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NON-LINEAR ANALYSIS OF REACTIVE POWDER CONCRETE (RPC) DEEP BEAMS WITH OPENINGS STRENGTHENED BY CFRP

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Abstract: *This paper mainly uses ANSYS V.15 , the finite element analysis software, to make nonlinear analysis of reactive powder concrete deep beams . The models simulating the test process were established, the calculation results of ANSYS are compared with the experimental results. Data of eight RPC deep beams tested by researchers were used for comparison with ANSYS models .Furthermore three parametric studies were carried out by changing the size of opening , location of openings and CFRP systems configuration . The comparison shows that ANSYS analysis results are similar to experimental results (the maximum difference in the ultimate load was less than 7.5 %), which indicates ANSYS analysis software can be used to simulate the mechanical property of reactive powder concrete structures.*

Keywords**:** *Non-linear analysis , Finite Element, RPC deep beams , opening , CFRP*

1. INTRODUCTION

ANSYS (ANalysis SYStem) is a comprehensive general-purpose finite element computer program that contains over 100,000 lines of code and more than (180) different elements. It is capable of performing static, dynamic, heat transfer, fluid flow, and electromagnetism analysis. It can be used in many engineering fields, including structures, aerospace, electronic and nuclear problems. In 1971, the earliest version of ANSYS program was released for the first time [1].

One of the main advantages of ANSYS is the integration of the three phases of finite element analysis: preprocessing, solution and postprocessing. Pre-processing routines in ANSYS define the model, boundary conditions, and loadings. Displays may be created interactively on a graphics terminal as the data are input to assist the model verification. Postprocessing routines may be used to retrieve analysis results in a

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variety of ways. Plots of the structure's deformed shape and stress or strain contours can be obtained in the post processing stage.

According to the ACI code Provisions for shear , deep beams are members with length of clear span measured face to face of supports(ℓn) not exceeding four times total depth (h) (ℓn ≤ 4h) or region of beams with concentrated loads within a distance (a) two times the total depth measured from the support (a ≤ 2h) that is loaded on one face and supported on the opposite face [2].

The presence of the web openings in the deep beams is because many ducts and pipes are necessary to accommodate essential services like air-conditioning, water supply , sewage, telephone, computer network and electricity .The depth of ducts or piping may range from a couples of centimeter to as much as half a meter[3] .

Reactive powder concrete is an ultra-high-strength and high ductility composite material with advanced mechanical properties. It is produced from ordinary materials (cement, very fine aggregate "0.15-0.6"mm, low water-cement ratio) , in addition to other materials (Silica Fume, Superplasticiser, steel fibers). The maximum particle size of materials is (0.6)mm, an optimization of the dry fine powder packing has to be managed for getting very dense matrix[4] .

In the present work, a finite element analysis has been conducted using ANSYS V.15 for eight beams deep with and without openings ,with and without CFRP strengthening tested experimentally by researchers in 2017 . A comparison of results has been made to calibrate to material models adopted in this study. And also three parametric studies were carried out by changing the size of opening , location of openings and CFRP systems configuration.

2.GEOMETRY OF TESTED RPC DEEP BEAMS

Eight simply supported RPC deep beams with and without web openings having a total span (L)of 1400 mm, overall depth (h) 400mm, and width 150 mm, with shear span to overall depth ratio (a/h),1 and clear span to depth ratio (ℓn/h), 3 .Seven beams had two square openings (150*150 mm) symmetrically about the center of specimens. The distance between the opening center and the beam centerline for all beams was equal to 400mm. The center of opening of all beams set at the shear span center, which is the critical load path. All beams tested under two points top loading .Two Ø 16 mm deformed bar were used as longitudinal tension reinforcement ,Table (1**)** showed the properties of steel bars.

Table (1) Properties of Steel Bars

Nominal Bar Diameter (mm)	Bar Area (mm^2)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation at Ultimate Stress (%)
16	201	612	727.9	6

RPC deep beams are divided into two group ,group one represents the beams (two beams) without strengthening ,group two represents the beams (six beams) strengthening by different patterns of CFRP strips. Figure (1) showed the details of RPC deep beams.

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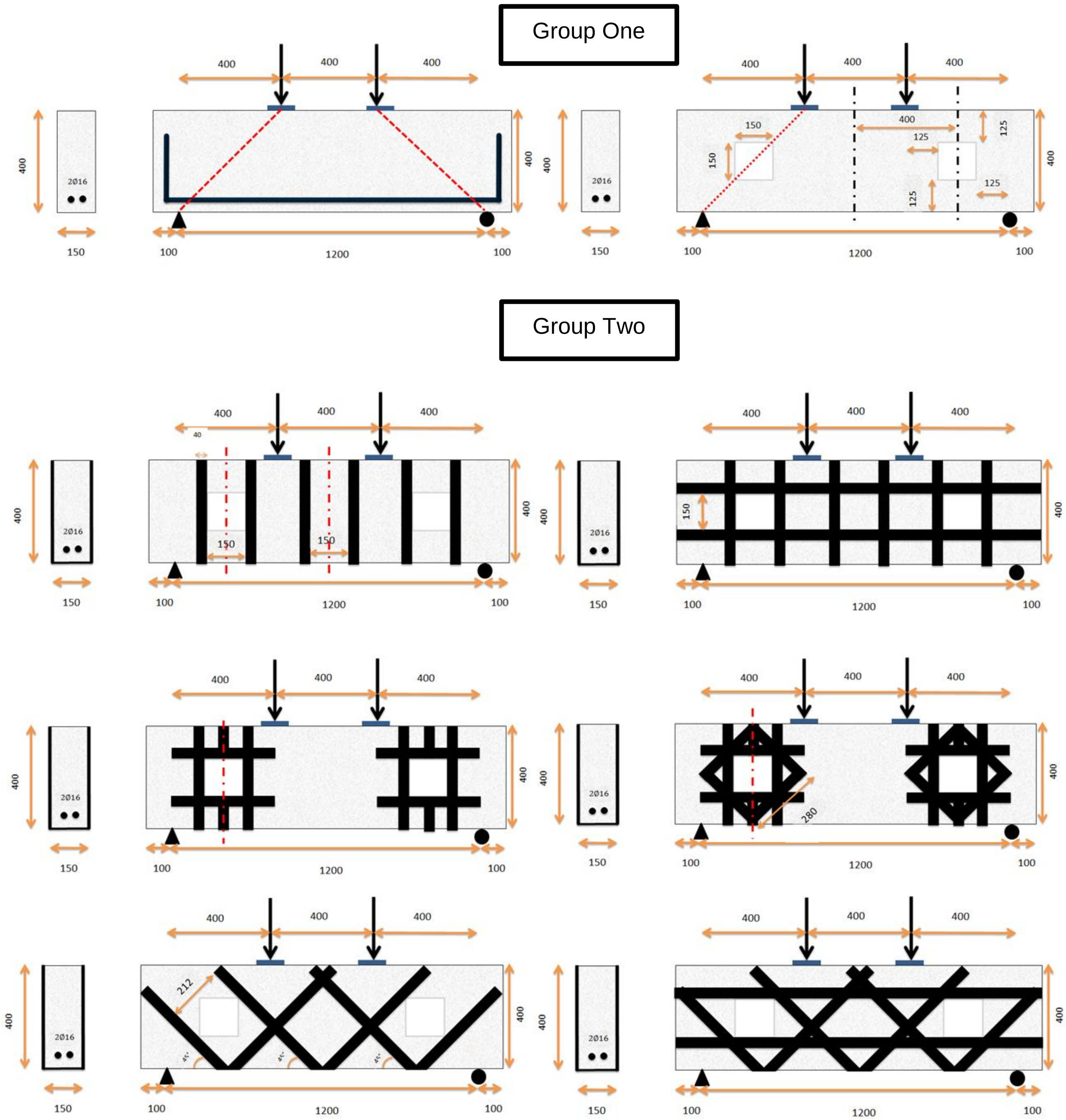

Figure (1) Detail and Geometry of Beams (All Dimensions in mm)

3. MECHANICAL PROPERTIES OF RPC

The results of laboratory tests has been adopted for compressive strength, tensile strength and modulus of elasticity ,as shown in Table (2).Furthermore, the strain-stress curve in Figure (2) was drawn by the data of modulus of elasticity test .

