Experimental study of Castellated Steel Beams

Mazin A. Al-Mazini[1]

(Received 29/3/2017; accepted 20/6/2017)

Abstract

In this study an investigation of castellated beam are presented. The experimental and analytical results of seven simple castellated beams and other one has webbed section are summarized in this study. The target of the search was to study the structural behavior and mode of failure of castellated beams which have different geometric shape of hole and varies lengths span of beams, and attempt to find out the possibility of Biodgett equation and Halleux equation to determine ultimate and limit load respectively. Four angle off cutting were used to achieve the change in the geometry of hole (45, 50, 60 and 90 degree). The specimens were made from IB 203x133x25 and were expanded to 1.5 times the standard depth. Ultimate and limit load, load-deflection relation shapes and mode of failure were presented and discussed. The experimental results showed that the ultimate and limit load of castellated beams decreases with increasing the angle of cutting and Biodgett equation gives acceptable results for estimating ultimate load when the angle of cutting 50° or less. Also it is found that the limit load of castellated beam by Haleux equation is incorrect when the angle of cutting greater than 50°. As well as ANSYS-12 was used to analysis these beams by nonlinear finite element method. Four- nodes shell element (SHELL 181) was used to represent the castellated and webbed beams. This model was validated by comparison of the experimental and numerical results of ultimate load and their corresponding modes of failure.

Keywords: Castellated beam, Geometry of Hole, Failure Pattern.

دراسة عملية للعتبات المركبة ذات الفتحات (كاستلد)

د. مازن المازني

الخلاصة

تناول هذا البحث دراسة عملية وتحليلية لسلوك العتبات المركبة ذات الفتحات (كاستلد). تتضمن الدراسة ملخص لنتائج عملية وتحليلية لسبعة من أعتاب كاستلد مسندة اسناد بسيط وعتب صلد واحد. الهدف من البحث هو دراسة السلوك الأنشائي وشكل الفشل للكاستلد التي لها فتحات ذات شكل هندسي مختلف وكذلك تم أخذ اطوال مختلفة من النماذج بالأضافة الى محاولة لمعرفة امكانية معادلة Biodgett لتحديد الحمل الاقصى ومعادلة Halleux لمعرفة الحمل المحدد. وقد استخدم أربعة زوايا قطع للحصول على أشكال هندسية مختلفة من الفتحات (٤٠ و ٥٠ و ٦٠ و ٩٠ درجة). تم صنع النماذج من IB 203x133x25 وتوسعت ١,٥ مرة من عمقها الأصلي. نوقش في هذه الدراسة الحمل الأقصى والحمل والمحدد ورسم علاقة الحمل مع الأود وكذلك توضيح شكل الفشل لكل عتبة. أوضحت النتائج العملية بأن الحمل الأقصى والحمل المحدد يقل بزيادة زاوية القطع للفتحات. معادلة Biodgett تعطي نتائج مقبولة لتقدير الحمل الأقصى عندما كانت زاوية القطع ٥٠ درجة فما دون. ايضا وجد أن تقدير الحمل المحدد بواسطة معادلةHaleux يكون غير صحيح عند زاوية قطع أكبر من ٥٠ درجة. بالأضافة الى ذلك تم أستخدام ANSYS-12 لتحليل هذه العتبات بطريقة العناصر المحددة غير الخطية. وقد أستخدم SHELL 181 لتمثيل النماذج. تم التحفف من صحة هذا النموذج من خلال [2]المقارنة بين النتائج التجريبية والعددية للحمل الأقصى وشكل الفشل للأعتاب.

[1] *PhD. at College of Engineering, Basrah University, Email: almazini_engineer@yahoo.com.*

1. Introduction

Castellated beam is a I-section steel beam is made by cutting longitudinally along its web in a regular alternative pattern so that the beam divided into two parts, then one part is moved and joint this two halves by welding to form regular opening[1].

There are five types of terms to define the castellated beam. The first is the web post, which it is the solid section of the web and the second term is the geometric shape of a hole. While the throat width is a horizontal cut length on the root beam. In addition, the part of web between the hole and the flange indicates to the throat depth. Finally, the expansion (α) refer to the percentage change of the depth of root (original) section of the beam to the depth of castellated section, (α=h/hc) as shown in Figure (1).

