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Role of compression diagonals in concentrically braced frames in moderate seismicity: A full scale experimental study

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ABSTRACT

According to European building code provisions, compression diagonals should be neglected during the analysis stage of concentrically braced frames (CBFs) with X and N type bracings, and the inelastic capacity of the tension bracings only should be considered in the design. This provides simplifications at analysis and design stages for practising engineers. Such an assumption can be rational in the high-seismicity context, where the compression bracings undergo buckling at the early stages of the seismic event, and the shear demand is very high. On the other hand, in moderate seismicity areas (that is estimated as the 90% of the seismic regions of the world), where the shear deformation demand for braced frames and the number of high-amplitude cycles are very limited, it may be reasonable to consider both tension and compression diagonals in the analysis. Accounting for compression diagonals at the analysis stage, and exploiting their post-buckling resistance and dissipative contribution in design, may allow using a higher behaviour factor, and increase the economic efficiency of CBF structures in moderate seismic regions. To understand the real seismic performance of braced frames in moderate seismicity areas, a sound characterization is needed, focusing on behaviour of compression diagonals. In the literature, many tests have been performed to analyse the behaviour of bracing elements, but they were mostly designed to meet high seismicity criteria with significant connection over-strengths.

The European research project RFSR-CT-2013-00022 MEAKADO investigated the influence of compression diagonals on the global performance of CBF structures, by means of experimental and numerical studies. This paper presents the results of full scale tests performed within this research project, focusing on the stiffness and post-buckling performances of double-angle bracings with bolted connections, which are the most common bracing configurations in the European construction market characterized by low-to-moderate seismicity. Experiments have shown that extra stiffness and strength provided by the contribution of the compression diagonals to the structural response are significant for moderate seismicity drift and shear demands, and may be worth considering in the analysis and design phases.

1. Introduction

Concentrically braced frame (CBF) configurations (Fig. 1) are very effective for resisting earthquake loads, thanks to their high lateral strength and stiffness. They are the economic alternatives to the costly moment resisting frames, thanks to their simpler connection details and smaller beam and column cross-sections, because the bending moment demands in the frame are widely replaced by axial forces developed in bracings. For these reasons, 80 to 90% of the existing steel frames are laterally braced by concentric bracings at least in one direction [1].

According to European seismic design standards, CBF structures with X and N type bracings can be designed relying only on the resistance, stiffness, and ductility of the tension bracings. This assumption is based on the early buckling of compression bracings, and their low post-buckling strength and stiffness. Therefore, designers reasonably neglect the compression diagonal during the structural analysis. These code assumptions originate from the traditional focus of the seismic engineering community on maximizing the building performance in the high-seismicity context. The application of the same assumptions to the low-to-moderate seismicity conditions may not be economically feasible. This issue has been recently highlighted by several researchers worldwide [3–13]. Gioncu and Mazzolani pointed out that the CBF is the most common typology for seismic-resistant steel structures, and among the weak points in their design is the common hypothesis to neglect the compression diagonal in X-bracings [3]. US seismic design provisions [14], contrary to Eurocodes [15], base the design strength of CBF systems on the plastic buckling strength.

Elghazouli [16] showed that a large portion of the over-strength in concentrically braced frames is actually mainly related to the disregarding of buckling in the compression brace, comparing the

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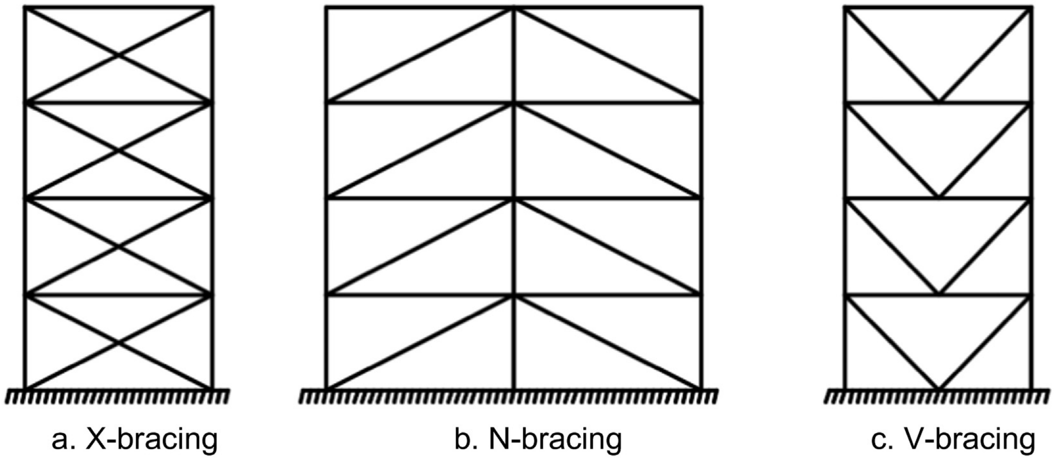

Fig. 1. Concentrically braced frame configurations classified by Eurocode 8 [2].

