International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 10 Issue 4 ǁ 2022 ǁ PP. 31-37

Irrgularities in RC Framed Buildings- A Review

Ishita Verma[1*] Shobha Ram[2] M. K. Bhardwaj[3]
[1]*Graduate student, Civil Engineering, Gautam Buddha University, Greater Noida, U.P., India*
[2]*Head, Civil Engineering, Gautam Buddha University, Greater Noida, U.P., India* [3]*Associate Professor, Civil Engineering, S.O.E.T., I.G.N.O.U., New Delhi*

ABSTRACT
Dynamic forces are induced in a structure, when the vibrations during an earthquake acts on it. Due to this, the structure becomes vulnerable to damage. Previous studies by many researchers had come to the conclusion that irregular structures are more vulnerable to damage that the regular structures. This paper presents a review of various studies that have been carried out, highlighting the behaviour of irregular buildings, effects of irregularity on the performance of the building and various methods of structural analysis. Types of damages in irregular buildings and the control measures to be taken into consideration to make an irregular building earthquake resistant have also been reviewed. This paper concludes that additional forces, moments and stresses may develop due to the irregularity in either plan or elevation or both in the structure. Suitable control methods should be taken into consideration for the safety of the structure.
Keywords: *irregularity, torsion, earthquake, structural control*

Date of Submission: 04-04-2022 Date of acceptance: 19-04-2022

I. INTRODUCTION

Building structures are provided to provide intended functions with safety. Safety during earthquake events demands seismic resistance to bear and safely transfer lateral forces imposed on structures by the motion of the earth. Though seismic resistance is generally imparted through structural means, architectural considerations play an important role in this respect. Generally, a simple regular structure in which all structural components provide seismic resistance uniformly is considered as desirable in a seismic condition. It is generally found that a regular structure provides a better performance in seismic conditions (IS 18932016).

The Indian standard IS-1893 (Part 1): 2016 defines a building to be torsionally irregular if maximum translation at one corner of a floor is more than 1.5 times of the same at any other point. The second yardstick is that the natural frequency of the first two translational modes should be more than the fundamental mode of rotation for such a torsionally irregular frame. In the case of torsionally irregular buildings, the Indian standard IS 1893 (Part 1): 2016 guides that the ratio of the maximum and minimum displacements at a floor level in a frame should not exceed 2 failing which the building configuration should be revised. The building should be made torsionally stiff by all possible means.

An earthquake activity generates mass generated inertial forces which are distributed among various structural elements depending on the distribution of stiffness and strength characteristics. Configuration characteristics of a building, which include the size and shape of building, attributes linked to nature, physical dimensions and structural characteristics of all elements, are some of the important parameters affecting the behaviour and performance of a building in a seismic event (Arnold, 2000). Low height with a larger base, equal storey heights, symmetrical nature of plan and vertical shape, uniform variation of mass and stiffness characteristics, short spans, redundancy and simplicity are considered as some of the desirable features of a building structure in view of its seismically desired properties (Arnold, 2000). A regular structure, in general, may be taken to be a uniform structure with respect to shape and distribution of mass, stiffness and strength. Various types of irregular structures are defined in IS 1893-2016. Due to any irregularity in a structure, undesirable behaviour patterns are found in the behaviour and performance in a seismic event.

Equation (1) provides the equation of motion of an undamped structure under a forced vibration condition. The free vibration condition of the same structure is obtained when the forces at the right hand side are taken to be zero.

$$[M][\ddot{x}] + [K][x] = [p(t)] \qquad ..(1)$$

The rank of matrices [M] and [K] determines the total degree of freedom of the structure. The off-diagonal terms in these matrices are considered as ‘coupling terms’. If matrices [M] and [K] are diagonal matrices, the structure is taken to be an uncoupled structure. If [M] is not a diagonal matrix; then the structure may be considered as dynamically coupled. In the case of [K] not being a diagonal matrix; the structure is considered as statically coupled. If both of these matrices are not diagonal matrices; both dynamic and static coupling is taken to be existing in the structure. In irregular structures either a single or both types of couplings may be present. In an uncoupled structure equations of motion are found to be simple algebraic equations which can be easily solved to get the responses in terms of forces and displacements in the structure. This is not so in an irregular structure which is coupled.

