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SEISMIC BEHAVIOUR OF STEEL CBFs DESIGNED IN ACCORDANCE WITH EN 1998-1(2005) AND prEN 1998-1-2(2024)

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Abstract

EN 1998-1(2005) provides the rules for the seismic design of buildings and is currently under revision for updates and amendments. As part of this update, the provisions for steel concentrically braced frames (CBFs) have been deeply revised to enhance their seismic performance. This study aims to compare the seismic behaviour of high-dissipative inverted-V CBFs designed according to the current generation, i.e., EN 1998-1(2005), and the latest drafts of the revised Eurocode 8 standards, i.e., EN 1998-1-1(2023), EN 1998-1-2(2024). The seismic response has been evaluated by means of nonlinear dynamic analyses carried out on planar models developed in OpenSees. The preliminary results of the study show that the upcoming version of Eurocode 8 leads to an overall better seismic behaviour of the examined inverted-V CBFs, promoting the exploitation of the inherent ductility of the structure along with a significant reduction of the total material consumption.

Keywords: concentrically braced frames, Eurocode 8, seismic design, steel structures, ductility demand.

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1 INTRODUCTION

Eurocodes, namely the set of standards providing the structural design rules in Europe, are currently under revision for updates and amendments. Among these, the current EN 1998-1(2005) [1], namely the standard devoted to the seismic design of structures, has been reorganised and split into two separate parts: EN 1998-1-1(2023) [2] and EN 1998-1-2(2024) [3], which are currently available as intermediate drafts (i.e., "pr" versions). Hence, in the new generation of Eurocode 8, the design rules common for all structural systems and materials are provided by EN 1998-1-1(2023), while the material-dependent and specific seismic load-resisting system provisions are given by EN 1998-1-2(2024). Many studies [4-14] have contributed to proposing improved design rules to enhance the seismic performance of Eurocode-compliant steel seismic resistant systems. In this framework, the seismic design rules for steel CBFs, which are widely used in seismic regions due to their high lateral stiffness and strength, have been substantially revised [15-21] in the new generation of Eurocode 8. In order to preliminarily assess the effectiveness of the new design rules for high-ductile inverted-V braced frames, this paper presents the initial findings of a study conducted on two inverted-V CBFs designed in accordance with EN 1998-1(2005) and EN 1998-1-2(2024), alternatively. The influence of the seismic design provisions provided by the two generations of Eurocode 8 is first discussed in terms of design outcomes, i.e., material consumption, and then in terms of seismic performance, which is evaluated through nonlinear time history analyses of the two designed frames.

