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Seismic assessment of a steel braced plan mass symmetric/asymmetric building structure

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ABSTRACT

This paper presents a seismic response investigation into a code designed concentrically braced frame structure that is subjected to but not designed for in-plan mass eccentricity. The structure has an accidental uneven distribution of mass in plan resulting in an increased torsional component of vibration. The level of inelasticity that key structural elements in plan mass asymmetric structures are subjected to is important when analysing their ability to sustain uneven seismic demands. In-plan mass asymmetry of moment resisting frame and shear wall type structures have received significant investigation, however, the plan asymmetric response of braced frame type structures is less well understood. A three-dimensional non-linear time history analysis model is created to capture the torsional response of the plan mass asymmetric structure to quantify the additional ductility demand, interstorey drifts and floor rotations. Results show that the plan mass asymmetric structure performs well in terms of ductility demand, but poorly in terms of interstorey drifts and floor rotations when compared to the plan mass symmetric structure. New linear relationships are developed between the normalised ductility demand and normalised slenderness of the bracing on the sides of the plan mass symmetric/asymmetric structures that the mass is distributed towards and away from.

1. Introduction

Plan asymmetric (or plan irregular) structures have uneven distribution of mass, stiffness or strength across the plan dimensions of the structure and are subjected to a torsional and translational rather than purely translational response during a seismic event. The plan mass asymmetric (PMA) structure investigated in this paper has an uneven distribution of mass in plan. Accidental mass eccentricity can occur due to uneven loading or an increased structural floor thickness. A translational response in Eurocode 8 [1] (EC8) is ensured by the structure being required to have a dominant fundamental model of vibration. Mass asymmetry is defined as the distance between the centre of mass (CM) and centre of resistance (CR) of the structure as can be seen in Fig. 1(b) and is termed the static eccentricity, e_s. EC8 sets out dimensional criteria to ensure plan symmetry and provides a torsional effects provision to be used in the lateral pushover method of design to account for an accidental level of mass eccentricity of 5%. However, no criteria exist limiting the torsional stiffness of the structure. The seismic performance of a plan mass symmetric (PMS) steel concentrically braced frame (CBF) structure designed with the EC8 lateral pushover method is evaluated and compared to the same structure but subjected to increasing levels of mass eccentricity (referred to as plan mass asymmetric (PMA) structure).

The cyclic response of bracing has been extensively investigated both experimentally; [2–7] and numerically in two-dimensions; [5, 8–12]. The two-dimensional models vary in sophistication; however they all only model the cyclic response of bracing in two dimensions as they only induce buckling in one plane. Two-dimensional analysis captures the important cyclic behaviour; however a structure that is susceptible to a torsional response requires a three-dimensional modelling approach. The seismic behaviour of CBF structures is therefore well-known numerically in two-dimensions, but less well explored in three dimensions. Three-dimensional finite element continuum modelling of individual brace elements that showed good agreement with test results was performed by [13]. Elastofibre brace elements with three-dimensional plastic hinges at the ends and mid-span were used by [14] and showed good agreement with multi-storey test results, however the model also required geometric imperfections to improve accuracy. Both of the above mentioned methods are computationally expensive. This paper therefore provides an efficient and sophisticated three-dimensional modelling approach that includes torsional vibration of the structure and takes brace buckling into consideration in- and out-of-plane.

Investigations into idealised single-storey [15–18], realistic plan asymmetric multi-storey moment resisting frame [19–21] and shear

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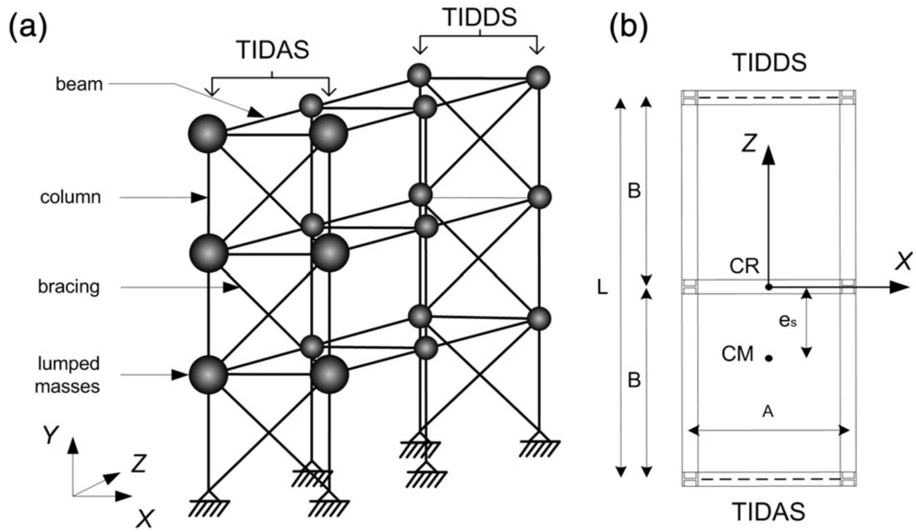

Fig. 1. (a) Three-dimensional view of plan mass asymmetric structure with lumped masses shown and; (b) plan view of structure (masses not shown).

wall [22,23] type structures are extensively covered in the literature. More recently braced plan asymmetric structures have received some attention, namely research by [24–28], but still require significant investigation to attain a similar level of understanding found in moment resisting and shear wall type structures.

