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Finite element modeling of cold-formed steel channels with solid and slotted webs in shear

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ABSTRACT

This paper presents finite element models of cold-formed steel channels with solid and slotted webs subjected to shear. The models were created in ANSYS and validated against test data. The effects of boundary conditions on the elastic shear buckling load and the ultimate shear strength were numerically investigated on the models with the test setup and realistic boundary conditions. The obtained results showed that the elastic shear buckling loads and the ultimate shear strengths of the slotted channels were affected considerably more by the boundary conditions when compared with the solid channels. Therefore, the actual boundary conditions should be considered in further parametric studies of the slotted channels.

1. Introduction

Cold-formed steel (CFS) framing has been successfully used in residential construction throughout the world. It has many advantages over wood framing, such as strength, durability, stability, non-combustibility, sustainability, and cost-effectiveness. However, steel conducts heat better than wood, which makes wood framing more thermally efficient unless special measures are taken to reduce thermal conductivity of CFS framing. One of the ways of reducing thermal bridging in CFS members is dividing the web area of studs and purlins by several staggered courses of slots [1–3]. The slots, however, compromise structural properties of CFS members.

The effects of the slotted webs on the strength and behavior of CFS channels in compression and bending were studied in [4–6]. The information about the shear strength and behavior of CFS channels with slotted webs is very limited [7]. The existing CFS design standards, such as AISI S100 [8], EN 1993-1-3 [9], and AS/NZS 4600 [10], deal with the shear strength of solid webs or webs with single holes and do not address the shear strength of the slotted channels.

The experimental study carried out by Degtyareva and Degtyarev [7] showed that the web perforations caused a significant reduction in the ultimate shear strength. It was also demonstrated that the slotted channels exhibited post-buckling strength due to tension field action. Tentative equations for the shear capacity of the slotted channels with and without tension field action were proposed in [7].

The obtained experimental results and the developed tentative equations apply only to one specific perforation pattern and size of the slots used in the study. CFS channels with other perforation patterns and slot sizes should also be studied. It was also pointed out that the shear strength and behavior of the CFS channels in laboratory shear tests may differ from those in real structures [7]. The effects of the boundary conditions on the shear strength of the slotted channels should be investigated.

The finite element (FE) method has been successfully used by many researchers and has proven to be a very effective and powerful tool for analysis of CFS members and predicting their strength and behavior. Pham and Hancock [11–13], Keerthan and Mahendran [14–18], Pham et al. [19] used the FE method for studying the elastic buckling and ultimate shear strengths of CFS channels with solid webs. Keerthan and Mahendran [20,21] also carried out the FE analysis of CFS channels with single holes.

Pham and Hancock [11–13] numerically studied the shear strength and behavior of CFS channels using the software package ABAQUS. They modeled the channels with the 4-node shell elements with reduced integration, type S4R. Three different element sizes were considered: 20 mm, 10 mm, and 5 mm. The convergence study showed that the 10 mm element size provided reasonable accuracy and was computationally efficient. Therefore,

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Nomenclature

a	shear span
b_f	channel flange width
b_{pl}	width of flange reinforcing plates
b_{WSP}	web side plate width
D	channel overall depth
e_h	edge distance of the bolt connection in the realistic boundary conditions
F_u	tensile strength of steel
F_y	yield stress of steel
h	depth of flat portion of web
h_{WSP}	web side plate height
r	inside bend radius
s_h	distance between bolts in the realistic boundary conditions
t	base steel thickness
t_{pl}	thickness of flange reinforcing plates
V	shear load
$V_{FEA\text{-}R}$	ultimate shear strength for the realistic boundary conditions
$V_{FEA\text{-}TS}$	ultimate shear strength for the test setup boundary conditions
$V_{cr\text{-}R}$	elastic shear buckling load for the realistic boundary conditions
$V_{cr\text{-}TS}$	elastic shear buckling load for the test setup boundary conditions
V_{test}	shear strength obtained from tests

the 10 mm element mesh was used in the studies. Non-linear stress–strain curves of the steel obtained from tensile coupon tests were incorporated into the models. The boundary conditions and the specimen loading repeated those in the tests except for only one channel beam was modeled to save computational time. The simulation for each specimen consisted of two steps. First, the elastic buckling analysis was performed on a perfect channel to obtain its buckling modes. Second, the non-linear analysis of the channel was performed accounting for the material plasticity strains and initial geometric imperfection to obtain the ultimate shear strength and failure modes. The initial geometric imperfections were based on the buckling eigenmodes with the magnitudes based on two scaling factors of $0.15t$ and $0.64t$ (where t is the thickness of section) as proposed by Silvestre and Camotim [22] and Schafer and Pekoz [23], respectively.

