ON THE SIGNIFICANCE OF MASS ECCENTRICITY ON THE ELASTIC AND INELASTIC TORSIONAL RESPONSE OF BUILDINGS

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Abstract

This paper investigates the significance of mass eccentricity on the elastic and inelastic torsional response of asymmetric buildings using a series of numerical modeling results. The main objective is to investigate how a virtually translational response may be achieved by relocating a key lateral load resisting element. For all the mass eccentricity configurations investigated, their response was compared with (i) the response of the model in which all mass eccentricities were reversed and, (ii) the model in which all the centres of floor masses were aligned along the vertical line passing through the centroids of the floors. The first three mass eccentricity cases investigated, may be regarded as equivalent to the effect of mass and/or stiffness distribution uncertainties, while the fourth case may be regarded as equivalent to the effect of ground rotational excitation. In order to assess the location of the key element, for which the torsional response of the structure was minimized under a translational ground motion along the y-direction, this element was shifted to all possible locations along the x-axis. The numerical modeling was performed with the structural analysis program SAP2000-V16 for the Kobe 1995 (component KJM000) and Erzincan 1992 (EW component) ground excitations. The results indicate an optimum location of the key element for which the torsional response of the four mass eccentricity cases was minimised. The elastic response of the structure was generally sensitive to small shifts of this element, from the location of where the torsional response is minimised. With larger shifts, the torsional response curves become smoother and eventually even flatten out. The inelastic torsional response was generally smoother than the elastic response, with the inelastic results indicating an extended range of possible locations of the key element, for which insignificant or small variations in the torsional response of the structure occurred. Reversing the accidental eccentricities, shifted the elastic torsional response curves to approximately symmetric locations with respect to the no eccentricity torsional response curves. The results suggest that for systems expected to respond beyond their elastic limits, an optimal structural configuration that is based on nominal mass locations (with no eccentricities), represents also a system which is expected to sustain reduced torsional distortion in the case of a possible spatial distribution of floor masses.

Keywords: earthquake design; accidental mass eccentricity; torsion; inelastic numerical modeling

1. Introduction

Modern design codes use the term 'accidental mass eccentricity', to account for uncertainties in the mass/stiffness distribution, unforeseen contribution of non-structural elements (i.e. infill walls) and base rotational excitation. Uncertainties in the mass, stiffness and strength distribution are accounted for by shifting the center of mass of each floor to a distance equal to $\pm\beta$b, where b is the floor dimension of the building normal to ground motion and β is a coefficient specified by the national design codes. This procedure has become an accepted practice in structural applications, but it is not an apparent assumption regarding the rotational components of ground excitations. The phase shift in the arrival of seismic waves at various locations on the ground surface which results in differential ground motion and the corresponding torsional ground component is less easily quantified [1,2,3,4,5]. Due to the inherent ambiguities in quantifying the rotational ground excitations and the associated challenge in introducing these effects into everyday structural design practices, a number of researchers have proposed equivalent accidental mass eccentricities to account for the effects of the torsional ground motion on the structure, in the same manner the other sources of accidental torsion are accounted for [6,7,8]. [9] noted that using equivalent accidental mass eccentricities to account for the effects of the torsional ground motion on the structure may not produce safe displacement demands, since the center of mass (CM) shift changes the dynamic characteristics of the structure. However, this is the specified code procedure and it should be mentioned that in the case of uncertainties in the distribution of mass or stiffness the accidental mass eccentricity, at any floor, may be random, but when the dominant contributor to accidental torsion is torsional ground excitation, an ordered shift of the CM of each floor is reasonable [9].

Past earthquakes have revealed that earthquake induced torsion in structures can result in severe structural damage and a considerable amount of research has been conducted in this area aiming to assess the torsional response [e.g.10, 11, 12, 13] and even more to develop design guidelines on how to minimize the effects of earthquake induced torsion in buildings [14, 15, 16, 17]. The effect of spatial variations of mass eccentricities on the elastic torsional response of buildings during earthquake excitation was discussed in recent papers [18, 19]. It was shown that for any spatial variation of mass eccentricities the top rotations and base torques have an inverted peak, which indicates an optimum location of the key structural element, for which the torsional response of the structure is minimized. When the spatial distribution of mass eccentricities is reversed, the required optimum location of the key element is shifted to a symmetrical position with respect to its nominal location when no mass eccentricities are taken into account. The aim of this paper was to investigate the significance of mass eccentricity effects on the response of building structures when they are pushed beyond their elastic limits during a strong ground motion. It complements the aforementioned paper and extends the research to the inelastic behavior of buildings structures. The main objective of this paper is to provide guidelines for designing structural buildings to sustain minimum torsion, as it is the main concern of practicing engineers. A parametric study is presented on 9-story common building types having a mixed-type lateral load resisting system (frames, walls, coupled wall bents) and representative heightwise variations of accidental eccentricities. Their response is investigated under the Erzincan-1992 and Kobe-1995 ground motions.