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Table (2) Mechanical Properties of RPC

Compressive Strength Of Cylinder (MPa)	Splitting Tensile Strength (MPa)	Modulus of Rupture (MPa)	Modulus of Elasticity (GPa)
83.44	5.35	10.38	39.2

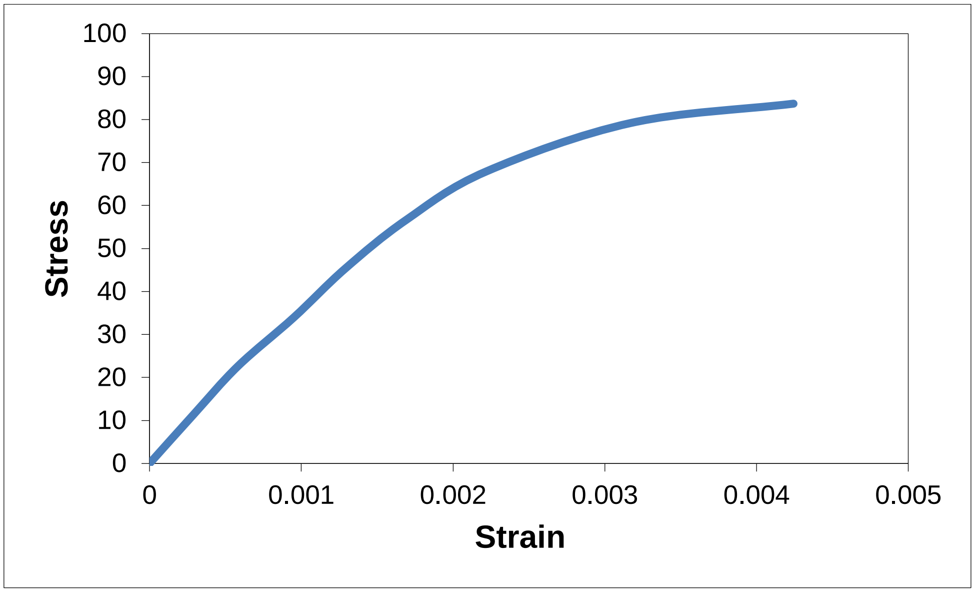

Figure (2) Strain-Stress Curve of RPC

4. FINITE ELEMENT MODELING

4.1 ELEMENTS TYPE

The elements adopted in the present study were:

- solid 65 used to simulate concrete.
- solid 185 used to simulate loading and supporting plates.
- link180 used to represent all steel bars.
- shell 41 used to represent CFRP strips .

4.2 REAL CONSTANT

The real constant for any element required specific data to work .The Table (3) shows the real constant data that used for all element except the Solid 185 (plate element) ,it has no real constant.

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Table (3) Elements Real Constant

Element Type	Real Constant	Value Adopted
Solid65 (Concrete)	Material No.	0
	Volume Ratio	
	Orientation Angle (THETA)	
	Orientation Angle (PHI)	
Link180 (steel bar Ø16)	Cross-sectional Area (mm2)	201*
	Initial Strain	0
Shell41 (CFRP sheet)	Shell thickness at node I,j,k,l	0.167
	Element axis rotation theta	**
	Elastic foundation stiffness	0
	Added area (mass/unit)	0

*When symmetry Asb =Asb/2
** Depends on the CFRP direction

4.3 MATERIAL PROPERTIES

There was a material properties for each element ,where material model number 1 indicated to Solid 65 (concrete element). The requirement of this element are linear isotropic , multi-linear isotropic and concrete parameters . The Table (4) shows material properties for RPC that used in the analysis.

Material model number 2 indicated to longitudinal reinforcement (Link 180). The requirement of this element are linear isotropic and bilinear isotropic properties, as shown in Table (5).

Material model number 3 indicated to steel plate (Solid 185) at loading and supporting points. The input data are shown in Table (6).

Material number 4 suggests to the Shell 41 element (CFRP strips) .The CFRP is assumed to be orthotropic material , where the properties of the CFRP composites are the same in any direction perpendicular to the fibers. The modulus of elasticity was taken to be 230 GPa and the Poisson's ratio was assumed to be equal to zero[6] .Table (7) shows the CFRP properties entered in the present work.

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Table (4) Material Model for Concrete

Material Properties for Element Solid 65		
Linear Isotropic		
Modulus of elasticity, MPa	EX	39300
Poisson's ratio	PRXY	0.2
Multi Linear Isotropic		
Points Number	Strain	Stress ,MPa
1	0.000288	11.317
2	0.000582	22.635
3	0.000950	33.953
4	0.001287	45.271
5	0.001688	56.589
6	0.002217	67.906
7	0.003173	79.224
8	0.004243	83.7
Concrete Parameters		
Shear transfer coefficients for an open crack	ShrCf-Op	0.1
Shear transfer coefficients for a close crack	ShrCf-Cl	0.15
Uniaxial tensile cracking stress, MPa.	UnTensSt	5.35
Uniaxial crushing stress (positive), MPa.	UnCompSt	83.44

Table (5) Material Model for Steel Reinforcement

Material Properties for Element Link 180		
Bilinear Isotropic		
Modulus of elasticity, MPa	EX	200000
Poisson's ratio	PRXY	0.3
Bilinear Isotropic		
Yield stress, MPa	Yield Stss	640
Tangent Modulus, MPa	Tang Mod	6000

Table (6) Material Model for Steel Plates

Material Properties for Element Solid 185		
Linear Isotopic		
Modulus of elasticity, MPa	EX	200000
Poisson's ratio	PRXY	0.3

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Table (7) Material Model for CFRP Strips

Material Properties for Element Shell 41	
Linear orthotropic	
EX	230000
EY	1
EZ	1
PRXY	0
PRYZ	0
PRXZ	0
GXY	1
GYZ	1
GXZ	1

4.4 GEOMETRY

In the finite element analysis, tested RPC beams experimentally, modeled by taking the benefit of the symmetry of the deep beams supports and loadings. The finite element mesh for quarter of the beam is shown in Figure (3) to simulate the RPC deep beams .

In this study, perfect bond between materials is assumed .Discrete representation (Link 180) was used to model steel reinforcement . The beam and plates were modeled as 8 node elements, while the steel bars were modeled as a straight elements, also the 4 node shell is used for modeling CFRP strips. the Figure (4) shows details of elements modeling.

