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ROT INDEX FOR ASSESSING THE TORSIONAL EFFECT ON THE SEISMIC PERFORMANCE OF RC BUILDINGS

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Abstract. *Due to the eccentric setback nature of structures, torsional moments will be induced by a set of lateral loads on buildings. Although the effect on the response of reinforced concrete buildings was the subject of intensive research over the last decades still lacks a criterion valid in both elastic and plastic region. In this study a criterion capable of assessing torsional effect is proposed. In order to evaluate the proposed criterion with code provisions, two test examples are considered. A torsionally stiff, mass eccentric one-storey and a four-storey horizontally irregular building designed according to Eurocode provisions subjected to bidirectional excitation are considered. Nonlinear dynamic analyses are carried out implementing natural record selected for three hazard levels. The performance of the proposed criterion is evaluated and its correlation with other structural response quantities like interstorey drifts, displacements, base torque, shear forces and diaphragm rotation is presented. Through this investigation it was found that the proposed criterion is able to provide a reliable prediction of the magnitude of torsional effects for all test cases considered.*

1 INTRODUCTION

In most current torsional provisions, the effect of torsion is treated implementing accidental and static eccentricity along with imposing restrictions on the design for buildings with irregular layout. Accidental eccentricity is defined as a fraction of the plan dimension of the layout perpendicular to the direction of applied lateral forces. When it comes to static eccentricity interpretation becomes more complicated, since there is no uniformity in definition. Many researchers define as static eccentricity the distance between centre of mass and centre of rigidity, while others the distance between centre of mass and shear centre. For one-story systems, there is a point on the diaphragm owns the following properties: (I) does not rotate when lateral load is applied through it (centre of rigidity), (II) the resultant of shear forces passes through it when no rotation is developed on the diaphragm (shear centre) and (III) remains stationary when the structure is subjected to torque loading (centre of twist). The various centers are coincident and load-independent for one-story systems, but the same does not happen for the multistory ones. Tso [1] clarifies the two approaches aiming to measure the story torsional moments for multistory buildings and concluded that if the proper definitions are used, the result remains the same irrespectively of which one is adopted. Inconsistent conclusions observed have been attributed to the varying model assumptions implemented, while a detailed overview has been presented by Rutenberg [2]. Many researchers also studied the efficiency of torsional codified provisions [3, 4, 5]. Lagaros *et al.* [6] proposed a combined topology and sizing formulation for the optimum design of RC buildings aiming to minimize the cost, the static and strength eccentricities as well as several combinations of them, in order to improve the torsional seismic response of RC buildings in various hazard levels, taking into account both design code and architectural restrictions.

As far as the inelastic state of response is concerned, De la Llera and Chopra [7, 8] proposed the base shear and torque surfaces (BST), which represent all combinations of base shear and torque that would lead to collapse of the structure when applied statically. Furthermore, they suggested a simplified model based on a super-element per building story, capable of representing the elastic and inelastic properties of the story. Paulay [9, 10] presented the centre of resistance and identified the plastic mechanism developed, aiming to estimate the torsional effects on the seismic response of ductile buildings, classified as either torsionally unrestrained or restrained. Myslimaj and Tso [11, 12] proved that the torsional effects can be alleviated for asymmetric wall-type systems by locating the centre of strength and the centre of rigidity on the opposite sides of the centre of mass. Anagnostopoulos *et al.* [13] pointed the inadequacies of the simplified one-story, shear-beam type systems for predicting the inelastic response of real, asymmetric, multistory frame buildings, subjected to torsion due to earthquake motions and consequently for deriving general conclusions about torsional provisions of the codes.

In order to assess the torsional effect on the seismic response of multistory buildings, a new index is proposed. Its performance is evaluated considering a single story and a four-story building. Symmetric counterparts were designed according to Eurocode pre-standards. Intentionally, asymmetry was not considered in the design in order to eliminate any torsional code influence from the results. The Code specified accidental eccentricities $0.05\,L_X$ and $0.05\,L_Y$ are also applied to each building. Two-component seismic excitations are used for the nonlinear dynamic analyses for all states of response. While base torque, diaphragm rotation, interstorey drifts, displacements and shear forces are chosen as response parameters of the buildings examined.

2 TREATMENT OF THE TORSIONAL EFFECT

Some fundamental features of the torsional response for multistory buildings are summarized here. Apart from eccentricity, as mentioned above, centre of rigidity can not be defined also in a strict manner for a story or stories of a multistory building. While Humar [14] interpreted the center of rigidity at a floor as the point through which the resultant lateral forces at that floor can pass without causing rotation at that floor. The other floors may or may not have rotations. Smith and Vezina [15] defined it at a particular level of a multistory building subjected to a particular vertical distribution of horizontal loading as the point in the plane of the floor through which the external horizontal load at that floor must act for it to apply no torque to the structure. There are also more definitions [16, 17] formulated but they are omitted here due to space limitations. Based on the undamped equations of motion for a multistory building, assuming linear behavior, subjected to earthquake ground motion along the x and y directions, the coordinates of the centers of rigidity are given by the equations below:

