Earthquakes and Structures, *Vol. 11, No. 6 (2016) 1027-1041*
DOI: http://dx.doi.org/10.12989/eas.2016.11.6.1027

Evaluating contradictory relationship between floor rotation and torsional irregularity coefficient under varying orientations of ground motion

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(Received March 9, 2016, Revised June 5, 2016, Accepted August 19, 2016)

Abstract. Different incident angles of ground motions have been considered to evaluate the relationship between floor rotation and torsional irregularity coefficient. The issues specifically addressed are (1) variability in torsional irregularity coefficient and floor rotations with varying incident angles of ground motion (2) contradictory relationship between floor rotation and torsional irregularity coefficient. To explore the stated issues, an evaluation based on relative variation in seismic response quantities of linear asymmetric structure under the influence of horizontal bi-directional excitation with varying seismic orientations has been carried out using response history analysis. Several typical earthquake records are applied to the structure to demonstrate the relative variations of floor rotation and torsional irregularity coefficient for different seismic orientations. It is demonstrated that (1) Torsional irregularity coefficient (TIC) increases as the story number decreases when the ground motion is considered along reference axes of the structure. For incident angles other than structure's reference axes, TIC either decreases as the story number decreases or there is no specific trend for TIC. Floor rotation increases in proportion to the story number when the ground motion is considered along reference axes of structure. For incident angles other than structure's reference axes, floor rotation either decreases as the story number increases or there is no specific trend for floor rotation and (2) TIC and floor rotation seems to be approximately inversely proportional to each other when the ground motion is considered along reference axes of the structure. For incident angles other than structure's reference axes, the relationship can even become directly proportional instead of inversely proportional.

Keywords: torsional irregularity coefficient; floor rotation; asymmetric structure; time history analysis

1. Introduction

Research in the field of earthquake engineering has confirmed that irregular structures are more vulnerable to damage than regular structures. Torsional irregularities play an important role in causing severe damage to the structure. Regarding the irregularities, most of the codes have almost similar provisions essentially based on principles of well-known standards of IBC06 (2006) and

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http://www.techno-press.com/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

ASCE-13 (2013).

Several investigations have been carried out to compare different seismic analysis methods for irregular structures (Moehle and Alarcon 1986, Chandler and Hutchinson 1987). Anagnostopoulos *et al*. (2015) has presented a detailed state of the art research review on earthquake induced torsion in structures. Duan and Chandler (1997) proposed an optimized procedure for seismic design of torsionally unbalanced structures. Ozmen (2002) evaluated structural and geometric aspects of torsional irregularity. Demir *et al*. (2010) carried out an investigation on torsional irregularity factor which affects multi-story shear wall frame systems. Stathi *et al*. (2015) proposed an index for the assessment of torsional effects in asymmetric structures, considering bidirectional excitation. Georgoussis (2014) presented a modified procedure for assessing the seismic response of elastic non-proportionate multi-story structures. Bosco *et al*. (2015) investigated the effectiveness of three static nonlinear procedures in order to predict the dynamic response of asymmetric structures. Zheng *et al*. (2004) analysed the provisions of different codes for torsional irregularity and concluded that there is no definite relationship between torsional effects and TIC. Tezcan and Alhan (2001) developed a parametric study and concluded that TIC limit defined by the Turkish earthquake code (TEC) does not satisfy the design requirements of irregular structures. They proposed a new limit for TIC which complies with the requirements of irregular structures. Dimova and Alashki (2003) carried out analytical and numerical investigation on regular structures and concluded that even small eccentricities in symmetric structures lead to irregular behaviour and excessive accidental torsional effects. Anagnostopoulos *et al*. (2015) presented a study on accidental mass eccentricities and evaluated the ineffectiveness of accidental mass eccentricity for torsionally stiff structures. Ozmen (2014) developed a parametric study on torsional irregularity coefficient using the clause 12.8.4.3 of ASCE-10 (2010) and found a contradictory relationship between floor rotations and torsional irregularity coefficient and described the floor rotations as the real representation of torsional behaviour.

It has been observed from the literature, that considering TIC as a measure of irregularity in a structure is questionable. Moreover, there is no clear-cut investigation available on TIC behaviour with respect to varying angles of excitation. Hence, an investigation has been made in this research to consider the torsional irregularity coefficient with varying incident angles using response history analysis. This research has been considered due to the fact that, seismic design of structures requires the direction of ground motions to be considered along the fixed reference axes of a structure and it is well known that for most tectonic regions in the world, it can hit the structure along any orientation. Therefore, this implies other possible seismic incident directions which would lead to an increase in the torsional irregularity of the structure. Hence, the response of the structural system depends on the orientation of the seismic input with regard to structural reference axes. Varying the orientation of the axes along which the horizontal ground motions are considered, leads to different structural responses.

Several researchers have investigated the influence of seismic incident angle on elastic as well as inelastic structural response. Considering the elastic structural response, analytical formulae for the determination of the critical angle of seismic incidence and the corresponding maximum structural response subjected to three correlated components have been developed by Athanatopoulou (2005). Athanatopoulou investigated the effect of the different orientation of seismic components on structural response using response history analyses (RHAs), and developed formulas for finding the peak response quantity over the entire range of excitation angles given the linear response histories for two orthogonal directions. The analyses concluded that, for the excitations used, the critical value of a response quantity can be up to 80% larger than the usual response produced when the as-recorded ground motion components are applied along the structural reference axes. Athanatopoulou also concluded that the critical angle corresponding to peak response over all angles varies not only with the ground motion pair under consideration, but also with the response quantity of interest.