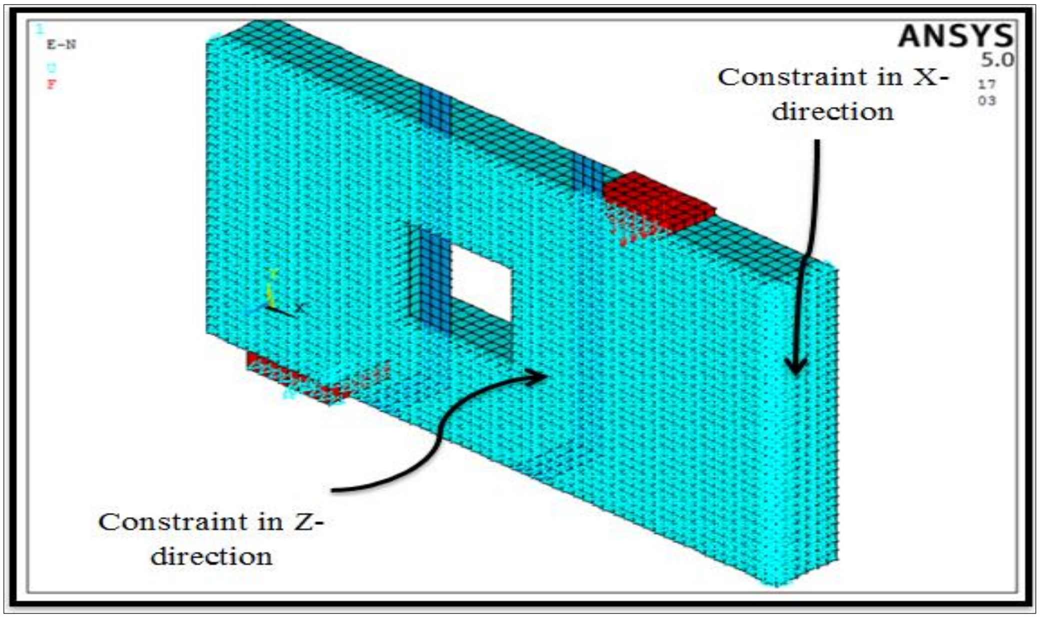

Figure (3) Geometry of the Numerical Model

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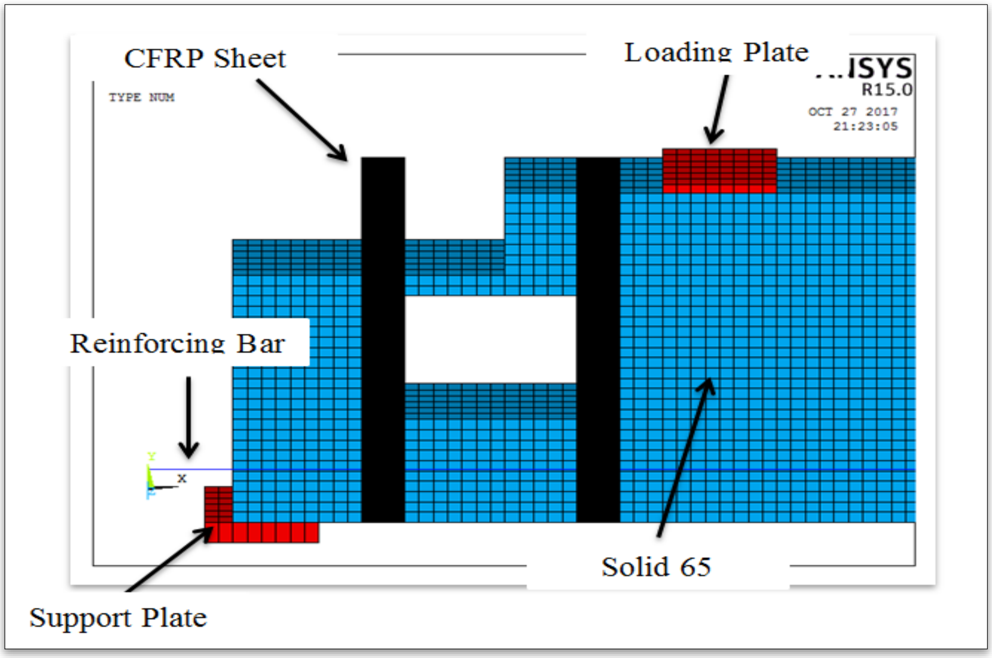

Figure (4) Details of Elements Modeling

4.5 LOADS AND BOUNDARY CONDITIONS

In ANSYS, the applied load was represented by dividing the total distributed load on the top nodes according to the area surrounded by each node to represent the distributed load in ANSYS program as shown in Figure (5). The supports were approximately as similar as in the experimental work.

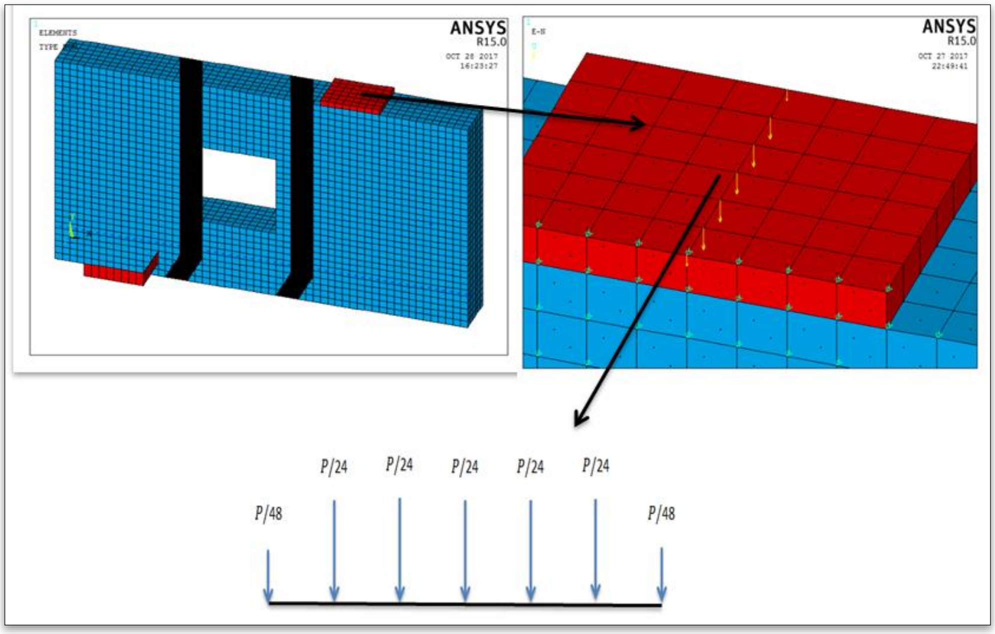

Figure (5) Details of Applied Load and Boundary Conditions

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5. RESULTS OF FINITE ELEMENT ANALYSIS

The results of finite element analysis using ANSYS program were compared with the experimental results for all tested beams. The numerical failure was similar to the failure mode of each beam that occurred in experimental work. ANSYS results including ultimate load, load-deflection response and crack patterns where a close to the experimental results.

5.1 NUMERICAL ULTIMATE LOAD

The comparison between the ultimate load from the experimental results and numerical models from finite element analysis of the analyzed beams are listed in Table (8) . The difference between the experimental ultimate load and that obtained by finite element analysis is not more than (7.5) %.

Table (8) Comparison Between the Experimental and Numerical Ultimate Loads

Beam	Ultimate Load(KN)		$[[pu)_{ANSYS} - pu)_{EXP.}] / pu)_{EXP.}]$ %
	$pu)_{EXP.}$ KN	$pu)_{ANSYS}$ KN	
CBS	594	622	4.71
CBO	177	182	2.83
BSE1	197	201	2.03
BSE2	240	258	7.5
BSE3	249	254	2.01
BSE4	315	329	4.44
BSE5	220	229	4.09
BSE6	268	274	2.24

5.2 LOAD-DEFLECTION CURVES

The load-deflection curve for each beam obtained from the finite element analysis together with the experimental curves are presented and compared in Figures from (6) to (13). In general, all these figures show a good agreement between the experimental and F.E.A curves.

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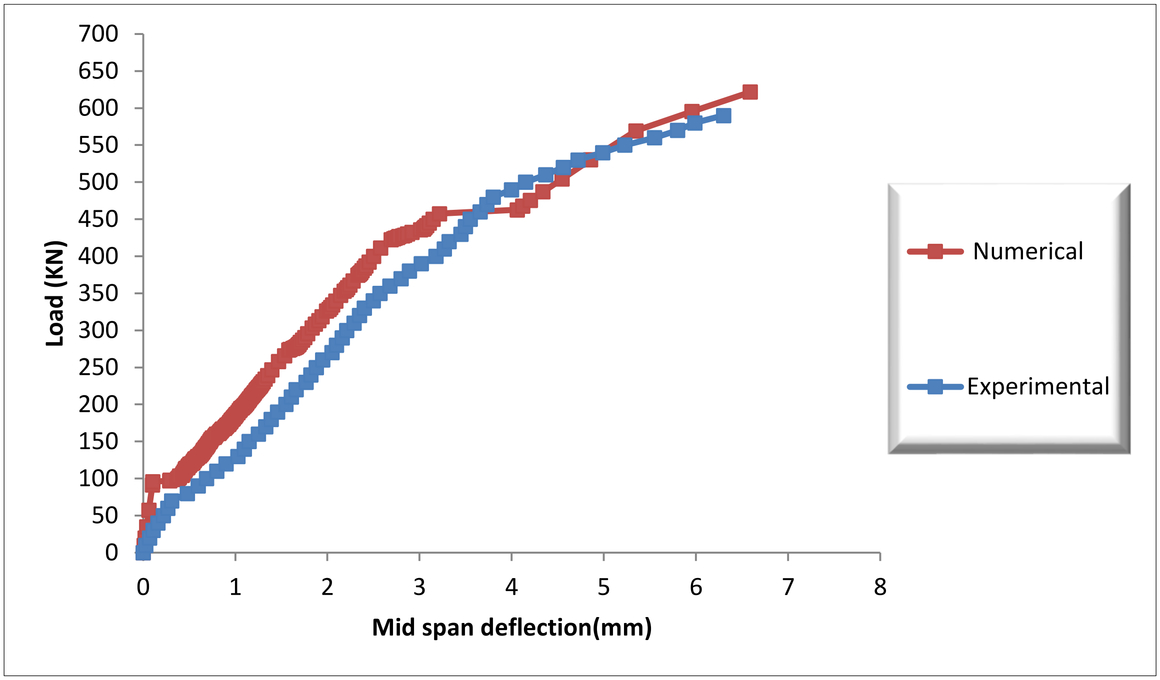

