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Beam tests of cold-formed steel built-up sections with web perforations

Liping Wang, Ben Young *

Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong

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ABSTRACT

The aim of this study is to investigate the flexural behavior, including the ultimate moment capacities and failure modes, of built-up cold-formed steel members with circular web holes. A total of 43 beams having ten cross-section sizes with different hole diameters were tested under four-point bending. The built-up sections were assembled by self-tapping screws from either two plain channels or lipped channels. Reduction of moment capacities and localized failure due to the presence of holes in the web plates of beams was observed in the tests. It is shown from the test results that when the hole diameter-to-web depth ratio (d_h/h_w) is 0.5, the influence of the holes on the moment capacities of beams is very small, however this is not the case when d_h/h_w further increases up to 0.7. Different approaches of determining the critical elastic local and distortional buckling moments including the influence of holes for the built-up open and closed sections were compared and discussed, and appropriate approach for built-up sections was recommended. The current direct strength method (DSM) was extended for the design of cold-formed steel built-up sections with holes in this study. The design strengths predicted by the DSM were compared with the test results. It is shown that the DSM formulae in the North American Specification are capable for predicting the design strengths of the built-up open and closed section beams with holes, using the critical elastic local and distortional buckling moments including the influence of holes determined by the recommended approaches in this study.

1. Introduction

Cold-formed steel sections are commonly used for floor joists and other structural members. Mono-symmetric or point-symmetric open sections, such as C-sections and Z-sections are typically used in cold-formed steel joists. These open section beams are prone to fail by lateral torsional buckling, due to the location of its shear center and centroid of the cross-section. One way to overcome this problem is to connect two individual sections together to form the double-symmetric built-up open sections or built-up closed sections. Discrete holes (perforations) are also commonly placed in the web of cold-formed steel joists to accommodate plumbing and electrical facilities. In this study, the built-up open and closed section beams with web perforations were investigated.

Investigation of perforated thin-walled elements and sections has been carried out, and some of the early studies were reviewed by Shanmugam [1]. Shanmugam and Dhanalakshmi [2,3] developed design formulae for predicting the ultimate load capacity of cold-formed channel and angle stub columns with single or multiple openings of different shapes. The perforations of the sections were considered as a kind of imperfection in the study performed by Szabo and Dubina [4]. Eccher et al. [5,6] applied the isoparametric spline finite strip analysis method to perforated thin-walled structures. Experimental investigation on cold-formed steel beams with holes subjected to pure bending was mainly focused on lipped channel sections in previous studies. Sivakumaran et al. [7] conducted some flexural tests on channel sections with different shapes of web perforations and recommended an approach to restore the strength of sections with large web openings. Four-point bending tests were also conducted by Moen et al. [8] on cold-formed steel lipped channel section joists with rectangular unstiffened web holes. The direct strength method (DSM) was firstly proposed by Schafer and Peköz [9] for cold-formed steel members without holes and is included in the North American Specification (NAS) [10] and Australian/New Zealand Standard [11]. Finite strip method was used for predicting the local, distortional, and global elastic buckling properties of a cross-section to predict ultimate strengths of the members using DSM. Moen and Schafer [12] extended the semi-analytical finite strip method to predict the local and distortional buckling of cold-formed steel members with holes, by considering appropriate modifications to the element thickness and choice of buckling half-wavelength. The DSM was further extended to beams with holes based on both experimental and theoretical investigations of lipped channel sections [12,13]. On the other hand, efforts have also been made to extend the DSM for the design of built-up closed section columns by Young and Chen [14] and built-up open section columns by Zhang and Young [15]. It was shown that the DSM can be used to predict the design strengths of cold-formed steel columns when the critical buckling stresses are determined appropriately using finite strip method for built-up sections.

* Corresponding author.
E-mail address: young@hku.hk (B. Young).

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In order to study the influence of web holes on the moment capacities of beams, a total of 43 cold-formed steel built-up open and closed section specimens with circular web holes were tested subjected to bending about the major *x*-axis in this study. Reduction of moment capacities and localized failure were found in the cold-formed steel built-up section beams with different sizes of web holes. The formulae of direct strength method (DSM) for single section beams with holes are available in the NAS [10]. However, the DSM of built-up sections with holes has not yet been investigated in previous studies. Therefore, the current DSM was reviewed and extended to the design of built-up open and closed section beams with holes in this study.

2. Experimental investigation

2.1. Test specimens

A total of 43 cold-formed steel built-up open and closed section specimens with circular web holes were tested subjected to bending about the major *x*-axis in this study. The built-up open sections were assembled by self-tapping screws from two lipped channels as shown in Fig. 1(a), and the built-up closed sections were assembled from two plain channels as shown in Fig. 1(b). The arrangements of screw spacing along the beam length of built-up open section specimens and built-up closed section specimens are shown in Figs. 2 and 3, respectively. The screw spacing is close to the web depth of the cross-sections. The screw spacing of the built-up sections is in accordance with the current specifications. The screws were replaced by bolts for the portions that the specimen connected to the load transfer plates and steel stiffening plates. The nominal diameter of the screw was 4.8 mm, and the nominal screw length was 12.5 mm. The circular holes were located in the moment span of the beams. The channel sections were brake-pressed from high strength zinc-coated grades G550, G500 and G450 structural steel sheets with nominal 0.2% proof stresses of 550, 500 and 450 MPa, respectively. Different plate thicknesses of 0.42, 1.2 and 1.9 mm were tested. Web holes were located on each channel of the built-up specimens in the moment span with the hole diameter-to-web depth ratio (d_h/h_w) ranged from 0.25 to 0.7. The measured cross-section dimensions and the hole diameters of each channel are reported in Table 1 for built-up open section specimens, and Table 2 for built-up closed section specimens. The total beam length of all test specimens was 1600 mm.

