Journal of Constructional Steel Research 125 (2016) 142–163

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Plastic analysis-based seismic design method to control the weak storey behaviour of concentrically braced steel frames

D.B. Merczel [a,b], J.-M. Aribert [a], H. Somja [a], M. Hjiaj [a,*]

[a] LGCGM/Structural Engineering Research Group, Institut National des Sciences Appliquées de Rennes, 20 Av. des Buttes de Coësmes 35708, Rennes Cedex 7, France
[b] Department of Structural Mechanics, Budapest University of Technology and Economics, Műegyetem rkp. 3-9, Budapest 1111, Hungary

ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form 1 May 2016
Accepted 15 May 2016
Available online 22 June 2016

Keywords:
Concentrically braced steel frame
Seismic design
Eurocode 8
Weak story mechanism
Plasticity-based design method

ABSTRACT

This article focuses on the likelihood of the weak storey behaviour and the weak storey collapse of diagonally concentrically braced frames designed according to Eurocode 8 provisions. The emphasis is primarily put on the nature and development of the weak storey behaviour in order to designate the effects that shall be taken into account in an effective design procedure. In a second stage, the focus is on developing supplementary conditions to Eurocode 8 based on plastic analysis that can enhance the designs by preventing the occurrence of weak storeys.

1. Introduction

Steel concentrically braced frame (hereinafter CBF) systems are economic forms of providing lateral resistance to high-rise buildings. Owing to the geometry, the lateral forces are resisted by truss action resulting mainly axial effects in the participating members. The truss behaviour incorporates large stiffness, which limits the lateral drifts and low-frequency vibrations in the braced buildings, and therefore provides occupancy comfort and impedes damages in the non-structural parts. Therefore, CBFs may be favoured over moment resisting frames in non-seismic design states or for low return period seismic actions. However, in the case of severe earthquakes, CBFs are known to have a bad performance [1–3].

According to the principles of capacity design, structures are to be provided with large plastic ductility capacity as this allows the reduction of the design horizontal forces. Although the steel material may assure considerable structural ductility, it is also necessary to distribute the inelastic deformations along the height of the building. In design, the expected behaviour of a CBF corresponds to the global plastic collapse mechanism depicted in Fig. 1a. In this case, the compression braces are buckled, and all the tensile ones are undergoing plastic deformation. This plastic mechanism provides the largest dissipation and lateral drift capacity as all the storeys of the building equally contribute.

Conversely, CBFs are susceptible to exhibit weak storey collapse by developing a localised storey mechanism as it is shown in Fig. 1b. In the weak storey phenomenon, the plastic deformations and drifts are localised on one or a limited number of storeys. Evidently, the dissipative and drift capacity of the weak storeys is by far inferior to the capacity of the whole CBF. Furthermore, the weak storey behaviour incorporates a significant bending of the columns, which may result in plastic hinges at the top and the bottom of the bent columns. The weak storey behaviour is unfavourable as it results in low seismic performance and may even lead to early collapse; therefore, it needs to be prevented.

In the following sections, the corresponding parts of EN 1998-1[4] (Eurocode 8 or EC8) will be summarised, various CBFs designed according to this standard will be presented, and their performance evaluation will be carried out via incremental dynamic analysis (IDA). A deeper insight into the observed weak storey behaviour will provide the basis for the determination of the most influential effects on the weak storey behaviour. Finally, new design criteria, based on plastic analysis, will be defined, which will be utilised to enhance the performance of the CBFs investigated in previous sections.

2. Eurocode 8 design of CBFs

In the design of building structures, Eurocode 8 provides two basic concepts for the seismic analysis. Earthquake-resistant buildings can either have a low-dissipative or a dissipative behaviour. In a dissipative structure, controlled inelastic deformations are expected to dissipate significant energy and damp the response of the structure, and in the

* Corresponding author.
E-mail address: mohammed.hjiaj@insa-rennes.fr (M. Hjiaj).

http://dx.doi.org/10.1016/j.jcsr.2016.05.008

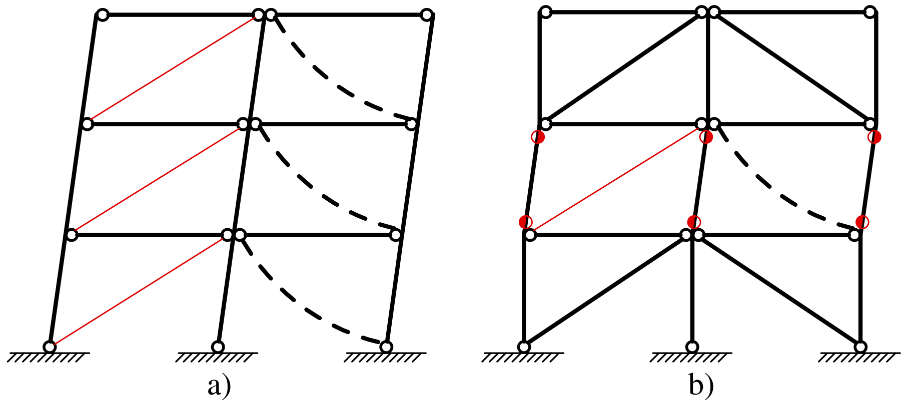

Fig. 1. Geometry model of collapse mechanism. (a) Global mechanism, (b) local mechanism.

meantime to provide adequate ductility to meet displacement demands. The behaviour factor, q, that accounts for this effect is 4 for CBFs, which is the lower boundary of high ductility class (DCH) structures. The seismic action is divided by the behaviour factor and the members are designed to resist only this reduced-intensity design action.

