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Study the Behavior of Steel Beam-Column with Web Opening

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ملخص البحث :

يقدم هذا البحث خلفية عن سلوك الكمرات و الاعمدة المعدنية ذات الفتحات في العصب من الابحاث السابقة باستخدام نماذج التحليل العددي و الاختبارات المعملية. كما يقدم توصيات لتصميم الكمرات المعدنية او المركبة ذات الفتحات في العصب لمختلف الاكواد. وضعت اكواد التصميم طرق مبسطة لتصميم العناصر المعدنية ذات الفتحات في العصب. و مع ذلك فان معظم هذه الطرق تعتبر العناصر المعدنية (الكمرات) مدمجة و مقيدة بدون وجود حمل ضغط محوري. معظم الابحاث السابقة درست تأثير فتحات العصب على سلوك الكمرات المعدنية المعرضة لعزوم الانحناء و على الاعمدة المعدنية المشكلة على البارد و المحملة بحمل محوري. اغلب الابحاث السابقة لم تدرس سلوك العناصر المعدنية ذات الفتحات في العصب و المعرضة لعزوم الانحناء و الضغط المحوري معا. وجود الفتحات في العصب في العناصر المعدنية لها عدة عيوب لان القطاعات تكون اكثر عرضة لانبعاج العصب. و بالتالي يحتاج القطاع الى تدعيم.

ABSTRACT:

This paper provides background information from previous research about the behavior of steel beam and column with web opening using experimental and finite element analysis models. It also presents the design recommendations for steel or composite beams with web opening for different design codes. Recent standards and codes of practice have put forwards simplified methods and procedures for the design of steel members with web opening However, most of these methods consider compact flexural steel members (beams) with restrained supports and without presence of axial compressive load. Most of previous researches studied the effect of web opening on the behavior of steel beam which is subjected to flexural moments and cold formed steel columns which are loaded by axial load. Previous researches did not study the behavior of steel elements with web opening which is subjected to flexural moments and axial load together. The presence of opening in web of steel sections has a disadvantages because these sections are more vulnerable to web buckling. So that, these sections need stiffeners.

Keywords: Steel Beam-Column, Web Opening, Buckling Behavior, Load Capacity

Introduction:

Openings in webs of steel beam or steel beam column are commonly used in steel framed structures to facilitate electrical, mechanical, and sanitary works in addition to access inspection equipments, ventilation ducts, air condition ducts, communication systems, fire protection systems. Another important reason for using web openings in steel beam or steel beam column sections is to reduce the material volume without affecting the structural strength or serviceability requirements.

Previous research:

The steel beams and columns were studied in much previous research by using experimental investigations and analytical solutions. Herein, some of this research are presented.

In 1990, David Darwin [1] prepared guide for design steel and composite beams with web openings which was under the direction of the committee on research of the American Institute of Steel Construction, as a part of a series of publication on special topics related to fabricated-structural steel. Its purpose is to serve as a supplemental reference to the AISC manual of Steel Construction to assist practicing engineers engaged in building design [26]. This design guide presents a unified approach to the design of structural steel members with reinforced or unreinforced web openings. The presented guide procedures are formulated to provide safe, economical designs in terms of both the completed structure and the designer's time. The design expressions are applicable to members with individual openings or multiple openings spaced far enough apart so that the openings do not interact but, castellated beams are not included. For practical reasons, opening depth is limited to 70 % of member depth. The procedure provides a straightforward solution of member capacity at web openings subjected to both bending and shear. The procedure accounts for the contribution of opening reinforcement more accurately than earlier techniques and provides an adequate margin of safety. Many aspects of the design of steel and composite members with web openings are similar. Under the combined loading, member strength is below the strength that can be obtained under either bending or shear alone. Design of web openings consists of first determining the maximum nominal bending and shear capacities at an opening M_m and V_m, and then obtaining the nominal capacities, M_n and V_n for the combination of bending moment and shear that occur at the opening. For steel members, the maximum nominal bending strength, M_m, is expressed in terms of the strength of the member without an opening. For composite sections, expressions for Mm are based on the location of the plastic neutral axis in the un-perforated member. The maximum nominal shear capacity, V_m, is expressed as the sum of the shear capacities, V_{mt} and V_{mb}, for the regions above and below the opening. Equations for maximum bending capacity and details of opening design depend on the presence or absence of composite slab and opening reinforcement. However, the overall approach, the basic shear strength expressions, and the procedures for handling the interaction of bending and shear are identical for all combinations of beam type and opening configuration. Thus, techniques that are applied in the design of one type of opening can be applied to the design of all.

In 1997, Abdel-Rahman [2] has presented a numerical and experimental study to investigate the load capacity of web perforated cold-formed steel members under axial compressive loading. Based on the parametric study, two effective design width equations for stiffened compression plates have been suggested and validated.