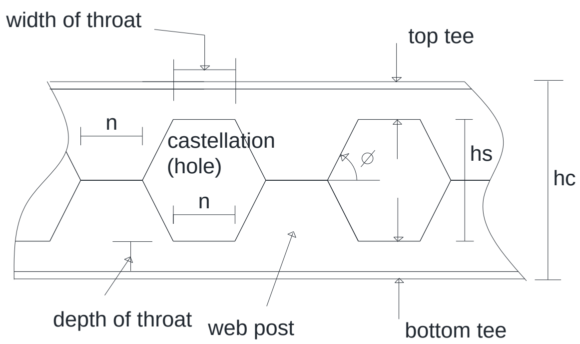


Figure 1. Castellated beam[1]

Two parameters are used to indicate the geometric shape of a hole which are the angle of cutting (ϕ) and the welded length (n). The angle of cutting effects on the number of castellation (N) per unit length of the beam. When the angle of cutting is large (N) is large too.

castellated beam will failed in web weld due to horizontal shear if the length of the web weld too short, while too long of the weld results large tee and may cause Vierendeel bending failure. So to balance these to failure can be use n=hc/4[2].

The main advantage of the castellated beam is it high vertical bending stiffness due to increasing its depth. Because of the high strength to weight ratio of castellated beam and their lower maintenance and painting costs, they can sometimes advantageously replace built-up girders. The mode of failure of castellated beam depends on shape of opening, slenderness ratio of web, type of loading and lateral support. There are fife types of failure that can be noted[3]:-

1- Vierendeel or shear mechanism: This failure is dependent on the presence a high shear forces in the holes through span. When the castellated beam is a short span with a small tee section and a long weld it will fail by this mode. Altifillisch (1957)[4] and Toprac and Cook (1959)[5] presented the first report about this mode.

2- Flexural mechanism: This failure occurrs in the section suffering high bending moment. This mode of failure was reported in the works of Toprac and Cook (1959)[5] and Halleux (1967)[6].

3-Lateral-torsional buckling: It is usually associated with long span beams with inadequate lateral support to the compression flange.

4- Rupture of a welded joint: If length of the welded joint is small this mean the horizontal shear stress is height and leads to rapture the beam, as found by Husain and Speirs (1971)[7].

5- Web post buckling (crippling): The buckling of castellated beam can be result from the effect of two different stress on both edges of opening which are one edge in tension stress and other in compression and this buckling led to twist the web post alonge its height. This mode was investigated by Sherbourne (1966)[8] and Halleux (1967)[6].

Artificial neural networks were developed to predict ultimate load capacity and post buckling of castellated beam by Amayreh et al. (2005)[9] and Gholizadeh et al. (2011)[10], respectively. Wakchaure (2012)[11] reported that the presence of the opening causes local effect in the beam lead to increase its deflection rapidly. Also, it found that castellated steel beam behaves satisfactorily with attaining requirements up to a maximum depth of web opening 0.6 of depth.

2. Research Significant and Objectives:

The fundamental objective of this work was to provide information on the fresh and behavior of castellated beamsto support the practical work of other partners in assessing the practical and to facilitate the introduction of general construction practice.

3. Experimental investigation

3.1 Details of test specimens

In this study, IB 203x133x25 is used as a parent beam to fabricate the castellated beams, as shown in see Figure (2). Tests were carried out on eight specimens included seven castellated beam with different cutting angle (6C45, 6C50, 8C60 11C90, 4C45, 4C50, 5C60) and one webbed section (C0). Details of the specimens are presented in Table (1). The specimen is labeled according to the number of hole and the degree of cutting angle, for example 4C45, this mean that the specimens have four holes with angle of cutting is 45o.