Figure (6) Experimental and Numerical Load-Deflection Curves for Beam CBS

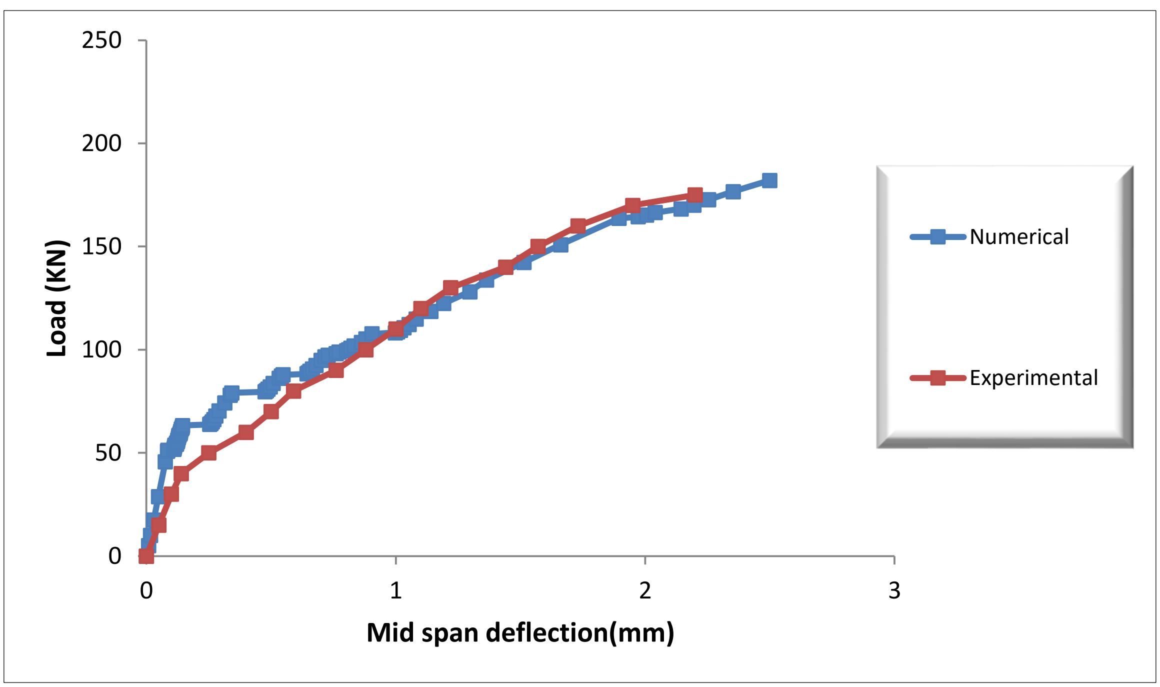

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Figure (7) Experimental and Numerical Load-Deflection Curves for Beam CBO

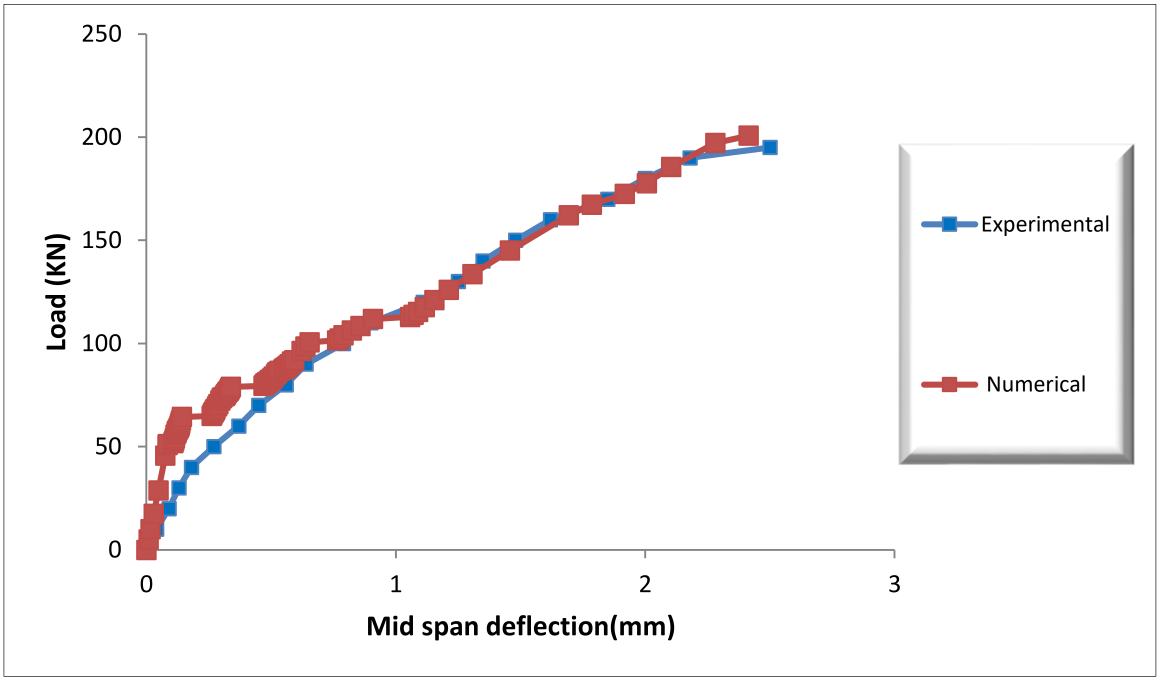

Figure (8) Experimental and Numerical Load-Deflection Curves for Beam BSE1

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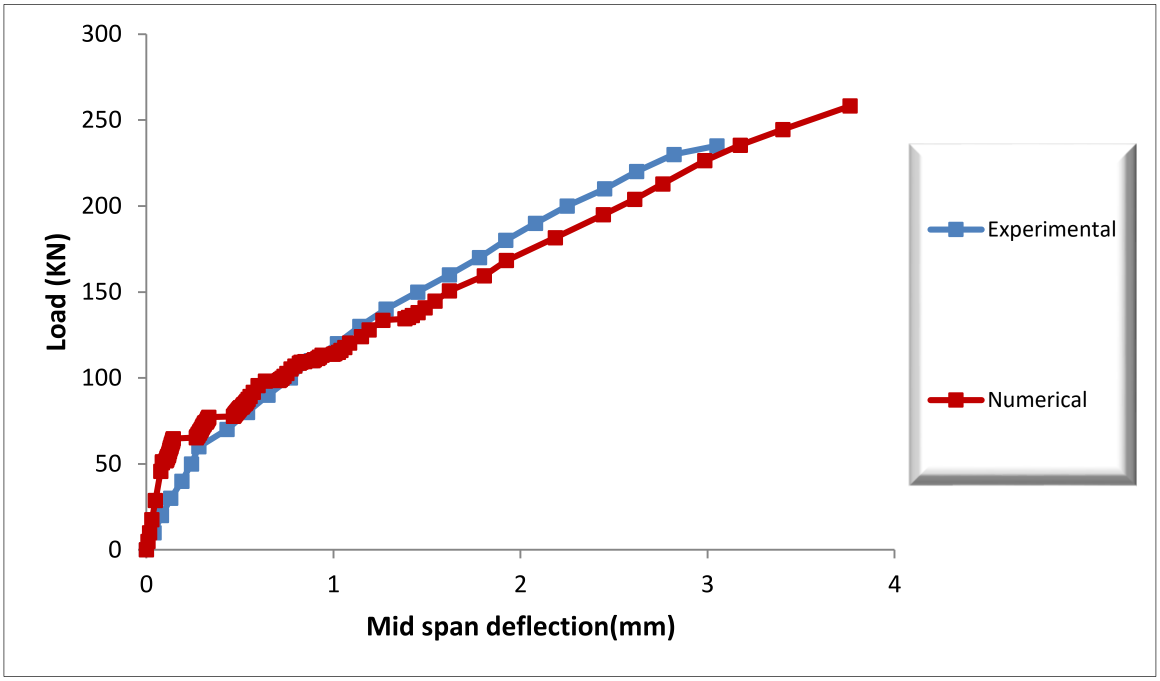

