Overview on research on the strength and behavior of cold-formed steel members with perforations

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Abstract. The paper presents an overview on research of the influence of perforations on the behavior and capacities of cold-formed steel members, with the most common channel sections. The key findings have been incorporated into American Specification with the development of the Direct Strength Method in design. The paper also introduces the application of the Direct Strength Method in previous studies on the impact of perforations on capacities of cold-formed steel channel members. The overview presented in this paper helps researchers to identify gaps for further investigation. Additionally, the obtained investigated results provide designers in better understanding the effects of perforations on the capacities of cold-formed steel channel members. It was found that there is a reduction in sectional capacities of channel sections with an increase in hole dimensions. Also, reduced hole heights and extended hole lengths are proposed to get optimal section capacities while maintaining the unchanged web hole area in general.

Keywords. Review, Web holes, Strength and behavior, Cold-formed steel members.

1 Introduction

The creation of openings in construction is often carried out on structural members to meet the technical requirements of the project. These holes are also commonly found in cold-formed steel structures, where it has been demonstrated to impact the behavior and capacity of such structural members. Research on cold-formed steel structures with openings has gained significant attention worldwide, providing valuable insights into the behavior of these structures. The research findings serve as a foundation for researchers to propose design recommendations considering the influence of these openings. Prominent contributors to research on this type of structure include research groups from the

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University of Sydney, Australia ([1]; [2], [3]), the University of Auckland, New Zealand [4] [5] [6] [7] [8], and Johns Hopkins University, USA [9], [10], [11], [12], [13].

The paper aims to summarize research studies on the behavior of cold-formed steel members worldwide, taking into account the influence of holes. This summary is intended to provide researchers with an understanding of existing knowledge and identify gaps for further investigation. Additionally, the article compiles certain research findings to assess the impact of such holes on sectional capacities of cold-formed steel sections, with a focus on the channel section – a widely used cold-formed section worldwide. These obtained results assist designers in evaluating the influence of web holes in the capacities of channel sections, enabling informed choices in practical design applications.

2 Overview on research studies on cold-formed steel members with perforations

Numerous research papers on cold-formed steel sections with perforations can be found in the existing body of literature. The impact of different hole shapes on the strengths of cold-formed stub columns was examined in ([14], [15], [16], [17]). These investigations focused on assessing the strength and behavior of perforated cold-formed steel columns experiencing local buckling. Both experimental and numerical studies were conducted to establish a database of local buckling strengths for cold-formed steel channel columns. The findings from these studies were subsequently employed to formulate design equations. The impacts of hole locations or hole lengths on stub column capacities were detailed in ([18], [19], [20], [21]). Tests and analyses were conducted on symmetrically perforated channel stub columns to explore the impact of hole size and web hole position on the ultimate strengths of the perforated columns. Subsequently, design formulations for perforated columns were introduced based on the insights gained from these studies. Moen and Schafer conducted numerous studies ([9], [10], [11], [12], [13],) to investigate the behavior and structural strength of cold-formed perforated steel sections. The findings from their research formed the foundation for suggesting the design of perforated sections through the Direct Strength Method, which was later incorporated into Specification AISI S100-16 [1]. Poologanathan and Mahendran ([22], [23], [24], [25]) examined the shear capacities of cold-formed Litesteel and steel channel beams with web perforations through experimental and numerical investigations. The findings derived from their research were utilized to enhance the shear design guidelines specified in AS/NZS 4600:2005 [26]. Effects of holes on the compressive capacities of aluminium alloy circular hollow sections were investigated by Feng et al [27] by developing experimental and numerical studies, which allows proposing new design equations based on the effective area method as regulated in The American Specification AISI S100-16 [28]. Fang et al ([29], [30]) studied the effects of web holes on the strength and behavior of back-to-back built-up aluminium alloy stub channel columns based on experimental and numerical investigations; this helps to assess the Australian/New Zealand Standard [31] and American Specification [32] in the design, and proposes the reduction factor equations for the design of these such columns. Also, Fang et al [33] studied the interior-one-flange web crippling strengths of steel channel sections with web holes at elevated temperatures based on the numerical investigation, followed by the proposal of reduction factors for this web crippling strength at ambient and elevated temperatures.