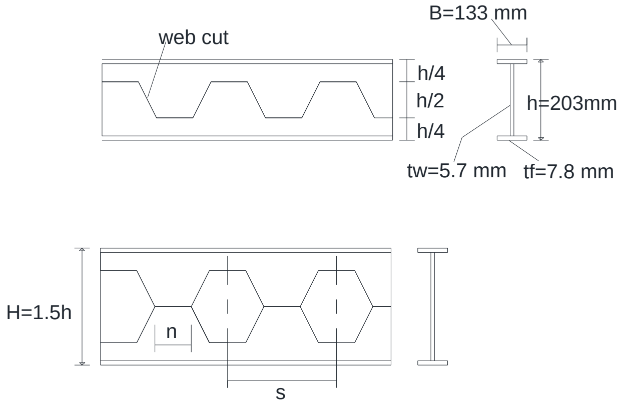


Figure 2: Castellated I-beam produced form original profile

Table (1): Details of the Tested specimens

specimen	Length M	Cutting Angle ϕ°	s mm	n mm	Type of load (No. of load)
6C45	2.4	45	400	100	1
6C50	2.2	50	372	100	1
8C60	2.4	60	300	100	1
11C90	2.3	90	200	100	2
4C45	1.6	45	400	100	1
4C50	1.5	50	372	100	1
5C60	1.5	60	300	100	2
C0	1.6	----	---	----	1

3.2 Material properties

The properties of the material of the steel were obtained according to ASTM A370[12]. Coupons were cut from flanges and web. The average yield stress and modulus of elasticity are 255 and 196500 MPa respectively.

3.4 Test procedure and instrumentation

The beams were tested as simply supported under one or two point static loads. To apply vertical force, a Torsee′s Universal Testing Machine with capacity 2000 kN at the laboratory of construction materials-University of Basrah was used. Dial gage with accuracy 0.01 mm per division was used to measure the vertical deflection at every stage of load. The maximum load that can be observed in the testing machine represents the ultimate of the specimen. Figure (3) shows the test set up of the specimens.

Figure (3): Test Set up of Castellated Beam

4. Finite Element Analysis

Beside the experimental study, numerical study by using the finite element method (FE) was conducted in the ANSYS Version 12.0 [13] program for each specimens. Castellated beams are simulated by using four node element (SHELL181), which has six degree of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes. The properties of the steel used in the finite element analysis are the same as those adopted in the experimental work. A bilinear isotropic material model with Von Mises yield criterion was used for the material to model the material nonlinearity. Table (2) presents the properties of steel entered in the program. The support and loading conditions of experimental beams were simulated in the analytical model by restraining the appropriate degrees of freedom.

Table (2): Properties of steel used

Linear isotropic	
Elastic modulus (Es) MPa	196500
Poisson′s ratios (υ)	0.3
Bilinear isotropic hardening	
Yield stress (Fy) MPa	255
Tangent modulus (ES2) MPa	20000

To simulate the geometry of the models and to satisfy the requirement of the used element′ s aspect, ratio, a fine mesh of 25 mm x 25 mm fineness was provided. Figure (4) shows a typical full mesh model for one of the analyzed castellated beams.

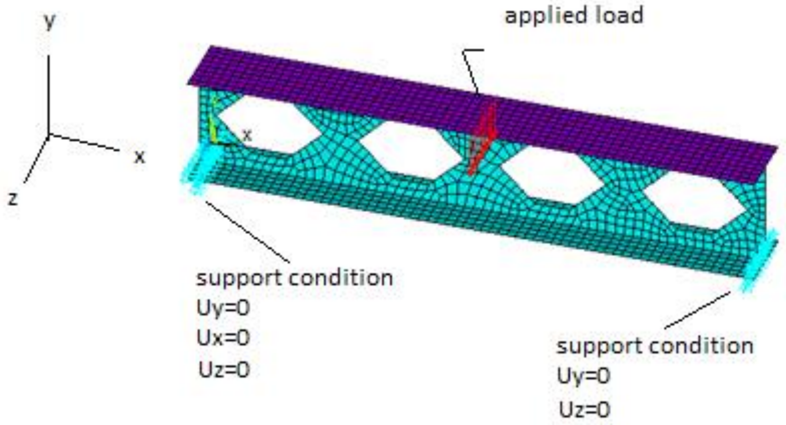


Figure (4): Typical finite element model showing the applied load, mesh and boundary c onditions.

5. Results and Discussion

The specimens 6C45, 6C50, 8C60 and 11C90 failed by web post- buckling (crippling), Figure (5) shows the failure modes of those specimens. The distinctive characteristics of web crippling is illustrated in Figure (6).