$$\begin{aligned} \mathbf{x}_{CR} &= \frac{\mathbf{K}_{Y\theta} - \mathbf{K}_{YX}\mathbf{K}_{X}^{-1}\mathbf{K}_{X\theta}}{\mathbf{K}_{Y} - \mathbf{K}_{YX}\mathbf{K}_{X}^{-1}\mathbf{K}_{XY}} \\ \mathbf{y}_{CR} &= \frac{\mathbf{K}_{X\theta} - \mathbf{K}_{XY}\mathbf{K}_{Y}^{-1}\mathbf{K}_{Y\theta}}{\mathbf{K}_{X} - \mathbf{K}_{XY}\mathbf{K}_{Y}^{-1}\mathbf{K}_{YX}} \end{aligned} \tag{1}$$

where $\mathbf{K}_X$, $\mathbf{K}_Y$, $\mathbf{K}_{XY}$, $\mathbf{K}_{X\theta}$ and $\mathbf{K}_{Y\theta}$ are the corresponding submatrices of the building global stiffness matrix. However, the matrices $\mathbf{x}_{CR}$ and $\mathbf{y}_{CR}$ were defined as diagonal matrices and the expressions (1) do not, in general, yield diagonal matrices implying that unique centers of rigidity do not always exist. In such a case, centers of rigidity can still be defined sometimes even if the expressions above does not yield diagonal matrices, but their locations depend on the applied set of static lateral forces (equations (2)).

$$\begin{aligned} \{\mathbf{x}_{CR}\} &= \left[\mathbf{P}_{Y}\right]^{-1} \frac{\mathbf{K}_{Y\theta} - \mathbf{K}_{YX}\mathbf{K}_{X}^{-1}\mathbf{K}_{X\theta}}{\mathbf{K}_{Y} - \mathbf{K}_{YX}\mathbf{K}_{X}^{-1}\mathbf{K}_{XY}} \mathbf{P}_{Y} \\ \{\mathbf{y}_{CR}\} &= -\left[\mathbf{P}_{X}\right]^{-1} \frac{\mathbf{K}_{X\theta} - \mathbf{K}_{XY}\mathbf{K}_{Y}^{-1}\mathbf{K}_{Y\theta}}{\mathbf{K}_{X} - \mathbf{K}_{XY}\mathbf{K}_{Y}^{-1}\mathbf{K}_{YX}} \mathbf{P}_{X} \end{aligned} \tag{2}$$

where $\mathbf{P}_X$ and $\mathbf{P}_Y$ being the vectors of static lateral forces applied. This means that different load distributions would lead to different locations of the centers of rigidity [18]. There is still a special class of building, named buildings with proportional framing, for which the various centers (center of rigidity, shear center and center of twist) exist and are at coincident locations, load independent and lying on a vertical line [18, 19]. The determination of the center of rigidity becomes even more complex in the nonlinear dynamic analysis.

A valid indicator also for the torsional behaviour in the elastic domain is the uncoupled frequency ratio Ω (uncoupled torsional frequency divided by the translational one). For a multi-storey building, whose predominant mode is translational the value of the ratio is greater than unity and is classified as torsionally stiff. A building is classified as torsionally flexible when its predominant mode is torsional. In case of torsionally stiff buildings the displacements on the flexible edge are increased in comparison with its symmetric counterpart. The opposite trend was observed for the stiff edge. Torsionally flexible buildings may exhibit displacement increase at both edges or largest translation at stiff edge. These indices are valid for the elastic range, where the response of all elements remain in the elastic state. When elements start yielding, the characteristics described above are affected. The instantaneous locus of the centre of rigidity changes, as a consequence the amount of eccentricity is influenced in the elastoplastic range. While for the plastic state of response strength eccentricity considered a more representative indicator, computed as the distance between the center of mass and the center of strength. The center of strength is defined as the point that if resultant of lateral forces act through it and story reaches to mechanism, no rotation happens in that story, when all the degrees of freedom of lower stories are restrained.

3 THE RATIO OF TORSION

Due to the eccentricity of structures, torsional moments will be imposed on the building by the existing lateral loads. These moments are sustained by the system as a pair of shear forces. So the torsion effect on buildings is quantified as torsion-induced displacements via torsion-induced shear forces on certain elements. Applying lateral loading P_i, shear forces V_{ij} are developed at each vertical structural element. Figure 1 shows a generalized floor plan view where shear walls and the corresponding shear forces are depicted.

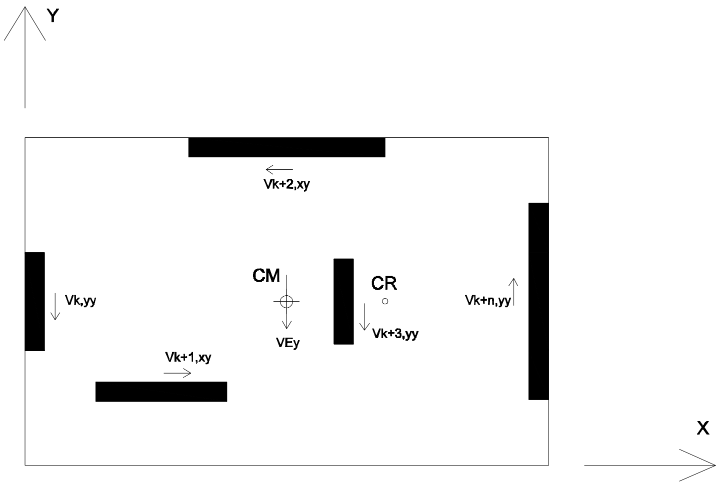

Figure 1: A typical plan view.

