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Influence of web members on the in-plane and out-of-plane capacities of steel storage upright frames

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ABSTRACT

Global buckling behaviour, with or without interaction with distortional buckling, of storage rack members is evaluated by tests carried out according to EN 15512 (2009) [1] on compression and out-of-plane bending of upright frame modules. Based on test results for both single upright sections and frame modules, completed by numerical simulation, the present paper attempts to demonstrate that the design buckling strength of uprights can be conveniently estimated by single section tests, providing that the length of these members is calibrated for the distortional–global interaction mode.

1. Introduction

Despite their lightness, storage rack structural systems are able to carry very high loads and can also reach considerable heights. Usually, upright members are of mono-symmetrical sections, subjected to axial compression and bending about both axes.

Even though in recent years numerous investigations have been devoted to the effects of holes and member slenderness on the ultimate capacity of pallet rack uprights, no analytical method for the design of rack structures is generally accepted. For this reason, the design of these structures is based on experimental tests prescribed by specific codes.

The slenderness of cold-formed sections requires three buckling modes to be considered, i.e. local, distortional and global, and, often, at least two of these modes might couple. The problem is further complicated by the fact that rack sections usually contain arrays of holes in order to enable beams to be clipped into position at variable heights. The design of these members is still based on tests. According to EN 15512 [1] provisions, similar to its predecessor FEM10.2.02:2000 [2], for single upright members, (i) compression tests are required in order to determine the sectional strength (stub column tests) and the influence of distortional buckling (upright column tests) and (ii) bending tests about minor axis are required.

Besides, compression and out-of-plane bending tests and tests on upright frame modules are required to observe and characterise the global buckling of upright members (e.g. columns) including the influence of web members (e.g. diagonals). This kind of design, expensive and rather empirical, does not allow all the design parameters to be considered in order to optimise the design of the upright, and so, at the end, the results remain approximate. In such conditions, the question is raised if simple compression tests on an appropriately calibrated length of upright member could possibly replace the more laborious and expensive tests on upright frame modules. The present paper attempts to provide evidence to support this assumption.

An extensive experimental program was carried out at the CEMSIG Research Centre (http://cemsig.ct.upt.ro) within the Civil Engineering Faculty of "Politehnica" University of Timisoara, in order to obtain experimental data regarding the behaviour of two types of pallet rack uprights. The experimental program included compression tests on upright members and bending tests on single uprights and frame modules, in order to determine the bending properties of perforated rack upright members. Additionally, pure distortional buckling tests and distortional–global interactive buckling tests of calibrated lengths have been carried out [3,4].

The experimental work has been completed with numerical simulations and, applying the ECBL (*Erosion of Critical Bifurcation Load*) approach [5], buckling curves have been calibrated in European format for single upright members [3,4].

2. Literature review

In the early applications of steel storage racks, the upright sections were perforated C-profiles, due to the ease of production. Today, the C-shape profile has been replaced by Σ like sections. These more complex shapes are the result of the section optimisation process

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that is based on two considerations: ease of assembly and structural efficiency (cost efficiency).

In order to increase the buckling strengths of the webs and flanges, small groove stiffeners are rolled into contemporary upright sections. These stiffeners eliminate the propensity to local buckling, but create, what Thomasson called a “local–torsional” buckling problem [6], i.e. distortional buckling. Therefore, optimisation of the shape of sections for the purpose of avoiding local buckling creates conditions for distortional buckling modes.

Analytically and numerically based methods have been proposed to evaluate the distortional strength of thin-walled cold-formed steel sections [7–10]. Recently, Moen and Schafer [11] reported the tentative to use of the direct strength method (DSM) for perforated thin-walled sections, but, at the end, concluding is still not possible to avoid testing in the design of storage rack structures. Therefore, for the moment, at least the perforated sections and non-standard restraint conditions make the numerical analysis too complicated to be used in the design of storage rack structures. Consequently, current design of these structures is based on test procedures.

Davies et al. [13] investigated the local buckling of rack sections. Compression tests on stub column members were carried out and the experimentally obtained results were compared with results obtained numerically using generalised beam theory (GBT) and finite element method (FEM) analyses. The main goal of the study was to show that extensive experimental testing could be unnecessary in the design stage of racking uprights.

Extensive research work regarding the behaviour of perforated thin-walled members and, particularly, rack sections was carried out at Sydney University. Koen [12] performed testing and FE analysis on stub columns and complete upright frames. The main goal of the research was to determine a series of reduction factors for the effective length of the uprights in compression to account for the discrete bracing restraints and to determine a revised column curve to be used for future structural design of storage rack uprights in case of flexural–torsional buckling failure.