Earthquake forces are mass driven inertia forces. It can be assumed that the total seismic force at any instant would apply at the location of the centre of gravity of mass (CM), most often in a horizontal direction. The total seismic force applied at CM may be considered in terms of its components in x and z axis directions, y being the direction of the vertical axis of reference. The structure resists the seismic force due to the stiffness of its vertically oriented structural components such as columns, walls or shear walls etc. For ideal conditions the centre of gravity of stiffness of seismic force resisting elements (CS) should be at the location of CM so that the seismic force is neutralised by the resisting force. If the location of CS and CM is not the one and the same, a couple forms between these two forces which acts in the x-z plane. This couple is equal to the force times the distance between CM and CS, this distance being known as 'Static eccentricity'. This couple acts as a torque on the structure and twisting rotational deformations are produced in the structure. Eccentricity for the calculation of torsion in buildings has been defined considering three different approaches (Jiang et al., 1993). Distance between the centre of mass and centre of resistance is called as 'Corrective eccentricity' and it has been reported to depend on the ratio of uncoupled lateral to torsional frequencies and the ratio of elastic strength demand to the actual strength of the structure (Bosco et al., 2015).

While calculating the location of the centre of stiffness, the shear resistance of all lateral load resisting elements is generally considered. It has been reported that non-structural elements also provide load paths for the transfer of shear forces laterally until those elements fail. Due to them building storeys are subjected to torsional forces and the overall behaviour of the structure is modified (Negro and Colombo 1997). An experimental study of nominally symmetric RC framed structures has revealed that accidental eccentricity must be considered in such structures for frequent earthquakes (Climent et al., 2014). It is also concluded that for high level of seismic activity the role of accidental torsion becomes less important compared to other factors (Climent et al., 2014). Effect of variations in mass distribution to change the location of centre of mass and variations in stiffness of lateral load resisting elements to change the location of centre of stiffness have been compared in respect of torsional effects generated in a structure (Colunga et al., 2007). It has been concluded that torsional influences are more affected by change in location of centre of mass.

This paper presents a review of studies that have been carried out by past researchers on the structural performance of irregular buildings, damages caused due to the presence of different types of irregularities, structural analysis methods used to analyse the irregular structure and control measures used to make the irregular structure earthquake resistant.

II. DAMAGES IN IRREGULAR STRUCTURES

A better performance of regular buildings has been mentioned in the case of February 27, 2010 Chile earthquake (Sepulveda et al, 2012). The existence of irregular plan configuration has been ascribed as a reason for more seismic damage in buildings due to generation of undesirable torsional effects which are absent in buildings having regular plans (Akyurek 2019, Raheem et al 2018, Zafarani et al 2018, Hong Hao 1997). The performance of torsionally coupled and uncoupled building structures has been seen to be different (Akyurek 2019).

The influence of variability in strength of concrete in producing torsional effects in RC framed buildings has been investigated (Stefano et al, 2014). It has been emphasised that more damages may be expected due to asymmetry in structures which may lead to torsional effects (Avila et al, 2018). In the case of Kashmir earthquake of October 2005, it has been reported that failures in buildings were mainly due to plan and vertical irregularities (Kim et al, 2009). In the 12 May 2008 Wenchuan earthquake in China, irregularities in plan and elevation; apart from other reasons; have been found to be responsible for many failures (Zhao et al, 2009).

Due to some failures, such as those of temporary supports or props, forces may be transferred in an irregular fashion and the structure may be subjected to irregularity effects (Buitrago et al, 2020). Seismic damages of soft storey buildings in the case of Mexico city on September 19, 2017 have been listed (Jara et al, 2019). It has been concluded in a parametric study that vertical irregularities may be more damaging than mass irregularities in a seismic event (Wang et al, 2018).

III. EFFECTS OF IRREGULARITY

Apart from structural eccentricities, which are produced in irregular plan structures, spatially varying ground excitations applied at multiple points in a structure are also responsible for torsional effects in structures (Hong Hao 1997). Such torsional responses by spatially varying excitations may be produced in regular structures as well (Hong Hao 1997, Datta 2010). Regular structures are susceptible for such torsional effects in those situations as well when frequencies of lateral and torsional excitations do not match (Ramos 1984). Magnification of accidental eccentricity in torsionally irregular buildings has been considered (Lin et al, 2016).

Buildings which are irregular in plan are considered 'torsionally sensitive' when the fundamental uncoupled torsional frequency is less than the fundamental translational frequencies along the principal building directions (Bakalis and Makarios 2018). Torsional effects in regular structures are reported to occur when the ground motion frequency is either three times or one third of the natural lateral frequency of the regular structure (Ramos 1984). In case of irregular structures, the angle of inclination of the major principal direction of the structure from the direction of the principal ground motion may also have to be considered along with other data of the ground motion in the horizontal and vertical directions (Datta 2010). It has been stated that base shear in a structure is reduced due to torsional effects produced due to building eccentricity and spatially applied multiple excitations (Hong Hao 1997). It has also been reported that torsionally irregular structures are subjected to greater amount of member forces and drifts (Han et al, 2017). The behaviour of irregular buildings in terms of lateral-torsional coupling in the inelastic range is defined in terms of 'normalized stiffness eccentricity' and 'normalized strength eccentricity', values of both being in the range of 0-1 (Ferhi and Truman, 1996). Torsionally coupled plan irregular buildings have been seen to have atleast two lateral and one torsional mode of vibration (Akyurek 2019). In such buildings, different modes of vibrations may dominate responses in the lateral horizontal directions (Akyurek 2019). It has been concluded in a study (Kostinakis et al, 2015) that maximum and average drifts are strongly related to spectral acceleration for irregular structures. A parametric study (Chandler and Hutchinson, 1992) has concluded that structural vibration time periods of short period structures may not have much effect on torsional responses and dynamic shear characteristics. It has been shown that torsional coupling is relatively less dependent on the ratio of peak ground acceleration to the velocity (Chandler and Hutchinson, 1992).