Thus, Kostinakis *et al*. (2008) examined the critical seismic incident angle and the corresponding maximum response on the basis of the formulae given by Athanatopoulou (2005) for special classes of buildings subjected to isotropic bidirectional ground motion. These findings are also confirmed in Kalkan and Kwong (2013) where the impacts of orientation of seismic excitation corresponding to the fault normal and fault parallel directions on numerous engineering demand parameters are shown based on an elastic 3-D model of a six story instrumented structure. The translational seismic motion at a particular point is recorded in two horizontal directions and one vertical direction. In general, these seismic components of ground excitation are correlated processes, but according to Penzien and Watabe (1974) there exists a set of orthogonal directions along which the components of ground motion may be considered uncorrelated. These directions, denoted principal directions, are used for the determination of their critical orientation, i.e. the orientation that yields the maximum value of each response quantity of interest. This determination can be achieved by application of the response spectrum method. Thus, Smeby and Der Kiureghian (1985), used random vibration theory and calculated the critical incident angle for the case of two horizontal seismic components with identical spectral shapes, as well as the spectral moments of response for the case of different spectral shapes. Lopez and Torres (2000), used the response spectrum procedure to calculate the critical angle of excitation and the corresponding peak engineering demand parameters for general case of three components of seismic excitation that may have identical or different spectral shapes. Menun and Der Kiureghian (1998) illustrated the CQC3 method for finding the critical orientation of ground motion and the associated peak response quantity. Lopez *et al*. (2000, 2001) proved that the critical value for a single response quantity can be up to 20% larger than the usual response produced when the seismic components are applied along the structural axes. Finally in Menun and Der Kiureghian (2000) the critical incident angle for the most unfavourable combinations of two or more simultaneous response quantities is determined. It is noted that all the above investigations are based on the evaluation of critical angle and critical response.

This research is an effort to fill the research gap by evaluating the impact of seismic incident angle on TIC and floor rotation. This research has also considered the relationship between floor rotation and TIC due to varying orientations of ground motion, particularly at critical orientation of ground motion. The linear response history analysis is used to evaluate a case study structure. Relative variations of the response and contradictory relationship between floor rotations and TIC due to varying angle of excitation have been discussed.

2. Evaluation methodology

The considered case study structure is subjected to bidirectional horizontal excitation represented by $\ddot{u}_{LG}(t)$ and $\ddot{u}_{TG}(t)$ along the orthogonal axes. The subscripts LG and TG represent the longitudinal ground motion component and transverse ground motion component. Due to bidirectional excitation, the following is obtained;

• For each ground motion record selected, calculate the TIC and floor rotations by varying incident angle from 0° through 180°.

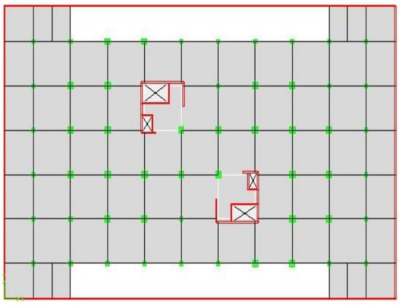
• Calculate the orientation effect ratio for TIC and floor rotations.
• Calculate the relative and maximum relative variation for TIC and floor rotation.

3. Description of the case study structure

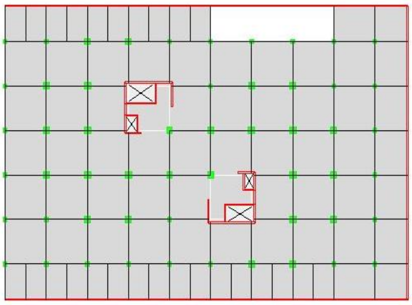
The case study structure is an eighteen-storey asymmetric building with reinforced concrete (RC) moment frames in two orthogonal directions as illustrated in Figs. 1 and 2. The 3-D software

Table 1 Linear elastic dynamic properties of Islamabad Stock Exchange Building

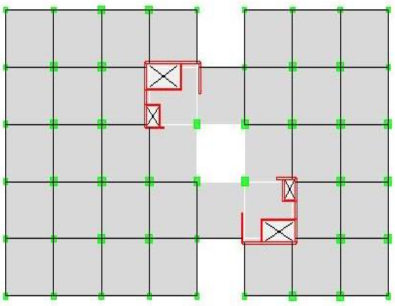
Mode	Period (T)	M_X (%)	M_Y (%)	Sum X (%)	Sum Y (%)
1	2.39	0.006	19.18	0.006	19.18
2	1.47	59.85	0.11	59.85	19.29
3	1.39	0.58	0.614	60.44	19.91
4	1.05	0.311	19.93	60.75	39.84
5	0.53	0.0001	0.21	60.75	40.05
6	0.52	4.99	0.007	65.74	40.05
7	0.44	0.144	0.67	65.88	40.73
8	0.33	3.86	0.085	69.74	40.81
9	0.33	10.77	0.053	80.51	40.86
10	0.24	0.00002	0.015	80.51	40.88



