  
Source: Authors, (2026).

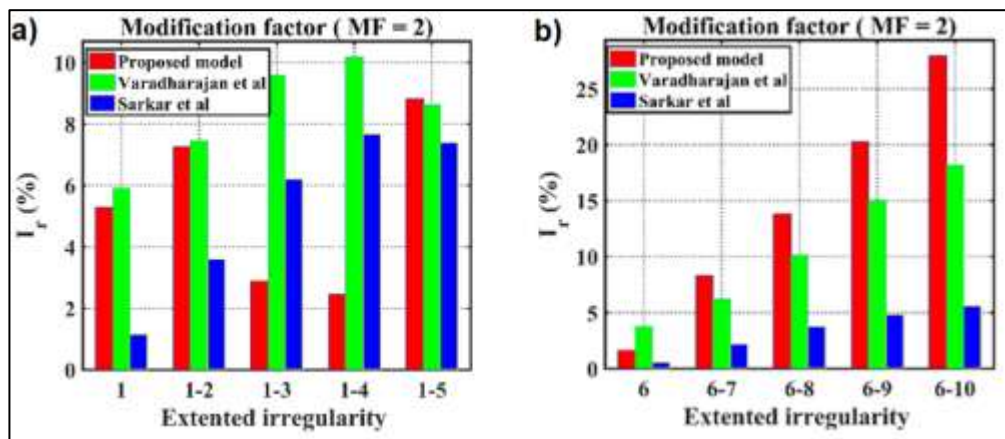


Figure 15: Comparison of the proposed index with the model index of Varadharajan et al and Sarkar et al for MF=2.0.  
Source: Authors, (2026).

Therefore, the influence of higher modes is integrated into the Irregularity Index ( $\lambda$ ), in contrast to the indices proposed by Varadharajan, et al. [12] and Sarkar, et al. [25], which do not account for such contributions

## IX. CONCLUSION

The analysis confirms that vertical mass irregularities substantially affect the dynamic seismic behavior of building structures. This investigation has provided a deeper understanding of these effects, underlining the importance of quantifying the influence of irregularity magnitudes on critical response parameters to support more efficient structural design practices. A procedure based on adaptive pushover analysis, which accounts for higher-mode effects, is assessed for estimating the deformation demands of irregular RC buildings. It does not require the execution of an "exact" nonlinear response history analysis, but only a series of nonlinear modal pushover analysis. Furthermore, this study aims to propose an irregularity index that can quickly identify the risky effects associated with modifying the weight of any story. It has been found that vertical mass irregularities generally have small effects on the inelastic response. Mass irregularities show relatively small effects on story shear demands. The roof drift demands, on average, do not change by more than 30% from the reference regular case. Likewise, additional mass, when applied at the first story generally, produced higher drift demands than regular structure for mass modification factors ( $MF > 1$ ). Consistently, the peak response value is observed at the second story across all irregular configurations, with minimal variation at mid-height and a rapid decline in the upper stories.

Generally, increasing the mass at the top of the structure has a more pronounced influence on roof drift and inter-story displacements than mass additions at mid-height or the base. Drift demands are formerly sensitive to both the degree and floor level of the mass irregularity. When the mass ratio was present at the top floor, the structures generally tended to produce greater drift demands than the corresponding regular structures, due to the contributions of superior modes. The current study instead attempted to quantify the degree of irregularity in high-rise buildings with irregular mass by proposing an irregularity index compared to other existing irregularity indices defined in the literature. A simple index based on the dynamic characteristics of the structure was defined to give a conservative measure of the increase in inter-story demand due to mass irregularity that can be used to set irregularity limits. Based on the analysis, the degree of mass irregularity in reinforced concrete buildings—especially when distributed across multiple elevations—has been accurately assessed using the proposed Irregularity Index ( $I_r$ ). Finally, additional comprehensive research is required to evaluate the impact of other forms of vertical irregularities, including those related to stiffness and strength.

## X. AUTHOR'S CONTRIBUTION

**Conceptualization:** Mohammed Hentri, Mostefa Lallam and Miloud Hemsas.

**Methodology:** Mohammed Hentri and Miloud Hemsas.

**Investigation:** Mohammed Hentri and Mostefa Lallam.

**Discussion of results:** Mohammed Hentri, Mostefa Lallam and Miloud Hemsas.

**Writing – Original Draft:** Mohammed Hentri.

**Writing – Review and Editing:** Mohammed Hentri, Mostefa Lallam and Miloud Hemsas.

**Resources:** Mohammed Hentri, Mostefa Lallam and Miloud Hemsas.

**Supervision:** Mostefa Lallam and Miloud Hemsas.

**Approval of the final text:** Mohammed Hentri, Mostefa Lallam and Miloud Hemsas.

## XI. ACKNOWLEDGMENTS

If necessary, quote entities that supported the development of the research.

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