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Imperfection amplitudes for nonlinear analysis of open thin-walled steel cross-sections used in rack column uprights

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ABSTRACT

When numerical models are used to predict behaviour of open thin-walled steel cross-sections, the nonlinear analysis results can be influenced by the magnitudes introduced as initial imperfection. At present, a wide range of values is considered in research concerning this topic. This paper explores up to what point the nonlinear analysis results are sensitive to the choice of imperfection magnitudes and attempt to refine the spectrum of magnitudes that should be used. The study focuses on rack uprights (with and without perforations) under compression and the numerical model has been validated with experimental tests conducted by the authors. Three different column lengths have been selected to reproduce a mainly local, distortional and global failure mode, so that coupled instabilities have not to be considered in this case. The results show that the ultimate load and collapse mode are both sensitive to imperfection amplitude, mainly in the case of distortional buckling.

1. Introduction

Computational methods have become an efficient and robust tool for structural analysis. In particular, the finite element method (FEM) is one of the most widely used methods; which is probably due to its capability to include the features of the real behaviour of structures in the numerical modelling.

The FE results are sensitive to many factors; such as the definition of the geometry and material, element type and mesh selected, loads and boundary conditions applied, analysis type, and solver control; among others [1]. The aim of this paper is not focussing on the global FE model implementation, but on a specific issue: equivalent geometrical imperfection magnitudes to be used to tackle the instability of cold-formed steel structural members subject to compression; specifically addressed to nonlinear analysis (GMNIA) of uprights.

The conventional procedure in collapse modelling consists of introducing the displacements produced by the critical buckling mode, conveniently scaled, as initial imperfection for use in subsequent nonlinear analysis. An equivalent imperfection magnitude is commonly used, which includes the effects of the material and geometrical imperfections and residual stresses owing to manufacturing process as well as possible load eccentricities. This article intends to show that the nonlinear analysis can give a prediction of the behaviour of the upright near or far from reality depending on the size of equivalent geometric imperfection introduced in the model. Since, as seen through the literature on the subject, a wide range of values is used by different authors, it is worth analysing the importance of this factor on the numerical result.

In the present numerical imperfection sensitivity analysis the range of imperfection values tested covers most of those cited in the research literature on this matter. In order not to limit the scope of the analysis, perforated (racks) and non-perforated sections have been considered. Results of experimental tests carried out by the authors' research group have been used as a

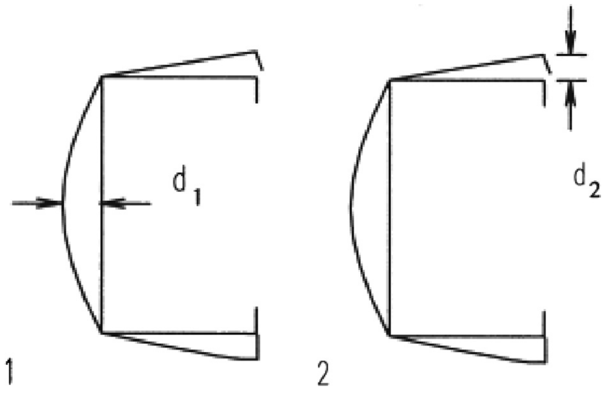

Fig. 1. Definition of geometric imperfections according to [2].

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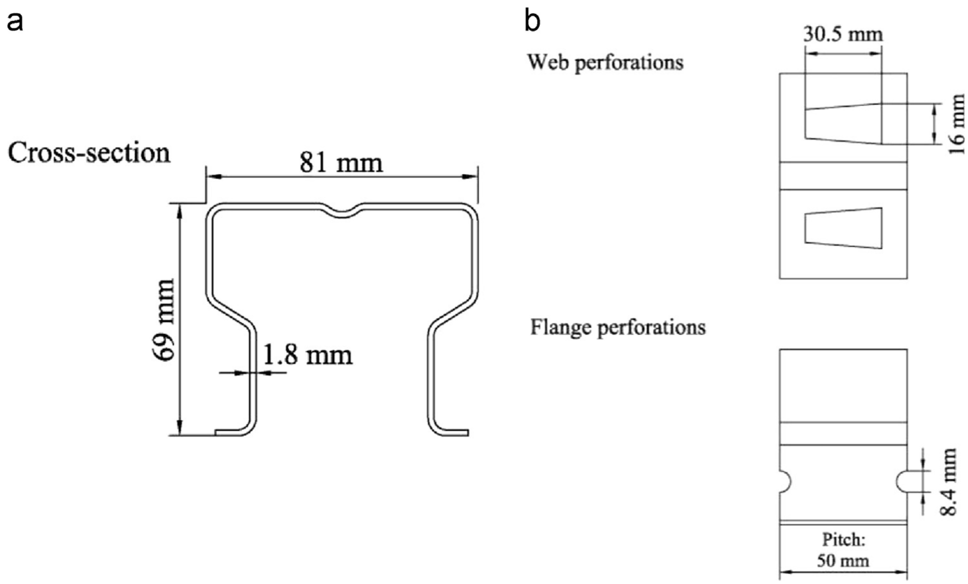

Fig. 2. (a) Main dimensions of the cross-sections. (b) Storage rack with periodic perforations in web and flanges.