2 INVERTED-V CBFs DESIGN RULES: EN 1998-1(2005) VS EN 1998-1-2(2024)

The seismic design rules provided for high-dissipative inverted-V CBFs, namely DCH and DC3 as per EN 1998-1(2005) and EN 1998-1-2(2024), respectively, are briefly compared in this section to facilitate the reading of the article. In the first generation of Eurocode 8, inverted-V CBFs in DCH were designed assuming a value of the behaviour factor q equal to 2.5. On the contrary, in accordance with EN 1998-1-2(2024), a value of q = 4 can be considered for the seismic design of inverted-V CBFs in DC3. Both the first and second generations of Eurocode 8 mandate the use of a tension-compression model for the braces to estimate the seismic effects on the chevron braced frames. In other words, both tension and compression diagonals should be considered in the structural analysis, and the nominal buckling resistance of the braces $N_{b,Rd}$ should be verified against the axial force due to earthquakes $N_{Ed,br}$. Both codes limit braces' global and local slenderness to prevent severe degradation and potential low-cycle fatigue fracture phenomena under cyclic loads. Indeed, for both DCH and DC3 the normalised slenderness of braces $\overline{\lambda}=\sqrt{N_{pl,Rd}/N_{cr,br}}$, where $N_{pl,Rd}$ and $N_{cr,br}$ are the nominal plastic resistance and the Euler critical load, respectively, should be lower than 2. Regarding the local slenderness, EN 1998-1(2005) allows only Class 1 cross-section as per EN 1993-1-1 [22] for braces in DCH. At the same time, while the cross-section of diagonal bracings should be Class 1 in DC3, more stringent requirements are provided by EN 1998-1-2(2024) in the case of circular, rectangular, or square hollow sections [23]. To promote a uniform dissipative behaviour of the diagonals along the building height, EN 1998-1(2005) requires controlling that the maximum overstrength ratio of the braces in tension, $\Omega_{d,max}$ = max($N_{pl,i}/N_{Ed,i}$), being $N_{pl,i}$ and $N_{Ed,i}$ the i-th story brace plastic resistance and axial force in the seismic design combination, respectively, does not differ from the minimum value $\Omega_{d,min}$ = min($N_{pl,i}/N_{Ed,i}$) by more than 25%. EN 1998-1-2(2024) provides a similar recommendation, but to be controlled is the ratio between the maximum $\Omega_{b,max}$ = max($N_{b,Rd,,i}/N_{Ed,i}$) and minimum $\Omega_{b,min}$ = min($N_{b,Rd,,i}/N_{Ed,i}$) buckling overstrength coefficients, which should be lower than 1.25 along the building height, with the unique exception of the top storey. As an additional recommendation, the diagonal bracings of the top storey in DC3 may be excluded from the set of dissipative braces and designed to behave elastically under the seismic design combination, promoting a shear-type behaviour of the CBFs [16-17]. EN 1998-1(2005) requires a hybrid approach for the design of non-dissipative members. Indeed, the resistance and stability of columns belonging to the braced bays should be checked against the axial force N_{Ed} calculated as:

$$N_{Ed}=N_{Ed,G} \text{ "+" } 1.1\, \gamma_{ov}\, \Omega_{d,min}\, N_{Ed,E} \quad (1)$$

where $N_{Ed,G}$ and $N_{Ed,E}$ are the axial forces in the column due to non-seismic and seismic actions, respectively, calculated in the seismic design combination, while γ_{ov} = 1.25 is the material overstrength factor. Beams should be designed to resist (i) all non-seismic actions without considering the intermediate support given by the diagonal bracings, and (ii) the internal forces calculated considering the nominal plastic resistance $N_{pl,Rd}$ in the braces in tension and the post-buckling resistance $\omega_{pb}N_{pl,Rd}$ for the braces in compression, with ω_{pb} = 0.30.

According to EN 1998-1-2(2024), the following conditions should be considered to design beams and columns in DC3:

(i) the most unfavourable combination of axial force N_{Ed}, bending moment M_{Ed}, and shear force V_{Ed} calculated as follows:

$$\begin{aligned} N_{Ed}&=N_{Ed,G} \text{ "+" } \omega_{rm}\, \omega_{sh}\, \Omega_{d,min}\, N_{Ed,E} \\ M_{Ed}&=M_{Ed,G} \text{ "+" } \omega_{rm}\, \omega_{sh}\, \Omega_{d,min}\, M_{Ed,E} \\ V_{Ed}&=V_{Ed,G} \text{ "+" } \omega_{rm}\, \omega_{sh}\, \Omega_{d,min} V_{Ed,E} \end{aligned} \quad (2)$$

where ω_{sh} = 1.1 is the strain hardening factor of the dissipative zones, while the value of the material overstrength coefficient ω_{rm} depends on the steel grade used in the dissipative zones;

(ii) the internal forces obtained considering the expected tensile resistance, $\omega_{rm}N_{pl,Rd}$, in the braces in tension and the expected post-buckling resistance, $\omega_{pb}\omega_{rm}N_{b,Rd}$ for the braces in compression.

