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NUMERICAL STUDY ON THE EFFECT OF OPENINGS IN STEEL IPE BEAMS STRENGTHENED BY CFRP PLATS

دراسة عددية لتأثير الفتحات في العتبات الحديدية المقواة بصفائح الألياف الكاربونية

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ABSTRACT :

This paper presents the numerical study of the nonlinear finite element behaviour of steel beams with openings strengthened by CFRP plates. A three dimensional nonlinear finite element model is developed using a most famous software package (ANSYS V.14.5). The steel beam and CFRP plates were simulated by four-node shell elements (SHELL 181) and one dimensional nonlinear spring (COMBIN 39) as interface element between steel beam and CFRP plates. Parametric studies were adopted to investigate the effect of shape, locations of the web openings and number of layers of CFRP plates which were used in strengthening the steel beam. The obtained results showed that the ultimate load decreases with the increase in the opening area. Circular web openings at the shear zone of the steel beams were caused smaller decreasing in the ultimate load capacity because of a very less stress concentration at the web openings, while the beams with rectangular opening results the lesser load carrying capacity, i.e. 38% less than their corresponding beams with circular or square opening. Applying CFRP plates around the web opening of steel IPE-beams was a successful method for increasing the load carying capacity and decreasing the deformations.Moreover, increasing the number of CFRP layers leads to increase the stiffness and shear resistance of the steel beam, hence, increasing the ultimate load capacity by (15-36 %).

Keywords: finite element , steel beams , web openings, CFRP plates

الخلاصة:

يتناول هذا البحث دراسة نظرية لسلوك العتبات الحديدية المحتوية على الفتحات والمقواة بصفائح الالياف الكاربونية.تم إجراء التحليل اللاخطي الثلاثي الأبعاد باستخدام طريقة العناصر المحددة وبالاعتماد على برنامج (ANSYS V.14) في هذه الدراسة.

تم استخدام العناصر الصفائحية ذات الاربع عُقد (SHELL 181) لتمثيل العتب الحديدي وكذلك الصفائح الكاربونية (CFRP) بينما مُثل الترابط بين العتب الحديدي والصفائح الكاربونية باستخدام عنصر أحادي البعد (COMBIN 39)ذو عقدتان.

دراسات عددية اجريت لتحري تاثير شكل ومواقع الفتحات الموجودة في العتب الحديدي وكذلك عدد طبقات صفائح الالياف الكاربونية (CFRP) التي تستعمل في تقوية العتب الحديدي.

انتائج المستحصلة من هذه الدراسة بينت انه قابلية التحمل للعتبات الحديدية تتناقص بزيادة مساحة الفتحات وقد تبين بان الفتحات الدائرية في منطقة القص تؤدي الى اقل معدل نقصان في قابلية التحمل وذلك بسبب قلة تركيز الاجهادات في الفتحة،بينما اظهرت العتبات ذات الفتحات المستطلية اقل قابلية تحمل حيث يصل النقصان الى (38%) مقارنة بالعتبات ذات الفتحات الدائرية والمربعة.

كما بينت النتائج ان استخدام صفائح الالياف الكاربونية حول الفتحات لتقوية العتبات الحديدية تعتبر طريقة ناجحة لزيادة قابلية التحمل ونقصان التشوهات. كما ان زيادة عدد طبقات الالياف الكاربونية يؤدي الى زيادة صلابة تلك العتبات وبالتالي زيادة قابلية تحملها بحدود (15- 36 %).

1. INTRODUCTION :

In the constructions of modern buildings, a system of conduits and pipes are important to oblige crucial like air-conditioning , water supply, power, phones, and PC system. Ordinarily, these ducts and pipes are underneath the beams and for aesthetic reason are hid by a false ceiling , so producing a dead space .when these ducts Pass through transverse openings of the floor beam a saving in the dead space will occure and results in a most compact designs.

Invistigations on different web openings patterns (square, rectangular, circular, concentric, and eccentric opening) were accomplished in the United States and Canada in the 1970s and 1980s, for individually composite and non-composite steel beams.

Various authors, Lawson [1], Darwin [2], Chung and Lawson [3], and Chung and Ko [4], have showed that composite and steel beams with web opening are possible to designed by the two methodologies (Perforated and Tee Section). To design these beams, Chung et al. [5] presented a stimulating technique, based on plastic section analysis approaches. General design approvals for steel and composite girders with opening are presented in the literature based on additional experimental and numerical studies, however these controlled by detailed procedures or empirical equations [6].

As indicated by Chung et. al. [7] in 2001, that are not exceptional of use beams or girders have web openings up to 75% of the depth if the services requires that (Fig. 1). Depening on the opening size, shape, and location, a significant reduction of the ultimate load may result due to these openings. A possible stiffeners welded close the web opening of Rectangular or circular openings are commonly used to increase the ultimate load of the beam.

Certainly a significant reduction of the flexural and shear capacity of the beam may occure if these openings are unstrengthened [8].

Recently , as aresult of their low weight, high tensile strength, and more resistance against corrosion ,using CFRP products has been more popular than other materials for strengthening structures .

In 2006, Hollaway et al.[9] studied one the the most main problems induced in the strengthening steel structures by CFRP products which is the bond between CFRP, steel, and adhesive and clarified how this problem can be eliminate.

In 2011, Narmashiri K, et al [10] presented the numerical and experimental invistigation on the flexural strengthening of steel I-beams by CFRP plate. Also a nonlinear FE analysis was used to understand the effect of CFRP plates strengthening on the structural behaviour of steel beams with openings .They concluded that ultimate load and failure modes were sensitive to the type and thicknesse of CFRP plates.

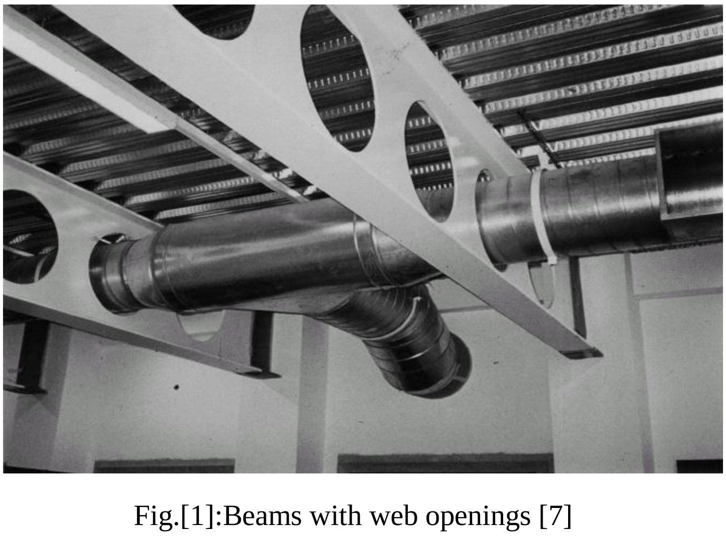

Fig.[1]:Beams with web openings [7]

2. FINITE ELEMENT ANALYSIS

The nonlinear finite element study is modeled using ANSYS software (Version 14.5). Shell element (SHELL181) was implemented in the model as shown in Figure 2, details in the ANSYS finite element help documentary [11]. Four nodeed element with six DOF per node, i.e., translations and rotations on the X, Y, and Z axis was adopted. SHELL181 is used to model both steel IPE-section and CFRP plates. This element capable for compute plasticity, stress stiffening, creep, large strain, and large deflections [11].

