Effect of Supporting Structure's Torsion on Floor Acceleration Demands in Buildings on Slopes

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1 Introduction

Components and systems that are neither a part of the gravity nor a part of the primary lateral load-resisting system but offer functionality to a building structure are termed as secondary systems or non-structural components (NSCs). The seismic response of these NSCs is either sensitive to the inertia forces or to the inter-story drifts. Thus, based on the sensitivity of their response, these NSCs can be subdivided under three main categories: (i) acceleration-sensitive NSCs, (ii) drift-sensitive NSCs, and (iii) combined acceleration- and drift-sensitive NSCs. The relative share of these NSCs to the total cost of the building can vary between 70–80% in the case of commercial buildings [1]. Specifically, in hospital buildings, the in-operability of these NSCs could hamper the post-earthquake relief operations, whereas, in the case of office buildings, it may lead to business interruption and downtime losses. Therefore, developing adequate seismic design provisions for ensuring seismic safety of NSCs on buildings got attention in the recent past.

Several studies have already been conducted in the past addressing seismic design of acceleration-sensitive NSCs [2]; however, the studies which especially focussed on incorporating the effect of supporting structures torsion on seismic response of NSCs are very limited. Yang and Huang [3] studied the behaviour of the NSCs mounted on a multi-story building, exposed to significant torsional deformations, under seismic actions. The amplification of equipment's acceleration due to the presence of torsion was observed to be dependent on the modal participation factor for the torsional modes of vibration. Agrawal and Datta [4] observed that yielding of the torsionally coupled primary system has a significant effect on the response of the secondary structure, which was observed to be reduced under the tuned condition and amplified

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S. Kolathayar and S. C. Chian (eds.), *Recent Advances in Earthquake Engineering*,
Lecture Notes in Civil Engineering 175,
https://doi.org/10.1007/978-981-16-4617-1_15

under the non-tuned condition. Agrawal and Datta [5] studied the response of the NSCs, mounted on the torsionally coupled primary structure, under bi-directional seismic ground motions and reported that under tuned conditions, with an increase in the eccentricity of the primary system, the response of the secondary system increases.

Aldeka et al. [6] studied seismic behaviour of the NSCs attached to irregular reinforced-concrete (RC) buildings. They found that the acceleration of NSCs increases with an increase in the input PGA, provided the primary structure responds elastically. They highlighted that NSCs attached to the flexible edge (FE) of high-rise buildings get more influenced by the torsional behaviour as compared to the low-rise buildings. Aldeka et al. [7] observed that the eccentricity ratio of the primary structure has an insignificant effect on the behaviour of the NSCs attached to the centre of rigidity (CR) of the primary structure. Surana et al. [8] investigated the floor acceleration demands in multi-story hillside step-back (SB) and split–foundation (SF) RC buildings. They found that both FEMA P750 and Eurocode 8 models undervalue the peak floor acceleration demands in hillside buildings. Vijayanarayanan and Goswami [9] conducted the linear and nonlinear time history analyses of some typical RC buildings resting on hill slopes. They observed the floor acceleration response along the FE to be higher than as that of the stiff edge (SE).

The past studies [2–9] reported that the dynamic characteristics of the primary structure plays a crucial role in seismic design of NSCs. So far, the various seismic design provisions which are in existence in different codes for seismic design of NSCs have been developed for regular buildings. In hilly terrain, the buildings are usually constructed following the land's slope to suit its geometry [8, 9]. These buildings on hill slopes pose both the plan and elevation irregularities due to the differences in the column heights within the same storey, and differences in the strength, mass, and stiffness of the successive stories, resting on a slope. As a consequence of the presence of plan irregularity, these buildings exhibit torsional response while subjected to excitation in across-slope direction. Thus, this study makes an attempt to study the effect of torsion on floor response of buildings resting on slope.

Accordingly, in this study, flat ground (FG) and SB buildings with two different heights (i.e., 2- and 4-storey) have been analysed to study their floor acceleration response. Floor response spectra (FRS) corresponding to NSC damping ratio of 5% are evaluated at two different floor levels, i.e., at the floor level immediately above the topmost foundation level and at the roof level, at different locations on the respective floors (i.e., at the FE, the CR and the SE). Torsional amplification factor (TAF), defined as the ratio between the floor spectral ordinate at the FE or SE to the floor spectral ordinate at the CR for any spectral period of interest, is computed in across-slope direction. A correlation of the TAF with the various parameters described in building codes to quantify the torsional irregularity in the buildings has been studied.