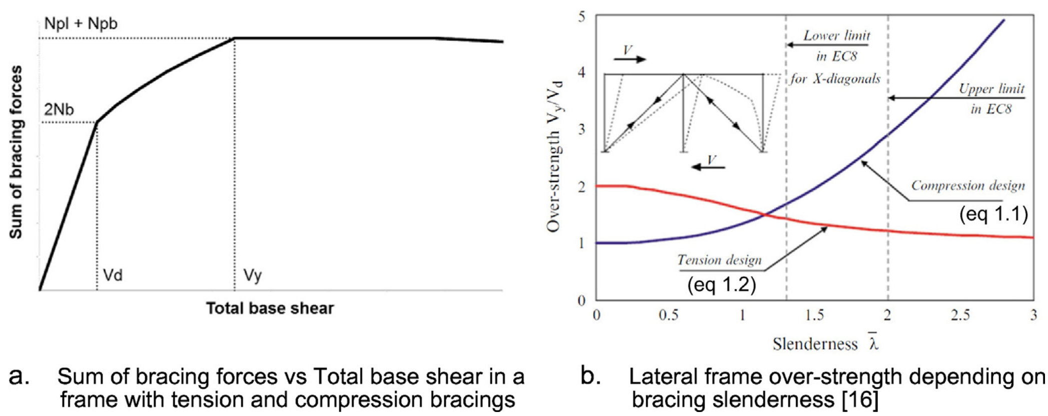

Fig. 2. Lateral frame over-strength arising from tension and compression design [16].

European and US approaches, with reference to an over-strength parameter "V_y/V_d". In compression-based approach, design base shear "V_d" is equal to the sum of the buckling strength of the compression diagonal (N_b) and the force developed at the tension bracing at the attainment of buckling strength. The latter value is very similar to N_b, therefore, V_d equals to "$2N_b$" (see Eq. (1.1)). V_y is the actual global resistance of braced frame, achieved when the tensile bracing yields at a force (N_{pl}), where compression bracing has a post-buckling force smaller than its buckling resistance ($N_{pb} < N_b$), as shown in Fig. 2a. The author [16] assuming the compression bracing preserves its buckling strength ($N_{pb} = N_b$) at this level, calculated the over-strength parameter of the compression based approach [14] as shown in Eq. (1.1).

$$\frac{V_y}{V_d} = \frac{N_{pl} + N_b}{2N_b} \tag{1.1}$$

In the tension based approach, the only difference is that design base shear "V_d" does not have an influence on the buckling strength of the compression bracing, and V_d equals the tensile plastic capacity of the bracing N_{pl}. Therefore, the over-strength parameter of the tension based approach is calculated as [15]:

$$\frac{V_y}{V_d} = \frac{N_{pl} + N_b}{N_{pl}} \tag{1.2}$$

Fig. 2b compares the tension and compression based design approaches, as a relationship between over-strength "V_y/V_d" and non-dimensional slenderness "$\bar{\lambda}$". In compression based design, when the bracing slenderness increases (N_b decreases), the lateral over-strength "V_y/V_d" increases. On the other hand, in the tension based approach, with increasing bracing slenderness, over-strength "V_y/V_d" decreases, reaching a value of 1.0 (no over-strength) with extremely high

Table 1
Behaviour factor "D_s" in Japanese seismic code [17].

Type of MRF (Ductility increases ↑)	Type of brace (← Ductility increases ←)						
	BA or		BB		BC		
	$\beta = 0$	$\beta \le 0.3$	$0.3 < \beta \le 0.7$	$\beta > 0.7$	$\beta \le 0.3$	$0.3 < \beta \le 0.5$	$\beta > 0.5$
FA	0.25	0.25	0.30	0.35	0.30	0.35	0.40
FB	0.30	0.30	0.30	0.35	0.30	0.35	0.40
FC	0.35	0.35	0.35	0.40	0.35	0.40	0.45
FD	0.40	0.40	0.45	0.50	0.40	0.45	0.50