The connection between steel section and CFRP plates was idealized by using one dimensional nonlinear spring interface elements (COMBIN 39) at the contact nodes.

The aim of the present study is to determine ultimate loads and the maximum deflection under the effect of various parameters; locations, shape of the web openings and number of strengthening layers by CFRP plates.

To simulate the collapse phenomena as perfectly as possible geometrical and Material non-linearities were modeled. A Newton Raphson algorithm was adopted in this model to get the nonlinear solutions. The displacement convergence criterion is used to monitor equilibrium.

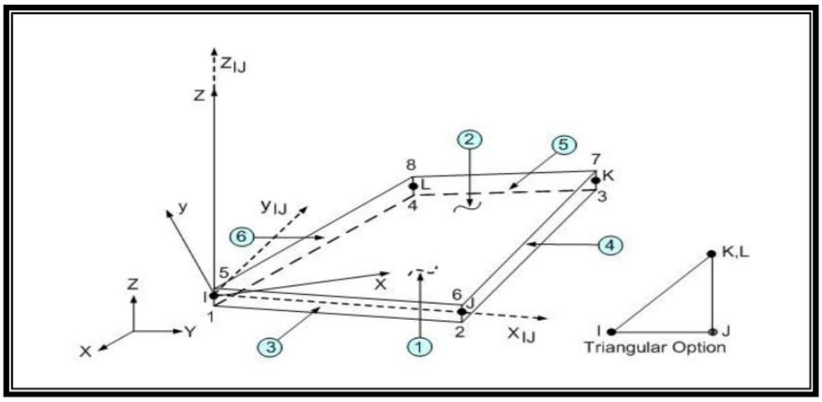

Fig. [2]: Geometry of Element (SHELL181) [11]

2.1. Material Modeling:

2.1.1. Steel Beam

A greatly simpler material to be modeled is steel since the physical characteristics of it are well known. The strain-stress diagram can be presented to be identical in both compression and tension. In the present study, the bilinear stress-strain relationship indicated in Figure (3) was used.

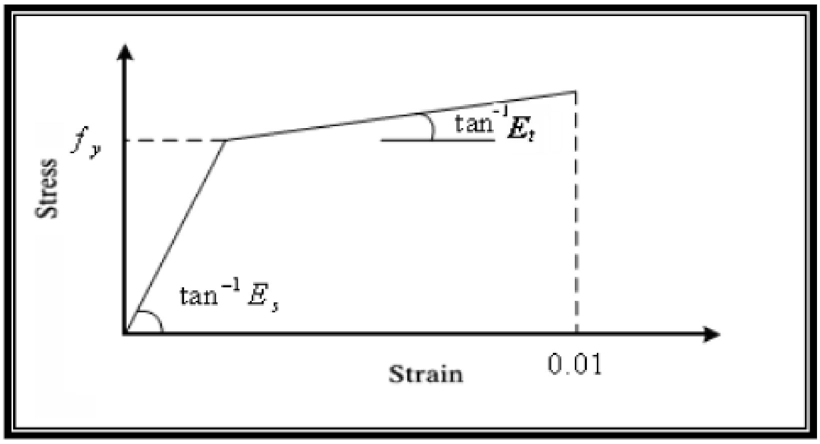

Fig.[3]:Idealization stress-strain behaviour of steel

Therefore, two branches may be represent the stress-strain curve of steel for simplicity: The first starts from the origin with a slope equal to modulus of elasticity E , up to yield stress fy .A second branch is limited to the strain 0.01 and have a very small slope up to ultimate stress f_u.

2.1.2 Carbon Fiber Reinforced Polymer CFRP

The behavior of carbon fiber polymer (CFRP) used in the present study is assumed to have linearly elastic stress-strain relation up to failure and does not exhibit any plastic deformation before rupture as shown in Figure(4). Failure of carbon fiber reinforced polymer occurs when the strain(ε_{pu}) corresponding to the rupture stress (f_{pu}) is reached.

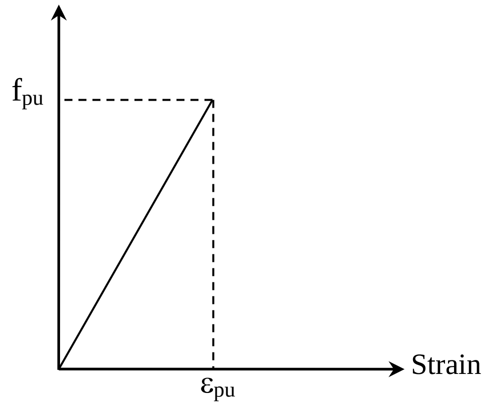

Fig.[4]:Idealization stress-strain relationship for CFRP plates

2.2. Validation of the Finite Element Model :

some of the previous work adopted by other studies is remodeled and analysed to verify the reliability of the assumed numerical model, including mesh and element types as follows :

Steel Beams with Unreinforced Web Opening:

The F.E model was validated by comparison with the experimental results of steel I-section beam of one circular web opening, as stated by Redwood and McCutcheon in 1968[13].The test specimen with their geometric details and material properties are shown in Figure (5) and Table (1).

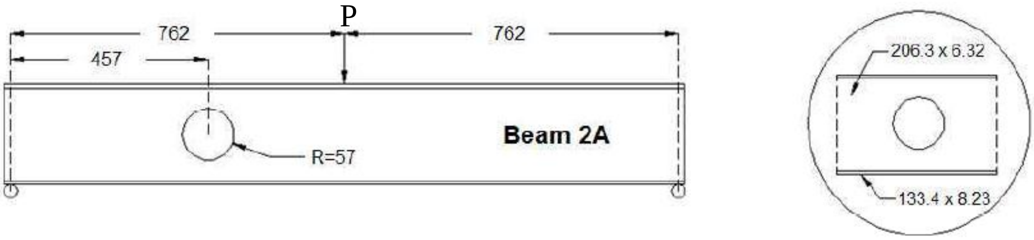

Fig.[5]: Specimen Geometry (all dimensions in mm)[13]

Table (1) : Materials Properties of Steel I-

Property	Dimensions (mm)	f_y (MPa)	f_u (MPa)
Flange	133.4×8.23	352	503
Web	206.3×6.32	376	512

The same steel beam is reanalyzed by ANSYS software package using 4- noded shell element to model both flanges and web, a 25mm element size was found to give the convergent solution . To satisfy continuities in stresses through element boundaries, a circular web opening was modeled in the web with suitable fine mesh pattern. The materials nonlinearity was adopted by a bilinear elasto-plastic behaviour with a 205,000 MPa Young's modulus and a 1% strain hardening.