2.2. Specimen labeling

The test specimens were labeled such that the shape of the built-up cross-section ("O" for "open section", and "C" for "closed section"), the hole diameter-to-web depth ratio (d_h/h_w), thickness (t) and the web depth (h_w) of the specimens can be identified. For example, the label "OH0.25T0.42-86" defines the built-up open section specimen as follows, where the open section (O) specimen has a web hole (H) in the middle of moment span with d_h/h_w equal to 0.25, and the thickness (t) and web depth (h_w) of the cross-section is equal to 0.42 mm and 86 mm, respectively. In addition, six built-up open section specimens and four built-up closed section specimens with two discrete holes symmetrically located in the moment span were also tested. A symbol of "S1" or "S2" was added after the web depth of the labels for these ten supplementary specimens, in which "S1" and "S2" indicates the spacing of two holes at 168 mm and 336 mm from center to center for built-up open and closed section beams, respectively. Finally, if a test was repeated, then a symbol of "R" was added to the end of the labels.

2.3. Material properties

The material properties of the test specimens were obtained from tensile coupon tests. The coupon specimens were prepared in accordance with the Australian standard AS 1391 [16]. The flat tensile coupons were extracted in the longitudinal direction of the beam test specimens. The material properties including initial Young's modulus (E), 0.2% proof stress ($\sigma_{0.2}$), tensile ultimate strength (σ_u), and strain at fracture (ε_f) based on the gauge length of 50 mm of the coupon specimens were obtained and summarized in Table 3.

An MTS testing machine was used to test the tensile coupons. A calibrated extensometer of 50 mm was used to measure the longitudinal strain during the tests. Two linear strain gauges were also attached at the center of two surfaces of each coupon, and the initial strain readings were used to determine the Young's modulus. Identical test procedure as reported by Wang and Young [17] was used in conducting the

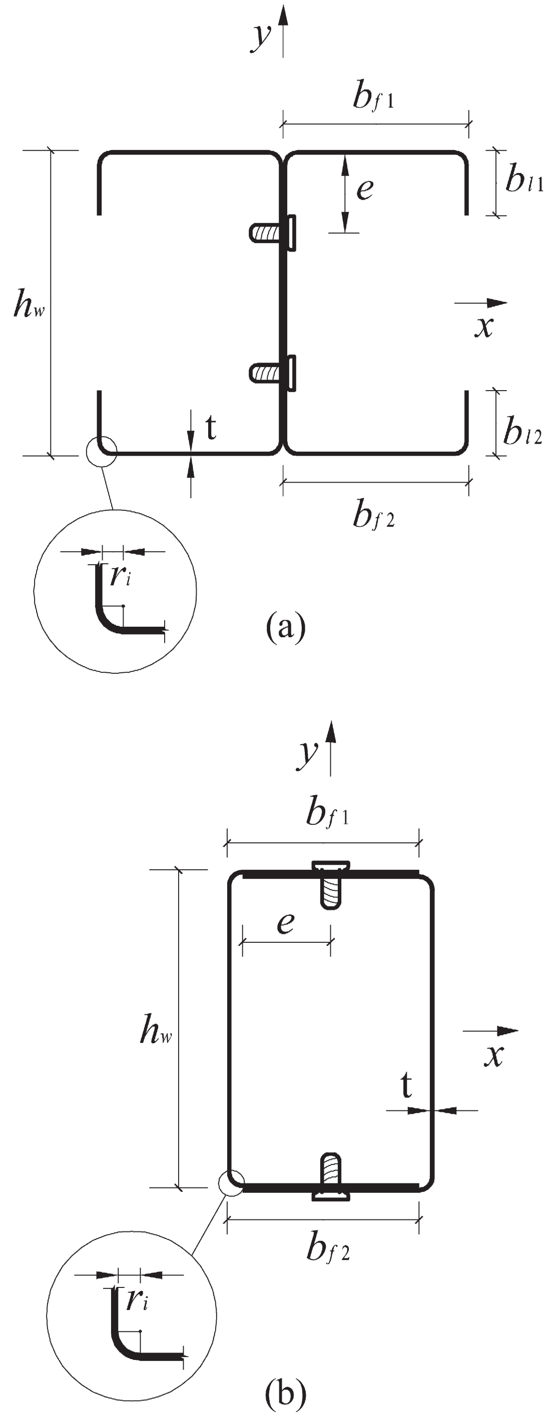

Fig. 1. Definition of symbols and location of screws in cross section. (a) Built-up open section. (b) Built-up closed section.