2 Numerical Study

2.1 Building and Modelling Details

A group of RC frame buildings with FG and SB configuration, having an identical plan shape as shown in Fig. 1, with two different building heights, i.e., 2- and 4-storey, are analysed in the current study. For SB buildings, the height above the topmost foundation level has been assumed to determine the number of storeys [8], whereas, the storeys below the topmost foundation level are obtained considering a slope angle of ~27°. The height of the storey is taken as 3.3 m and set constant for all the storeys. In SB buildings, the short columns are assigned a height of 1.1 and 2.75 m, in successive stories resting on slope. Three-dimensional structural models of the FG and SB buildings with 2- and 4-storey (above the topmost foundation level), considered in this study, are created in OpenSees [10]. The beams and columns are modelled using *ForceBeamColumn* elements, while the slab is modelled as a rigid diaphragm. The effective cracked moment of inertia for beams and columns is considered as 30% of the gross moment of inertia as per guidelines given in ASCE 41-17 [11]. Dead loads and live loads are considered as per recommendations of Indian standards, IS 875 Part 1 [12] and IS 875 Part 2 [13], respectively. The buildings considered are designed as special moment-resisting frames (SMRF) for Seismic Zone V on soil type I (rock site), following the provisions of the relevant Indian standards, IS 456 [14], IS 1893 Part 1 [15], and IS 13920 [16]. The typical beams and columns are proportioned to result longitudinal reinforcements between 0.75–1.5% and 2–4%, respectively.

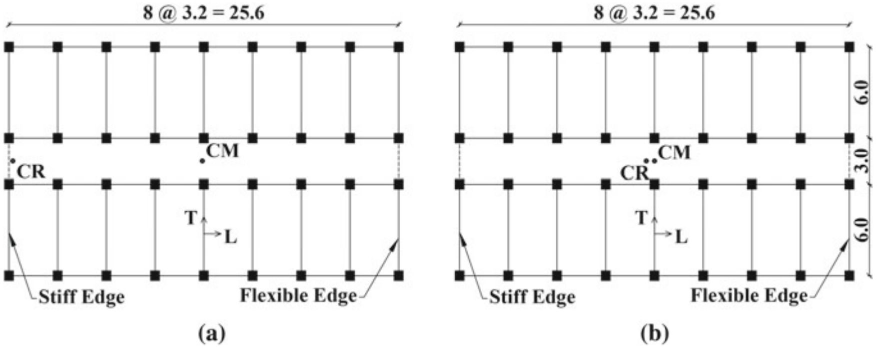

Fig. 1 Typical plan layouts: **a** floor plan of SB building, at the floor immediately above the topmost foundation level, and **b** floor plan of the SB building, at the roof level. The dotted lines determine the boundaries of the floor slab (CM and CR represents the locations of the centre of mass and centre of rigidity in the floor plan, Longitudinal (L) direction is considered to be along-slope, whereas, transverse (T) direction is considered to be across-slope)

Table 1 Dynamic characteristics of the building models considered

Building model		Period of vibration (s)		Period ratio	Modal mass participation ratio (%)	
N	Direction	First mode (T_1)	Second mode (T_2)	T_2/T_1	α_{m1}	α_{m2}
2FG	Along-slope	0.63	0.21	0.34	65.00	05.65
	Across-slope	0.85	0.26	0.30	64.00	08.77
4FG	Along-slope	1.23	0.40	0.33	72.00	08.07
	Across-slope	1.74	0.53	0.31	71.00	09.28
2SB	Along-slope	0.62	0.21	0.34	38.66	03.78
	Across-slope	0.88	0.31	0.35	39.43	36.24
4SB	Along-slope	1.21	0.39	0.33	51.68	05.70
	Across-slope	1.74	0.53	0.31	50.93	07.12

N–no. of floors above the topmost foundation level, FG–building on the flat ground, SB -step-back building, α_{m1} and α_{m2} are the modal mass participation ratios corresponding to the fundamental and second modes of vibration in a given direction of excitation