Figure(6) shows the finite element idealization which is adopted herein.

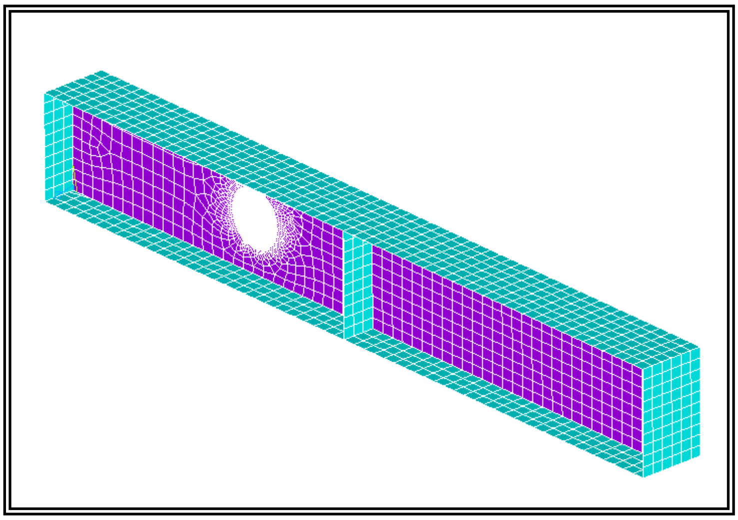

Fig.[6] : Finite element idealization of steel beam

Figure(7) shows the relation between the bending moment at the center of the web opening and the vertical deflection at the central span of both **Redwood** test results and the results obtained from the present study .It was observed that a good agreement with the experimental data was result especially in the elastic region and a small difference was observed in the plastic region may be resulted to the 1% strain hardening assumed in the finite element model. Also geometrical imperfection existing in this beam may be the attribute of this difference.

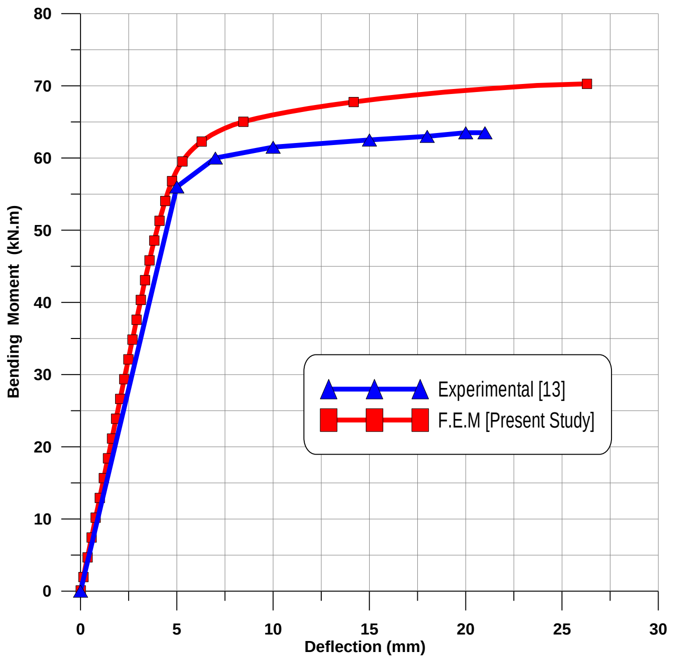

Fig.[7] : Bending moment – deflection curve of steel I-section beam

3. PARAMETRIC STUDY:

A parametric study is focused to study the behaviour of steel IPE-beam having :

1-Different Shapes of web openings.
2-Different locations of web openings.
3-Different number of CFRP layers.

The IPE300 standard section [14] was used in the parametric study with 2200 mm total length. The geometry,supports, loading and mechanical properties plotted and listed in figure (8) and table (2).

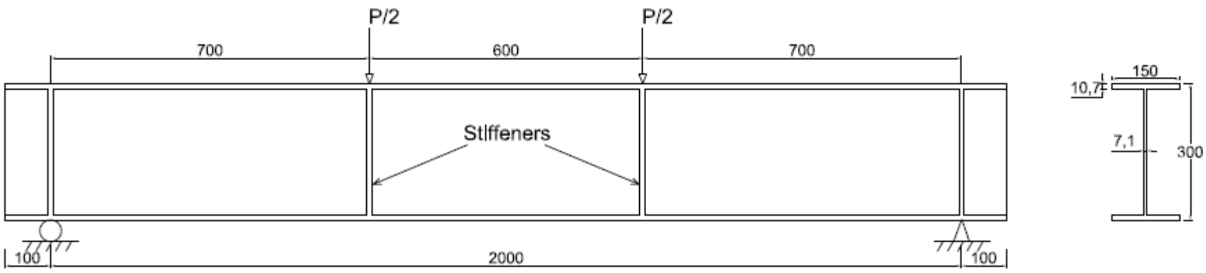

Fig. [8] : Specification and dimensions of Steel IPE-300

Table (2) : Material Properties of Steel IPE-

Property	thickness (mm)	f_y (MPa)	f_u (MPa)
Flange	10.7	253.2	407.8
Web	7.1	253.2	407.8

The one of the main steps in the FE solution is how to select the appropriate element size. By minimizing the elements size until it has a insignificant weight on the results this is practically solved. So this procedure called a convergence study to control an suitable mesh density.However in the present study the mesh convergence was carried out to obtain the adequate size of elements. It was found that a suitable elements size less than (25×25mm) had a negligible effect on mid-span deflections, accordingly the mesh density of (25×25mm) was adequate to use in this study. Figure(9) illustrates the finite element model which was selected for parametric study.

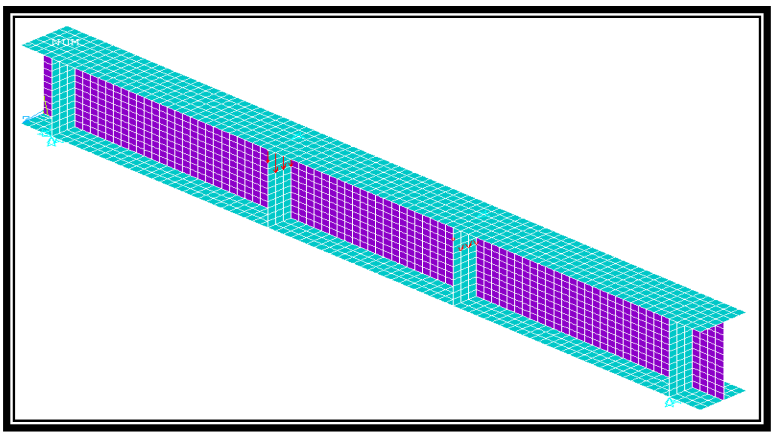

Fig.[9] : Finite element mesh of steel IPE-beam

Numerical case studies were classified into three groups according to the shape of web opening in the steel IPE-section . Beams of group (1) have circular opening with radius of (150 mm) , group (2) have square opening with dimensions are (150 x 150 mm) while group (3) have rectangular opening with dimensions are of (150mm depth x 250 mm width). Each group consisted of nine beams , the first three beams were analyzed without strengthening while the others were analyzed with strengthening by using CFRP plates which their dimensions (50 mm width × 1.4 mm thickness) around web opening with different number of layers. The tensile strength of this type of CFRP is (about 2400 N/mm^2) and about 131000 N/mm^2 modulus of elasticity.

