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PROPOSALS FOR A MORE PRACTICAL SEISMIC DESIGN OF STEEL X-CBFS TO EC8

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Abstract: *The European structural seismic design guideline (Eurocode 8 or EC8) prescribes a design process for concentrically X-braced steel frames (X-CBFs) that is challenging for practitioners to apply. This is due to the complex relationship between several parameters that are part of the seismic design process, which often results in excessively heavy structural solutions and systems with high levels of overstrength. This research work tries to propose and evaluate a number of possible amendments to the code towards both a more practical design procedure, as well as more efficient designs. Such modifications focus on the criteria of the European code related to the limitation of the non-dimensional slenderness parameter and the enforcement of homogenous dissipative behaviour. It is concluded that the relaxation of either of the currently imposed limits may lead to identical frame behaviour in comparison to frames designed to the existing version of Eurocode 8. These proposals could be considered as viable modifications to be integrated in future versions of the code.*

Introduction

Concentrically-braced steel frames (CBFs) are widely used as seismic-resistant systems, in large part due to a significant research work conducted in the past decades (Black *et al.*, 1980; Tremblay, 2002; Goggins *et al.*, 2005). This knowledge played a vital contribution to the definition of the seismic design requirements currently established in Eurocode (EC8) (CEN, 2004).

To what regards the recommendations of EC8 for X-CBFs, the code allows for the dissipative inelastic behaviour to occur in the braces, whereas beams and columns should be capacity designed to remain elastic. The code controls the distribution of overstrength, Ω, throughout all braces, with a maximum allowed difference of minimum and maximum levels of Ω to less than 25%. This criterion has been shown lead to heavier and more expensive CBF design solutions (De Luca *et al.*, 2006; Tremblay, 2007). Moreover, several issues of the design process of EC8, namely related to over-restrictive or conflictive requirements, have also been documented in recent literature (Elghazouli, 2003; Elghazouli, 2010; Malaga-Chuquitaype and Elghazouli, 2011; Tremblay and Elghazouli, 2011; Naqash *et al.*, 2014).

In order to address the limitations described above, this research study mainly focuses on the proposal of modifications to the existing requirements of EC8 towards a more efficient and practical application of the code. The impact of these code amendments on the seismic performance of X-CBFs is assessed through the comparison to structures designed according to the existing version of the European code.

Current EC8 seismic design rules for X-CBFs and possible modifications

For the seismic design of steel X-CBFs, an intricate design process is prescribed by EC8, as discussed by Elghazouli (2009). Inelastic behaviour should occur only in the braces, and premature failure of beams, columns and connections should be avoided. For the design of the diagonals, EC8 limits the non-dimensional slenderness parameter, $\bar{\lambda}$, to a maximum of 2.0. This should be coupled with a lower limitation of 1.3 in the case of X-CBFs. The ratio between the maximum and minimum diagonal overstrength, Ω, should be limited to 1.25. Capacity design principles should be applied to the design of non-dissipative components (beams, columns,

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connections). To calculate the resistance of the dissipative and non-dissipative members, EC8 refers the designer to the requirements of EC3-1-1 (CEN, 2005).

For the research study detailed in this paper, a number of modifications to the current design requirements of EC8 were assessed. These amendments mainly relate to the relaxation of the upper limit of the non-dimensional slenderness, $\bar{\lambda}$, and to the maximum allowed maximum-to-minimum overstrength. The considered design variants are summarized in Table 1. The considered amendments were applied independently in the design of the frames presented in the next section. In order to have a base for comparison of the obtained designs, the seismic design to the current version of EC8 was also considered in this research study.

EC8 clause	Variant	Modification
Cl. 6.7.3(1): $\bar{\lambda}$	VAR1	Modification of the upper limit value from 2.0 to 2.5
Cl. 6.7.3(8): $\Omega_{i,max}/\Omega_{i,min}$	VAR2	Disregard the diagonals of the top storey for the verification
	VAR3	Modification of the maximum allowed value from 1.25 to 1.5
	VAR4	Apply the verification between adjacent storeys instead of the whole structure

Table 1. Proposed amendments to EC8-1 for X-CBFs.

