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EFFECT OF THE DAMPING RATIO OF NON-STRUCTURAL COMPONENTS ON FLOOR ACCELERATION DEMANDS IN TORSIONALLY IRREGULAR BUILDINGS

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Abstract

To investigate the effect of damping ratio of non-structural components on floor acceleration demands in torsionally irregular buildings, reinforced-concrete moment-resisting frame buildings resting on flat ground (regular), and on hill slopes (irregular) are analyzed. Bi-directional linear dynamic analyses are conducted, by applying a suite of far-field ground motions, along two orthogonal axes, to obtain the floor response of the investigated frames. From the obtained floor acceleration response of the investigated buildings, the elastic floor response spectra are derived at two different floor levels: (i) the floor with maximum eccentricity in the irregular building, and the corresponding floor in the reference regular building; and (ii) at the roof levels, for both the regular and irregular buildings, for NSC's damping ratios of 1%, 2%, 5%, and 10%. The effect of damping ratio of the NSCs is studied in terms of damping modification factors, at three different locations on each of the considered floor levels, i.e. (i) at the flexible edge, (ii) at the center of rigidity, and (iii) at the stiff edge. The derived median damping modification factors, as obtained from the time-history analyses are compared with the recommendations of EC 8 and other existing models available in the literature. It is observed that the recommendations of EC 8 underpredict damping modification factors significantly, for non-structural components, tuned to structural modes of vibration, especially, for low damping ratios of the non-structural components, and also for relatively flexible non-structural components, for high damping ratio of the non-structural components.

Keywords: Damping Modification Factors, Floor Response Spectra, Non-structural Component, Seismic Design, Torsional Irregularity.

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1 INTRODUCTION

Components and systems which are neither a part of the gravity load-resisting system nor a part of the lateral load-resisting system, but offer functionality to the buildings are termed as '*non-structural components*' (NSCs) or '*secondary systems*'. The typical examples of these NSCs in a building include electrical and mechanical equipments, architectural elements, bookshelves, suspended ceilings, furniture, and elevators. Typically, NSCs in buildings are either sensitive to the inertia forces, or to the inter-story drifts, or sometimes to both. Thus, based on sensitivity of their response, these NSCs are sub-categorized as: (i) acceleration-sensitive NSCs, (ii) displacement-sensitive NSCs, and (iii) combined acceleration- and displacement-sensitive NSCs. Seismic safety of NSCs is not only crucial due to their higher contributions to the total cost of the buildings (e.g. 70-80% of the total cost of the structure, especially in commercial buildings [1]), but, inoperability of these NSCs due to damage during earthquakes (specifically in lifelines buildings, e.g. hospitals) could lead to increased casualties, and delayed post-earthquake recovery operations. As a result, assessing the adequacy of the existing provisions, and developing new provisions, for ensuring seismic safety of NSCs is considered as an essential step in performance-based earthquake engineering.

It is a well-established fact in the literature [2-8] that dynamic response of the acceleration-sensitive NSCs is affected by the characteristics of both the structure and NSC itself. The typical structural characteristics which affects seismic response of NSCs include e.g. modal periods, height of the structure, stiffness distribution along the height of structure, strength of the structure, and its lateral-load resisting system [2-5]. On the other hand, the NSC's characteristics which affects their seismic response include the location of NSCs in the building, period of the NSCs, and the damping ratio of the NSCs [2-5]. A critical review of the existing literature suggests that most of the NSCs exhibit a low damping ratio, which typically ranges between 1-2% [9-12]. However, the various national building codes [13, 14], as well as most of the past studies [6-8] considered the NSC damping ratio equal to 5%.

Few studies conducted so far [2-5] identified the influence of damping ratio of the NSCs, on their floor acceleration demands. Medina *et al.* [2] conducted a study on the elastic and inelastic regular moment-resisting frame buildings, and observed that a lower damping ratio of the NSCs leads to amplification of the acceleration response, and a reduction in the NSC damping ratio from 5% to 2%, can result approximately 50% amplification in the acceleration demands on NSCs. Anajafi and Medina [4] conducted investigations on code designed structures to study the influence of the damping ratio of the NSC on the floor acceleration demands, and identified that the amplification/de-amplification in the floor accelerations, due to a decrease or increase in the damping ratio of the NSC, is a function of the tuning ratio (defined as the ratio of between the period of the NSC, T_s, to the fundamental period of the building, T_1). Further, the effect of damping ratio of the NSCs was observed to be more pronounced, when NSCs are tuned to any structural modes of vibration, and less pronounced (minimal) for the non-tuned conditions. These findings of the investigations by Anajafi and Medina [4] were further supported by the recorded floor motions in 47 instrumented buildings, located in California [5]. Based on these findings, Anajafi and Medina [4] proposed a simplified tuning ratio dependent model to estimate damping modification factors (DMFs) to scale up or down the ordinates of the 5%-damped elastic floor response spectra, to account for the actual damping ratio of the NSCs.

