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Review Article

Critical review of codal provisions on the torsional irregularity

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Buildings with irregularities have consistently been highly vulnerable to seismic events. The earthquake events have been showing the failure patterns of the reinforced concrete buildings with various irregularities. But the large number of buildings have been existing and being constructed with irregularities both in the urban as well as rural areas of developing countries. Various irregularities have been defined in international standards. But still, there is a need to study the combined irregularities of the building. In this study, the various country codal provisions on torsional irregularities in the reinforced concrete buildings have been reviewed and compared. Most of the codes have considered the edge displacements as the measure of torsional irregularity criteria. The amplification factorshave been used for structural eccentricity and accidental eccentricity to increase the design forces. The torsional flexibility based on the ratio of the natural period of torsional mode and translational mode, stiffness eccentricity ratio, and the mass factor based on the radius of gyration of mass about the center of mass of the building have been introduced in the draft code IS 1893-2023, Part-2. The limiting value have been prescribed by the code for torsional flexibility factor to prevent the failure of buildings due to torsional flexibility. In this paper, various significant factors affecting the seismic performance of the buildings due to torsional irregularity have been reviewed.

Keywords: Accidental eccentricity, Codal provisions, Design eccentricity, Torsional flexibility, Torsional irregularity

1 Introduction

Seismic events demonstrated the catastrophic failure of the reinforced concrete buildings (Reconnaissance report EERI[1]) with torsional irregularity. But the large number of buildings are existing and being constructed with various irregularities in developing countries. Even in the developed nations presence of irregularities are noted. Based on the seismic behaviour of the building, plan irregularity leads to Torsional irregularity and Torsional flexibility as per IS (1893)[2]. When the fundamental (First) mode of the building is Torsional mode, then the building is said to be torsionally flexible. This leads to higher displacements at the flexible side of the building with respect to the stiffer side. The building configuration must be changed to make the translational mode the first two modes of the building. The poor structural configurations lead to non-uniform distribution of stiffness, mass, and strength. Hence the center of mass and center of stiffness do not coincide and an eccentricity arises leading to torsional forces on the building (Torsional irregularity). The draft code IS 1893-2023[3], Part-2 gives the limits for torsional flexibility factor (Tamizharasi[4]) to prevent the seismic damage of buildings due to torsional flexibility which depends on the ratio of the natural period of torsional mode and translational mode, stiffness eccentricity ratio, and the mass factor based on radius of gyration of mass about the center of mass of the building. The draft code limits the maximum displacement at one end of slab to be less than 1.2 times the average displacement of both ends and if it is in the range of 1.2 to 1.4, the building structural configuration has to be revised to have first two modes as translational modes. The symmetrical distribution of the mass, stiffness, and strength in the building will not have the above irregularities. The value of more than 1.4 is not permitted and hence building configuration should be revised.

As per the code IS 1893-2016, the torsional irregularity is defined as that of the maximum displacement at one end of the slab if exceeds 1.5 times the maximum displacement at the other end of the slab and the first mode of the building is the torsional mode. If the above range is 1.5 to 2.0, the

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building configuration shall be revised such that the first mode of the building is translational. More than 2.0 is not allowed as per this code.Non-uniform distribution of mass and stiffness produces torsional effects leading to catastrophic failure of the buildings. (Dowrick[5]).To cater to the effect of the torsion in the building design, the static/ structural eccentricity, and accidental eccentricity is considered in the design (Eurocode 8[6]) and the code advocates for sufficient torsional resistance and stiffness. Nina Zheng *et al*.[7] evaluates the codal provisions of China, USA and Europe on the torsional irregularity. Kober. D and Zamfirescu. D[8] presents the issues related to codal provisions on torsional irregularity. Bijily Balakrishnan and Pradip Sarkar[9] has evaluated the codal provisions on torsional irregularity using SAP2000 with asymmetric model building. Durgesh C. Rai[10] gives the limiting value of the eccentricity and shear wall/bracing arrangement for mitigating the torsional effects.

2 Materials & Methods

Significant Parameters which are important factors affecting the seismic performance of the buildings due to torsional irregularity as reviewed from the literature are discussed.