Without loss of generality the seismic action is considered along one direction only. While force V_{Ey}, is being developed, with few exceptions, elements along x direction are expected to remain elastic. They will therefore sustain the base torque, as a pair of forces, and restrain the diaphragm rotation. The shear forces acting on the lateral resisting structural elements satisfy the following expression:

$$\sum_{k=1}^{n} \left| V_{kij} \right| \neq \sum_{k=1}^{n} V_{kij} \tag{3}$$

where n is the number of vertical structural elements of the floor diaphragm, while i and j denote the direction of the shear force of the element k and that of earthquake with reference to the structural axes x and y respectively. The sum of the absolute values of resisting elements' shear forces differs from their algebraic. This observation is attributed to torsional components of the shear forces, since torsional moment is sustained by the system as a pair of opposing forces. For the plan view of Figure 1 and seismic action along the y direction only, the following relations are satisfied:

$$\sum_{k=1}^{n}\left|V_{kxy}\right| \neq \sum_{k=1}^{n}V_{kxy} = 0$$
$$\sum_{k=1}^{n}\left|V_{kyy}\right| \neq \sum_{k=1}^{n}V_{kyy} = V_{Ey} \tag{4}$$

The torsion induced in the floor is usually computed from the shear forces of the structural elements, while the elements torsional moments are neglected.

The proposed criterion Ratio Of Torsion (ROT) represent a measure to quantify the torsional effect induced by asymmetry in plan layout. The general formulation of ROT is defined as:

$$ROT = \frac{\sum_{k=1}^{n}\sum_{i=x,j=y}^{y,x}\left|V_{kij}\right| - \left|V_{Ex}\right| - \left|V_{Ey}\right|}{\left|V_{Ex}\right| + \left|V_{Ey}\right|} \tag{5}$$

where V_{Ex} and V_{Ey} the design base shear along x and y directions.

Static equilibrium leads to:

$$\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kxj} = V_{Ex}$$
$$\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kyj} = V_{Ey} \tag{6}$$

ROT formulation take the form:

$$ROT = \frac{\sum_{k=1}^{n}\sum_{i=x,j=y}^{y,x}\left|V_{kij}\right| - \left|\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kxj}\right| - \left|\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kyj}\right|}{\left|\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kxj}\right| + \left|\sum_{k=1}^{n}\sum_{j=y}^{x}V_{kyj}\right|} \tag{7}$$

For implementing the proposed index for multi-storey buildings, equation (7) can be computed for every floor of a building. Taking into consideration that the ROT value does not follow any particular trend or uniform distribution for the different floors, it is considered more representative for multi-story buildings to be computed equal to the sum of its value of all floors, according to:

$$\sum_{m=1}^{l} ROT \tag{8}$$

where l the number of building's stories. As in the case of one-storey systems, its value is computed for every analysis step and the maximum is compared to maximum values of other response quantities related to torsion as base torque and upper diaphragm's rotation.

4 NUMERICAL MODELING AND SEISMIC LOADS CONSIDERED IN THIS STUDY

Nonlinear static or dynamic analysis needs a proper simulation of the structure in the regions where inelastic deformations are expected to develop. In order to consider the inelastic behaviour either the plastic-hinge or the fibre approach can be adopted. For some researchers the plastic hinge approach has limitations in terms of accuracy and therefore fibre beam-column elements are preferred [20]. According to the fibre approach, each structural element is discretized into a number of integration sections restrained to the beam kinematics, and each section is divided into a number of fibres with specific material properties (A_{fib}, E_{fib}). Every fibre in the section can be assigned to different material properties, e.g. concrete, structural steel, or reinforcing bar material properties, while the sections are located at the Gaussian integration points of the elements. The main advantage of the fibre approach is that every fibre has a simple uniaxial material model allowing an easy and efficient implementation of the inelastic behaviour. In the numerical test examples section that follows all analyses have been performed using the OpenSEES [21] platform. A bilinear material model with pure kinematic hardening is adopted for the structural steel, while geometric nonlinearity is explicitly taken into consideration. For the simulation of the concrete the modified Kent-Park model, where the monotonic envelope of concrete in compression follows the model of Kent and Park [22] as extended by Scott *et al.* in [23], is employed. This model was chosen because it allows for an accurate prediction of the demand for flexure-dominated RC members despite its relatively simple formulation.

5 NUMERICAL EXAMPLES

The results of time history analyses for the different numerical examples are presented in terms of maximum values of the response parameters over pairs of applied motions. As response parameters interstorey drifts, displacements, shear forces of the columns, base shear and diaphragm rotation were considered and their structural behavior was examined. For this purpose a number of nonlinear time history analyses have been carried out employing three natural ground motion records for each hazard level (2%, 10%, 50%) chosen from the Somerville and Collins [24]. The records of each hazard level are scaled to the same PGA where in order to ensure compatibility between the records, in accordance to the hazard curve taken from the work by Papazachos *et al*. [25]. These records attribute different frequencies and different amount of energy so as to draw more general conclusions.

The design spectrum used correspond to soil type B (characteristic periods T_B = 0.15 sec, T_C = 0.50 sec and T_D = 2.00 sec). Moreover, the importance factor γ_I was taken equal to 1.0, while the damping correction factor η is equal to 1.0, since a damping ratio of 5% has been considered.