Others demonstrated that modal pushover analysis could accurately predict storey drifts, overturning moments and storey shears in multi-storey steel braced frame structures containing plan stiffness asymmetry when compared to nonlinear time history analysis (NLTHA) [24]. The effects of torsion on the behaviour of a peripheral steel braced frame system using a three-dimensional model that was designed for 5% eccentricity according to ASCE 7-05 [29] were studied by [26]. The authors note that the hysteretic behaviour of bracing differs from that of shear wall and moment resisting frames in terms of force–deformation relationship and structural redundancy. They observed that in contrast to frame type structures torsional amplifications in the elastic systems exceeded those in the inelastic. The response was improved by aligning the bracing on several lines throughout the building and not just at the periphery of the building. This conclusion is reiterated in separate findings by [25] who also observed that a lack of redundancy exists in steel braced frame structures after brace fracture and significant torsion is observed after fracture, and that the response of the structure is improved if the bracing is located closer to the CM of the structure. The effect of torsional stiffness and torsional flexibility of Iranian code [30] designed multi-storey structures was studied by [27] and concluded that structures with low torsional stiffness should not be permitted using the code specified linear static procedure. The torsional response of a CBF steel structure designed to resist 5% mass eccentricity according to EC8 torsional effect provision (see Eq. (1)) was experimentally investigated by [28].

The objective of this paper is to compare the additional demands placed on a PMA CBF structure over a PMS CBF structure using a sophisticated three-dimensional NLTHA model. This study investigates the effect of accidentally shifting the CM in the symmetric structure causing it to be asymmetric. In this paper we develop relationships between brace ductility demand and slenderness in the PMA structure and also make contributions towards understanding the effects of peak ground acceleration amplification.

2. Plan mass asymmetric structure

The PMA structure investigated in this paper is a two-by-one bay three-storey CBF steel structure as shown in Fig. 1. The two end frames of the structure in the x-direction are braced providing lateral support. The columns and beams are 203 × 203 × 46 mm UC and 305 ×165 × 40 mm UB sections throughout, respectively. The structure has a 2.5 m high first storey, a 2.2 m high second storey and a 2.2 m high third storey. The plan dimensions are as follows; A = 3.3 m, B = 3.3 m and L = 6.6 m (see Fig. 1(b)). The structure is idealised in that bracing which is located at each end and in one direction only. This allows for the simplest direct comparison between each braced bay response for this class of structure as static eccentricity is only provided in one direction. The idealised multi-storey structure bridges the gap between overly simplified single-storey models in early research with more recent case specific real-world models. Out-of-plane stiffness of the structure is provided by moment resisting connections, with the CBF having approximately 8 times the lateral stiffness of the MRF. The rigid floor plate is modelled by applying rotational restraint in the vertical y-direction (refer to Fig. 1(a)) to the connecting nodes.

The side of the structure with the mass distributed towards it has an increased torsional demand and is referred to as the torsion induced demand amplification side (TIDAS) and the side with the mass distributed away from it is referred to as the torsion induced demand de-amplification side (TIDDS). Two of the key parameters affecting the seismic torsional response of mass asymmetric structures are the lateral torsional frequency ratio, Ω_θ, and the static eccentricity, e_s. A structure is torsionally stiff if $\Omega_\theta > 1$ and torsionally flexible if $\Omega_\theta < 1$. Ω_θ is varied from 0.75 to 1.25. The maximum e_s investigated is 15% (0.15 L as per Fig. 1(b)) as any greater level of mass distribution would be unlikely to occur in a real-world scenario. The EC8 torsional effects factor, δ, applied to the seismic action effects in Eq. (1) can be used to increase the stiffness of the TIDAS of the structure for a $e_s = 5\%$.

$$\delta = 1 + 0,6\frac{x}{L_e} \tag{1}$$

where x is the distance from the element under consideration to the CM of the structure measured perpendicularly to the seismic action; and L_e is the distance between the two outermost lateral load resisting elements. The structural parameters of the PMS structure are as follows; $e_s = 0.0\,L$, $\Omega_\theta = 1.0$ (neither torsionally stiff nor torsionally flexible) and 30 × 30 × 3 mm square hollow section (SHS) concentric bracing ($\bar{\lambda} = 1.68$) throughout the structure. Changing the nodal masses changes the lateral torsional frequency ratio. The structure was designed for a peak ground acceleration, $a_g = 0.35$ g. The behaviour factor, q for a concentrically braced steel structure designed for medium ductility class (DCM) is 4. The behaviour factor is an approximation for the ratio of