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TOWARDS MORE REALISTIC IDEALIZATIONS OF BRACE-TO-FRAME CONNECTIONS FOR THE DESIGN OF STEEL CBFS TO EC8

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Abstract: *At a preliminary stage, steel seismic design is conventionally carried out by assuming idealized member connections. Only after the definition of the main structural members, one proceeds with the sizing of the connections, whose actual geometry/behaviour may or not invalidate the preliminary assumptions. The present study investigates the implications of connection-related design assumptions for steel concentrically-braced frames (CBFs) designed to Eurocode 8. This goal is achieved via an automated seismic analysis and design framework applied to define a comprehensive group of code-compliant CBF archetypes. The effect of conventional idealizations, at the frame design stage, of the diagonal-to-frame gusset connections is examined. Due to the combined effects of member length reduction and boundary condition flexibility on the member's normalized slenderness, full compatibility of the aforementioned assumption is shown to be unassured. A regression-based modified normalized slenderness factor is proposed to adress this incompatibility.*

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).

Structural design procedures generally allow for the use of simplified models for the computation of the engineering demand parameters of interest. In order to facilitate the structural analysis and design process, such models are often idealized depictions of the reality of the structure. For steel CBFs, for example, braces are generally represented through centreline-to-centreline member lengths, in conjunction with fully-pinned boundary conditions. The validity of these assumptions clearly depends on the geometry and behaviour of actual brace-to-frame connections. However, the use of more realistic design assumptions is generally difficult to accomplish, since connection sizing usually comes after the initial definition of the main structural members. At this point, more realistic numerical models, that explicitly simulate previously idealized aspects, might indicate the non-compliance with the design requirements, and design corrections are thus required This loopback in the design process could, in principle, be dealt with more realistic idealizations at the onset.

In order to overcome the aforementioned limitations, this research study evaluates the implications of brace connection-related design assumptions for steel CBFs. A comprehensive archetype suite is defined, using an integrated seismic analysis and design framework. This framework combines a Python-based (PSF, 2017) algorithm that interacts with OpenSees (PEER, 2006). By defining and designing an extensive set of CBF archetypes, different aspects related to the seismic design to EC8 are thoroughly discussed. In particular, the non-explicit consideration, at the design stage, of the contribution of diagonal-to-frame gusset connections is evaluated. Several assessments are then conducted to demonstrate the level of compatibility associated with such idealizations and the geometrical and behavioural characteristics of the connection itself. The results obtained lead to the proposal of practical measures to be taken at the design stage to ensure a higher level of compatibility between conventional connection-related design idealizations and the reality of the structure.

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Seismic design of steel CBFs to Eurocode 8

For the seismic design of steel 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. Several concentric bracing configurations can be adopted (see Figure 1), and different upper limit reference values of the behaviour factor, q, as a function of the adopted ductility class and bracing system, are proposed. 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 for X-CBFs. The ratio between the maximum and minimum diagonal overstrength should be limited to 1.25. Capacity design principles should be applied to the design of non-dissipative components (beams, columns, 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).

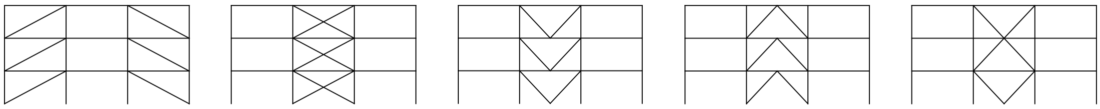

Figure 1. Examples of concentric bracing configurations in EC8.

Within the European framework for seismic design of connections, EC8 prescribes that for fillet weld or bolted non-dissipative connections, the condition shown in Equation (1) should be met. According to the code, the resistance of the connection, R_d, should be calculated following the requirements of Part 1-8 of Eurocode 3 (EC3-1-8) (CEN, 2005), whilst R_{fy} relates to the plastic resistance of the connected dissipative member. It is important to note, however, that EC3-1-8 does not explicitly address the design of diagonal-to-frame gusset plate connections. A number of concepts and recommendations available in the literature can be used to circumvent this issue. The first major gusset design concept concerns the so-called Whitmore section, which, as denoted by Thornton and Lini (2011), allows to spread a brace force through a gusset plate with a 30º angle. This methodology establishes two equivalent dimensions of the gusset plate, namely: i) the Whitmore length, L_W, taken as the distance, orthogonal to the direction of the brace, between both corners of the Whitmore triangles; and ii) the plate buckling length, L_b, taken as the average distance between the brace's physical end and the faces of the beam and column members. By defining an equivalent geometry of the gusset, tension and compression checks of the plate can be conducted, as per Equation (2) (Sabelli, 2006). In the equation, t_p and f_y are the thickness and material yield strength of the plate, respectively, and N is the axial demand on the gusset plate. This demand, as discussed before, should consider material overstrength of the connecting dissipative member (see Equation (1)). The seismic design of these connections should also consider the control of clearance distances in the gusset plate, that aim for sufficient tolerance of large inelastic deformations and end rotations associated with the braces (Hsiao *et al.*, 2012). This clearance is a function of the thickness of the gusset plate, as shown in Figure 2. A thorough discussion of other recommended detailing practices is discussed by Astaneh-Asl et al. (2006).