It has been reported that adequate effort of studies has not been made yet to understand the behaviour of stepped RC frame irregular buildings (Sarkar et al 2010). Examination of irregularity in a stepped RC framed building has been taken up and a regularity index has been defined (Sarkar et al, 2010). An effort has been made to determine irregularity of such RC frames by a 'Regularity Index', determined as a ratio of the first mode participation factors for the irregular and regular frames (Sarkar et al 2010). The results obtained by the approach have been found to be accurate (Sarkar et al 2010). The index has been seen to be dependent on many factors which include height of building and nature of vertical geometric irregularity being created. There is a consequent shift in the ratio between time periods of stepped and regular RC frames and spectral acceleration due to variation in vertical geometric irregularity in stepped RC frames. While spectral acceleration increases due to the stepped construction, the time period of the stepped frame first decreases – then finds a bottom – and then gradually increases as the value of regularity index is decreased from a unit value (Sarkar et al 2010). The base shear demand of such buildings has been seen to be hugely dependent on time period of the building, thus being critically affected by the irregularity in the building (Sarkar et al 2010). A modification in the expression for the determination of fundamental time period of stepped buildings has been proposed using the regularity index and the results of the study have been validated with free vibration analysis results.

The nature of open ground storey is somewhat like providing the vertical irregularity in a concentrated manner while the stepped construction may create a uniform vertical irregularity. Peak spectral amplifications in floor spectra in the case of open ground storey RC frames have been found to be much greater than those in the case of RC frames with uniformly infilled with unreinforced masonry walls (Suranaa et al, 2018). Such amplifications of floor response spectra have been reported to be dependent on dynamic characteristics of the buildings; such as mode shapes; which are shaped by irregularities to a great extent (Suranaa et al, 2018). It has been the view that building codes need to be amended to consider the role of mode shapes to determine the floor response spectra in such building structures.

The issue of lateral torsional coupling in irregular buildings has been addressed by many researchers (Chandler et al, 1986; Gupta et al, 1994; Hejal and Chopra, 1989; Jiang et al, 1996; Kan et al, 1981; Nelson et al, 1997; Thambiratnam et al, 1994; Yoon and Smith, 1995). It has been reported that coupled nature of translational and rotational deformations may be critical in design of irregular buildings (Ferhi and Truman, 1996). Effect of stiffness and strength eccentricities in inelastic zone for irregular structures has been examined (Ferhi and Truman, 1996). Presence of infill walls in an RC framed building has been recognised as an agent to bring in-plan irregularity effects (Negro and Colombo, 1997). A parametric study of irregular buildings has considered the use of shear walls in the generation of irregularities

(Tezcan and Alhan 2001). It has been emphasised that even a regular distribution of infill walls may produce irregularity in a frame. When such infill wall panels fail in a seismic event, stiffness at a particular storey would change and such a change may be instrumental in producing a soft storey or weak storey effect in a building (Negro and Colombo, 1997). A mention has been made about 'piloti type buildings of Korea' which have lower portion made of an RC frame. The upper portion comprising of many storeys has a load bearing brick structure. Such a dual type structure is said to be having torsional irregularity as well as other types of vertical irregularities (Lee and Ko, 2007). Creation of irregularity in structures due to changes made in them has been addressed to with the help of an 'irregularity index' (Can He et al., 2019). A method to develop fragility curves for plan irregular RC framed buildings has been proposed (Jeong and Elnashai, 2007). Use of an adaptive neural network with a fuzzy inference system has been seen to be effective in predicting the response of free plan nominally symmetric buildings (Sepulveda et al, 2012). The approach of 'Performance based design' has been considered in a study for irregular RC framed buildings (Giannakouras et al,2019).

IV. METHODS OF STRUCTURAL ANALYSIS

Many methods have been used for the seismic analysis of structures. Static and dynamic analysis procedures have been recommended (IS1893-2016). Modal analysis procedure for linear dynamic systems for seismic excitations has been discussed (Chopra 1996). Goel and Chopra (1994) have discussed a dual design approach in which design eccentricities for moderate and intense earthquake ground motions are considered to be different to satisfy the dual requirements of no damage in moderate conditions and controlled damage in intense earthquake motions.