An additional uniform bending moment in the direction of the braced bays, equal to 0.20 times the nominal plastic moment resistance of the column's gross section, should be included in the verification of columns under condition (iii). To avoid the use of strong but deformable beams [15], EN 1998-1-2(2024) requires checking that the beam-to-brace stiffness ratio K_F, namely the ratio between the flexural stiffness k_b of the brace-intercepted beam and the vertical stiffness of the bracings $k_{br,v}$, is greater than 0.2:

$$K_F=\frac{k_b}{k_{br,v}} \geq 0.2 \quad (3)$$

3 STRUCTURAL ARCHETYPES

The structural archetype is a six-storey residential steel building with perimeter inverted-V CBFs in both directions, as depicted in Figure 1. The gravity frame system is designed in accordance with EN 1993-1-1. The seismic design of the chevron CBFs has been carried out according to EN 1998-1(2005) and EN 1998-1-2(2024), alternatively, following the design rules given in DCH and DC3, respectively. The elastic and reduced response spectra are calculated according to the equations provided in EN 1998-1-1 (2023), assuming a soil class C and a behaviour factor q = 2.5 in DCH and q = 4.0 in DC3, in line with the provisions of the relevant seismic design code. S355 steel grade is used for both dissipative (i.e., braces) and non-dissipative (i.e., beams and columns) members. Table 1 summarises the cross-section of the designed frames; cold-formed circular hollow sections are adopted for braces, while wide flange cross-sections are used for beams and columns.

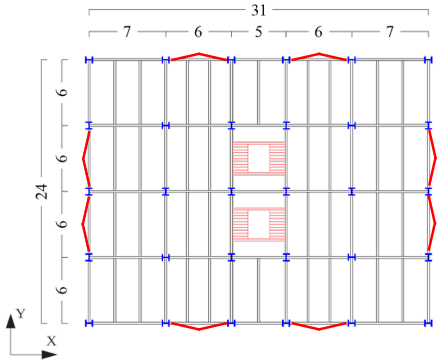

Figure 1. Plan layout of the six-storey building - Dimensions in meters

Table 1. Cross-sections of structural members

Storey	EN 1998-1(2005)			EN 1998-1-2(2024)		
	Braces (d x t)	Beams	Columns	Braces (d x t)	Beams	Columns
6	168.3 x 6	HEB 360	HEB 550	168.3 x 8	HEB 360	HEB 280
5	177.8 x 10	HEM 360	HEB 550	139.7 x 8	HEM 400	HEB 280
4	193.7 x 12	HEM 450	HEB 600	168.3 x 8	HEM 400	HEM 280
3	219.1 x 12.5	HEM 500	HEB 600	168.3 x 8	HEM 400	HEM 280
2	244.5 x 12	HEM 550	HE 600x399	168.3 x 10	HEM 500	HEM 320
1	273 x 12	HEM 600	HE 600x399	177.8 x 12.5	HEM 650	HEM 320

Figure 2 shows the material consumption of the two designed frames, given in terms of the structural weight of braces, beams, and columns of the seismic-resistant system in direction X (see Figure 1). It can be observed that, due to the use of a larger q factor in the design procedure, the material consumption of braces in DC3 is lower compared to DCH. As a consequence of using smaller cross-sections for braces, although the capacity design principles in DC3 are more stringent with respect to DCH for non-dissipative members, the material consumption of beams is almost equal to 18 tons for both frames, while the steel consumption for columns is equal to 16 and 24 tons in DC3 and DCH, respectively. Thus, the EN 1998-1-2 (2024) provisions for the examined DC3 inverted-V CBFs resulted in a 20% reduction in total material consumption compared to the DCH-compliant frame.

