

## Analysis of Fiber Reinforced Concrete Deep Beams with Large Opening Strengthened by CFRP Laminates

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### ABSTRACT

*In this study, the behavior of reinforced concrete deep beams with large opening, used for efficient creation of doors, windows, and passage openings, which were strengthened by carbon fiber-reinforced polymer (CFRP) sheets, is examined. This analysis was carried out using finite element method and ANSYS computer program. The fiber reinforced concrete deep beams were subjected to a point monotonic loading. The results of the suggested analysis procedure were verified with experimentally tested deep beams given in reference [1]. The parametric study examined the CFRP sheets configuration and their thickness used as external reinforcement, and the results of strengthened beams are compared with reference unstrengthen deep beams to insure the effectiveness of external reinforcing method. The strengthened beams indicate an increase in load carrying capacity up to 25, 53 and 59% for vertical orientation CFRP sheets with 0.7, 1.4 and 2.8 mm thickness respectively. On the other hand, horizontal strengthening raises beams strength by 54, 78 and 90% for 0.7, 1.4 and 2.8 mm thickness respectively. Meanwhile deep beams with ring type configuration sheets augmented the strength by 85, 92 and 97% for the three types of the used sheet thicknesses. Load-deflection relationships indicate that the combined reinforced concrete and CFRP laminate system possess some nonlinear deformability. The use of CFRP laminates on the deep beams was found to have an influence on the stress concentration and the mode of failure. Anchoring the CFRP laminates around the opening regions helped in using a larger portion of the strength of the laminates. The deep beams strengthened by CFRP sheets exhibited diagonal shear cracks that were developed at a much slower rate and were ultimately accompanied by the peeling off of the CFRP laminates.*

**Keywords:** Deep Beam, Opening, CFRP laminate, Structural Concrete, Cracks, Finite Element.

## تحليل العتبات الخرسانية العميقة المسلحة بالالياف والحاوية على فتحة كبيرة والمقواة بشرائط CFRP

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### الملخص

في هذا البحث تم دراسة تصرف العتبات الخرسانية العميقة الحاوية على فتحات كبيرة، خاصة بالابواب والنوافذ وفتحات المرور، المقواة بشرائط البوليمر المسلحة بالياف الكاربون (CFRP). تم تحميل هذه العتبات الخرسانية المسلحة الحاوية على الالياف الحديدية بحمل مركز في نقطة واحدة وأجريت دراسة تأثير سمك الياف الكاربون واتجاهها كتسليح خارجي كمتغيرات تم تحليلها باستخدام طريقة العناصر المحددة وبرنامج (ANSYS). ان نتائج تحليل العتبات الخرسانية العميقة الحاوية على فتحة كبيرة باستخدام هذا البرنامج المقترح قد تطابقت مع نتائج عملية لعتبات مماثلة مفحوصة في المصدر [1]. لقد أظهرت عملية تقوية العتبات بشرائط البوليمر (CFRP) باتجاه عمودي زيادة في الحمل الاقصى بلغت 25، 53 و 59% لهذه الشرائط بسمك 0.7، 1.4 و 2.8 مم على التوالي مقارنة مع عتبات عميقة غير مقواة. بينما تقوية العتبات بشرائط البوليمر الافقية اعطت زيادة في الحمل قدرها 54، 78 و 90% للأسماك شرائط 0.7، 1.4 و 2.8 مم على التوالي، في حين تقوية العتبات العميقة بشرائط حلقيية (∩) قد زادت المقاومة بنسبة 85، 92 و 97% للأسماك الثلاثة للشرائط. كما ان علاقة الحمل - الأود تشير بان النظام المركب من خرسانة مسلحة وشرائط ال (CFRP) تمتلك بعض التشوه اللاخطي. ان تقوية العتبات العميقة بشرائط البوليمر (CFRP) تعمل على التأثير في تمركز الاجهادات وشكل الفشل. اضافة لذلك فان تثبيت شرائط البوليمر (CFRP) حول مناطق الفتحات ساعدت على استخدام الجزء الاكبر من مقاومة المقطع المركب. ولوحظ من تصرف العتبات العميقة الحاوية على فتحات كبيرة والمقواة بتلك الصفائح بان ظهور تشققات قص كانت بسرعة أقل لحين بلوغ المقاومة القصوى وانفصال تلك الشرائط.

الكلمات الدالة: عتبات عميقة ، فتحات ، اشرطة CFRP ، خرسانة انشائية ، تشققات ، عناصر محددة.

## 1.INTRODUCTION

According to ACI 318-14 the simply supported beam is classified as deep beam when the clear span is equal to or less than four times the overall depth or the application of concentrated load is within a distance equal to or less than two times the depth from the support face [2]. In most code specifications empirical formulas are used to design these members without considering the existence of the openings. One of the effective methods used by the researchers in the analysis and design methods is strut-tie models (STM) based on a series of concrete compressive struts and steel tensile ties connected at frictionless joints [1, 3 and 4]. However, the existence of any large opening between the applied loading force point and the support will disrupt the flow of force and may reduce the concrete strut in the truss analysis as the stress field exceeds the yield criteria causing significant reduction in load carrying capacity. The direct load paths between the applied load point and support points would interfere with the size and location of the selected opening [4, 5].

Limited experimental works [1, 3] show that STMs provide conservative reliable results in the first crack strength capacity ranges of deep beams with openings, meanwhile they underestimate the ultimate load and prediction the failure mode. Moreover, there is no unique STM existing for a particular beam and size effect on the shear behavior of reinforced concrete specimens which increases in the calculated result divergence.

A large opening for creation of doors, windows, passage openings, and air conditioning dictates with its negative effect on strength and serviceability could impose to strengthening specific areas around the opening by means of advanced composite materials such as carbon fiber-reinforced polymer (CFRP) strips, which have recently drawn great attention, instead of the traditional materials represented by steel bars or external steel sheet strengthening [6, 7, 8]. Nowadays, external simple installation, low labor cost, high tensile strength, approximately no relaxation, and immunity to corrosion have made CFRP an attractive alternative material in repair and strengthening works. Peeling off CFRP sheets and their arrangement around the opening is still one of major fields of CFRP which needs more investigations.

Recently the Finite Element simulation method is recognized as one of best realistic methods for analytical solutions of reinforced concrete structures considering their nonlinear behavior. Subsequently the nonlinear analysis of reinforced concrete deep beams with and without openings by three dimensional finite elements method under static loads has been carried out by many researchers [9, 10, and 11].

