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Distortional Influence of Pallet Rack Uprights Subject to Combined Compression and Bending

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ABSTRACT

A pallet rack is a structure in which the beams and uprights are cold-formed steel sections. The beam-upright connections are normally clipped in order to select the beam levels required and for ease of assembly. For this reason, the uprights contain holes and perforations distributed along their length. The complexity of these components, with local, distortional and torsional/flexural buckling behaviour, represents a challenge in structural design. The loads acting on the structure are induced by the weight of pallets to be stored, and transmitted to the uprights by the semi-rigid connection system. Therefore, the uprights are thin-walled singly symmetrical perforated open cross-sections bearing axial load and bending moment simultaneously. The main objective of this paper is to analyse the influence of the bending moment on the load bearing capacity of rack uprights subject to axial load together with bending moment. Bending is induced by means of axial forces eccentrically applied. The influence of bending on the strength capacity of rack uprights is analysed through finite element analysis, where residual stresses and strength enhancement induced during cold forming of sections are also considered. Experimental tests have been performed reproducing the load conditions in order to validate the FEA results. The ultimate load has also been calculated according to the European Standards and compared to experimental results.

1. Introduction

The main components of a steel storage pallet are the uprights, the pallet beams and the diagonals. The uprights are usually subjected to axial load and bending moment. The loads carried by the pallet beams are transmitted to the uprights through semi-rigid connections. When the loads are symmetrically distributed, at both sides of an upright, then it is working in pure compression. Whereas when the loading scheme is asymmetric, then the upright is subjected to compression and bending. The case of pure axial load is extremely rare in rack design practice and it is generally associated with the verification of lacings. With reference to the uprights, in addition to the contribution due to axial load, it is of fundamental importance to take into account also the presence of bending moments along the principal axes of the cross-section [1].

Extensive research has been focused on members loaded under pure compression; among these, [2,3] that are devoted to experimental testing of compressed members. Three methods (analytical, experimental and FEA) to estimate the effective area and the position of the centre of gravity for perforated sections are presented in [2]. Experimental deformations were measured on specimen lengths prone to distortional buckling failure in order to analyse the interaction between distortional and global buckling modes [3].

However, little research has been done to date about the behaviour of uprights subjected to combined compression and bending. Miller and Pekoz [4] investigated the behaviour of cold-formed steel lipped-channel columns with rectangular perforation patterns eccentrically loaded, and code predictions were compared with empirical responses. The results from an experimental investigation and a finite element analysis of cold-formed channel columns with inclined simple edge stiffeners subjected to eccentric loads presented by Zhang et al. in [5], show that loading position affects the load carrying capacity and failure mode of specimens. Mohri et al. [6] investigated bi-symmetric cross-sections under combined bending and axial forces and compared a non-linear model for the stability analysis to non-linear finite element results. An experimental campaign [7] is conducted on the behaviour of cold-formed steel lipped-channel beam-columns under bi-axial bending and compression to characterize the failure modes and the member capacity, and the results are used to verify the reliability of code predictions about the strength of beam-columns.

Concerning racks, Davies et al. [8] compared both GBT (with treatment of perforations) and FEA for predicting the failure load of perforated cold-formed steel sections subject to axial load and bending with test

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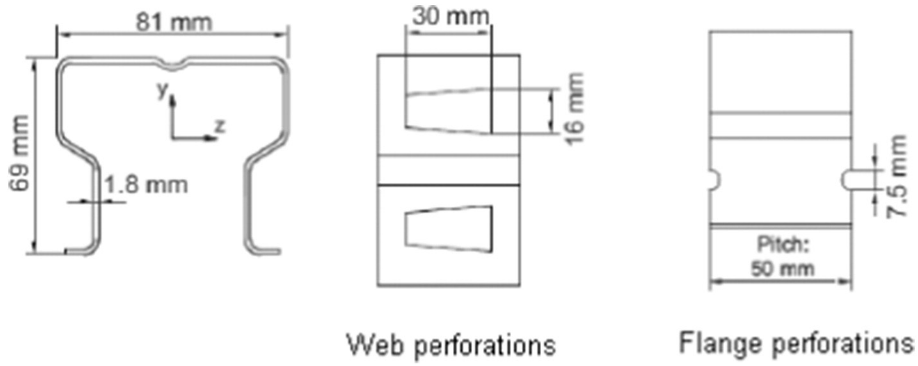

Fig. 1. Main dimensions of the analysed rack upright.

results. Crisan et al. [9] carried out a testing programme including bending about minor axis of single uprights with web in compression and tension, according to Annex A.2.9 [10]. Bernuzzi and Simoncelli [11] analysed the interaction between axial loads and bending moments in rack uprights, therefore three European design approaches were compared to evaluate the beam-column capacity.

