Influence of Web Holes on Cold-Formed Steel Members

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The use of cold-formed steel (CFS) members in structural engineering has been on the increase recently due to a wide range of benefits. The placement of electrical and/or plumbing installations within the floor or wall thickness requires that members are being manufactured with holes along the web, inevitably affecting their resistance.

cold-formed steel web holes experimental investigations

1. Introduction

Cold-formed steel (CFS) members with web holes have been used widely in the recent past due to their lightweight structure, cost-effective advantages over the entire construction cycle, structural efficiency, practicality, etc. They are often employed as columns [1][2][3][4][5][6][7][8][9][10][11][12][13][14][15][16], beams [3][4][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31], and the load-bearing structures of sheathed panel shear walls, light frame strap-braced walls, partition walls, curtain/facade walls, floor joists, etc. Mainly, the C-, Z-, and Σ-sections and their varieties are used. These elements are often produced with holes along the web to facilitate electrical, heating or plumbing installations. Consequently, a resistance decrease of the member is expected. This issue has been addressed by adding stiffeners along the section [9][16][32] and hole edges [4][13][14][15][22][28][33][34][35][36]. Since the behaviour of CFS elements is dictated by instability effects rather than the yield of the material, the size and location of web holes along the element can prove to be an important factor [6][8][14][17][18][21][23][24][25][28][30][37][38][39][40][41][42][43][44][45][46].

Previous research was mainly focused on short- and medium-length elements, since they are prone to distortional and local bucking. In such cases, the location of a hole may coincide with the position where the maximum displacement of the buckling half-waves is expected [2]. Longer elements tend to buckle in a global mode, assuming that the ultimate member resistance is not influenced by the position and the number of web holes along the element. Although the majority of research has been focused on elements subjected to pure compression or bending, in recent years, web crippling [33][34][35][36][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61][62][63][64][65] and shear [43][44][45][46][66][67][68][69][70][71][72][73] behaviour have been analysed as well. However, a commonly occurring case in the engineering practice of combined compression and bending [32] should have attracted more attention from researchers. This issue has been addressed when it comes to CFS members without web holes [74][75][76][77][78][79][80][81][82][83][84] and CFS members with small and densely arranged perforations typical for rack uprights [85][86][87][88].

2. Bending

2.1. C-Section Beams

Extensive experimental research on the flexural, shear, and the combination of flexural and shear behaviour of CFS C-section elements with holes was conducted by Shan et al. [23]. The investigation stage of the flexural behaviour and strength was presented in [24]. Test specimens consisted of two connected simply supported C-section beams subjected to four-point bending test. Most of the specimens failed in local buckling, while some failed in the distortional. The bending resistance was mostly influenced by the web-opening-depth-to-web-flat-width ratio. Three different methods were examined for the determination of the moment capacity. The most accurate method was the effective net section approach, while the modification of the 1986 edition of AISI specification [89] using modified effective web area overestimated the bending resistance.

A somewhat different test setup was used by Shan et al. in [25], which was also one of the phases of the research presented in [23]. The interaction of flexural and shear behaviour showed that the local buckling around the hole and in the zone of load application was the governing failure mode. The ultimate resistance was evaluated by the use of the interaction equation incorporated in [89], and it was concluded that the predicted strength was accurate enough if the influence of the web holes was accounted for by the modification of the individual shear and bending capacities.

CFS C-section beams with rectangular web holes were experimentally tested by Moen et al. [29]. Test specimens consisted of two back-to-back connected beams. In each test, the failure first appeared in just one of the two beams. In most cases, distortional buckling with the maximum displacement at the hole was noticed, followed by unstiffened strip buckling of the compressed web above the hole. The unstiffened strip buckling was eliminated in cases where the hole depth was close to the web height. Nonetheless, an instantaneous local buckling of the compressed flange above the hole occurred. The flexural capacity of the tested specimens was compared to the one provided from the DSM equations of AISI S100-2007 [90]. Sufficient accuracy was achieved, although in some cases the ultimate capacity was underestimated.