2.2 Dynamic Characteristics of the Considered Buildings

The dynamic characteristics of the buildings investigated in the present study are summarized in Table 1. Consistent with the observations of the previous studies [8], in case of SB buildings, the period corresponding to the fundamental mode of vibration (T_1), is controlled by the number of storeys above the topmost foundation level, in both the directions of excitations (i.e., along and across slope). The structural response in low-rise SB buildings is dominated by the fundamental mode in the building portion above the topmost foundation levels, whereas, at the storey just above the topmost foundation level as well as in the building portion below the topmost foundation level, it is dominated by the higher modes of vibration. These observations are important in understanding the floor acceleration response of the SB buildings, as it is significantly influenced by the dynamic characteristics of the structure.

2.3 Ground Motion Records Selected for Analysis

In order to study the behaviour of the considered buildings, bidirectional linear time-history analyses are conducted by implementing the suite of 22 pairs of far-field recorded earthquake ground motions as given in the FEMA P695 [17]. The moment magnitude of these ground motions ranges from M_w 6.5 to M_w 7.6 with an average magnitude of M_w 7.0. The time-history analyses are performed by applying both the horizontal components of a seismic ground-motion records at the same time, along the two orthogonal directions (i.e., along the slope and across the slope). For each of the

FG and SB buildings, a total of 44 linear time history analyses have been conducted by interchanging the two orthogonal components of seismic ground-motions along two principal axes of the buildings. The viscous damping effects in the time history analyses are considered by defining a Rayleigh damping of 2.5% [18] at periods equal to 1.5 times the fundamental mode period, and the period resulting in 95% cumulative mass participation in both the directions.

3 Torsional Irregularities in Step-Back Buildings

Torsional irregularity is one of the most prominent type of the structural irregularity which is often observed in the existing housing stocks. There are several factors which in turn induce torsional irregularity in buildings, some of which include the use of unequal column heights within the same storey, non-uniform distribution of stiffness of the lateral load-resisting elements in the building plan, asymmetric placement of infill walls in the building. The presence of any of the aforementioned factors results in a net difference in the location of the CM and CR, often referred as the eccentricity in the floor plan. The presence of eccentricity in any floor induces torsional effects in the building, usually causing an amplification in the seismic response at the FE.

According to ASCE 7-16 [18] provisions, if the ratio between the maximum horizontal displacement (Δ_{max}) at one end and the average horizontal displacement (Δ_{avg}) at the two ends of the structure is greater than 1.20, then the structure is considered as torsionally irregular. Further, when this ratio exceeds a value of 1.40, the structure is said to have an extreme torsional irregularity. Similarly, according to IS1893:2016 [15], a building is said to have a torsional irregularity, when the ratio between the maximum horizontal displacement (Δ_{max}) at one end, and the minimum horizontal displacement at the other end (Δ_{min}) exceeds a value of 1.50. Contrarily, a different sort of definition of torsional (plan) irregularity is defined in Eurocode 8 [19], and the torsional irregularity is said to exist, when the normalized eccentricity ratio (e/r, where e is the eccentricity between the CM and CR, and r is the torsional radius) surpasses a value of 0.30. In the present study, three different indices are used to assess the extent of torsional irregularity in the investigated structures.

Figure 2 presents the variation of these three indices, i.e., normalized eccentricity ratio $\Delta_{max}/\Delta_{avg}$ and $\Delta_{max}/\Delta_{min}$ obtained from a 3D linear dynamic analysis along the height of 2- and 4-storey SB buildings. The maximum torsional effects are observed to exist at the storey immediately above the topmost foundation level. This observation is consistent among all the three indices considered herein to quantify the effect of torsion. Further, at the roof level, the extent of torsion present in the 2-storey SB building is higher than as compared to the 4-storey SB building, implying reduction in the torsional effects at the roof level, with an increase in the number of storeys.