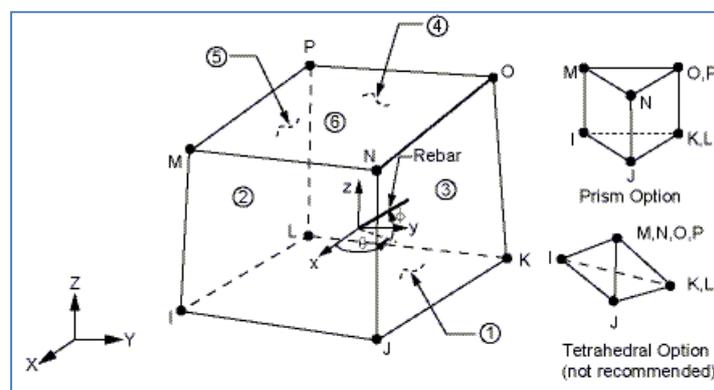
The aim of this work is to adopt a finite element model using ANSYS computer program to predict the load capacity and behavior of reinforced concrete deep beams with large opening strengthened at certain areas by CFRP sheets in different configurations and thicknesses under monotonic loading action.

## 2.FINITE ELEMENT IDEALIZATION

Modeling of the specimens in ANSYS, finite element program is performed using four different element idealizations for concrete; rebar reinforcement; steel plates; and CFRP sheets.

### 2.1. Reinforced Concrete Idealization

SOLID65 element is used for the 3-D modeling of fiber reinforced concrete. The solid is capable of plastic deformation, cracking in tension and crushing in compression. In addition the rebar has capability of modeling reinforcement behavior. The element is defined by eight nodes having three degrees of freedom at each node, translation in x, y, and z directions. The geometry and node locations of this element are shown in **Figure.(1)**. Smearred cracking approach has been considered in modeling the concrete cracks in this study [12].



**Figure.(1):** Concrete element SOLID65 geometry [12]

### 2.2. Steel Reinforcement Rebar Idealization

LINK8 element is used for modeling the 3-D reinforcement rebar with three degrees of freedom at each node: translation in the nodal x, y, and z directions. Bending of the element is not considered, while plasticity, stress stiffening, and large deflection capabilities are included. The geometry, node locations, and the coordinate system for this element are shown in **Figure.(2)** [12].

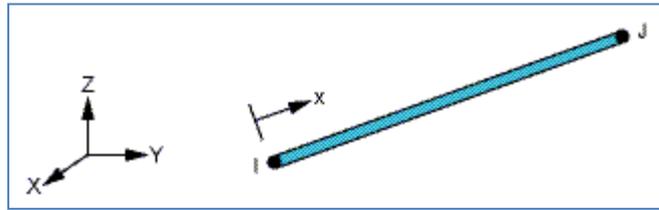


Figure.(2): Reinforcement bar element LINK8 geometry [12]

### 2.3. Steel Plate's Idealization

SOLID45 element is used for the steel plates at supports and under the load application points. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions.

The element has plasticity, stress stiffening, large deflection, and large strain capabilities. The geometry, node locations, and the coordinate system for this element are shown in Figure.(3). This element is added at these locations to distribute the stresses, avoid stress concentration problems and to prevent local crushing of concrete elements near the support points and load application locations.

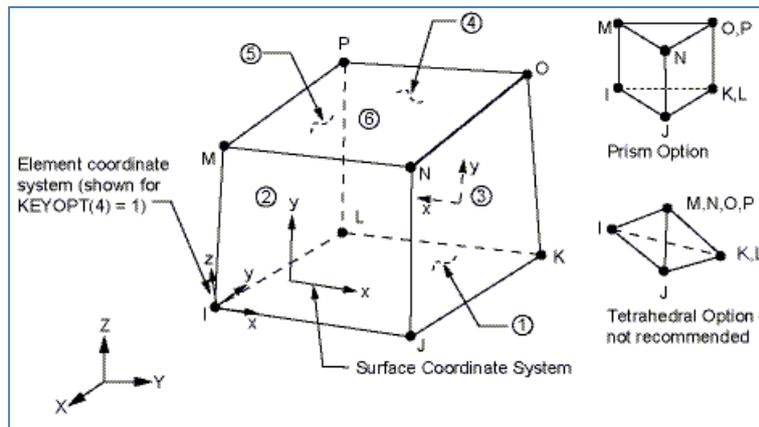


Figure.(3): Steel plate element SOLID45 geometry [12]

### 2.4. CFRP Sheets Idealization

SHELL41 element is used to simulate the CFRP sheets in the strengthened beam. SHELL41 is a 3-D element having membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. It is intended for structural parts where bending of the elements is of secondary importance compared with membrane force through sheets. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions.

The geometry, node locations, and the coordinate system for this element are shown in Figure.(4).The element has variable thickness, stress stiffening, and large deflection characteristics.

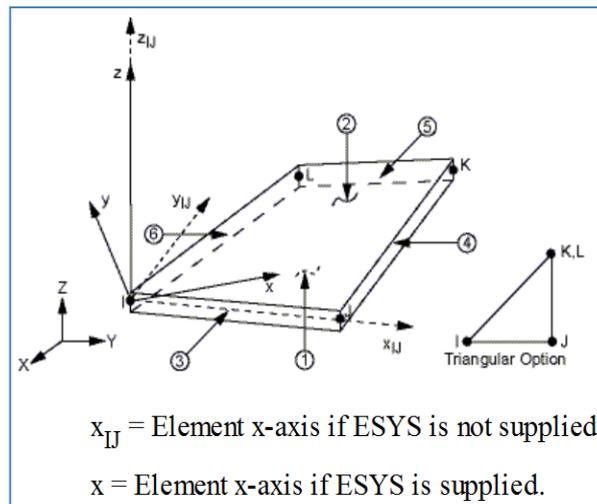


Figure.(4): CFRP laminates element SHELL41 geometry [12]

### 3.REAL CONSTANTS

In the finite element simulation, the second step after choosing the elements types is to prescribe the real constants of the elements. For Solid65 all data in this article are equal to zero and that physically means no smeared reinforcement was used in this simulation, where the analysis was directed toward discrete reinforcement approach, and the cross sectional area for the existed longitudinal steel reinforcement was (79 mm<sup>2</sup>) as stipulated in the real constant of link8 elements. The loading plate and support plates were simulated using SOLID45 element which does not require any real constant as it's a three dimensional element and its dimensions can be specified by the space occupied by the elements. The CFRP element SHELL41 has three different types of real constants according to its thickness 0.7, 1.4 and 2.8 mm.

