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EFFECT OF WEB OPENING ON THE AXIAL LOAD CAPACITY OF STEEL COLUMNS WITH COLD FORMED THIN WALLED SECTION (CFS)

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ABSTRACT

In this paper, an experimental study has been presented to investigate the effects 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. Ten of the tested steel columns specimens have a box section with dimensions of (100×100×2) mm (height × width× thickness), and the other ten columns specimens have a channel sections with dimensions of (100×50×2) mm (height × width× thickness). To investigate the effect of the number and the shape of web opening on the axial compressive strength of steel columns, each ten columns with same cross section shape was divided into three groups of three columns in addition to the reference column which has no web openings. All groups of columns have same opening area which is located at the web of the section, but each group has a different opening shape (square, rectangular, and circular shapes), and each steel column within each group has different numbers of opening distributed along column length (one, two, and three openings). Each steel column specimens was subjected to an increasing static load up to column failure which indicated by the reloading of the test machine. The study has shown that for most of the tested columns, increasing the numbers of web openings results in decreasing the column axial strength compared to the reference steel column. The maximum percentage of the reduction in the columns axial compressive strength caused by the presence of web opening was found to be about 30% and 45% of the reference columns strength for columns with box and channel shape sections, respectively. It has also been found that 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.

KEYWORDS: Web opening; Axial loads; Steel columns; Compressive failure; Thin walled sections

تاثيروجود الفتحات في وترة المقاطع الفولاذية ذات الجدران النحيفة المشكلة على البارد على تحمل الاحمال المحورية للاعمدة الفولاذية

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الخلاصة

يقدم هذا البحث دراسة عملية لتاثير الفتحات في منطقة الوترة على تصرف و فشل الاعمدة الفولاذية المكونة من مقاطع نحيفة الجدران. و المعرضة الى قوة انضغاط محورية . تم اخذ عشرين نموذج مصغر لاعمدة فولاذية بطول كلي يبلغ 500 ملمتر و بمقاطع بشكل صندوفي و مقاطع بشكل قناة مشكلة على الطريقة الباردة .عشرة من نماذج الاعمدة الفولاذية تتالف من مقاطع بشكل صندوقي وذات ابعاد 100×100×2 ملمتر (طول ×عرض×سمك) و العشرة الاخرى من نماذج الاعمدة تتالف من مقاطع بشكل قناة و بابعاد 100×50×2 ملمتر (طول ×عرض×سمك). لمعرفة تاثير شكل و عدد فتحات الوترة على تصرف و تحمل الاعمدة الفولاذية للقوة المحورية, تم تقسيم كل عشرة اعمدة بنفس شكل المقطع العرضي الى ثلاث مجاميع كل مجموعة تتالف من ثلاث اعمدة اضافة الى العمود المرجعي غير الحاوي على فتحات . كل مجموعة من الاعمدة الفولاية تحتوي على نفس مساحة الفتحة الواحدة الموجودة في منطقة الوترة ولكن كل مجموعة تحتوي على شكل معين للفتحات (مستطيل, مربع, و دائري) و كل عمود من الاعمدة الثلاثة ضمن كل مجموعة يحتوي على عدد مختلف من الفتحات ضمن منطقة الوترة (فتحة واحدة, فتحتان و ثلاثة فتحات). تم تسليط حمل محوري ستاتيكي متزايد منتظم على كل عمود لمعرفة اقصى حمل محوري ممكن تحملة من قبل كل عمود. تم الاستنتاج انه في اغلب الاعمدة الفولاذية التي تم فحصها في هذه الدراسة فان زيادة عدد الفتحات في منطقة الوترة تؤدي الى نقصان ملحوص في مقاومة العمود لقوة الانضغاط المحورية بالمقارنة مع مقاومة العمود المرجعي. لقد اظهرت النتائج ايضا ان النقصان في مقاومة العمود للقوة المحورية تكون اقل عند استخدام فتحات دائرية الشكل بالمقارنة مع النقصان الحاصل في مقاومة العمود للقوة عند استخدام فتحات مسنطيلة او مربعة الشكل.

الكلمات الدالة: فتحات الوترة، احمال محورية، الاعمدة الفولاذية، فشل انضغاط، مقاطع نحيفة الجدران.

1. INTRODUCTION

Openings in webs of cold formed thin walled steel column sections (CFS) are commonly used in steel framed structures to facilitate electrical, mechanical, and sanitary works in addition to have access for services and inspections. Another important reasons for considering web openings in steel column sections are to reduce the material volume without affecting the structural strength or serviceability requirements in addition to reduce the cold bridging effect when open web channel section steel column are used in the external wall panels at cold regions. However, the presence of opening in thin walled steel sections has a disadvantage side since CFS sections are more vulnerable to local buckling due to its high width to thickness ratios. Nevertheless, no precise design methods appear to be available for this type of steel members.

Recent standards and codes of practice have put forwards simplified methods and procedures for the design of steel members with opening ((ISAI, 1991), (EC3, 2006), (AISC, 2005)). However, most of these methods consider flexural steel members (beams) with restrained supports and without presence of axial compressive load. Moreover, the suggested equations and procedures by these standards and codes are very conservative because they are derived based on assumptions that cover a wide range of possibilities. For example, most of suggested methods restrict the openings to specific locations over the beam depth and /or along the beam length which limit the applicability of these methods.

One the other hand, several experimental, numerical, and analytical research works have been published on the behaviour and design on thin walled cold formed steel columns under compression. For instance, Abdel-Rahman (1997) has presented a numerical and experimental study to investigate the load capacity of web perforated cold-formed steel (CFS) members under axial compressive loading. A finite element-based analytical model has been developed and validated using a series of cold formed steel channels stub-columns test. The finite element model was used to perform a comprehensive parametric study on the perforated plates of CFS compression members to assess the axial stress distribution and the effective design width of the perforated plates. Based on the parametric study, two effective design width equations for stiffened compression plates have been suggested and validated.