In Figure (6) the fibers along CD are stressed in compression while those along AB are stressed in tension. Edge buckling occurred in all specimens mentioned above along CD and EF. There is not available exact solution of the web crippling. However an approximate elastic method of analysis was presented by Biodgett [14]. It is based on Olander's Wedge method [15]. The maximum bending stress, σt max, can be determined by equation (1), that follows.

$$\sigma_t \max = \frac{3\tan\theta}{4\,s\,x\,n\,\theta^2} \quad \text{-----------} \quad (1)$$

The maximum bending stress must not exceed the allowable stress, Fa [14]

$$F_a = \left[1.0 - \frac{10.434}{C_c^{\,2}}\left(\frac{h}{w}\right)^2\right]0.6F_y \quad \text{---------} \ (2)$$

where

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} \quad \text{------------}(3)$$

The allowable shear force, Fall can be obtained by substitution from equation (1):

$$F_{all} = \frac{4\,w\,\mathrm{X}\,n\,\theta^2}{3\tan\theta}F_a \quad \text{------------} \ (4)$$

The allowable midpoint concentrated loads, P_{all}, can be determined by:

$$P_{all} = \frac{4\,F_{all}\ \text{X}\,6.93}{s} \qquad \text{-----------------} \ (5)$$

in which:

w = thickness of web (mm)

F_y = nominal yield stress of steel (MPa)

6C45

6C50

8C60

11C90

Figure 5: Specimens failed in post tension

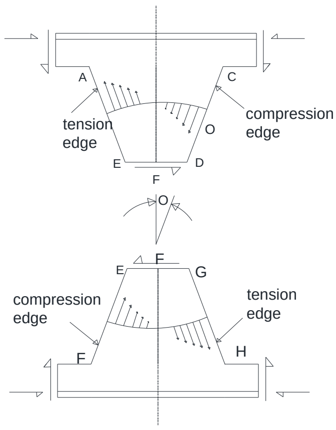
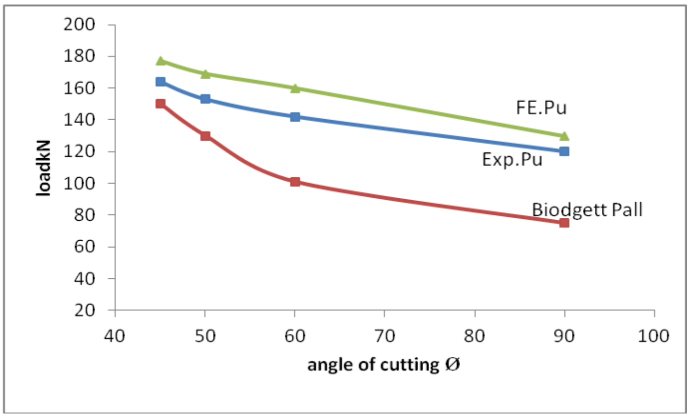


Figure 6: Web buckling due to shear



Exp.P_u observed maximum load at laboratory
FE.P_u maximum load obtained from finite element analyses

Figure (7): Load-angle of cutting relationships

From Figure (7), it can be observed that, in general, the ultimate loads from experimental work, finite element and Biodgett equation decreases with increase of angle of cutting, small difference between values of the finite element analysis and the experimental evidence. However, Biodgett equation exhibtted lower ultimate load value than those extracted from the experiment investigation, the difference between them increase with increasing angle of cutting.

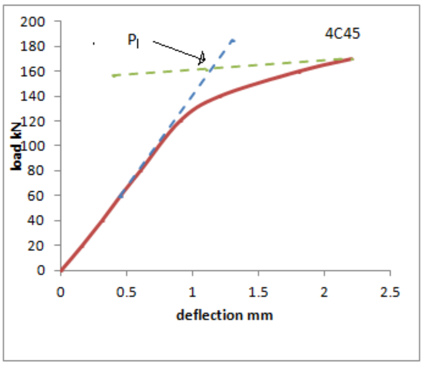
Specimens 4C45, 4C50 and 5C60 failed by Vierendeel mechanism. Figure (8) shows the shape of that failure. In this secton of the study, the experimental value of limit load (P_l) was compared with that calculated theoretically. Limit load is the load after which the deflection becomes large in relation to purely elastic deflection. Halleux's tangent intersection method[16] was used to calculated the experimental value of the limit load. Figure (9) presents the load deflection curves of the specimens 4C45, 4C50 and 5C60 and marks the limit load value for each specimen on the curve. While the theoretical limit load was obtained by applying Halleux's method[17]. This method is depends on the kinematic theorem, and proposes the mechanism of the failure as illustrated in Figure (10). The limit load can be determined by equating internal work due to bending and the external work due to deflection, as given later on in Eq. (6).