### 4.MATERIAL PROPERTIES

In this research, material nonlinearity is considered for both steel reinforcement and concrete, while steel plates for loading and support are considered elastic with isotropic properties. Five point stress – strain curve was selected for concrete with compressive strength of (34.5) MPa. The equations that were first presented by Desayi, P. and Krishnan [13] are used to describe the stress-strain relation of concrete. The equations are given below, and applications of these equations are shown in Figure.(5).

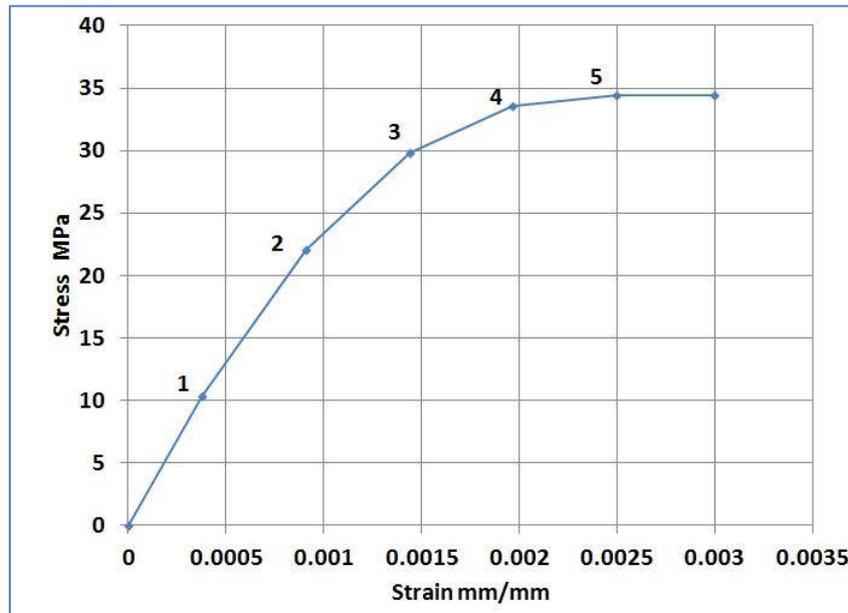


Figure.(50: Stress-strain curve for concrete in compression [2]

The first point represent  $(0.3f'_c)$  with initial slope equal to  $E_c$ , While the stress in fifth point equal to  $f'_c$  with strain equal to  $\epsilon_o$ . The other points can be computed from equations:

$$f = \frac{E_c \epsilon}{1 + \left(\frac{\epsilon}{\epsilon_0}\right)^2} \quad , \quad E_c = \frac{f}{\epsilon} \quad , \quad \epsilon_0 = \frac{2 f'_c}{E_c}$$

Where:

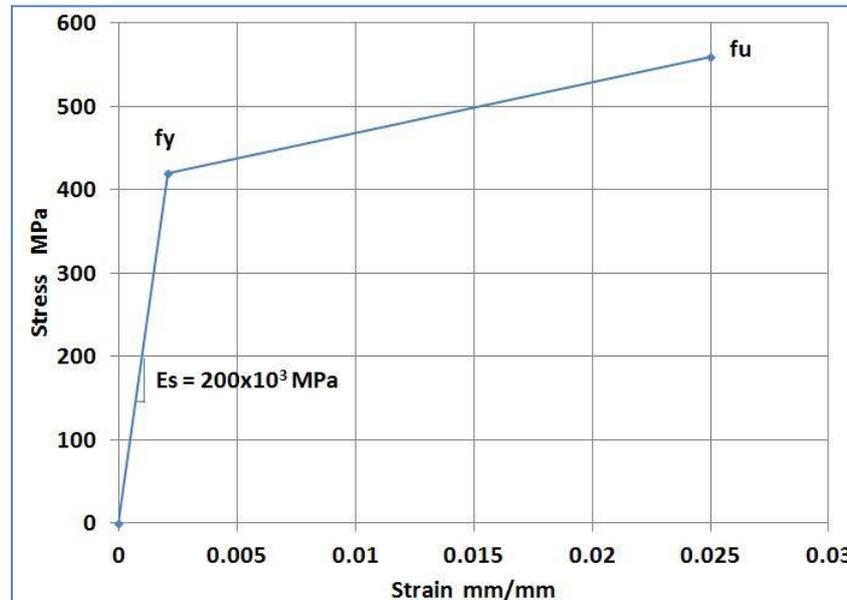
$f$  : Stress at any strain.

$\epsilon$  : Strain at a certain stress  $f$ .

$\epsilon_0$  : Strain at ultimate compressive strength.

$E_c$  : Concrete modulus of elasticity.

Cracking and crushing of concrete are determined by a failure surface, once the failure surface is surpassed and concrete cracks if any principal stress is tensile, while the crushing occurs if all principal stresses are compressive. Other important parameters required by the software ANSYS for completion of concrete element description were the open and close crack values, which represent the ability of concrete to transfer the shear forces through developed cracks when they are (open and close), and (0.3 and 1) values were used respectively. Poisson's ratio of 0.18 is fixed for the concrete in this research.



**Figure.(6): Stress-strain curve for steel bars**

Figure.(6) represents bilinear stress-strain curve for steel bars with yield stress equal to 420 MPa and ultimate strength equal to 560 MPa. Poisson's ratio is 0.3 for steel bars.

To prevent local failure of concrete due to knife edge action from applied load point or support points, steel plates were used for that reasons. These plates predominately are subjected to bearing stress from two sides therefore elastic material properties were assumed in the defining of this material in the FE program.

CFRP sheets are very high tensile strength materials with approximately linear behavior and low ductility, their maximum strength reach to about 3000 MPa, although this value differs from one manufacturer to another, therefore CFRP sheets rarely fail by tensile. On the other hand CFRP sheets are orthogonal materials where the above mentioned strength can be achieved only in the direction of their grid. In simulation of CFRP sheets in the ANSYS program linear elastic properties was assumed with Young's modulus of  $240 \times 10^3$  MPa in the x-axis for the beam strengthened in the horizontal direction while 6.89 MPa were used for the other transverse directions as the program is does not accept zero value for  $E_y$  and  $E_z$  . Similarly for the beam strengthened in the vertical direction, the Young's modulus is taken to be  $240 \times 10^3$  MPa in the y-axis while E for the other axes is 6.89 MPa.