In 1998, Abdel-Rahman and Sivakumaran [3] have also used a finite element model to perform a parametric study and suggest effective design width equations to be used in determining the ultimate strength of cold-formed steel beams and columns under compressive axial loads. The parametric study includes web slenderness values between 31 and 194, perforation width to web width ratios up to 0.6, and perforation height to perforation width ratios up to 3.0. The accuracy of the suggested equations was validated by a comparison with the ultimate load results of several experimental studies available in the literature.

In 2000, Veríssimo et al. [4] have presented a computational analyses study to obtain design aids which may be used to facilitate the design of openings in webs of composite and non-composite W shapes steel beam sections. The suggested design aides were intended to identify the region in the steel beam web at which the openings do not affect the steel beam strength under conditions and circumstances and then obtain more economic and efficient web openings.

In 2001, Shanmugam and Dhanalakshmi [5] have presented a numerical study using the finite element package ABAQUS to develop a design equation to determine the ultimate load capacity of perforated channel short columns containing single or multiple openings of square and circular shapes. The suggested equations use web plate slenderness and opening area ratio as the main variables. The accuracy of the suggested design equation is validated against number of experimental and finite element results available in published literature.

In 2001, Chung KF, Liu TCH, and KO ACH [6] carried out an analytical and numerical investigation to study the vierendeel mechanism in steel beams with circular web openings. They conducted a finite element analysis considered the non-linearity of both material and geometry. The moment capacities of the tee-sections above and below the openings may be evaluated. The load carrying capacities of typical universal steel beams with circular web openings are also presented and discussed. Also, they suggested an empirical shear-moment interaction curve at the perforated section for practical design against the vierendeel mechanism. They found that shear yielding in steel beams with circular web openings is very important as it promotes the plastic hinge formation at the high moment side but, such effect is less significant in steel beams with rectangular web openings where the bending moment is often dominant.

In 2003, Chung KF and Liu CH [7] carried out a comprehensive finite element investigation on steel beams with web openings of various shapes and sizes. They observed that all steel beams with large web openings of various shapes behave similarly under a wide range of applied moments and shear forces and the failure modes are common in all beams. Comparison on global moment-shear interaction curves of those steel beams shows that they are similar to each other in shape, and thus, it is possible to derive empirical moment-shear interaction curves to assess the load capacities of all steel beams with web openings of various shapes and sizes. Furthermore, they detected that the most important parameter in assessing the structural behavior of perforated section is the length of tee sections above and below the opening.

In 2003, Chung KF, Liu TCH, and KO ACH [8], employed the results of their comprehensive finite element investigation on steel beams with web openings of various shapes and sizes to compare between the different curves of the global moment-shear interaction. They observed that all curves are similar to each other in shape. Also, they proposed a design method using a generalized moment-shear interaction curve to determine the load capacities of steel beams of various shapes and sizes. The design method is simple, straightforward, and highly efficient in structural economy for engineers in their practical design.

In 2008, Salhab and Wang [9] have suggested a method to calculate the equivalent web thickness of thin-walled channel sections with perforated webs to be used in the design of solid sections. The suggested method was based on a regression analysis of a numerous of finite element simulation results of elastic local buckling resistance of perforated plates under axial compressive load. It has been shown that the equivalent thickness is significantly related to the plate width to thickness ratio, the total width of perforation at the critical section and the width of the perforation zone.

In 2009, Hagen NC, Larsen PK, and Aalberg [10] developed numerical simulations to provide data for the development of a design model for the shear capacity of steel girders with web openings, with and without opening reinforcement. They designed the numerical model such that the girder is in a state of pure shear at the opening center. The obtained results are presented in terms of ultimate shear capacity and distribution of transverse web deformations and von Mises stresses. Based on the numerical data, a design model is presented that accounts for the reduction in web shear area, shear buckling of the web and the effect of opening position, vertical stiffeners, and opening reinforcements.

In 2009, Hagen NC and Larsen PK [11] modified the design procedure for the shear capacity of steel girders with large web openings that based on the shear buckling capacity of webs, as given by Euro code 3, to account the effect of the openings by means of reduction factors determined based on numerical simulations. Guidelines are given for the use of the design procedure in practical design. They presented equations for determination of the secondary effects, as well as some cut-off factors that limit the shear capacity for certain opening configurations beside the requirements for design of welds. Furthermore, equations for shear and primary moment interaction were presented. Finally, two design examples illustrate the features of the guidelines in practical design of girders with openings.

In 2011, Sweedan and El-Sawy [12] have also used the finite element method to investigate the critical axial elastic local web buckling load of cellular beam–column elements. The effect of the plate length and width, and the perforations diameter, and spacing on the elastic buckling load of perforated web plate has also been investigated. The results of the parametric study have helped to enhance the understanding of the elastic local buckling behaviour of web plates of cellular beam–column elements under compression.