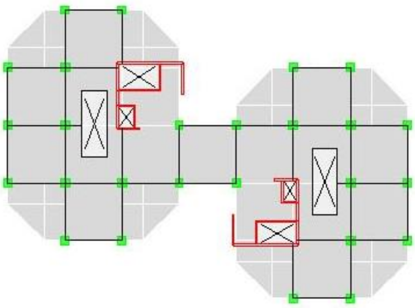
(a) 1st and 2nd basement plan



(b) Ground floor plan



(c) 1st floor to 3rd floor plan



(d) 4th to 15th floor plan

Fig. 1 Floor plans of case study building in XY plane

(a) Actual structure (b) Software model

Fig. 2 Case study building

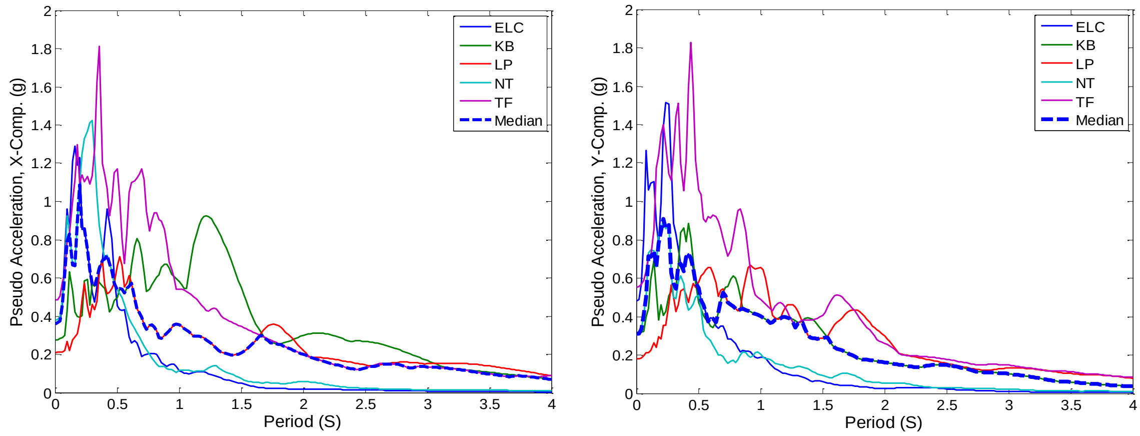
model of this structure was developed using SAP2000 (2012). Centreline dimensions were used in the structural modelling, the columns were assumed to be fixed at the base level. For evaluation of response histories, masses were distributed proportionally to the floor nodes. The building includes two basements of height 3.2 m, ground floor of height 4.5 m and the height of stories from first floor to top roof is 3.2 m. The concrete floors were modelled in terms of 150 mm elastic shell with rigid diaphragm and the modulus of elasticity is set to a value of 20 MPa. Columns and Beams were modelled with linear elastic modulus of 25 MPa and 20 MPa. The default constant damping parameter of software has been used to define a modal damping of 5% for all modes. The dynamic properties of the structure have been presented in Table 1. Each mode shape is illustrated as vibration period (T), the mass participation ratio (M %) and the sum of the participation ratios up to the considered modal shape (Sum). The structural irregularity leads to lateral-torsional behaviour for modes 1 and 2.

4. Input ground motions

The selected ground motions are first applied at structure's fixed reference axes and the response of TIC and floor rotation is recorded. Then the seismic incident angles are varied from 0° to 180° with an angle interval of 10° and the variation in response is recorded. Peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) of ground motions used in this research are presented in Table 2.

Table 2 Earthquake records

Earthquake	Name	Station	Component	PGA (g)	PGV (m/s)	PGD (m)	Notation
Kobe 1/16/1995	KB	0 KBU	KOBE/KBU000	0.31	0.55	0.15	$\ddot{u}_{LG}(t)$
Kobe 1/16/1995	KB	0 KBU	KOBE/KBU090	0.30	0.31	0.07	$\ddot{u}_{TG}(t)$
Northridge 10/1/1987	NT	17645 Saticoy st	WHITTIER/A-STC090	0.38	0.41	0.09	$\ddot{u}_{LG}(t)$
Northridge 10/1/1987	NT	17645 Saticoy st	WHITTIER/A-STC180	0.30	0.26	0.07	$\ddot{u}_{TG}(t)$
Imperial valley 6/6/1938	ELC	El Centro Array # 9	IMPVALL/B-ELC000	0.37	0.14	0.01	$\ddot{u}_{LG}(t)$
Imperial valley 6/6/1938	ELC	El Centro Array # 9	IMPVALL/B-ELC090	0.49	0.19	0.01	$\ddot{u}_{TG}(t)$
Loma Prieta 10/18/1989	LP	APEEL 10	LOMAP_A10000	0.21	0.29	0.19	$\ddot{u}_{LG}(t)$
Loma Prieta 10/18/1989	LP	APEEL 10	LOMAP_A10090	0.18	0.50	0.17	$\ddot{u}_{TG}(t)$
Taft 7/21/1952	TF	Kern County	KERN_TAF021	0.48	0.23	0.04	$\ddot{u}_{LG}(t)$
Taft 7/21/1952	TF	Kern County	KERN_TAF111	0.55	0.29	0.07	$\ddot{u}_{TG}(t)$



(a) X-Component (b) Y-Component

Fig. 3 Pseudo acceleration response spectra of ground motions; damping ratio 5%, the blue dashed line corresponds to median spectrum of all records

5. Variation in torsional irregularity coefficient of structure with varying seismic incident angle

To assess the variation in torsional irregularity in the structure, the clause 12.9.5 of ASCE 7-13 (2013) regarding torsional irregularities in the structure is utilized. In the given clause exception for amplification of accidental torsion moment (M_{ta}) caused by center of mass is given for structures which utilize accidental eccentricities. Since the accidental torsion has not been determined as part of the dynamic analysis, the torsional amplification factor according to this clause needs to be assessed and is defined as

$$A_x = \left(\frac{\delta_{max}}{1.2\delta_{avg}} \right)^2 \tag{1}$$

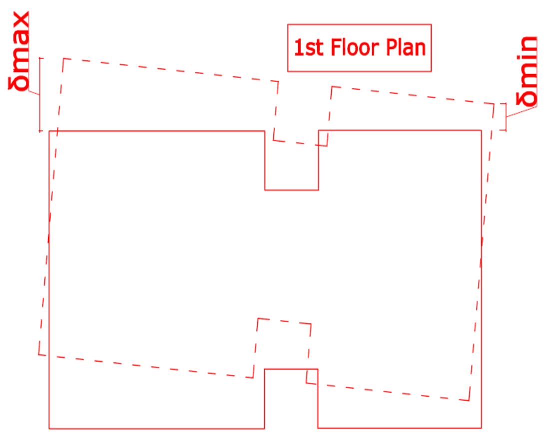
Where δ_{max} represents the maximum displacement of extreme point at level x and δ_{avg} represents displacements of extreme points at level x, respectively, with an assumption of $A_x = 1$. The maximum and average displacements are explained in Fig. 4. The above provision can alternatively be illustrated as follow