The flexural behaviour, bending resistance, and failure modes of CFS members with circular web holes were investigated by Wang and Young [30]. Built-up beam specimens were subjected to a four-point bending test. Open and closed cross-section types were considered, as well as the influence of cross-section size and hole dimensions. It was discovered that the bending resistance decrease becomes more pronounced when the hole-diameter-to-web-height ratio exceeds the value of 0.5. The calculation of critical elastic local and distortional buckling moments was investigated through different approaches since the design equations in current design codes are intended to be applied only in cases of a single beam. It was concluded that AISI S100-2012 is efficient in the prediction of the design strength of the built-up beams with holes.

In their following research [18], Wang and Young used the data previously collected in [30] to form an extensive parametric study on built-up sections. The parametric study included various section slenderness and hole sizes.

Flexural resistance from the numerical analyses and test data from the previous research were compared to the calculated design resistances from AISI S100-2016. The DSM equations proved to be fairly accurate in the cases of open built-up sections with holes, whereas in cases of closed built-up sections with holes, the DSM equations were quite conservative. For this reason, modifications for the DSM equations for built-up closed section beams with holes were proposed.

The numerical and analytical study by Yuan et al. [19] dealt with the influence of the circular web holes on the distortional buckling of a mono-symmetric CFS C-section beams subjected to a uniform bending moment along its length. Numerical analyses were carried out by the use of a sophisticated FEM modelling tool, while an analytical model was established according to the recommendations provided in EN 1993-1-3. The compressed stiffened element (in this case, the flange) behaves as an elastically supported strut, since the lips of a channel section act as edge stiffeners. The spring stiffness along the length depended on the boundary conditions and the flexural stiffness of the adjacent plane elements of the cross-section. The decrease in the rotational stiffness of the web with regard to the compressed flange-lip element, caused by the introduction of web holes, could be introduced by the application of the proposed reduction factor. Additionally, although the increase in the hole size had reduced the distortional buckling moment, the half-wavelength associated to it had increased.

In their further research, Yu et al. [20] continued to study the influence of the circular web holes on the distortional buckling of the mono-symmetric CFS C-section beams. A detailed analytical study verified by FEM analyses revealed that the flange and lip system model presented by Hancock [26] (originally developed for members without holes) can be employed for the prediction of the distortional buckling stress of C-section beams with holes, provided that the rotational spring stiffness is correctly reduced. Furthermore, the proposed analytical method estimated the critical stress of the distortional buckling more accurately than the modified EN 1993-1-3 method [19]. The conclusion derived in [19] is in line with the one provided herein.

The flexural behaviour of CFS C-section beams with rectangular web holes was researched by experimental and numerical parametric analyses by Zhao et al. [21] in order to evaluate the reliability of the design method incorporated in AISI S100-2016. A four-point bending test was applied on test specimens with a wide range of hole and lip sizes. Specimens with shorter lips tended to buckle in a distortional–local mode interaction controlled by the distortional buckling, while those with longer lips were prone to failure in a local–distortional mode interaction controlled by the local one. Similarly to [30], the bending strength reduction became more apparent when the hole-height-to-web-depth ratio exceeded the value of 0.4. Experimental and FEM parametric results were compared to the DSM design predictions from AISI S100-2016. Modifications of the current design equations were necessary for beams which had exhibited failure in a local–distortional mode interaction controlled by local buckling, since the predicted design strengths lead to discrepancies compared to test results in a large number of specimens.

Numerical research by Moen and Schafer [3], mentioned in the previous section, had also covered the problems of the elastic buckling behaviour of beams with holes. As with columns, separate models are also needed in the case of beams for each type of elastic buckling, since the hole has a different influence on each buckling mode. The concept of “weighted average” cross-section properties for the approximation of flexural-torsional buckling load can also be extended to beams with holes. In addition, the principle of reduced thickness for the prediction of distortional buckling can be applied to beams as well. However, for the determination of local buckling load, only half-wavelengths smaller than the length of the hole are investigated in the net-section model.

Numerical research on the buckling behaviour of C-section beams with perforations of various shapes, sizes, numbers, spacing, and edge distances was carried out by Ling et al. [17]. Although a decrease in the buckling moment was expected with the introduction of web holes, it is worth mentioning that the lowest decrease was reported for a hexagon-shape opening.