$$R_d \geq 1.1 \times \gamma_{ov} \times R_{fy} \quad (1)$$

$$\text{Tension: } N \leq t_p L_W f_y$$
$$\text{Compression: } N \leq 0.658^{f_y/f_e} f_y t_p L_W \text{, where } f_e = \pi^2 E\left(1.2L_b/\sqrt{t_p/12}\right)^{-2} \quad (2)$$

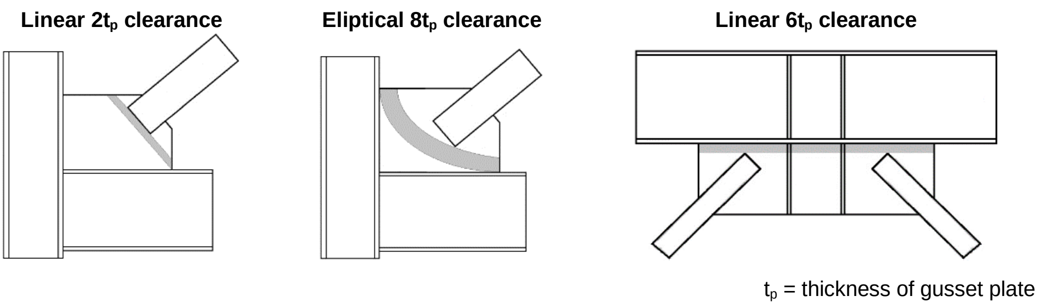

Figure 2. Clearance models for diagonal-to-frame gusset connections (Hsiao et al., 2012).

Population of archetypes

In this study, an extensive group of CBF archetypes was defined, in order to extract conclusions from a representative universe of case study buildings. This was achieved within a framework that encompasses both numerical linear-elastic analysis, using OpenSees, as well as scripted Python verification routines reflecting the design checks of EC8. The process is based on new user-defined information: a given design iteration is tested, compliance or violation of the EC8 requirements is graphically conveyed, and the user may then define a new iteration. Additional design requirements (e.g. construction-related) should be enforced by the user when defining the design iteration. Once the CBF design solution (i.e. member sizes) is established, additional fully-automated tools for the design of connections were developed. Through an optimization procedure, the lightest combination of rectangular plate width and thickness that complies with the imposed design requirements is determined for all connections.

For the current study, a vast suite of steel CBF buildings was defined and seismically designed to EC8 using the aforementioned tool. Several conventional design assumptions were adopted in this process (Elghazouli, 2009), such as: i) column continuity along the height of the building; ii) pinned-ended beams, braces and structure's base; iii) member lengths delimited via centreline intersections. The population of archetypes was designed for two seismic locations in Portugal, namely Porto and Lagos, of by low- and moderate seismicity, respectively. All bracing typologies shown in Figure 1 were considered, in combination with two different plan configurations with 3, 5 and 8 storeys. In both configurations, the first storey height was set at 4.5m, and 3.5m was used for the remaining storey heights. Regarding the adopted in-plan configuration, it varies according to floor area, as well as number and width of beam bays in the transverse and longitudinal directions (see Table 1). In both configurations, the lateral load-resisting system in the longitudinal direction is composed by the two external frames. Internal longitudinal frames were assumed as gravity-carrying systems. The focus of the research study was on the longitudinal building direction. Depending on the seismic location, different numbers of braced spans were adopted in the design, as summarized in Figure 3.

Plan configuration A		**Plan configuration B**	
Overall dimensions *	**Span widths** **	**Overall dimensions** *	**Span widths** **
18 by 12	{6+6+6} by {6+6}	24 by 18	{4.5+5+5+5+4.5} by {6+6+6}
Notes * longitudinal by transversal building in-plan dimension ** {beam spans in the longitudinal frames} by {beam spans in the transversal frames}			

Table 1. Summary of longitudinal and transversal spans (dimensions in meters).