In 2011, Prakash, B.D., Gupta, L.M., Pachpor, P.D., and Deshpande, N.V. [13] carried out a finite element analysis using ANSYS software for steel and composite beams with unreinforced and reinforced centrally single rectangular web opening. The scope of their study deals with aspect ratio for opening, deformation characteristics, load carrying capacity and vierendeel mechanism. They observed that the web opening in low shear and high moment region tend to perform better than web opening in the high shear low moment region. Therefore, they recommended that it is preferable to provide web openings in the bending predominant region. Also, they observed a considerable reduction in stress ratio and deflection by increasing the amount of strengthening of the web opening.

In 2011, Ahmed Ashour [14] developed a parametric study to investigate the effect of position of the web openings, opening dimensions, clear spacing between openings and reinforcement around openings in steel girders. He conducted a finite element analysis (FEA) by COSMOS DESIGN STAR (2008) software package to provide guidelines and rules in the design of steel beams with web opening. Furthermore, He assessed one of the most famous design guidelines namely "Design of steel and Composite beams with web openings by David Darwin" [1]. He detected that guideline gives very closely results in case of beams with un-reinforced web openings which that provided by FEA. Therefore, he recommended David Darwin guidelines [1] to be a part of a chapter in the Egyptian code of practice for steel construction and bridges (ASD) entitled "Design of beams with web openings", taking in regard some considerations.

In 2012, Akwasi Manu Assenso Antwi, Dr. J. Kent Hsiao [15] studied the behavior of steel beams with web openings and how the stresses will vary in the beam when it contains unreinforced or reinforced rectangular web openings. Four samples were used in this study: solid wide flange beam, a wide flange beam with web opening and two beams with reinforced web openings. The reinforcement of openings was one sided or both sides horizontal plates located above and below the opening. They generated the models by the finite element analysis software (NISA 2003). They obtained the von Mises stresses and the first principal stresses for the studied beams from the nonlinear static analysis to determine the yield and fracture of the beam. Results from the finite element showed a slight difference with the results from hand calculation method provided by AISC design guidelines for design steel beams web opening. Finally, they concluded that; providing reinforcement on both sides of the opening is a better option in decreasing both the von Mises stress and the first principal stress in a beam with web opening.

In 2013, Marwa S. Abdul Gabar [16] studied the structural behavior of three steel plate girders under shear. The first plate girder was prepared without web openings, and the second plate girder contained two circular opening at the center of each web panel, the diameter of the opening is 60% of the web depth, while the third plate girder was with reinforced strip welded around the circular web openings. The aspect ratio of the panels is one and they all have the same dimensions. The obtained experimental results from second and third plate girders have been compared with those obtained from the reference plate girder. The comparison indicates that the reduction in the ultimate shear load for plate girder with web opening is 51% and for the plate girder with reinforced web opening is 35%. In addition, formulas were presented to predict the ultimate shear load of perforated steel girders with large openings. Furthermore, a nonlinear finite element analysis (FEA) was carried out using the package software program (ANSYS V.11) for the tested plate girders. The results of finite element models were compared with the results of experimental tests. It could be observed from the comparison that there is a good agreement between the analytical and the experimental results. Finally, a parametric study with varying size of the reinforcement around the web openings was performed by using the ANSYS program, and it was found that the thickness of the reinforcement strip has higher effect than its width on the ultimate shear capacity of perforated plate girder.

In 2014, Prof. R. R. Jichkar, Prof. N. S. Arukia, and Prof. P. D. Pachpor [17] carried out a parametric study using ANSYS Workbench Software to investigate the buckling load of several steel beams with different loading and support condition with circular, square, and hexagonal web openings. Their investigation extended to study the deflection pattern at the center of the beam for different parametric condition by same depth of web opening to the depth of beam ratio and for various combinations of shapes of opening. They obtained from the finite element results if the section of beam increases buckling load will also be increases and it will be decreases as the web opening are provided in the section. Also, they found that the value of buckling load is nearer same for square and hexagonal web opening of same section of beam but different for circular web opening of the same section, and the value of buckling load is nearer same for unrestrained and simply supported end condition but higher in restrained end condition for same section of beam. In addition, they observed that increasing the number of web opening in the beam will decrease the buckling load, but it will decrease the deflection. Finally, they obtained that cellular beam subjected to mid span concentrated load provide higher moment carrying capacity than those supporting uniformly distributed load.