2. Methodology

Figure 1 illustrates the configuration of the investigated building, a typical concrete wall-frame dual system along the y-direction and a wall system in the x-direction. The story height is equal to 3.5m and the lateral resistance along the y-direction is provided by four resisting elements: a flexural shear wall, W, with a cross section of 35/350cm, a coupled wall bent, CW, composed of two walls of 35/250cm at a distance of 5m, connected by lintel beams 30/80cm at the floor levels and, also, by two moment resisting frames, FR, composed by two columns of 70/70cm, 6 meters apart, connected by beams of 40/70cm cross section. To investigate the effect of mass and or stiffness eccentricity on the elastic and inelastic torsional response of buildings the three mass eccentricity cases (a), (b), (c) shown in Fig. 2 were investigated, while the effect of ground rotational excitation was investigated for the mass eccentricity case (d) of Fig. 2. For each case, the corresponding building model is labelled as *MassEc*(+) and its response is compared with (i) the response of the model (labelled *MassEc*(-)) in which all mass eccentricities are reversed and (ii) the model (labelled *NoEc*) in which all the centres of floor masses are aligned along the vertical line passing through the centroids of the floors. In order to assess the location of the key structural element (i.e.: the coupled wall bent CW of the assumed building) for which the torsional response of the structure was minimized when it was subjected to a translational ground motion along the y-direction, the CW bent was shifted to all possible locations between -7.5m to +7.5m, along the x-axis. In all the investigated mass eccentricity models, it was assumed that the storey masses were lumped at the CM [20]and equal to m=154 kNs^2/m,with a polar moment of inertia equal to mr^2, where r is the radius of gyration about the CM.

As the objective of this paper was to investigate the response of inelastic systems, a strength assignment for all the lateral load resisting bents was required. The non-linear properties of the building are based on the capacity design assumption (strong column-weak beam model), which suggests that the potential locations of plastic hinges are at the end sections of beams and at the bases of columns and walls. The strength distribution of the various bents was based on static considerations about the response of the symmetrical counterpart building, where all the floors are restrained against any rotation. This assumption is associated with the fact that minimizing the torsional response of a structural building requires a strength assignment compatible with a practically translational response. Under a lateral load equal to 20% of its total weight (V_d=0.2W_{tot}=2721.6 kN), the required bending (yield) capacities were found as follows: (i) in the frame beams, at the faces of the columns, equal to 442.5 kNm, (ii) at the bases of the ground columns of the FR bents, equal to 277 kNm, (iii) in the CW connecting beams equal to 827.5 kNm, (iv) at the bases of W and W_x walls equal to 11895 and 30027 kNm respectively and, (v) at the wall bases of the CW bent equal to 4719 kNm. It is worth mentioning here that when the coupled wall bent CW 'moves' to coordinates higher than +2m, both the criteria of EC8-2004 (Clause 4.2.3.2, Eqs. (4.1a), (4.1b)) for in plan regularity are satisfied and therefore a planar static analysis is permitted.