$$\eta_I = \frac{\delta_{max}}{\delta_{avg}} \tag{2}$$

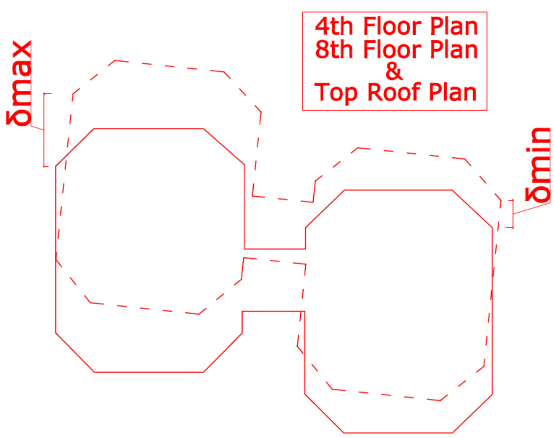
$$\delta_{avg} = \frac{\delta_{max} + \delta_{min}}{2} \tag{3}$$

Where η_I represent torsional irregularity coefficient (TIC). The value of $\eta_I \leq 1.2$ represent that there is no torsional irregularity in the structure and when $\eta_I > 1.2$ the structure is torsionally irregular. It has been found that the TIC depends on many factors as can be seen in Ozmen (2002) but since here the study involves variation in the incident angle, therefore TIC is explored under the influence of varying orientations of ground motion.

The structural response has been presented for TIC and its variation with seismic incident angle for 1st, 4th, 8th and top roof story in Fig. 5. For this purpose the maximum and minimum floor displacements at extreme points of the diaphragm have been evaluated for ground motions rotated 0° through 180° with an angle interval of 10°. It has been illustrated in Fig. 5 that TIC for this structure is high at lower floors and it keeps on decreasing in upper floors but this trend is valid only when the ground motion is applied along structure's reference axes. As can be seen in Fig. 5,



(a) 1st floor plan



(b) 4th floor, 8th floor and top roof plan

Fig. 4 Maximum and minimum displacements

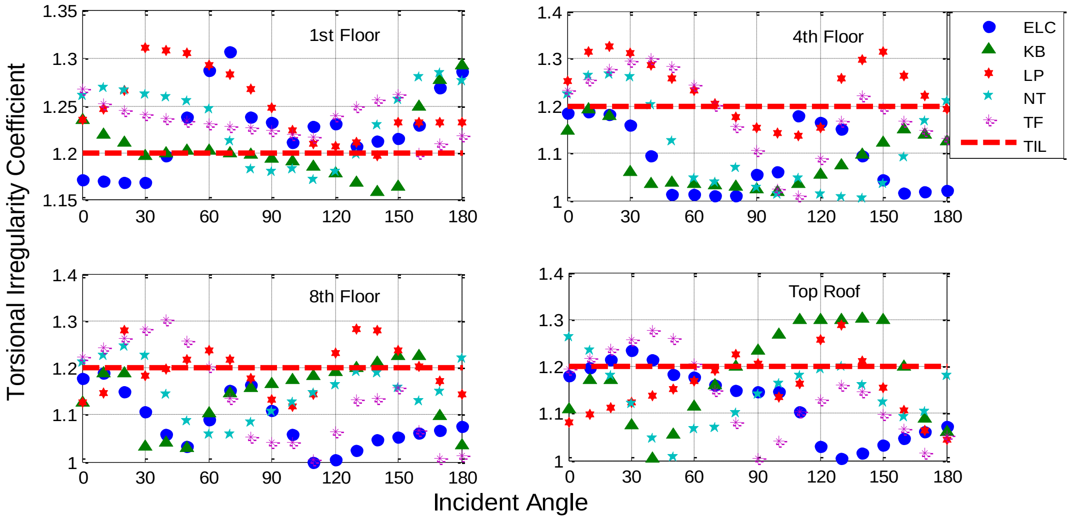


Fig. 5 Variation in TIC; the dashed red line correspond to the torsional irregularity limit

TIC's decreasing trend is significantly affected in upper stories with varying orientation of ground motions. According to the relationship defined in Ozmen (2014), irregularity coefficient in upper stories of the structure should have been reduced further but it has been observed that this relationship holds only true when ground motions are applied at structure's reference axes as illustrated in Fig. 5. At top roof story, for incident angle at reference axes of the structure, the irregularity coefficient is sufficiently lower than stories below but as the seismic incident angle is varied, the torsional irregularity coefficient has reached to a maximum value on top roof floor, higher than the maximum irregularity in 1st floor. Hence a clear contradiction with the trend described in Ozmen (2014) is noticed when the TIC is checked with varying incident angles. However, it is interesting to note that there is more number of scattered responses above torsional irregularity limit in 1st floor than the floors above for almost all ground motions. Hence there are more chances of occurrence of irregularity in lower floors. Overall a relative variation up to 20% has occurred between the maximum response and response obtained when the ground motions were applied at structure's reference axes.

6. Variability in floor rotation as the incident angle is varied

To further evaluate the behavior of the structure in terms of irregularity, the structural response with respect to the floor rotation has been recorded and presented in Fig. 6. It is notable to understand that the structure's response in terms of floor rotation is significantly different than the response in terms torsional irregularity coefficient despite of the fact that both can be depicted as an irregularity in the structure. Since floor rotation presents a better illustration of structural irregularity therefore, the floor rotation responses at 1st, 4th, 8th and top roof story is presented in this section. Contrary to the torsional irregularity coefficient, the floor rotations seem to increase upward with the floor numbers but this trend occurred only when the ground motions were applied along the structure's reference axes. When the seismic incident angle was varied, the floor