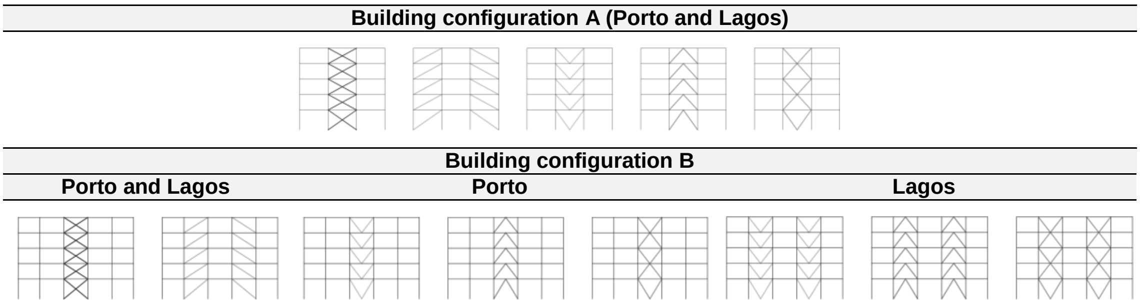

Figure 3. CBF configurations adopted for each seismic location and building configuration.

All LLRS frames were designed to resist gravity and seismic loads according to Eurocode. European IPE and HEA sections were adopted for all beams located in unbraced and braced spans, respectively, whilst HEB and HEM sections were adopted for the columns. Commercial circular hollow sections were adopted for the braces. S275 steel grade was adopted for the beams, diagonals and brace-to-frame gusset plates, whilst S355 was used for the columns. Seismic design was conducted for ductility class DCM of EC8, adopting a behaviour factor of 4 and 2 for diagonal bracings and V-bracings, respectively. Finally, two different design variants were considered for the application of the seismic analysis and design framework. In particular, a specific clause imposed by Eurocode 8 for CBFs was not followed, namely by changing the upper-bound limitations of $\bar{\lambda}$ from 2.0 to 2.5 (Silva *et al*., 2018). The implications of this design criterion modification are discussed in the remaining sections of the paper. A total of 120 CBF archetype buildings were considered herein.

Centreline-to-centreline versus physical brace lengths

Based on the design solutions achieved before, a number of observations merit discussion, such as the effect of these plates on the real dimensions of the diagonals. In this context, the typical reduction of brace lengths, from the centreline-to-centreline (L_{CL}) assumption made during the frame design stage to the physical end-to-end member length (L_R), was quantified, as summarized in Figure 4. The results are shown using boxplots, in which the median, 25% and 75% quartiles, and the inner fences for outlying data points are shown.

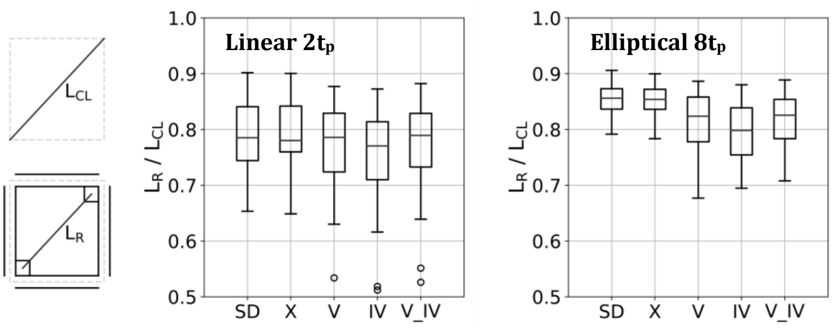

Figure 4. Effect of gusset plate on brace length reduction.

Figure 4 allows concluding about the significant reductions in diagonal lengths from L_{CL} to L_R. With the linear $2t_p$ clearance method, length reductions were in the order of 60% to 90% (median values of around 75%). In turn, with the use of the elliptical clearance, less pronounced brace length reductions were obtained. This implies that, since the length of members was lower than the conventional design assumption, the actual buckling capacity is larger than that estimated at the design stage. If a more accurate brace length would have been adopted instead, and provided that the critical design criteria would be related to compression or buckling checks. lower brace-sizes would be permitted,

Effect of the flexibility of diagonal-to-frame connections

According to Hsiao et al. (2012), the out-of-plane rotational behaviour of brace-to-frame gusset connections can be simulated trough a rotational spring, located at the physical end of the brace.