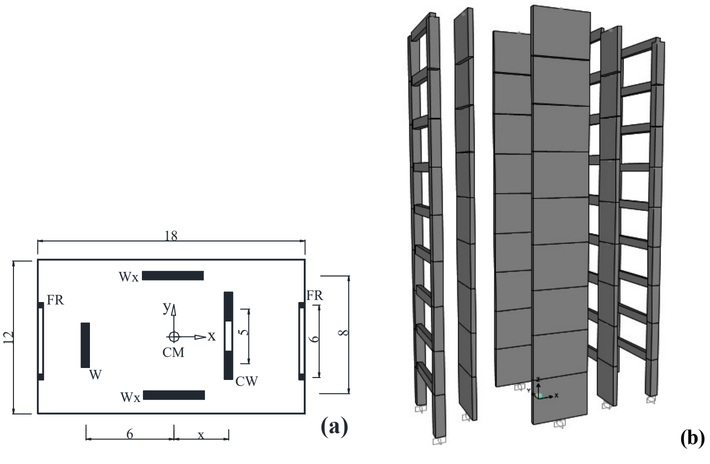

Fig. 1Plan configuration and perspective view of the investigated building

The numerical modeling was performed with the structural analysis program SAP2000-V16 for the Kobe 1995 (component KJM000) and Erzincan 1992 (EW component) ground excitations (Fig. 3), acting along the y-direction and scaled to PGA=0.5g. The non-linear analysis involved a direct integration history analysis using the Wilson time integration method with the theta parameter set equal to 1.4 and the damping matrix was assumed to be stiffness and mass proportional (the damping ratio was taken equal to 5% for the first and third coupled periods of vibration for each specific location of the coupled wall bent CW). Prior to the application of the assumed ground motion, the effect of a gravity loading equal to 35 kN/m acting on the beams of the FR and CW bents was first considered. It was also assumed that the rest of the gravity loading is sustained by columns (not shown in Fig. 1), which do not contribute to the lateral resistance of the system.

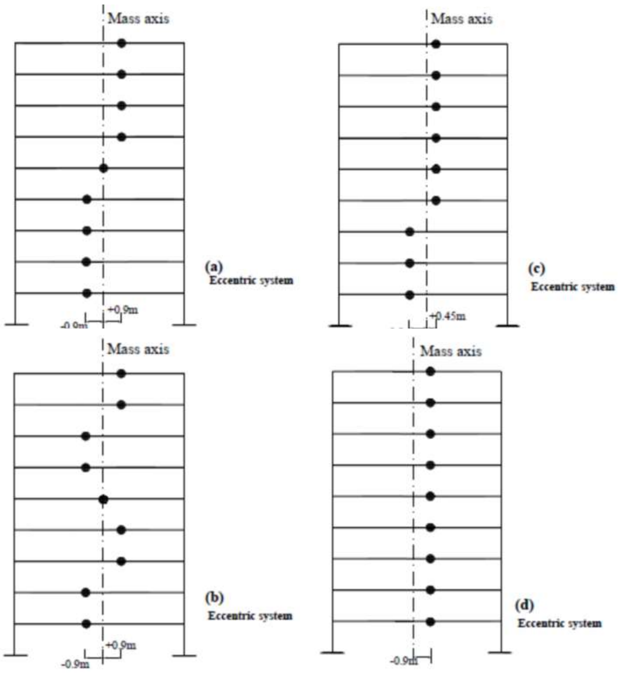

Fig. 2 Elevation of the four mass eccentricity cases

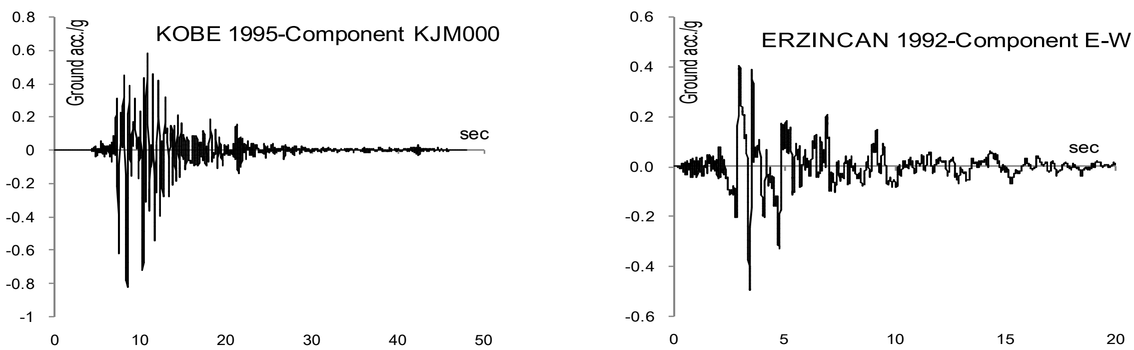

Fig. 3 Ground excitation for the Kobe 1995 (component KJM000) and Erzincan 1992 (EW component)