Figure (9) Experimental and Numerical Load-Deflection Curves for Beam BSE2

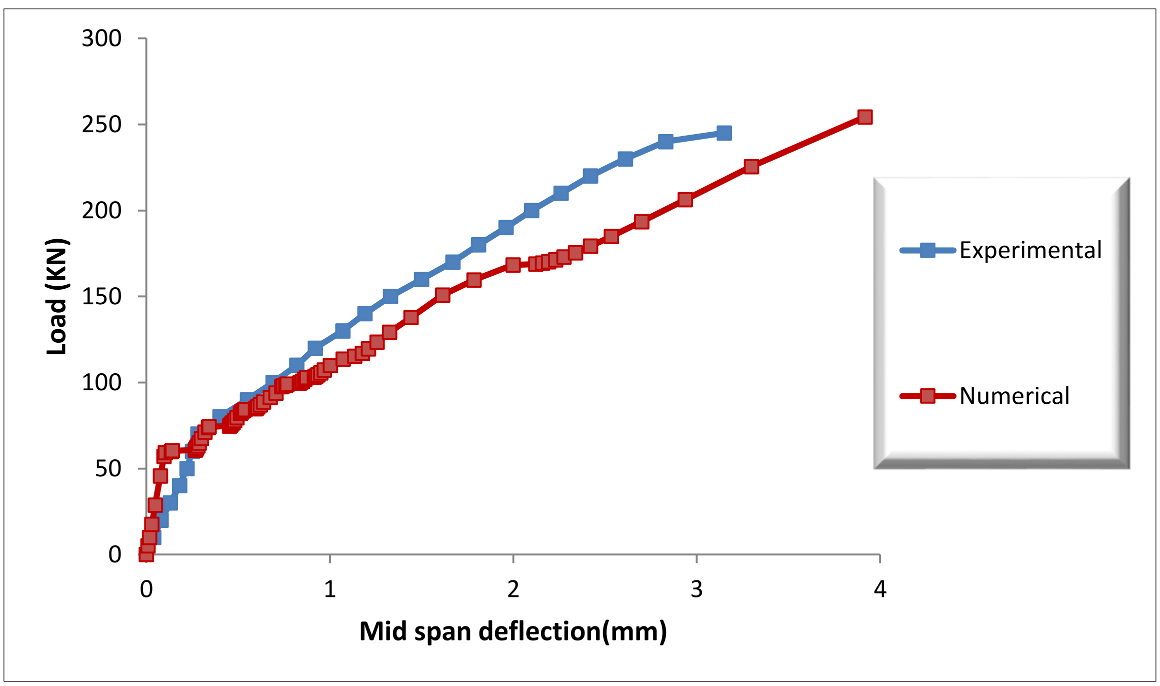

Figure (10) Experimental and Numerical Load-Deflection Curves for Beam BSE3

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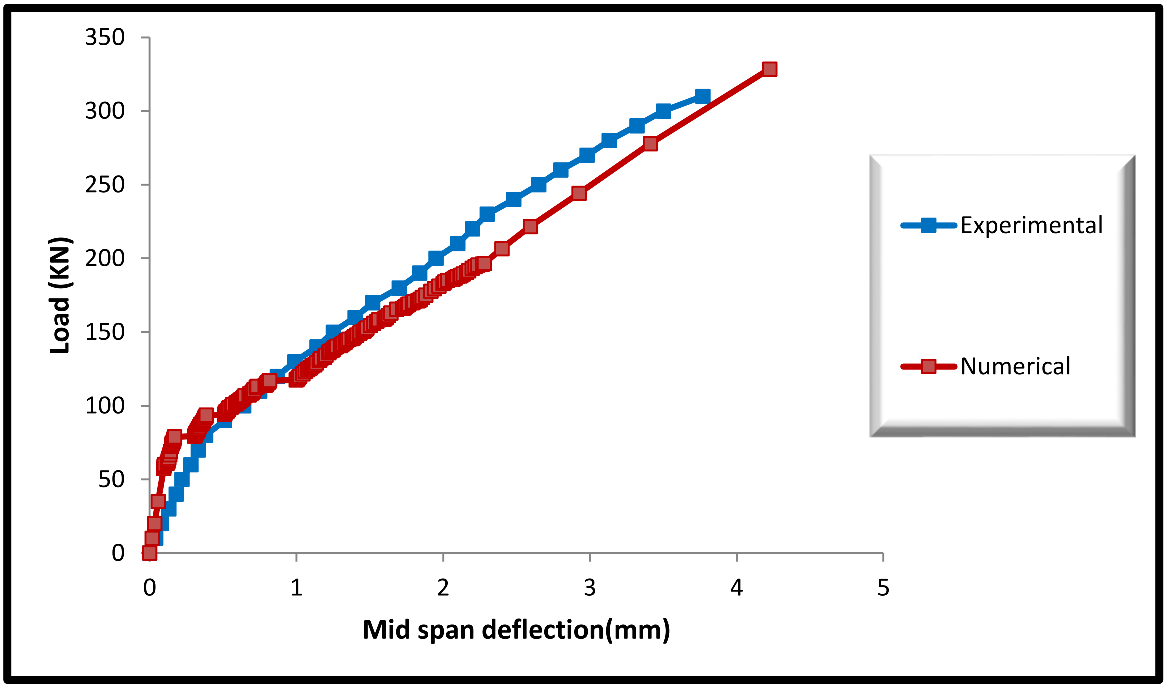