It has been reported that nonlinear static analysis methods have not been found effective in calculating displacements in plan irregular structures which have translational and rotational components of displacements (Bosco et al, 2015). Nonlinear static methods have been reported to make errors in determining the rotations of decks and are not very effective in assessing the behaviour of multi storey framed buildings (Bosco et al., 2015). Application of pushover method in regard to the application of forces in view of dynamic eccentricities has been examined (Bakalis and Makarios, 2018). The pushover method has been used for scaling the seismic records for nonlinear analysis of irregular buildings (Reyes et al, 2015). It has been found in some cases of analysis of RC frames that irregular frames with vertical irregularity may not be necessarily inferior to regular frames and the Pushover method may underestimate some response parameters in the upper portions of the frames (Athanassiadou, 2008). Modal analysis has been applied in the case of a plan irregular SDOF building and it has been reported that ductility demands may suddenly increase along the direction in which the irregularity exists in such buildings (Ghersi et al, 2001). Use of nonlinear static analysis methods has been found to be effective for torsionally sensitive plan irregular buildings (Erduran, 2008).

Multi-modal pushover method, Modal pushover method and Modified modal pushover methods have been quoted to have been developed for irregular buildings (Rofooei et al, 2018). A dynamic based pushover analysis method has been proposed which considers translational and rotational displacements separately while applying the pushover analysis (Rofooei et al, 2018). A method called 'Corrective eccentricity method' is proposed in which two pushover analysis steps are made in both horizontal directions (Bosco et al, 2015).

Non-linear dynamic spectral approach has been used in determining the response of vertically irregular buildings (Varum et al, 2012). An application of non-linear time history method was made on vertical and mass irregular buildings and performance levels were defined in terms of seismic fragilities (Wang et al, 2018). It has also been suggested that conventional nonlinear methods may not provide accurate results in the case of irregular structures (Mazza, 2014).

Paucity of research data on behaviour of vertically irregular stepped moment resisting RC framed buildings, which are a particular kind of vertically irregular buildings, has been indicated (Sarkar et al 2010). It has been reported (Sarkar et al 2010, Mazza 2016) that higher modes of vibration may be dominant in case of vertical irregular stepped framed buildings. Incremental dynamic analysis is suggested as the most appropriate method for stepped RC frames (Mazza 2016). Use of non-linear dynamic method has been emphasised in the case of setback buildings (Lin et al, 2019). A modal response history analysis has been applied on such a building with a two degree of freedom system approach in place of a single degree of freedom system (Lin et al, 2019).

In irregular frames, apart from dominance of higher modes of vibrations, there are differences in nature of inter storey drifts along the building height, compared to regular frames. But in a study on RC irregular frames with open ground storey (Suranaa et al, 2018); the higher second mode has been found to have a nominal modal mass participation factor ranging from 1 – 7% as compared to 91 – 99% for the first mode. This may point towards the fact that the nature of vertical irregularity in an RC frame may affect the modal mass participation of different modes. A need for a scaling procedure of response history analysis of unsymmetrical plan buildings has been emphasised (Reyes et al, 2015). In such buildings, many different lateral torsional vibration modes may provide comparable contribution in the overall response of vibration due to the fact that effective modal mass of the fundamental mode of vibration is less compared to higher modes (Reyes et al, 2015). The contribution of higher modes of vibration has been considered as an important concern (Rofooei et al, 2018).

Use of a parameter called 'Torsional irregularity (β) given by a ratio of the maximum drift and the average drift at a storey has been made to determine the effects of spectrum matching procedure of non-linear analysis of irregular buildings having different plan shapes. Differing results have been obtained for such buildings (Reyes et al, 2014). Exploration of directions; in plan for which the seismic vulnerability of irregular buildings may be the minimum; has been conducted (Mazza, 2014). A parameter called 'Frequency ratio' which is equal to the ratio of the frequencies of first rotational and first translational mode is said to classify an irregular building as either torsionally flexible or torsionally stiff. A lower value of the frequency ratio defines a torsionally flexible building or vice-versa (Lin et al, 2016).

V. STRUCTURAL CONTROL

Protection of building structures in seismic events poses difficult problems in the case of irregular structures (Soto et al, 2018). Use of active control devices alongwith a passive base isolation system using the evolutionary game theory has been studied for irregular buildings (Soto and Adeli 2018).

Effect of structural vertical irregularity on the placement of supplemental damping devices has been studied (Landi et al, 2015) with a possible utilization for the retrofit of RC framed buildings in an area where seismic classification has been revised. Different types of RC frames including those having soft storey and setbacks were considered (Landi et al, 2015). Providing braces has been considered to be one of the best methods to protect a plan-irregular building from torsional effects during seismic vibrations (Akyurek 2019).