The studies conducted so far to evaluate the influence of damping ratio of the NSCs on estimated floor acceleration demands are mostly based on NSCs mounted on regular buildings. The dynamic behaviour of the buildings is significantly altered by presence of torsion in the buildings, resulting coupling between translational and torsional motions. Thus, the present study aims to investigate the influence of the damping ratio of NSCs on the floor acceleration demands, in torsionally irregular buildings. Accordingly, two different buildings, i.e. the reference regular building, and the irregular step-back building are considered for assessments in the present study. Bi-directional linear time-history analyses are conducted using a suite of recorded far-field ground motions. The elastic floor response spectra are obtained at two different floor levels, i.e. (i) at the floor with maximum eccentricity between centre of mass (CM) and centre of rigidity (CR) in the irregular building, and at the corresponding floor in the reference regular building; and (ii) at the roof levels, for both regular and irregular buildings, for NSC's damping ratios of 1%, 2%, 5%, and 10%. From the obtained floor response spectra, DMFs are derived at the CR in the reference regular building, and at CR, flexible edge (FE) and stiff edge (SE) in the irregular step-back building. The derived DMFs from time-history analyses are compared with the recommendations of EC 8 [14] and other models [4] in the existing literature, and the influence of the damping ratio of the NSCs on floor acceleration demands in torsionally irregular buildings is discussed and quantified.

2 NUMERICAL STUDY

2.1 Details of the investigated buildings

In the present study, two different 4-storied reinforced-concrete (RC) moment-resisting frame buildings, i.e. the reference regular building resting on plain ground, and the step-back irregular building on sloping ground are considered. The plan and elevations of the considered buildings are shown in Fig. 1. The step-back building considered in the assessments rest on a ground, having a slope of 2:1 (H:V), resulting a moderate slope angle of 27.3 degrees. In both, the regular and irregular buildings, the floor-to-floor height is considered as 3.3 m and set constant for all floors. In the irregular building, the ground supported short columns are of two different heights, i.e. 1.1 m and 2.75 m, in the successive storeys. Three-dimensional numerical models of the regular and irregular buildings are developed in OpenSees [15]. The structural elements, i.e. beams and columns are modelled as *ForceBeamColumn* elements*,* and floor slabs are defined as rigid diaphragms. The effective stiffness of RC beams and columns is modelled as per the recommendations of ASCE 41-17 [13]. Gravity loads (dead and live loads) on the considered buildings are applied as per the relevant Indian Standards [16, 17]. The investigated set of buildings are designed as the Special Moment Resisting Frame (SMRF) buildings, following the provisions of the Indian Standards [18-20], at the rock/stiff site, for the highest seismic zone (Zone V) in India. The member sizes are proportioned to result the longitudinal reinforcement in beams between 0.75-1.5 %, and in columns between 2-4 %, consistent with the typical design practice adopted in North India.

2.2 Dynamic characteristics and torsion in the investigated buildings

As highlighted in the past research [2-8], the floor response is significantly affected by the dynamic characteristics of the building, therefore, the dynamic characteristics of the investigated buildings are summarized in Table 1. Past investigations [21] on irregular step-back buildings suggest that in such buildings, the period corresponding to the fundamental mode of vibration is usually controlled by the number of storeys measured on the uphill side (Fig. 1(d)), irrespective of the direction under consideration. The very same effect is evident in the obtained periods of vibration in the present study (Table 1), where the first mode periods for the reference regular and irregular step-back buildings are in close agreements. In addition, the irregular step-back buildings are subjected to torsion, due to non-coincident locations of CM and CR (Fig. 1(b)). In the present study, CR is obtained considering the definition of the single floor eccentricity. The additional details about estimation of CR in the investigated step-back building is available elsewhere [21]. Based on the obtained estimates of the eccentricity between CM and CR, it is observed that in the investigated irregular step-back building, the maximum torsional effects exist at the base floor (Fig. 1(b)), which further reduces while moving upwards, from base floor to the roof level (Fig. 1(a)). Accordingly, in the present study, the detailed results are reported for these two floor levels only.