In 2014, Mara Junus, Parung Herman, Tanijaya Jonie and Djamaluddin Rudy [18] studied the behavior of beam-column sub-assemblages castella due to cyclic loading. Knowing these behaviors can be analyzed the effectiveness of the concrete filler to reduce the damage and improve capacity of beam castella. Test beam consists of beam castella fabricated from normal beam [CB], castella beams with concrete filler between the flange [CCB] and normal beam [NB] as a shown in Figure (1). Results showed castella beam [CB] has the advantage to increase the flexural capacity and energy absorption respectively 100.5% and 74.3%. Besides advantages, castella beam has the disadvantage that lowering partial ductility and full ductility respectively 12.6 % and 18.1%, decrease resistance ratio 29.5 % and accelerate the degradation rate of stiffness ratio 31.4%. By the concrete filler between the beam flange to improve the ability of castella beam, then the beam castella could increase the flexural capacity of 184.78 %, 217.1% increase energy absorption, increase ductility partial and full ductility respectively 27.9 % and 26 %, increases resistance ratio 52.5 % and slow the rate of degradation of the stiffness ratio 55.1 %.

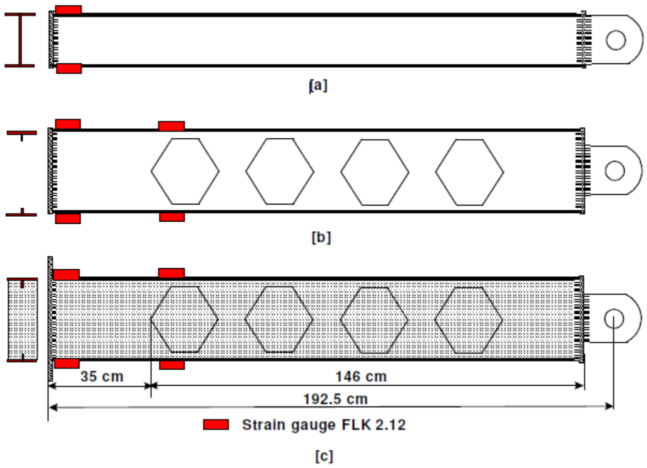

Figure (1) Beam test for the [a] Normal beam [b] Castellan beam [c] Castellan composite beam by *Mara Junus et al., 2014*

In 2015, Fattouh M. F. and Mahmoud Shahat [19] studied the accuracy of using Darwin guidelines in cases of steel beams with non-compact or slender sections. An analytical investigation had been developed by using nonlinear finite element modelling technique. ANSYS program was used considering both geometric and material nonlinearities. They found Darwin guidelines give conservative results and can be used for non-compact and slender web beams with un-reinforced or reinforced square openings with height (ho) up to 0.7 of the beam depth (d) when the opening is located at 10% of the beam span from the support yet, it can be applicable for rectangular openings with aspect ratio (ao/ho) equal to 2.0, when the opening height not exceeding 0.5 the beam depth. In addition to that, Darwin's guidelines may be used for non-compact and slender web beams which have un-reinforced or reinforced openings with height-to-beam depth ratio (ho/d) up to 0.70 for square opening and located at a high moment zone. As well as they observed Darwin's guidelines cannot be used for non-compact and slender web beams which have un-reinforced or reinforced openings located at the moment-shear combination zones.

In 2015, Fattouh M. F. and Mahmoud Shahat [20] studied the effect of web openings on the capacity of beams having non-compact sections to determine the critical positions of web openings. Thus, supposing the suitable technique for web strengthening according to shape, size, and location of the opening with respect to beam length. The study also investigated the efficiency of different types of stiffeners welded at the opening regions to increase the beams ultimate load carrying capacity as shown in Figure (2). They found that the load capacity of the perforated beam is not affected by the opening shape (square, rectangular or circular) if the opening height does not exceed 25% of beam depth and the opening is located at any position along the beam span unless at the mid of beam span. Addition to that, Increasing the opening width-to-height ratio (ao/ho) at the first third of the span sharply decreases the capacity of the perforated section while increasing this ratio at the middle third of the span slightly decreases the capacity of perforated section. They also observed the providing a single circular opening with diameter-to-beam depth ratio (ho/d) up to 70% has a negligible effect on the capacity of the beam except at mid span when it is reduced by 8% -12 %. The usage of two extended horizontal stiffeners upper and lower the opening is the most effective type of reinforcement to compensate the strength loss of the beam at the perforated section. The usage of any type of horizontal stiffeners increases the load capacity of the perforated beam with a high rate at critical shear zone than at high moment zones. Reinforcement of the web opening with vertical stiffeners has negligible effect on the capacity of the perforated section.

