

Numerical Analysis for Reinforced Concrete Beams with Circular Openings in Flexural and Shear Zones Strengthened by Steel Plates

Ahmed Ali AL-Dhabyani ^(1,*)

Abdulwahab AL-Ansi ^(1,*)

¹ Department of Civil Engineering, Faculty of Engineering, University of Science and Technology, Yemen

* Corresponding author: ahmedail123@gmail.com, w.alansi@ust.edu

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Abstract:

In the modern building construction, openings in beams are necessary to accommodate several service pipes and ducts. Due to these openings, high stress concentration occurs at its edges. Local cracks also appear around the openings as a result of the reduction in the beam stiffness, the load carrying capacity and the shear capacity. There are many studies which were conducted to develop and test different strengthening methods for the beams opening to increase the ultimate load capacity of the beams. However, from a practical point of view, it is better to have one strengthening method having the same specifications to be used in both; shear and flexural zones for circular opening beams in buildings. In spite of the prior studies, no study has addressed this issue; therefore, there is a need to study such a case. In this paper, an analytical study was conducted to investigate the behavior of the reinforced concrete (RC) beams with circular openings in flexural and shear zones strengthened by steel plates. A 3D FE modeling (ABAQUS 6.12) software was used to simulate five different specimens of RC beams. The study results showed that when the openings were strengthened by steel plates, the ultimate load carrying capacity increased, but the deflection was decreased when compared to the openings without strengthening. In addition, the model reliability was verified via good agreements between the experimental and numerical results.

Keywords: Beams with openings, Circular openings, Steel plates, Flexural and shear zones, Finite elements, ABAQUS.

التحليل الرقمي للجسور الخرسانية المسلحة التي تحتوي على فتحات دائرية في منطقتي العزم والقص مقواه بصفائح صلبة

الملخص:

في المباني الحديثة، من الضروري تزويدها بالفتحات في الجسور الخرسانية لاستيعاب العديد من أنابيب الخدمات والقنوات. ونظراً لهذه الفتحات، فإنها تؤدي إلى التركيز الشديد في الإجهاد يحدث عند حواف الفتحات. كما تظهر الشقوق المحلية حول الفتحات مما يؤدي إلى انخفاض في جساءه الجسور، وقدرها لتحمل الحمل وقدرتها لمقاومة القص. وهناك العديد من الدراسات التي أجريت لتطوير واختبار طرق مقاومة وتدعيم مختلفة للجسور التي تعترض لزيادة قدرة الحمولة القصوى. ومع ذلك، من الناحية العملية، من الأفضل استخدام طريقة تقوية واحدة لها نفس المواصفات ليتم استخدامها في كليهما؛ في مناطقتي القص والعزم للجسور التي تحتوي على الفتحات الدائرية في المباني. على الرغم من الدراسات السابقة، لم تتناول أي دراسة هذه المسألة؛ لذلك، هناك حاجة لدراسة مثل هذه الحالة. في هذه الورقة، أجريت دراسة تحليلية لفحص سلوك الجسور الخرسانية المسلحة (RC) التي تحتوي على فتحات دائرية في مناطقتي العزم والقص مقواه بصفائح صلبة. تم استخدام برنامج (ABAQUS 3D) (FEmodeling) لمحاكاة خمس عينات مختلفة من الجسور الخرسانية المسلحة. وأظهرت نتائج الدراسة أنه عندما تم تدعيم الفتحات بواسطة ألواح الصلب، زادت القدرة على حمل الحمولة القصوى، ولكن تم تقليل التشوه مقارنة بالفتحات دون تدعيم. بالإضافة إلى ذلك، تم التحقق من صلاحية النموذج عبر توافق جيد بين النتائج التجريبية والتحليلية.

الكلمات الافتتاحية : الجسور مع فتحات، الفتحات الدائرية، ألواح الصلب، مناطقتي القص والعزم، العناصر المحددة، الأباكوس.

1. Introduction:

In modern buildings, providing openings in beams is necessary to accommodate essential services, including water supply, sewage, air-conditioning, electricity, telephone, computer network and fire system. Usually, the pipes and ducts are placed underneath the beams soffits and covered by suspended ceilings for aesthetical purposes, thus creating a dead space. If service ducts are provided at the bottom of the beam, the floor height increases and the overall height of the building also increases. The floor space is limited in most of the cases, and it is very important to pass service ducts through a transverse opening in the reinforced concrete beam. Structural engineers face a major problem in retaining the load carrying capacity and the beam stiffness without increasing the depth. Providing pipe and duct openings in beams results in decreasing flexural and shear zone strengths, forming local cracks around the openings and reducing the beam stiffness. Many studies including [1 -5] were conducted to investigate the behavior of RC beams with different strengthening methods. These studies concluded that there was an increase in the beam stiffness when using different strengthening methods. Some other studies were similar to the current study like the study of Suresh et al [6] who conducted a numerical and experimental study investigating the behavior of 14 steel fiber RC beams with duct openings strengthened by steel plates using ABQUSE software. Their study concluded that the openings in the shear zone reduced the load carrying capacity by 55% and by 70% in the flexural zone. While Sheikh [7] conducted an experimental study to investigate the behavior of 27 RC beams in flexural and shear zones with different opening shapes and sizes at different locations. The result showed that the ultimate load carrying capacity of the RC beams with openings in the shear zone was extremely less than that of the RC beams with openings in the flexural zone. In addition, the rectangular openings reduced the ultimate load carrying capacity more than the square openings by 4%, while the circular openings reduced the ultimate load carrying capacity more than the square openings by 8%. Furthermore, Aykac [8] investigated the behavior of the RC beams with square and circular openings in the flexural zone and tested nine concrete beams. He concluded that the beams with square openings carry a load smaller than the bending load, the beams with circular openings carry a load equal to the bending load, and the final load was reduced by 35%. Recently, the study of Kumar et al [10] investigated the behavior of RC beams with circular openings in