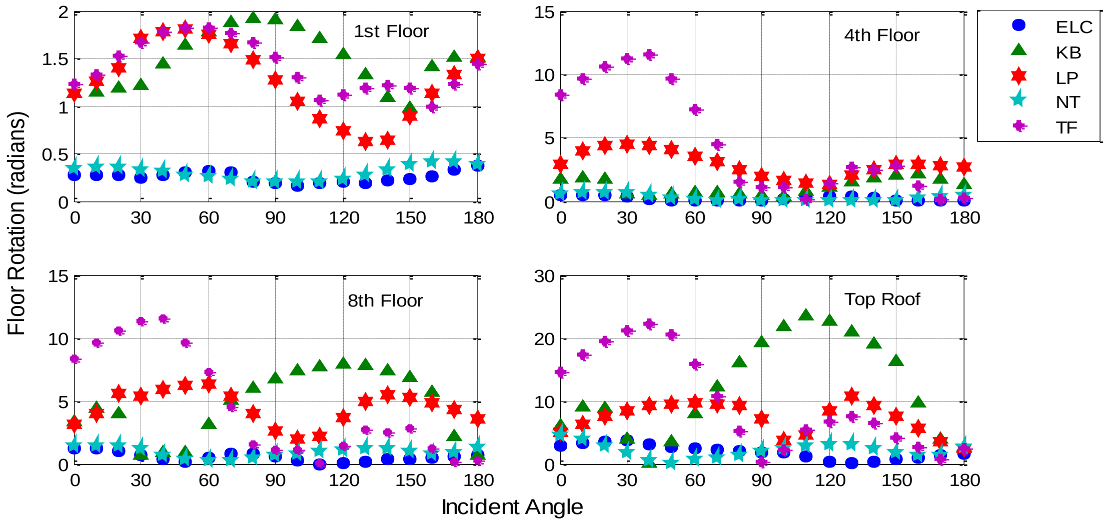


Fig. 6 Variation in floor rotation x 10^{-4}

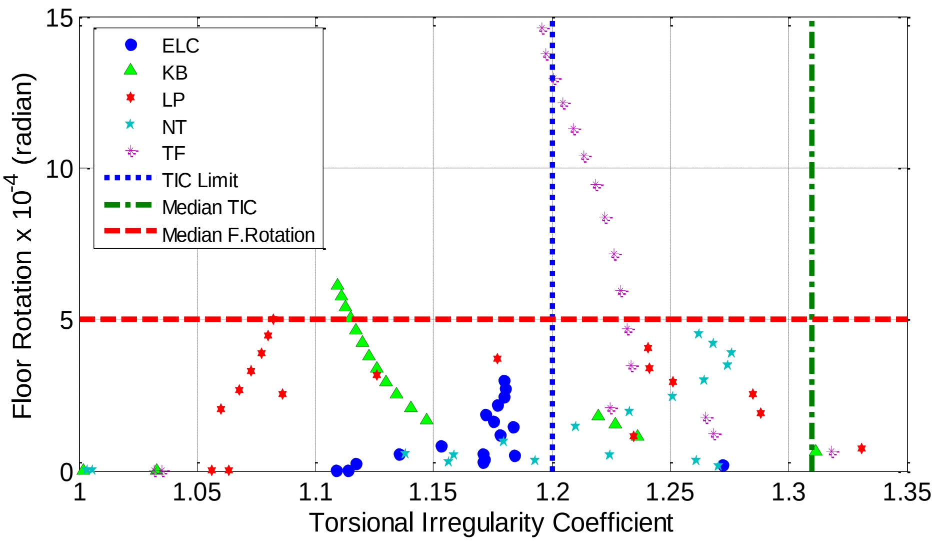


Fig. 7 Scattering of height-wise floor rotations plotted with TIC; the red dashed line correspond to the median of maximum floor rotations; the blue dashed line correspond to the torsional irregularity coefficient (TIC) limit; the green dashed line correspond to the median of maximum torsional irregularity coefficient (TIC)

rotations have found to decrease upward for several angles which again contradict with the relationship described by Ozmen (2014). However, it is interesting to note that the floor rotation response is contradictory to TIC also stated by Ozmen (2014). There seems to exist approximately inverse relationship between TIC and floor rotation and this inverse relation between floor rotations and TIC is true as long as the ground motions are along the reference axes of structure. There is significant variation in the trend of floor rotation response with varying incident angle. For example, floor rotation for Taft earthquake at 90° in Fig. 6 illustrates that the floor rotation is constantly decreasing upward with increasing height which contradicts the relationship of floor rotation with story number as described by Ozmen (2014). Not only that, the response contradicts with the inversely relationship between floor rotation and TIC i.e., as the floor rotation response decreases along the height of the structure, the TIC also decreases, showing almost a direct proportional relationship. This has happened at few incident angles only. For most of the incident angles, no specific trend is observed. Fig. 7 describes a scatter plot of TIC and floor rotation. It can be seen that both TIC and floor rotation seems to be incompatible to each other.

7. Contradictory behavior of floor rotation and torsional irregularity coefficient

As explained in previous sections that TIC decreases as the story number increases and this happens only when the ground motions are applied along reference axes of the structure. It is illustrated in Fig. 5 that for Loma Prieta earthquake at 130° TIC at 1st floor, 4th floor, 8th floor and top roof is 1.21, 1.25, 1.27 and 1.29. Same increasing trend with increasing floor number is observed for Taft earthquake at 40° and 50°. For Northridge earthquake when the ground motions are considered along reference axes of the structure it can be seen that TIC keeps on decreasing as the story number increases but suddenly an increased amount of TIC is observed at top roof which again contradicts the trend of TIC for ground acceleration along structure's reference axes. Hence it can be said that higher mode effect has significantly influenced the structure and has affected the displacement response of the structure due to which TIC contradicts with its trend even when the ground acceleration was at structure's reference axes. It can be concluded that TIC either decreases with floor number or remains constant or in some cases increases as well, when the ground motion is along reference axes of the structure.