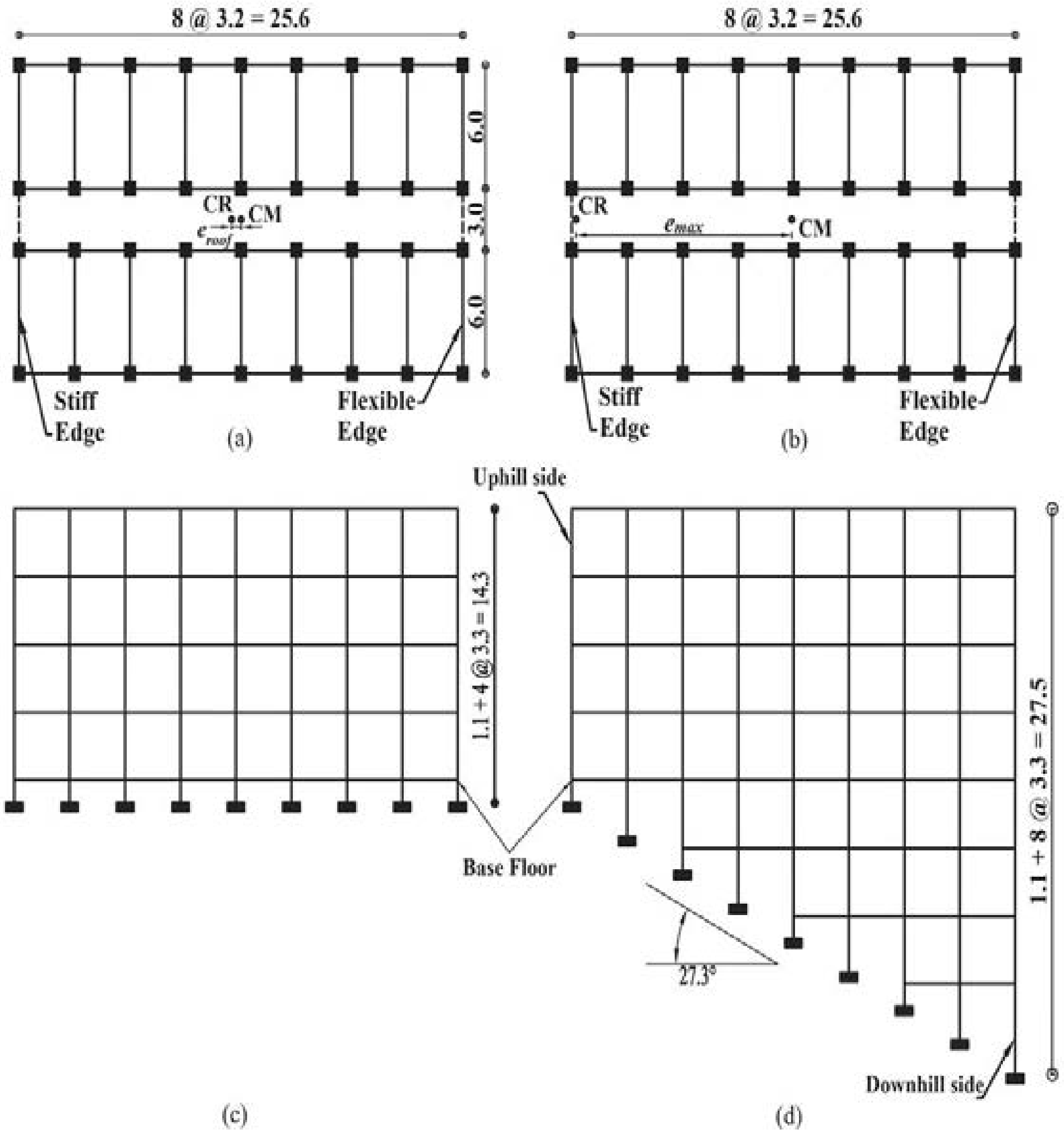

Figure 1: Typical plan and elevation layouts: (a) floor plan of the step-back building, at the roof level, (b) floor plan of the step-back building, at the base foundation level, (c) elevation of the reference regular building, and (d) elevation of the step-back building, in the direction along the slope. The dashed lines define the boundary of the floor slab. CM and CR denotes the locations of the center of mass and center of rigidity in the floor plan. All dimensions are in meters.