The purpose of this paper is to investigate eccentrically compressed rack members in order to reproduce compression and uniform bending load case and analyse the influence of distortional buckling in the upright. Uniform axial bending and compression were reproduced by means of a loading set-up specifically designed to apply eccentric axial loads. Experimental tests are performed on 700 mm upright length with eccentricities defined on the non-symmetrical axis of the cross-section. Two different methodologies to obtain the load carrying capacity of the upright by FEA are presented and compared to experimental results. Finally, the failure load is also obtained through the European Standards in order to analyse its agreement with experimental measurements.

2. Experimental tests

2.1. Analysed cross-section and material testing

The analysed rack upright (steel grade S355) is shown in Fig. 1. It is a commercial open cold-formed steel section, whose main dimensions are: web width of 80 mm, flange height of 69 mm, 1.8 mm of thickness and 4.4 mm of corner radii. The holes are located at the middle position of flange parts.

Most of rack sections are manufactured by cold-roll forming. As a consequence, the mechanical properties of the material may be different from the virgin sheet coil. Therefore, several tensile coupons were cut out from flat and corner areas of the upright in order to determinate their stress–strain behaviour. Flat coupons were cut out from the only part of the flange without any perforation. All corners radii of the cross-section have the same value, thus the enhancement of its mechanical properties was evaluate though coupons obtained from corner area shown in Fig. 2.

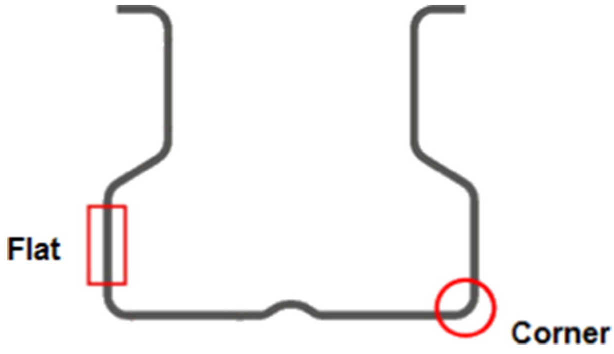

Fig. 2. Flat and corner zones were tensile coupons were cut out.

Table 1 shows the values of yield and ultimate strength obtained from the tensile tests following the recommendations of EN100002-1 European Standard. It can be observed that the yield and ultimate strength in corner areas are 17.5% and 7.7% higher than in flat areas due to strain hardening, respectively. Moreover, the engineering stress–strain curves for all tensile coupons are plotted in Fig. 3. It can be observed the enhancement of the yield stress and ultimate stress of corner coupons as a consequence of strain hardening. On the other hand the ductility has decreased.

2.2. Experimental set-up

Several experimental tests have been done to determine the load carrying capacity of the rack upright subject to a combined compression and bending. Bending is induced by means of axial forces eccentrically applied. At each end of the rack upright a plate made of 30 mm thick steel is used to restrain the distortion and warping displacement of the section (Fig. 4). In order to introduce the eccentric axial force, a second steel plate of 15 mm of thickness is fixed to the first one through a system of slotted holes and bolts, which allows the lateral displacement (Z direction) of the longitudinal upright axis from the application point of the axial force (Fig. 5). In addition, the whole sample has the flexural deformation modes pinned at both ends by means of two steel balls that fix the load application point (Fig. 6). Finally, a special device avoids the rotation around the longitudinal axis of the specimen by means of guides and cylinders (Figs. 6–7).

The axial load is applied by means of a hydraulic jack, with a load speed of 150 N/s and measured by a force transducer. The shortening

Table 1
Yield and ultimate strength of flat and corner areas of the rack section.

Sample	f_y (MPa)	f_u (MPa)
Flat 1	417	478
Flat 2	416	483
Flat 3	422	479
Flat (Mean)	418	480
Corner 1	486	506
Corner 2	500	527
Corner 3	510	521
Corner 4	477	510
Corner 5	478	510
Corner 6	492	530
Corner (Mean)	491 (Δ17.5%)	517 (Δ7.7%)

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