For floor rotations, a very clear trend is observed when the ground motion is applied along reference axes of the structure and no contradiction with the trend is observed. Fig. 6 illustrates a very clear trend of increasing floor rotation with increasing story number at 0° angle. Hence it can be said that floor rotation is a more clear representation of torsional irregularity in case of linear dynamic analysis and ground motions at structure's reference axes. However, when the incident angle is varied, floor rotation response appears to deviate from the trend. For example, for Kobe earthquake at 40° angle it can be seen in Fig. 6 that floor rotation is decreased as the story number is increased. Same is observed for Taft and El Centro earthquakes at 90° and 120°. Hence it can be said that floor rotation increases in proportion to the floor number when the ground motion is considered along reference axes of the structure. For all other incident angles, floor rotation either decreases in proportion to the floor number or there is no specific trend.

Beside this a contradictory behavior of floor rotation and TIC has been observed. Except for Northridge and El Centro earthquake, the relationship between floor rotation and TIC seems to be approximately inversely proportional when the ground motion is applied along structure's reference axes. This relationship doesn't comply for Northridge earthquake because the TIC response at top roof has contradicted the trend at 0° angle. The TIC response for El Centro earthquake remains approximately constant, therefore, doesn't comply with relationship. The relationship between floor rotation and TIC varies as the incident angle is varied. Hence it can be said that inversely proportional relationship between floor rotation and TIC occurs only when the ground motion is considered along reference axes of the structure. For other incident angles the relationship can even become directly proportional. For example, for Loma Prieta earthquake at 130° angle both TIC and floor rotation increases in proportion to the floor number.

The results have been further quantified to evaluate and confirm the effect of orientation O_R in the irregularity response using the relationship shown below

$$O_R = \frac{\beta_P(\phi_i)}{\beta_0(\phi_0)} \tag{4}$$

For

$\phi_i = 0°, 10°, 20°, \ldots\ldots\ldots\ldots, 180°$

Where

$\beta_P(\phi_i)$=TIC/floor rotation for incident angle $\phi = \phi_i$

$\beta_0(\phi_0)$=TIC/floor rotation for incident angle ϕ=0° when the earthquake acceleration is applied along the structural reference axes.

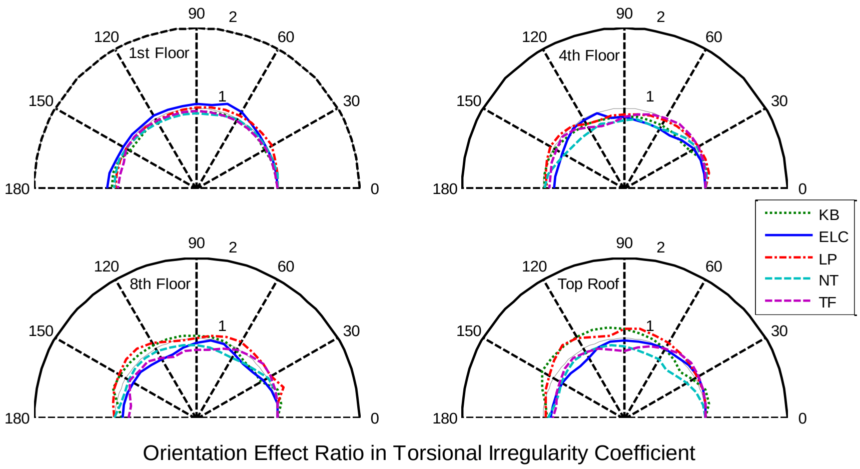


Fig. 8 Polar plots of orientation effect ratio in TIC; the tangential lines demonstrate the magnitude of orientation effect ratio and; the radial lines demonstrate the incident angle

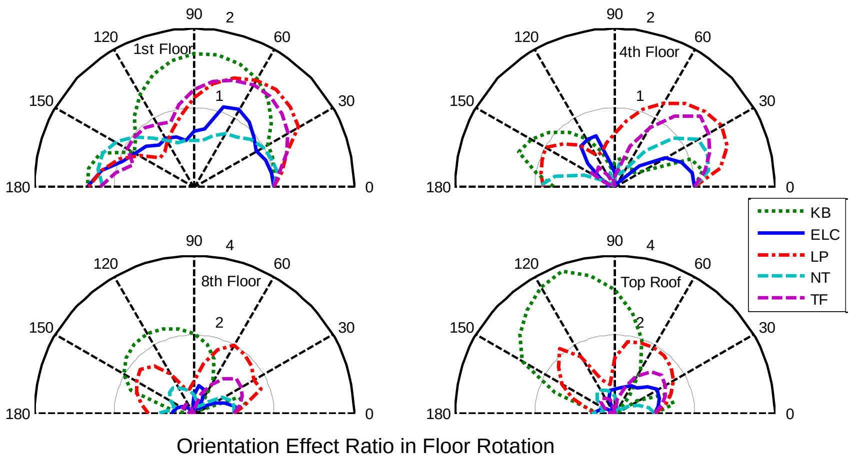


Fig. 9 Polar plots of orientation effect ratio in floor rotation; the tangential lines demonstrate the magnitude of orientation effect ratio and; the radial lines demonstrate the incident angle

Orientation effect ratios for TIC and floor rotations, developed due incident angles of seismic excitation are shown in Figs. 8-9. It can also be observed that maximum irregularity has occurred when the incident angle is not along the reference axes of the structure. This verifies the results produced in Figs. 5-6. It has been observed that the response quantities at critical angle can be up to 283% larger than the response produced, when the seismic components are applied along structure's reference axes.