2.1 Static or structural eccentricity

Due to non-uniform distribution of mass, stiffness, and strength in the building the center of mass does not coincide with the center of stiffness. The torsional response of the building increases with increase in the eccentricity. The distance between them termed as static or structural eccentricity is taken into account in various codal provisions. An additional amplification or modification factor is used to amplify the static/structural eccentricity in the design force calculations in various codal provisions to cater to the torsional irregularity as shown in the Table 1.

2.2 Accidental eccentricity

Apart from the static/structural eccentricity, even when the building is symmetric and having uniform distribution of mass and stiffness, accidental eccentricity arises due to a) earthquake ground motions, b) changes in the loading on the building over the period of time, c)the quality of construction. Hence most of the codes provides 0.5 to 1 percent of building dimension perpendicular to the seismic force as accidental eccentricity value for design force calculations in addition to the static/structural eccentricity as shown in the Eq. (1).

Table 1 — IS Codal provisions on eccentricity. (with respect to coefficients of equation 1 and 2).

Sl. No	Seismic Code	A	B	C
1	IS 1893-2016	1.5 – ESA 1.0 – DA	0.05	1.0
2	IS 1893-2023 (Draft)	1.8 –ESA 0 – TH &RS	0.05 0.05	0 0

DA – Dynamic Analysis, ESA – Equivalent Static Analysis, RS – Response spectrum method

2.3 Stiffness, strength and mass distribution

This depends on the structural configuration of the building in the plan and elevation. Symmetric shapes with uniform distribution of mass, stiffness, strength and loading of the building in plan and elevation is choosen in a way that centre of mass and centre of stiffness coincides such that static or structural eccentricity is made to zero.

2.4 Torsional ground motions

During seismic events, the torsional component in the ground motion produces torsion in the building. This is taken into account in the way of accidental eccentricity during design force calculations in addition to structural eccentricity.

2.5 Torsional flexibility

Due to the lack of torsional stiffness, even if the building is having symmetry in all aspects, building may rotate due to torsional mode during seismic events leading to the damage of structural elements in perimeter of the building especially columns. Lateral load resistance of the building may be increased by the way of bracings or construction of shear wall to prevent the failure of the building.

2.6 Strength, stiffness, ductility

The basic traits required for any building (symmetric/unsymmetric) for its effective seismic performance are strength, stiffness and ductility. This will provide sufficient storey hinge mechanisms and energy dissipation preventing catastrophic failure of the buildings.

2.7 Damping

The inherent structural damping present in the building protects the buildings with torsional irregularity and controls the seismic response. In some buildings, passive devices are provided for seismic response control.

2.8 Natural frequency

The building should be designed with required torsional stiffness such that the first two fundamental frequencies of the building are of translational mode followed by the torsional mode to avoid damage due to torsional flexibility.

2.9 Ratio of the translational time period and torsional time period

If the ratio of translational time period to torsional time period is equal to one, then there will be coupled mode. Hence this ratio shall be less than 0.9 (IS 1893-2023)1. To avoid the coupling of the translational and torsional mode, the building shall be designed such that the ratio of translational time period and torsional time period is less than 0.9. This is possible if the eccentricity between center of mass and center of stiffness is made near to zero and the design of building with required torsional stiffness

2.10 Torsional stiffness

Even though the building is symmetric in all aspects, due to torsional flexibility, the first mode of the building becomes torsional mode leading to damage of the weak structural members present in the perimeter of the building. Hence the building should be designed with required uniform torsional stiffness especially the structural members located in the perimeter of the building.

2.11 Lateral load resisting system

In general, for any building to perform effectively during the seismic events, the lateral load resisting systems such as moment frames, bracings, shear wall are designed with required strength, stiffness, and ductility to protect the building from failure during seismic events.

Hence the basic requirements of effective seismic performance of the buildings are a) Lateral Load Resisting System, b) Symmetric Plan and Vertical structural configuration, c) Sufficient Torsional Stiffness, d) load paths and connections David Dowrick[5]. Das *et.al*[11] and Anagnostopoulos[12] have reviewed the literature on buildings with various irregularities. It is observed that different study leads to different results because of unrealistic one-dimensional models assumed in various studies. Archana *et.al*[13], have studied the building with both plan and vertical irregularity.