A novel generation of cold-formed steel channel sections featuring edge-stiffened web holes has been developed, garnering interest from both researchers and users. The elastic buckling analysis for cold-formed columns and beams incorporating edge-stiffened holes was conducted using simplified methods, as outlined in [11], and detailed in ([34], [35]). Chen et al. [36] further presented experimental and numerical programs focusing on compression tests of cold-formed channel sections, comparing those with edge-stiffened web holes and those without holes. The research revealed a 22% increase in the compression resistance of channel sections with edge-stiffened web holes. In contrast, sections with unstiffened holes experienced a 20% reduction in compression resistance compared to plain channel sections. Subsequently, Chen et al. [4] conducted a parametric study to broaden the spectrum of strength results by varying column slenderness, stiffener length, hole size, hole spacing, hole location, and fillet radius. The findings from the numerical study were then compared with predictions from existing Australia/New Zealand [37] and American specifications [28]. This comparative analysis led to the refinement of design equations. Additionally, Chen et al. [5] delved into the strength and behavior of cold-formed steel channel beams with edge-stiffened web holes through a combination of experiments and numerical investigations. The results from both tests and numerical analyses showcased moment enhancements in channel beams with edge-stiffened web holes compared to their plain counterparts. Chen et al. [6] and Chen et al. [7] conducted studies on back-to-back cold-formed steel channel columns and beams featuring edge-stiffened holes. These investigations involved both experimental and numerical approaches, aiming to assess the adequacy of design provisions outlined in AISI S100-16 [1] and AS/NZS: 2018 [42] for such members. Chi et al [8] investigated the strengths of back-to-back cold-formed steel channel columns with edge-stiffened holes. The study demonstrated the strength improvements of the back-to-back channel columns with edge-stiffened holes compared to channel columns without web holes. In Chen et al. [38], a series of shear tests and numerical investigations were conducted to assess the shear capacities of a channel section with both edge-stiffened and unstiffened web holes. It was found that the shear capacities of the channel section with edge-stiffened web holes increased by 14.5% on average compared to those of the channel section with unstiffened web holes. The test and numerical results were compared to the design predictions from specifications AISI and AS/NZS; it was found to be unconservative by 7% of the design of the channel sections with edge-stiffened web holes; the shear capacity reduction factor was subsequently proposed for the design. Uzzaman et al [39] investigated the effects of edge-stiffened holes on web crippling behavior under end-two-flange loading conditions based on experimental and numerical investigations. These obtained results were the bases for the design recommendations in the form of web crippling strength reduction factors. Also, Uzzaman et al [40] presented a combination of experimental and program numerical investigation to investigate the impacts of edge-stiffened holes under interior-two-flange loading conditions on the web crippling strength and behavior. The web crippling strength reduction factors are recommended for the design of cold-formed steel channel sections. Subsequently, parametric studies on the behavior of cold-formed stainless steel channel sections with circular web holes under end-one-flange and interior-one-flange loading were developed by Fang et al [41] and Fang et al [42]. The parametric study results were used to propose new web crippling strength design formulae using reliability analyses. Web crippling capacity was studied by Chen et al [43] on fastened cold-formed steel channels under two-flange loading conditions. It was found that the proposed reduction factor proposed by Uzzaman et al [39] provides close predictions to the obtained test results.