Figure (11) Experimental and Numerical Load-Deflection Curves for Beam BSE4

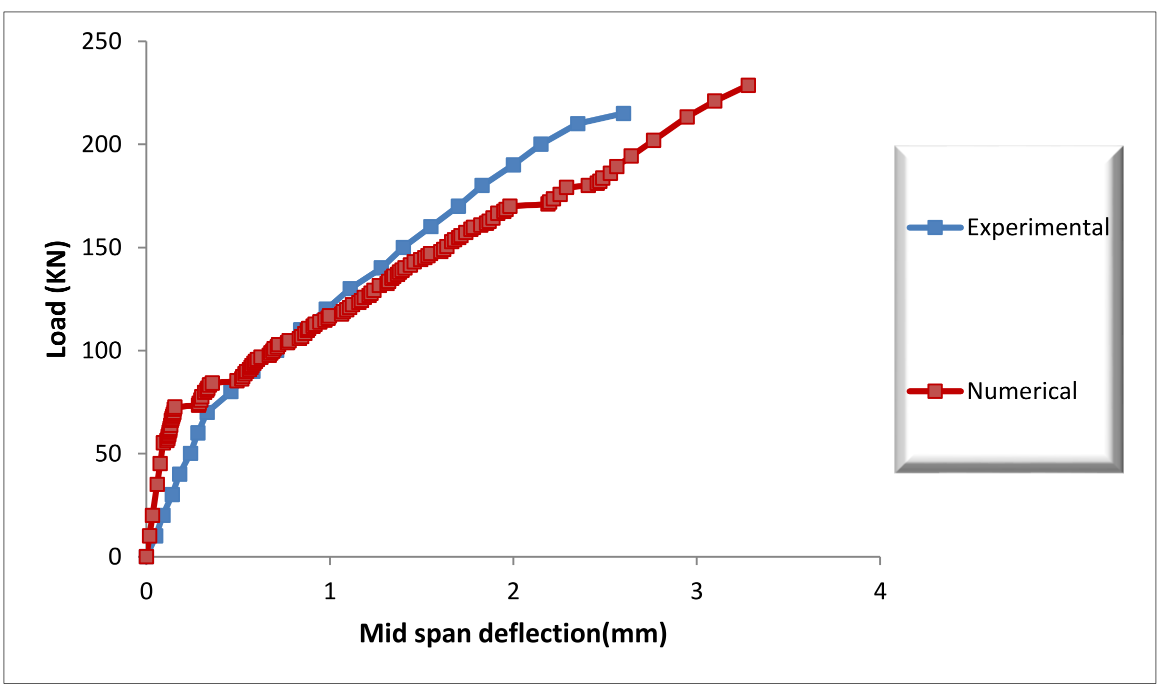

Figure (12) Experimental and Numerical Load-Deflection Curves for Beam BSE5

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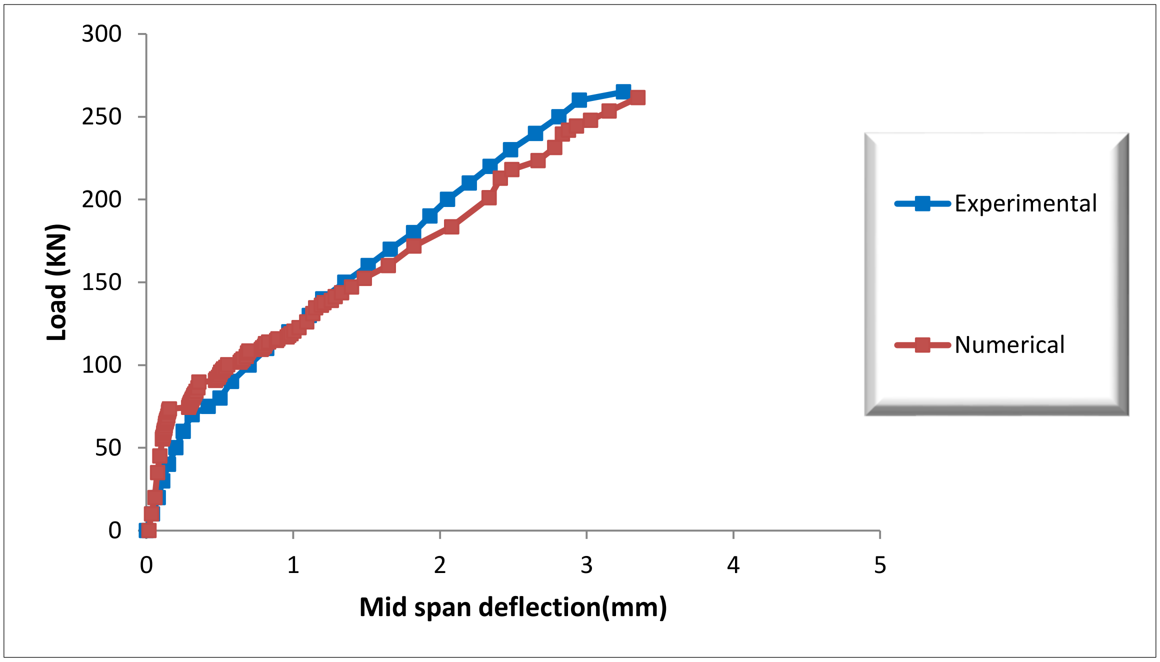

Figure (13) Experimental and Numerical Load-Deflection Curves for Beam BSE6

5.3 CRACK PATTERNS

The numerical-model painted the cracks at all stages of loading. Cracking-patterns in the beams was obtained using the Crack/Crushing plot option in ANSYS V.15. According to ANSYS program, the first crack which represented slight crack is symbolized by a red circle outline at an integration point, the second crack which represents moderate crack is symbolized by a green circle outline, and the third crack which represents failure crack is symbolized by a blue circle outline. The results showed a good agreement in crack patterns and failure mode between numerical and experimental tested beams as shown in Figure(14) and Figure(15) .

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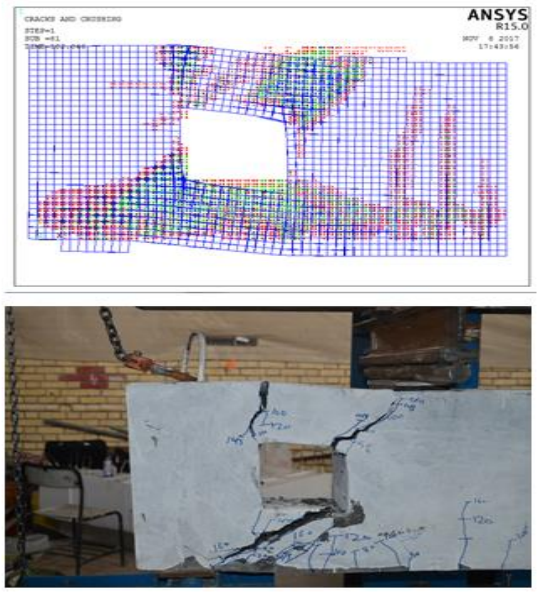

Figure (14) Crack Pattern for Beam CBO at Failure Load

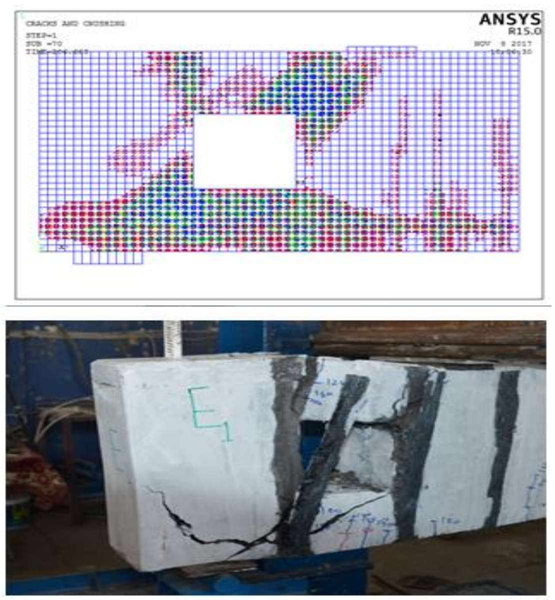

Figure (15) Crack Pattern for Beam SBE1 at Failure Load

6. NUMERICAL PARAMETRIC STUDY

In the present work, an important factors were studied by using numerical models to investigate their influence on the behavior RPC deep beam with openings .The considered parameters are the size of opening , location of openings and CFRP systems configuration .

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6.1 OPENINGS LOCATION

The first assumption in this parameter was change the horizontally location of the opening with respect to the shear span . Five models with different distances from the support center to the opening center as 175 ,225 ,250 , 275 and 300 mm were used in this assumption as shown Figure (16). The results showed that when the location of opening was changed horizontally from the critical location at the center of shear span , the strength of beam was increased significantly , whenever was opening Located further away from critical location toward middle of span . as shown in Figure (17) .

The second assumption in this parameter was change the vertically location of the opening with respect to the shear span . Two models with different distances from the bottom face of beam to the opening center as 125 and 275 mm were used in this assumption as shown in Figure(18). The results showed that when the location of the opening changed vertically from the critical location at the center of the shear span ,the strength of beam was increased significantly as shown in Figure (19) .

The reason of increase the strength in the two assumptions due to the opening moving from the critical location at shear span that deals with the previous study.