2.3 Ground motions and linear dynamic time-history analyses

In the present study, the suite of 22 pairs of far-field recorded earthquake ground motions (having moment magnitudes varying between M_w 6.5 to M_w 7.6, with an average value of M_w 7.0, as specified in the FEMA P695 [22]) are considered. For performing the bi-directional time-history analyses, both the horizontal components of seismic ground-motion records are applied simultaneously, along the two orthogonal axes of the investigated buildings. A total of 44 linear time history analyses have been performed for each of the investigated buildings, by interchanging the two horizontal components of seismic ground-motions, along the two principal axes of the buildings. The viscous damping in the considered buildings is modelled as Rayleigh damping of 2.5% [23], and it is defined corresponding to the periods equal to 1.5 times the fundamental mode period ($1.5T_1$), and the period resulting in a total of 95% cumulative mass participation, in both directions.

Building Type	Mode of Vibration	T_{ALS}	T_{ACS}	α_{mx} (%)	α_{my} (%)
Regular	First mode	1.23	1.73	72.00	71.00
	Second mode	0.40	0.53	08.07	09.28
	Third mode	0.24	0.28	02.50	03.52
Irregular	First mode	1.21	1.74	52.00	51.00
	Second mode	0.39	0.53	05.78	07.29
	Third mode	0.23	0.29	01.72	14.00

T_{ALS} and T_{ACS} are the modal periods of vibration in the along and the across-slope directions of excitations, respectively, whereas, α_{mx} and α_{my} are the modal mass participation ratios in the along and across-slope directions of excitations, respectively.

Table 1: Dynamic characteristics of the investigated regular and irregular buildings.

3 RESULTS AND DISCUSSIONS: DMFS FOR FLOOR RESPONSE SPECTRA

In the present study, a total of 5,104 elastic floor acceleration response spectra are computed at different floor levels, along the height of both the regular and irregular buildings. These floor response spectra are computed at the CR in the regular building, and at the CR, the FE and the SE in the irregular building, for NSC's damping ratios of 1%, 2%, 5% and 10%. The obtained floor acceleration response spectra are used to estimate DMFs, i.e. the ratio between the floor spectral acceleration ordinate at any given period, corresponding to a NSC's viscous damping ratio, ξ_s, to the floor spectral acceleration ordinate at the same period, corresponding to NSC's viscous damping ratio of 5%, as defined through Eq. 1

$$DMF(T_s, \xi_s) = \frac{S_a(T_s, \xi_s)}{S_a(T_s, 5\%)} \tag{1}$$

where, $DMF(T_s, \xi_s)$ is the damping modification factor corresponding to NSCs period of vibration, T_s, and damping ratio, ξ_s, $S_a(T_s, \xi_s)$ is the floor spectral acceleration corresponding to NSCs period of vibration, T_s, and damping ratio, ξ_s, and $S_a(T_s, 5\%)$ is the floor spectral acceleration corresponding to NSCs period of vibration, T_s, and damping ratio of 5%. These DMFs are derived at all the floors, for both the regular and the irregular building, however, the results at the base floor and at the roof level are reported herein, for the sake of brevity.

Figure 2 presents the variations of DMFs in the across-slope direction (in which the torsional effects are present in case of the irregular step-back building), for the investigated regular and irregular buildings, at the base floor. It is to be noted that at the base floor, the CR and the SE are in close proximity to each other (Fig. 1(b)), and thus, the median floor response spectra at the CR and the SE overlaps with each other, in case of the irregular building. It can be observed that at the base floor level, the median DMFs estimated from the elastic floor response spectra (derived from the floor motions) at CR are in close agreement with those recommended in EC 8, for non-tuned response of the NSCs, whereas, non-conservative for the tuned response of the NSCs, especially, when NSCs are tuned to higher modes of vibration. These observations can be attributed to the fact that the NSCs are subjected to limited filtering effects by the structure, due to insignificant contributions of the different modes of vibration at the base floor level.