8. Maximum seismic response variation due to incident angle

The directional effects of varying orientations of ground motions are quantified in terms of relative variation and maximum relative variation and are defined as

$$D_{RV} = \left(\frac{\beta(\text{Ø}_i) - \beta(\text{Ø}_0)}{\beta(\text{Ø}_0)} \right) x\,100 \tag{5}$$

The influence of the incidence angle on seismic response is evaluated on this structure in order to further investigate its seismic performance, which is known to exhibit an unusual dynamic behavior. Nineteen different earthquake directions are considered, changing the angle of orthogonal components of the selected accelerograms by 10 degrees for each analysis (from 0° to 180°). The results in terms of relative variation for TIC and floor rotations are shown in Figs. 10-11 considering the selected sets of accelerograms. The variations of the seismic responses are evaluated with respect to the response obtained by applying the input without any variation in orientation of ground motions. The incidence angle of the seismic input motion causes a significant variation of the response of asymmetric RC structures; the variation with respect to the case in which the ground motion is applied without any rotation is about 2% to 283% for response quantities as illustrated in Figs. 10-11. For this reason, defining irregularity in the structure based on ground motions along reference axes of the structure is questionable.

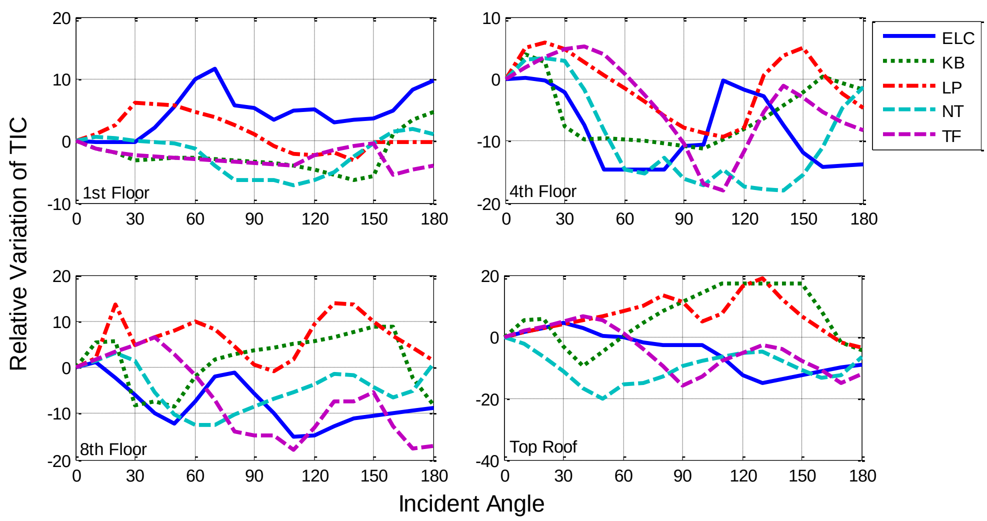


Fig. 10 Relative variation of TIC

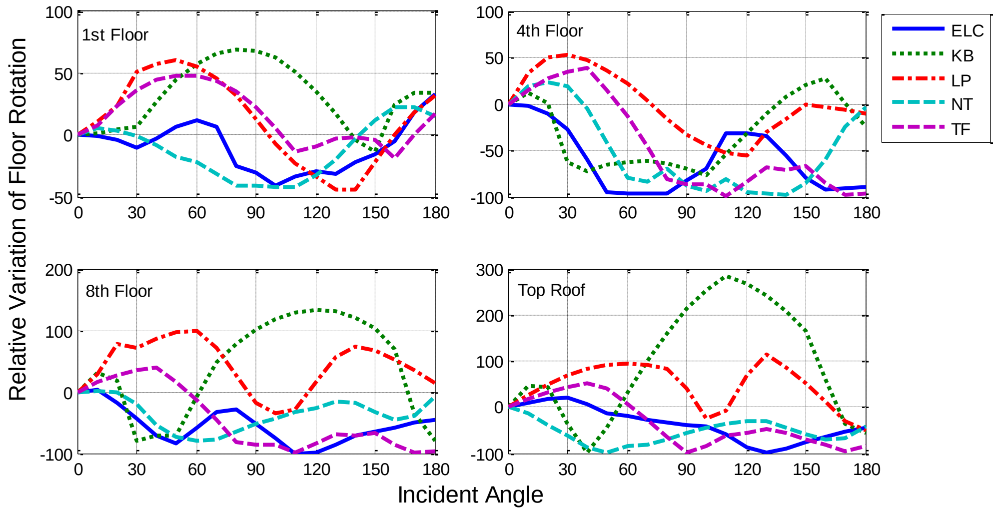


Fig. 11 Relative variation of floor rotation

9. Conclusions

The contradictory behavior of TIC and floor rotations under varying incident angles for the considered asymmetric buildings has been evaluated. The following conclusions can be made;

• The contradictory relationship established between floor rotation and torsional irregularity coefficient in Ozmen (2014) deviates from the investigated results when variation in the incident angles of ground motion components is considered.

• TIC decreases upward along the height of the structure for most of the earthquakes when the ground motion is considered along the structure's reference axes. This trend does not hold true when the incident angle is varied. For incident angles other than reference axes of the structure, TIC even increases with story number or there is no specific trend.

• Floor rotation increases upward in proportion to the story number when the ground motion is considered along the structure's reference axes. For incident angles other than reference axes of the structure, floor rotations either decrease as the story number increases or there is no specific trend.

• There seems to have an inverse relationship between TIC and floor rotation for some ground motions, when the excitation is considered along the structure's reference axes. This relationship does not exist when the incident angle of ground motion is varied. For incident angles other than reference axes of the structure, the relationship between TIC and floor rotation can even become directly proportional to each other.

• Floor rotation seems to reflect a more clear representation of torsional irregularity even with varying incident angles.

Acknowledgments

This research is supported by the Australia Research Council (Project No. LP140100030) and the National Natural Science Foundation of China (Project No. 51678322 and 51650110509).

References

Anagnostopoulos, S., Kyrkos, M., Papalymperi, A. and Plevri, E. (2015), “Should accidental eccentricity be eliminated from Eurocode 8?”, *Earthq. Struct.*, **8**(2), 463-484.

Anagnostopoulos, S.A., Kyrkos, M.T. and Stathopoulos, K.G. (2015), “Earthquake induced torsion in buildings: critical review and state of the art”, *Earthq. Struct.*, **8**(2), 305-377.