Table (3) : Beam types and section properties

Group No.	Beam Symbol	Shape of opening	Location of Opening	No.of opening	Strengthening
Control Beam	BC	Without opening			Without strengthening
1	B**C**OC	Circular	Mid span	1	Without strengthening
	B1**C**OS	Circular	Center of shear Zone	1	Without strengthening
	B2**C**OS	Circular		2	Without strengthening
	B**C**OC-1S	Circular	Mid span	1	One layer strength.
	B1**C**OS-1S	Circular	Center of shear Zone	1	One layer strength.
	B2**C**OS-1S	Circular		2	One layer strength.
	B**C**OC-3S	Circular	Mid span	1	Three layer strength.
	B1**C**OS-3S	Circular	Center of shear Zone	1	Three layer strength.
	B2**C**OS-3S	Circular		2	Three layer strength.
2	B**S**OC	Square	Mid span	1	Without strengthening
	B1**S**OS	Square	Center of shear Zone	1	Without strengthening
	B2**S**OS	Square		2	Without strengthening
	B**S**OC-1S	Square	Mid span	1	One layer strength.
	B1**S**OS-1S	Square	Center of shear Zone	1	One layer strength.
	B2**S**OS-1S	Square		2	One layer strength.
	B**S**OC-3S	Square	Mid span	1	Three layer strength.
	B1**S**OS-3S	Square	Center of shear Zone	1	Three layer strength.
	B2**S**OS-3S	Square		2	Three layer strength.
3	B**R**OC	Rectangular	Mid span	1	Without strengthening
	B1**R**OS	Rectangular	Center of shear Zone	1	Without strengthening
	B2**R**OS	Rectangular		2	Without strengthening
	B**R**OC-1S	Rectangular	Mid span	1	One layer strength.
	B1**R**OS-1S	Rectangular	Center of shear Zone	1	One layer strength.
	B2**R**OS-1S	Rectangular		2	One layer strength.

Table 3 (continue)

	B**R**OC-3S	Rectangular	Mid span	1	Three layer strength.
	B1**R**OS-3S	Rectangular	Center of shear Zone	1	Three layer strength.
	B2**R**OS-3S	Rectangular		2	Three layer strength.

3.1 Effect of Shape of Web Openings:

Three different shapes of web openings were developed in the present study. Circular opening ,square opening, and rectangular opening were used at mid span and center of shear zone of the beam as listed in Table (3).

Fig.(10) shows the effect of shape of web openings when the location of openings at the mid-span of the beam, from this figure can be noticed that the shape of web openings had insignificant effect on the behavior of steel IPE-beam. But, when the web openings locates at the center of the shear zone of the beam, it noticed that the shape of web openings is greatly affected on the behavior, as shown in Fig.(11) and Fig.(12). The beam with rectangular web opening at shear zone indicated that the ultimate load capacity was smaller than by (38 %) from the same beams with circular web opening due to the large stress concentration at the web opening as well as the increase in opening area caused a reduction in shear resistance.

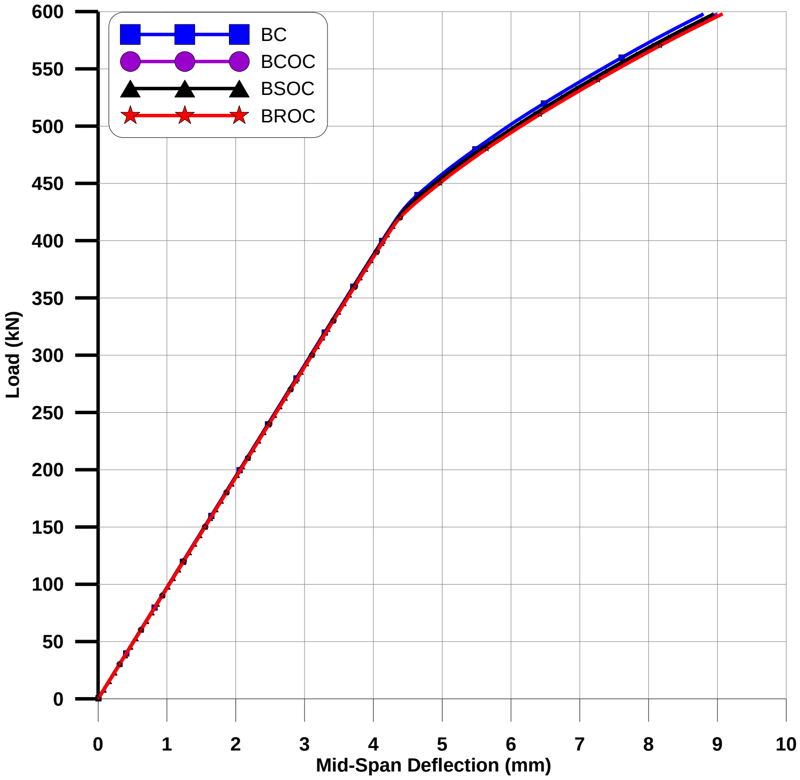

Fig.[10]: load deflection curves of beams with various shape of central opening without strengthening

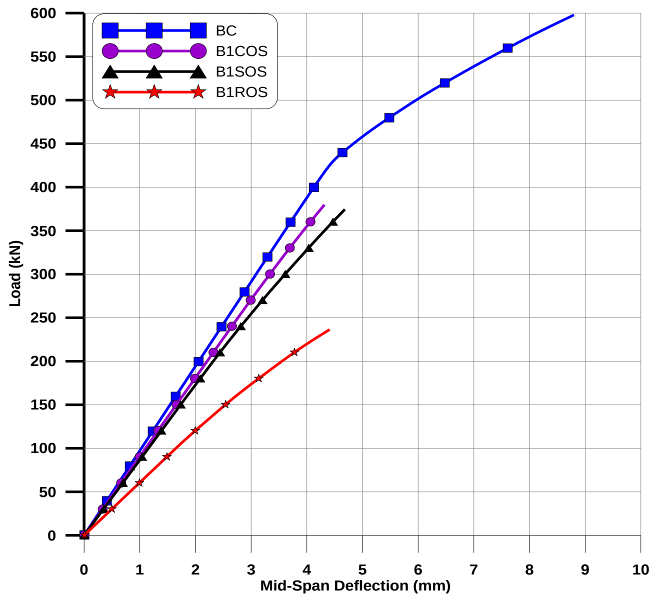

Fig.[11]: load deflection curves of beams with various shape of one opening at shear span without strengthening