## 5.BEAM MODELING

In order to verify the application of the suggested method to the analysis of deep beams with large opening by finite element method, the tested beam by Dipti et. al. [1] was

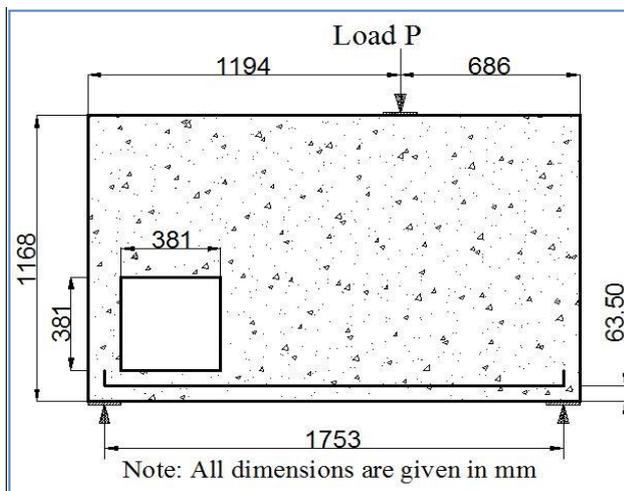
simulated using ANSYS program version 11, as described in following articles. The dimensions and meshing of the beam are shown in Figure 7 and Figure 8 respectively.

### 5.1. Meshing

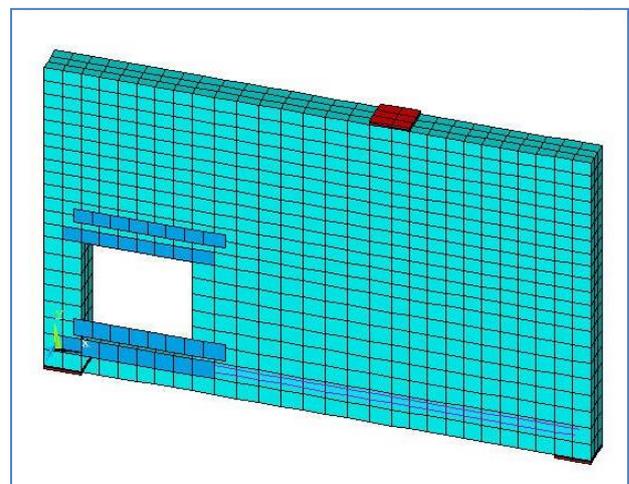
In order to obtain accurate simulation of this beam with exact location of the opening, concrete covers and location of steel rebars, small element length of 32 and 38 mm were chosen and that leads to significant numbers of nodes and elements. On the other hand, these large element numbers allow the model to capture the real behavior of the beam. A total of (2944) nodes, (1656) concrete, (54) steel rebar, and (36) steel base plate elements in addition to a variable CFRP elements existed along the tested beam.

### 5.2. Supports

The supports were modeled in such a way that pin reaction was created in one end by restraining the translation in X, Y, and Z directions at the center line of base plate and creating roller support at the other end by restraining the translation in Y and Z directions at the center of base plate and allowing the horizontal movement in x-direction.



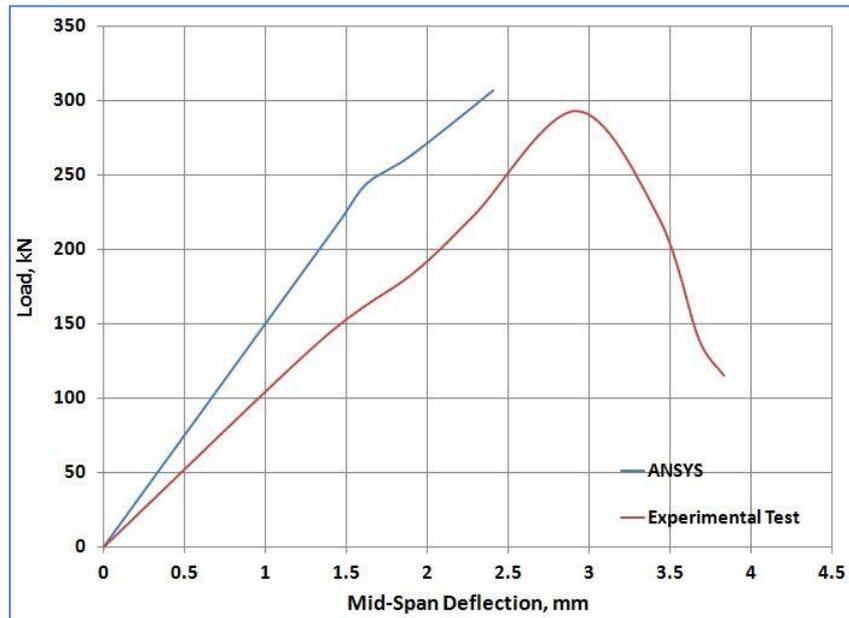
**Figure.(7):**Dimensions of beam tested by Dipti[3]



**Figure.(8):** Meshing of deep beam

## 6.RESULTS AND DISCUSSION

A comparison between the experimental test results [1] and F.E. modeling response is presented in Figure 9, where a good agreement has been achieved between the two curves, although the experimental beam showed a more ductile behavior than FE modeling because a numerical solution cannot achieve the descending part of the load-deflection curve.



**Figure.(9):** Load-deflection curves for deep beams with large opening tested by Dipti [1] and simulated by ANSYS

The suggested method of analysis was used to investigate the behavior of deep beams with a unique large opening strengthened with CFRP sheets around the opening. In these processes three arrangements of CFRP sheets were used with three different thicknesses for each arrangement in the process of strengthening around the opening. In the first case, horizontal sheets were used, while in the second case vertical sheets were used. In the last case, ring strengthening was applied around the opening.

In **Table.(1)** the designation and properties of analysis of strengthened deep beams are shown according to direction of CFRP sheets and their thickness.

**Table.(1):** Failure load and maximum mid-span deflection of strengthened deep beam

Item	Beam designation	Direction of sheets	Thickness of CFRP sheets, mm	Failure load, kN	Deflection at mid-span, mm	Increasing in strength compared with un-strengthened beam, %
1	DB07V	Vertical	0.7	367	2.62	25
2	DB07H	Horizontal	0.7	453	2.29	54
3	DB07R	Ring Type	0.7	542	1.91	85
4	DB14V	Vertical	1.4	450	1.98	53
5	DB14H	Horizontal	1.4	522	2.11	78
6	DB14R	Ring Type	1.4	564	2.06	92
7	DB28V	Vertical	2.8	467	1.37	59
8	DB28H	Horizontal	2.8	558	1.96	90
9	DB28R	Ring Type	2.8	578	2.16	97

Figure.(10) represents load-deflection curve for strengthened deep beams with CFRP sheets of 0.7 mm thickness. The results show increase in load carrying capacity by 25, 54 and 85% for vertical, horizontal and ring type orientation of sheets respectively, compared with non- strengthened deep beam. Figure.(11) and (12) show the same curves for CFRP sheets of 1.4 mm and 2.8 mm thickness respectively. These curves illustrate increase in beam capacity by 53, 78 and 92% for sheets of 1.4 mm thickness while rise in strength for 2.8 mm thickness sheets which is not greater than 59, 90 and 97% compared with non-strengthened beam. Further investigation of the above mention curves Figure.(10 , 11 and 12) indicates generally that increase in sheets thickness leads to comparable increase in the member strength while mid-span deflection decreases in the same manner. For 0.7mm sheet thickness, the effect of CFRP orientation was very obvious in the behavior of the structural member while other sheet arrangements, the results does not show the same behavior and this is because with increase in CFRP sheets the failure occurs in the concrete in a distance from the opening. Also it's obvious that ring type reinforcing sheets are more effective in structural behavior in all investigated beam as it combines the advantage of two types of sheets but it consumes more than double materials of CFPR plates. From load-deflection curve all nine members that were investigated show almost linear behavior up to 265 kN load then the nonlinear behavior starts with as the cracks propagated along the depth of the members.