Use of tuned mass dampers has been studied for control of response of RC setback frames in which displacements, storey shears and peak accelerations have been shown to decrease respectively by 45%, 30% and 20% due to such use (Mathur et al, 2003). A possible drawback of a tuned mass damper is that it is effective only in the small fundamental frequency range of the structure for which it is tuned (Akyurek 2019). Other means of control include the use of multi-tuned mass dampers (MTMD), base isolation systems (BIS), hybrid base isolation systems (HBIS) and circular tuned liquid column dampers (CTLCD) (Akyurek 2019). Glauser et al, (1997) have studied the use of a passive isolator, a passive as well as active hybrid system and an active vibration absorber for controlling seismic vibrations. Various studies for control of seismic vibrations in irregular buildings have been undertaken (Lin et al, 1999).

Use of supplemental damping devices, remaining independent of the structure, for strengthening of an old irregular building has been reported (Rai, 1999).

It has been reported that ratio of effective time period of a base isolated structure to time period of the reference structure without base isolation happens to be inversely proportional to torsional amplification in the isolated structure (Colunga et al., 2007).

Performance of viscoelastic dampers has been reported to be more effective than that of viscous dampers in plan irregular structures for control of torsional vibrations (Kim and Bang, 2002). Use of modal analysis for locating viscoelastic dampers and viscous dampers has been made and parametric studies have been conducted on plan irregular structures (Kim and Bang, 2002; Petti and Iuliis, 2008).

In a study it has been found that isolation system provided at the base of the building should be flexible and the centre of stiffness of the isolating medium should be near to the centre of stiffness of the superstructure (Seguin et al., 2013).

Effect of static eccentricity has been studied on base-isolated structures for maximum responses in terms of displacements in isolators and ductility demands (Colunga et al., 2002)

VI. CONCLUSION

It has been concluded that different forms of irregularity have different types of effect on the performance of the structure. Systematic studies should be undertaken so that appropriate control measures may be taken considering special effects of each of them.

REFERENCE

[1]. Seismic response characteristics of high-rise RC wall buildings having different irregularities in lower stories, Engineering Structures, Volume 29, Issue 11, 2007, Pages 3149-3167, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2007.02.014.

[2]. W. Jiang, G.L. Hutchinson, A.M. Chandler, Definitions of static eccentricity for design of asymmetric shear buildings, Engineering Structures, Volume 15, Issue 3, 1993, Pages 167-178, ISSN 0141-0296, https://doi.org/10.1016/01410296(93)90051-5.

[3]. P. Negro, A. Colombo, Irregularities induced by nonstructural masonry panels in framed buildings, Engineering Structures, Volume 19, Issue 7, 1997, Pages 576-585, ISSN 0141-0296, https://doi.org/10.1016/S0141-0296(96)00115-0.

[4]. Melina Bosco, Giovanna A.F. Ferrara, Aurelio Ghersi, Edoardo M. Marino, Pier Paolo Rossi, Predicting displacement demand of multi-storey asymmetric buildings by nonlinear static analysis and corrective eccentricities, Engineering Structures, Volume 99, 2015, Pages 373-387, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2015.05.006.

[5]. A.M. Chandler, G.L. Hutchinson, Effect of structural period and ground motion parameters on the earthquake response of asymmetric buildings, Engineering Structures, Volume 14, Issue 6, 1992, Pages 354-360, ISSN 0141-0296