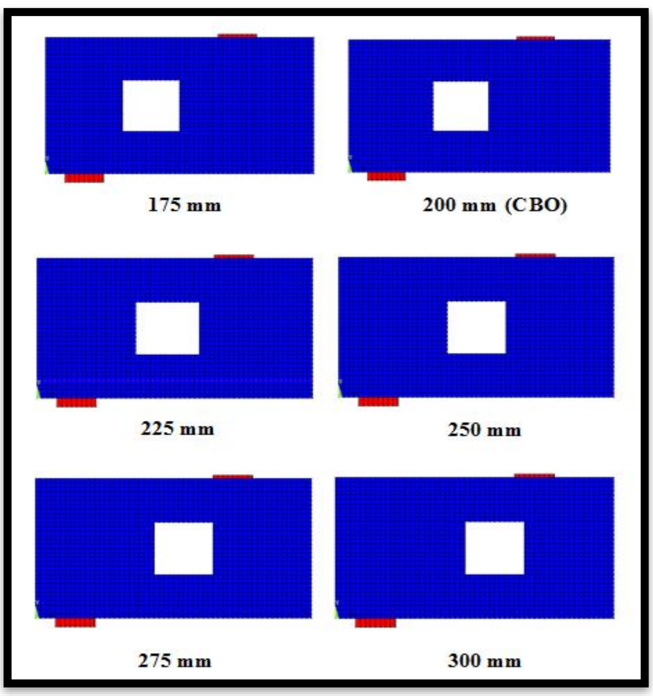

Figure (16) Horizontal Changes in Locations of the Opening

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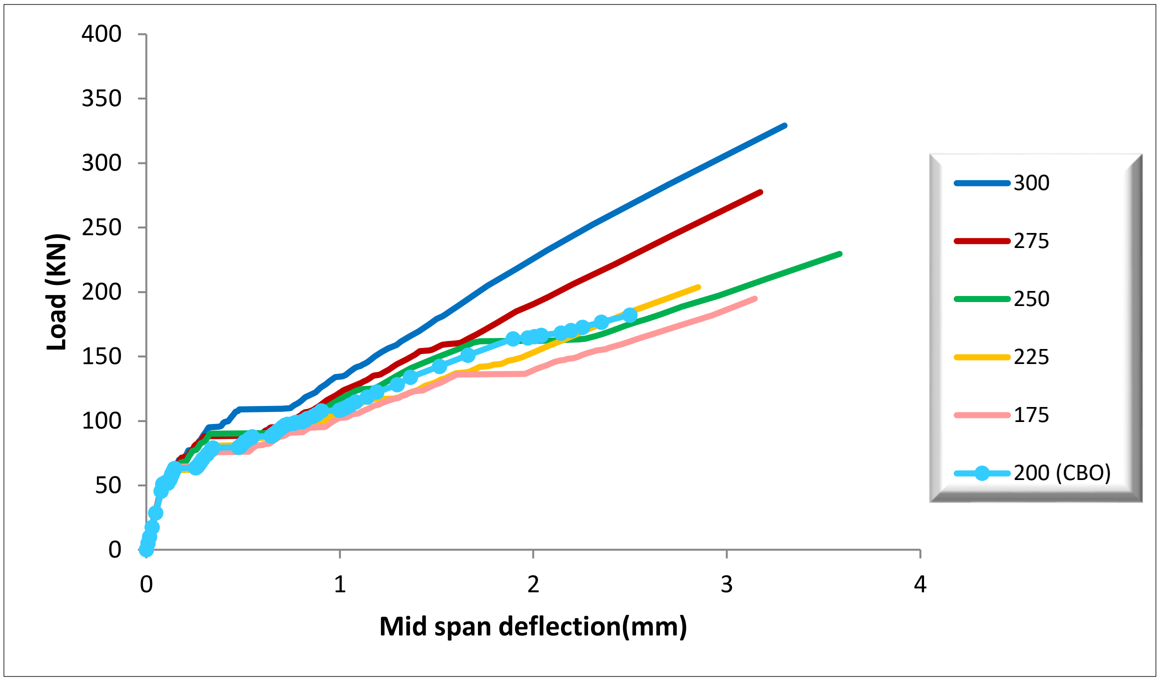

Figure (17) Load-Deflection Curves of first Assumption

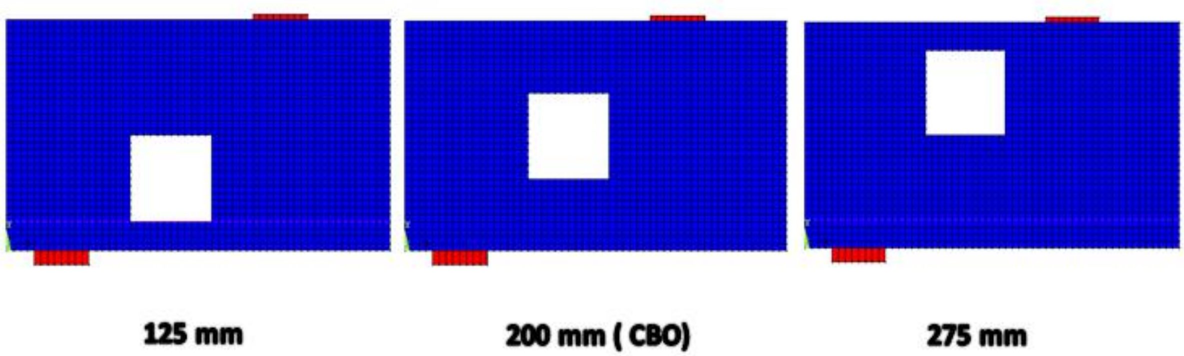

Figure (18) Vertical Changes in Locations of The Opening

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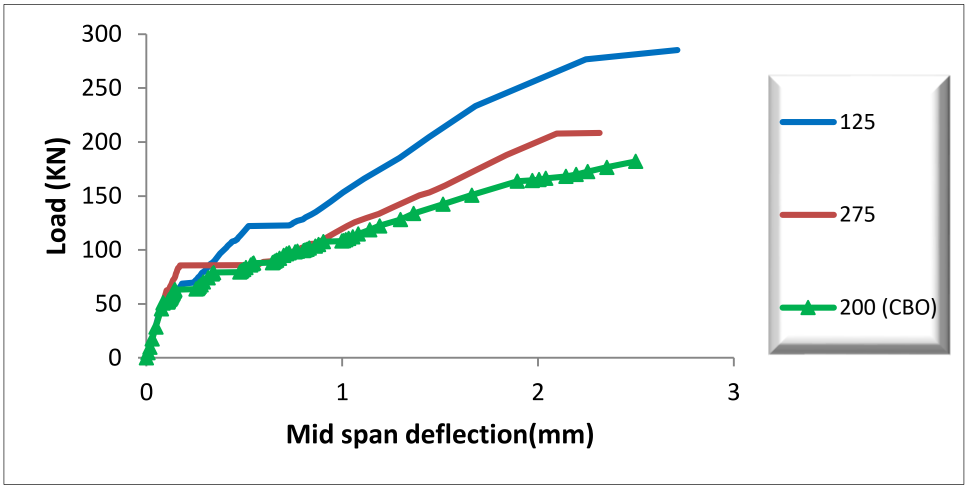

Figure (19) Load-Deflection Curves of Second Assumption

6.2 OPENINGS SIZE

To explain the effect of opening size on the behavior of RPC deep beam with openings ,four sizes of opening were provided (50x50 , 100x100 , 200x200 and 250x250 mm) at the center of shear span .Figure (20) shows the load deflection curves of several cases of deep beams which have different opening sizes compared with numerical beams (CBS and CBO). The results showed that the ultimate load was decreased with increasing the opening size . The strength of beam was decreased Significantly compared with solid beam , Table (9) shows the reduction in strength due to existence of different opening sizes compared with numerical solid beam .The explain of decreasing the strength with increasing the size of opening due to the diagonal cracks at corner along a line joining the support and load points cracks crossing minimum distances to occur the failure.