Case study building

For the evaluation of the impact of the code amendments summarized in Table 1, a 4-storey archetype building was considered (see Figure 1). The braced frames, with a single middle braced bay, are positioned in the vertical direction of the plan elevation figure, at the edges of the structure. All other internal frames were assumed to provide no lateral resistance to the structure. The subject of investigation in this study pertains only to the braced frames in the vertical direction of the plan view of the figure.

For the design of the archetype X-CBFs, the slabs are considered to act as rigid diaphragms, thus, each storey mass can be equally distributed by the two braced frames of the building, as shown in Table 2. In the designs, an S275 beams and diagonals, and S355 columns were adopted. European H open sections were adopted for the beams and columns and SHS (square hollow sections) for the braces. The building was considered to be located in the city of Lisbon in Portugal. The acceleration response spectrum specified by EC8 for this location is shown in Figure 2. The adopted behaviour factor was determined according to IFBD methodology (Macedo *et al.*, 2019).

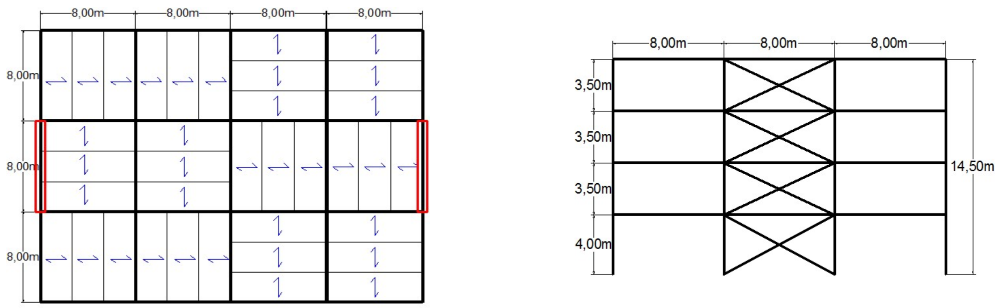

Figure 1. Plan and elevation views of the archetype building.

Storey	Load type	Load [kN/m²]	Frame storey mass [t]
Top	g_k	4.7	184
	q_k	1.5	
Intermediate	g_k	4.7	220
	q_k	3.0	

Table 2. Characteristic vertical loads and seismic masses.

A summary of the dynamic properties and steel weight associated with the design variants considered is included in Table 3. As denoted by the results shown in the table, the proposed amendments are effective in producing more flexible and lighter design solutions when compared to the fully-compliant design to EC8. Across the population of designs, VAR2 was the most impactful variant in terms of lateral flexibility and steel weight. Based on this observation, one might presume that similar consequences should occur regarding the effect of the proposed variants on the seismic performance of the archetypes. This evaluation is detailed in the next sections of this manuscript

Variant	T_1 [s]	q	Steel weight [t]
EC8	0.91	1.6	15.5
VAR1	1.01	1.8	14.9
VAR2	1.15	2.3	14.4
VAR3	1.00	1.8	14.9
VAR4	1.02	2.1	14.6

Table 3. Dynamic properties and steel weight summary.

Numerical modelling and ground motion records

The seismic performance assessment of the X-CBFs was performed trough the numerical simulation in OpenSees (PEER, 2006). Beams and columns were simulated with distributed plasticity, with a single inelastic force-based (FB) beam-column element per structural member, and with 10 integration points (IPs) per element. A bilinear Hardening Material model with a 0.5% strain-hardening ratio was adopted for these members. For the diagonals, a distributed plasticity approach, with 10 FB elements along the length, with 10 IPs, was adopted (Karamanci and Lignos, 2014). Braces were assumed as pinned at both ends. An initial deformed shape of the members, allowing for the development of global buckling phenomena, was considered through a deformed triangular shape with a maximum mid-span imperfection of 1‰ of the member's length (Uriz et al., 2008). The number of fibres in each brace section was set at 60, with a Steel02 Material model with a 0.3% strain-hardening ratio, coupled with the low-cycle fatigue constitutive model Fatigue Material model (Hsiao et al., 2013). Rigid floor diaphragms were simulated through an equal degree-of-freedom approach, in addition to horizontal rigid elastic truss elements connecting the end nodes of all steel beams. Global second-order effects associated with the gravity frames were considered with a lean-column approach. All columns were assumed pinned at the base.