4C45

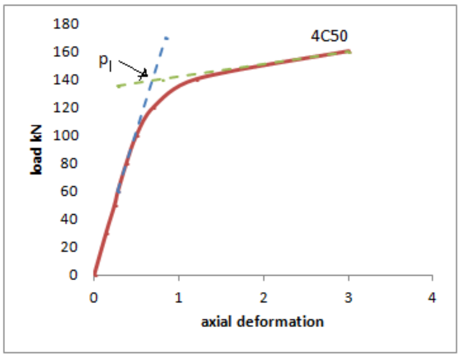
4C50

5C60

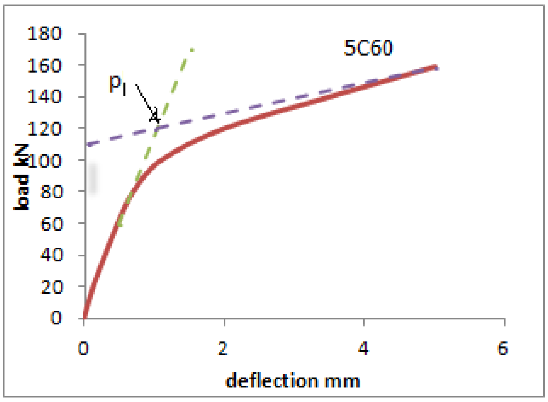
Figure (8) Castellated specimens failing Vierendeel mechanism



(a)



(b)



(c)

Figure (9): Load deflection curves of the castellated specimens 4C45, 4C50 and 5C60

$P_l = (8Z_t * F_y)/n$ --------(6)

where: P_l=limit load

Z_t = plastic section modulus of the T-section (mm^3)

F_y = yield stress of steel (MPa)

n = width of the welded joint (mm)

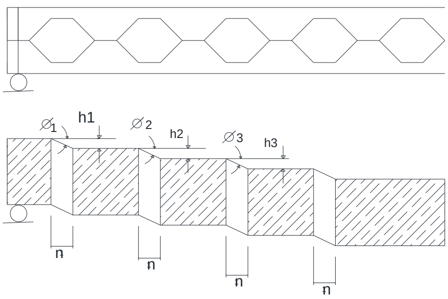


Figure (10): Mechanism of failure as illustrated by Halleux[16]

Experimental limit loads and those calculated by Halleux's method are presented in Figure (11).

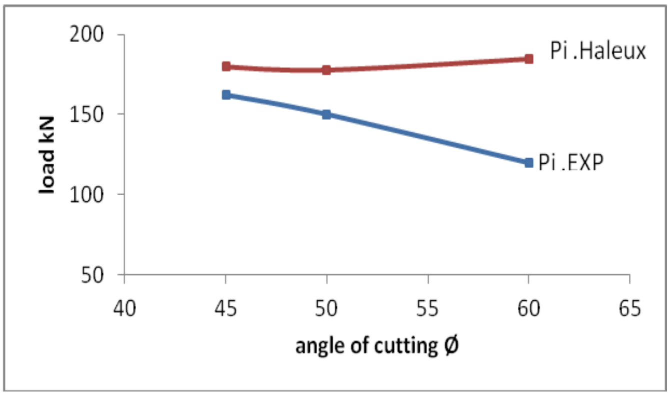


Figure 11. Compassion between Pl.Halleux and Pl.EXP. results

It can be observed from Figure (11) that, P_l from Haleux equation does not give significant effect of angle cutting on P_l value on the other hand,$P_{l.EXP.}$ decrease with increasing of Ø. From the above result, it can be concluded that Halleuxs equation is not useful to estimate of P_l for a castellated beam with Ø greater than 50degrees.

Figure (12) shows that; with decreasing angle of cutting the finite element analysis gives bitter agreement with experimental results than with larger Ø.