In Eurocode 8, the criteria for the verification of dissipative structures follow the capacity design philosophy. For the design analysis, only a reduced-intensity seismic action is considered, as a substantial part of the seismic input energy is expected to be dissipated by plastic deformations. Plastic deformations are strictly required to occur in dissipative members that are to be designed with sufficient ductility, whereas the yield or collapse of non-dissipative zones is to be evaded. To ensure the elastic behaviour of non-dissipative zones, their seismic design is required with a sufficient overstrength. In CBFs, the braces are meant to be the dissipative members. Therefore, CBFs are designed so that the yield of the diagonals takes place before the failure of the columns, the beams and the connections.

For the sake of homogeneous dissipative behaviour, a simultaneous yield of the braces on every storey has to be ensured. Eurocode 8 aims to promote this by a condition given for the overstrength factors, Ω_i, realised on the different storeys, making them closely uniform. It needs to be verified that the maximum overstrength does not differ from the minimum by more than 25%.

$$\frac{\Omega_{\max}}{\Omega} \leq 1.25 \tag{1}$$

where

$$\Omega = \min \Omega_i \tag{2}$$

$$\Omega_{\max} = \max \Omega_i \tag{3}$$

$$\Omega_i = \frac{N_{pl,Rd,i}}{N_{br,Ed,i}} \tag{4}$$

For the design of columns and beams, Eurocode 8 requires the fulfilment of the following condition:

$$N_{Rd}(M_{Ed}) \geq N_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \Omega \cdot N_{Ed,E} \tag{5}$$

where $N_{Rd}(M_{Ed})$ is the axial resistance in accordance with Eurocode 3, taking into consideration the interaction with the design bending effect M_{Ed}. $N_{Ed,G}$ and $N_{Ed,E}$ are the axial forces due to the non-seismic and the seismic actions, respectively. The material overstrength factor, γ_{ov}, accounts for the random variability of the material properties. Its recommended value is 1.25, but it may be varied in National Annexes. The amplification coefficient 1.1 represents the increase of the yield stress of the dissipative members due to strain hardening. The total overstrength, $1.1\gamma_{ov}\,\Omega$, is a way to account for the resistance reserve of the diagonal members. In principle, it ensures that the resistance of the non-dissipative members is adequate until the plastic yield of the diagonals.

In addition, Eurocode 8 defines limitations to the relative slenderness:

$$\bar{\lambda} \leq 2.0 \tag{6}$$

and for X-braced configurations also:

$$1.3 \leq \bar{\lambda} \tag{7}$$

The upper bound defined in Eq. (6) is imposed to prevent the rapid degradation of the resistance of the braces. Furthermore, this limits the plastic out-of-plane deformation of gusset plates, which are prone to low-cycle fatigue fracture. The lower bound Eq. (7) assures the sufficient flexibility of the diagonals in compression.

With its requirements, Eurocode 8 assumes and attempts to promote the development of the global plastic mechanism. However, Eurocode 8 criteria are based on the elastic response of the structure subjected to the reduced-intensity seismic action via the q-factor. These may not be well adapted to control the inelastic response, particularly if the CBF exhibits a weak storey behaviour. That is to say, in an elastic analysis, due to the truss action of the bracing, only negligible bending can be expected. On the contrary, the columns in a weak storey response are subjected to significant bending, so the requirement imposed on the axial resistance of the columns, Eq. (5), may not be satisfactory to provide adequate column sections. In a weak storey response, the axial forces of the braces may also be different from the ones obtained by elastic analysis; therefore, the uniformity condition of the storey overstrength factors, Eq. (1), may be violated.

The drawbacks related to the Eurocode 8 design of CBF have been addressed before by various authors. Elghazouli [1] deals with the main behavioural issues involved in the seismic design of typical forms of concentrically braced frames. Tremblay [5] also gives a comprehensive description of the seismic behaviour of CBFs and suggests novel additional bracing configurations that may favour the global mechanism. Martinelli et al. [6] apply the tension only concept of EC8 while proposing a new strategy based on the definition of a set of static equivalent seismic forces, computed from response spectrum analysis. Having observed the relevance of the resistance reserve provided by the columns, Elghazouli [7] proposes that the ratio of the sum of the horizontal stiffness provided by the continuous columns and the axial stiffness of the brace on every floor shall be kept sufficiently high to prevent the localisation of the ductility demand on a weak storey. In their articles, Longo et al. [8,9] and Brandonisio et al. [2] highlight certain