2.2. C-Section Beams with Edge-Stiffened Web Holes

In order to limit the resistance reduction to as low as possible, hole edge stiffeners are introduced in beams. The previously discussed numerical research by Grey and Moen [4] examined the influence of hole edge-stiffening on the elastic buckling behaviour of beams as well. The concept of global, distortional, and local buckling load determination follows the same ideas as stated in [3] for members with unstiffened holes.

The behaviour and design of beams with edge-stiffened holes was studied and presented in detail by Yu [28]. FEM analyses were performed in order to investigate the elastic buckling of CFS thin plates and C-section beams with edge-stiffened holes. Critical buckling loads of thin plates with edge stiffeners, subjected to in-plane bending, were higher compared to plates without edge stiffeners. As the hole diameter became larger, the difference between the critical buckling loads was higher. The most efficient length of edge stiffener proved to be 0.06 times the plate width. Moreover, the shape of the first buckling mode was the same, regardless of the presence of the hole. Two different C-sections were analysed for member buckling. Sections were chosen in a manner such that one was prone to the local and the other to the distortional buckling. An increase in the buckling moment was recorded in cases of both local and the distortional buckling when edge-stiffened holes were introduced. Smaller spacing between holes influenced the increase in the buckling moment, since the longer spacing allowed the original lower buckling mode to occur in the area between holes, which means that the beam exhibited the same performance as the one without holes. Thus, the hole spacing of 305 mm proved to lead to optimal performance. Finally, the new design procedure based on the DSM was proposed for channel beams with optimized edge-stiffened holes.

With a similar test preparation as in [15], the same group of researchers conducted a bending test on 14 back-to-back built-up channel specimens [22], of which 6 had edge-stiffened holes. Specimens with one, three, and five web holes were examined. As in their study on axial strength, members with edge-stiffened holes demonstrated a higher moment capacity by as much as 15.4%, while the capacity of the same section with un-stiffened holes was reduced by 15.1%, both compared to that of a plain channel. In all cases, members failed dominantly in the distortional buckling mode. Since the design equations provided by Moen and Schafer [3][29][91] were given for un-stiffened holes, they underestimated the moment capacities of specimens with edge-stiffened ones.

The first to introduce a machine learning model for purposes of prediction of the moment capacity of CFS members with web holes were Dai et al. [31]. They employed the XGBoost tool in order to develop the model. For the model to be trained, a number of FE models should be created and validated against experimental results in the existing literature. Further, a parametric study using the XGBoost model was conducted and a set of new design equations was proposed since the current design equations appeared to be unreliable for moment capacity calculation.

2.3. C-Section Beams with Web Reinforcement

Since the member resistance decreases noticeably when web holes are introduced, in addition to hole edge-stiffening, one of the methods to limit the decrease considers reinforcement of the hole itself.

Several different reinforcement schemes were experimentally tested by Sivakumaran et al. [92] on CFS C-section beams with web openings in order to determine the most adequate one. Test specimens consisted of two face-to-face connected beams subjected to a four-point bending test. Three groups of specimens were tested: a group without web holes, one with a single web hole, and one with a single reinforced web hole, both positioned in the mid-span. Additionally, three different hole shapes were taken into account: circular, square, and rectangular. Specimens without holes failed due to local buckling of the compressed flange and compression in the web zone. The same character of failure could be observed in the members with holes, where it was observed that the local buckling occurs at the location of the opening. In addition, the bending capacity was reduced by approximately 10% compared to the members without holes. Two different hole reinforcement schemes were analysed. The reinforcement was beneficial in the zone close to the compression edges of the opening, whereas their location in the zone close to the tension edges was insignificant. Furthermore, screw fasteners of the reinforcement should be placed as close as possible. The bending capacity of the members with reinforced web holes was close to that of members without holes.

2.4. Comparison and Discussion

After design equations in compression were proposed and established, the research community turned to the design due to bending. Wang and Young [18] gave their proposal for built-up elements that fail in local buckling and Zhao et al. [21] modified it and added the group of equations for distortional buckling. For elements with edge-stiffened holes, Grey and Moen [4] provided provisions for lateral-torsional and distortional buckling, while a year later Yu [28] made his proposal for local buckling, which had a lot of similarities with the Wang's and Young's [18] solution.

