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Optimization of Sectional Capacities of Cold-Formed Steel Channel Sections with Perforations

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Abstract. Perforated cold-formed steel members are extensively used to facilitate the installation of technical systems. The presence of these holes, however, can diminish the capacities of such members. To address this concern, the capacities of such steel sections are determined by using the Direct Strength Method according to the AISI S100-16. This approach employs elastic buckling analyses to predict the strengths of cold-formed steel (CFS) sections or members. Applying this method, the study investigates the influence of varying web hole sizes on the sectional strengths of CFS channel sections. The elastic buckling analyses are carried out by utilizing a CUFSM software module introduced by the American Iron and Steel Institute. Obtained results provide insights for analyzing and selecting suitable web hole dimensions to enhance the strengths of these channel sections. It revealed that the sectional capacities can reach the optimal values with the hole heights varying between 0.4 and 0.5 times of the investigated section depths.

Keywords. Optimization, sectional capacities, channel sections, CFS, web holes, perforations

1. Introduction

Cold-formed steel channel members often have pre-punched webs for accommodating technical equipment installations. Such holes have been demonstrated to significantly affect the strengths of these sections [1], and they are accounted for in the design according to the American Specification [2]. These hole shapes can be various including rectangular, circular and slotted web holes. The strengths of these channel sections are assessed by applying the Direct Strength Method (DSM) as presented in [3]–[5], which offers the sectional strengths on the basis of the determination of elastic buckling loads. Such these loads are calculated using a module software program CUFSM which was developed by the American Iron and Steel Institute [6,7], building upon the previous findings [8-10].

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Numerous studies in the literature have explored CFS sections with perforations, particularly focusing on their hole effects on the strengths of CFS short members under compression [1, 11–13]. Additionally, research has investigated how the locations and lengths of web holes influence the strengths of these columns [14-16,17]. Moen and Schafer conducted extensive research [8-10], [18-21] to examine the strength and behavior of CFS sections with web holes. Subsequently, the design of these such sections with web holes was made and incorporated into the AISI S100-16 [2] with the application of DSM method, which will be utilised in this study. The paper aims to explore the sectional strengths of CFS channel sections with web holes utilizing the DSM design specified in AISI S100-16, focusing on variations in dimensions of rectangular web holes. Subsequently, recommendations will be provided for optimizing the sectional strengths of the investigated sections with perforations.

2. The Direct Strength Method for designing CFS sections with perforations

Perforated steel section design adheres to Chapters E and F in AISI S100-16 Specification [1], addressing columns and beams, respectively. The paper focuses solely on studying the sectional strengths of such sections; and, therefore, the global buckling strengths (P_{ce} or M_{be}) approach yield loads (P_y or M_y).

For CFS sections with web holes subject to compression, the nominal strength can be determined as the smallest of these values: The yield load; The local buckling load; The distortional buckling load.

The yield load for the net section

$$P_{ynet} = A_{net}F_y \tag{1}$$

The local buckling load:

$$P_{nl} = \begin{cases} P_y & for\ \lambda_l \leq 0.776 \\ \left[1 - 0.15\left(\dfrac{P_{crl}}{P_y}\right)^{0.4}\right]\left(\dfrac{P_{crl}}{P_y}\right)^{0.4} P_y & for\ \lambda_l > 0.776 \end{cases} \tag{2}$$

The distortional buckling load

For $\lambda_d \leq \lambda_{d2}$, with the slenderness λ_{d2} is given in Equation (6), the following equations can be applied:

$$P_{nd} = \begin{cases} P_{ynet} & for\ \lambda_d \leq \lambda_{d1} \\ P_{ynet} - \left(\dfrac{P_{ynet} - P_{d2}}{\lambda_{d2} - \lambda_{d1}}\right)(\lambda_d - \lambda_{d1}) & for\ \lambda_{d1} < \lambda_d \leq \lambda_{d2} \end{cases} \tag{3}$$