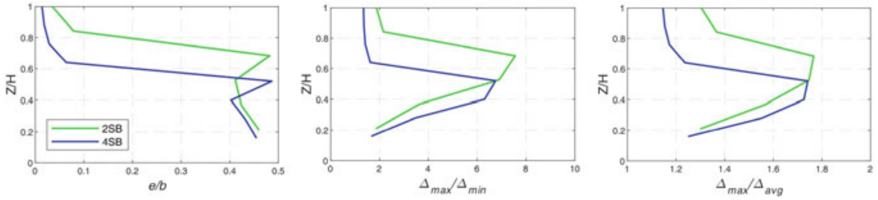

Fig. 2 Variations of the torsional irregularity indices for SB buildings considered in this study. *Z* is the height of the floor measured from the bottommost foundation level, and *H* is the total height of the building measured from the bottommost foundation level. Here, *b* is the width of the floor plan, in the direction perpendicular to the excitation

4 Results and Discussion

4.1 Spectral Amplification Function

In the present study, the bi-directional linear dynamic analyses have been conducted and FRS corresponding to NSC damping ratio of 5% are evaluated at the CR, FE, and SE, at two different floor levels, i.e., at the floor level where the effect of torsion is maximum (i.e., the storey immediately above the topmost foundation level), and at the roof level, in both the directions. The floor response is presented in the form of spectral amplification factors (SAF), defined as the ratio between the 5%-damped FRS to 5%-damped ground response spectra, in the direction under consideration.

Figures 3 and 4 present a comparison of the obtained SAFs as a function of tuning ratio (T_s/T_1), for the investigated 2- and 4-storey buildings, in the direction along and across the slope. Sharp peaks in the spectral amplification functions can be observed corresponding to the different contributing modes of vibration, at the floor level under consideration.

It can be observed that the median floor response of both FG and SB buildings are almost identical, especially at the CR, in along slope direction (Figs. 3a, c and 4a, c). Further, there are minor differences in the median SAFs in along slope direction, at the storey immediately above the topmost foundation level, especially at the FE and the SE (Figs. 3c and 4c). On the other hand, significant differences exist in the floor response at the CR, when compared with the floor response obtained at the FE or the SE, in across-slope direction (Figs. 3b, d, and 4b, d). In general, the floor spectral accelerations are observed to be more at the FE and less at the SE, when compared with the respective values at the CR, in across-slope direction. Further, this difference at the FE is significantly higher at the storey immediately above the topmost foundation level (Figs. 3d and 4d). This observation can be explained with the fact that the storey immediately above the topmost foundation level has the highest torsional irregularity (Fig. 2). The effect of torsion in floor response is observed to be maximum under the tuned response of the NSC, i.e., at $T_s/T_1 \sim 0.30$–0.40 and at $T_s/T_1 \sim 1.00$ (Figs. 3b, d and 4b, d). Further, the observed amplification in acceleration demands due to torsion is limited to the influence zones of the different contributing

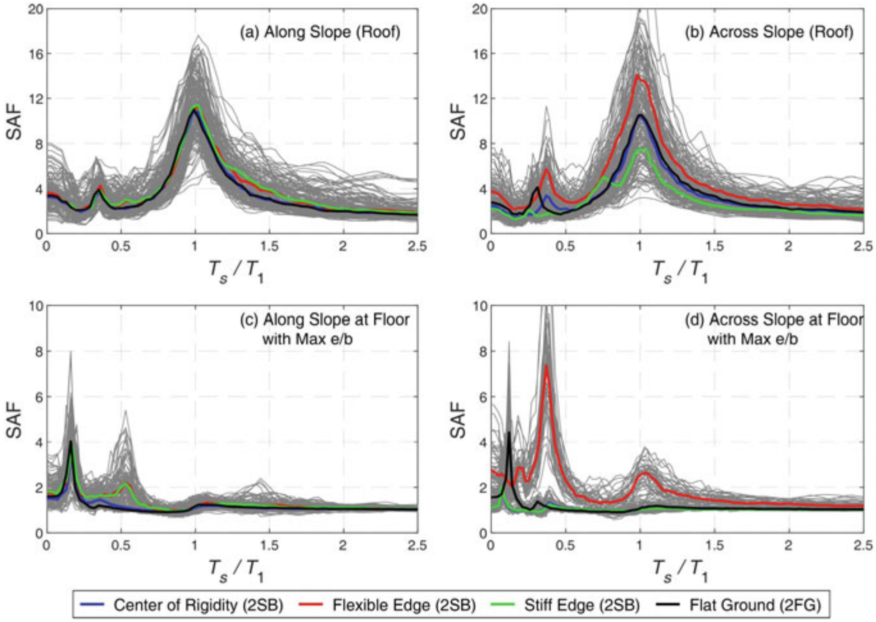

Fig. 3 Comparison of the SAF obtained for the 2FG building with those obtained for 2SB building at the CR, at the FE, and at the SE. Different coloured lines represent the respective median values