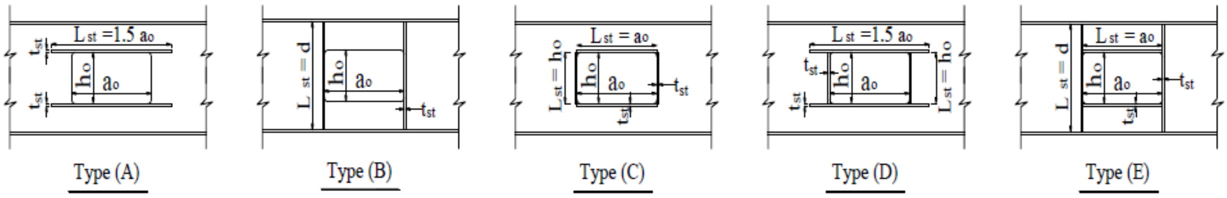

Figure (2) Different type of web opening reinforcement by *Fattouh M. F. and Mahmoud Shahat, 2015*

In 2015, Samadhan G.M. and Laxmikant M.G. [21] an experimental investigation was planned and conducted on seven models of steel beams with web openings. The initiative was to identify the maximum load behavior, and deflection of steel beams with openings in the web. The performance of such beams has been considered only for vertical loads. Hot rolled steel beams with web openings were tested to failure. The beams were simply supported at the ends and subjected to a concentrated load applied at the mid-span. The openings considered in the experimental study are circular and rectangular only. All the beams were analyzed by the finite element method by using general finite element analysis software ANSYS and the results were compared with those obtained experimentally. Test results showed that the ultimate load-carrying capacity and the stiffness decrease with increase in opening area. A comparison of the experimental and analytical results showed that the finite element analysis using the ANSYS software could predict the elastic and ultimate load behavior of steel beams with web openings up to reasonable degree of accuracy. The load–deflection curves obtained by finite element analysis in ANSYS also matched with results of the experiments. Circular web openings were found to be very effective in all respects, like it shows a very less stress concentration at the web openings, easy to fabricate and architectural appearance, etc. Rectangular openings were found to be very critical as they show very high stress concentration around the corner regions. It is also seen that the deformations of the rectangular openings are large compared to the other type of web openings. The rectangular web openings of 0.75d have a very high stress intensity compared to the other depth of openings such as 0.62d and 0.50d.

In 2015 Marsel G. et al. [22] studied the buckling behavior of perforated cold formed steel C-section columns using experimental tests and nonlinear finite element models. They studied the effect of column length by taking two lengths 350mm and 1000mm. Computer simulations showed good agreement with the experimental data. Discrepancy between the results was less than 10%. Despite the close results, the values of buckling forces for the tests and simulations corresponded to the different values of displacements. This might be the result of closing the gaps, which, in their turn, occurred due to the initial geometric imperfections of the columns. Simulation tests for short columns (350 mm) showed very close results, however, the deformed shape obtained from modeling was completely opposite to the one from the experimental tests. This demonstrates the need for a more detailed modeling with the particular attention paid to nodal connections and wooden plates in the top of the models. Analytical calculations made in accordance with EN 1993-1-3-2009 showed considerably lower results. This probably means that the building codes provide more careful values of buckling forces for this type of profile.

In 2016, Sadjad A. Al-Jallad and Haitham Al Thairy [23] constructed experimental study to investigate the effects of the number and the shape of web opening on the behavior and failure of steel columns with cold formed thin-walled sections (CFS) subjected to axial compressive load. Twenty small scale steel columns with cold formed box and channel sections and a total length of 500 mm have been considered in the experimental tests as shown in Figure (3) and Figure (4). They found that the increasing of the numbers of web openings results a considerable decreasing of the column axial compressive strength compared to reference columns with no web openings. It has been concluded that for web opening with a ratio of opening width to total section width (w/W) less than to 0.45 the increasing of the numbers of web openings results a decreasing of the column axial compressive strength compared to the reference steel columns which has no web openings. While, for opening with ratio of opening width to total section width (w/W) greater than 0.45 the increasing of number of openings has no considerable effect on axial compressive strength if compared with column of one opening. This study has also shown that the maximum percentage of the reduction in the columns axial compressive strength caused by the presence of web opening was found to be 30% for columns with box shape sections and 45% for column with channel shape sections compared to columns with no web openings. The presence of opening at the web of steel columns composed of thin-walled cold formed sections (CFS) will increase the possibility of local buckling failure at the locations of the openings. The reduction in the axial compressive strength of the column specimens caused by the presence of web openings is lower for the circular shape openings compared to that for rectangular and/or square shape web openings. The circular shape of opening located at the mid-length of the column is the best shape and position of a single opening that could be created at the web of steel column sections.