Abdel-Rahman and Sivakumaran (1998) 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 (CFS) 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.

Veríssimo et al. (2000) 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 particular conditions and circumstances and then obtain more economic and efficient web openings.

Shanmugam and Dhanalakshmi (2001) 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. An extensive parametric study has been carried out using the finite element model of channel sections containing openings to suggest design equations using regression analysis. The suggested equations use web plate slenderness and opening area ratio as the main variables along with plate slenderness and opening shapes and sizes. The accuracy of the suggested design equation is validated against a number of experimental and finite element results available in published literature.

Salhab and Wang (2008) 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. Different design variables were considered in the suggested method including the depth, thickness, perforation patterns, and dimensions of the plate. 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.

Sweedan and El-Sawy (2011) 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. An extensive parametric study has been conducted to identify the behaviour and buckling of wide range of perforated web plates under different combinations of axial compressive load and bending moment. 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.

Karagah et al. (2015) has presented an experimental study to investigate the effect of the opening caused by the corrosion on the axial load capacity of steel piles subjected to monotonic axial load. A 13 H-shaped short steel columns were used in the experimental tests and were treated to simulate different degrees and patterns of corrosion. The recorded remaining axial capacities of the tested steel columns were compared to the axial capacities predicted by design provisions of the current standards and codes namely AISC, AASHTO, and AISI. It has also concluded that the effective width method suggested by AISI gives the best prediction of the axial load capacity of steel columns subjected to sever corrosion.

This paper aims to present an experimental investigation on the effect of the shape and numbers of web openings on the behaviour and particularly failure of steel columns with cold formed sections thin walled CFS. Twenty small scale steel columns with box and channel sections have been considered in the experimental tests. Each group of ten columns with same section shape has been divided into three groups of three columns in addition to the reference column. All groups of columns have the same opening area which is located at the web of the section, but each group has a different opening configuration and each column within each group has different numbers of opening distributed along column length. All tested columns were subjected to increasing monotonic static axial loads up to column failure which is indicated by the reloading of the test machine. The experimental test results will be help to more understanding of the behavior and failure of steel column with opening web under axial compression.

2. TEST SETUP AND EXPERIMENTAL PROGRAM

In this section, a detailed description will be presented to the experimental program conducted in the current study including the steel columns specimens and the test setup.

2.1. Steel columns

The main objective of the present study is to investigate the effect of number and shape of web openings on the axial compressive strength of the thin walled section steel columns. To achieve this goal, the column specimens must be prepared to capture this effect during the tests when they are loaded up to failure. To do so, twenty small scale steel column specimens with cold formed thin walled box and channel sections and a total length of 500 mm were used in the tests. The cross sectional dimensions of the steel column specimens were selected, so that the column sections can be considered as slender or thin walled sections according to ASIC specifications (AISC, 2005). The main failure modes of steel columns composed of thin walled section is the local buckling of the section. Moreover, the columns length has been selected, so that the columns behave as short columns according to AISC specification (AISC, 2005) which means that the column would fail by full or partial yielding of the column section before the column failure by the global buckling (AISC, 2005). For example, for the box section columns, the axial yielding strength is 270.48kN while the elastic buckling strength is 10210kN. Ten of the column specimens have a box section with dimensions of (100×100×2) mm (height × width× thickness) and the other columns have channel sections with dimensions of (100×50×2) mm (height× width× thickness). To investigate the effect of number and shape of web openings on the axial load strength of the columns, each ten columns with same section shape were divided into three groups of three columns in addition to the reference column which is without web openings. All groups of steel columns have the same opening area, but each group has a different opening shape (i.e. square, rectangular, and circular shapes) as shown in Fig. 1 and Fig. 2. Moreover, each column within each group has different numbers of opening distributed along column length (i.e. one, two, and three openings), Fig. 1, Fig. 2, and Table 1 show the geometry and web opening locations and details of columns specimens. The material properties of the steel columns was determined using a uniaxial tensile test of a steel coupon cut from the steel plate from which all column specimens were made and the tensile test results are shown in Table 2. Each steel column was subjected to an increasing static load up to column failure which indicated by the reloading of the test machine gages.