3. Results and discussion

Figures 4.1-4.2, 5.1-5.2, 6.1-6.2 and 7.1-7.2 show the response of models, *MassEc*(+) (red lines), *MassEc*(-) (blue lines) and *NoEc* (black lines) for the eccentricity cases of Fig. 2(a), (b), (c) and (d) respectively. Fig. 4.1, 5.1, 6.1 and 7.1 present the rotations at the top floor, Θ, and the normalized base torques $\overline{\mathrm{T}} = T/rV_d$ sustained under the unidirectional ground motion of the Kobe 1995 (component KJM000), while Fig. 4.2, 5.2, 6.2 and 7.2 show the torsional response under the Erzincan 1992 (EW component) ground excitation. The elastic torsional response of the structure is denoted by the subscript 'e' (in solid lines), while the inelastic response is denoted by the subscript 'in' (in dotted lines).

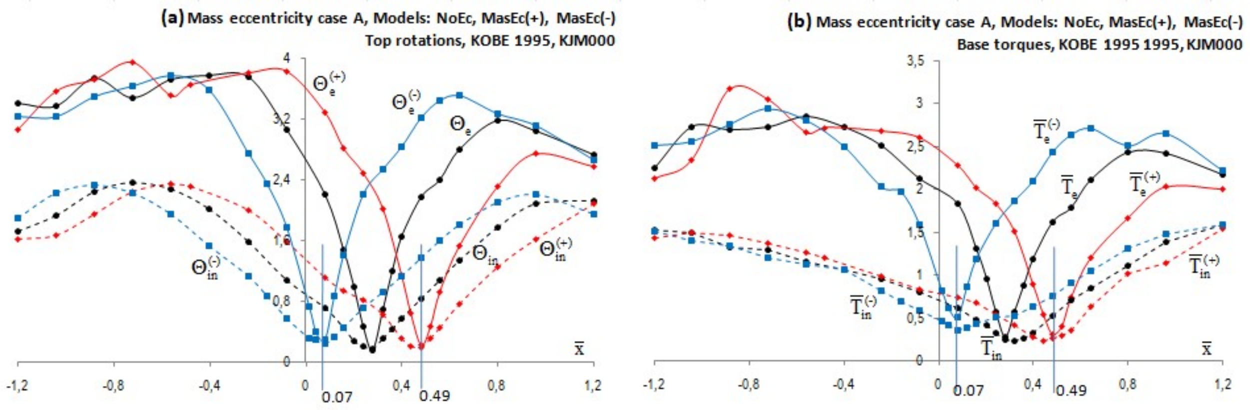

Fig. 4.1 Mass eccentricity case A: Top rotations Θ ($x10^{-2}$ rads), and normalized base torques $\overline{\mathrm{T}}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Kobe 1995 ground excitation.

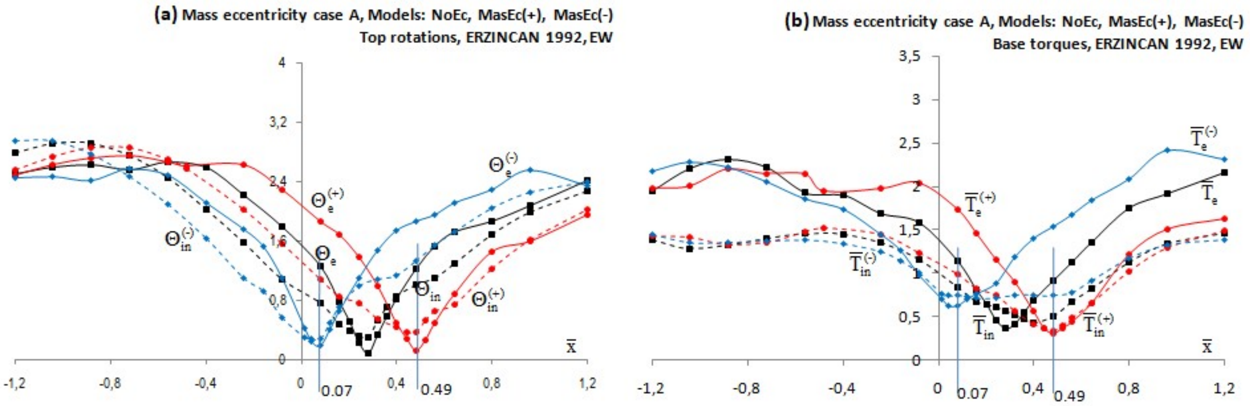

Fig. 4.2 Mass eccentricity case A: Top rotations Θ ($x10^{-2}$ rads), and normalized base torques $\overline{\mathrm{T}}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Erzincan 1992 ground excitation