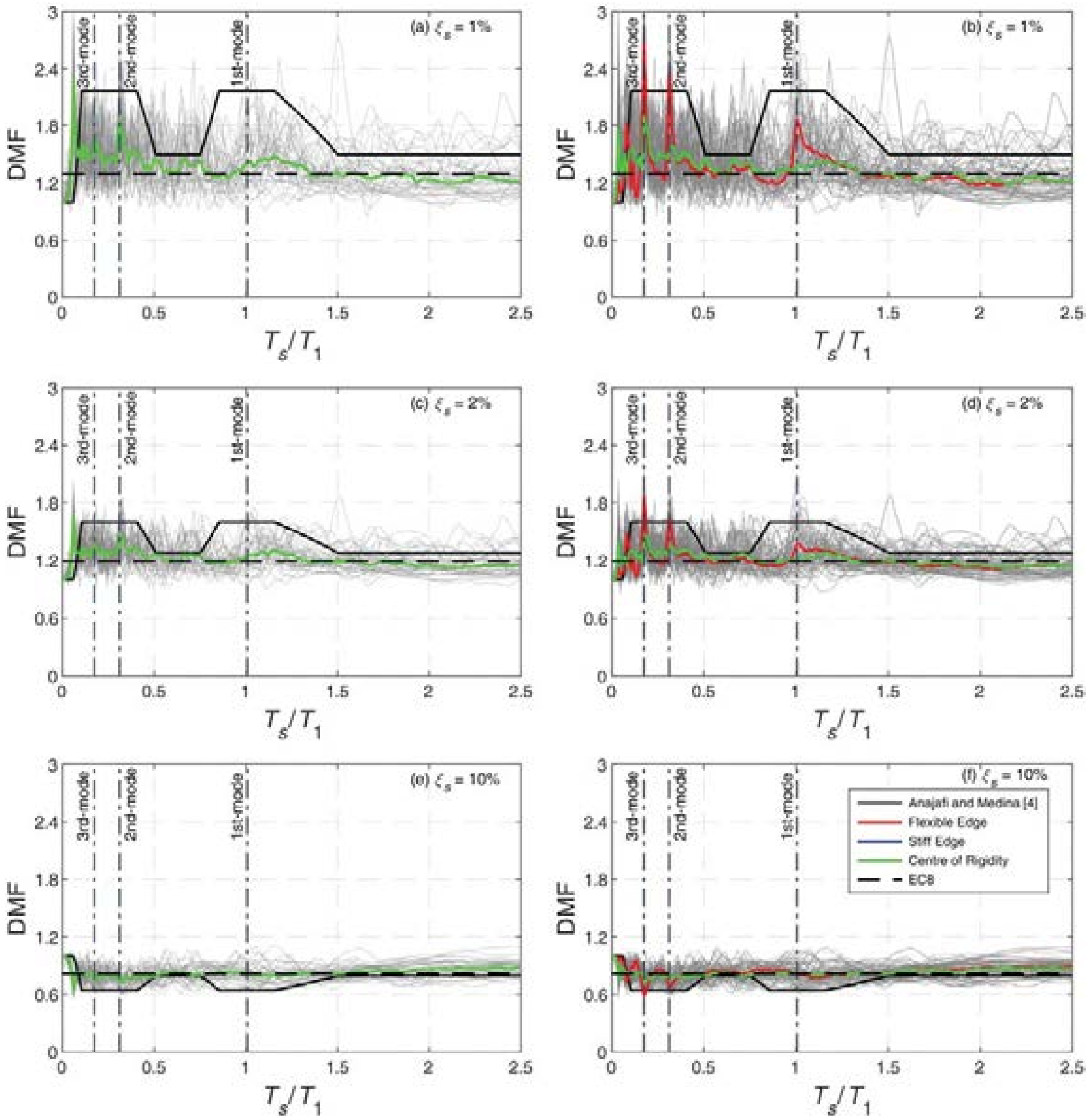

Figure 2: Comparisons of DMFs at the base floor (computed using linear dynamic analyses), with the available model in literature and EC 8. The first column in the plots corresponds to the derived DMFs for the regular building, whereas, the second column corresponds to the derived DMFs for the irregular building.