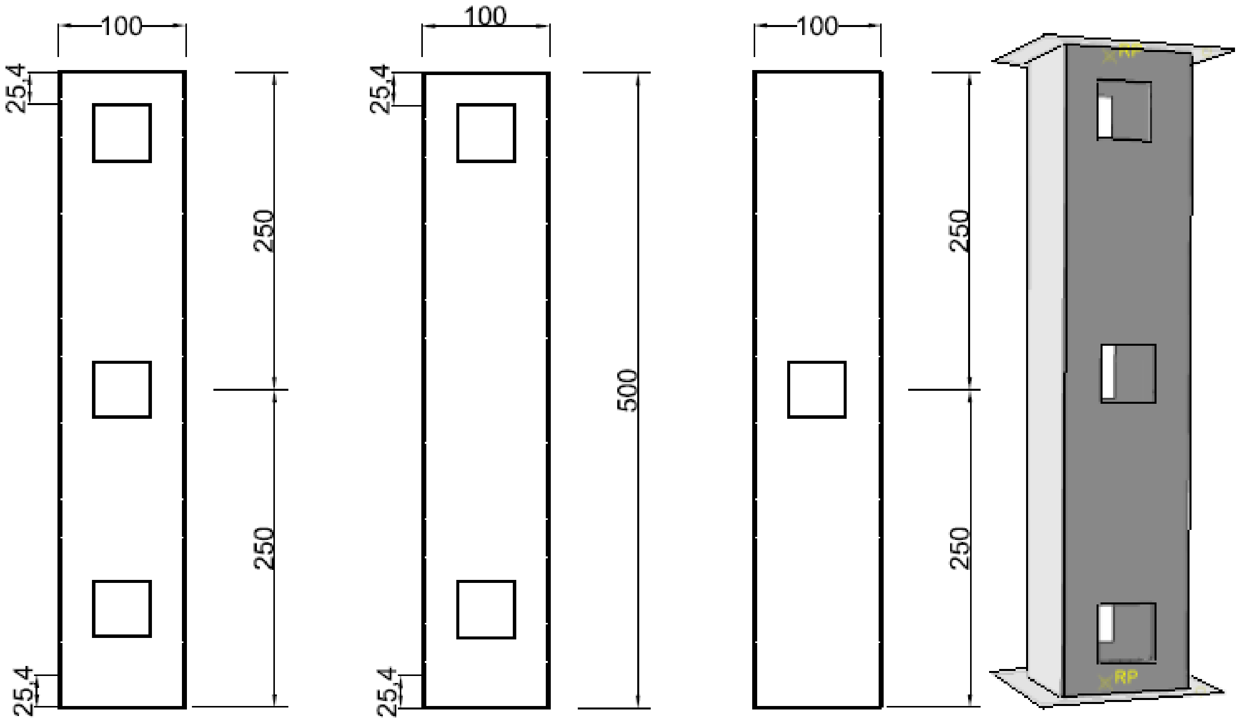


Fig. 1. Typical distribution of web openings along the steel columns length for all opening shapes

Table 1. Dimensions and geometrical properties of the steel column specimens used in experimental tests with web opening details

columns designations	Cross section shape	Cross section dimensions (W×H×t)(mm)	Opening shapes	Opening dimensions (*w*×*h*) or *d* (mm)	(opening width/section width) (w/W)	Number of web openings
CP	HRS*	100×100×2	Reference	N/A	N/A	N/A
C1	HRS	100×100×2	Square	44.3×44.3	0.443	1
C2	HRS	100×100×2	Square	44.3×44.3	0.443	2
C3	HRS	100×100×2	Square	44.3×44.3	0.443	3
C4	HRS	100×100×2	Rectangular	65×30.2	0.650	1
C5	HRS	100×100×2	Rectangular	65×30.2	0.650	2
C6	HRS	100×100×2	Rectangular	65×30.2	0.650	3
C7	HRS	100×100×2	Circular	50	0.500	1
C8	HRS	100×100×2	Circular	50	0.500	2
C9	HRS	100×100×2	Circular	50	0.500	3
UP	C**	100×50×2	Reference	N/A	N/A	N/A
U1	C	100×50×2	Square	44.3×44.3	0.443	1
U2	C	100×50×2	Square	44.3×44.3	0.443	2
U3	C	100×50×2	Square	44.3×44.3	0.443	3
U4	C	100×50×2	Rectangular	65×30.2	0.650	1
U5	C	100×50×2	Rectangular	65×30.2	0.650	2
U6	C	100×50×2	Rectangular	65×30.2	0.650	3
U7	C	100×50×2	Circular	50	0.500	1
U8	C	100×50×2	Circular	50	0.500	2
U9	C	100×50×2	Circular	50	0.500	3

* Hollow rectangular or box section
** Channel section.

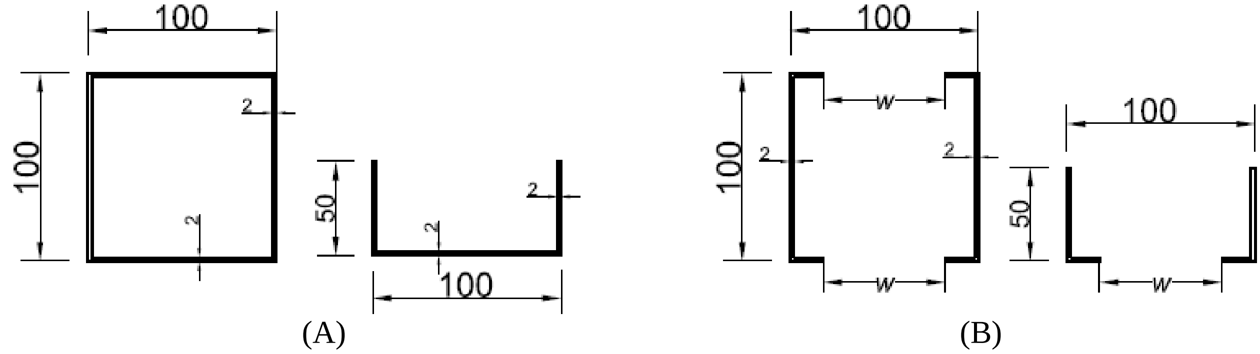


Fig. 2. Cross sectional dimensions of the steel column sections (A) and typical sections at opening location (B)

Table 2. Mechanical properties of the steel material from the uniaxial tensile test

Steel coupon Thickness t (mm)	Steel coupon width w (mm)	Steel coupon length L (mm)	F_y (N/mm^2)	E(N/mm^2)	F_u(N/mm^2)	ε_u
2	15	200	420	201×10^3	534	0.107

Where F_y , E, F_u, and ε_u are the yielding stress, the modulus of elasticity, the ultimate tensile stress, and ultimate tensile strain of the steel material, respectively.