The equivalent geometry and material properties of the plate are used to compute a bilinear moment-rotation relationship. This model was applied to every diagonal-to-frame connection of every archetype and each brace member, with a length equal to the physical length of the diagonal, was simulated using the modelling approach by Karamanci and Lignos (2014). Regarding the boundary conditions at both ends of the member, a total of four scenarios were considered: i) fully-pinned; ii) fully-fixed; iii) out-of-plane rotational springs; and iv) in-plane rotational springs. Across all cases, the members were subjected to increasing levels of axial shortening demands. Buckling loads for pinned-pined (N_{P-P}), fixed-fixed (N_{F-F}), and real boundary condition (N_R) models were computed and compared with the buckling curves of EC3, as shown in Figure 5. The analysis shown in the figure indicate the high similarity between the curve with a pinned-pinned model and the real out-of-plane buckling behaviour of the diagonal. A slight reduction on the slenderness levels is visible, meaning that, due to the real out-of-plane boundary condition behaviour, members are less slender than with a fully-pinned connection assumption. Also, for the in-plane comparison with a fixed-fixed model, one may infer that the level of mismatch is above that of the out-of-plane comparisons. By accounting for the influence of the real boundary conditions, the normalized slenderness levels increased with respect to a fixed-fixed assumption and the buckling reduction factors associated with the latter were found to be slightly conservative. This is related to the fact that, even though the in-plane rotational stiffness of the gusset plate is very high, it is not infinite as per the fully-fixed assumption.

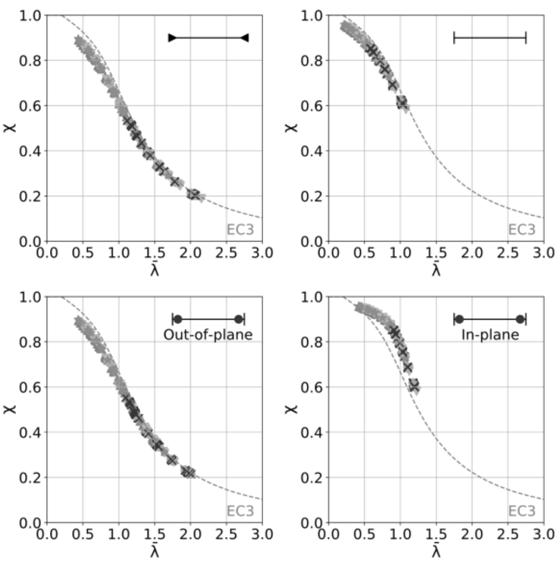

Figure 5. Influence of boundary conditions on buckling reduction factors (elliptical $8t_p$ gusset design).

It is important to note that, even though several frame designs were conducted with a modified design clause, in particular, allowing diagonal's normalized slenderness below 2.5, when both the physical length and the behaviour of the gusset plates is accounted for, the maximum levels of this parameter were around 2.0. This important observation points towards the possible relaxation of the limit currently specified in Eurocode, without any significant reduction in the seismic performance of the CBF, provided that conventional design assumptions (i.e. centreline-to-centreline pinned-ended diagonals) are made during the frame design stage. Furthermore, it should be recalled that EC8 prescribes that the seismic design of X-CBFs be conducted by limiting the minimum level of normalized slenderness to 1.3. Even though this was considered during the design process of the CBF archetypes, a centreline-to-centreline diagonal length and fully-pinned connections at the extremities of the diagonal were assumed. However, as Figure 5 denotes, since the combined effect of a member's length reduction and real boundary condition behaviour entails a generalized reduction in the out-of-plane slenderness, the lower limit of 1.3 was, in certain cases, violated. This observation highlights the need for a more explicit consideration of these two factors at the frame design level, perhaps by considering slenderness correction factors that reflect the results shown so far.

Normalized slenderness correction in EC8

As established so far, two important aspects influence the level of consistency between the design assumptions and the actual behaviour of the CBF diagonal members. In order to correct the level of mismatch between the conventional design assumption and more realistic conditions, the results obtained regarding both incompatibility aspects can be put together. Accordingly, a factor (Λ) was proposed and implemented, in order to correct the design normalized slenderness of the brace (centreline length, fully-pinned boundary conditions, $\bar{\lambda}_{CL,P-P}$), to the real value, as per Equation (3) and Table 2. This correction parameter was calculated via multi-variable regression procedures, as a function of $\bar{\lambda}_{CL,P-P}$ the inclination of the diagonal, α, CBF typology, clearance model and brace buckling plane of interest. A comparison of the measured Λ with those obtained with the proposed expression is shown in Figure 6. Two metrics of prediction agreement are shown, namely the R^2 parameter and the normalized root mean square error, computed according to Equation (4).

