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On the seismic behaviour of tension-only concentrically braced steel structures

George A. Papagiannopoulos

Department of Civil Engineering, University of Patras, GR-26504 Patras, Greece

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ABSTRACT

This paper summarizes the estimated results from three-dimensional non-linear time-history seismic analysis of tension-only concentrically braced steel structures. The braces of these type of steel structures are properly detailed in order to sustain only tension and no compression. In particular, a cheap and easy to fabricate brace detailing allows the brace to slide when in compression and to develop a resisting force when in tension. A comparison between steel structures designed with the proposed tension-only braces and with buckling-restrained braces is performed on the basis of commonly used seismic response and demand indices. It is shown that tension-only and buckling-restrained braced structures may exhibit similar behavior. Nevertheless, column overstress in compression is larger for the tension-only braced structures. Preliminary conclusions regarding the use of the proposed tension-only braces as a seismic force-resisting system for steel structures are drawn.

1. Introduction

Concentrically braced frames (CBFs) constitute a popular seismic force-resisting system for steel structures. They are typically separated in ordinary concentrically braced frames (OCBFs) and special concentrically braced frames (SCBFs). Seismic codes distinguish these two types of CBFs by enforcing appropriate design and detailing requirements, even though OCBFs generally are not recommended for areas of high seismicity [1,2]. Useful overviews on the seismic behaviour of CBFs and of SCBFs taking into account the properties and the configurations of the braces can be found in literature, e.g., [1–4] and references therein.

Buckling-restrained braced frames (BRBFs) are a special type of CBFs where braces are appropriately detailed against global buckling and strength loss [1,2,4,5]. A BRBF is usually more flexible than a SCBF and its design is governed by code-specified drift limits [1]. BRBFs tend to concentrate damage in specific storeys producing large permanent drifts [1,4,5] as well as to induce substantial deformational demands at beam-column joints, e.g., [6]. Alternative types of braces that can be used in a CBF and seem to exhibit a stable hysteretic behaviour is the three-segment brace recently proposed by Seker et al. [7] and the superelastic shape memory alloy (SMA) brace proposed by McCormick et al. [8]. A comparative study on the seismic performance of CBFs with SMA braces and BRBFs, has been also performed [9].

To avoid common brace buckling problems, CBFs with tension-only braces (employing steel rods) have been proposed [10–12] but their use seems to be restricted only in seismic retrofitting of existing structures [13–15]. On the other hand, application of tension-only braces in SCBFs is prohibited [2,3], whereas in [1], tension-only bracing type behaviour due to purely elastic buckling of the braces is mentioned but without any further recommendation. The use of tension-only braces (using spiral strand ropes or cables) in a seesaw configuration [16–18] seems to be a promising seismic force-resisting system but further research is demanded before its codification.

The purpose of this paper is to revisit the concept of the tension-only concentrically braced frames in an effort to recommend an improved version for them. The motivation behind the recommendation of tension-only braces is essentially to avoid buckling of the brace. This buckling avoidance is accomplished by means of a specific brace detailing that allows the brace to slide when in compression and to develop a resisting force when in tension. Removing brace buckling issues certainly improves the overall design process of concentrically braced frames and renders unnecessary any slenderness considerations related to their seismic behavior [19].

Slotted holes has been initially introduced in the seismic design of connections of CBFs by FitzGerald et al. [20] and Grigorian et al. [21]. They basically constitute modified bolted connections designed to dissipate energy through friction in both tension and compression. However, an unstable hysteretic behaviour can be met in slotted bolted connections due to problems associated with friction and wear between steel surfaces as well as with brittle failures when the bolt-shank impacts the end of the slot. Variants of slotted-bolted connections in

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E-mail address: gpapagia@upatras.gr.

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braced frames have been proposed aiming to dissipate energy by straight-line or rotational sliding [22,23] and a remedy to bolt impact has been suggested [24]. Slotted-bolted connections have been also used in the sliding hinge joint moment connection [25], in the asymmetric friction connection [26] and in shear connections [27], whereas a detailed review regarding their ductile behaviour as well as their implementation in praxis can be found in [28–30]. Application of slotted-bolted connection in reducing the gusset plate-frame interaction of BRBFs has been very recently presented by Zhao et al. [31].

Focusing our interest in the implementation of slotted-bolted connections in steel CBFs [22,23], positioning the bolts in the middle of the slotted holes performed in one or more steel plates, permits energy dissipation through sliding. Sliding continues until bolts reach the end of the slotted holes, where a resisting force is developed. Taking into account that a steel brace exhibits both tension and compression during a seismic motions, the sliding joint details of [22,23] can be used. However, problems associated with the absence of a stabilizing compressive force under reversals of motions may occur.

The idea proposed in this paper is to employ the sliding joint concept but now by positioning the bolts (pins) directly at the one end of the slotted hole. The detail of this sliding joint is indicatively shown in Fig. 1. A high-strength pin slides along the slotted hole performed on a brace of hollow section (Fig. 1b). The brace bears cuts of a length *L* in order to be connected with the gusset plate that holds the pin (Fig. 1a and c). This way the steel braces work only in tension and compression cannot be developed as long as the clearance of the slotted hole is not exceeded by the sliding pin. The proposed brace detailing is considered to be cheaper and easier to fabricate in comparison with the corresponding detailing of other bracing systems, e.g., [32,33]. On the other hand, the impact of the pin to the end of a slotted hole is a matter of serious concern not only from the design point of view but most importantly from the fact that current seismic design codes do not accept or promote impact type of behavior in structures. Nevertheless, the proposed tension-only braces are studied herein in order to check if they can satisfy basic seismic response and demands indices when used in a steel structure. Additionally, a comparison of concentrically tension-only braced frames with BRBFs is performed. The use of the proposed tension-only braces as a seismic force-resisting system for steel structures is finally assessed.