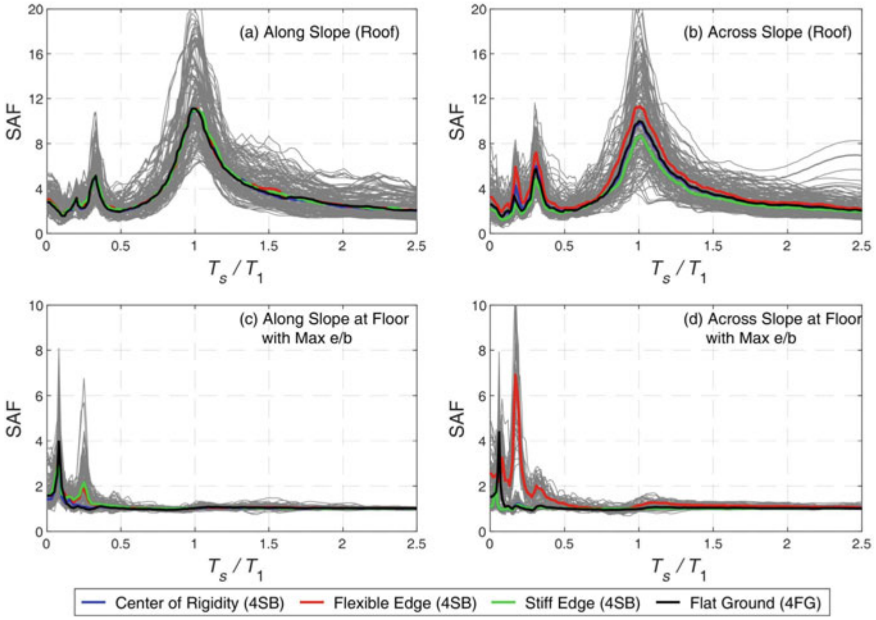

Fig. 4 Comparison of the SAF obtained for the 4FG building with those obtained for 4SB building, at the CR, at the FE, and at the SE. Different coloured lines represent the respective median values

modes of vibration, and at higher tuning ratios ($T_s/T_1 \geq 2.0$), i.e., beyond the influence zone of the higher as well as the fundamental mode of vibration, the median SAFs at the CR, the FE and the SE converge. These observations underline two important facts: (i) the most critical values of TAFs are expected to occur under tuned response of NSC, in the influence zones of either the higher or the fundamental modes of vibration, and (ii) for non-tuned response corresponding to the higher tuning ratios ($T_s/T_1 \geq 2.0$), a building's torsion has an insignificant effect on SAFs. Accordingly, in the subsequent section, the most critical values of the TAFs are studied with the various torsional irregularity indices used in seismic design of buildings.

4.2 Torsional Amplification Factor (TAF)

Figure 5 presents the variation of the TAFs (computed as the ratio between SAF at the FE to SAF at the CR, under the tuning condition, i.e., when the period of the NSC coincides with one of the modes of vibration of the building) with four different indices, namely, $\Delta_{\text{max}}/\Delta_{\text{min}}$, $\Delta_{\text{max}}/\Delta_{\text{avg}}$, floor rotation ($F_\theta$) and angular acceleration (α_θ), at the floor level under consideration. These indices are computed from linear dynamic analysis for each of the ground-motion records separately. It can be observed that usually, at the FE, torsional amplification occurs, whereas, at the SE, a torsional de-amplification occurs. The magnitude of the TAF is higher for the higher modes of vibration as compared to the fundamental mode of vibration, at the storey immediately above the topmost foundation level. On the other hand, the torsional amplification is comparable, for NSCs tuned to the fundamental or higher modes of vibration.