2.12 Eccentricity

The general expression used in various codes for design eccentricity is given in

equations (1) and (2) as below

$$e = Ae_S + Bb \quad \ldots(1)$$

$$e = Ce_S - Bb \quad \ldots(2)$$

Where "e" is the design eccentricity to be used,

e_S the static eccentricity (between centre of mass and centre of stiffness)

b is the dimension of the building perpendicular to the seismic force

A and C are amplification factors

B is the factor for accidental eccentricity (5 to 10% of building dimension perpendicular to Earthquake force).

The static (structural) eccentricity is due to the eccentricity between the center of mass and the center of stiffness. The causes of accidental eccentricity (Bb) are a) Deviation in construction from the original configurations b) Construction and Materials quality c) Non-uniform / Unsymmetrical loading over the building d) due to torsional ground motions. The above unforeseen eccentricity is accounted in the design stage as shown in the above equations to increase the seismic force due to eccentricity. Generally, in all the seismic codes, the accidental eccentricity is taken as 5 to 10 percentage of the building dimension perpendicular to the seismic force acting on the building. The above equations consider the dynamic amplification (A and C) for static/ structural eccentricity and (B) 5 to10 percent of the building dimension for accidental eccentricity. Based on the eccentricity values, torsional demand on the structural members (flexible side and stiff side) are evaluated during the design stage. The design eccentricity is based on single floor in most of the codes but few codes considers all the floors. The difference between the two methods will be very less. Most of the codes consider the edge displacements for specifying the criteria for torsional irregularity. Table 1 gives the IS 1893 provisions on the eccentricity values.

An amplification of 1.5 times the static eccentricity is required in static analysis, while it is 1.0 for dynamic analysis, wherein the amplification is not required for dynamic analysis. In draft code IS1893-2023, the amplification factor is increased to 1.8 for static/structural eccentricity in the flexible side alone for the equivalent static method. In the time history and response spectrum method, the static/structural eccentricity shall not be considered. For all the methods of analysis, accidental eccentricity is taken as five percent of the building dimension perpendicular to the seismic force.

$$A\text{x} = (\delta\text{max}/1.2\delta avg)^2 \quad \ldots(3)$$

The above amplification factor as given in Eq. (3) is used for accidental eccentricity in IBC[14] (International building code) whereas it is used for both static and accidental eccentricity in the NEHRP[15] document. Based on the torsional irregularity of various country codes, the design limits in terms of Natural period ratio, torsional, accidental and structural eccentricity is proposed by Tamilarasi[4]. For Indian code IS1893-2016[2], the limits of natural period ratio lies in the range of 0.65 to 0.70 and Accidental Eccentricity, Structural Eccentricity, and Torsional Eccentricity, are 5 percent, 1 percent and 5 to 6 percent respectively.Accidental eccentricity provisions in the code increases the design capacity of the structural members to resist torsional forces due to the effects of torsional ground motion, changes in loading arrangements, mass and stiffness distributions. Rather than increasing the forces for designing the structural members, it is very important to make the building configuration such that the center of mass is very close to the center of stiffness to reduce the torsional effects (Tamilarasi)[4]. Particularly the structural members in the circumference of the building is affected due to torsional irregularity due to twisting of the building.

2.13 Technical documents

FEMA P-2012[16]evaluates the irregularities in building codes of various countries. This document have the details of irregularities related to torsional stiffness, torsional strength, soft storey, weak storey, along with other irregularities. In this document, the torsional irregularity is assessed based on stiffness irregularity and strength irregularity. The criteria for stiffness-based irregularity is the ratio of max displacement at one end of the slab to the average displacement of both ends shall not exceed 1.2 and it is said to be the extreme condition if the ratio exceeds 1.4. The criteria for strength-based irregularity is the demand-capacity ratio. ASCE/SEI 41-17[17]evaluates the torsional behavior due to strength irregularity based on the Demand-Capacity Ratio (DCR) of the structural elements of the building.

$$DCR = \frac{\text{Seismic Force Demand on the building}}{\text{Strength capacity of the building}} \quad \ldots(4)$$

If the above ratio is more than one, then the seismic demand (Forces/Displacements) exceeds the capacity then the structure may not be able to withstand the seismic forces. The maximum DCR at one end of the building is more than other end of the building by a factor of 1.5, the building is said to have torsional strength irregularity leading to rotation of the building during the seismic events. The earthquake forces act on the weaker side of the building and hence damages occur due to the rotation of the building during earthquake. During retrofitting weaker side of the building is strengthened by bracings /shear walls to control the seismic response.Due to less torsional stiffness, even in the symmetric buildings, torsional flexibility arises.