For $\lambda_d > \lambda_{d2}$, the distortional buckling load of the CFS sections with perforations can be presented as follows:

$$P_{nd}=\begin{cases} P_y & for\ \lambda_l \le 0.561 \\ \left[1-0.25\left(\dfrac{P_{crd}}{P_y}\right)^{0.6}\right]\left(\dfrac{P_{crd}}{P_y}\right)^{0.6} P_y & for\ \lambda_l > 0.561 \end{cases} \tag{4}$$

where P_y - the yield load; A_{net} - the net section area; λ_l, λ_d - local and distortional buckling slenderness, respectively; P_y, P_{ynet} - the axial yield loads corresponding to the gross section and the net sections; The slenderness λ_{d1}, λ_{d2} for the distortional buckling modes; P_{crd}, P_{crl} – the elastic distortional and local buckling values of perforated sections; P_{d2} - the load of distortional buckling at the slenderness λ_{d2};

$$\lambda_{d1}=0.561\left(\frac{P_{ynet}}{P_y}\right) \tag{5}$$

$$\lambda_{d2}=0.561\left[14\left(\frac{P_y}{P_{ynet}}\right)^{0.4}-13\right] \tag{6}$$

$$P_{d2}=\left[1-0.25\left(\frac{1}{\lambda_{d2}}\right)^{1.2}\right]\left(\frac{1}{\lambda_{d2}}\right)^{1.2} P_y \tag{7}$$

Under flexure, the nominal strength can be the smallest of the following valuefcs: The yield moment; Local buckling moment; Distortional buckling moment

The yield strength:

$$M_{ynet}=F_y\, S_{fnet} \tag{8}$$

The local buckling moment:

$$M_{nl}=\begin{cases} M_y & for\ \lambda_l \le 0.776 \\ \left[1-0.15\left(\dfrac{M_{crl}}{M_y}\right)^{0.4}\right]\left(\dfrac{M_{crl}}{M_y}\right)^{0.4} M_y & for\ \lambda_l > 0.776 \end{cases} \tag{9}$$

The distortional buckling value:

For $\lambda_d \le \lambda_{d2}$, with λ_{d2} is calculated as in Equation (13), the following equations can be used:

$$M_{nd}=\begin{cases} M_{ynet} & for\ \lambda_d \le \lambda_{d1} \\ M_{ynet}-\left(\dfrac{M_{ynet}-M_{d2}}{\lambda_{d2}-\lambda_{d1}}\right)(\lambda_d-\lambda_{d1}) & for\ \lambda_{d1} < \lambda_d \le \lambda_{d2} \end{cases} \tag{10}$$

For $\lambda_d > \lambda_{d2}$, subsequently the distortional buckling value under bending is given as following equations:

$$M_{nd} = \begin{cases} M_y & \text{for } \lambda_l \leq 0.673 \\ \left[1 - 0.22\left(\dfrac{M_{crd}}{M_y}\right)^{0.5}\right]\left(\dfrac{M_{crd}}{M_y}\right)^{0.5} M_y & \text{for } \lambda_l > 0.673 \end{cases} \tag{11}$$

where M_y - the yield moment value; M_{ynet}, M_y - the yield moment values of net and gross sections; S_{fnet} - the net section modulus value to the outer fibre at the first yield; M_{crd} and M_{crl} - the elastic moment values for distortional and local buckling modes.

$$\lambda_{d1} = 0.673\left(\frac{M_{ynet}}{M_y}\right)^3 \tag{12}$$

$$\lambda_{d2} = 0.673\left[1.7\left(\frac{M_y}{M_{ynet}}\right)^{2.7} - 0.7\right] \tag{13}$$

$$M_{d2} = \left[1 - 0.22\left(\frac{1}{\lambda_{d2}}\right)\right]\left(\frac{1}{\lambda_{d2}}\right) M_y \tag{14}$$

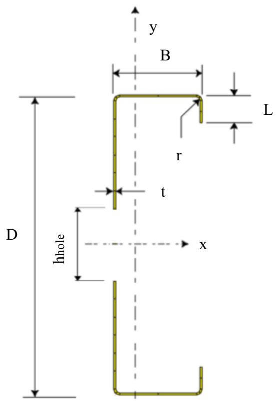
3. Optimising Capacities of CFS Channel Sections Subjected to Bending or Compression

For this investigation, section C25024 is utilized, as depicted in figure 1 and detailed in table 1. The lengths of web holes (L_{hole}) vary between 0.5D and 3.0D, and their heights (h_{hole}) range between 0.2D and 0.8D (with D represents the investigated sectional depths). Material properties considered in this study include the value of Young's modulus is taken as 203,400 MPa, and yield stress value of F_y equal to 345 MPa.

