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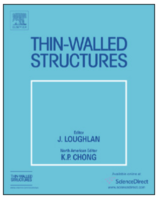

Full length article

Experimental investigation and evaluation of Direct Strength Method on beam-column behavior of uprights

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ABSTRACT

Uprights in storage racks being predominantly subjected to axial compression are also subjected to bending moments, hence acting as beam-columns by nature. The design of uprights is currently based on experimental or high-end computational methods, but analysis based-design involves lesser design office effort enabling development of innovative and optimized sections. The major challenges in this design are perforation, buckling interaction and combined loading. Although recent attempts use Direct Strength Method (DSM) to determine the nominal strength of uprights, experimental evidence on beam-column behavior of uprights that validate analytical equations are scarce. With this background, 16 experiments were carried out on uprights subjected to axial or biaxial compression, considering biaxial compression for constant and linearly varying moments. Interaction of distortional mode with global modes is evident from the experiments, which is generally ignored in DSM. In this paper, DSM is briefly explained and the choice of appropriate yielding moment is exemplified. The experimental results are presented in terms of DSM for both Linear Interaction (LI – from current code of practice) and Nonlinear Interaction (NLI – from literature). The results show that NLI may lead to unconservative design for eccentrically loaded specimens with linearly varying moments.

1. Introduction

The logistic operations involves storage and handling of goods and materials that necessitate the usage of vertical storage systems. The industrial storage racks, simply called racks, are such vertical storage systems used to store large volume of materials in less floor area. Usually the racks are made of cold-formed steel (CFS) sections, and these are advantageous in terms of high strength to weight ratio, ease in fabrication and erection. The rack comprises of vertical column uprights, horizontal beams, diagonal bracings and horizontal members. Two upright members connected by bracings with/without horizontal members form an upright frame. A number of upright frames inter connected by beams at various heights form a rack system.

The rack systems are mainly divided as drive through, drive in and selective rack systems. Fig. 1(a) and (b) are examples of selective rack and drive-in rack systems. The main difference between these two racks is the orientation of upright frame. The beam to upright connection is generally assumed to be boltless shear connection, but in reality the connection is semi-rigid in nature, and resists moment according to its connection stiffness. The end upright frames, loading and unloading sequence, connection semi-rigidity, out of plumb in upright frame, sway effect and connection eccentricity inevitably impart the bending moment in uprights.

The upright sections are usually mono-symmetric thin-walled open sections. These are susceptible to (i) element level local buckling (L), (ii) cross section level distortional buckling (D) and (iii) member level global buckling (G). Uprights fail in one of these L, D or G modes or by any combination of these modes and/or by yielding. The failure mode depends on geometry of the cross section, slenderness of the member, load position and initial imperfection of the member.

The complexities in optimized cross section geometry and perforation pattern of uprights challenge the researchers in developing simple design equations. The rack design codes, Rack Manufacturers Institute (RMI) [1] and EN15512 [2], recommend the test based design procedure with simple empirical design equations. One of the early researches on buckling behavior of simply supported, perforated rack column subjected to axial compression combined with bending moment is detailed in [3], in which the perforations are considered in terms of effective thickness. The detailed numerical investigations on design of racks as per RMI and AISI recommendations are presented in [4].

DSM is extended to simply supported lipped channel column subjected to discrete web perforations along the length [5]. It

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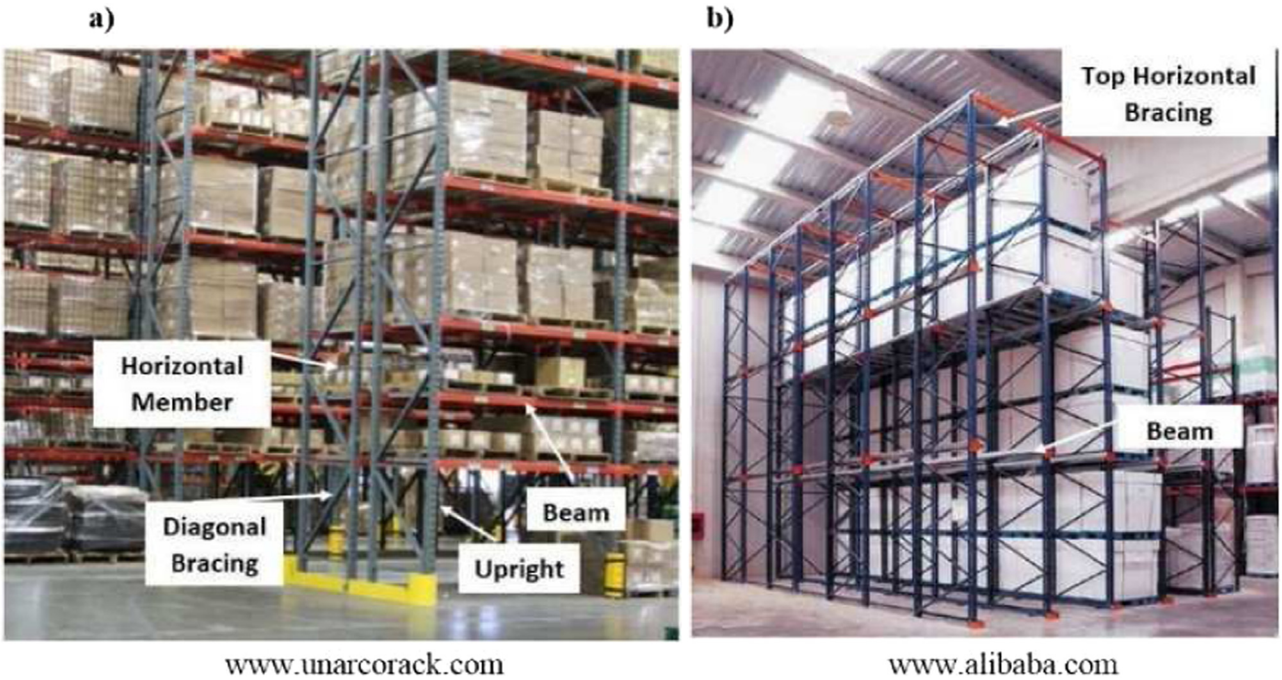