$$\bar{\Lambda}_R = \Lambda \cdot \bar{\lambda}_{Cl,p-p}, \text{ where } \lambda = C_1 \cdot \bar{\Lambda}_{Cl,p-p}{}^{C_2} \cdot A^{c_3} \text{ and } \alpha \text{ in degrees} \quad (3)$$

$$\text{NRMSE} = \sqrt{\sum_{i=1}^{n} \left(\frac{\Lambda_{\text{predicted}} - \Lambda_{\text{measured}}}{\Lambda_{\text{measured}}} \right)^2 / \text{N}}, \text{ where n} = \text{\# of data points} \quad (4)$$

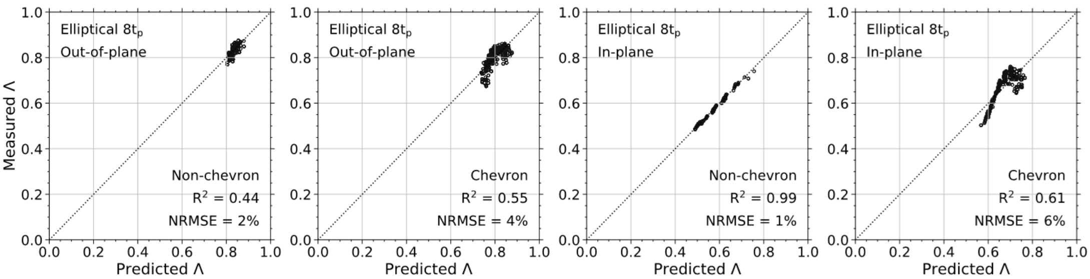

Figure 6. Measured versus predicted Λ values for the population of steel CBF archetypes (elliptical $8t_p$ gusset design)..

Parameters of Equation (3)		Out-of-plane		In-plane	
		Non-chevron	Chevron	Non-chevron	Chevron
Linear $2t_p$	C_1	8.224×10^{-2}	9.973	1.947×10^{-1}	8.599
	C_2	1.164×10^{-1}	1.533×10^{-1}	-3.943×10^{-1}	-1.609×10^{-1}
	C_3	6.138×10^{-1}	-6.533×10^{-1}	3.620×10^{-1}	-6.482×10^{-1}
	NRMSE	3%	6%	1%	8%
Elliptical $8t_p$	C_1	4.075×10^{-1}	8.919×10^{-1}	4.786×10^{-1}	8.111×10^{-1}
	C_2	5.448×10^{-2}	1.207×10^{-1}	-4.532×10^{-1}	-2.113×10^{-1}
	C_3	1.939×10^{-1}	3.143×10^{-2}	1.264×10^{-1}	-4.224×10^{-2}
	NRMSE	2%	4%	1%	6%

Table 2. Proposed parameters for normalized slenderness correction factor.

As demonstrated in Figure 6, the values of Λ range between 0.5 and 0.9, depending on the combination of CBF typology, clearance model and buckling plane of interest. As also shown in the figure, the agreement between the predicted and the measured values of Λ obtained with the proposed expression was reasonably accurate across the entire universe of archetypes.

Furthermore, “average errors” (i.e. NRMSE) between 1% and 8% were found across the multiple scenarios, entailing, in the authors’ opinion, an acceptable compromise between accuracy and practicality of the methodology.

Conclusions

This study addressed a number of practical aspects regarding the seismic design of steel concentrically-braced frames (CBFs) to Eurocode 8. This was attained through a comprehensive population of CBF building archetypes. Several evaluations were conducted to validate conventional frame-design assumptions that do not explicitly account for the contribution of diagonal-to-frame gusset connections. The following main conclusions were obtained:

- The design and nonlinear numerical modelling of the diagonal-to-frame gusset plates allowed identifying the influence of the connection on the normalized slenderness of the brace. In specific, this effect is a function of brace centreline length reductions due to the presence of the gusset plate, in conjunction with boundary conditions that differ from idealised scenarios;
- By superimposing the aforementioned aspects, a correction factor, Λ, was proposed. This factor aims to correct the incompatibility of the normalized slenderness, estimated under centreline length and fully-pinned brace assumption, $\bar{\lambda}_{CL,P-P}$, to the real value, $\bar{\lambda}_{R}$. Λ was shown to depend on $\bar{\lambda}_{CL,P-P}$, brace inclination, CBF typology and connection clearance model;

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