As per ASCE 7-16[18] the load combination of full seismic force (100 Percent) in one direction (X) and 30 percent in the perpendicular direction (Y) and vice versa is applied to the building. This takes into account the ground motion severities of the seismic events leading to safe design forces onto the buildings. This provision is especially important for the buildings with torsional irregularities wherein the response of weak and strong directions of the building is observed. The redundancy factor 1.3 shall not be applied in the design if the above rule is applied. As per the code, the torsional irregularity is said to exist in the building wherein the 75 percent of the lateral strength is concentrated on one side of the centre of mass of the building.

FEMA P-2012[16] allows the extremely torsional irregular buildings in seismic design categories E and F if the proposed criteria mentioned in the document are satisfied which will prevent the building from failure. The equivalent static lateral force method of analysis is allowed by this document for torsionally irregular buildings which is prohibited by ASCE/SEI 7-16[18]. The document recommends the redundancy factor of 1.3 for the torsionally irregular buildings. The following aspects are recommended by FEMA P-2012[16] towards seismic safety of the building with torsional irregularity. The load combination of full seismic force (100 Percent) in one direction (X) and 30 percent in the perpendicular direction (Y) and vice versa is taken during design force calculations. The torsional irregularity is said to exist in the building wherein the 75 percent of the lateral strength is on one side of the centre of mass of the building. For the buildings with extreme torsional irregularity, the accidental torsional moment is applied where the 0.05b (b – dimension of building perpendicular to earthquake force) is not sufficient to cater the design force. This document do not recommends the DCR based criteria for Torsional Strength Irregularity for design as provided in ASCE/SEI41-17[16].

The torsional strength irregularity is codified in ASCE/SEI 41-17[17] and torsional stiffness irregularity is addressed in ASCE/SEI 7-16[18] along with other types of irregularities. ACI 318-14[19] and ANSI/AISC 341-16[20]evaluates the weak-column strong-beam irregularity. Fardis[21] and Japanese building code[22] advocates for having symmetric structure with simple, good design to prevent failures due to irregularities and the Japanese code has developed the eccentricity ratio (R_e) factor and F_e factor to modify the design forces based on the torsional eccentricity levels.

As per ASCE/SEI 7-16[18] torsional irregularity criteria is defined as displacement of one end of the slab exceeds 1.2 times the average displacement of the two ends of the slab when the load is applied with an eccentricity value of five percent of the building dimension perpendicular to the seismic force. In the literature, it is found that eccentricity is amplified and torsional irregularity increases as the building moves from linear to non-linear stage. Hence the study of simple elastic one-dimensional models found in the literature may not be sufficient for understanding of torsional irregularity and its collapse potential. Three-dimensional model with non-linear dynamic analysis can be opted for buildings with torsional irregularity for getting more insights. The amplification factor Ax used for eccentricity increases the design forces and also the design should satisfy the drift limits imposed by the code thereby reduces the collapse potential of the building with torsional irregularity.

FEMA P-749[23] advocates for prohibition of buildings with irregularities in Seismic Design Categories E or F. Torsional irregularity is evaluated based on end displacements of the slab. In irregular buildings, damage concentrates in particular location of building leading to failure. This document elaborates about soft-storey, extreme soft-storey, weak storey, extreme weak-storey which is prohibited in seismic design categories E and F. This document advocates for amplifying factor for design earthquake forces to avoid failure during earthquake events. To increase the torsional resistance, during the design stage, the earthquake force is applied with eccentricity of plus or minus five percent of the building dimension perpendicular to earthquake force direction and higher forces is taken for the design to ensure required torsional resistance of the building. The document recommends for hundred percent design force in X – direction with simultaneous application of 30 percent in Y-direction and vice versa application and higher values are taken for design. The amplification factor is used with accidental eccentricity for further increase in torsional resistance of the torsional irregular buildings.