The models employed for the verification of the proposed criterion are a single-story torsionally stiff structure and a four-story, torsionally stiff, horizontally irregular building. The models are analysed for bidirectional ground motions. In all test examples the following material properties are considered: Concrete C20/25 with modulus of elasticity equal to 30GPa and characteristic compressive cylinder strength equal to 20MPa, longitudinal and transverse steel reinforcement B500C with modulus of elasticity equal to 210GPa and characteristic yield strength equal to 500MPa. Apart from the symmetric design, three different mass distributions were considered for every system, corresponding to eccentricity 5%, 10%, 20% of the plan dimension. The symmetric counterpart is denoted as *sym*, while the mass eccentric variants characterized by 5%, 10% and 20% eccentricity are denoted as *ecc0.05*, *ecc0.10* and *ecc0.20* respectively. The eccentricity is introduced by assuming non-uniform mass distribution, which results in a shift of the mass centre, while the centre of rigidity coincides to their geometric centre. Each variant differs with reference to the location of CM and the moment of inertia J. Asymmetric brick partition wall and asymmetric live load distribution are some usual causes of mass eccentricity. For the reasons explained above the coordinates of the rigidity center are computed on a floor by floor basis. The first three periods of vibration are listed for the two test examples in Tables 1 and 2. The results presented in the current study apply to maximum values obtained from three time-history analyses for each hazard level.

	T_1	T_2	T_3	$\Omega_x = \frac{T_x}{T_t}$	$\Omega_y = \frac{T_y}{T_t}$
sym	0.3593^{x}	0.3484^{y}	0.2526^{t}	1.4224	1.3793
ecc0.05	0.3620^{x}	0.3512^{y}	0.2524^{t}	1.4342	1.3914
ecc0.10	0.3753^{x}	0.3539^{y}	0.2519^{t}	1.4898	1.4049
ecc0.20	0.4320^{x}	0.3549^{y}	0.2509^{t}	1.7218	1.4145

Table 1: Vibration periods and uncoupled frequency ratios for Test Example 1.

	T_1	T_2	T_3	$\Omega_x = \frac{\omega_t}{\omega_x}$	$\Omega_y = \frac{\omega_t}{\omega_y}$
ecc	1.0074^{x}	1.0059^{y}	0.6988^{t}	1.4416	1.4395
ecc0.05	1.0218^{x}	1.0074^{y}	0.7006^{t}	1.4585	1.4379
ecc0.10	1.0633^{x}	1.0074^{y}	0.6851^{t}	1.5520	1.4704
ecc0.20	1.1933^{x}	1.0074^{y}	0.6313^{t}	1.8902	1.5958

Table 2: Vibration periods and uncoupled frequency ratios for Test Example 2.

5.1 Test example 1

The first test example is a single-story 3D framed structure. Its symmetric variant is shown in Figure 2, while some properties of the eccentric variants are denoted in grey.

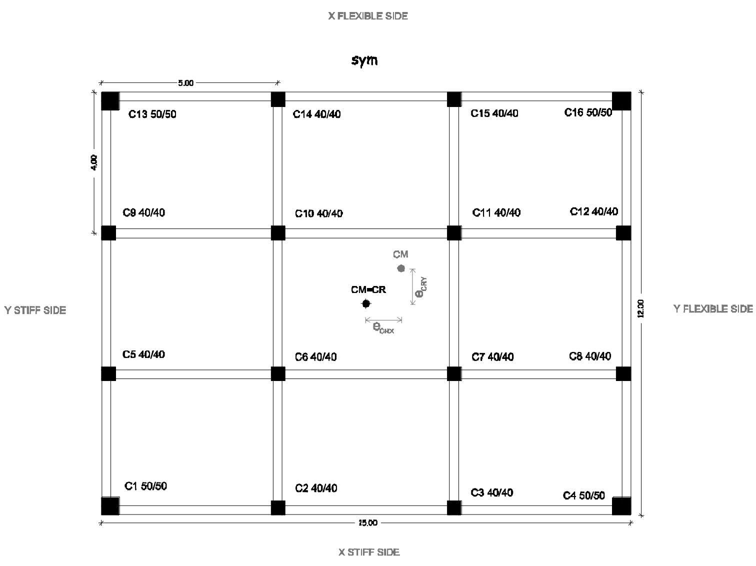

Figure 2: Plan view for Test Example 1.

The basic features of the behaviour of torsionally stiff systems described above is observed for all response quantities. It is noticed that monotonic variation (increase, decrease) of response quantities disappears for eccentricity values greater than 10% percentage. Another significant remark is that for realistic layouts the established trends are valid for the elastic state of response. Once the system enters the elastoplastic state and elements start yielding, the stiffness is not constant affecting the position of the centre of rigidity. The centre of rigidity in those (elastoplastic, plastic) states is instantaneous preventing us from defining the flexible and stiff side of the system. The above described behaviour was observed for response quantities along both directions but due to space limitations only those of y direction will be presented in the current section (see Figures 3a, 3b, 4a, 4b). A decrease is recorded for response quantities for elements at the stiff side (col1, col6), while these quantities for the columns at flexible side (col11, col16) are increasing.