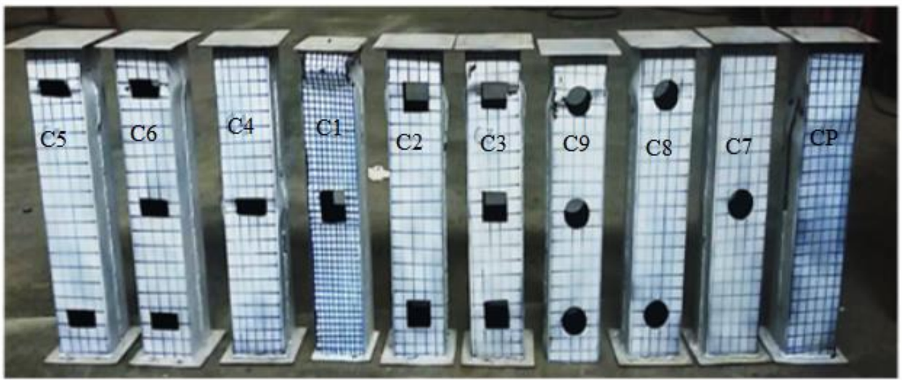

Figure (3) Steel columns with box section by *Sadjad A. Al-Jallad and Haitham Al Thairy*, *2016*

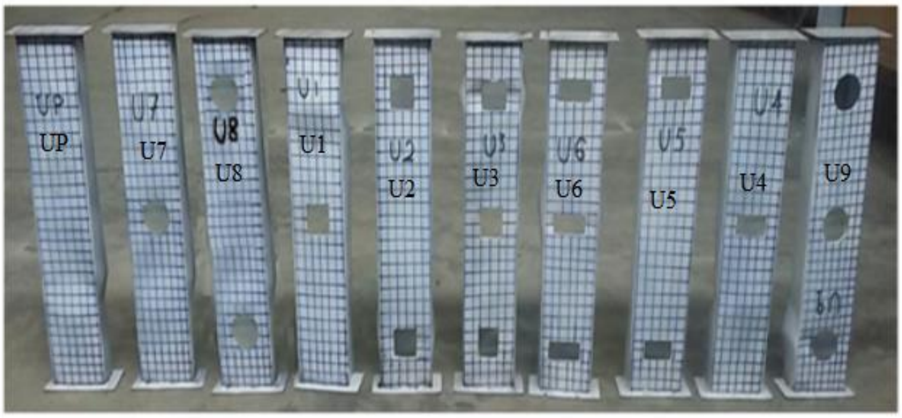

Figure (4) Steel columns with channel section by *Sadjad A. Al-Jallad and Haitham Al Thairy, 2016*

In 2016, Muhammad Abed Attiya [24] studied numerically the behavior of cold–formed thin–walled steel column with opening by using ANSYS software. To simulate the behavior of cold-formed steel column under static load, two groups of steel column were analyzed which was studied experimentally in 2016 by Sadjad A. Al-Jallad and Haitham Al Thairy. Finite element model details with mesh size and boundary conditions are explained in Figure (5). He found that the results which was obtained from ANSYS were in a good agreement with the results of experimental tests. Using the stiffener at the ends of steel column increased failure load by about (12%) and (7%) for box and channel sections respectively. While when using stiffener only near the opening, there is no effect on failure load for two sections. On the other hand, stiffening the column ends and near the opening, failure load increases to (18.6%) and (11.2%) for box and channel section, respectively. Stiffening of columns has three opening at the column ends and near all openings increases failure load to about 40% and 49.3% for box and channel section respectively. Whereas using stiffener about central opening alone or on bottom hole alone has no effect on the failure load. Effect of opening location was clear when its position changed up to 40% of column length from the column end. The increment in failure load was about 9.3% and 17% for box and channel section respectively. Beyond this position, increment in failure was rarely kept constant. Increasing column length has clear effect on axial-displacement and failure load. It is found that increasing the length of box section column to twice original one, increases the axial displacement by about 126% and decreases the failure load by approximately 18%. While for channel section, increase column length to 1.4 %, axial displacement increased by about 133% and failure load decreases by approximately 27.5%.