In ASCE and IBC[14] seismic codes, the seismic design category (SDC) is classified as A,B,C,D,E,F based on the location of the building, importance factor, occupancy/functionality of the building. A being the lowest risk to F being highest risk wherein the hazard level is higher. The basic features considered in the design with increasing design category are ductility, energy dissipation, and collapse prevention. For still higher categories E and F, the design considers redundancy and overstrength factors wherein the higher design forces are taken. Special provisions/criterion such as dynamic analysis, 100-30 percent loading in both directions, are considered for the building with irregularities in the high-risk seismic design category E and F. In few codes, the extreme torsional irregularities are prohibited for seismic design category E and F where the hazard level is very high. In SDC – F, special energy dissipation devices are used to ensure Immediate occupancy requirements of building like hospitals, power plants etc. FEMA P-2082[15]gives two criteria for torsional irregularity. (a) Seventy-five percent of lateral strength is provided at one side of the centre of mass (b) the maximum displacement at one end of the slab is higher than 1.2 times the average displacements at two ends of the slab. If the value exceeds 1.4, then it is said to be extreme torsional irregularity. The slab is assumed to be rigid floor diaphragm. The soft storey is defined as the lateral stiffness is less than seventy percent of the storey above or less than eighty percent of the average lateral stiffness of the three stories above. If the above values are sixty percent and seventy percent then it leads to extreme soft storey irregularity. If the storey lateral strength is less than eighty percent of the storey above, it is defined as the weak storey irregularity. If the value is sixty-five percentage, then it leads to extreme weak storey irregularity. The above irregularities are not permitted in the higher seismic design category D, E, and F. In some cases, the design forces are increased by twenty-five percentage for buildings with above irregularities. A redundancy factor of 1.3 is used to increase the design loads for the buildings with extreme torsional irregularity for higher seismic design categories D, E, and F. The redundancy factor is determined based on the configuration and lateral load resisting structural elements providing the load path during the seismic events. The value of the factor is taken as 1 for redundant building having multiple load paths and 1.3 for non-redundant buildings. The hundred percent-thirty percent orthogonal load combination in both direction vice-versa shall be applied for buildings with torsional irregularities. Three-dimensional dynamic analysis is advocated for buildings with torsional irregularities.

2.14 Vertical irregularity

As per ASCE/SEI 7-16[18], if a storey has a stiffness less than seventy percent of the storey above or less than eighty percent of the average stiffness of three stories above, then the building is said to have soft storey irregularity. Similarly, if less than sixty percent of the storey above or less than seventy percent of the average stiffness of three stories above, leads to extreme soft storey condition. Many of the buildings failed in the recent seismic events due to this irregularity leading to highest damage potential next to torsional irregularity compared to other irregularities. Particularly the soft storey in the lower part of the building is more serious than the middle of the building. As per ASCE/SEI7-16[18], if the lateral strength of the storey is less than eighty percent of the storey above then the storey is defined as a weak storey. If less than sixty five percent, leads to extreme weak storey condition. Weak storey near the ground level leads to more catastrophic failure of the building than soft storey irregularity. Another irregularity the weak-column / strong–beam wherein the moment capacity of the column is less than the beam is more serious with respect to collapse potential compared to other forms of irregularity. In the non-linear stage, hinges are well distributed in the symmetric buildings without any irregularities, whereas in buildings with irregularities, the damage may be localized and additional forces are acted on the building (not accounted for in the design) due to asymmetry leading to failure of the building.In the past earthquakes, it is observed that, most of the buildings were damaged due to torsional and soft storey irregularities and strong beam-weak column deficiency in the buildings. Hence the code provisions for the above irregularities are most important to prevent the failure of such kind of buildings. One of the main reasons for major failures of the building during 1985 Mexico earthquake, 1989 Loma Prieta earthquake, 1994 Northridge earthquake, and the 1995 Kobe earthquake is the torsional motion induced by the seismic event (Humar[24]).

2.15 National building code of Canada

In the National Building Code of Canada, NBCC 2020[25] the limit for torsional irregularity is specified as the ratio of maximum displacement to average displacement measured at the ends of the slab with a value of 1.5. This criterion is same for most of the codes with limits ranging from 1.2 to 2.0.Humar[24]. Similarly, dynamic analysis is preferred in almost all the codes for the buildings with torsional irregularity. In dynamic analysis the response of the building for various time history records (seismic events) are evaluated. In NBCC[25], the accidental eccentricity is taken as ten percent of the building dimension perpendicular to the seismic force which is higher than other codes whereas the value in the other codes is five percentage. The static eccentricity is amplified by 1.8 in the draft code IS 1893-2023 and it is 1.5 in 2016 version. In Mexican code, it is amplified by 1.5. In almost all other codes the value is one for static eccentricity.