2.2. Test setup

The uniaxial loading universal test machine available at laboratory of Mechanical Engineering Department in College of Engineering / The University of Al-Qadissiya shown in Fig. 3 was used to apply monotonic axial compressive static loads on the steel column specimens. To ensure a uniform distribution of the axial compressive load over the column cross section, a steel plate with dimensions (150×150×5) mm (height × width× thickness) was placed at the loaded top end of each column as shown in Fig. 3. Dial gages were used to record the axial and lateral displacements at top end and at mid-span of the column, respectively, as shown in Fig. 3. The axial compressive load was applied incrementally using a load increment of 5kN until the column exhibits failure. The boundary conditions of the steel columns specimens simulate the simply supported case with the top end of the column being unrestrained in the vertical direction.

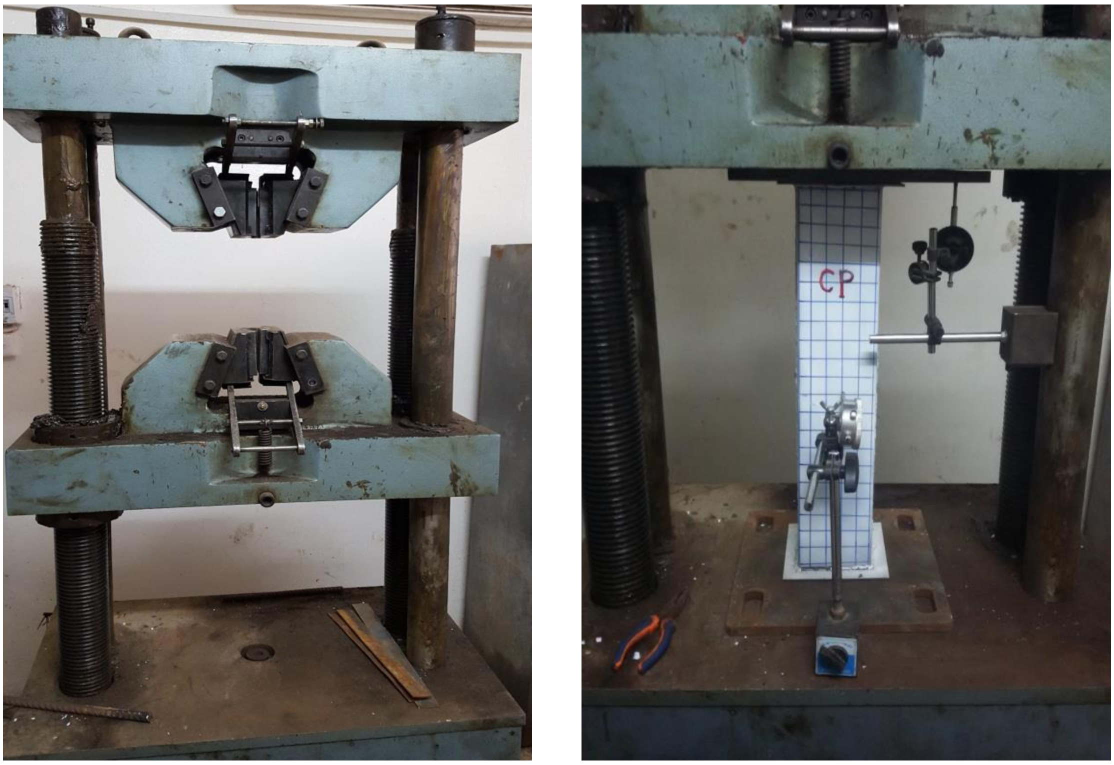


Fig. 3. Universal test machine used in the experimental tests

3. RESULTS AND DISCUSSIONS

This section presents and discusses in details the results extracted from the experimental tests conducted in this study in terms failure modes, load displacement behavior, and ultimate axial compressive load. The section will come up with several conclusions that may help to more understanding of the behavior and failure of thin walled cold form section (CFS) short steel column under axial compression.

3.1. Failure modes

Fig. 4 and Fig. 5 show failure modes of the tested steel column specimens for the two cross section shapes and for different numbers and shapes of web openings. These figures illustrate that all tested columns have experienced local buckling of columns sections but at different locations along column length depending on numbers and shapes of the web openings. It can be seen from Fig. 4 that for the closed section (box) steel columns and for the three shapes of web opening considered in the experimental tests, the location of the local buckling has moved toward the end of the column when the numbers of web openings has increased from one to three. On the other hand, Fig. 5 shows that for the tested open section (U) columns and for the three shapes of web opening, the location of the local buckling was at the ends of the column when the numbers of web openings is equal to one and located at the middle of the column length, while the location of the local buckling moved toward openings when openings increased from one to three. This behavior may be attributed to the effect of the column axial stiffened which is affected by the presence of the opening in the column section. When the number of web openings along column length increases, the column axial stiffness will be considerably reduced and the column will exhibit less axial strength.