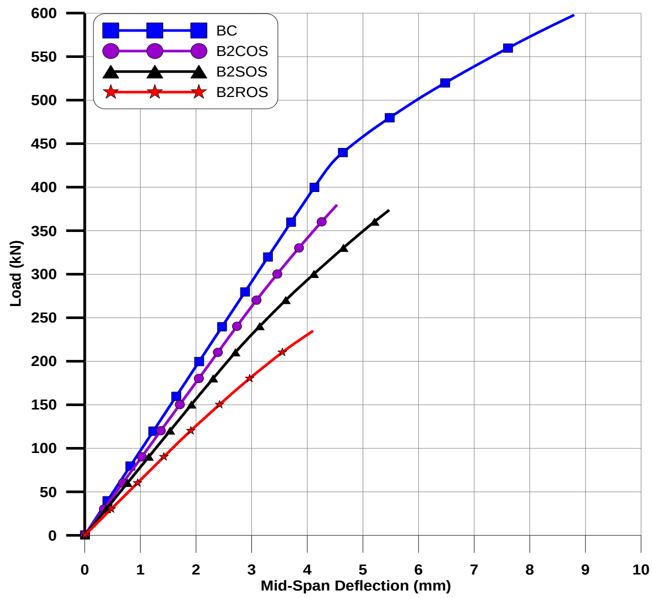

Fig.[12]: load deflection curves of beams with various shape of two opening at shear span without strengthening

3.2 Effect of Location of Web Openings:

Two locations of web openings were used , the first location at mid-span and the second location at the center of the shear zone of the beam. Figs.(13-15) show the effect of the location for the different shape of web openings. These figures show that the effect of the web opening at mid-span of the beam is very slightly on the ultimate load because of the shear force in the mid span equal to zero , while the effect of web opening at center of shear zone was vary significantly on the ultimate load so that for the circular and square opening, the ultimate load capacity decreased by (26.5%) and about (60.5%) for the rectangular opening as a result of decrease in the shear resistance in this zone. Also, can be noticed that , existence of two web opening at the shear zones is not significantly affect the ultimate load but increases the central deflection by (5 %).

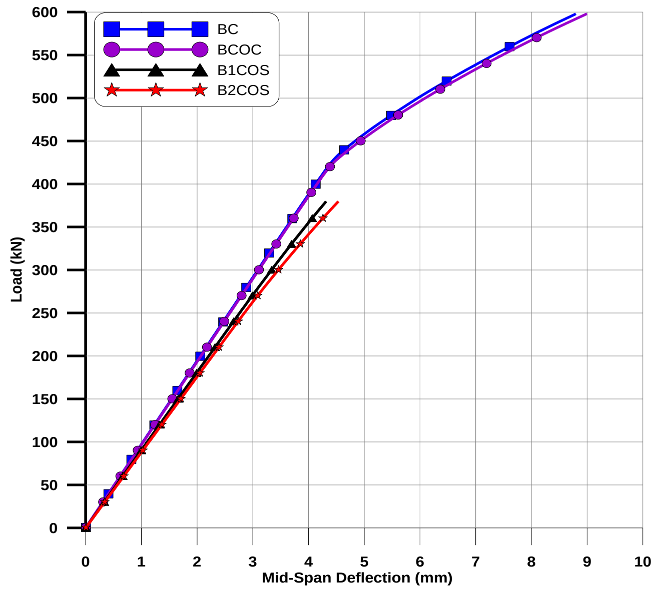

Fig.[13]: load deflection curves of beams with circular opening at different locations

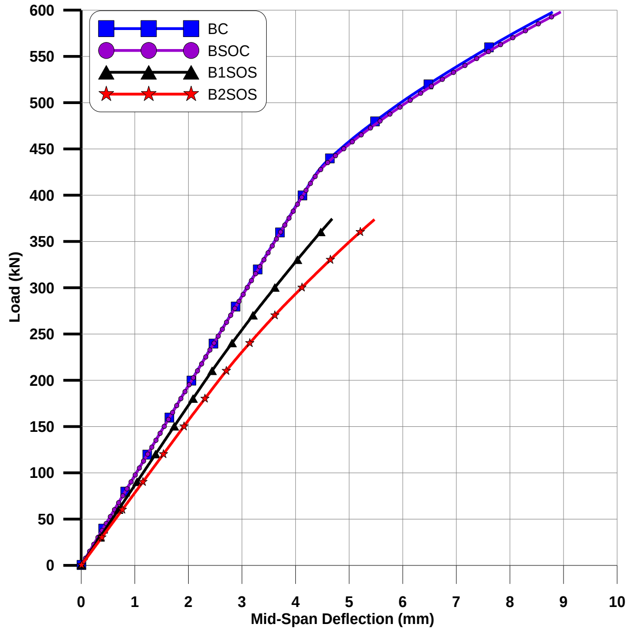

Fig.[14]: load deflection curves of beams with square opening at different locations

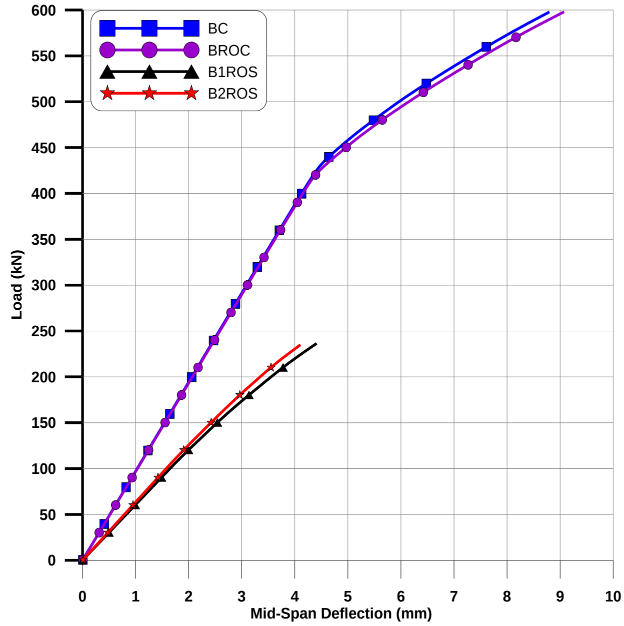

Fig.[15]: load deflection curves of beams with rectangular opening at different locations

3.3 Effect of Number of CFRP Layers :

Different number of CFRP layers were used in the strengthening of the steel IPE-beam around the web opening , one and three layers of CFRP were studied. Figures.(16-24) show the effect of different numbers of CFRP layers on the behavior of steel IPE-beam with web openings.

These figures show that the effect of number of layers of CFRP on the beam with central web opening was not considerable on the ultimate load while the effect of multi layers seems evidential on the beam with opening at shear zone so that the increasing in the number of layers of CFRP conduces increasing in the load carrying capacity by (4-14 %) for one layer of CFRP while (15-36 %) for three layers , this behavior occures for the reason that the flexural strength and stiffness of the beam were increased when increasing the number of layers of strengthening.