2.16 Torsional irregularity provisions of Japanese code

The eccentricity ratio (Re) in Japanese code[22] if exceeds 0.15, then the building is said to exhibit torsional irregularity. The Re value depends on the structural eccentricity and torsional rigidity. Based on Re values, basic factor Fe is fixed by the code Edmund Booth[22]. For Re less than or equal to 0.15, then Fe is equal to 1 and Re values between 0.15 and 0.3, the Fe value is linearly interpolated. For Re value greater than or equal to 0.3, the Fe value is taken as 1.5. The design base shear value is modified by the factor Fe. During Kobe earthquake in Japan, buildings having torsional irregularity made the building to twist and rotate and hence the flexible side having exceeded the capacity leading to collapse and failure of the building. In the real earthquakes it is found that among various irregularities, the torsional irregularity due to stiffness and strength, soft storey, weak storey, and strong beam-weak column has the highest collapse potential compared to other irregularities which cause damage concentration at the selected locations of buildings where the irregularities are present.

2.17 New Zealand code

As per the New Zealand codeNZS 1170.5:2016[26], the accidental eccentricity is ten percentage of building dimension perpendicular to the earthquake force. The modification factor for structural eccentricity is one. The equivalent static lateral load method is used if eccentricity value is less than or equal to 0.3 times the building dimension perpendicular to earthquake force. The earthquake force is applied at design eccentricity plus or minus ten percent of building dimension.

The ratio of displacements at the ends of the slab is measured to be in the range of 3/7 to 7/3. The draft code DZ TS 1170.5:2024[27] defines the torsional irregularity criteria if the ratio of maximum displacement at one end of the slab to the other end exceeds the value of 1.4 if the earthquake load is applied with an eccentricity of ten percentage of building dimension perpendicular to the applied seismic force. Three-dimensional Non-linear time history analysis or response spectrum method is preferred for the buildings with torsional irregularity. The accidental eccentricity in the code is ten percentage of building dimension perpendicular to the seismic force.

3 Results and Discussion

National and International Codal provisions on torsional irregularity present in the buildings are reviewed and discussed. Various significant parameters affecting the seismic performance of the building due to the torsional irregularity are studied. The torsional irregularity in the building is due to torsional eccentricity and/or torsional flexibility. The torsional eccentricity is due to the non-uniform distribution of stiffness and mass in the building due to its configuration. The buildings exhibit torsional mode as the first mode leading to torsional irregularity due to torsional flexibility.

The four main aspects of the building to be considered for improved seismic performance are Uniform or Symmetric structural configuration both in plan and elevation without any eccentricity. Sufficient uniform/symmetric lateral stiffness and strength to avoid eccentricity. The required amount of ductility so as to have sufficient energy dissipation capacity during the seismic event to avoid brittle and sudden failure of the structural members. The building should possess sufficient torsional stiffness by means of lateral load resisting systems to avoid the fundamental mode as torsional mode and coupling with translational mode thereby reducing the damage of the structural members in the perimeter of the building due to torsional irregularity. Prakashvel *et al.*[28] have reviewed various retrofitting strategies for buildings with irregularities. Based on the work carried out by Tamizharasi[29] various recommendations are given to IS 1893-2023 draft code on torsional irregularities. Mohan and Hareen[30] have evaluated the seismic response of the building with plan and vertical irregularities using push over analysis and found that vertical irregularity due to infill wall increases the torsional response of the building.

The total eccentricity which includes the structural and accidental eccentricity is termed as torsional eccentricity. In some of seismic codes the total eccentricity is based on single floor considered and few codes all floor is considered. But as long as the centre of mass and centre of stiffness lies in the two vertical lines throughout all the floors, the above two approach gives the similar results.

4 Conclusion

In general, the seismic codal provisions are formulated based on each types of irregularities present in the building. But in reality, multiple irregularities are present in the building which needs to be addressed. Severe damages occur in the buildings with multiple irregularities. Translation and rotation are caused due torsional irregularity. The torsional irregularity may be due to combined plan and vertical irregularities which leads to failure of structural elements present in the perimeter of the buildings due to floor rotation in addition to translation.

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