All design equations are given for the same yield moment of net cross-section-to-yield-moment-of-gross-cross-section ratio M_{yn}/M_y = 0.8. The exception is the design equation for elements with edge-stiffened holes, introduced in [28], which does not account for the aforementioned ratio. For the elements of low slenderness, the equation given in [17] proved to be the most fitting, while for elements with higher slenderness, AISI S100-2016 turned out to be the most appropriate.

3. Web Crippling

3.1. C-Sections

As a result of their usually slender web, CFS flexural members are prone to web crippling due to high local stress concentration. Moreover, the presence of holes along the web may result in enhanced susceptibility to such effects, especially if the holes are located in the vicinity of the support or the location of the concentrated load.

In their comprehensive research, apart from the investigation on the buckling of compressed elements, Davis and Yu [59] also studied the crippling strength of members with web holes. Test specimens were built-up face-to-face and back-to-back C-sections without lips subjected to the interior-two-flange (ITF) loading condition. The reduction factors for the modification of the AISI [93] design equations were proposed to take into account the effect of circular and square web holes.

Besides the stub column tests, Sivakumaran [94] also carried out web crippling tests on 55 interior-one-flange (IOF) loaded C-section specimens with various hole shapes and sizes. The study found that the 1984 edition Canadian CFS design code [95] yielded about 15% lower web crippling strength compared to experimental.

The same conclusion was derived from the experimental investigation by Sivakumaran and Zielonka [60]. In addition, the web hole height has a more pronounced influence than its length. Moreover, an equation for the web crippling strength reduction factor was proposed to account for the influence of web openings.

During the 1990s, several studies were carried out in the Center for Cold-Formed Steel Structures at the University of Missouri-Rolla. The specimens comprised two back-to-back connected C-sections. The first and the most detailed study was carried out by Langan et al. [61], considering unreinforced and reinforced specimens subjected to the end-one-flange (EOF) and IOF loading conditions. Since the web crippling provisions of the 1986 edition of AISI Specifications [89] were incapable of predicting the web crippling strength of members with web holes, design recommendations were provided. Reduction factor equations were derived for the EOF and IOF cases, and provisions for web reinforcement were given. Extensions were provided by Deshmukh et al. [62] and Uphoff et al. [63]. LaBoube et al. [47] presented a brief summary of the previous studies and drew out the most important conclusions.

Uzzaman et al. [48] conducted experimental research on C-section members with various sizes of circular web holes subjected to ITF loading conditions, in which the load was not applied directly above the hole. The influence of the fastening of flanges to the bearing plates was also considered. Test results were used to validate FEM models, followed by a parametric study. The leading factors for the web crippling strength decrease were hole-to-web-depth ratio and the clear-distance-from-hole-to-the-bearing-plate-to-web-depth ratios. Finally, reduction factors were proposed for the ITF loading condition.

A similar investigation carried out by Uzzaman et al. [49][50] considered both end-two-flange (ETF) and ITF loading conditions. However, in this case the hole was located directly under the concentrated load. The tests and FEM analyses were conducted on 82 specimens, followed by a numerical parametric investigation, which lead to the same conclusion as in [48]. The equations for web crippling strength reduction factors for both ITF and ETF loading conditions for the cases of unfastened and fastened flanges to the support were proposed. In a further study on the web crippling strength of C-sections subjected to the ETF loading condition by Uzzaman et al. [51], similar conclusions as in [48] regarding the web crippling strength reduction factors were outlined.

The web crippling behaviour and strength of the CFS elements with holes subjected to the end-one-flange (EOF) loading condition was investigated by Lian et al. [52][53]. A total of 74 specimens were tested (52 with and 22 without web holes). Test specimens comprised a pair of C-sections with holes of variable dimensions, centred above the bearing plate or offset from it. In addition to the experimental testing, parametric numerical analyses were performed. Web crippling behaviour was mostly influenced by the following ratios: hole to web depth; bearing plate length to web depth; and clear distance from hole to the bearing plate to web depth. Modifications of the design equations given in AISI S100-2016 for web crippling strength reduction factors for the EOF loading condition for the cases of unfastened and fastened flanges to the support were proposed. The web crippling behaviour under the IOF loading condition was studied in a similar manner by the same researchers [54][55].