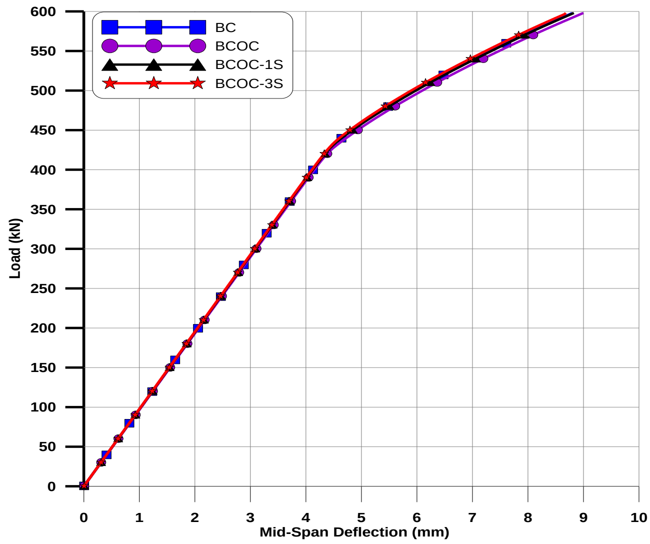

Fig.[16]: load deflection curves of beams with central circular opening with and without strengthening

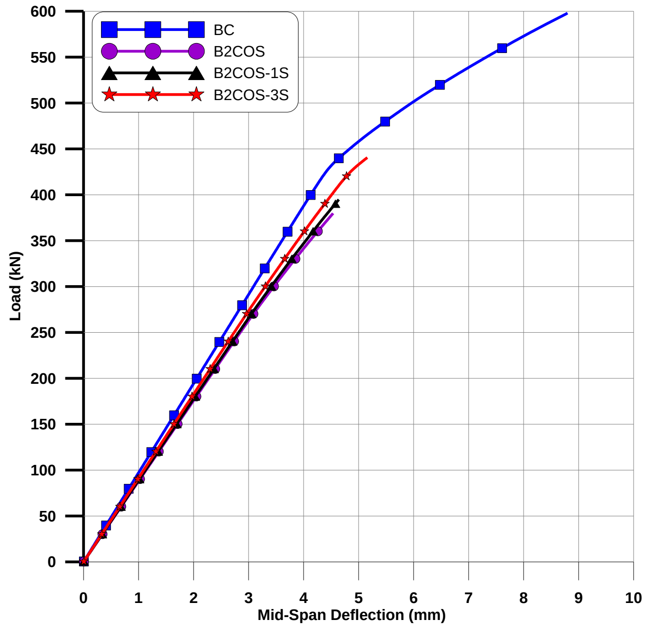

Fig.[17]: load deflection curves of beams with one circular opening at shear span with and without strengthening

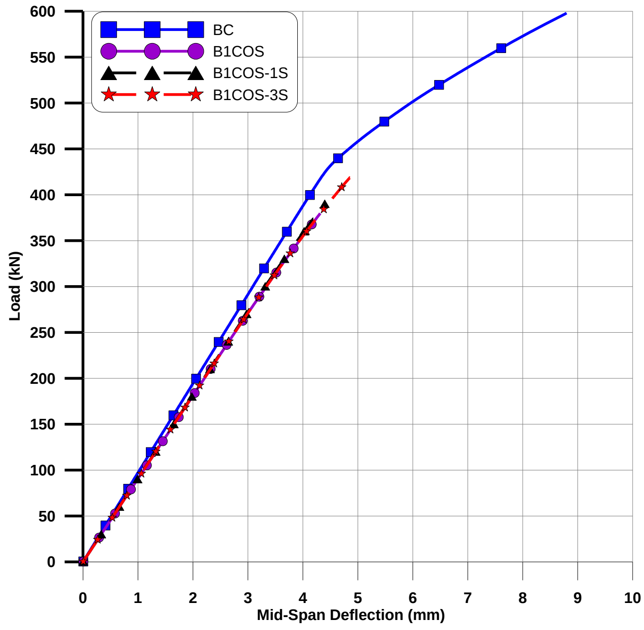

Fig.[18]: load deflection curves of beams with two circular opening at shear span with and without strengthening

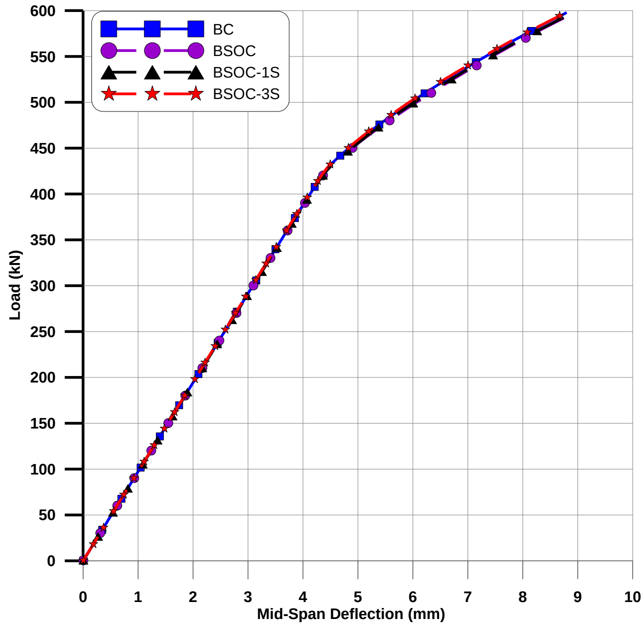

Fig.[19]: load deflection curves of beams with central square opening with and without strengthening

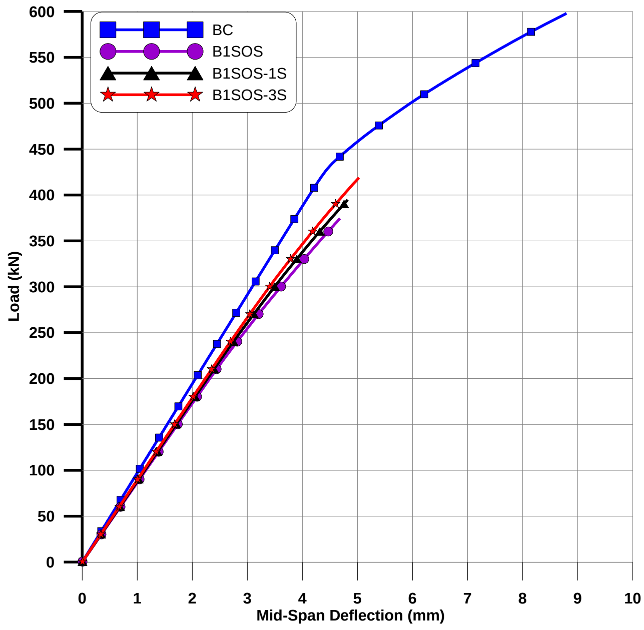

Fig.[20]: load deflection curves of beams with one square opening at shear span with and without strengthening