Table 2 reports the median values of TAFs obtained at the FE, and the SE, of the SB buildings, investigated in the present study. It is to be noticed that the maximum value of the median TAF at the roof level is 1.67, whereas it is 6.17 at the storey immediately above the topmost foundation level. Contrarily, the minimum value of TAF at the roof level is 0.56, whereas it is 0.96, at the storey immediately above the topmost foundation level. These values can be explained through Fig. 2, which showed the presence of severe torsional effects, in the storey immediately above the topmost foundation level, in SB buildings. Further, a TAF value close to unity (at the SE), at the storey immediately above the topmost foundation level can be attributed to closer proximity of the CR and the SE (Fig. 1a).

Table 3 reports the correlation coefficients of different torsional irregularity indices investigated in the present study, with the estimated TAFs, at the FE. In addition, the coefficient of variations (CoVs) in estimating the considered torsional irregularity indices, from the linear time history analyses, using natural earthquake ground motions, are also presented. For the investigated SB buildings, TAFs are observed to be best correlated with the parameter $\Delta_{\text{max}}/\Delta_{\text{min}}$. The correlation of TAFs with $\Delta_{\text{max}}/\Delta_{\text{avg}}$ is observed to be slightly lesser than as compared to $\Delta_{\text{max}}/\Delta_{\text{min}}$ (Table 3). Further, the correlation of TAFs with the floor rotation (F_θ) and angular acceleration (α_θ) is observed to reduce significantly. On the other hand, the CoVs in estimation