A ground motion suite consistent with the seismicity of the design site was adopted in his study. In accordance to the requirements of EC8, a total of ten ground motions were selected for each group, thus meaning that the average between the numerical responses of the structure to each ground motion may be considered to accurately replicate the response to the design value of the action effect. The SelEQ tool (Macedo and Castro, 2017) was employed for this selection. Figure 2 shows the average ground motion spectrum and the targeted EC8 spectrum.

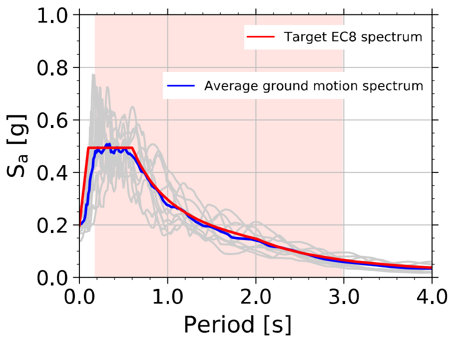

Figure 2. Ground motion record suite.

Pushover analyses

In order to identify potential problems in seismic behaviour introduced by the proposed amendments to the seismic design process of EC8, the numerical response of the archetype X-CBFs under pushover analyses was considered. To this end, an assessment of the behaviour of the frames was carried out by applying a lateral load pattern proportional to the mass and to the fundamental vibration mode. In Figure 3, the lateral load-deformation behaviour of the archetypes is shown in terms of capacity curves representing the total base shear versus the global (or roof) drift ratio. As one may infer from the figure, the proposed code modifications entail clear effects on the lateral behaviour of the structures. EC8-compliant archetypes exhibited stiffer and stronger characteristics, namely due to the fact that the design to EC8 tends to lead to oversized (and therefore heavier, stiffer) structural solutions. It is important to note that the post-yield branches of the pushover curves showed identical gradients across all curves. However, VAR4 exhibited a more rapid branch gradient increase for levels of lateral deformation close to 1.5% of global drift. Such observation, which relates to the formation of undesirable structural collapse mechanisms (e.g. soft-storey) was confirmed through a more detailed look into the lateral deformations along the height of the building at a global drift ratio of 1%, as shown in the figure. Based on these results, VAR4 was discarded as a viable modification to EC8, as it potentially leads to undesirable behaviour of the X-CBFs.

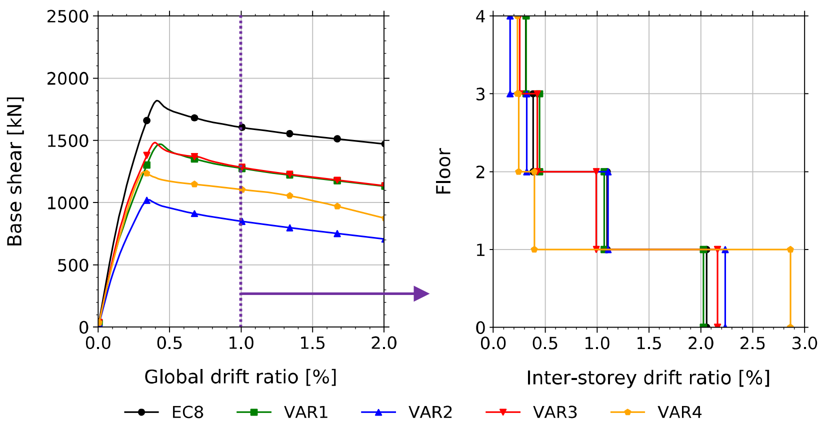

Figure 3. Pushover results.

Response-history analyses

Regarding the response of the case study X-CBFs, designed to the different variants considered in this study, at the Ultimate Limit State (ULS) intensity level of EC8, Figure 4 shows the inter-storey drift patterns obtained. As per the results shown in the figure, the average deformation distribution of the X-CBFs is identical between the archetypes fully designed to EC8, and with the proposed Variants 1 and 3. Furthermore, the results also indicate some concentration of lateral deformations at the bottom storey of the VAR2 archetype. This observation indicates that Variant 2 (disregard the diagonals of the top storey for the Ω ratio verification) is more susceptible to the formation of an undesirable soft-storey mechanism in comparison to Variants 1 and 3.

