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Design of cold-formed steel built-up sections with web perforations subjected to bending

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ABSTRACT

The flexural behaviour including the moment capacities and failure modes of cold-formed steel built-up sections with circular web holes was investigated. Finite element analysis was performed on a wide range of cold-formed steel built-up section beams with different sizes of perforations under four-point bending. The built-up sections included both I-shaped open sections assembled from two lipped channels back-to-back and box-shaped closed sections assembled from two plain channels face-to-face. Finite element (FE) models have been developed to simulate the simply-supported cold-formed steel built-up section beams. The FE models for the built-up open sections and built-up closed sections were verified against the test results that have been conducted by the authors. The validated models were employed to carry out extensive parametric studies on cold-formed steel built-up section beams with various section slenderness and hole sizes. The beam strengths obtained from the numerical analysis together with the available test data were compared with the design strengths calculated from the current direct strength method (DSM). The critical elastic local and distortional buckling moments including the influence of holes that are required in DSM calculation were determined by rational finite strip analysis. It is shown that the DSM formulae in the North American Specification AISI S100-16 are capable for predicting the design strengths of the built-up open section beams with holes, while are quite conservative for the closed section beams with holes. Modifications are proposed for the DSM formulae for built-up closed section beams with holes. In this study, the current DSM was extended to cover the cold-formed steel built-up open and closed section beams with holes.

1. Introduction

Web openings are commonly employed in the cold-formed steel joists to let electrical and plumbing facilities pass through. The most common shape of holes is circular, although various shapes can be used for web opening in floor joists [1]. Cold-formed steel joists of open sections such as C-sections and Z-sections can be used. These joists have weak torsional rigidities and are prone to fail by lateral torsional buckling. A good solution for this problem is to “build-up” two individual sections together to form the double-symmetric built-up open sections or built-up closed sections. The failure behaviour and strength of built-up open and closed section beams with circular web perforations are investigated in this study.

The structural behaviour of perforated steel members have been investigated by a number of researchers. These studies included perforated plates conducted by Narayanan and Chow [2], Shanmugam et al. [3,4], El-Sawy and Nazmy [5]; and structural members with perforated elements by Yu and Davis [6], Ortiz-Colberg [7], Sivakumaran [8], Davies et al. [9], Pu et al. [10]. It was found that the compression capacity of stub column reduces as the perforation length increases [11]. The influence of hole width and height on the strength of members strongly depended on the web slenderness ratio [12]. Regarding to the research on cold-formed steel flexural members with perforations, Shan et al. [13] studied the influence of web openings on the flexural behaviour of beams with openings. Sivakumaran et al. [14] conducted some flexural tests on perforated channel sections considering different hole shapes and identified the most effective approach to restore the strength of sections with large web openings. Seo et al. [15,16] used the equivalent reduced web thickness concept and proposed appropriate design rules for LSB sections with web holes. Four-point bending tests on cold-formed steel lipped channel section joists with rectangular unstiffened web holes were completed by Moen et al. [17]. Numerical study was undertaken by Ling et al. [18] to investigate the lateral-torsional buckling behaviour of cold-formed C-channel purlins under varying perforated conditions. Previous studies were primarily focused on cold-formed steel open sections with web