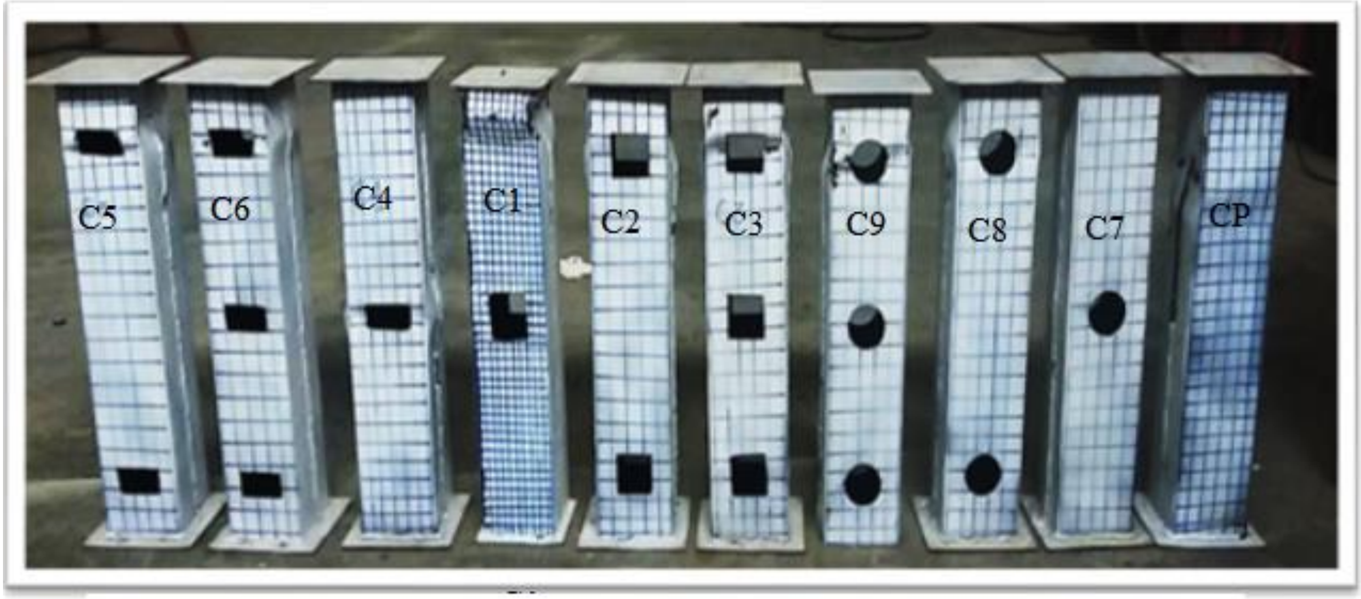


Fig. 4. Failure modes of steel columns with box sections

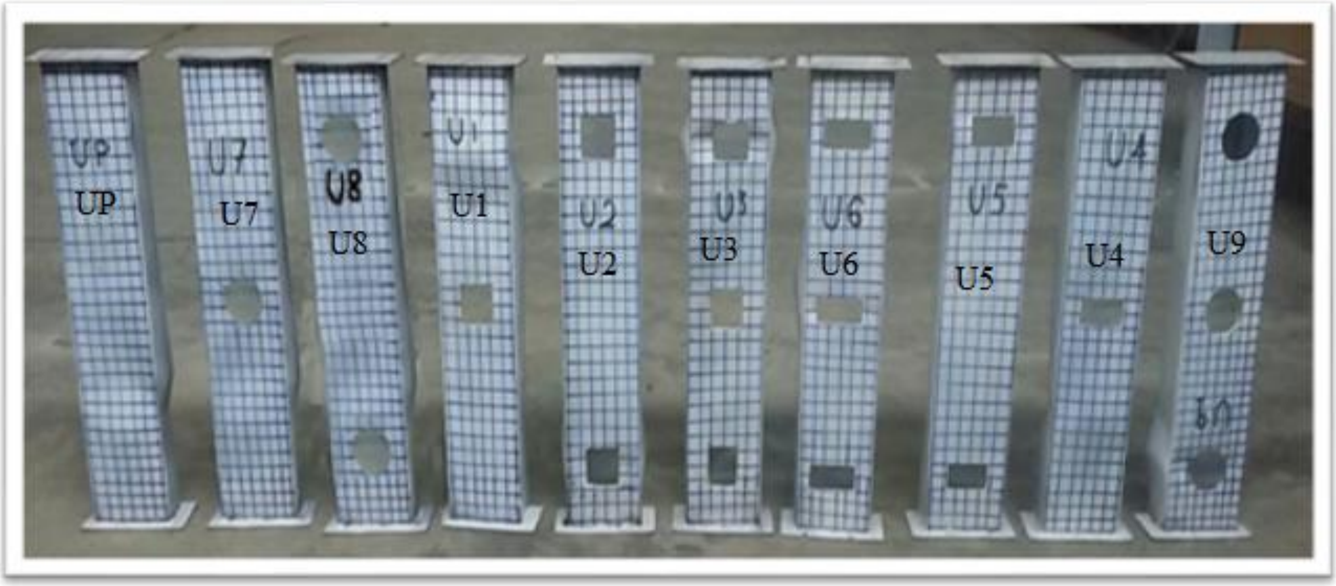


Fig. 5. Failure modes of steel columns with channel sections

3.2. Axial load-axial displacement behavior

Fig. 6 and Fig. 7 show the effect of numbers of web opening on the axial compressive strength-axial displacement relationship of the tested steel columns for different shapes of web openings and for box and channel sections. It can be noticed from these figures that for most tested column specimens, the behavior of the steel column became more flexible and the maximum displacement at which the column has experienced failure decreased when the number of web opening along the column length has been increased. This is an expected behavior since increasing the number of web opening reduced the column axial stiffness owing to decreasing of the cross sectional area of the tested steel column.