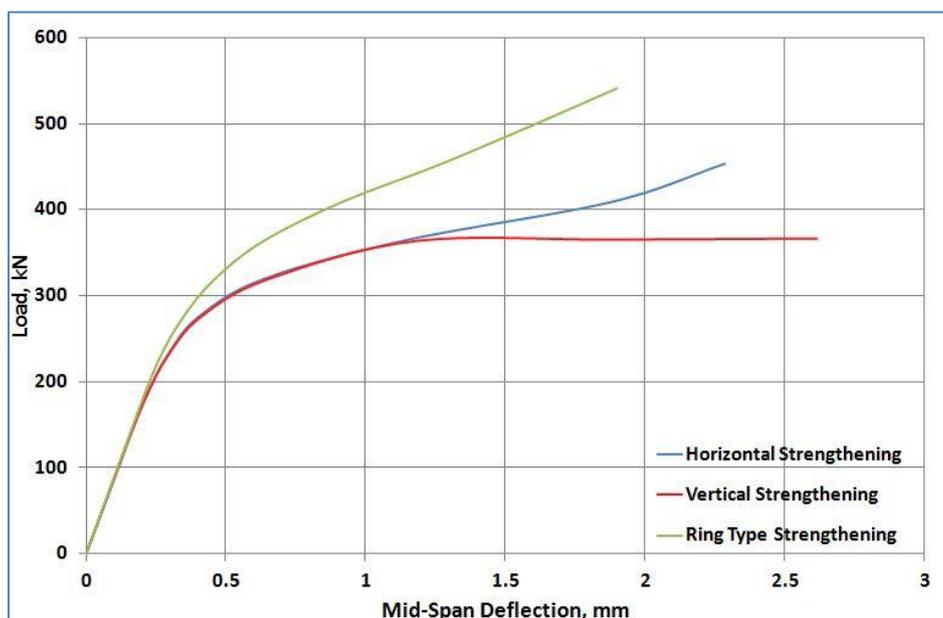


Figure.(10): Load-deflection curves for deep beams strengthened with 0.7 mm CFRP sheet.

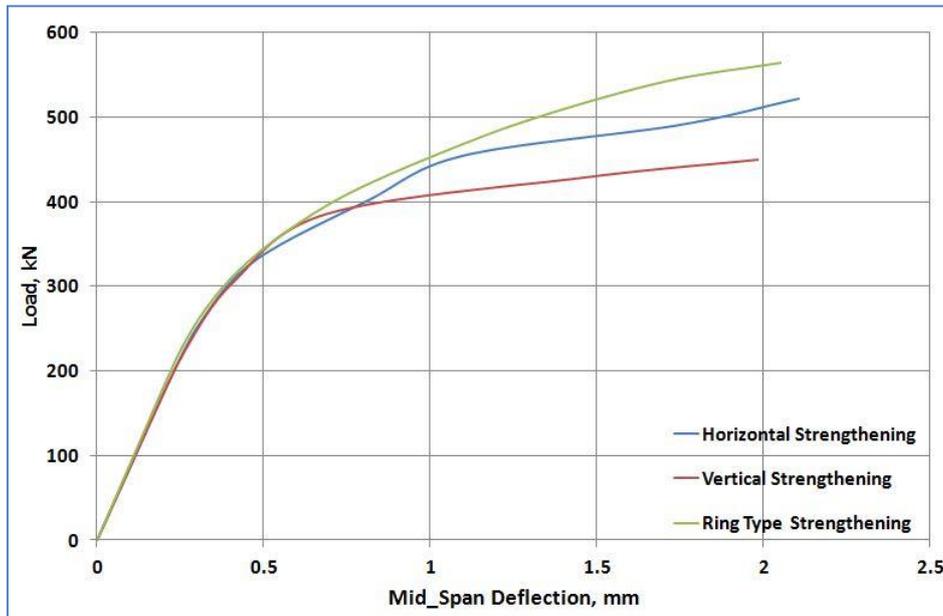


Figure.(11): Load-deflection curves for deep beams strengthened with 1.4 mm CFRP sheet.