A similar procedure as described in [49][50], but on ferritic stainless CFS channel sections without lips subjected to the ITF loading condition, was employed in the research by Yousefi et al. [57][58], which also proposed the design equations for the web crippling strength reduction factors.

3.2. C-Sections with Edge-Stiffened Web Holes

The influence of hole edge-stiffening on the web crippling strength of CFS C-sections under IOF and EOF loading conditions was investigated by Uzzaman et al. [33]. Experimental tests were carried out on three groups of 12 specimens: plain sections, sections with unstiffened holes, and sections with edge-stiffened holes. The consequent parametric study explored the influence of web slenderness and hole diameter. The reduction of web crippling strength was up to 12% and 28%, for the IOF and EOF loading conditions, respectively, for the case of unstiffened holes. For the case of edge-stiffened holes, the strength decrease was only 3% for the IOF loading condition, while there was no strength decrease for the EOF loading condition.

The next phase of the experimental testing was to apply the ETF [34] and ITF [35] loading conditions. Both studies were carried out by Uzzaman et al. on 30 web crippling tests, which were accompanied by extensive FEM parametric analysis. It was revealed that the member web crippling strength decrease was minimal, while in some cases it was even improved. In their further experimental and numerical research [36], specimens with fastened flanges demonstrated higher web crippling capacity.

3.3. Comparisons and Discussion

Web crippling of a thin-walled sections is a phenomenon that, in the field of CFS members with holes, has been dealt with for as long as a half a century. Since Davis and Yu [59] proposed equations for web crippling strength reduction factors as functions of the hole-size-to-web-flat-height ratio (d/h), most of the following researchers followed their course. As researchers became more familiar with the web crippling behaviour, more variables were added to design equations. During the past decade in particular, a great effort was put in to develop the most suitable reduction factor equations. However, the essence of the equations remained the same in all research, only with variations in values of numerical constants.

In case of IOF loading, the decrease in the reduction factor is gradual, which means that the d/h ratio does not greatly influence the web crippling strength. An experimental study conducted by Lian et al. [54][55] showed that a significant decrease in bearing capacity can be expected in cases of unstiffened flanges. Based on the experimental research conducted by Lian et al. [52][53] and their proposed equations for the EOF loading cases, it can be concluded that the configurations with the offset holes showed the highest web crippling resistance, unlike the ones with the centred holes. In both cases, the equation proposed in AISI S100-2016 is intended for use in cases within the prescribed provisions.

The most examined case of the web crippling is the case of ITF loading. The web crippling strength decrease was more rapid in comparison to the one-flange loading, which might be caused by the high-intensity local stresses in the vicinity of both sides of the holes.

As in the case of interior-flange loading, the web crippling strength due to the end-flange loading decreases at a faster rate in the case where both flanges are loaded with a concentrated load.

In all cases in which experimental testing was performed on elements with edge-stiffened holes, it was shown that the hole stiffening had a favourable effect on the web crippling strength, i.e., no decrease in load-bearing capacity was observed in relation to the elements without holes.

4. Shear

4.1. C-Sections

The behaviour of a C-section with web openings and a linearly varying shear force was investigated by Eiler et al. [66]. Experimental testing was conducted on a total of 46 test specimens with circular, elliptical, and diamond-shaped holes. Design equations were proposed for the reduction factors that are applied to the shear strength of the same beams without web holes.

In recent years, a group of researchers at the University of Sydney led by Gregory J. Hancock has been investigating the influence of web holes on the behaviour of single CFS members subjected to shear. The effect of circular and square web holes on the buckling behaviour of thin-walled plates and CFS C-sections was numerically investigated by C.H. Pham [43]. The solutions of the Spline Finite Strip Method (SFSM) [96] were utilised. Three load distribution cases for the C-section were investigated, while on the plate only uniform distribution was taken into consideration. It was found that, for small web openings, shear buckling coefficients were only slightly reduced compared to the cases without web holes. A considerable difference in shear buckling coefficients was calculated when the holes were larger. Additionally, the influence of the bending moment applied at one or both ends of the section was negligible. Design equations were proposed for the approximation of the shear buckling coefficients for square plates and C-sections.