The research studies mentioned above focused on the investigation of cold-formed steel sections, examining those with either circular or slotted holes. Similarly, cold-formed steel sections with square or rectangular holes are frequently manufactured to meet the demands of building service installations. The literature also encompasses information on these cold-formed sections featuring rectangular holes. Yao and Rasmussen ([44], [45]) conducted studies on the effects of rectangular holes on the strength and behavior of cold-formed steel channel columns. Their work involved the development of experimental and parametric studies. The strengths obtained from these column studies were utilized to propose new design equations for cold-formed perforated steel channel columns, utilizing the Direct Strength Method as specified in AS/NZS 4600:2005[26]. Crisan et al. [46], [47] conducted experimental and numerical investigations to analyze the behavior of cold-formed steel pallet rack columns featuring rectangular holes. Their research enabled the formulation of buckling curves for these specific sections. Shakerley and Brown [48] explored the effects of rectangular holes on the elastic buckling of plates. Additionally, Pham [49] investigated the impacts of hole locations on the elastic global buckling loads of cold-formed steel channel members with rectangular holes. Sivakumaran [50] reported on the local buckling capacities of cold-formed stub steel channel columns with rectangular holes. Shan et al. ([51], [52]) and Schuster et al. [53] conducted research studies investigating the effects of rectangular web holes on the reduction of shear strength in channel sections. Pham et al. [1] and Pham et al. ([2], [3]) studied the behavior of cold-formed steel channel sections with square holes in shear, proposing extensions to the Direct Strength Method for shear.

Based on the aforementioned comprehensive review, it is evident that the Direct Strength Method (DSM) has been developed and incorporated into American design standards AISI S100-16 [28] to consider the impact of holes on the capacities of such members. This method has demonstrated its advantages over traditional design approaches [54], and has been applied in investigating the strength of cold-formed steel channel members [55] [56] Therefore, this paper will introduce the application of DSM in the design, and summarize obtained results for providing recommendations to designers, enabling them to understand the behavior of cold-formed steel members, followed by providing proper selections in the design.

3 Application of The Direct Strength Method in Design of Cold-formed Steel Channel Sections with Perforations

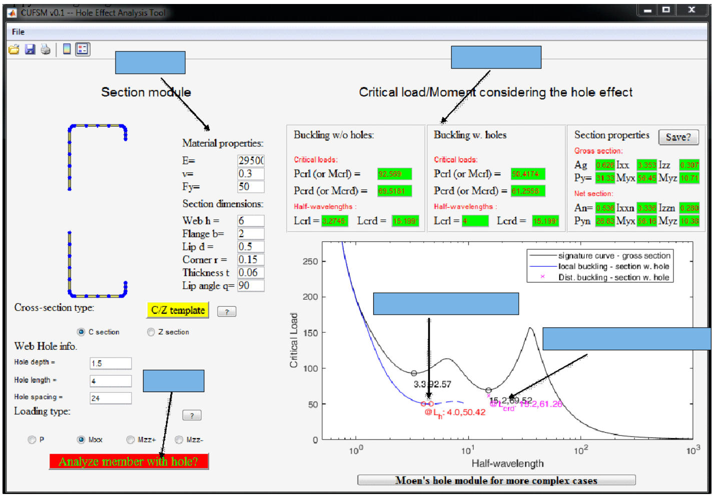
The American Specification AISI S100-16 employs the Direct Strength Method (DSM) to determine the capacities of cold-formed steel structural members. This innovative approach enables the prediction of cold-formed steel section capacities with perforations by relying on elastic buckling loads. Elastic buckling analyses are essential when applying the DSM in the design. However, determination of the elastic buckling loads for cold-formed steel sections with perforations can be challenging when using existing buckling analysis software programs [55]. Therefore, a new simplified method has been developed by Moen and Schafer [11] to determine elastic buckling loads of cold-formed perforated steel sections. This development is crucial for implementing the Direct Strength Method (DSM) in the design of perforated cold-formed steel sections, as outlined in AISI S100-16 [28].

The recently devised module in the CUFSM software program, created by The American Iron and Steel Institute[57], [58] and based on the research findings of Moen and Schafer [9], [10], [11], [12], [13], facilitates an easy determination of the elastic buckling loads for such sections by designers. The program operates with straightforward inputs and promptly provides elastic buckling analyses for both cross-sections with and perforations, as depicted in Figure 1 [55] . More details for the applications of this software programs can be found in Pham [55]. Based on the obtained results in Pham [55] on elastic buckling loads, it was found that the elastic local buckling loads are notably influenced by the heights of web holes, whereas the lengths of web holes have a significant impact on the elastic distortional buckling loads.