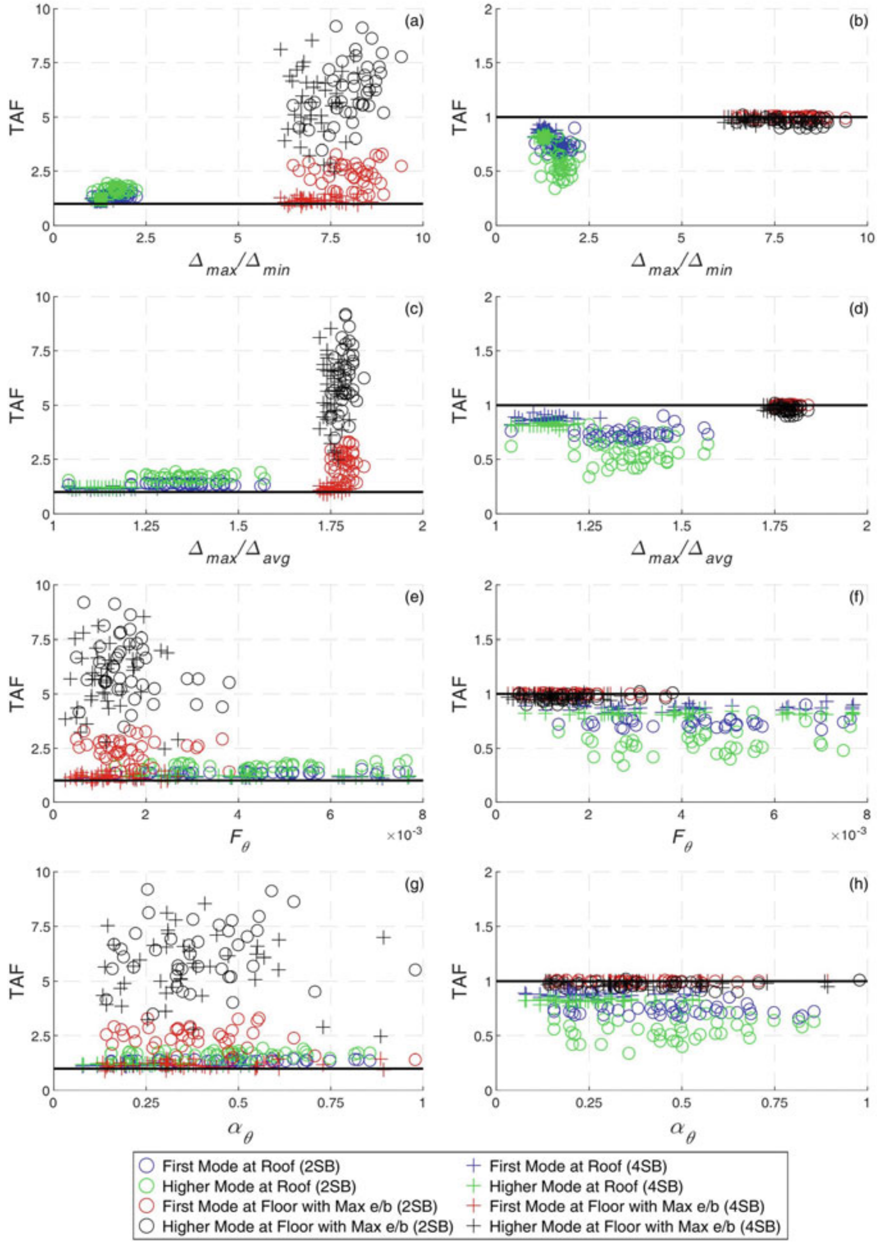

Fig. 5 Variation of the TAF at different floors of the investigated SB buildings with different torsional irregularity indices considered in the present study. Plots on the left column reports TAF at the FE, whereas, plots on the right column reports TAF at the SE. The horizontal black colour line is drawn corresponding to a TAF equal to unity to distinguish the cases of torsional amplification and de-amplification, respectively

Table 2 Median values of torsional amplification/de-amplification factors

Building model	Flexible edge				Stiff edge			
	Roof level		Floor with maximum *e*/*b*		Roof level		Floor with maximum *e*/*b*	
	First mode	Higher mode	First mode	Higher mode	First mode	Higher mode	First mode	Higher mode
2SB	1.36	1.67	2.47	6.17	0.72	0.56	1.00	0.96
4SB	1.15	1.20	1.14	5.67	0.87	0.82	1.00	0.97

Table 3 Correlation coefficient of TAFs at the FE with different torsional irregularity indices and CoVs in estimating torsional irregularity indices from the time history analyses

Torsional irregularity index	Correlation coefficient	Coefficient of variation			
		2SB (Floor with maximum *e*/*b*)	4SB (Floor with maximum *e*/*b*)	2SB (Roof level)	4SB (Roof level)
$\Delta_{\max}/\Delta_{\min}$	0.61	0.08	0.08	0.14	0.09
$\Delta_{\max}/\Delta_{\text{avg}}$	0.58	0.01	0.01	0.07	0.04
F_θ	-0.39	0.46	0.49	0.51	0.53
α_θ	0.06	0.48	0.50	0.42	0.46

of these indices are observed to be the least for the parameter $\Delta_{\max}/\Delta_{\text{avg}}$, followed by $\Delta_{\max}/\Delta_{\min}$. Further, the estimation of floor rotation (F_θ) and angular acceleration (α_θ) are observed to exhibit significantly higher CoVs. From the presented results and discussions, it is inferred that the torsional irregularity indices, e.g., $\Delta_{\max}/\Delta_{\min}$ or $\Delta_{\max}/\Delta_{\text{avg}}$, offers a superior choice for incorporating the effect of torsion in seismic design of NSCs.

5 Conclusions

This paper investigated the effects of inherent torsion in buildings on floor acceleration demands, for seismic design of NSCs. A total of 176 bi-directional linear time history analyses were conducted, and the FRS were evaluated at two different floor levels. The derived FRS were further used to study the TAFs and its correlation with the indices representing the extent of the torsional irregularity present in the building. The following major conclusions are drawn from this study:

- In SB buildings, the effect of torsion is maximum at the storey immediately above the topmost foundation level, in the direction across the slope. These torsional effects are observed to reduce along the height of the building, above the topmost foundation level.

- Torsion of the buildings is observed to have a higher impact on the design floor acceleration demands, when the NSC is tuned with one of the modes of vibration of the building. For non-tuned response, outside the influence zone of the different modes of vibration of the building, the effect of torsion is observed to be insignificant.
- For the elastic response of the building, torsional amplification occurs at the FE, whereas a de-amplification occurs at the SE. The median values of the TAFs are observed to be 6.17 and 1.67, at the storey immediately above the topmost foundation level, and at the roof level, respectively.
- TAFs are observed to be better correlated to the torsional irregularity indices, $\Delta_{max}/\Delta_{min}$ or $\Delta_{max}/\Delta_{avg}$ as compared to other indices such as the floor rotations and angular accelerations. Further, these torsional irregularity indices, $\Delta_{max}/\Delta_{min}$ or $\Delta_{max}/\Delta_{avg}$, are also observed to exhibit low CoVs, when obtained from time history analyses, as compared to floor rotations and angular accelerations.