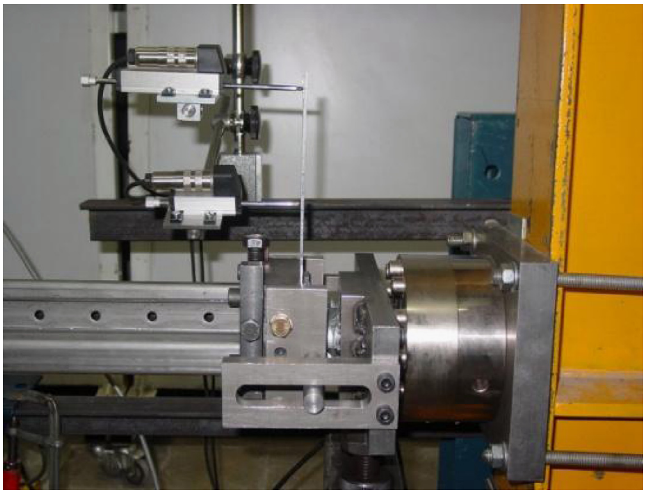

Fig. 3. Compression test. Experimental setup.

reference for calibration and validation of numerical model. Conclusions regarding influence and fitting of imperfection magnitudes analysed will be derived from this study.

2. Literature review on numerical imperfections

The equivalent geometric imperfection sizes used in this field can be divided into two groups: those used in predominantly sectional failure modes (local-L and distortional-D) and those used when the failure mode is mainly global. It may be said, in simplified form, that the first would be suitable for the analysis of columns of short and intermediate length, and the latter for long column lengths.

In sectional failure modes (L, D) initial imperfection magnitudes are usually defined either as a function of the plate thickness (t) or the web width (w) of the cross section. Fig. 1 [2] defines two types of imperfection: type 1 is the maximum local imperfection in a stiffened element, and type 2 is the maximum deviation from straightness for a lip stiffened or unstiffened flange.

In local mode, we find imperfection magnitudes of (i) $0.006w$ [2–4] and $w/200$ [5–7] among those that are defined in terms of the web width, and (ii) a wide spectrum of values ranging from $0.1t$ [8–12] to $1t$ [11] when the imperfection is defined as a function of the plate thickness. Intermediate values in use are $0.34t$ [1] and $0.5t$ [11]. The most cited reference on this subject [2] suggests $0.006w$ and EN 1993-1-5:2006/AC:2009 [5] recommends $w/200=0.005w$ for local buckling.

In addition to the previous ones, the expression suggested by Walker (1975) to scale initial imperfections in FE models is successfully used by Gardner and Nethercot [12], Yang and Hancock [13], Becque and Rasmussen [14] and Ashraf et al. [15]. In [16,17] the first local buckling mode is multiplied by a factor, 0.01 and 1 mm respectively.

In distortional mode, we find imperfection magnitudes of (i) $f/50$ [5,7] where f is the flange width of the cross-section, and (ii) a wide spectrum of values ranging from $0.1t$ [8–10,18] to $1.5t$ [19] when the imperfection is defined as a function of the plate thickness. Intermediate values in use are $0.15t$ [18,20], $0.5t$ [19], $0.64t$ [20], $0.94t$ [1] and $1t$ [2–4,19,21]. Reference [2] suggests $1t$ and EN 1993-1-5:2006/AC:2009 [5] recommends $f/50=0.02f$ for distortional buckling.

The imperfections specified in [5] are being used by the authors' research group [6], although they were not defined for cold-formed structures. These magnitudes are similar to those suggested in [2].

In global mode, the imperfection magnitudes usually used or tested to create the perturbed mesh range from $L/5000$ [12] to $L/750$ [18,19,21,22] where L is the member length. Intermediate values in use are $L/2000$ [12,19,23,24], $L/1500$ [14,19,24,26,27], $L/1250$ [18], and $L/1000$ [3,4,7,9,12,18,19,21,23–25]. EN 1090-2:2008 [22] recommends $L/750$ and ECCS [25] does $L/1000$, being the latter the most commonly used for global buckling.

Combinations of imperfection magnitudes varying between $0.075t$ and $0.2t$ (mostly $0.1t$), for local/distortional buckling, and $L/750$–$L/2000$ (mostly $L/1000$), for global buckling, are used in [8–10,18,23,28]. As in [18], for columns experiencing distortional/global interaction and practical purposes, pure global initial imperfections may be taken as the most detrimental ones, in the sense that they lead to the lowest ultimate loads. As in [19], statistically it is not recommended to combine all imperfections to cumulate their negative effects because of their random compensation. In this paper coupled instabilities have not been analysed.

As can be realized from this literature review, quite different values are adopted by researchers to scale the numerical models.