Gilbert and Rasmussen [14] conducted an extensive experimental testing program in order to characterise the behaviour of individual steel storage rack components. The report presents the results of coupon tests, stub column tests, pallet beam-to-column connection tests, base plate floor connection rotational and uplift tests, upright frame shear tests and four point bending tests of uprights.

Baldassiono [15] studied the influence of perforations and load eccentricity on the upright performance. In the study, compression tests on both perforated and non-perforated specimens with different lengths and different load eccentricities were considered.

Roure et al. [16] studied the buckling of short columns (mainly local buckling failure). Local–distortional interaction was also considered in the calculations through the concept of reduced thickness of the stiffeners.

Casafont et al. [17] studied the behaviour of different rack sections with respect to distortional buckling. The distortional buckling mode can be observed in moderately long specimens, i.e. longer than the stub columns used for the determination of the local buckling strength, but short enough to avoid the effects of global buckling. Further, the effect of interactive buckling on the member strength was studied and based on these results it was shown that the accuracy of the current design procedure can be improved if the effect of interaction is considered in the calculations.

Reading all these papers and reports, it can be observed that the problem of mode interaction involving coupling between distortional and overall modes, and the erosion of theoretical buckling strength of perforated sections in compression, as well as the effect of imperfections and inelastic deformations are not tackled; at least not quantitatively. This was one of the reasons to perform the present study.

However, in last two decades, the significant progress in the application of numerical techniques for the simulation of the complex behaviour of cold-formed steel members, including interactive buckling, enabled structural engineers to apply the so called *numerical testing* instead of laboratory tests in the design of pallet rack structures. Of course, it is still necessary to calibrate the numerical models by a reference experimental test but, after that, those models can be sufficiently reliable to replace the actual experimental tests and can be used to extend the experimental results database.

Geometric and material non-linear with imperfection analysis (GMNIA) can be successfully applied to simulate the real behaviour of cold-formed steel sections and to evaluate their effective properties. Two general reports related to numerical models and methods applied in the simulation, presented in two editions of Coupled Instability in Metal Structures Conferences, CIMS 1996 and 2000, by Rasmussen [18] and Sridharan [19], reviewed the main contributions and milestones in the progress at the date. They concluded that the most used computational models are the ones applying the semi-analytical [20] and spline finite strip [21] and the finite element methods [22]. At CIMS 2008, summarizing the advances and developments of computational modelling of cold-formed steel members, Schafer [23] emphasised that the primarily focus is the use of the semi-analytical finite strip method, considering the implementation of the constrained finite strip method (cFSM) [24]. This method allows for discrete separation of local, distortional and global deformations, and collapse modelling using shell finite elements.

A good alternative to FSM/cFSM is the application of modal decomposition via the GBT method, which has achieved a significant development in the last decade by the work of the Lisbon team led by Camotim [25]. Using this method makes it possible to select the deformation modes to be considered in the analysis. Using GBT, it is possible to analyse members made of one or several isotropic or orthotropic materials, with various common support conditions.

Camotim et al. [26] summarised the main concepts and procedures involved in performing a GBT buckling analysis together with the development and numerical implementation of a GBT-based beam finite element formulation. This formulation includes local, distortional and global deformation modes and can handle general loadings. GBT-based results were compared with values obtained by shell finite element analyses showing that despite the huge difference between the numbers of degrees of freedom involved in the two analyses (orders of magnitude apart), excellent agreement was found in all cases.

Dinis et al. [27] examined the local–distortional mode interaction behaviour of cold-formed steel lipped channel columns. ABAQUS finite element code and 4-node shell elements were used to simulate their behaviour. Further, Camotim and Dinis [28] studied the coupled instabilities in cold-formed steel lipped channel columns using the ABAQUS finite element software. The work investigated the influence of geometrical imperfections on the elastic post-buckling interactive mechanics of lipped channel sections and included local/distortional, distortional/global and local/distortional/global mode interaction.

Rossi et al. [29,30] examined the combined distortional and overall flexural–torsional buckling behaviour of cold-formed stainless steel sections considering the experimental work [29] and, at the same time, analysing the design aspects [30].

Silvestre et al. [31] studied the performance of the direct strength method (DSM) to estimate the ultimate strength of lipped channel columns affected by local/distortional mode interaction. The study was conducted using ABAQUS and involved the