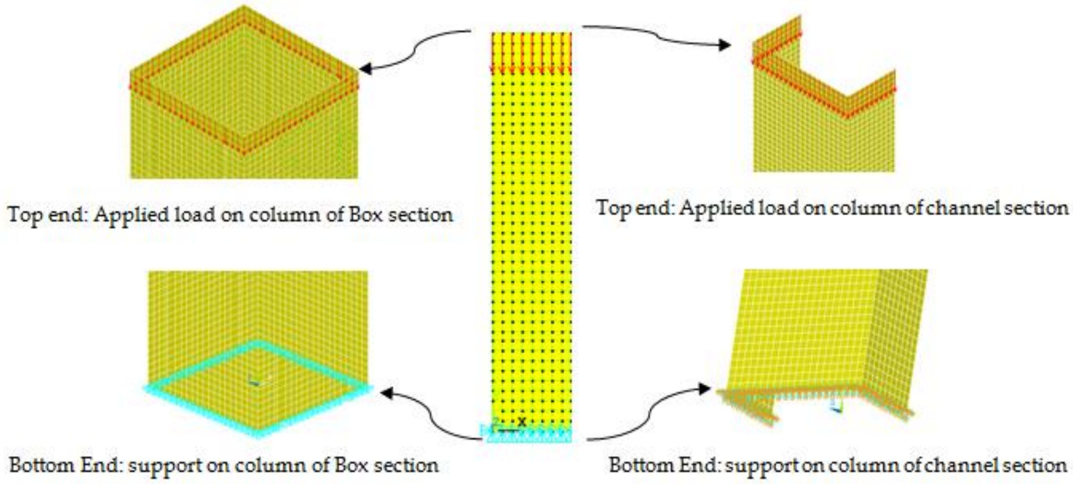

Figure (5) Finite element model of steel columns with channel and box section by *Muhammad Abed Attiya, 2016*

In 2021, Hanan Hussien El-Tobgy et al. [25] studied experimentally and numerically the structural behavior of castellated beam-column steel elements. An experimental investigation was performed on twelve short and long castellated beams, columns, and beam-column elements. They found that the castellation has no effect on the linear buckling load for elements subjected to pure axial loading. Otherwise, the castellation ratio has significantly affected the linear buckling moment of the pure bending elements. Additionally, the castellation process increases the major axis inertia of the section but does not affect the minor axis inertia. Pure bending strength is mainly governed by the major axis inertia, particularly for beams restrained against lateral-torsional buckling. On the other hand, pure axial capacity is governed by the section area and minor axis inertia. Accordingly, castellation process significantly enhances pure bending strength, but does not enhance the pure axial strength. However, for beam-columns, the strength enhancement ratio depends on the eccentricity ratios (e/d).

Design recommendations for steel or composite beams with web opening

In this section, a brief overview on various design codes and standards will be presented in the following lines.

AISC (2005), Load and resistance factor design specification for structural steel buildings [26]

Web openings in structural floor members may be necessary to accommodate various mechanical, electrical, and other systems. Strength limit states, including local buckling of the compression flange, web, and tee-shaped compression zone above or below the opening, lateral buckling and moment-shear interaction, or serviceability may control the design of a flexural member with web openings. The location, size, and number of openings are important and empirical limits for them have been identified. One general procedure for assessing these effects and the design of any needed reinforcement for both steel and composite beams is given in the ASCE Specification for Structural Steel Beams with Web Openings (ASCE, 1999), With background information provided in Darwin (1990) and in ASCE Task.

BSI (2000), Structural use of steelwork I buildings – Part 1: Code of practice for design rolled and welded sections, BS-5950, British standard institute. [27]

The code stated that the effects of openings should be considered in design. BS-5950(4-15)

For isolated unreinforced circular openings, clause (4-15-2-1): it may be in the web of a beam without considering net section properties provided that:

- The member has a class 1 plastic or class 2 compact cross-sections.
- The cross-section has an axis of symmetry in the plane of bending.
- The openings are located within the middle third of the depth of the cross-section.
- The openings are located within the middle half of the span of the member.
- The spacing center-to-center of adjacent openings measured parallel to the axis of the member is not less than 2.5 times the diameter of the larger opening.
- The distance from the centerline of each opening to the nearest point load is not less than the depth of the member.
- The load on the member is substantially uniformly distributed.
- The shear due to point loads does not exceed 10 % of the shear capacity of the cross-section.
- The maximum shear in the member does not exceed 50 % of the shear capacity of the cross-section.

If the dimensions, openings, or loading do not satisfy a) to i) the member should be designed using net section properties with satisfying (4-15-3-2) to (4-15-3-6).

For reinforced opening, clause (4-15-2-2): Web reinforcement may be provided adjacent to openings to compensate for the material removed. It should be carried past the opening for such a distance that the local shear stress due to force transfer between the reinforcement and the web does not exceed 0.6 p_y.

For multiple openings, clause (4-15-4): member should be designed using net section properties with satisfying (4-15-4-2) to (4-15-4-8).

EN 1993-1-1:2005. Euro code 3: Design of steel structures, Part 1-1: General rules and rules for building. [28]

Pending the issue of Annex N of EC3 the design of beams with web openings, other than those required for fasteners, should be in accordance with 4.15 of BS 5950-1:1990.

