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Original Research Article

# Determination of inelastic seismic demands of RC moment resisting setback frames

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ABSTRACT

In this paper, an extensive parametric study is conducted on plane RC moment resisting frames with setbacks. Firstly, a parameter called as 'irregularity index' is proposed based on the dynamic characteristics of the frame to quantify the setback irregularity. Secondly, this paper aims to determine the affect of setback presence on inelastic deformation demands. To achieve this purpose, building frames with different arrangements of setbacks are modeled and designed in accordance with the European standard code of practice. These frames are subjected to an ensemble of 13 ground motions scaled to different intensities in order to obtain different performance levels as prescribed by SEAOC 1995 and analyzed by time history analysis. Results of the analytical study indicate strong influence of the parameters like beam–column strength ratio, number of stories, geometrical irregularity and the performance level under consideration on inelastic seismic demands. Furthermore, a seismic response database consisting of 13,728 non-linear dynamic analyses is generated, and non-linear regression analysis is performed on this database to propose simple formulae to estimate different seismic parameters in terms of the proposed irregularity index. The applicability of author proposed equations in PBD and DBD is briefly discussed.



## 1. Introduction

The setback presence is quite common in the modern buildings, functional and aesthetic requirements being the main reasons for its preference. In urban areas, the setback buildings are quite useful as they provide adequate sunlight and ventilation for the bottom stories and approve with the building byelaw restrictions of 'floor area ratio' aspect prescribed by the Indian Building code [1]. The setback results in abrupt reductions in floor area of the buildings and it results in the variation of mass and stiffness along the building height. This variation of mass and stiffness changes the dynamic characteristics of the setback buildings as compared to their regular counterparts. The irregularity aspect has not been effectively considered by the seismic design codes which is shown by poor seismic performance of the setback buildings during the past earthquakes [2–4], and this depicts the inadequacy of the current seismic codes (which employ elastic analysis) based on which these buildings were designed.

The research works regarding the setback structures started in early 1970s with researches like Pekau and Green [5]; Humar and Wright [6] observed the inter-storey drifts to

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be higher at tower portion of the setback, but a reverse trend was observed in case of base portion of the setback. It is to be noted that in case of setbacks, the term 'base' refers to the lower level (largest number of bays) of the setback, and the term 'tower' refers to the upper level of the setback (smallest number of bays). A greater damage concentration was observed at the vicinity of the setback by Shahrooz and Moehle [7]. Wood [8] observed no difference in the seismic response of setback and regular structures. Wong and Tso [9] concluded that the first modal response is capable of representing the displacement response of the setback structure. Duan and Chandler [10] observed similar results of static and dynamic analysis for the setback structures, and suggested the strengthening of tower portion of the setback. Mazzolani and Piluso [11] had observations similar to Wood. Chen et al. [12] observed the damage concentration to be greater at the tower portion of the setback. Romeao et al. [13] observed better seismic performance of the setback frames as compared to the regular frames. Tena-Colunga [14] did not observe any undesirable damage concentration near the vicinity of the setback and contrastingly Khorey et al. [15] observed excessive damage concentration in setbacks (tower portion) in the upper stories. Karavasilis et al. [16] based on the results of parametric study conducted on a large number of steel frames observed greater damage concentration at the tower portion of the setback. Athanassiodu [17] observed adequate seismic performance of the setback frames designed as DCM and DCH as per ductility provisions of EC 8 [18].

D' Ambrisi et al. [19] proposed a modified pushover analysis method for determining the seismic response of building structures, and found comparable results by both pushover and inelastic dynamic analysis for setback frames.

Andreas Kappos and Stefanidou [20] proposed a new deformation design method based on inelastic analysis for the setback frames. The authors found the adequate seismic performance of the setback frames designed as per the proposed method. Xilin Lu et al. [21] performed non-linear time history analysis of the tall setback building and found excessive damage concentration in stories adjacent to setbacks.

The above literature review shows that the seismic response of the setback structures is rather unclear as some researchers indicate their adequate seismic performance [9,11,14,17], whereas other researchers suggest the opposite view [5–7,21].

As evident from the literature review, the current researchers are seriously considering the aspect of setback irregularity in determining the seismic response of a structure, and in formulating the seismic design methodologies. Nevertheless, some of the seismic design codes like EC 8:2004 [18] recognize the aspect of setback irregularity and prescribe dynamic analysis for seismic evaluation of such structures. In addition, EC 8:2004 prescribes a 20% reduction on value of behavior factor for irregular structures.

However, the procedures for estimating the deformation demands as prescribed by EC8:2004 [18] are based on single degree of freedom systems and elastic analysis. Furthermore, the previous research works regarding the setback irregularity mainly focus on the modification of equal displacement rule ($\mu = q$) which is valid for the relation as shown in Eq. (1)

$$T_b > T_c \text{ (Long period structures)} \tag{1}$$

where $T_b$ is the time period of the building, and $T_c$ is the critical time period of the ground motion considered.

However, in reality the fundamental time period of the structures may fall below the critical time period of the ground motion as shown below in Eq. (2)

$$T_b < T_c \text{ (Short period structures)} \tag{2}$$

As per EC 8:2004, the displacements for short period structures ($T_b < T_c$) can be computed using Eq. (3) as

$$\mu = 1 + (q-1)\frac{T_c}{T_b} \tag{3}$$

where $\mu$ is the displacement ductility and $q$ is the behavior factor.

Furthermore, the displacements and inter-storey drift ratio calculated by EC 8:2004 are based on the following assumptions as described in Eqs. (4) and (5).

$$D = D' \times q \tag{4}$$

$$d = d' \times q \tag{5}$$

where $D$ is the maximum displacement, $D'$ is the yield value of maximum displacement under reduced design lateral forces, $d$ is the maximum inter-storey drift, and $d'$ is the yield value of maximum inter-storey drift under reduced design lateral forces.

These relations (Eqs. (4) and (5)) imply that the codes assume the uniform inter-storey drift profiles along height of the frames for the irregular structures also, and this assumption is contradictory to the results of the previous research works regarding the setback structures [16,17]. Therefore, these procedures are unsuitable for design of the setback structures and there is a strong need for new procedures to determine the realistic seismic deformation demands. Nevertheless, these new procedures should be adapted as per the framework of the current seismic codes in order to include the aspect of structural irregularity in different stages of the building design.

Following the footsteps of previous research works [11,16], the present study at first aims to quantify the setback irregularity in the form of a parameter called as 'irregularity index' based on dynamic characteristics of the frame. Secondly, this study aims at determining the influence of parameters like beam–column strength ratio ($r$), setback irregularity, number of stories and ground motion characteristics etc. on heightwise variation of inelastic deformation demands for the building frames (with different configurations of setbacks subjected to an ensemble of 13 ground motions scaled to different intensities to achieve different performance levels) with $T_b < T_c$ to create a seismic response database. Based on nonlinear regression analysis conducted on the seismic response database, the equations to estimate the inelastic deformation demands are proposed. Thirdly, following the footsteps of Panagiotakos and Fardis [22], the authors have proposed the mean relation factors between inelastic and elastic deformation demands which can be readily used in initial stages of DBD and later stages of PBD. Finally, the applicability of the proposed relations and mean relation factors in performance-based design (PBD) and displacement based design (DBD) is discussed in brief through examples of a setback building model.