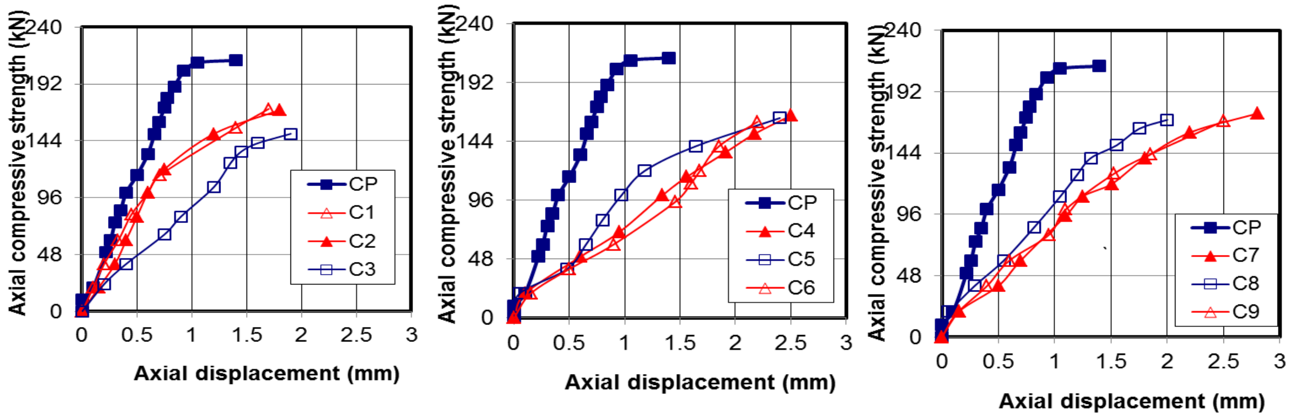


Fig. 6. Effect of the numbers of web opening of the load-displacement behaviour of box shaped steel columns

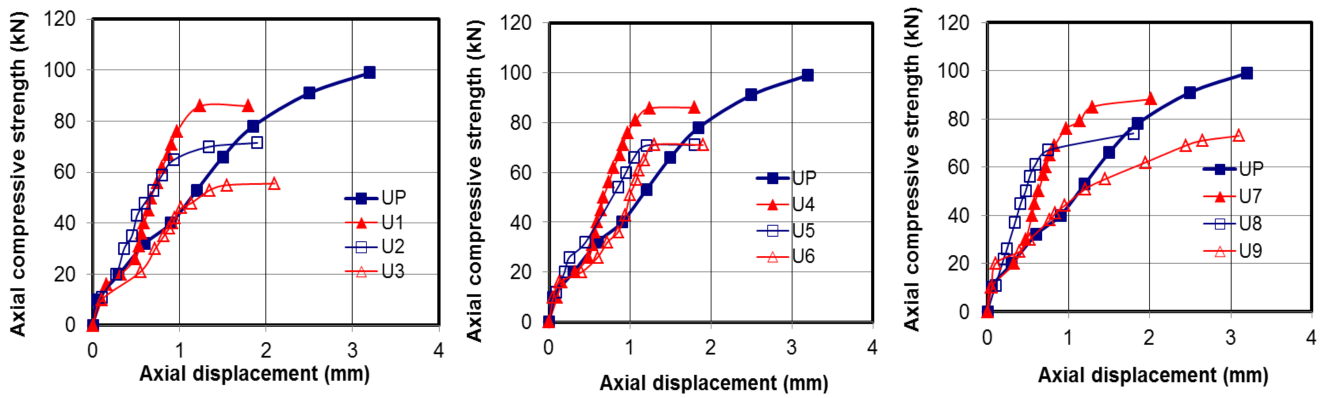


Fig. 7. Effect of the numbers of web opening of the load-displacement behaviour of U shaped steel columns

On the other hand,

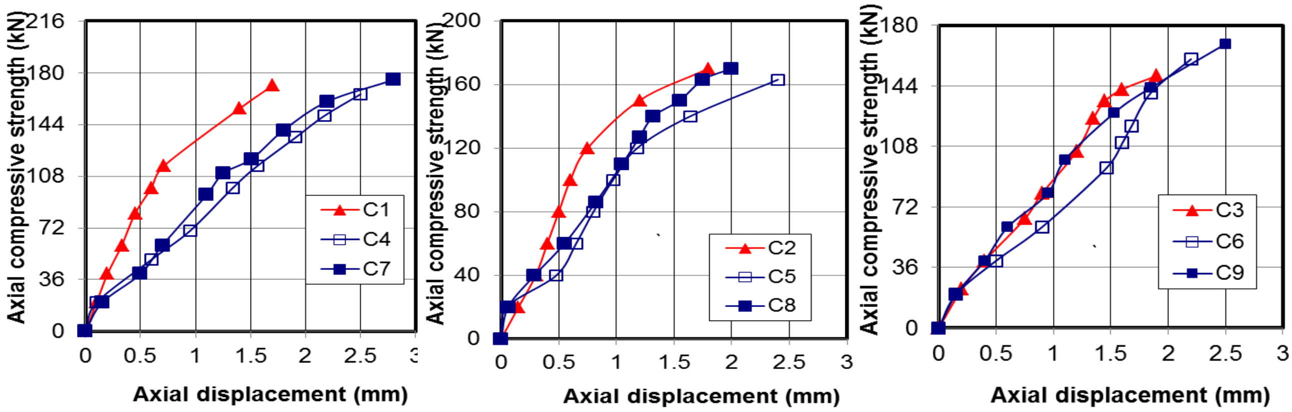


Fig. 8 and Fig. 9 show the effect of the shape of web opening on the axial compressive strength-axial displacement relationship of the tested steel columns for different numbers of web openings for box and channel sections. These figures have revealed that for the both box and channel cross sections shapes considered in the present study the steel columns with a circular shape of web opening show higher values of the axial compressive strength compared to the columns with rectangular and square shapes of web openings. In addition, the columns with square shape of the web opening provide higher values of the axial strength than the column with square shape of the web opening. The reason for this behavior can be justified by the effect of localized stresses generated at the edges of the openings. For the circular shape of web openings, the stresses around the edges of the openings will be distributed more evenly. However, for rectangular and square openings shapes, the stresses would be more localized at the openings corned and the column will be more vulnerable to local buckling.