The elastic torsional response curves in Fig. 4-7 have an inverted peak, which suggests that for a suitable shift of the coupled wall bent along the x-axis, the elastic torsional response of the structure is minimised. The locations of the inverted peaks where the torsional response of the structure is minimised is predicted with sufficient accuracy by the analytical solution proposed by [19] (Table 1). The location of the inverted peaks in Table 1 are denoted as $\overline{x}(+)$ (or $\overline{x}(-)$) for the model *MassEc*(+) (or *MassEc*(-)) for each of the eccentricity cases of Fig. 2(a) to (d) and the corresponding values are also shown, by separate vertical lines, in Fig. 4 to 7. As demonstrated in this paper, the predicted optimum locations of the CW, for the eccentricity cases of Figs. 2(a) to (d) are pointing to almost symmetrical locations, with respect to the optimum location of the CW bent (for example $\overline{x}(0)$), when no accidental mass eccentricities are accounted for (this nominal coordinate of the CW is depicted by the inverted peak of the black lines of Model *NoEc*).

Mass eccentricity case	Models	Optimum locations of CW
Fig.2(a) Reversed case	*MassEc(+)* *MassEc(-)*	$\overline{x}(+) = 0.49$ $\overline{x}(-) = 0.07$
Fig.2(b) Reversed case	*MassEc(+)* *MassEc(-)*	$\overline{x}(+) = 0.36$ $\overline{x}(-) = 0.20$
Fig.2(c) Reversed case	*MassEc(+)* *MassEc(-)*	$\overline{x}(+) = 0.41$ $\overline{x}(-) = 0.16$
Fig.2(d) Reversed case	*MassEc(+)* *MassEc(-)*	$\overline{x}(+) = 0.55$ $\overline{x}(-) = 0.02$

Table 1 Predicted optimum normalized locations of the key element (CW bent) in models *MassEc(+)* and *MassEc(-)* for the mass eccentricity cases shown in Figs. 2a-2d.

The results presented in Fig. 4-7 show that the elastic response of the structure changes rapidly with small shifts of the coupled wall bent from the location of the inverted peak, but with larger shifts, this response becomes smoother and eventually even flattens out. The inelastic torsional response of the investigated mass eccentricities configurations, was generally smoother than the elastic response, with the inelastic torsional response curves exhibiting a more extended range of possible locations of the couple wall bent for which the torsional response of the structure was minimised. The inelastic torsional response presented in Figs. 4-7 suggest that the inelastic torsional response of the structure was generally less sensitive to spatial variations of the coupled wall, confirming reports by [21] that the effects of accidental eccentricity on the inelastic torsional response of building structures may be insignificant.

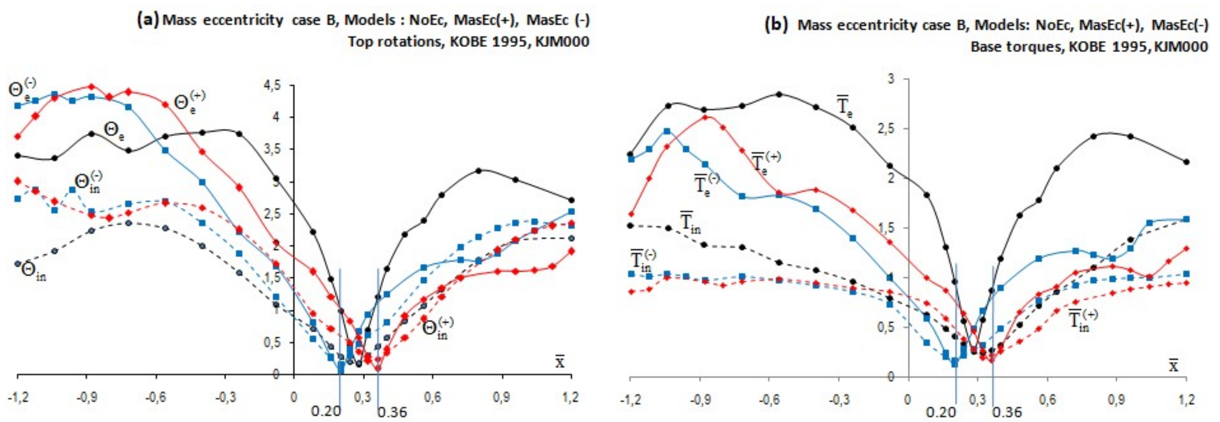

Fig. 5.1 Mass eccentricity case B: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Kobe 1995 ground excitation.