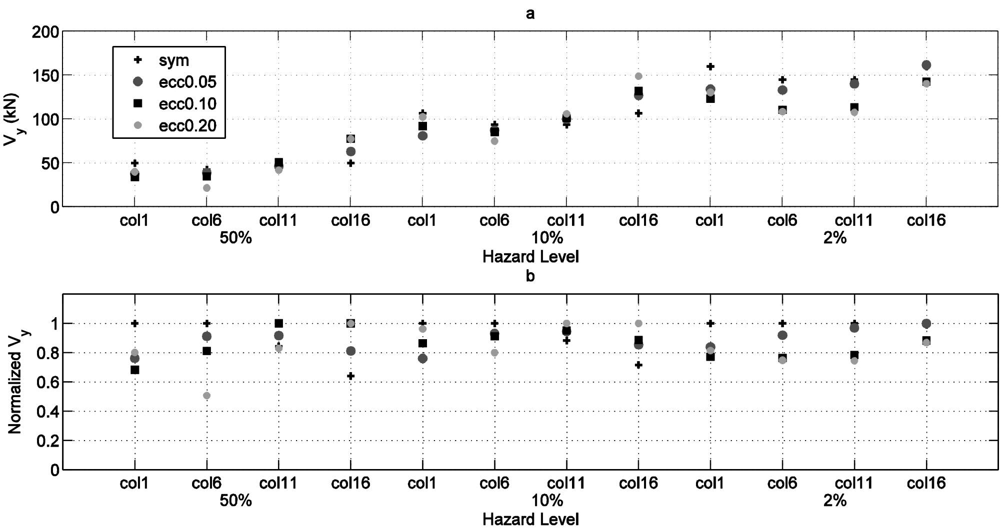

Figure 3: Test example 1 – Column shear forces (a) maximum absolute values and (b) normalized values along y direction for each variant and hazard level.

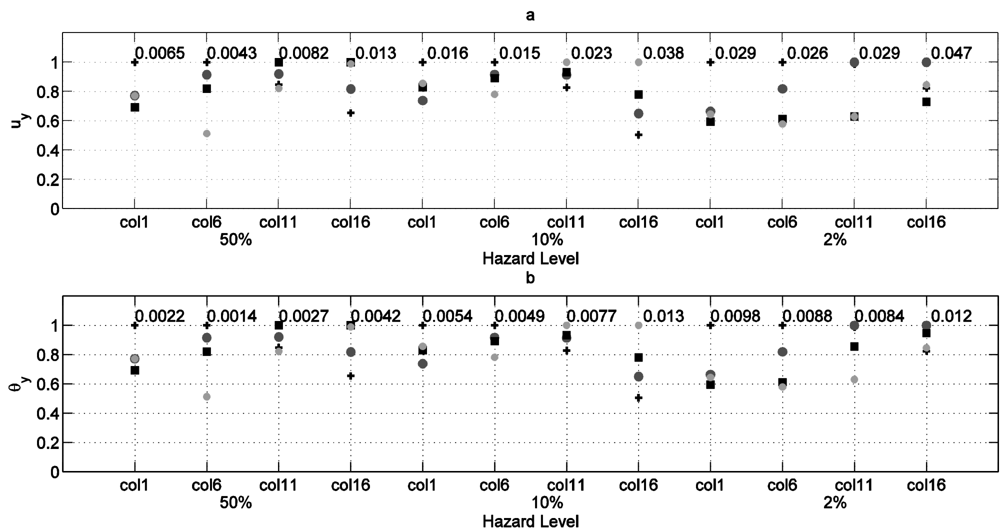

Figure 4: Test example 1 – Column (a) normalized displacement values (in m) and (b) normalized interstorey drift values (%) along y direction for each variant and hazard level.

The response values related to torsion (upper diaphragm's rotation, base torque and ROT) and their normalized values are shown in Figures 5(a) to 5(f). According to ROT, in this case the shear forces imposed were amplified six times for *ecc0.20* in 2/50 hazard level. Another interesting remark is that maximum base torque values do not always follow the distribution of the maximum diaphragm rotation values. Figures 5b, 5c show that for *ecc0.20* variant a decrease of diaphragm rotation is noticed to its maximum value from 10/50 to 2/50 hazard level, whereas an increase is recorded of maximum base torque values for the corresponding states.

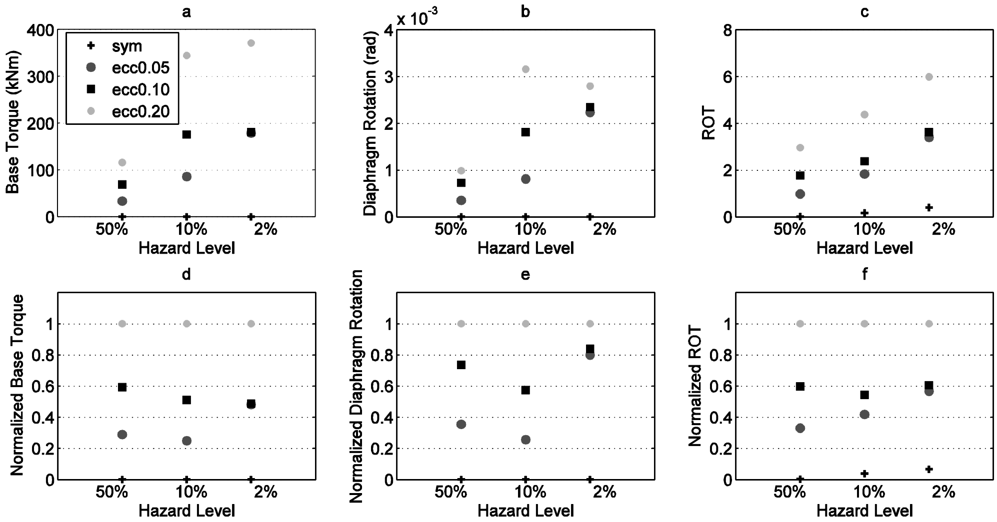

Figure 5: Test example 1 – (a)Base torque, (b) diaphragm rotation, (c) ROT, (d) normalized base torque, (e) normalized diaphragm rotation, (f) normalized ROT for each variant and hazard level.