Table 1. The investigated CFS channel section dimensions (according to the unit "mm").

Channel	Thickness (t)	Depth (D)	Width (B)	Lip length (L)
25024	2.4	254	76	21.5

The crucial requirement for applying the Direct Strength Method in design is to carry out sectional buckling analyses. The buckling analyses were conducted for these examined CFS sections featuring web holes, utilizing the software module CUFSM ([6], [7], [22]), as depicted in figure 2. According to findings from Pham [23], it was revealed that the local buckling loads were solely impacted by the ratios of hole heights to sectional depths (h_{hole}/D), whereas elastic distortional buckling moments were contingent upon the length and depth ratios (L_{hole}/D) of the investigated sections. Consequently, the local buckling or distortional buckling moment values were calculated by varying the lengths and the depths of the holes as illustrated in the figure 3.



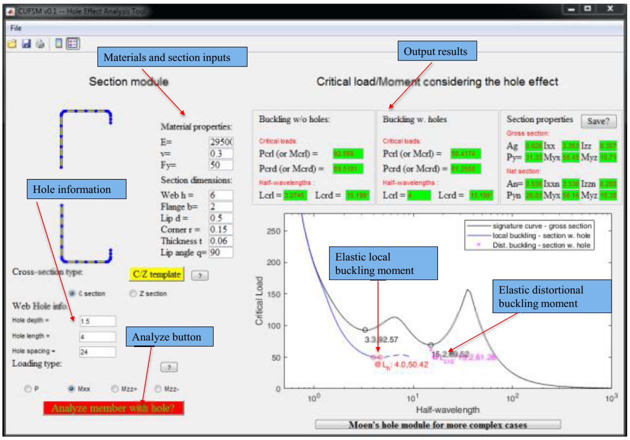
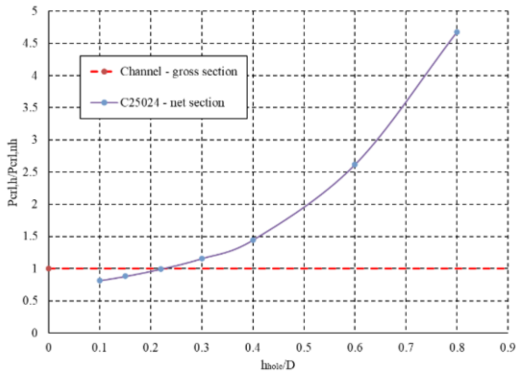
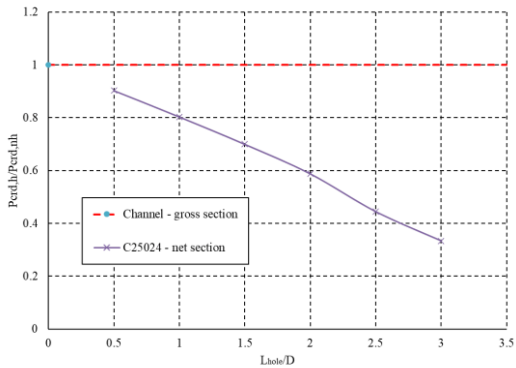


Figure 1. Nomenclature. **Figure 2.** The module software program CUFSM.