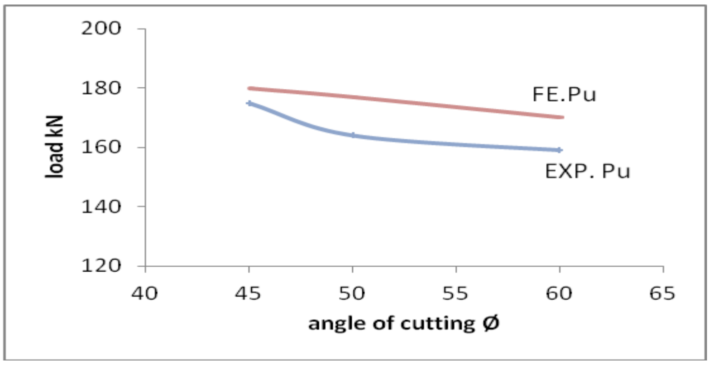


Figure 12. Variation of ultimate load with angle of cutting; Ø by the finite element analysis and the experimental investigation

Figure (13) shows an experimental compression between the load- deflection relations of the webbed (C0) and the castellated beam (4C45), it observed that, the stiffness of the castellated beam was greater than that of the webbed beam. Failure pattern of the webbed beam was flexural with yielding of bottom flange, as shown in Figure (14), while the castellated beam failed by Viemdeel mechanism As result, the webbed beam the ultimate load greater than that of the castellated beam. This is mainly because the webbed section has failed in flexure thus giving load-carrying capacity greater than that failing in shear.

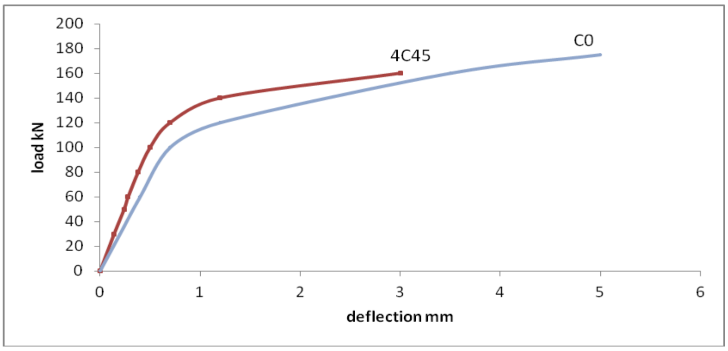


Figure (13): Load-deflection relationship of C0 and 4C45

Figure 14. Failure Mode of specimen C0

After analyzed the castellated beam by ANSYS program, we noted the distribution of stress is around the openings and slight stress in the web post regions, as shown in Figure (15) and Figure (16) shows the typical specimens after failure