[6]. A.Benavent-Climent, L. Morillas, D. Escolano-Margarit, Inelastic torsional seismic response of nominally symmetric reinforced concrete frame structures: Shaking table tests, Engineering Structures, Volume 80, 2014, Pages 109-117, ISSN 0141-0296
[7]. Arturo Tena-Colunga, Jose Luis Escamilla-Cruz, Torsional amplifications in asymmetric base-isolated structures, Engineering Structures, Volume 29, Issue 2, 2007, Pages 237-247, ISSN 0141-0296
[8]. Jinkoo Kim, Sunghyuk Bang, Optimum distribution of added viscoelastic dampers for mitigation of torsional responses of plan-wise asymmetric structures, Engineering Structures, Volume 24, Issue 10, 2002, Pages 1257-1269, ISSN 0141-0296
[9]. L. Petti, M. De Iuliis, Torsional seismic response control of asymmetric-plan systems by using viscous dampers, Engineering Structures, Volume 30, Issue 11, 2008, Pages 3377-3388, ISSN 0141-0296
[10]. Carlos E. Seguin, Jose L. Almazan, Juan C. De la Llera, Torsional balance of seismically isolated asymmetric structures, Engineering Structures, Volume 46, 2013, Pages 703-717, ISSN 0141-0296
[11]. Arnold Christopher, Farzad Naeim (ed.), The Seismic Design Handbook, 2nd edition, 2000.
[12]. A.Tena-Colunga, L. Gomez-Soberon, Torsional response of base-isolated structures due to asymmetries in the superstructure, Engineering Structures, Volume 24, Issue 12, 2002, Pages 1587-1599, ISSN 0141-0296
[13]. Manuel Buitrago, Juan Sagaseta, Jose M. Adam, Avoiding failures during building construction using structural fuses as load limiters on temporary shoring structures, Engineering Structures, Volume 204, 2020, 109906, ISSN 0141-0296
[14]. Xiao-Huang-Can He, Xian-Xun Yuan, Wei-Jian Yi, Irregularity index for quick identification of worst column removal scenarios of RC frame structures, Engineering Structures, Volume 178, 2019, Pages 191-205, ISSN 0141-0296
[15]. Athanasios P. Bakalis, Triantafyllos K. Makarios, Dynamic eccentricities and the "capable near collapse centre of stiffness" of reinforced concrete single-storey buildings in pushover analysis, Engineering Structures, Volume 166, 2018, Pages 6278, ISSN 0141-0296
[16]. Pradip Sarkar, A. Meher Prasad, Devdas Menon, Vertical geometric irregularity in stepped building frames, Engineering Structures, Volume 32, Issue 8, 2010, Pages 2175-2182, ISSN 0141-0296
[17]. Juan C. Reyes, Andrea C. Riaño, Erol Kalkan, Carlos M. Arango, Extending modal pushover-based scaling procedure for nonlinear response history analysis of multistory unsymmetric-plan buildings, Engineering Structures, Volume 88, 2015, Pages 125137, ISSN 0141-0296
[18]. C.J. Athanassiadou, Seismic performance of R/C plane frames irregular in elevation, Engineering Structures, Volume 30, Issue 5, 2008, Pages 1250-1261, ISSN 01410296
[19]. J.M. Jara, E.J. Hernández, B.A. Olmos, G. Martínez, Building damages during the September 19, 2017 earthquake in Mexico City and seismic retrofitting of existing first soft-story buildings, Engineering Structures, 2019, 109977, ISSN 0141-0296
[20]. H. Varum, A. Pinto, A. Costa, P. Vila Real, Simplified models for assessment and optimal redesign of irregular planar frames, Engineering Structures, Volume 42, 2012, Pages 245-257, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2012.04.033.
[21]. Jianze Wang, Kaoshan Dai, Yexian Yin, Solomon Tesfamariam, Seismic performancebased design and risk analysis of thermal power plant building with consideration of vertical and mass irregularities, Engineering Structures, Volume 164,
[22]. 2018, Pages 141154, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2018.03.001.
[23]. Mariantonieta Gutierrez Soto, HojjatAdeli, Vibration control of smart base-isolated irregular buildings using neural dynamic optimization model and replicator dynamics, Engineering Structures, Volume 156, 2018, Pages 322-336, ISSN 01410296