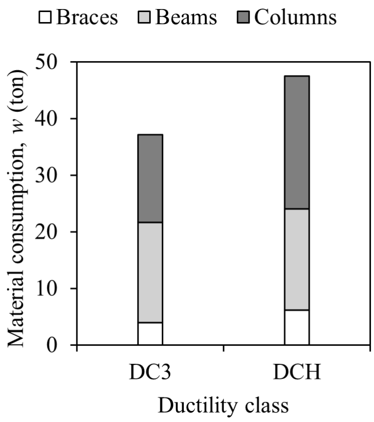

Figure 2. Material consumption of the designed frames

4 STRUCTURAL MODELLING

Planar models have been developed in OpenSees [24] to evaluate the seismic response of the designed frames, as depicted in Figure 3. The nonlinear behaviour of braces, beams, and columns is simulated using force-based beam-column elements [25]. Moreover, a fibre modelling approach is used for the cross-section of structural members, assigning the Steel02 [26] material model with the expected mechanical properties of the steel (S355). The brace fracture due to low-cycle fatigue phenomena is considered by using the fatigue material model [24], and the parameters are estimated in accordance with past works [27]. To accurately reproduce the post-buckling behaviour of diagonal members, each brace has been discretised into six elements, and an initial geometrical out-of-plane imperfection with a maximum value equal to 1/1000 of the effective length of the member has been assigned to bracings, as suggested in previous studies [28-29]. Rotational springs have been positioned at the brace ends to simulate the out-of-plane behaviour of the gusset plates, while rigid links are used for the column and beam's end zone, following the procedure described in [30]. The in-plane rigidity of the slab is simulated using rigid link constraints. At the same time, a leaning column representing the gravity columns tributary to the braced frames has been included to take into account the P-Δ effects in the numerical model. The Rayleigh damping approach with tangent stiffness has been adopted to estimate the damping forces in the nonlinear time history analyses, assigning a damping ratio of 2% at the first and second vibration modes of the investigated frame.

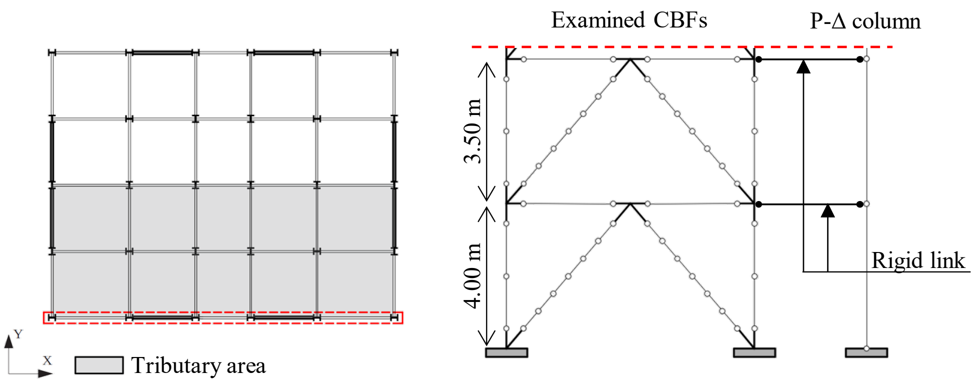

Figure 3. Modelling assumptions in the numerical model

5 SELECTED RECORDS

This section describes the criteria used to select the fourteen ground motions to evaluate the seismic behaviour of the designed frames. The seismic records were individually scaled to match the target response spectrum at the Near-Collapse (NC) limit-state, i.e. the return period T_R = 1600 years [3], and such that (see Figure 4) the following compatibility criteria provided by the EN 1998-1-1(2023) were satisfied: (i) the ratio between the average spectrum of the set of ground motions and the target spectrum falls in the range from 0.75 to 1.3 and has an average value larger than 0.95 in the range of period of interest (i.e., [0.2 T_1, 1.5 T_1], being T_1 the first-mode vibration period of the frame), (ii) in the same range, the response spectrum of each accelerogram does not fall below 50% of the target spectrum, and (iii) the suite of selected accelerograms does not contain two components of the same record, as well as no more than two records from the same earthquake.