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Nomenclature

b_f	width of flange
b_l	depth of lip
C_P	correction factor in reliability analysis
d_h	hole diameter
e	location of screw in cross section
F_m	mean value of fabrication factor
f_y	yield stress
h_w	overall depth of web
M_{crd}	critical elastic distortional buckling moment including the influence of holes
M_{crl}	critical elastic local buckling moment including the influence of holes
M_d	predicted design strengths of beams
M_{DSM}	nominal flexural strength predicted by current direct strength method
M_{DSM*}	nominal flexural strength predicted by modified direct strength method
M_{EXP}	moment capacities obtained from experimental investigation
M_{FEA}	moment capacities obtained from finite element analysis
M_m	mean value of material factor
M_{nd}	nominal flexural strength for distortional buckling
M_{ne}	nominal flexural strength for lateral-torsional buckling
M_{nl}	nominal flexural strength for local buckling
$M_{nl\text{-}m}$	nominal flexural strength for local buckling using the modified equations
M_y	member yield moment
M_{yg}	member yield moment of gross section
M_{ynet}	member yield moment of net cross section
P_M	mean value of experimental / FEA -to-predicted moment ratio
S_f	gross section modulus referenced to the extreme fiber at first yield
S_{fnet}	net section modulus referenced to the extreme fiber at first yield
t	thickness of steel plate with coating
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_P	coefficient of variation of experimental-to-predicted moment ratio
β_0	target reliability index
β_1	reliability index using the load combination of 1.2 dead load + 1.6 live load
β_2	reliability index using the load combination of 1.2 dead load + 1.5 live load
λ_d	slenderness for distortional buckling
λ_l	slenderness for local buckling
λ_0	demarcation value of local slenderness failed by yielding of net section
$\sigma_{0.2}$	0.2% proof stress (yield stress)
ϕ_b	resistance factor for beams

holes. There are few investigations on the structural behaviour of perforated built-up sections subjected to bending. Wang and Young [19] conducted a series of beam tests on the cold-formed steel built-up open and closed sections with web perforations.

The design rules of perforated members have also been investigated by many researchers. Miller and Peköz [20] treated the perforated web of the wall stud as two unstiffened elements subjected to stress gradient for sections bending about the strong axis. Abdel-Rahman and Sivakumaran [12] developed the effective design width equations for plates having square and elongated perforations in compression. Moen and Schafer [21] extended the finite strip method to predict the local and distortional buckling of cold-formed steel members with holes, in which modifications to the element thickness and determination of buckling half-wavelength were appropriately considered. The direct strength method (DSM) was extended for the design of beams with holes based on the results from both experimental and theoretical investigations of lipped channel sections [22,23]. It was shown that the DSM can be adopted to predict the design strengths of cold-formed steel columns when the critical buckling stresses were predicted appropriately using finite strip method for built-up sections [24,25]. However, the influence of web holes on the elastic buckling stresses of cold-formed steel built-up section beams, and the feasibility of DSM for the built-up sections with holes have not yet been investigated.

This paper presents the details of the numerical study into the failure behaviour and strength of built-up sections with circular web perforations located in the moment span. The main aim of this research is to investigate the effect of web perforations with different diameters on the moment capacities of cold-formed steel built-up sections with different slenderness. Moment capacities of beams obtained from numerical study and experimental investigation were compared with the predicted strengths using the current formulae of direct strength method (DSM) in the North American Specification [26]. The current DSM formulae were also evaluated and modified for the design of cold-formed steel built-up open and closed section beams with holes in this study.

2. Finite element model for built-up section beams

2.1. General

The finite element software ABAQUS [27] was used to develop numerical models and perform nonlinear analysis of the built-up section beams with web holes in the test program conducted by Wang and Young [19]. In consideration of the huge computation time cost and the potential convergence problems with many contact elements of the built-up sections in finite element analysis, only half of the finite element (FE) model was created using symmetric properties of loading, support and geometry of the beams. The measured cross-section dimensions and initial local geometric imperfections of the test specimens were used in the FE models.

2.2. Material model and element type

The cold-formed steel sections were created using S4R shell elements based on the measured out-to-out dimensions and the base metal thicknesses of the test specimens. The rounded corner of the sections was ignored since the inner radius of the corner is very small. The nonlinear properties of the cold-formed steel material was included in the FE models based on the measured stress-strain curves obtained from the flat tensile coupon tests conducted by Wang and Young [19]. The plastic curves of true stress and logarithmic true plastic strain based on the measured stress-strain data were used as the material model. The meshing size of the models is approximately 5 × 5 mm (length by width) for beams with nominal web depth of 86 mm and 10 × 10 mm for beams with nominal web depth of 136 mm. A smooth transition of the mesh was adopted around the web holes of the beams. The quadrangular shell elements were used in the FE beam models.

2.3. Boundary and loading conditions

It should be mentioned that during the tests, both the loads and reaction forces were distributed from the load transfer plates to the