Thin-Walled Structures 112 (2017) 159–172

Contents lists available at ScienceDirect

Thin–Walled Structures

journal homepage: www.elsevier.com/locate/tws

# An experimental investigation into perforated and non-perforated steel storage rack uprights

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ARTICLE INFO

*Keywords:*
Storage rack uprights
Perforation
Axial compression tests
Distortional-global buckling interaction
Direct Strength Method (DSM)

ABSTRACT

This paper presents an experimental investigation into the behaviour of steel storage rack uprights subjected to axial compression. Material tensile tests were carried out to determine the material properties of cold-formed steel uprights. Geometrical imperfection measurements were recorded for the specimens prior to testing. A total of 67 specimens were tested under axial compression, including four different cross-sections, various lengths and specimens with and without perforations. The focus of the study is to investigate the influence of perforations on the performance and failure mode of steel storage rack uprights, and comparisons of performance and failure modes between perforated and non-perforated members are provided. The interaction of distortional-global buckling is also discussed, and the results of this study explicitly show that the strengths obtained from the tests highlight the underestimation of the existing distortional strength curve of the Direct Strength Method (DSM) on perforated steel storage rack uprights. Hence, based on the test results, a modified DSM for perforated uprights is proposed.

## 1. Introduction

Cold-formed steel sections are widely used as steel uprights, beams and bracings in steel storage rack structures. Upright members used in storage racking generally have many perforations, and the perforated uprights have arrays of holes along the length, which allow the beam to be connected at variable heights and the bracing to be bolted to form the frames. The stability behaviour is of prime importance for cold-formed steel members, but under the influence of continuous perforations the buckling behaviour and load capacity of an upright may vary.

The rising demand of cold-formed steel in industry necessitates simple and reliable design methods, and attracts researchers to investigate its structural behaviour. Over recent decades, researchers have published a number of journal articles reviewing and summarising the development of cold-formed steel members. The perforated sections and non-standard restraint conditions make a numerical analysis too complicated to be used in the design of storage rack structures. Therefore, the current design codes for steel storage racks (North America (RMI) [1], Australia and New Zealand (AS/NZS4084) [2] and Europe (EN 15512) [3]) provide test procedures to obtain the strength requirements for storage rack design. Several researchers have also investigated the behaviour of cold-formed steel uprights by experimentation. Casafont et al. [4] presented an experimental investigation into the structural behaviour of steel storage rack uprights subjected to compression. Koen [5] performed an experiment on stub uprights and complete upright frames to determine a series of reduction factors for the effective length of the uprights in compression. A series of compression tests examining perforation patterns were carried out by Rhodes and Schneider [6]. These concentrated on plain channel cross-sections with perforation layouts systematically varied to examine the effects of perforation position, dimensions and quantity on the section performance. Roure et al. [7] gathered a comprehensive set of experimental results from upright cross-sections subject to compression. These papers only focus on short or intermediate length uprights. However, intermediate and high uprights are widely used in high-rise steel storage rack structures which have had a dramatic increase in use in recent years, and it is therefore essential to study their stability behaviour. Another important characteristic of cold-formed steel uprights is the presence of continuous perforations on the web and flanges. The perforations have been demonstrated by researchers to have a significant influence on the stability behaviour of uprights. Compression tests on 24 short and intermediate length cold-formed steel uprights with and without slotted web holes were conducted by Moen and Schafer [8]. More recently, Moen and Schafer [9] reported the tentative use of the direct strength method (DSM) for perforated thin-walled sections, and concluded that practical testing is necessary in

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http://dx.doi.org/10.1016/j.tws.2016.11.016
Received 11 April 2016; Received in revised form 23 October 2016; Accepted 21 November 2016

**Table 1**
Properties of test specimens.

| Specimen | b (mm) | h (mm) | t (mm) | $A_{net}$ ($mm^2$) | L (mm) |
|---|---|---|---|---|---|
| **75-55-1.8** | 75 | 55 | 1.8 | 376.7 | 250, 650, 1200, 1800 |
| **75-55-1.8-H** | 75 | 55 | 1.8 | 279.1 | 250, 450, 650, 900, 1200, 1500, 1800, 2200 |
| **90-66-1.8** | 90 | 66 | 1.8 | 500.8 | 300, 700, 1200, 2000, 2700 |
| **90-66-1.8-H** | 90 | 66 | 1.8 | 405.0 | 300, 500, 700, 900, 1200, 1500, 2000, 2400, 2700 |
| **90-66-2.0-H** | 90 | 66 | 2.0 | 450.0 | 300, 700, 1200, 2000, 2700 |
| **100-80-1.8** | 100 | 80 | 1.8 | 547.0 | 300,700,1200,1800,2800 |
| **100-80-1.8-H** | 100 | 80 | 1.8 | 449.2 | 300, 500, 700, 900, 1200, 1500, 1800, 2300, 2800 |
| **100-80-2.0-H** | 100 | 80 | 2.0 | 499.1 | 300, 700, 1200, 1800, 2800 |
| **100-80-2.3-H** | 100 | 80 | 2.3 | 574.0 | 300, 700, 1200, 1800, 2800 |
| **120-80-2.0** | 120 | 80 | 2.0 | 653.8 | 375, 1125, 1875, 2650 |
| **120-80-2.0-H** | 120 | 80 | 2.0 | 554.9 | 375, 750, 1125, 1500, 1875, 2250, 2650, 3000 |