5.2 Test example 2

For the second test example a horizontally irregular building exhibiting bidirectional eccentricity subjected to two-component ground motion is examined (Figure 6). As expected, it was not possible to design a totally symmetric counterpart that complies with the restrictions imposed by codes [19]. Consequently a small amount of eccentricity 0.9% appears and the reference variant is denoted as *ecc*, instead of *sym* used in the previous cases. The rest variants exhibit the same amounts of eccentricities as in the already examined examples (5%, 10%, 20%).

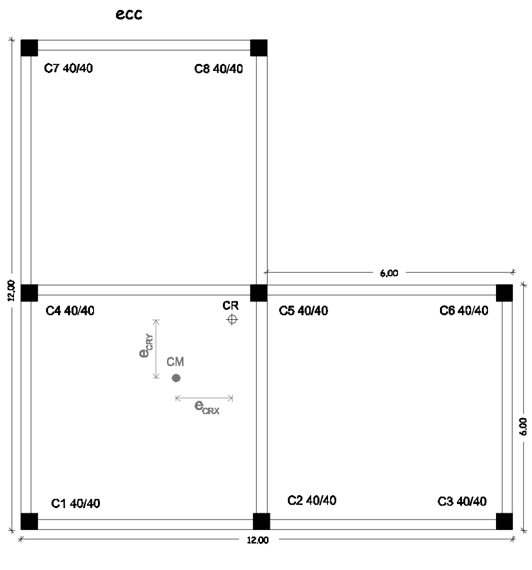

Figure 6: Plan view for Test Example 2.

For all response quantities (shear forces, displacements, interstorey drifts) an already noticed trend has been observed but due to space limitations only those correspond to y direction will be presented here. Figures 7 and 8 give consistent increase of response quantities for elements at flexible edge (col1, col7) and the opposite for those at stiff edge (col3, col6) till 10% eccentricity. For *ecc* variant almost zero value was noticed for base torque, diaphragm rotation and *ROT* values for the elastic state of response (50/50). For the other variants, the corresponding values are increased following the eccentricity rule. The same happens for the other two hazard levels. The non-zero *ROT* values for *ecc* variant at 10/50 and 2/50 hazard level may rise due to the fact of asymmetric yielding (the system does not possess two axes of symmetry) which affects the CR position creating eccentricity greater than the initial. The behavioral trend identified previously for horizontally regular systems has been verified also for horizontally irregular systems.

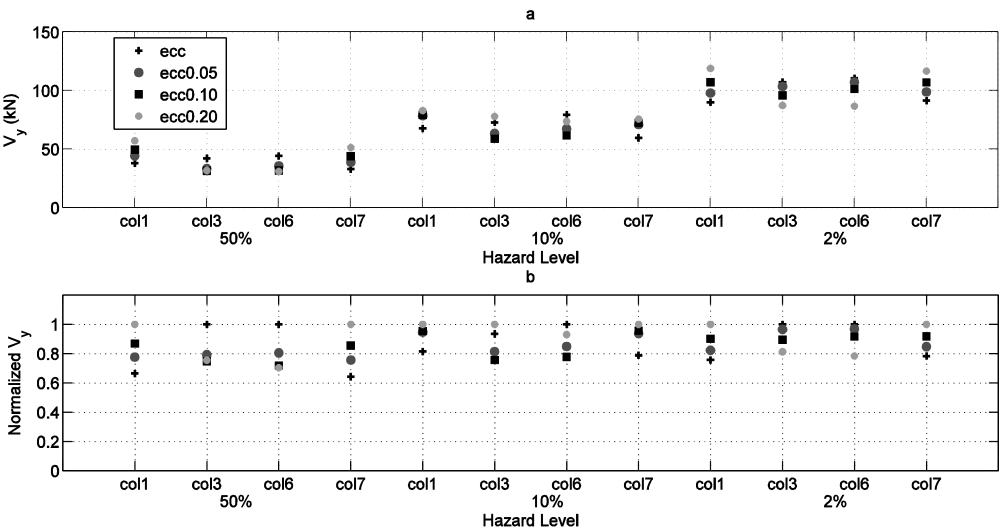

Figure 7: Test example 2 – Column shear forces (a) maximum absolute values and (b) normalized values along y direction for each variant and hazard level.