Fig. 1. Storage racks (a) selective rack and (b) drive-in rack.

describes a way to account for the perforations in elastic critical buckling loads using CUFSM 4.05 [6]. The DSM is further extended to perforated rack columns in terms of dedicated reduced thickness equations for each mode [7–9]. The influence of number of perforations in reduced thickness equations for local buckling and warping effect in global buckling are included in [10]. Another notable research based on Erosion on Critical Bifurcation Load (ECBL) method for uprights is reported in [11].

The research by Teh et al. [12] on racks emphasize the need for 3D buckling analysis, and it includes Wagner effect, warping torsion and shear center eccentricity in critical buckling load calculations. In particular, their example shows that the critical buckling load increases when warping deformation is restrained. The continuous research on racks by Bernozzi et al. [13–16] explains the influence of warping in current design codes and verification checks through detailed numerical study.

Some experimental as well as numerical researches on unperforated lipped channel, uniaxial beam-column behavior of CFS members are reported in [17–19]. Recently in [19], experimental research of lipped channel beam-columns subjected to concentric and eccentric (uniaxial and biaxial) compression are presented in terms of DSM.

The beam-column design space becomes complex in a combination of aspects namely geometry, perforation, boundary conditions and method of analysis. With such complexity in design, DSM finds acceptance among engineers and researchers because of its simplicity. Literature review reveals that only scant experimental evidences are available for calibrating the beam-column design methods. To the author's knowledge, there is no experimental work reported on uprights subjected to biaxial bending along with axial compression. In this paper, the axial and biaxial compression experiments on uprights are briefly explained. In the case of beam-column design, the procedure of DSM is explained with respect to the selection of appropriate yield moment. The experimental results are then presented in terms of DSM framework. This study examines the nature of conservativeness of DSM for upright beam-column subjected to constant or linearly varying moment, along with axial compression.

2. Beam-column experiments

Experiments were conducted to understand the buckling behavior of upright member loaded concentrically, or with biaxial eccentricity to create constant/linearly varying moment along the member length. Two types of specimens were considered in this study, and for the authors' convenience these have been named as Type B and Type C. These specimens are different from each other in cross section, shape, dimensions, perforation pattern and material yield strength. Limited geometrical details of Type B and Type C upright sections are shown in Fig. 2(a)–(b). The web and flange perforations are shown in Fig. 2(c)–(f). The cross section properties are calculated using a computational utility developed by Thin-walled Steel Structures group at IIT Madras, India.

The gross section properties are presented in Table 1. The specimen lengths for the experiments were decided by limiting the ratio of half buckling wavelengths corresponding to minimum critical load for G mode to that of D mode within the range of 2–4. For this purpose, the gross section dimensions were used in CUFSM to find critical buckling wavelengths. Accordingly Type B specimen length ranges from 1860 to 2060 mm, and Type C specimen length ranges from 1770 to 1960 mm.

The yield strength, ultimate strength and elastic modulus of the material for Type B and Type C specimens, as listed in Table 1, were determined from the tension tests of coupons fabricated from specimens. The centroid of the gross section is considered as origin. As there is an axis of symmetry, the biaxial eccentricity is considered only in one half of the section with respect to symmetry axis. The eccentricity details and positive axes directions are shown in Fig. 3.

The specimen groups and eccentricity coordinates are given in Table 2. Eccentricity coordinates at top end and bottom end are represented as numerator and denominator respectively. The proportional moments due to eccentricity, applied in Y-plane (X–Z axes plane) and Z-plane (X–Y axes plane) are graphically illustrated in Fig. 4(a)–(d), and their respective moments are shown along the axes using double headed arrows. As shown in Fig. 4 (a) and (b), set1 and set3 members are subjected to moments that are proportional to axial load and constant along the length. Fig. 4