2. Description of the steel structures under study

Three dimensional steel structures, used for office-residence purposes, having 4, 6 and 8 storeys (Type A) as well as a typical 2-storey industrial building (Type B) are selected for seismic response computations.

A typical floor plan view and front views for the 4- and 6-storey structures of Type A are shown in Figs. 2 and 3, respectively. Each bay has a span of 6.0 m, whereas the height of each storey is 3.0 m. The stressed black lines in Fig. 2 indicate the position of the braces. Type A and Type B steel structures are designed with tension-only braces or with buckling-restrained braces (BRBs).

The configuration of the braces can be in inverted V, diagonal and multistory X forms, as shown in Fig. 4. In that figure, the middle case of diagonal bracing corresponds to a different position of the braces in the frames of the perimeter from that shown in Fig. 2. Moreover, the symbols used, i.e., A4a, A4b, A4c mean that the structure under study corresponds to Type A, has 4 storeys and the brace configuration differs and may be *a* (inverted V), *b* (diagonal) or *c* (multistory X). Similarly one defines, A6a, A6b, A6c and A8a, A8b, A8c for the cases of 6- and 8-storey structures of Type A, respectively.

The floor plan of the Type B 2-storey structure is shown in Fig. 5. Each bay has a span of 6.0 m, and the height of each storey is 3.0 m, whereas the stressed black lines indicate the position of the braces. Only the B2a structure is studied which means that the inverted V configuration of Fig. 4 is employed.

Type A and B structures are designed according to EC3 [34] and EC8 [35] for the combinations: i) 1.35·dead load + 1.5·live load and ii) dead load + 0.3·live load + seismic load. In particular, dead and live loads on floors have been considered to be 8.0 kN/m^2 and 3.0 kN/m^2, respectively, whereas the seismic load is calculated using the design spectrum of EC8 [34] that corresponds to a PGA of 0.36 g and to a soil of class D. Fixed-based conditions are assumed and soil-structure-interaction effects are neglected, even though this is not realistic when soil of class D is considered. Behavior factors are conservatively considered to be equal to 2.5 for the *a* and *c* configurations and equal to 4.0 for the *b* configuration of Fig. 4. Effects of accidental torsion are also taken into account, even though, placing of braces on axis with the perimeter of the structures almost precludes torsional effects. Orientation of columns follows [36], forming, thus, a strong perimeter frame. Steel grade is S275.

Sections for beams and columns as well as the cross-sectional area of the core of the BRBs are shown in Table 1, whereas the corresponding sections of beams, columns and braces for the case of tension-only braced structures are shown in Table 2. In both tables, the symbols A4a etc., are previously explained. Figs. 6 and 7 display the sections at an exterior frame of the structure A6b having buckling-restrained and tension-only braces, respectively. More details regarding the design of the steel structures under study using BRBs can be found in [37]. The design of tension-only braces is performed using the analysis option for tension-only braces of SAP 2000 [38].

For the steel structures with BRBs, the design storey drift is considered to be 1.5% and the design axial displacement which the BRB should accommodate is two times this drift, i.e., 8.04 cm. For the steel structures with tension-only braces, the design drift is also 1.5% and, thus, the design slot clearance is 4.02 cm. All connections for steel structures with BRBs and tension-only braces are moment-resisting ones, except those of the BRBs that are pinned and those of the tension-only braces that are pinned but with axial translation free. The moment connections are expected to provide reserve strength and to reduce both the drift and the residual drift of the stories.

3. Structural modelling and seismic motions used

The steel structures having buckling-restrained and tension-only braces, are subjected to the 7 accelerograms of Table 3 and their seismic response is determined through non-linear time-history analyses using the computer analysis software RUAUMOKO 3D [39]. These accelerograms correspond to recordings of near-field strong ground motions because these type of ground motions have been repeatedly reported in the literature to produce large residual deformations in steel structures. The two horizontal components of these accelerograms are used interchangeably in both directions but their variation using an angle of incidence is not studied.

Diaphragm action is assumed at every floor due to the presence of a composite slab. Large deformation and second order effects are also taken into account [39] and an inherent viscous damping of 3% of critical is considered. Beams and columns are modelled using standard frame elements with concentrated plasticity assuming a strain hardening of 2%. The interaction of axial load with biaxial moment is considered for all columns. Column panel zone deformations as well as gusset plates are not modelled in the analyses performed herein and are left out for a future work.

The BRB model used for seismic response purposes should include an appropriate isotropic hardening law or a combination of isotropic and kinematic hardening [36,40,41]. This is particularly important when assessing the force demands imposed to beams and columns by the BRBs by non-linear time-history seismic analysis However, for reasons of conservativeness in the seismic response calculations performed herein, the BRB is modelled as an inelastic truss member [39] on the basis of the equivalent area [41]. The post-yield stiffness of the BRB core is assumed to be 2% of the axial elastic stiffness. A nominal