[24]. Semih S Tezcan, Cenk Alhan, Parametric analysis of irregular structures under seismic loading according to the new Turkish Earthquake Code, Engineering Structures, Volume 23, Issue 6, 2001, Pages 600-609, ISSN 0141-0296, https://doi.org/10.1016/S0141-0296(00)00084-5.
[25]. Jui-Liang Lin, Chih-Chia Tsaur, Keh-Chyuan Tsai, Two-degree-of-freedom modal response history analysis of buildings with specific vertical irregularities, Engineering Structures, Volume 184, 2019, Pages 505-523, ISSN 0141-0296
[26]. Seong-HoonJeong, Amr S. Elnashai, Fragility relationships for torsionallyimbalanced buildings using three-dimensional damage characterization, Engineering Structures, Volume 29, Issue 9, 2007, Pages 2172-2182, ISSN 0141-0296
[27]. M. De Stefano, M. Tanganelli, S. Viti, Variability in concrete mechanical properties as a source of in-plan irregularity for existing RC framed structures, Engineering Structures, Volume 59, 2014, Pages 161-172, ISSN 0141-0296
[28]. EmrahErduran, Assessment of current nonlinear static procedures on the estimation of torsional effects in low-rise frame buildings, Engineering Structures, Volume 30, Issue 9, 2008, Pages 2548-2558, ISSN 0141-0296
[29]. Aurelio Ghersi, Pier Paolo Rossi, Influence of bi-directional ground motions on the inelastic response of one-storey in-plan irregular systems, Engineering Structures, Volume 23, Issue 6, 2001, Pages 579-591, ISSN 0141-0296
[30]. Ferhi, K.Z. Truman, Behaviour of asymmetric building systems under a monotonic load—II, Engineering Structures, Volume 18, Issue 2, 1996, Pages 142-153, ISSN 0141-0296, https://doi.org/10.1016/0141-0296(95)00074-7.
[31]. Konstantinos Kostinakis, Asimina Athanatopoulou, Konstantinos Morfidis, Correlation between ground motion intensity measures and seismic damage of 3D R/C buildings, Engineering Structures, Volume 82, 2015, Pages 151-167, ISSN 0141-0296
[32]. Durgesh C. Rai, Supplemental damping for seismic strengthening: a case study, Engineering Structures, Volume 21, Issue 7, 1999, Pages 603-614, ISSN 0141-0296, https://doi.org/10.1016/S0141-0296(98)00007-8.
[33]. Jui-Liang Lin, Wei-Chun Wang, Keh-Chyuan Tsai, Suitability of using the torsional amplification factor to amplify accidental torsion, Engineering Structures, Volume 127, 2016, Pages 1-17, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2016.08.042.
[34]. Gina J. Lee-Glauser, Goodarz Ahmadi and Lucas G. Horta, Integrated passive / active vibration absorber for multistory buildings, Journal of Structural Engineering, April 1997, pp. 499-504
[35]. Shaleen Mathur and SajalKanti Deb, Seismic response control of RC setback building with friction dampers, The Indian Concrete Journal, November 2003, pp. 1469-72.
[36]. Han-Seon Lee, Dong-Woo KoSeismic response characteristics of high-rise RC wall buildings having different irregularities in lower storiesEngineering Structures 29 (2007) 3149–3167
[37]. Ferhi A. and Truman K.Z., Behaviour of asymmetric building systems under a monotonic load – II, Engineering Structures, Vol. 18, No. 2, pp. 142-153, 1996
[38]. Chi-Chang Lin, Jin-Min Ueng and Teng-Ching Huang, Seismic response reduction of irregular buildings using passive tuned mass dampers, Engineering Structures, 22 (1999) 513-524
[39]. Mohammad M. Zafarania, Amir M. Halabianb, Supervisory adaptive nonlinear control for seismic alleviation of inelastic asymmetric buildings equipped with MR dampersEngineering Structures 176 (2018) 849–858
[40]. Anil K. Chopra, Modal analysis of linear dynamic systems: Physical interpretation, Journal of Structural Engineering, Vol. 122, No. 5, May 1996, pp. 517-527
[41]. Rakesh K. Goel and Anil K. Chopra, Dual-level approach for seismic design of asymmetric plan buildings, Journal of Structural Engineering, Vol. 120, No. 1, January 1994, pp. 161-179.