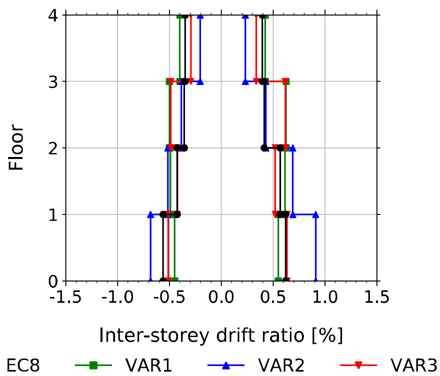

Figure 4. Response-history results (lateral deformations at the ULS).

Considering a ground motion group scaling compatible with the DL, SD and NC limit states of EC8-3 (CEN, 2005), it is possible to compare the brace ductility demands observed across the different design variants, as per Figure 5. As shown in the figure, increased ductility demands of the archetypes designed with the amended clauses of the code, in comparison to the archetypes fully designed to EC8, were observed. This was expected, taking into consideration that the amendments effectively target the reduction of overstrength, entailing that the nonlinear response of the structure is further explored. Even though ductility demands increase, one should recall that these design variants allow for the use of less stocky diagonals, which not only unburdens some of the difficulties imposed the existing set of requirements of the code. It is worth noting the noticeable concentration of ductility demand in compression on the first-storey braces designed according to Variant 2. This observation points towards the undesirable performance entailed by designs conducted based on the VAR2 amendment.

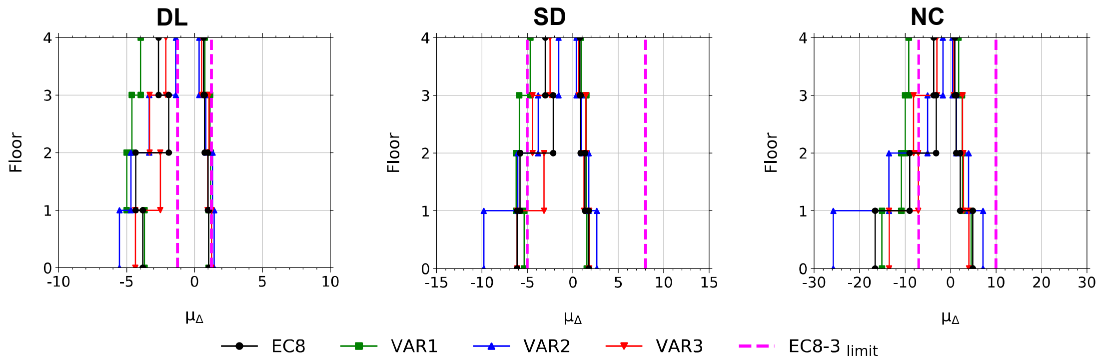

Figure 5. Response-history results (brace ductility demands).

Another important observation that can be extracted from the above pertains the fact that all variants, including those fully designed to the current version of the EC8, violate the compression ductility demand limits defined in EC8-3. This indicates some inconsistency between the requirements of Parts 1 and 3 of EC8, since a newly designed structure does not meet the seismic performance requirements defined for existing steel buildings. This is indicative that some level of conformity between the different European seismic code parts should be reflected in future versions of the code.

Conclusions

In this research study, several modifications to the seismic design of X-CBFs to EC8 was achieved. A total of four variants were evaluated, namely the relaxation of the maximum allowed value of $\bar{\lambda}$ (from 2.0 to 2.5) and the maximum value obtained for the $\Omega_{i,max}/\Omega_{i,min}$ ratio (from 1.25 to 1.5), in addition to two independent modifications to the calculation procedure of the latter (disregard the diagonals of the top storey, and application of the verification of the $\Omega_{i,max}/\Omega_{i,min}$ criterion between adjacent storeys instead of the whole structure).

Pushover and response-history showed that Variants 1 and 3 lead to generally similar behaviour in comparison to the X-CBF designed to current version of EC8. On the other hand, Variant 4 entailed the formation of soft-storey mechanisms, and was therefore discarded. Variant 2 exhibited a larger concentration of brace inelastic demands at the bottom storey, and the consequences of the use of this amendment could potentially lead to undesirable seismic performance. Based on these results, Variants 1 and 3 could potentially be viable solutions to mitigate some of the difficulties associated to the application of EC8 to the design of X-CBFs, without a detrimental effect to the seismic performance.

Acknowledgments

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