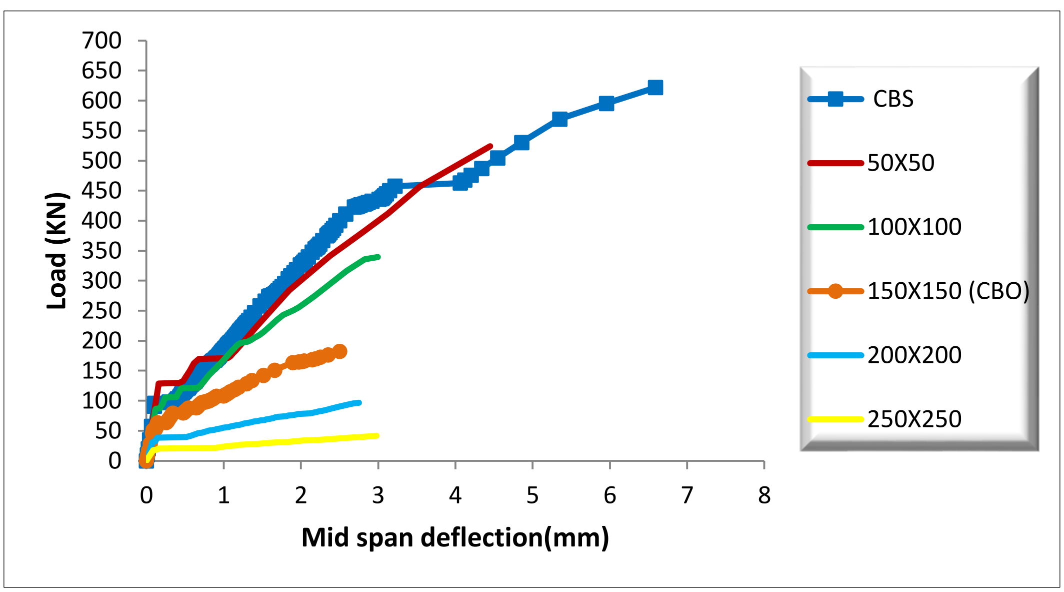

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Figure (20) Load-Deflection Curves of Several Cases of Deep Beams with different opening sizes

Table(9) The Strength Reduction in Deep Beams Due to Existence of Different opening sizes

Model	Ultimate Strength (KN)	Strength Reduction Respect to Solid Beam %
Beam without Opening (Solid)	623	______
Beam with Opening (50x50)	524	15.89
Beam with Opening (100x100)	339	45.59
Beam with Opening (150x150)	182	70.79
Beam with Opening (200x200)	97	84.43
Beam with Opening (250x250)	42	93.26

6.3 CFRP SYSTEMS CONFIGURATION

To study the effect of these three system on the strengthening process of RPC deep beam with openings ,three model (full warp , U-wrap and two sides wraps) were used by taking CFRP strips patterns of BSE2 as a case study .The models were have the same system shape in front view as shown in Figure (21) . According to results of ANSYS as shown in Figure (22) , the ultimate load and the mid span deflection of three systems were very close and the difference was not noticeable . The explain of that behavior is the failure of deep beam with opening (which located at the load path) occurs at the corners of opening , because that was no difference among the three configuration Systems.

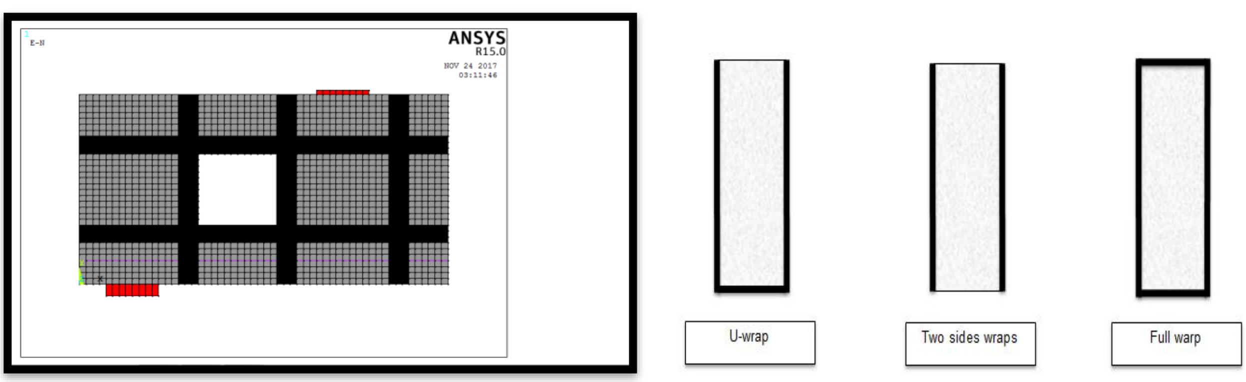

Figure (21) Front and Side View of Full warp, U-wrap and Two sides wraps Models

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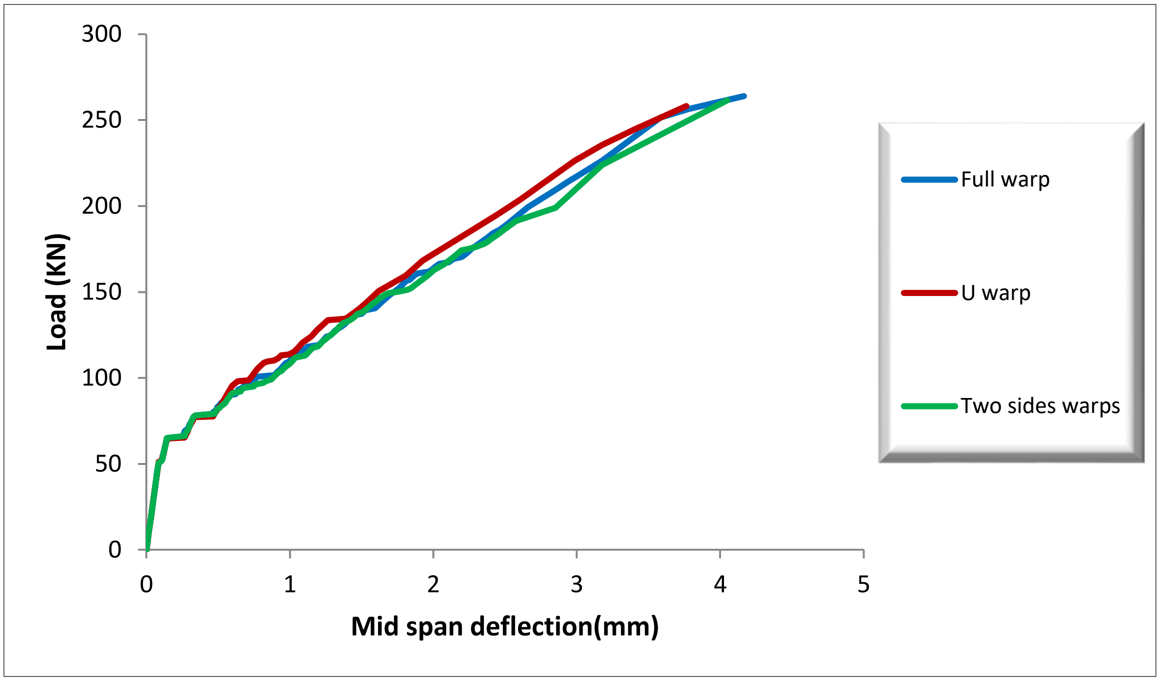

Figure(22) Load –Deflection curves of Full Warp, U-Wrap and Two Sides Warps Models

7. CONCLUSIONS

1- The comparison between the F.E.A and the experimental results asserted the validity of the numerical analysis and the methodology developed. The maximum difference in the ultimate load was less than 7.5 %.

2-From the comparison between the numerical models (full warp),(U-warp) and (two sides warps), it can be observed that there is no significant effect for the vertical anchorage warp if it used for the deep beam with openings.

3- The presence of opening in deep beam (at critical location of shear span) decrease the strength and increase the deflection , and that effect become higher with increasing the size of opening .When the opening size were (50x50 ,100x100 ,150x150 ,200x200 and 250x250) mm the ultimate load decreased about (15.89 ,45.59 , 70.79 , 84.43 , 93.26) % respectively.

4- When the location of opening was changed horizontally from the critical location at the center of shear span , the strength of beam was increased significantly about (12 - 80)% .

5-When the location of the opening changed vertically from the critical location at the center of the shear span ,the strength of beam was increased significantly about (14 - 57)% .

6- The crack patterns at the final load from the finite element model had a good match with the noticed failure of the experimental results.

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