Keerthan and Mahendran [14–18,20,21] modeled CFS channels in ABAQUS using thin, shear flexible, isometric quadrilateral shell with four nodes and five degree of freedom per node, utilizing reduced integration and bilinear interpolation scheme, type S4R5. They tried 10×10 mm, 10×5 mm, and 5×5 mm mesh sizes and concluded that the 5×5 mm mesh size resulted in an accurate representation of shear buckling deformations and provided suitable accuracy for all considered CFS sections. The 5×5 mm mesh was used in their numerical studies. They found that corner radiuses had a negligible effect on the shear behavior and strength. Therefore, the channels were modeled without the corner radiuses. Keerthan and Mahendran used simply supported boundary conditions when they studied the elastic shear buckling [14,15] and modeled web side plates (WSP) as rigid bodies at the section shear center at the supports and the loading point when they studied the ultimate shear strength [16,17,20,21]. When the simply supported boundary conditions were used, the load was applied to the channels webs and flanges based on the shear flow to eliminate torsion in the models. The load was assumed to be uniformly distributed through the web and the flanges. The elastic perfectly plastic material model was specified when the ultimate shear strength was studied. The fabrication tolerance limit of $h/150$ (where h is the depth of the flat portion of web measured along the plane of the web) was used as the initial geometric imperfections magnitude.

The above mentioned studies demonstrated that the FE method can predict the elastic buckling and ultimate shear strengths of CFS channels with solid webs and webs with single openings with reasonable accuracy. They also showed that the FE is capable of accounting for the effects of different boundary conditions on the shear strength.

The primary objectives of this study were to develop FE models of CFS channels with solid and slotted webs subjected to shear and to numerically investigate the effects of boundary conditions on the shear buckling and ultimate shear strengths. The developed FE models will be used in numerical studies of the shear strength and behavior of slotted channels with different slot sizes and perforation patterns.

2. Finite element modeling of solid and slotted cold-formed steel channels in shear

In this study, the CFS channels with solid and slotted webs tested in [7] were modeled using the software package ANSYS. The tested profiles are shown in Fig. 1. Properties of the tested channels are given in Table 1. This section describes the developed FE models and their validation.

2.1. Element types and material properties

Two identical channels bolted back-to-back were tested in the experimental program [7]. Due to the symmetric conditions, only one-half of one channel was modeled as shown in Fig. 2. In the tests, the channels webs were clamped between two WSPs at the end supports and at the loading point, while only one WSP at each location was used in the models. The CFS channels, reinforcing plates and WSPs were modeled with the four-node element with six degrees of freedom at each node, type SHELL181. The channels and reinforcing plates were modeled as elastic-perfectly plastic materials using the bilinear isotropic hardening material model (BISO). The WSPs were assumed to be elastic. The elastic modulus and Poisson's ratio of the channels, reinforcing plates, and WSPs were taken as 200,000 MPa and 0.3, respectively. The screw connections between the reinforcing plates and the channels in the longitudinal direction were modeled with COMBIN39 nonlinear spring elements, which allowed for taking the connections flexibility into consideration. The force–deflection behavior of the COMBIN39 elements was elastic for the forces up to the screw strength and perfectly plastic beyond the deflection corresponding to the screw strength. The screw strength and flexibility were determined in accordance with AISI S310 [24].

2.2. Finite element discretization

The channels, the reinforcing plates, and the WSPs were discretized with quadrilateral element meshes. To determine an appropriate mesh density, a convergence study was carried out on the solid and slotted channel models. The test specimen C-150-0.9-1 was modeled using the maximum element sizes of 10 mm, 5 mm, and 2.5 mm. Figs. 4(a) and 5(a) show the elastic shear