The present study was conducted for low-rise buildings with FG and SB configuration exhibiting linear elastic response, and it needs to be further extended for taller buildings, considering their inelastic response.

Acknowledgements The first author's fellowship is granted by the Ministry of Education (MoE), Government of India (GoI). The investigations reported in this paper were conducted under the ISIRD project grant (F.No. 9-385/2019/IITRPR/3220) of the second author. The financial support received from both MoE and ISIRD Project Grant of IIT Ropar is thankfully acknowledged. The seismic ground-motion records used in this study were obtained from PEER NGA WEST 2 database.

References

1. Taghavi S, Miranda E (2003) Response assessment of non-structural building elements, PEER 2003/05 report. University of California at Berkeley, Berkeley, CA, Pacific Earthquake Engineering Research Center
2. Villaverde R (1997) Seismic design of secondary structures: state of the art. J Struct Eng 123(8):1011–1019
3. Yang Y, Huang W (1993) Seismic response of light equipment in torsional buildings. Earthq Eng Sruct Dynam 22(2):113–128
4. Agrawal AK, Datta TK (1998) Seismic response of a secondary system mounted on a torsionally coupled non-linear primary system. J Earthq Eng 2(3):339–356
5. Agarwal AK, Datta TK (1999) Seismic response of a secondary system attached to a torsionally coupled primary system under bi-directional ground motion. ISET J Earthq Technol 36(1):27–42
6. Aldeka AB, Chan AHC, Dirar S (2014) Response of non-structural components mounted on irregular RC buildings: comparison between FE and EC8 predictions. Earthq Struct 6(4):351–373
7. Aldeka AB, Dirar S, Chan AHC, Martinez-Vazquez P (2015) Seismic response of non-structural components attached to reinforced concrete structures with different eccentricity ratios. Earthq Struct 8(5):1069–1089
8. Surana M, Singh Y, Lang DH (2018) Effect of irregular structural configuration on floor acceleration demand in hillside buildings. Earthq Eng Struct Dynam 47(10):2032–2054

9. Vijayanarayanan AR, Goswami R (2020) Floor acceleration spectrum for RC moment frame buildings on slopes. In: 17th world conference on earthquake engineering, 17WCEE Sendai, Japan
10. Pacific Earthquake Engineering Research Center (PEER) (2009) OpenSees (Open system for earthquake engineering simulation), developed by PEER, University of California, Berkeley, California. http://opensees.berkeley.edu/
11. ASCE 41–17 (2017) Seismic evaluation and retrofit of existing buildings. American Society of Civil Engineers, Reston
12. IS 875-Part 1 (1987) Indian standard–code of practice for design loads for buildings and structures (Dead loads). Bureau of Indian Standards, New Delhi
13. IS 875-Part 2 (1987) Indian standard–code of practice for design loads for buildings and structures (Live loads). Bureau of Indian Standards, New Delhi
14. IS 456 (2000) Indian standard—plain and reinforced concrete, code of practice. Bureau of Indian Standards. New Delhi
15. IS 1893-Part 1 (2016) Indian standard—criteria for earthquake resistant design of structures, part 1-general provisions and buildings. Bureau of Indian Standards, New Delhi
16. IS 13920 (2016) Indian standard—ductile design and detailing of reinforced concrete structures subjected to seismic forces—code of practice. New Delhi, India
17. Federal Emergency Management Agency (FEMA) (2009) Quantification of seismic performance factors. FEMA P695, Washington, DC
18. ASCE (2017) Minimum design loads and associated criteria for buildings and other structures, ASCE 7–16. American Society of Civil Engineers, Reston, Virginia
19. CEN (2004) Eurocode 8: design of structures for earthquake resistance—part 1: general rules, seismic actions, and rules for buildings. EN 1998–1, Brussels, Belgium