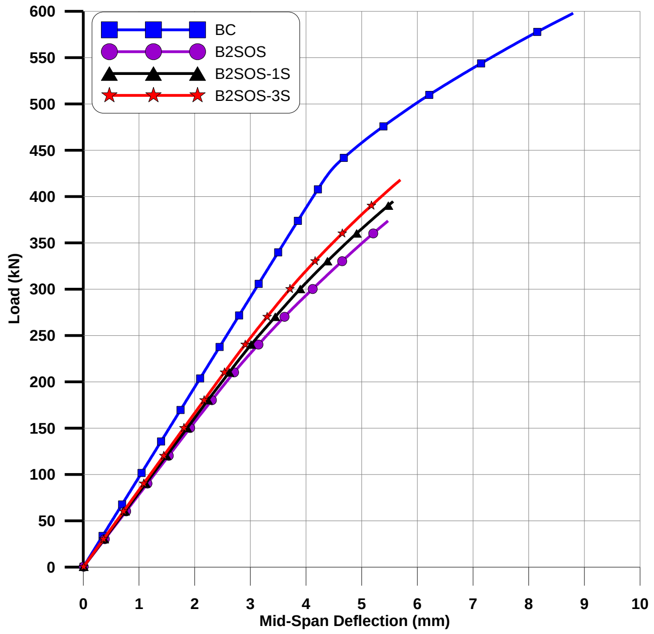

Fig.[21]: load deflection curves of beams with two square opening at shear span with and without strengthening

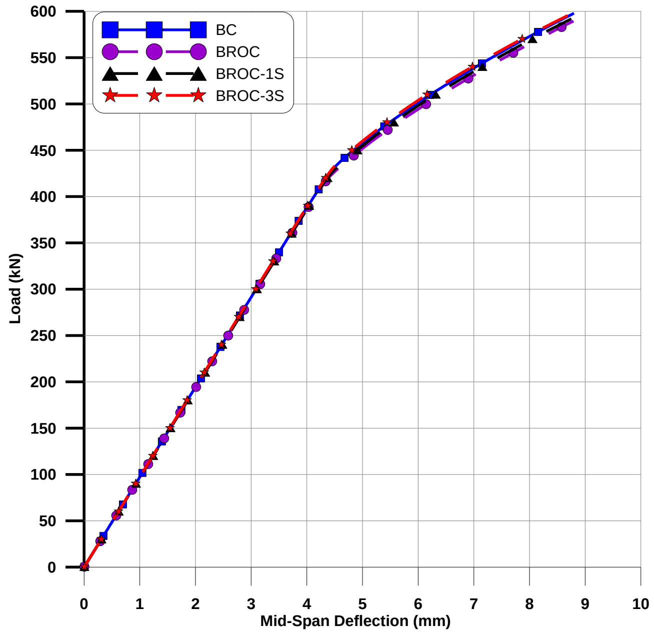

Fig.[22]: load deflection curves of beams with central rectangular opening with and without strengthening

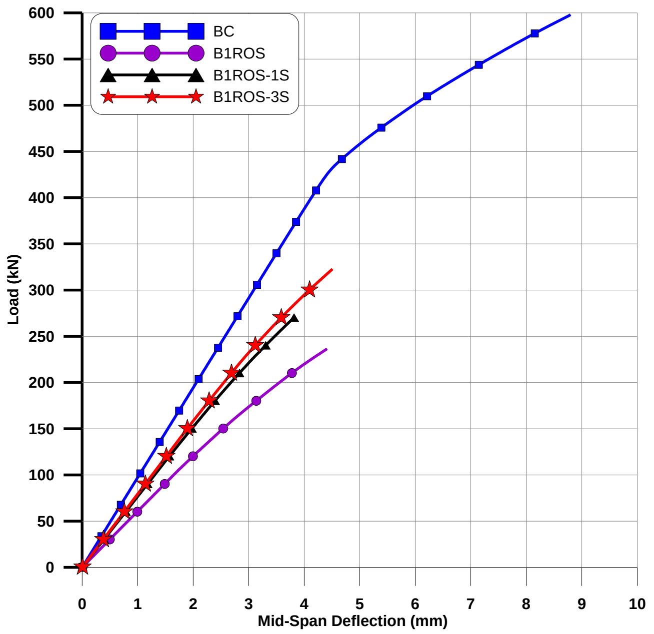

Fig.[23]: load deflection curves of beams with one rectangular opening at shear span with and without strengthening

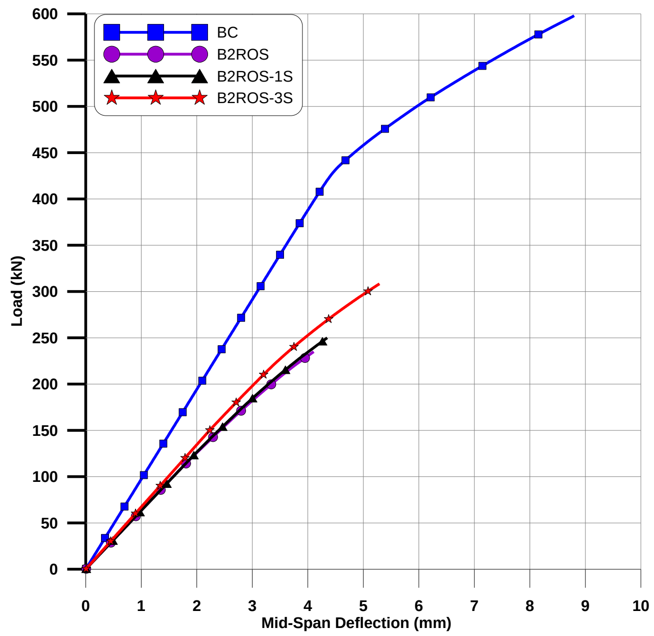

Fig.[24]: load deflection curves of beams with two rectangular opening at shear span with and without strengthening

3.4 Modes of Failure :

Three modes of failure were noticed in the present study including local steel flanges yielding, CFRP-plate debonding and combination between them as shown in figurs (25-27).