The elastic buckling analysis results from this software program are used for the determination of capacities of cold-formed steel sections or members as presented in Pham [56] with the application of the DSM in design. Figure 2 shows the sectional capacities of cold-formed steel channel sections with the variation of hole sizes, where D is the depth of the section; Lhole, hhole are the the length and the height of the web holes, respectively; (Ps,h; Ps,nh) and (Ms,h; Ms,nh) are the sectional capacities with and without perforations under compression and bending, respectively. The investigated results in Pham [56] showed that:

In general, there is a decline in sectional capacities observed with an increase in hole dimensions.

It was discovered that perforated channel sections with smaller hole heights and longer hole lengths were suggested to achieve optimal section capacities, considering the same web hole area. However, the opposite trend was observed for these sections when subjected to bending with long hole lengths.



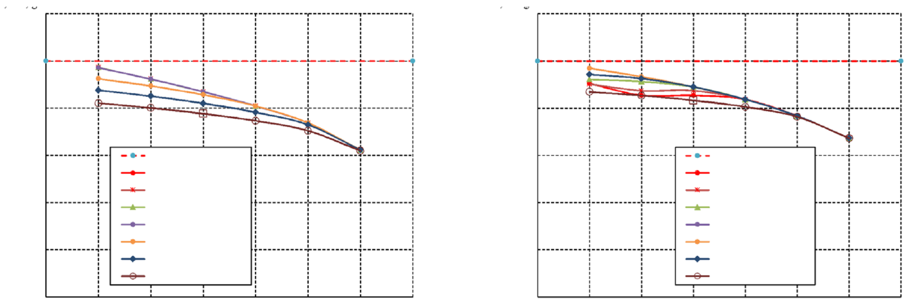
Material properties:
E= 29500
v= 0.3
Fy= 50
Section dimensions:
Web h = 6
Flange b= 2
Lip d = 0.5
Corner r = 0.15
Thickness t 0.06
Lip angle q= 90
Cross-section type:
● C section ○ Z section
Web Hole info.
Hole depth = 1.5
Hole length = 4
Hole spacing = 24
Loading type:
○ P ● Mxx ○ Mzz+ ○ Mzz-
Analyze member with hole?

Buckling w/o holes:
Critical loads:
Pcrl (or Mcrl) = 92.569
Pcrd (or Mcrd) = 69.5181
Half-wavelengths :
Lcrl = 3.2745 Lcrd = 15.1991

Buckling w. holes
Critical loads:
Pcrl (or Mcrl) = 50.4174
Pcrd (or Mcrd) = 61.2558
Half-wavelengths :
Lcrl = 4 Lcrd = 15.1991

Section properties
Gross section:
Ag 0.626 Ixx 3.353 Izz 0.307
Py= 31.33 Myx 56.45 Myz 10.71
Net section:
An= 0.536 Ixxn 3.336 Izzn 0.280
Pyn 26.83 Myx 56.16 Myz 10.38

Fig. 1. The module CUFSM software program



a) Compression b) Bending

Fig. 2. Sectional capacities of C25019 section

4 Conclusion

The paper presents an overview on the impacts of the web holes on the strength and behavior of cold-formed steel members, which will be the base for researchers to find the gaps for further studies. Also, the paper introduces the Direct Strength Method and its application in design and investigation. Based on the previous investigations of the sectional capacities of cold-formed steel channel sections, several remarks can be provided as follows:

Elastic local buckling loads are greatly impacted by the heights of web holes, whereas the lengths of web holes have significant influences on elastic distortional buckling loads;

Suggestions were provided for perforated channel sections with reduced hole heights and extended hole lengths to attain optimal section capacities while maintaining the same web hole area. These sections displayed an opposing trend for bending with long hole lengths.

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