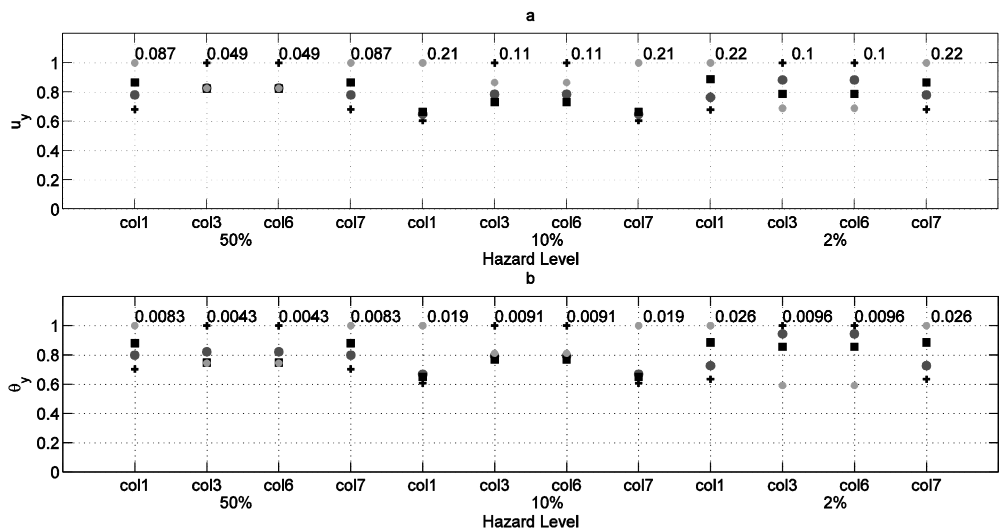

Figure 8: Test example 2 – Column (a) normalized displacement values (in m) and (b) normalized interstorey drift values (%) along y direction for each variant and hazard level.

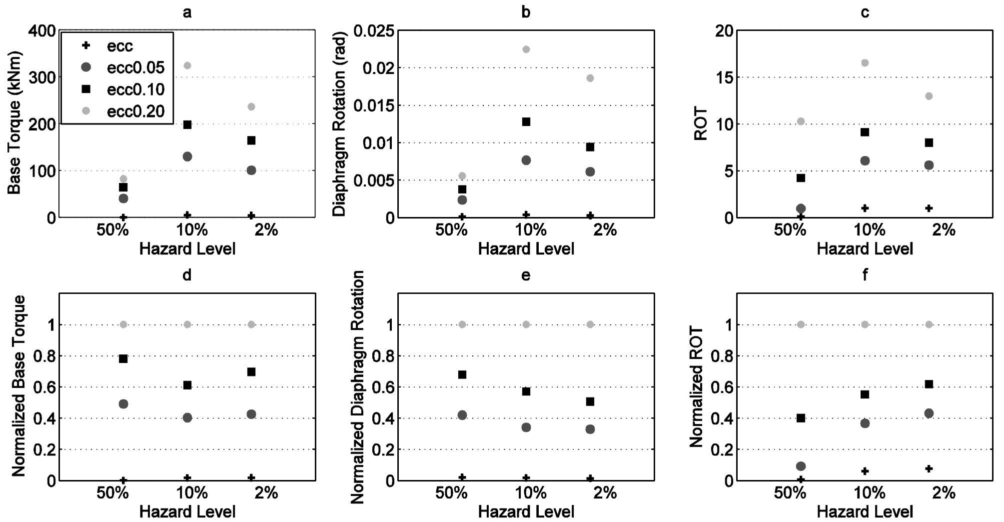

Figure 9: Test example 2 – (a)Base torque, (b) diaphragm rotation, (c) ROT , (d) normalized base torque, (e) normalized diaphragm rotation, (f) normalized ROT for each variant and hazard level.

The response quantities of Figure 7 and 8 are referred to the elements of the fourth floor. Similar variation qualitatively was observed for the other floors. The envelopes of maximum values of shear forces and interstorey drifts for column 7 along the height are shown in Figures 10 and 11 for all variants. Column 7 is located on the stiff side along y direction and on the flexible along x direction. Consistent decrease of the response quantities along x direction for all floors was recorded in the elastic state, while in the elastoplastic and plastic state of response some exceptions appeared due to asymmetric yielding. Along y direction column 7 exhibits monotonic increase till 10% eccentricity for the elastic and elastoplastic range. Some exceptions appeared in 2/50 hazard level.

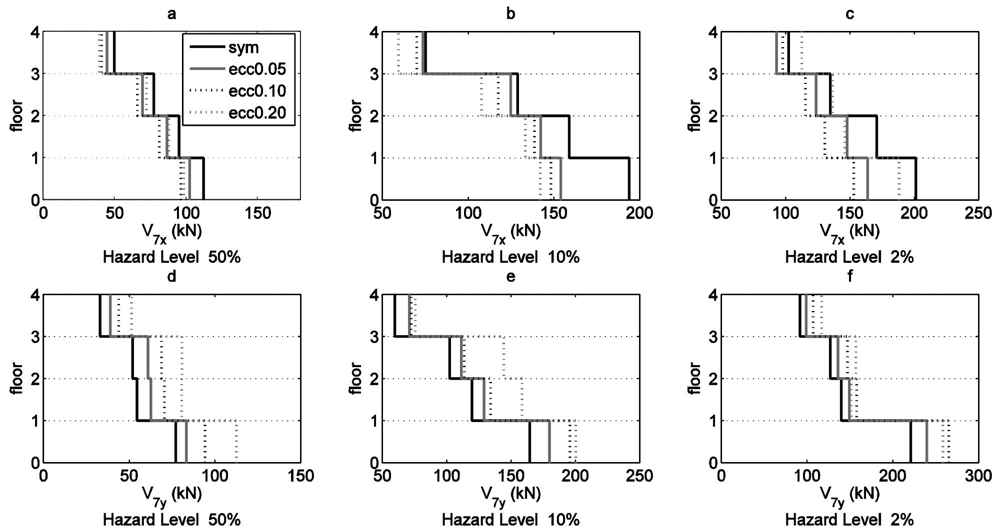

Figure 10: Test example 2 – Column 7 shear forces' maximum absolute values anlong x (a, b, c) and y (d, e, f) direction for all floors and hazard levels.