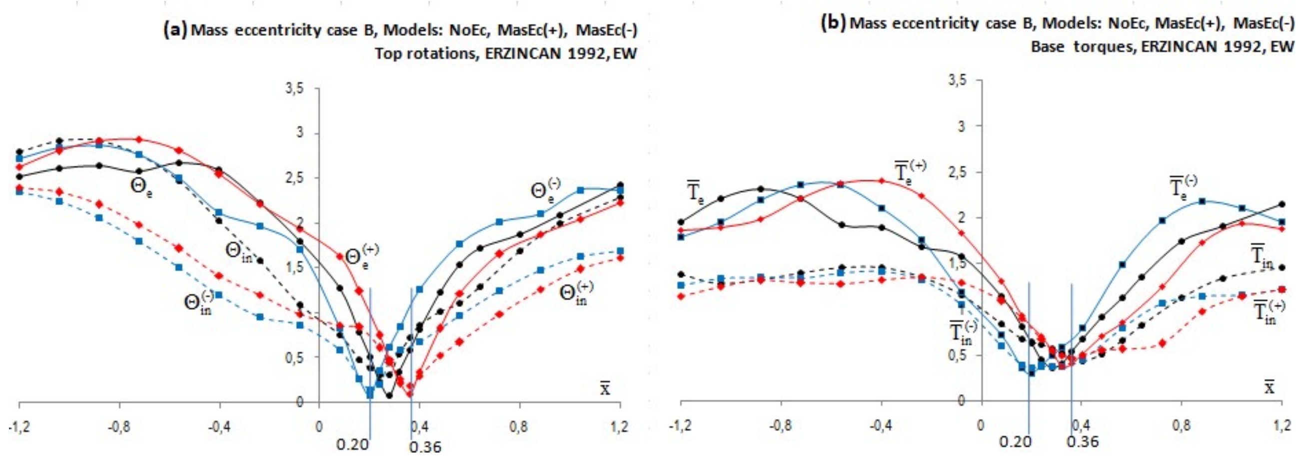

Fig. 5.2 Mass eccentricity case B: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Erzincan 1992 ground excitation

At the locations of the CW bent for which the torsional response of the structure is minimized, the elastic response of the structure is essentially translational (along the y-direction) and its post elastic response may be interpreted as follows: when the elastic behavior is practically translational, the effective seismic forces developed on a medium or low height structure are basically proportional to the first translational mode of vibration. Therefore, a strength assignment obtained from a planar static analysis under a set of lateral loads simulating the aforementioned mode of vibration, represents a system in which all potential plastic hinges at the critical sections are formed at approximately the same time. As a result, the system is further pushed into the inelastic region in a translational mode. In other words, the almost concurrent yielding of the most stressed potential plastic hinges of all the bents in the direction of the ground motion, maintains the translational response, attained at the end of the elastic phase. This response is in agreement with the observations of [22] in single story buildings where it is concluded: their nonlinear response depends on how the building enters the nonlinear range, which in turn depends on its elastic properties (i.e. the stiffness and mass distributions), and on the capacities of its resisting elements (i.e. the strength distribution). This response is also in agreement with the observation by [23] and [24], who reported that the torsional reponse increases when one structural element yields, while the other element is still in the elastic range, or when one element unloads, while the other element remains in the yield plateau. This implies that during the response, the elements would yield at approximately the same time, having similar yield durations and that they would unload at a similar time.