Lawson RM. Design for openings in the webs of composite beams. The steel construction institute/CIRIA joint publication SCI-P068. [29]

In 1987, this publication is intended to provide interim guidance for designers in an important area of design where information is lacking. It has been prepared by Dr R M Lawson (formerly of CIRIA and now of the Steel Construction Institute (SCI)). The work leading to this publication has been funded by the British steel corporation (sections), the department of the environment and CIRIA, under a CIRIA research project. The publication deals with the design of simply supported composite beams with rectangular openings in the webs. The beams comprise steel I-sections and concrete slabs with steel decking as permanent formwork. Design is based on plastic analysis of the cross-section, considering the moment transfer by vierendeel action across the opening. A relatively straightforward method of analysis is presented, and this is summarized in step-by-step approach. Comparison with available test data shows that the method is conservative but reasonably accurate. The method can also be used for non-composite and notched beams. A step-by-step design approach suitable for use in a computer analysis is produced. Additional checks are made on the local instability of un-stiffened webs and on the extra shear and bending deflection resulting from the openings. It is assumed that the beam design, where not affected by the opening, is checked separately. The moment and shear (V) at the lower moment side of the opening will be used in the analysis. The additional moment to be transferred across the opening, in the form of vierendeel moments is VL where L is the opening length. All the forces resulting around the opening have been calculated using analytical approach. Solution for non-composite beams and notched beams are presented. Guidelines on the positioning and size of we openings are highlighted. The proposed analysis method is a simplification of those that have been put forward by various researchers. It is conservative as regards ultimate strength, with respect to the available test data. A number of aspects have been suggested of the further research concerning the contribution of the concrete slab in the resisting shear, the local instability of un-stiffened webs above openings, the effect of low degrees of partial shear-connection, testing of beams with practical stiffening arrangements, and assessment of appropriate serviceability conditions.

Chung KF, Lawson RM. Simplified design of composite beams with large web opening to Euro code 4. [30]

A design method [32] for composite beams with large web openings was first formulated in accordance with BS5950 and calibrated against full-scale test in 1992. With the release of the draft of Euro code 4 in 1994, this paper represents the design method in the format of publication rules to Euro code 4 for detailed design of composite beams with large web openings. Moreover, the designer needs advice at the scheme design stage and this paper presents general information on sizing of openings as a function of the utilization of the shear and the bending resistances of composite beams. Furthermore, the effect of these openings on deflections is estimated by a simple factor, which is dependent on the size and location of the openings. Typical design tables for composite beams with large rectangular openings are presented. Design rules for other forms of construction such as circular openings and notched beams are also presented with general detailing rules to assist designers.

CSA (2001), Limit States Design of Steel Structures, S16-01, Canadian standards association, Toronto, Ontario. [31]

The effect of all openings in beams and girders shall be considered in the design. At all points where the factored shear or moments at the net section would exceed the capacity of the member, adequate reinforcement shall be added to the member at that point to provide the required strength and stability. Refer to clause (14-3-3), Unreinforced circular openings may be in the web of un-stiffened prismatic Class 1 and Class 2 beams or girders without considering net section properties, provided that:

The load is uniformly distributed.

The section has an axis of symmetry in the plane of bending.
The openings are located within the middle third of the depth and the middle half of the span of the member.
The spacing between the centers of any two adjacent openings, measured parallel to the longitudinal axis of the member, is a minimum of 2.5 times the diameter of the larger opening.
The factored maximum shear at the support does not exceed 50% of the factored shear resistance of the section.

Conclusion:

Following conclusions can be derived from the previous studies:

1- Shear yielding in steel beams with circular web openings is very important as it promotes the plastic hinge formation at the high moment side.
2- Steel beams with large web openings of various shapes behave similarly under a wide range of applied moments and shear forces and the failure modes are common in all beams
3- Web opening in low shear and high moment region tend to perform better than web opening in the high shear low moment region.
4- Providing reinforcement on both sides of the opening is a better option in decreasing both the von Mises stress and the first principal stress in a beam with web opening.
5- The thickness of the reinforcement strip has higher effect than its width on the ultimate shear capacity of perforated plate girder.
6- The value of buckling load is nearer same for square and hexagonal web opening of same section of beam but different for circular web opening of the same section
7- Increasing the number of web opening in the beam will decrease the buckling load but it will decrease the deflection
8- Darwin's guidelines cannot be used for non-compact and slender web beams which have un-reinforced or reinforced openings located at the moment-shear combination zones.
9- Reinforcement of the web opening with vertical stiffeners has negligible effect on the capacity of the perforated section.
10- Deformations of the rectangular openings are large compared to the other type of web openings.
11- Increasing the length of box section column to twice original one, increases the axial displacement by about 126% and decreases the failure load by approximately 18%. While for channel section, increase column length to 1.4 %, axial displacement increased by about 133% and failure load decreases by approximately 27.5%.
12- The castellation has no effect on the linear buckling load for elements subjected to pure axial loading.
13- The castellation ratio has significantly affected the linear buckling moment of the pure bending elements.

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