Note: H – Perforated member.

the design of storage rack structures. The type of perforations described in the above papers is different from the perforations in the uprights of storage racks. There is a significant difference between the influence of large web holes on the performance of an upright and that of the perforations systematically located in the web and flanges.

Local, distortional and global buckling are three typical types of buckling which a cold-formed steel member may experience [10]. Since the 1970 s there has been substantial research activity in the field of cold-formed structures which has led to numerous published works on the local, distortional and global buckling of cold-formed steel sections, (for example see [11–14]). However, single buckling modes were the focus of the above studies, while research on interactions involving distortional buckling has been conducted very recently. Kwon et al. [15] experimentally investigated the interaction between distortional buckling and material yield. Crisan et al. [16] carried out an experimental study on the interaction between distortional and overall buckling of perforated uprights. Pedro et al. [17] reported experimental and numerical results concerning local-distortional buckling interaction in fixed-end cold-formed steel web-stiffened lipped channel uprights. Dinis and Camotim investigated the interaction between local-distortional buckling ([18–20]) and distortional-global buckling [21] using the finite element method. Nandini and Kalyanaraman [22] investigated the interaction between distortional buckling and lateral-torsional buckling, also using the finite element method. Ren et al. [23] studied the distortional buckling interactions of cold-formed steel purlins under uplift loading in purlin-sheeting systems. Due to the complex nature and the limitations of research into buckling interactions on perforated rack members, and the effects of systematic perforations and strong stiffeners which eliminate the occurrence of local buckling, the interaction of distortional-global buckling on intermediate and long perforated members is thus considered to be sufficiently important to warrant further investigation.

In this paper, an experimental investigation into the behaviour of cold-formed steel storage rack uprights subjected to axial compression is presented. Material tensile tests were carried out to determine material properties of cold-formed steel uprights. Geometrical imperfection measurements were recorded for the specimens prior to testing. Compression tests were conducted on 67 steel rack uprights, with and without perforations, in various sections and lengths. On the basis of the test investigations, the influence of parameters including the cross-sections, the length of specimens, and the perforations on the ultimate load bearing capacity of rack uprights are studied. Comparisons of the performance and failure modes of perforated and non-perforated uprights are examined in detail. The Direct Strength Method (DSM) is employed to compare with the test results. A modified DSM for perforated uprights obtained from test results is also proposed.

## 2. Test program

### 2.1. Specimens

A total of 67 tests on short, intermediate and long specimens with and without holes were categorised into four types of cross-section (see Table 1). The specimens were labelled to specify section type: for example, 90-66-1.8-H-900 represents a web length (b) of 90 mm, a flange height (h) of 66 mm, a thickness (t) of 1.8 mm and an overall length of 900 mm. The 'H' indicates that the specimen is perforated, while for a specimen without perforations, the 'H' is absent. Fig. 1 shows the cross-sectional geometry and illustrates the typical perforation locations and dimensions at the web and flange. It can be seen from the figure that triangular and circular holes are located at the web and flanges respectively; these perforations along the length of the upright allow the beam to be connected at variable heights, and steel bracings are usually bolted to the upright and act to stiffen the framework. It should be mentioned that for reasons of commercial confidentiality some geometrical details of the complex cross-sections are not permitted to be published.

### 2.2. Material properties

A series of tensile coupon tests were conducted to determine the basic stress–strain response of the cold-formed steel specimens. Flat coupon samples were cut longitudinally from the rear flange of the cold-formed uprights. Three coupon samples selected from a batch of the specimen were tested using a computer controlled material tensile machine. The tension test followed the standard test procedure for tension testing of metallic materials in GB/T228-2002 [24]. The coupon sample was fully clamped at both ends, leaving a specified clear distance in the middle section to measure the elongation under tension. The goal of the coupon test was to obtain the precise tensile yield and ultimate strength for each steel rack upright specimen. A summary of the average ultimate and average 0.2% proof strengths obtained from three coupon samples are given in Table 2. It can be seen from the table that the yield strengths are found to be great in the perforated specimens than in the non-perforated specimens, indicating that the perforations have significant impact on the yield strength. This can be explained by the perforating procedure, which influences the cold forming process. The bending residual stresses produced from the cold-forming process are minor [25,26] and their influence on the performance of the cold-formed steel uprights are thus ignored.