In case of irregular building, when NSCs are tuned to higher modes of vibration, the estimated DMFs at FE from EC 8 are underestimated by a factor of 2.12 and 1.56 (Fig. 2(b) and 2(d)), for NSC's damping ratios of 1% and 2%, respectively. On the other hand, at the base floor level, the DMF model proposed by Anajafi and Medina [4] provided significantly conservative estimates of the DMFs at the CR (Fig. 2(a)-(d)), for low damping ratios of the NSCs (i.e. 1% and 2%). However, this conservatism vanished at the FE, especially under the tuned response of the NSCs corresponding to higher modes (Fig. 2(b) and 2(d)). Further, the DMFs obtained from EC 8 (at the CR and the FE), corresponding to NSC's damping ratio of 10% are observed to be reasonable at the base floor, upto tuning ratios of 1.50 (Fig. 2(e)-(f)), for both the regular and irregular buildings. Contrarily, at the base floor, for NSC's damping ratio of 10%, the DMF model proposed by Anajafi and Medina [4] provided non-conservative estimates of the DMFs under tuned response of NSCs (Fig. 2(e)-(f)), at the CR and the FE.

Figure 3 presents similar results at the roof level of regular and irregular buildings investigated in the present study. It is to be noted that at the roof level, only minor eccentricity exist in between CM and CR (Fig. 1(a)), thus, at the roof level, torsional effects are minimal. This effect is manifested in the form of almost overlapping median floor response spectra, for a given damping ratio of interest, at the CR, the FE and the SE (Fig. 3(b), 3(d), and 3(f)).