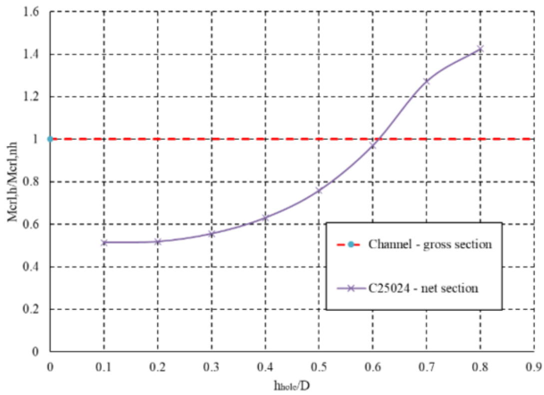


(a) The local buckling loads

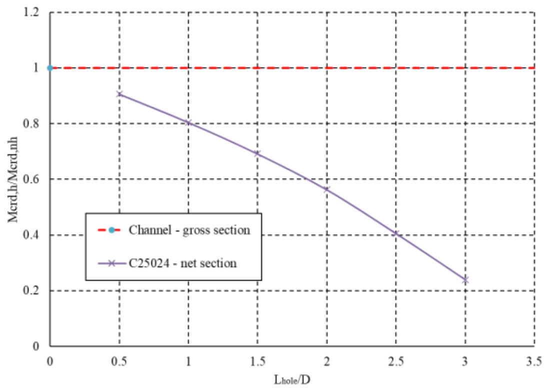


(b) The distortional buckling loads

Figure 3. The buckling loads of CFS channel sections with web holes under compression.



(a) The local buckling moment values



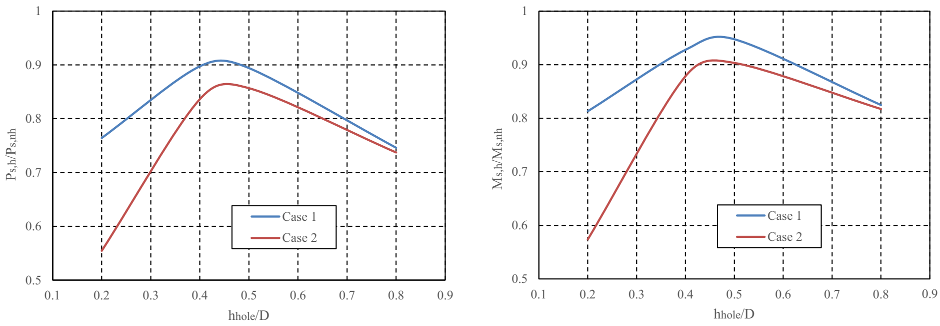
(b) The distortional buckling moment values

Figure 4. The buckling moments of channel sections under flexure.

For local buckling, the analysis reveals that as the hole lengths increase, local buckling loads exhibit upward trends. For small heights of web holes, the local buckling occurs in the areas of the net cross-section, while for larger ones, it manifests at the flat areas of the webs between perforations. Notably, these such loads of the net sections with small hole heights are lower than these of the gross sections, leading to local buckling primarily at the net cross-sections. Conversely, with larger heights, local buckling loads of these former sections exceed these of the latter ones, resulting in local buckling predominantly in flat areas of the webs between holes. For distortional buckling, investigated results indicate that elastic distortional buckling loads exhibit downward trends when the ratios (L_{hole}/D) increase (see figures 3(b) and 4(b)).

The DSM equations presented in Section 2 are employed to calculate the compressive and flexural strengths of CFS channel sections while considering variations in web hole sizes. To optimize hole dimensions for advantageous sectional strengths, a study was conducted for a variety of hole sizes, maintaining identical hole areas but varying relationships between the web hole heights and their lengths. Two cases of hole areas are considered in this investigation, including $0.4D^2$ (Case 1) and $0.6D^2$ (Case 2). The investigated results are illustrated in figure 5.

Figure 5 shows that for small hole heights, changing the hole areas significantly affects the sectional capacities of the investigated section. This is most evident when the hole height is 0.2D. For larger hole heights, variations in the hole areas have a negligible impact on their sectional capacities (typical when the hole height is 0.8D). In general, for both investigated cases, the sectional capacities of the investigated sections reach optimal values when the hole heights vary between 0.4D and 0.5D, with “D” is the depths of investigated sections. This hole height values can be proposed in the design to get the optimize sectional capacities.



a) Compression b) Flexure

Figure 5. Sectional capacities of channel sections regarding the identical hole areas

4. Conclusions

The objective of this paper is to study the sectional strengths of CFS channel sections with web holes using the DSM regulation outlined in the American Specification. The study specifically focuses on variations in rectangular hole dimensions. Subsequently, recommendations can be provided for optimizing sectional capacities of the investigated CFS sections with web holes under flexure or compression, as follows:

Variations of sectional capacities are found to be significant for small hole heights but reveal negligible for large ones regarding the variations of hole areas.

The hole heights should be taken between 0.4D and 0.5D to get the optimal values of sectional capacities.

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