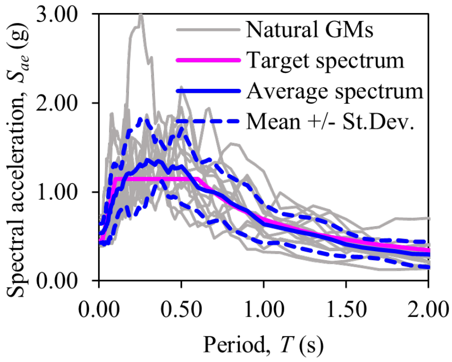

Figure 4. Record selection

6 SEISMIC PERFORMANCE ASSESSMENT

Nonlinear time history analyses are performed to compare the seismic performance of the examined frames at the NC limit state. Figure 5a depicts the mean values of maxima and minima interstorey drift ratios (*IDR*s) obtained from the dynamic analyses for both DC3- and DCH-compliant CBFs. Although the frame in DC3 is characterised by larger values of *IDR*s along the building's height with a tendency of damage concentration at story 3 (min IDR = -1.7%) with respect to the frame compliant with EN 1998-1(2005), the new seismic design rules in the latest draft of the second of Eurocode 8 leads to a satisfactory seismic response. The mean values of the brace ductility demand, calculated in tension as the ratio d_T/d_{pl}, being d_T the axial elongation of the brace and d_{pl} the corresponding axial displacement at yield, and in compression as the ratio d_C/d_b, where d_C is the axial shortening of the brace and d_b is the axial displacement at brace buckling, are given in Figure 5b. It is worth mentioning that the frame in DCH is characterised by a very limited plastic engagement of diagonal bracings in tension, as confirmed by the values of the brace ductility demand, which range between 0.81 and 1.27. On the other hand, the new design rules in DC3 resulted in significantly larger values of the brace ductility demand along the building height, with peak values equal to -8.15 in compression and 4.43 in tension. As a conclusive remark, it can be recognised that the design rules provided by EN 1998-1-2(2024) lead to an overall better seismic performance of the high-ductile frame, promoting the exploitation of the inherent ductility of the structure along with a significant reduction of the total material consumption (see Figure 2) with respect to frame compliant with EN 1998-1(2005).

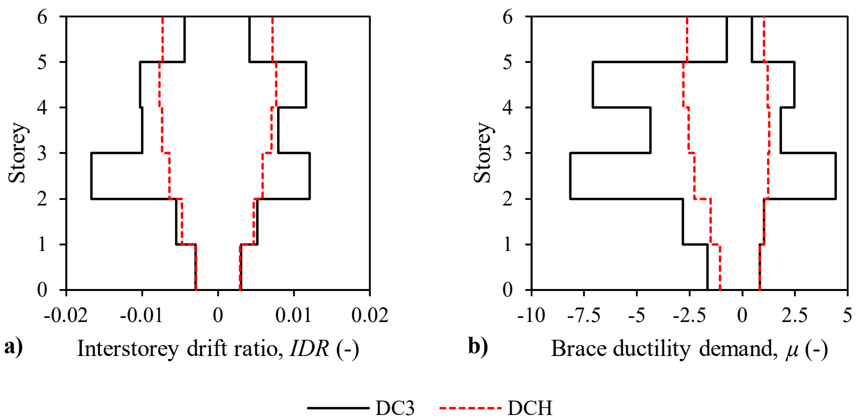

Figure 5. Mean values of peak a) interstorey drift ratios, b) brace ductility demand

7 CONCLUSIONS

The initial findings of a numerical study comparing the effectiveness of seismic design rules for high-ductile inverted-V CBFs, as provided in the first generation and the latest draft of the second generation of Eurocode 8, are discussed in this paper. For this purpose, a six-storey residential building equipped with inverted-V CBFs in both directions has been designed in accordance with EN 1998-1(2005) and EN 1998-1-2(2024), alternatively, following the design rules given in DCH and DC3. The outcomes of the study show that the upcoming version of Eurocode 8 results in an overall better seismic performance of the examined inverted-V CBFs, with the DC3-frame characterised by a larger energy dissipation capacity, together with a significant reduction in total material consumption compared to the frame in DCH. Although these preliminary results have provided initial evidence of the effectiveness of the rules given by EN1998-1-2(2024), further research considering different structural archetypes, brace configurations, and advanced numerical analyses is needed to thoroughly investigate the global and local seismic performance, as well as to identify potential area of improvements for the seismic design of high-ductile inverted-V CBFs.

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