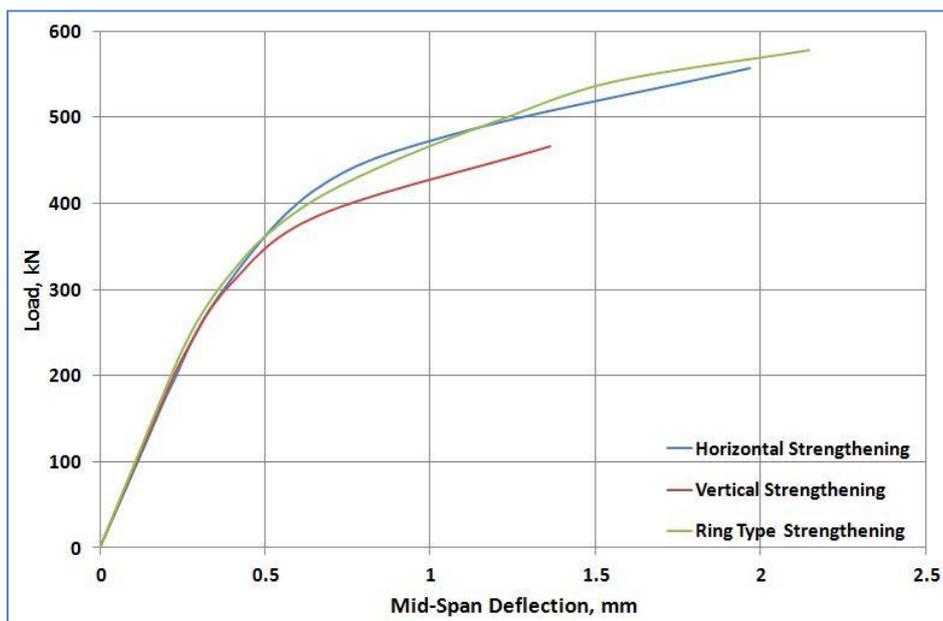
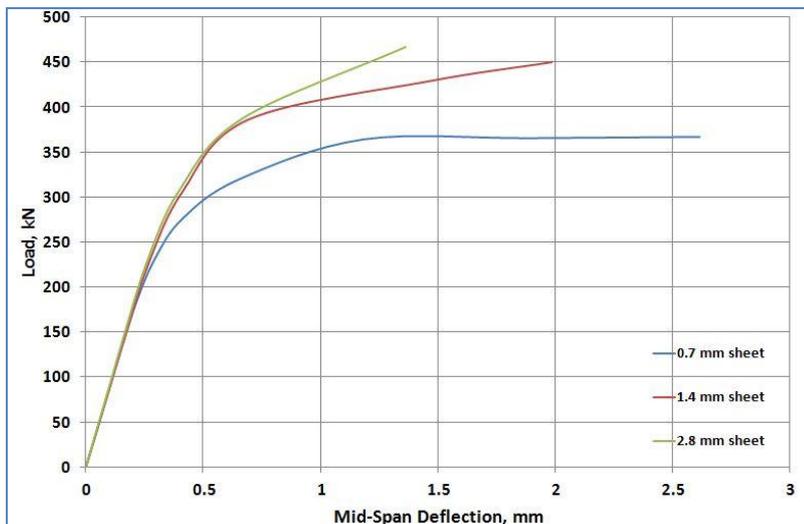


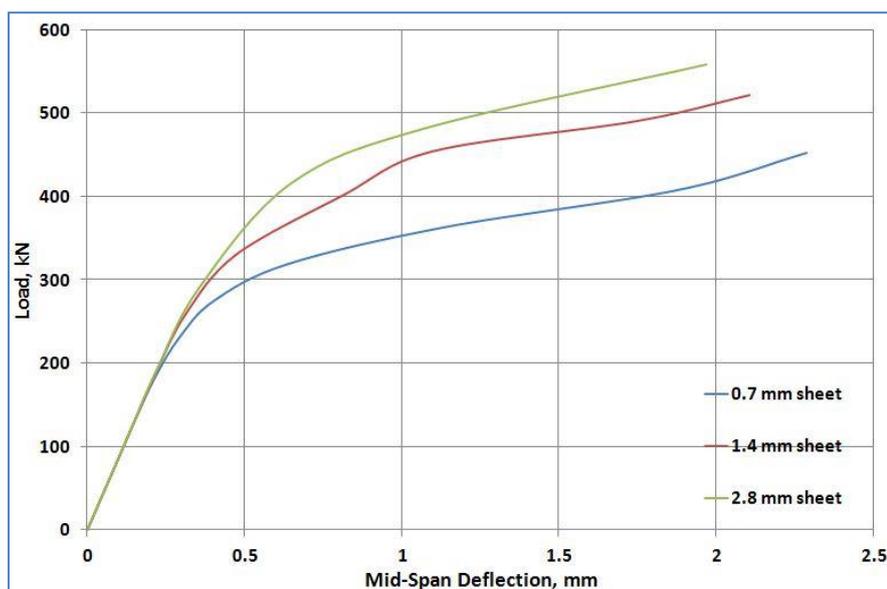
Figure.(12): Load-deflection curves for deep beams strengthened with 2.8 mm CFRP sheet.

Figure.(13,14) and (15) show load-deflection curves for the same beams which were illustrated before, however the comparison is made among these figures for the thickness of CFRP sheets. In Figure.(13) where the CFRP sheets are oriented vertically, the increasing in the sheet thickness raises the load carrying capacity by 25, 53 and 59%, while when the sheets are oriented in the horizontal direction, the beam capacity increases by 54, 78 and 90% compared with non-strengthened beam. That proves that the horizontal orientation of strengthening sheets is more effective than the vertical one. In the ring type of strengthening

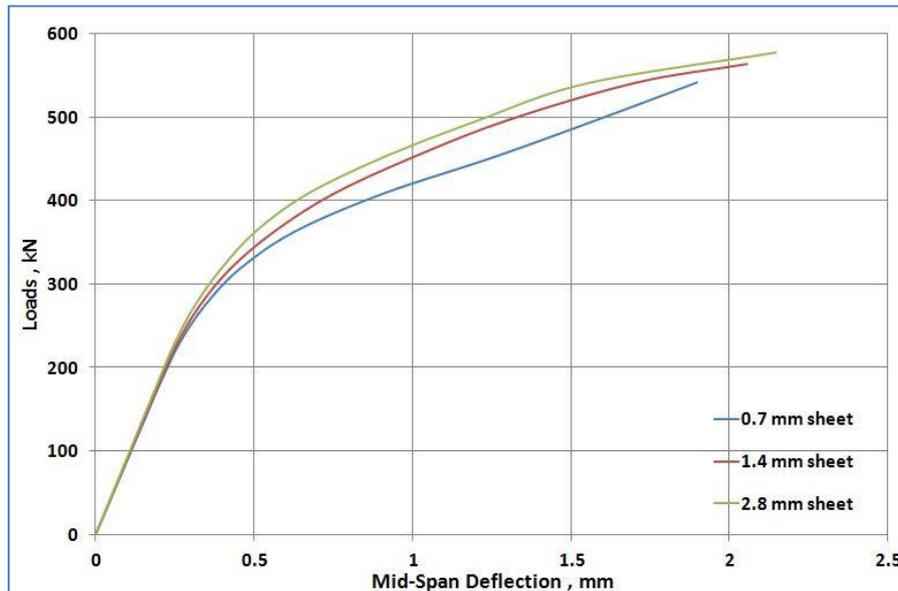
the highest load capacity has been achieved where the load is augmented by 85, 92 and 97% compared with unstrengthen beam.