ASCE (2010), *Minimum Design Loads for Building and Other Structures*, SEI/ASCE 7-10, American Society of Civil Engineers, Reston, VA.

ASCE (2013), *Minimum Design Loads for Building and Other Structures*, SEI/ASCE 7-10, American Society of Civil Engineers, Reston, VA.

Athanatopoulou, A. (2005), “Critical orientation of three correlated seismic components”, *Eng. Struct*., **27**(2), 301-312.

BCP (2007), *Seismic Provision for Building Code of Pakistan*, Ministry of Housing and Works Government of Pakistan.

Bosco, M., Ferrara, G. A., Ghersi, A., Marino, E.M. and Rossi, P. P. (2015), “Seismic assessment of existing rc framed structures with in-plan irregularity by nonlinear static methods”, *Earthq. Struct*., **8**(2), 401-422.

Chandler, A. and Hutchinson, G. (1987), “Evaluation of code torsional provisions by a time history approach”, *Earthq. Eng. Struct. Dyn*., **15**(4), 491-516.

Chopra, A. (2007), *Dynamics of structures: Theory and applications to equation engineering*, Prentice Hall, Englewood Cliffs, NJ.

Demir, A., Demir, D.D., Erdem, R.T. and Bagci, M. (2010), “Torsional irregularity effects of local site classes in multiple storey structures”, *Int. J. Res. Rev. Appl. Sci.*, 258-262.

Dimova, S.L. and Alashki, I. (2003), “Seismic design of symmetric structures for accidental torsion”, *Bull. Earthq. Eng*., **1**(2), 303-320.

Duan, X. and Chandler, A. (1997), “An optimized procedure for seismic design of torsionally unbalanced structures”, *Earthq. Eng. Struct. Dyn.*, **26**(7), 737-757.

Georgoussis, G.K. (2014), “Modified seismic analysis of multistory asymmetric elastic buildings and suggestions for minimizing the rotational response”, *Earthq. Struct.*, **7**(1), 39-55.

Hong, H. and Goda, K. (2010), “Characteristics of horizontal ground motion measures along principal directions”, *Earthq. Eng. Eng. Vib*., **9**(1), 9-22.

IBC, I. (2006), International building code, International Code Council, Inc.(formerly BOCA, ICBO and SBCCI) **4051**, 60478-65795.

Kalkan, E. and Kwong, N.S. (2013), “Pros and cons of rotating ground motion records to fault-normal/parallel directions for response history analysis of buildings”, *J. Struct. Eng*., **140**(3), 04013062.

Kostinakis, K.G., Athanatopoulou, A.M. and Avramidis, I.E. (2008), “Maximum response and critical incident angle in special classes of buildings subjected to two horizontal seismic components”, *Proceedings of the 6th GRACM International Congress on Computational Mechanics*.

López, O.A. and Torres, R. (1997), “The critical angle of seismic incidence and the maximum structural response”, *Earthq. Eng. Struct. Dyn*., **26**(9), 881-894.

Lopez, O.A., Chopra, A.K. and Hernandez, J.J. (2000), “Critical response of structures to multicomponent earthquake excitation”, *Earthq. Eng. Struct. Dyn.*, **29**(12), 1759-1778.

López, O.A., Chopra, A.K. and Hernández, J.J. (2001), “Evaluation of combination rules for maximum response calculation in multicomponent seismic analysis”, *Earthq. Eng. Struct. Dyn*., **30**(9), 1379-1398.

Magliulo, G., Maddaloni, G. and Petrone, C. (2014), “Influence of earthquake direction on the seismic response of irregular plan RC frame buildings”, *Earthq. Eng. Eng. Vib*., **13**(2), 243-256.

Menun, C. and Der Kiureghian, A. (1998), “A replacement for the 30%, 40%, and SRSS rules for multicomponent seismic analysis”, *Earthq. Spectra*, **14**(1), 153-163.

Menun, C. and Kiureghian, A.D. (2000a), “Envelopes for seismic response vectors. I: theory”, *J. Struct.*

Eng., **126**(4), 467-473.
Menun, C. and Kiureghian, A.D. (2000b), “Envelopes for seismic response vectors. II: Application”, *J. Struct. Eng.*, **126**(4), 474-481.
Moehle, J.P. and Alarcon, L.F. (1986), “Seismic analysis methods for irregular buildings”, *J. Struct. Eng.*, **112**(1), 35-52.
Özmen, G. (2002), “Structural aspects of torsional irregularity”, *5th International congress on advances in civil engineering*, Istanbul.
Özmen, G., Girgin, K. and Durgun, Y. (2014), “Torsional irregularity in multi-story structures”, *Int. J. Adv. Struct. Eng.*, IJASE, **6**(4), 121-131.
Penzien, J. and Watabe, M. (1974), “Characteristics of 3dimensional earthquake ground motions”, *Earthq. Eng. Struct. Dyn.*, **3**(4), 365-373.
SAP2000 (2012), “Integrated finite element analysis and design of structures”, Computer Program, Computers and Structures, Inc., Berkeley.
Stathi, C.G., Bakas, N.P., Lagaros, N.D. and Papadrakakis, M. (2015), “Ratio of Torsion (ROT): An index for assessing the global induced torsion in plan irregular buildings”, *Earthq. Struct.*, **9**(1), 145-171.
Smeby, W. and Der Kiureghian, A. (1985), “Modal combination rules for multicomponent earthquake excitation”, *Earthq. Eng. Struct. Dyn.*, **13**(1), 1-12.
Tezcan, S.S. and Alhan, C. (2001), “Parametric analysis of irregular structures under seismic loading according to the new Turkish Earthquake Code”, *Eng. Struct.*, **23**(6), 600-609.
Zheng, N., Yang, Z., Shi, C. and Chang, Z. (2004), “Analysis of criterion for torsional irregularity of seismic structures”, *13th World conference on earthquake engineering*, Vancouver, BC, Canada.

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