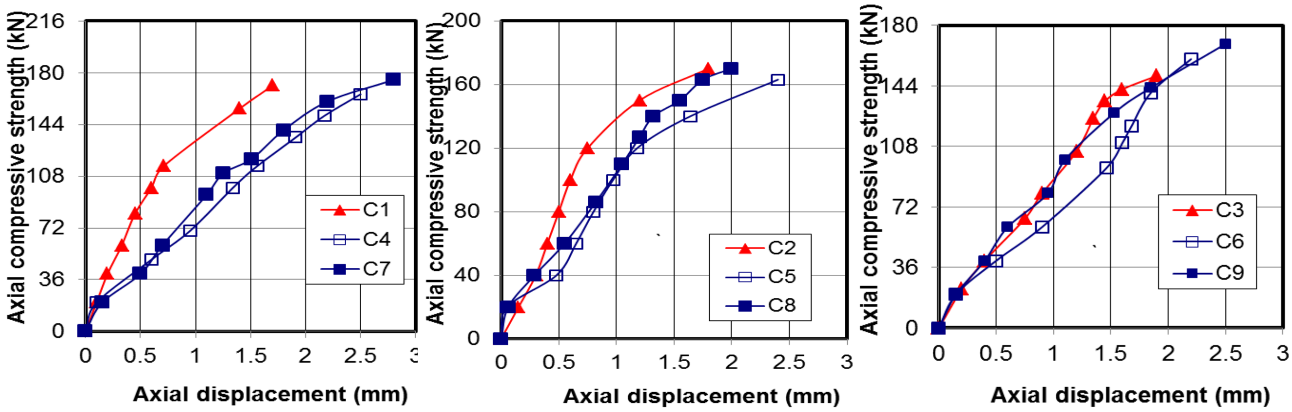


Fig. 8. Effect of the shapes of web opening of the load-displacement behaviour of box shaped steel columns

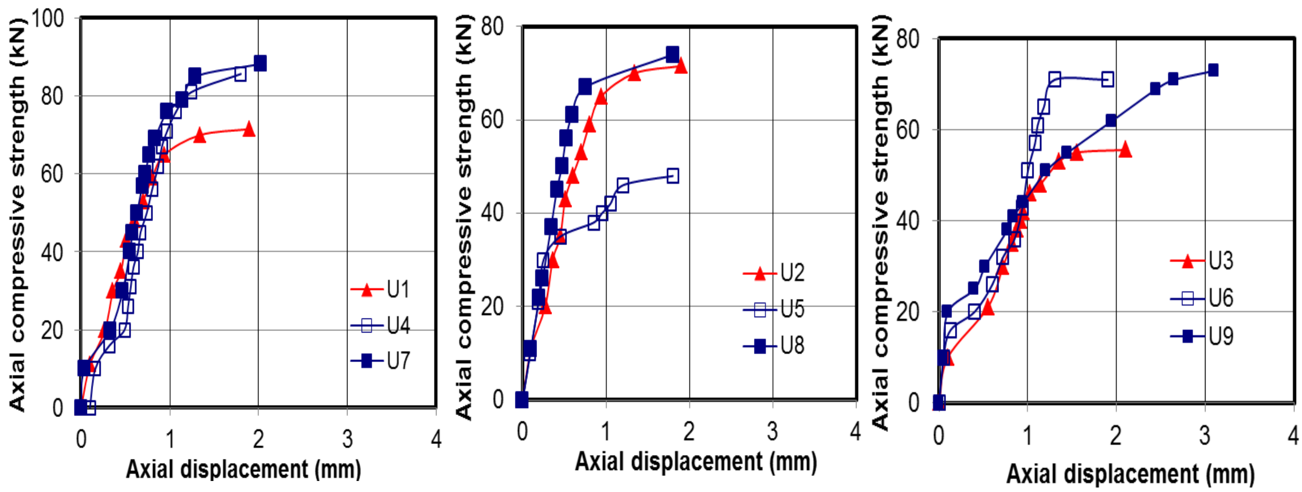


Fig. 9. Effect of the shapes of web opening of the load-displacement behaviour of U shaped steel columns

3.3. Ultimate axial compressive load

The axial compressive load at failure for each steel column specimen listed in Table 1 was recorded, and Table 3, Table 4 and Fig. 10 present the test results. It is obvious from these figures and tables that the column axial compressive strength for both box and U shapes steel column section was significantly affected by changing the numbers and the shape of web openings. The results generally indicates that for opening with a ratio of opening width to total section width (*w*/*W*) less than 0.45 the increasing of the numbers of web openings results a decreasing of the column axial compressive strength compared to the reference steel column which has no web openings. On the other hand, for opening with ratio of opening width to the total section width (*w*/*W*) greater than 0.45 the increasing of number of opening has no considerable effect on axial compressive strength if compared with column of one opening.

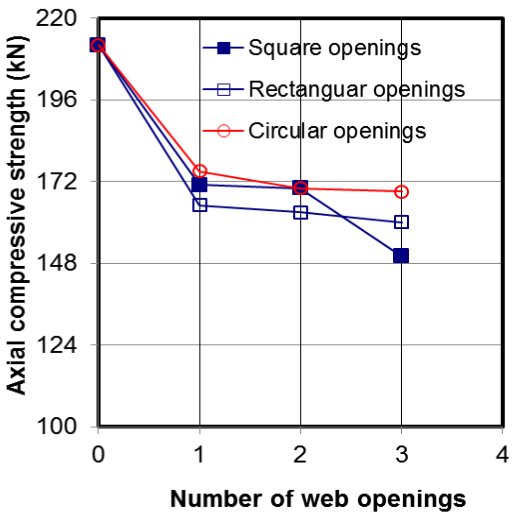
Moreover, Table 3 and Fig. 10 show that for both column sections considered in the experimental test, the reduction in the axial compressive strength of the steel column specimens caused by the presence of web openings is lower in the case of circular shape opening compared to square and rectangular shapes. The maximum percentage of the reduction in the axial compressive strength in columns with box sections due to the presence of web openings are about 30%, 25%, and 19% compared to the reference columns for square, rectangular, and circular shape openings, respectively. Similarly, the maximum percentage of the reduction in the axial strength in columns with U sections due to the presence of web openings are about 45%, 29%, and 26% compared to the reference columns, for square, rectangular, and circular shape openings, respectively. As mentioned previously, this behavior can be explained by the effect of the stress developed at the openings edges. These stresses has less effect in the case of circular opening because it distributed almost equally around the circular openings edges while for square and rectangular shapes opening, the stresses are localized at the opening coroners which may increase the possibility of local buckling. It can also be noticed from Table 3, Table 4 and Fig. 10, that the maximum percentage of the reduction in the axial strength due to the presence of opening was almost similar for both box and channel sections which are %43 and %45 for box and channels sections, respectively.