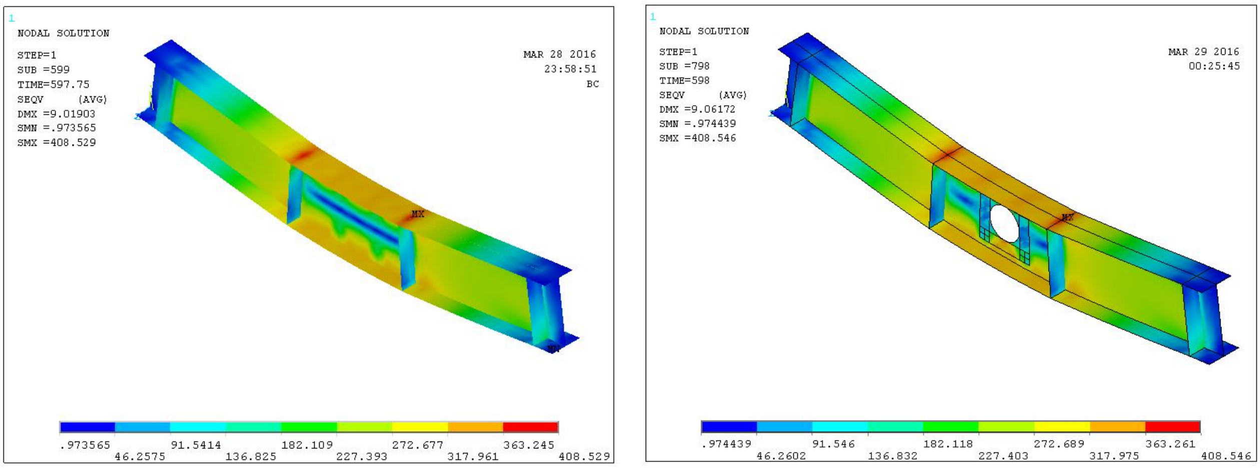

Fig.(25): Local yielding of top flanges under the applying loads of beams BC and BCOC-1S

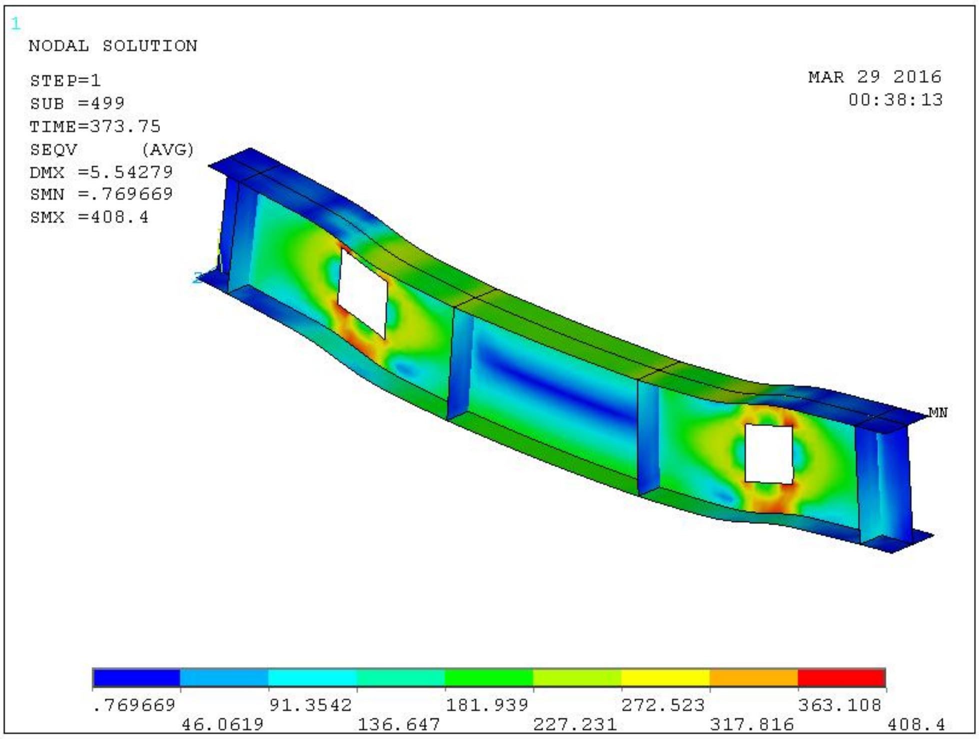

Fig.(26): Local yielding around the openings of beam B2**S**OS

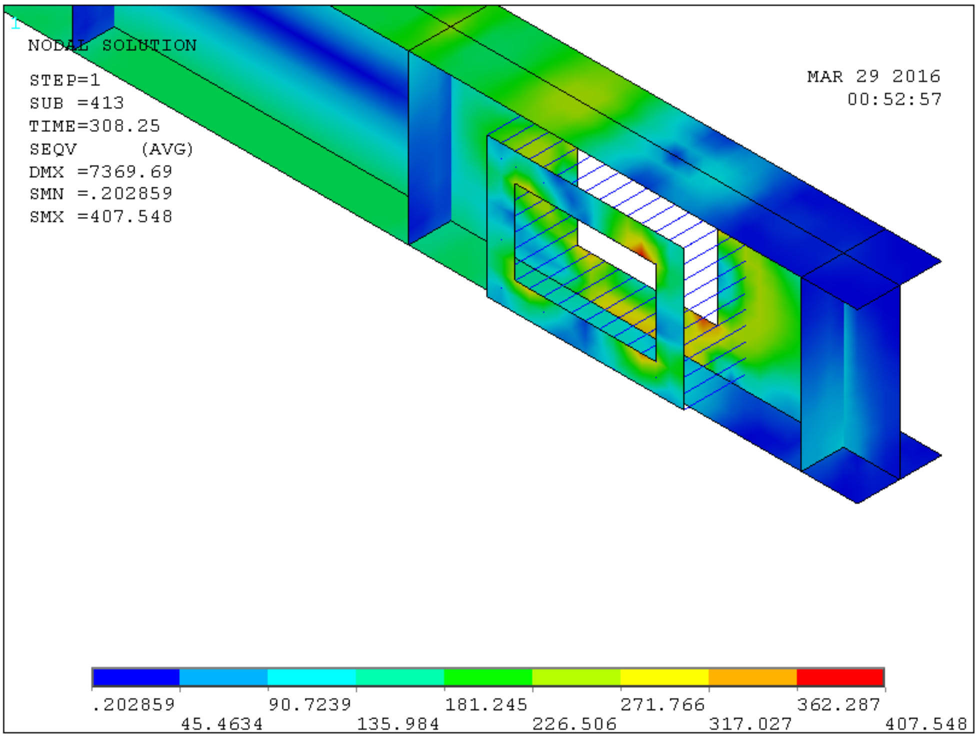

Fig.(27): CFRP plate debonding then steel yielding around the openings of beam B2ROS-3S

4. CONCLUSIONS :

according to the numerical results obtained in the current study , several points can be concluded and summarize as follows :

1. The obtained results indicated that a significant reduction in stiffness and the ultimate load of the steel beams with increase the opening area in the shear zone.
2. The ultimate load of the steel beams with web openings at midspan was not affected noticeably by the shape of web opening.
3. Circular web opening at the shear zone of the steel beams were found that caused smaller decreasing in the ultimate load capacity because of insignificant stresses concentration at the boundaries of web opening, while the beams with rectangular opening resulted a significant reduction in the load carrying capacity (about 38%) compared with their corresponding beams have square or circular opening.
4. Applying CFRP plates around the web opening of steel IPE-beams was a successful method for increasing the load capacity and decreasing the deformations.Moreover, increasing the number of CFRP layers leads to increase the stiffness of the steel beam and therefore, increasing in the ultimate load capacity by (15-36 %).
5. Strengthening the web with CFRP Plats decreased vertical deflection of the beam, appropriately, especially in the plastic region.

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