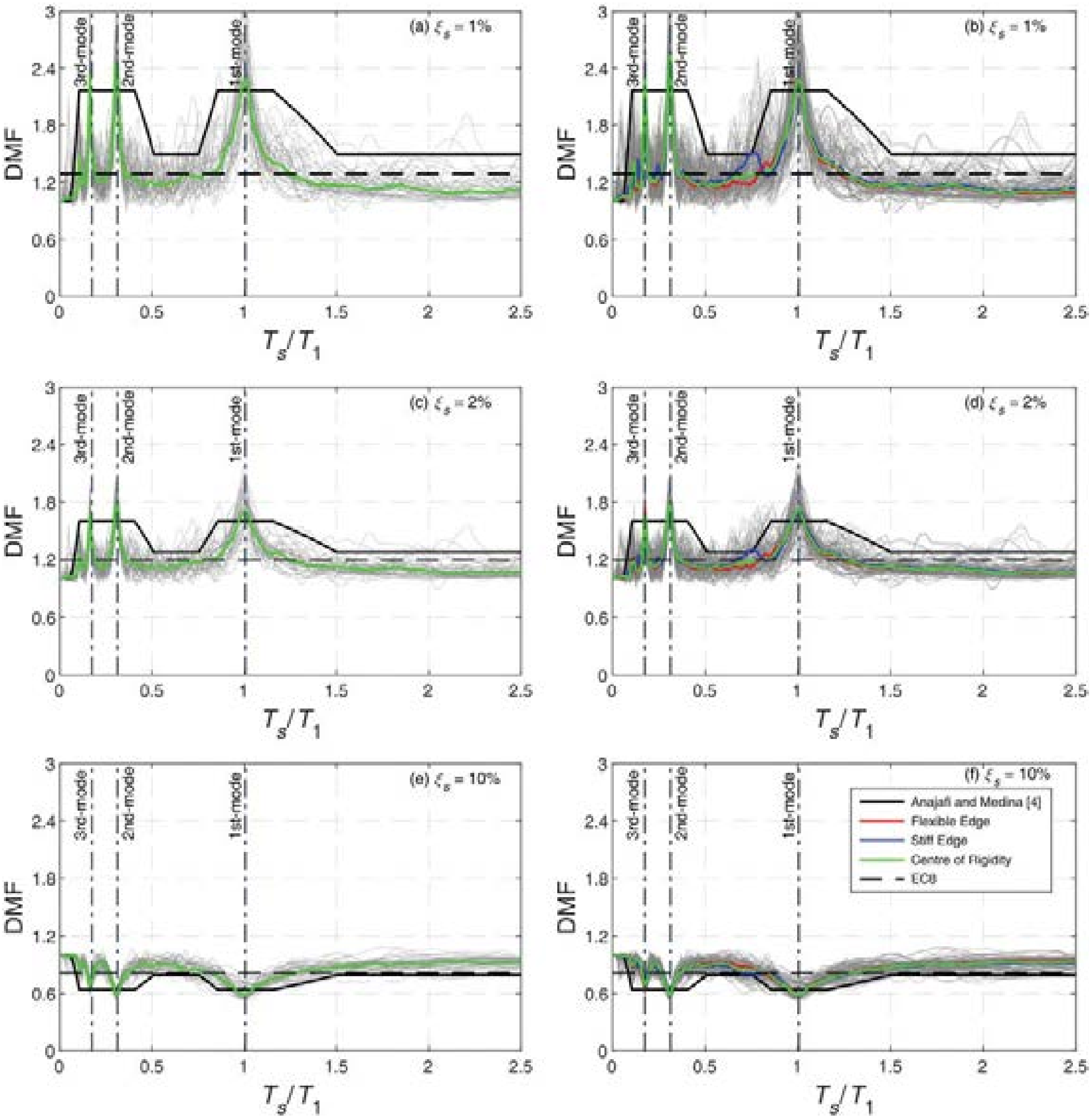

Figure 3: Comparisons of DMFs at the roof level (computed using linear dynamic analyses), with the available model in literature and EC 8. The first column in the plots corresponds to the derived DMFs for the regular building, whereas, the second column corresponds to the derived DMFs for the irregular building.

From Fig. 3, it is further evident that DMFs are tuning ratio dependent, and sharp peaks are observed in DMFs corresponding to the structural modes of vibration. As a result, the DMF model recommended in EC 8 underestimated median DMFs (obtained from floor response spectra) by a factor of 1.94 and 1.50 (Fig. 3(a)-(d)), for NSC's damping ratios of 1% and 2%, respectively, when NSCs are tuned to the structural modes of vibration. For the non-tuned response of the NSCs having low damping ratios (i.e. 1% and 2%), the DMF model recommended in EC 8 is observed to be reasonable, at the roof level (Fig. 3(a)-(d)). Contrarily, the model proposed by Anajafi and Medina [4] provided slightly non-conservative estimates of DMFs for tuned response of the NSCs to the structural modes of vibration, for both regular and irregular buildings ((Fig. 3(a)-(d))). For high damping ratio of NSCs (i.e. 10%), at the base floor level as well as at the roof level, both the models, i.e. EC 8 and the one proposed by Anajafi and Medina [4] provided slightly non-conservative estimates of DMFs, for tuning ratios more than 1.50 (Fig. 2(e)-(f) and Fig. 3(e)-(f)), at both locations on the floor plan, i.e. at the CR and at the FE.

The observations presented in the study highlighted some of the shortcomings of the existing models in the literature and building codes to account for the actual damping ratio of NSCs in its seismic design and warrants a need for more reliable estimation of DMFs, for seismic design of NSCs.

4 CONCLUSIONS

This study investigated the effects of damping ratio of non-structural components on floor acceleration demands for the reference regular and irregular step-back buildings. A total of 88 bi-directional linear time history analyses were conducted, and 5,104 floor response spectra were evaluated at different floor levels of the investigated buildings. DMFs were computed for the NSC damping ratios of 1%, 2%, 5%, and 10% and compared with the existing DMF prediction model available in the literature as well as in EC 8. The following major conclusions are drawn from this study:

- Consistent with the observations of the earlier studies [4-5], DMFs are observed to be tuning ratio dependent. This observation is found to be valid for both regular and torsionally irregular step-back building, investigated in the present study.
- Due to the presence of severe torsion at the base floor level, the estimated (median) values of DMFs, at the CR and the FE differs significantly, for the irregular step-back building. This effect was observed to be more pronounced for low damping ratio of the NSCs (i.e. 1% and 2%), especially, when NSCs are tuned to structural modes of vibration.
- For the range of damping ratios investigated in the present study, the DMF model recommended in EC 8 under predicted the median DMFs for the floor response spectra upto a factor of 2.12, when NSCs were tuned to structural modes of vibration.
- For higher damping ratio of NSCs (i.e. 10%), due to limited filtering effects at the base floor, the model proposed by Anajafi and Medina [4], provided non-conservative estimates of DMFs, for NSCs tuned to structural modes of vibration. Further, both the investigated models, i.e. the existing DMF prediction model [4] as well as EC 8 were found to be non-conservative, for relatively flexible NSCs (T_s/T_1>1.50).

The present study was conducted considering mid-rise regular and irregular step-back buildings, exhibiting their elastic response. Further the study used ground motions recorded in far-field. Separate studies are recommended to further examine DMFs for other buildings types, for ground motions having different characteristics, and also considering the inelastic response of the buildings.

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