Shear experimental testing on 40 C-section specimens with circular web holes was carried out by Keerthan and Mahendran [67]. Simply supported specimens consisted of two bolted back-to-back sections, with and without straps, subjected to a mid-span loading (three-point test). Since short beams without straps experienced combined shear and flange distortion action, the distortion of the flange occurred as a result of distortional buckling. Shear strength was compared to that predicted in the 2005 edition of AS/NZS 4600 [97] and by LaBoube et al. [98]. Since the predictions were either too conservative or unreliable, enhanced design equations were proposed. In their following study, Keerthan and Mahendran [68] conducted a numerical investigation and extensive parametric analysis based on the previously published experimental results and conclusions.

S.H. Pham [44] studied shear buckling and shear strength of CFS C-section members with web holes and with or without intermediate transverse web stiffeners. The experimental investigation and the strategy for a new approach of the DSM design in which the Vierendel mechanism [99] is recognised are summarised in [69][70][71]. Test specimens included two bolted back-to-back C-section beams with a shear-span-to-web-depth ratio (aspect ratio—AR) of 2.0. Web depth and shear span were 200 and 400 mm, respectively. Since, at this aspect ratio, the ultimate state is controlled by bending, in order to isolate the shear failure mode, dual actuator testing equipment was used. Circular holes with diameters ranging from 50 to 145 mm and square holes with sizes from 40 to 120 mm were taken into account. As expected, the shear strength decrease became more pronounced with larger holes and a failure occurred in a proximity of the hole. Furthermore, it was revealed that the design provisions in the specification for structural steel buildings [100] were reliable, contrary to the ones provided by AISI S100-2016, which appeared to be overly conservative.

The extension of the previous research carried out by D.K. Pham et al. [45] on 30 C-section specimens with ARs of 1.0, 2.0, and 3.0 and with different sizes of square, rectangular, circular, and industrially slotted web holes included the same dual actuator test rig as in [44]. It was found that the current DSM design method was reliable for the design of sections with a hole size up to 80 × 240 mm, and a new proposal for the DSM design of shear members with elongated web holes that relies on the Vierendeel mechanism approach was presented.

Based on the previous research, D.K. Pham et al. [72] conducted an FEM parametric investigation for a better understanding of the previous conclusions.

Experimental research by C.H. Pham and Hancock [46] was carried out with the aim to develop a new, simplified equation for shear yielding load (V_y), which is one of the required inputs in the DSM shear design equations. A total number of 24 C-section specimens with a web depth of 200 mm, variable thickness, and square web holes (40 × 40 mm, 80 × 80 mm, and 120 × 120 mm) were tested, followed by an FEM parametric analysis, varying the section thickness and hole size.

4.2. C-Section Beams with Web Reinforcement

The influence of web hole reinforcement in a high-shear zone was also experimentally investigated on built-up CFS beams by Acharya et al. [73]. Test specimens were subjected to a mid-span concentrated load. As in [92], the same three groups of specimens were considered. Circular and square web holes with a height of about 65% of the web depth were taken into account. Three reinforcement schemes were considered. Scheme A, considering solid plate reinforcement around the holes, could not adequately improve the shear strength of the section, while scheme B, in the form of joist section reinforcement in the zone of the hole, could be used only to reinforce the circular web opening. However, reinforcement scheme C, consisting of bridging channels around the hole, proved to be the most suitable to overcome the shear effects due to two reasons: (i) the failure mode shape of specimens with the reinforcement scheme C closely resembles the members without holes, and (ii) the shear resistance was higher compared to the members without holes.

4.3. Comparisons and Discussion

Namely, two different concepts can be recognised. Eiler et al. [66] gave a proposition for the calculation of reduction factors which were later multiplied with the shear resistance of members without web holes. Their concept was later adopted and simplified by Keerthan and Mahendran [67]. Several years later, S. H. Pham [44] introduced an approach in which the shear resistance of a member with web holes is determined directly by taking into account the cross-sectional and hole properties. A similar idea was also recognised in the work of D. K. Pham et al. [45].

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