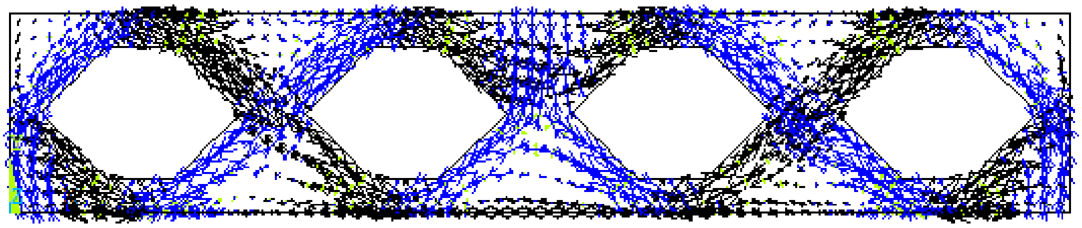


Figure 15. Stress Distribution in the Castellated Beam

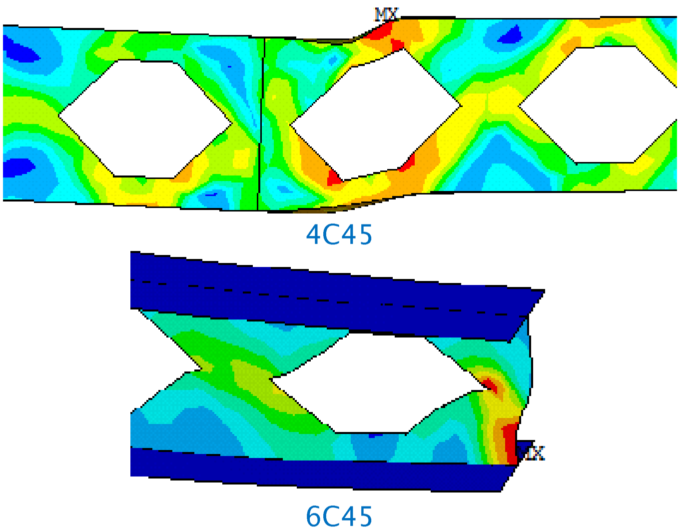


Figure 16. Von Mises stress distribution for specimens

Conclusions

1- The ultimate load of castellated beam decreases with increasing the angle of cutting about 25%. Prediction of the ultimate load by Biodgett equation gives acceptable results when the angle of cutting does not exceed 50°.
2- Limit load of the castellated beam decrease with increasing the angle of cutting, and cannot be predicted the limit load by Haleux's equation when the angle of cutting is larger than 50°.
3- Finite element analysis gives good agreement predict the ultimate load with the experimental evidence. Where the convergence about 78%.

References

[1] Tsavdaridis, Konstatinos and Kingmas (31 july 2014)/" Application of structural Topology Optimization to Perforated Steel Beams". Computers and Structures (Science Direct) 158:108-123.
2007;45:517–27.
[2] Knowles, P.R. Design of castellated beams. (for use with BS 5950 and BS 449) Constrado, Croydon, UK, 1985.
[3] Kerdal, D., and Nethercot, D.A. 1984."Failure Modes for Castellated beams". Jornal of Constructional Steel Research, Vol. 4, pp 295-315.
[4] Altifilish, M.D., Cooke, B.R., and Toprac, A.A., 1957. "An Investigation of open Web Expanded Beams". Welding Research Council Bulletin, Series No. 47. pp 77S-88S.
[5] Trorac, A.A., and Cooke, B.R. 1959. "An Experimental Investigation of open-Web Beams". Welding Research Council Bulletin, New York, Series No. 47, pp 1-10.
[6] Halleux, P. 1967. "Limit Analysis of Castellated Steel Beams". Acier-Stahi-Steel, 32:3, 133-144.
[7] Husain, M.U., and Speirs, W.G. 1971. "Failure of Castellated Beams Due to Rupture of Welded Joints". Acier-Stahi-Steel, No1.
[8] Sherbourne, A.N. 1966. "The Plastic Behavior of Castellaed Beams". Proc. 2nd Commonwealth Welding Conference. Inst. of Welding, No. C2, London. PP 1-10.
[9] Amayreh, L., and Saka, M. P., "Failure Load Prediction of Castellated Beams Using Artificial Neural Networks". Asian Journal of Civil Engineering (Building and Houseing). Vol. 6, Nos. 1-2 ,2005, pp. 33-54.
[10] Gholizadeh, S., Pirmoz, A., and Attarrejad, R. "Assessment of Load Carrying Capacity of Castellated Beams by Neural Networks", Journal of Constructional Steel Research 67, 2011, pp. 770-779.
[11] Wakchaure, M.R., and Sagade, A.V. "Finite Element Analysis of Castellated Steel Beam", International Journal of Engineering and Innovative Technology (IJEIT), Vol. 2, Issue 1, July 2012.
[12]- ASTM A 370-05, (2005), "Standard Test Method and Definition for Mechanical **Testing** of Steel Products", Annual Book of ASTM Standard, Vol. 01.01. ASTM, Philadelphia, PA.
[13] ANSYS, (1981), "ANSYS Help", Release 11.0, USA, Copyright 2006. Edition, John Wiley and Sons New York.
[14] Blodgett, O. W., "Design of Welded Structures", The James F. Lincoin Arc Welding Foundation. Cleveland, Ohio, 1968.
[15] Older, H. C., ASCE Transaction Paper No. 2698, 1954.
[16] Redwood R. G., "Ultimate Strength Design of Beams with Multiple Openings", Paper presented at the ASCE Annual Meeting and National Meeting on Structural Engineering. Pittsburgh, Pa., September 1968.
[17]Hope, B. B. and Sneikh, M.A., " The Design of Castellated Beams," Transactions of Engineering Institute of Canada, Vol. 12, No. A-8, September 1969.