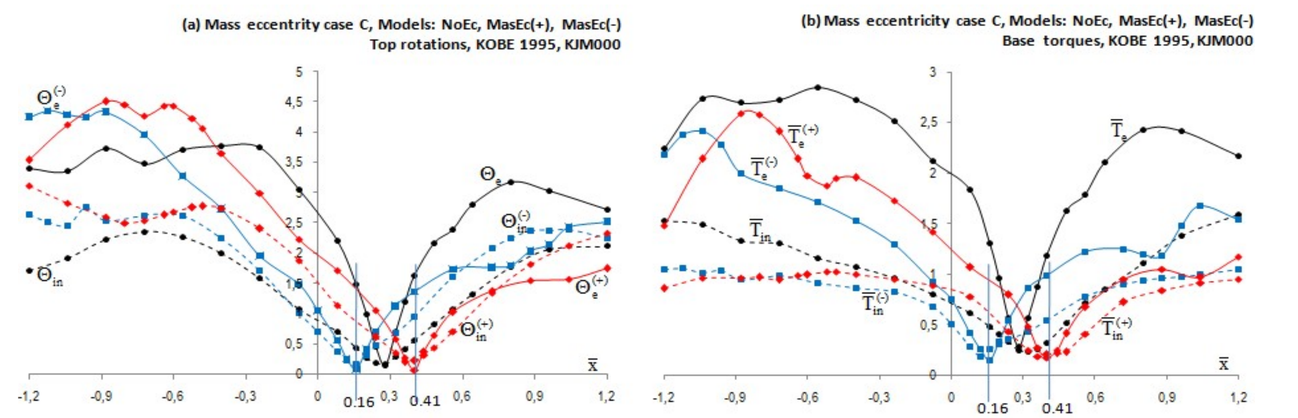

Fig. 6.1 Mass eccentricity case C: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Kobe 1995 ground excitation.

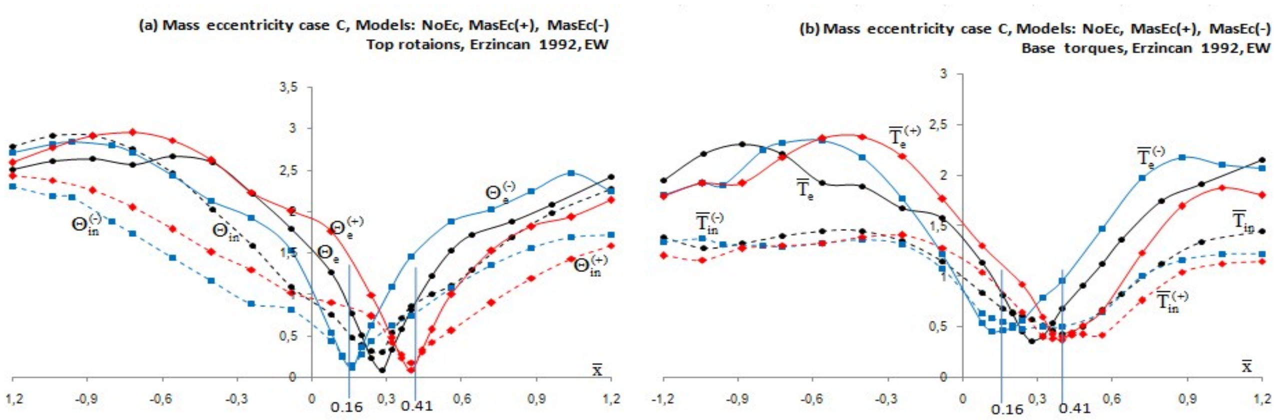

Fig. 6.2 Mass eccentricity case C: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Erzincan 1992 ground excitation.