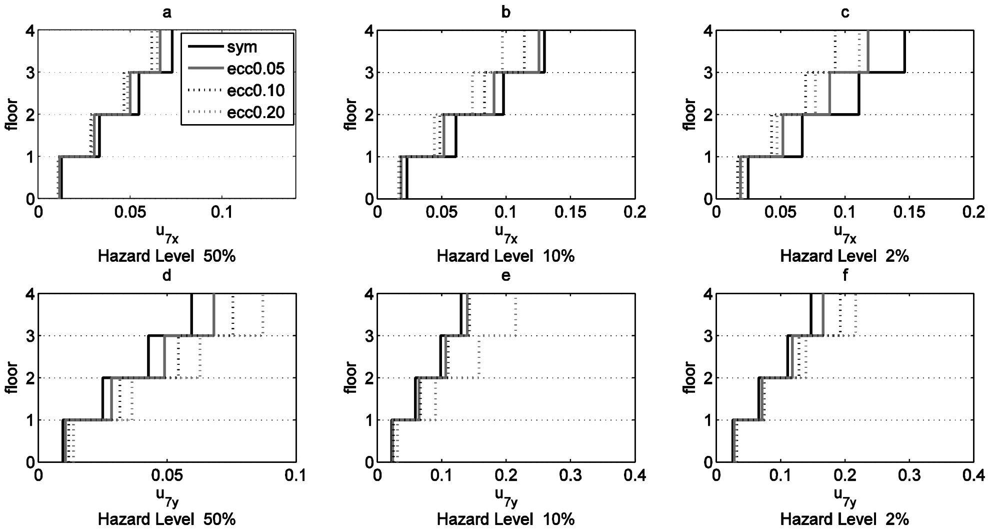

Figure 11: Test example 2 – Column 7 drifts' maximum absolute values anlong x (a, b, c) and y (d, e, f) direction for all floors and hazard levels.

A remarkable observation, also noticed by other researchers [26, 27], for both test examples considered is that maximum diaphragm rotations do not usually occur at the same time as maximum translations.

6 CONCLUSIONS

In order to investigate the effect of torsion on the seismic response of mass eccentric torsionally-stiff structures, two test examples are considered. In particular, a single-story regular framed structure exhibiting bidirectional eccentricity and a four-story horizontally irregular building are studied. Nonlinear dynamic analyses are conducted using natural accelerograms calibrated for the three hazard levels. The main objective of the current study is to propose a new assessment criterion for the torsional effect on asymmetric plan buildings, defined as the ratio of torsion.

The performance of the suggested index proved to be efficient since it was noticed that its variation follows the one of base torque introduced to a system. According to its formulation, ROT quantifies the torsional effect in terms of shear forces calculating the amplification of internal shear forces developed at individual elements due to the introduced torque. It is noteworthy that diaphragm rotation was not in agreement with base torque for all test cases. Specifically, for the first structural model, while values of base torque and ROT increase from 10/50 to 2/50 state of response for *ecc0.20* variant, the diaphragm rotation value presents a reduction. Taking into consideration that ROT value for the symmetric counterpart of a system is zero, it offers a measure for the torsion-induced shear forces that provides the percentage of their amplification compared to those developed implementing it for the same excitation avoiding analysis procedure of it. Additionally, the fact that ROT criterion is based on the internal shear forces, which can be computed by any structural software, it is independent of the arrangement of resisting elements and the geometry of the structure establishing it applicable on any system.

Another important remark is that the already observed trend in most studies from literature for torsionally stiff buildings - increased response quantities at flexible edge and decrease at the stiff one - has been not only noticed in the studied single-story regular system, but also confirmed for a four-story building exhibiting horizontal irregularity. It was also recorded that maximum diaphragm rotations do not occur for the same time step as maximum translations.

Moreover, during a seismic excitation is difficult to predict the distinct mechanisms mobilized and the number of resisting elements that yield since it depends on various factors such as system properties and the input ground motion. As a consequence, it cannot be predefined if the structure undergoes elastic, elastoplastic or plastic state of response. In the literature many assessment criteria exist exhibiting efficient performance in elastic state and others in plastic state. ROT appeared to be independent of the state of response since its performance was satisfactory for all states of response.

Finally, ROT assessment criterion can be extended to design one through optimization procedure. Since it was observed that the variation of ROT magnitudes follows the variation of magnitude of response parameters correlated to torsion such as base torque. Consequently, minimizing the value of ROT would lead to minimization of the torsion-induced internal shear forces.

Summarizing all the above, a simple criterion is offered to assess structure's performance against lateral-torsional coupling. ROT represents a rational formulation applicable to one-storey as well as multistory buildings for all levels of excitations. The formulation is based on the internal shear forces of the structure, which can be obtained by routine computations, increasing its objectivity and applicability, offering as well a useful tool to engineers. It is encouraging that in a companion study on such multistory buildings similar findings were obtained. Through the optimization procedure ROT can also be extended to a design criterion.

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