**Figure.(13):** Load-deflection curves for deep beams strengthened with vertical CFRP sheet

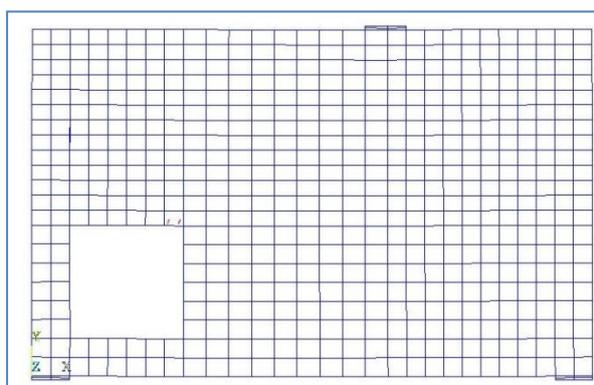


**Figure.(14):** Load-deflection curves for deep beams strengthened with horizontal CFRP sheet.

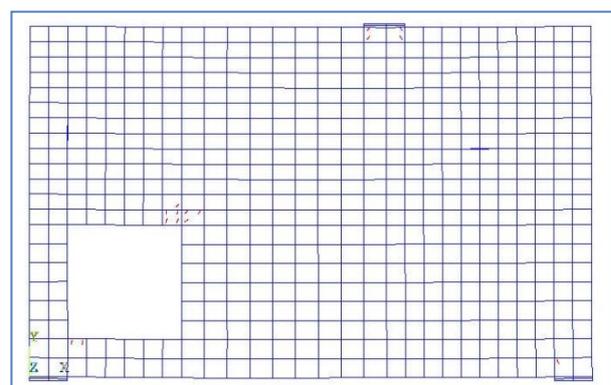


**Figure.(15):** Load-deflection curves for deep beams strengthened with ring type CFRP sheet.

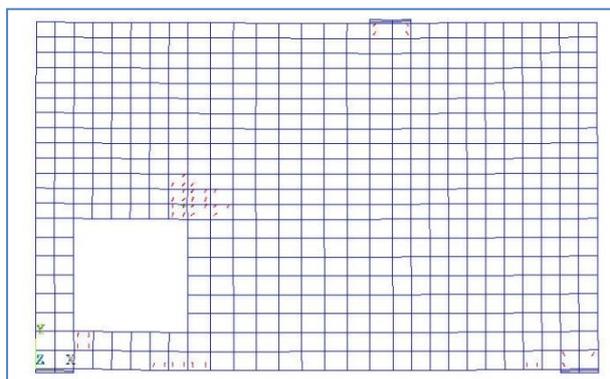
Figure.(16) represents cracks and concrete crush patterns in the deep beam DB07H at different load stages, where the max load capacity of this beam is 453 kN and 2.29 mm mid-span deflection. Cracks occur in this beam when the principal stresses at a point exceed the tensile stress of the concrete, while crushing occurs when principal stress at a point reaches concrete ultimate strength ( $f'_c$ ). Observation of the above mentioned figure shows that first cracks occur at 141.4 kN and then the crack propagates with the increasing of the load and new cracks appear at bottom of the beam with some crushing under the applied load and support points due to the stress concentration. The opening is subjected to diagonal tensile forces to the left as shown very clearly at load stage 408.3 kN (see figure 16-f) almost when the load reaches its maximum value.



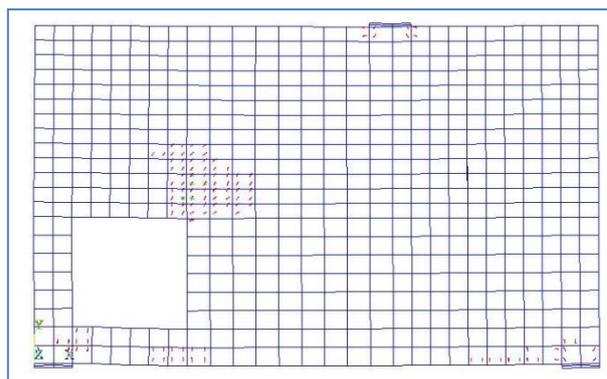
**(a)** First cracks pattern at load 141.4 kN



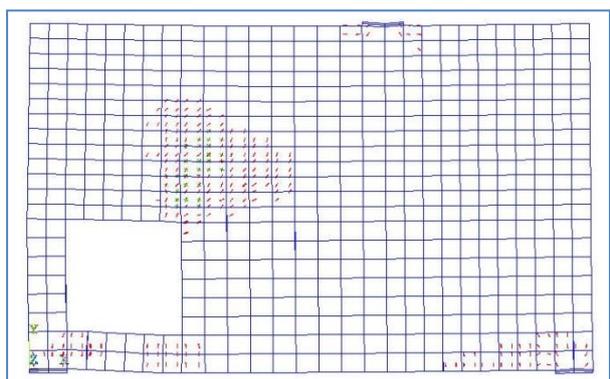
**(b)** Cracks and crushes at load =185.8 kN



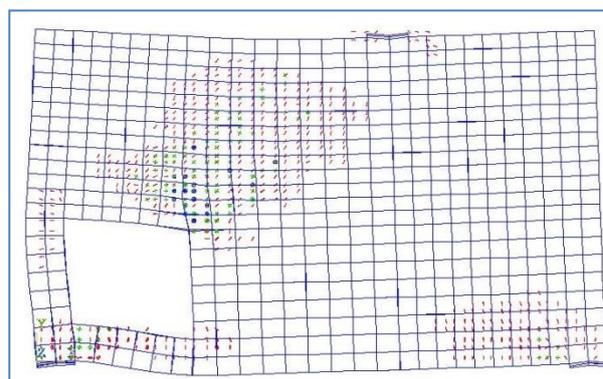
(c) Cracks and crushes at load 230.3 kN



(d) Cracks and crushes at load 274.8 kN



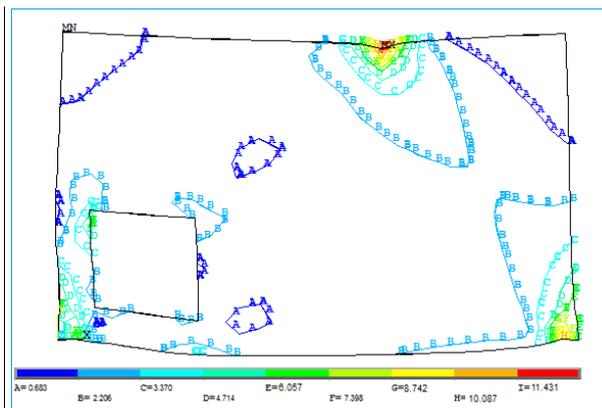
(e) Cracks and crushes at load 319.3 kN



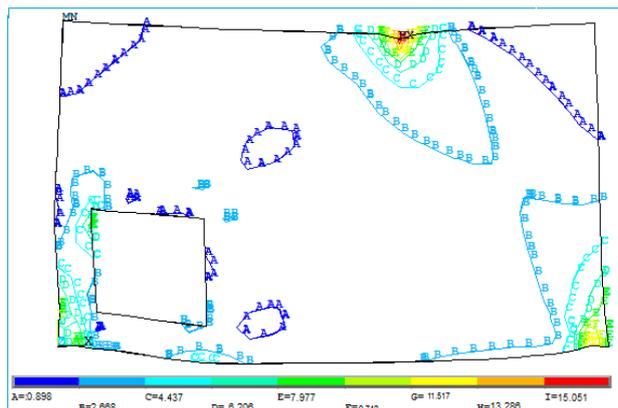
(f) Cracks and crushes at load 408.3 kN

**Figure.(16):** Cracks and concrete crushes patterns at deep beam strengthened by horizontal CFRP sheet of 0.7 mm thickness at different load stages.