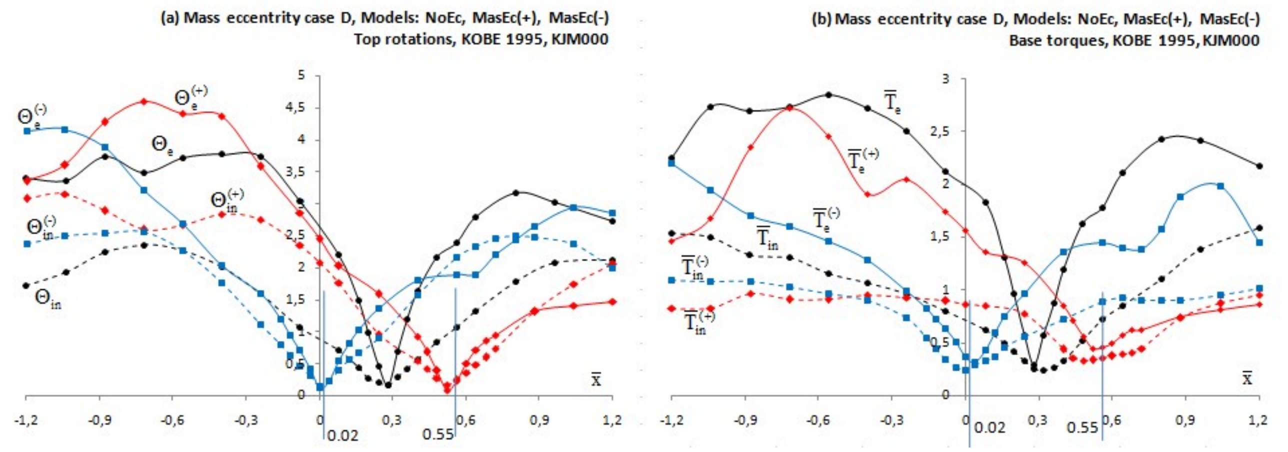

Fig. 7.1 Mass eccentricity case D: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Kobe 1995 ground excitation.

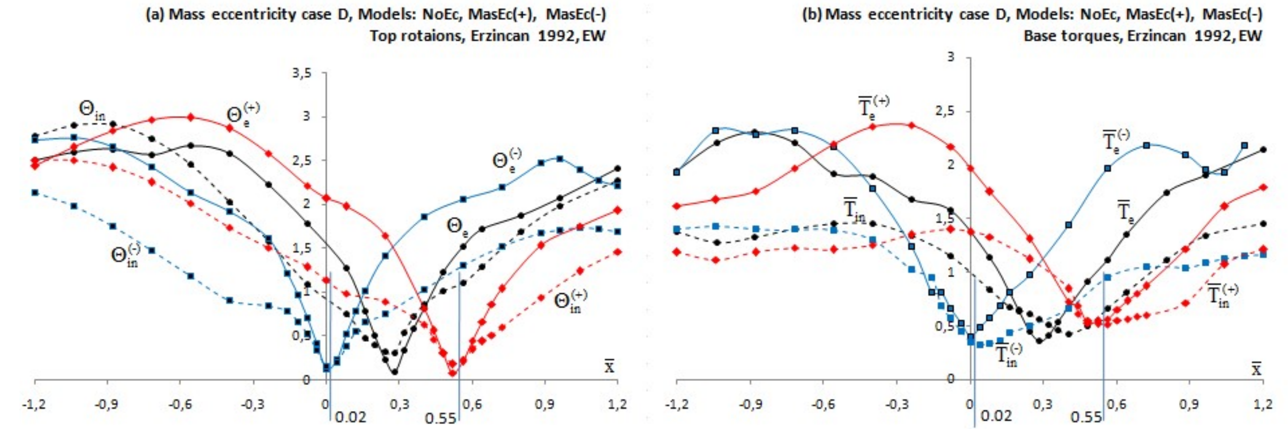

Fig. 7.2 Mass eccentricity case D: Top rotations Θ (x10^{-2} rads), and normalized base torques $\overline{T}$, of *NoEc* (black lines), *MassEc(+)* (red lines) and *MassEc(-)* (blue lines) models responding as elastic (subscript 'e') and inelastic (subscript 'in') systems under the Erzincan 1992 ground excitation

4. Conclusions

This paper discusses the significance of mass eccentricity on the elastic and inelastic torsional response of buildings. Based on the numerical modelling results for the Kobe 1995 (component KJM000) and Erzincan 1992 (EW component) ground excitation the following main conclusions may be drawn:

- The elastic torsional response curves have an inverted peak, which suggests that for a suitable shift of the coupled wall bent, the elastic torsional response of the structure is minimised.
- Small shifts of the coupled wall bent from the location of the inverted peak, where the torsional response of the structure was minimized, resulted in significant changes in the torsional response of the structure. With larger shifts of the coupled wall bent from the location of the inverted peak, the torsional response curves become smoother and eventually even flatten out.
- The locations of the inverted peaks where the torsional response of the structure is minimised is predicted with sufficient accuracy by the analytical solution proposed by [19].
- Reversing the accidental eccentricities, shifted the elastic torsional response curves to approximately symmetric locations with respect to the no eccentricity reference torsional response curves.
- The inelastic torsional response was generally smoother than the elastic response, with the inelastic results indicating an extended range of possible locations of the couple wall bent, for which insignificant or small variations in the torsional response of the structure occurred.
- For systems expected to respond beyond their elastic limits during a strong ground motion, an optimal structural configuration that is based on the nominal locations of the floor masses represents also a system which is expected to sustain reduced torsional distortion in the case of a possible spatial distribution of floor masses.

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