Table 3. Ultimate axial compressive load versus numbers of web openings of box section steel columns

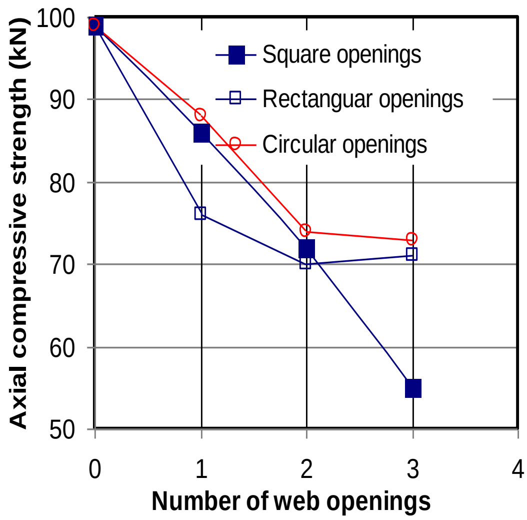
Box section steel column					
Square openings		**Rectangular openings**		**Circular openings**	
Ultimateload (kN)	**No. of openings**	**Ultimateload**	**No. of openings**	**Ultimateload**	**No. of openings**
212	0	212	0	212	0
171	1	165	1	175	1
170	2	163	2	170	2
150	3	160	3	169	3

Table 4. Ultimate axial compressive load versus numbers of web openings of channel section steel columns

Channel section steel column					
Square openings		**Rectangular openings**		**Circular openings**	
Ultimateload (kN)	**No. of openings**	**Ultimateload**	**No. of openings**	**Ultimateload**	**No. of openings**
99	0	99	0	99	0
86	1	76	1	88	1
72	2	71	2	74	2
55	3	70	3	73	3



(A)



(B)

Fig. 10. Effect of the number and the shapes of web opening of the load-displacement behaviour steel column; (A) box section, (B) U sections

4. CONCLUSIONS

This paper has presented an experimental study to investigate the effects of web opening on the ultimate axial compressive strength of cold formed thin walled sections (CFS) steel columns under compressive load. Small scale steel columns with cold formed box and channel sections have been considered in the experimental tests. Each group of ten columns with same cross section shape was divided into three groups of three columns in addition to the reference column. All groups of columns have the same opening area located at the web of the section, but each group has a different opening shape and each column within each group has different numbers of opening distributed along column length. All tested columns were subjected to increasing monotonic static axial loads up to column failure which is indicated by the reloading of the test machine. The following may be drawn from the presented study:

1. The experimental tests conducted in this study have shown that 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. On the other hand, increasing of the numbers of web openings has a trivial effect on the column axial compressive strength compared to columns with only one web opening. This conclusion is valid for both cold formed box and channel sections considered in this study.
2. 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 opening has no considerable effect on axial compressive strength if compared with column of one opening.
3. 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.

4. 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.
5. 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.
6. 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.

5. REFERENCES

Abdel-Rahman N. and Sivakumaran K.S., 1998. Effective design width for perforated cold-formed steel compression members. Canadian Journal of Civil Engineering. 25: 319.330

Abdel-Rahman N. M. 1997. Cold-Formed Steel Compression Members With Perforations. PhD Thesis, Civil Engineering department, Mcmaster University, Canada.

AISI. 1991. The specification for design of cold-formed steel structural members. Washington, DC, USA: American Iron and Steel Institute.

ASCE. 2005. Specification for structurl steel buildings (LRFD) . Inc, Chicago, IL. American Institute of Steel Construction. USA.

Eurocode 3 - design of steel structures —Part 1–1:general rules and rules for buildings. BS EN 1993-1-1:2005, European Committee For Standardization, February 2006 and April 2009 [Incorporating Corrigenda, 63- 64].

Karagah H., Shi C., Dawood M. , Belarbi A. , 2015. Experimental investigation of short steel columns with localized corrosion. Thin-Walled Structures 87: 191–199.

Salhab B., Wang Y.C. 2008. Equivalent thickness of cold-formed thin-walled channel sections with perforated webs under compression. Thin-Walled Structures 46:823–838.

Shanmugam N.E. Dhanalakshmi. M. 2001. Design For Openings In Cold-Formed Steel Channel Stub Columns. Thin-Walled Structures 39: 961–981

Sweedan A. M.I., El-Sawy K.M. 2011. Elastic local buckling of perforated webs of steel cellular beam–column elements. Journal of Constructional Steel Research 67 1115–1127.

Veríssimo G. D. , Fakury R. H. , Ribeiro J. C. L. Design Aids For Unreinforced Web Openings In Steel And Composite Beams With W-Shapes, Engineering Journal / Third Quarter / 20

Yu W.W. 2000, Cold-Formed Steel Design. 3rd Edition, John Wiley & Sons, Inc., United States of America.