[42]. IS 1893-2016 Criteria for Earthquake Resistant Design of Structures Part 1 General provisions and buildings (Sixth revision), Bureau of Indian Standards, Manak Bhawan, New Delhi - 110002
[43]. J. I. Ramos, Torsional oscillations in symmetrical structures, Appl. Math. Modelling, 1984, Vol. 8, December 1984, pp. 433-441
[44]. Datta, T.K., Seismic analysis of structures, John Wiley & Sons Pvt. Ltd., pp.42, 2010
[45]. Hong Hao, Torsional response of building structures to spatial random ground excitations, Engineering Structures, Vol. 19, No. 2, pp. 105-112, 1997
[46]. Mariantonieta Gutierrez Soto, HojjatAdeli, Vibration control of smart base-isolated irregular buildings using neural dynamic optimization model and replicator dynamics, Engineering Structures, 156 (2018) 322–336
[47]. Osman Akyurek, NakinSuksawangb, TiauwHiongGoc, Vibration control for torsionally irregular buildings by integrated control system, Engineering Structures, 201 (2019) 109775
[48]. Fabio Mazza, Nonlinear seismic analysis of R.C. framed buildings with setbacks retrofitted by damped braces, Engineering Structures, 126 (2016) 559–570
[49]. Giacomo Bernagozzi, Luca Landi, Pier Paolo Diotallevi, Truncation error analysis on modal flexibility-based deflections: application to mass regular and irregular structures, Engineering Structures, 142 (2017) 192–210
[50]. Mitesh Surana, Mayur Pisode, Yogendra Singh, Dominik H. Lang, Effect of URM infills on inelastic floor response of RC frame buildings, Engineering Structures, 175 (2018) 861–878
[51]. Luca Landi, Filippo Conti, Pier Paolo Diotallevi, Effectiveness of different distributions of viscous damping coefficients for the seismic retrofit of regular and irregular RC frames, Engineering Structures, 100 (2015) 79–93
[52]. Juan C. Reyes, Andrea C. Riano, Erol Kalkan, Oscar A. Quintero, Carlos M. Arango, Assessment of spectrum matching procedure for nonlinear analysis of symmetric- and asymmetric-plan buildings, Engineering Structures, 72 (2014) 171–181
[53]. Leonardo Avilaa, Graça Vasconcelos, Paulo B. Lourenço, Experimental seismic performance assessment of asymmetric masonry buildings, Engineering Structures, 155 (2018) 298–314
[54]. Fabio Mazza, Modelling and nonlinear static analysis of reinforced concrete framed buildings irregular in plan, Engineering Structures, 80 (2014) 98–108
[55]. Sung Jig Kim, Amr S. Elnashai, Characterization of shaking intensity distribution and seismic assessment of RC buildings for the Kashmir (Pakistan) earthquake of October 2005, Engineering Structures, 31 (2009) 2998_3015
[56]. Sang Whan Han, Tae-O Kim, Dong Hwi Kim, Seong-JinBaek, Seismic collapse performance of special moment steel frames with torsional irregularities, Engineering Structures, 141 (2017) 482–494
[57]. Juan C. Reyes, Andrea C. Riano, Erol Kalkan, Carlos M. Arango, Extending modal pushover-based scaling procedure for nonlinear response history analysis of multistory unsymmetric-plan buildings, Engineering Structures, 88 (2015) 125–137
[58]. Fayaz R. Rofooeia, M.R. Mirjalili, Dynamic-based pushover analysis for one-way planasymmetric buildings, Engineering Structures, 163 (2018) 332–346
[59]. Chopra AK, Goel RK, Chintanapakdee C., Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands, Earthquake Spectra, 2004; 20(3): 757–78.
[60]. Goel R.K., Chopra A.K., Evaluation of modal and FEMA pushover analyses: SAC Buildings, Earthquake spectra 2004; 20(1): 225–54.
[61]. Bin Zhaoa, Fabio Taucer, TizianaRossetto, Field investigation on the performance of building structures during the 12 May 2008 Wenchuan earthquake in China, Engineering Structures, 31 (2009) 1707_1723
[62]. Sang Whan Han, Tae-O Kim, Dong Hwi Kim, Seong-JinBaek, Seismic collapse performance of special moment steel frames with torsional irregularities, Engineering Structures, 141 (2017) 482–494
[63]. Cesar Sepulved, Juan Carlos De la Ller, Andres Jacobsen, An empirical model for preliminary seismic response estimation of free-plan nominally symmetric buildings using ANFIS, Engineering Structures, 37 (2012) 36–49
[64]. P. Negro and A. Colombo, Irregularities induced by non-structural masonry panels in framed buildings, Engineering Structures, Vol. 19, No. 7, pp 576-585, 1997
[65]. Melina Bosco, Giovanna A.F. Ferrara, Aurelio Ghersi, Edoardo M. Marino, Pier Paolo Rossi, Predicting displacement demand of multi-storey asymmetric buildings by nonlinear static analysis and corrective eccentricities, Engineering Structures, 99
[66]. (2015) 373–387
[67]. Jui-Liang Lin, Wei-Chun Wang, Keh-Chyuan Tsai, Suitability of using the torsional amplification factor to amplify accidental torsion, Engineering Structures, 127 (2016) 1–17
[68]. P. Giannakourasa, C. Zeris, Seismic performance of irregular RC frames designed according to the DDBD approach, Engineering Structures 182 (2019) 427–445
[69]. Dhiman Basu_, N. GopalakrishnanAnalysis for preliminary design of a class of torsionally coupled buildings with horizontal setbacks, Engineering Structures, 30 (2008) 1272–1291
[70]. Chandler AM, Hutchinson GL. Torsional coupling effects in the earthquake response of asymmetric buildings, Engineering Structures, 1986; 8(4): 222–36.
[71]. Gupta RK, Hutchinson G.L., Horizontal and vertical seismic response of torsionally coupled buildings, Engineering Structures, 1994; 16(1): 11–24.
[72]. Hejal R, Chopra A.K., Earthquake response of torsionally-coupled farmed Buildings, Journal of Structural Engineering, ASCE 1989; 115(4): 834–51.
[73]. Jiang W, Hutchinson G.L., Wilson J.L., Inelastic torsional coupling of building models, Engineering Structures, 1996; 18(4): 288–300.
[74]. Kan C.L., Chopra A.K., Torsional coupling and earthquake response of simple elastic and inelastic systems, Journal of Structural Engineering, ASCE 1981; 107(ST8): 1569– 88.
[75]. Nelson T.K., Wilson J.L., Hutchinson G.L., Review of the torsional coupling of asymmetrical wall-frame buildings, Engineering Structures, 1997; 19(3):233–46.
[76]. Thambiratnam D.P., Corderoy J.B., Effects of asymmetry on the response of multistorey buildings to earthquakes, Engineering Structures, 1994; 16(3): 210–21.
[77]. Yoon Y.S., Smith B.S., Estimating period ratio for predicting torsional Coupling, Engineering Structures, 1995; 17(1): 52–62.
[78]. Athanasios P. Bakalis, Triantafyllos K. Makarios, Dynamic eccentricities and the “capable near collapse centre of stiffness” of reinforced concrete single-storey buildings in pushover analysis, Engineering Structures, 166 (2018) 62–78