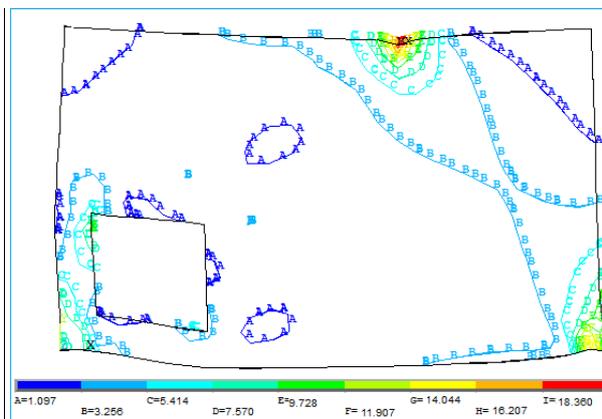
Figure.(17) shows Von Misses stress patterns in the concrete through the same deep beam (DB07H) whose crack pattern was previously shown. This figure shows the contour line of stresses; where each line has specific color given in its legend in the same figure under the beam. Also each line has specific letter designation (A, B, C ...etc). The stress counter lines show concentration of stress around the opening and applied load and support points, and these stresses increase rapidly with increasing the applied load. The generation of the cracks shown in Figure.(16) confirms the stress distribution contour shown in Figure.(17).



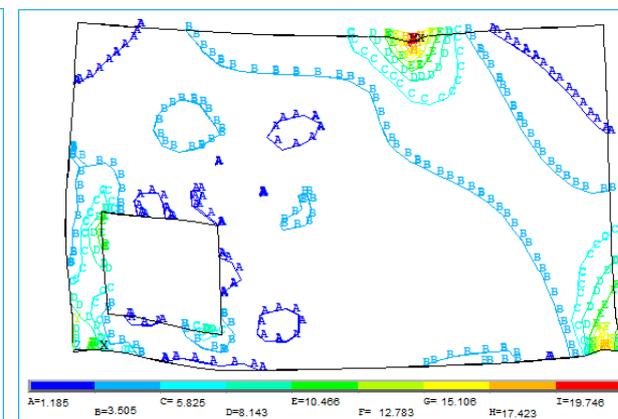
(a) Stress pattern at load 141.4 kN



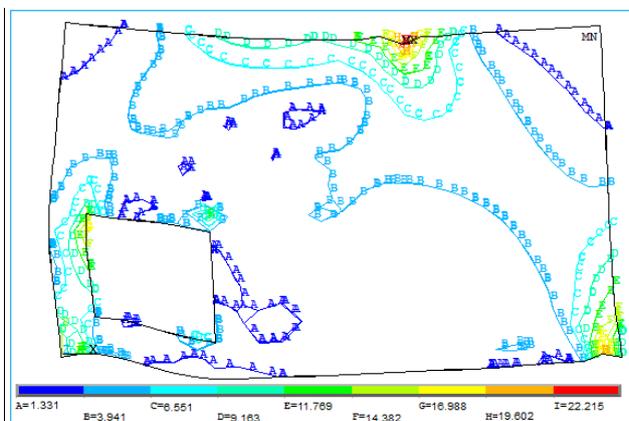
(b) Stress pattern at load 185.8 kN



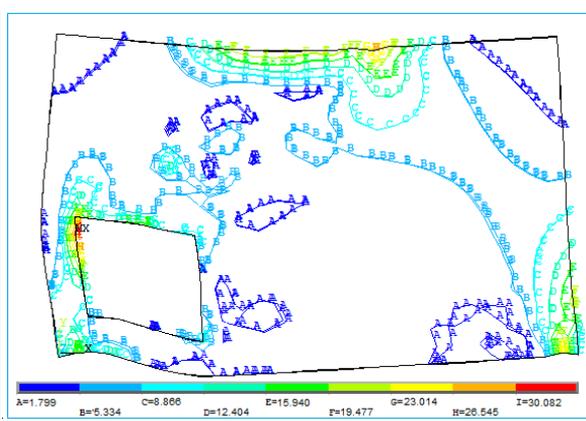
(c) Stress pattern at load 230.3 kN



(d) Stress pattern at load 274.8 kN



(e) Stress pattern at load 319.3 kN



(f) Stress pattern at load 408.3 kN

**Figure.(17):** Stress patterns at deep beam strengthened by horizontal CFRP sheet of 0.7 mm thickness at different load stages.

## 7.CONCLUSIONS

From the analysis of results of deep beams with large opening strengthened by CFRP sheets, the following conclusions can be drawn concerning the efficiency of strengthening types and the ANSYS program to perform further types of analysis:

-The load-deflection relation for deep beams with large opening shows a good agreement between the experimentally tested beams and that simulated by ANSYS program.

-The three configurations of CFRP sheets, horizontal, vertical and ring type show an increase in the load capacity in different ratios according to their thickness. The best of them has the ring type strengthening, which exhibits an increase in the strength by 85, 92 and 97% for 0.7, 1.4 and 2.8 mm sheet thicknesses respectively.

-The ring type strengthening with CFRP sheets is superior to the vertical type of strengthening by 240, 74 and 83%, and to the horizontal type of strengthening by 57, 18 and 8% according to sheet thicknesses 0.7, 1.4 and 2.8 mm respectively.

-The Load-deflection curves for deep beams strengthened with horizontal CFRP sheets show approximately the same flexural rigidity and deflection at ultimate load when the sheet thickness is increased, but in vertical orientation of these sheets this property is reduced by 33% and 93% when the thickness is changed from 0.7 mm to 1.4 mm and to 2.8 mm respectively. Whereas the ring type strengthening revealed an inverse behavior as the deflection at ultimate load is increased by 8% and 12% respectively when the thickness is increased at the same degree.

-The crack generation around the large opening in strengthened by CFRP sheets displays diagonal shear cracks which were developed at a much slower rate.

-The cracks generation pattern and the stress distribution contour indicate the weakest point around the large opening is at the most top point above the support which needs further studies to enhance the region strengthening.

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