the flexure zone with and without steel plates. They reported that the load carrying capacity increased by 40% to 55% when the flexure zone was strengthened by steel plates. However, Latha [11] conducted a numerical study in which several openings with different shapes and sizes in the RC beams were investigated by using ANSYS software. The study found that the ultimate load capacity was not affected when the diameter of circular openings was less than 44% of the depth of the rectangular RC beams, but the ultimate load capacity was reduced at least 34.29% when the diameter of circular openings was more than 44% of the RC beams. Nevertheless, from a practical point of view, it is better to have one strengthening method having the same specifications to be used in both; shear and flexure zones for circular opening beams in buildings. In spite of the prior studies, no study has addressed this issue. Therefore, there is a need to study such a case. In this paper, the behavior of RC beams with circular openings in both; flexural and shear zones strengthened by steel plates was conducted using ABQUSE (6.12) software.

2. Experimental Program:

In the experimental study of Suresh et al [6], tests were conducted on RC beams with and without duct openings in the shear zone. The tests consisted of thirty specimens under two-point loading [6]. The cross section of the thirty specimens was 150mm x 300mm and the length was 2000mm. The material properties used are shown in Table (1). The details of the tested specimens are shown in Figure (1). The results of Suresh et al [6] and their model data of the experimental study were used to verify the model in the current study.

Table 1: Properties of Materials [6]

Material	Poisson ratio	Compressive strength (MPa)	Modulus of Elasticity (MPa)	Density ton/mm ³	Yield stress (MPa)
Concrete	0.2	22.7	22369	2.4e-9	-
Reinforcing steel	0.3	-	200000	7.8e-9	415
Steel plate	0.3	-	200000	7.8e-9	250

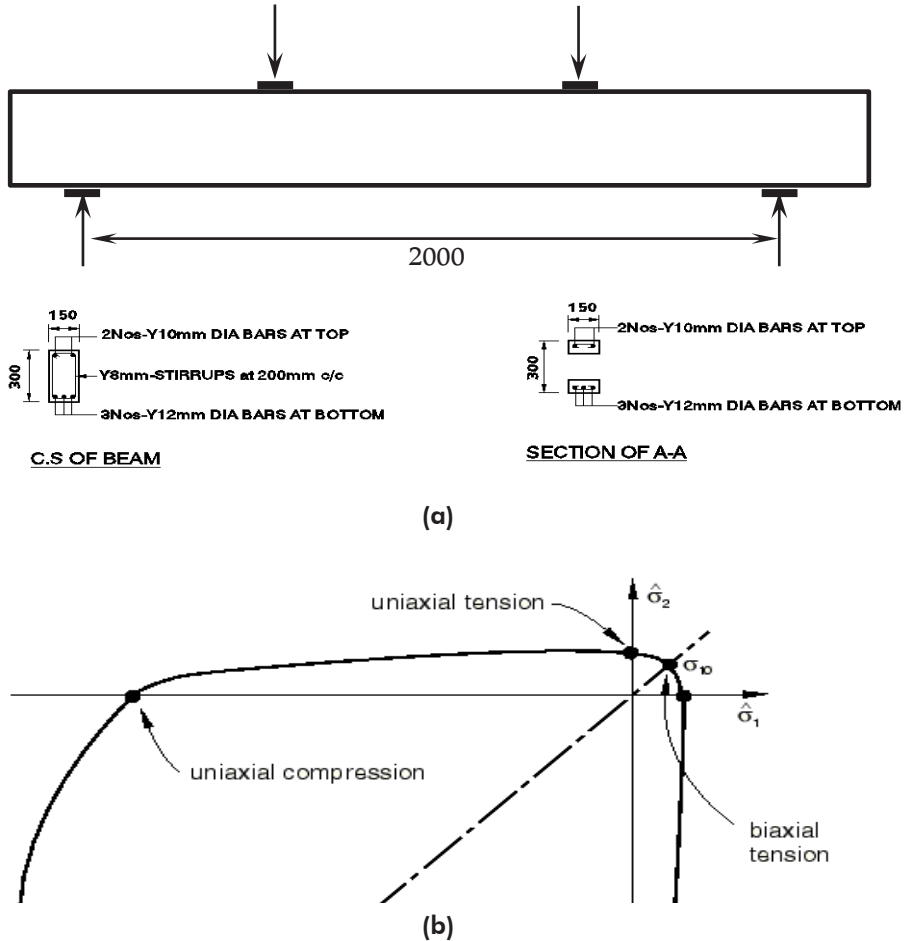


Figure 1: Reinforcement Details for all Specimens (a) Reinforcement Details of RC Beams without Openings (b) Model Set-Up of the Experimental Work [6]

3. Finite Element Modeling:

The Finite Element Method (FEM) is widely used in the structural design and analysis. The aim of FEM analysis is to re-create mathematically the behavior of an actual engineering system. This paper presents the behavior of reinforced concrete (RC) beams, with and without openings in the shear and flexural zones strengthened by steel plates of 4mm thickness surrounding the openings.

The five specimens were simulated in ABAQUS model. One specimen without openings was considered as the control beam, two RC beams were with openings and without strengthening steel plates and the last two RC

beams were with openings and with strengthening steel plates. All the beams had the same cross section (150mm x 300mm), the same length (2000mm), the same reinforcement, and 3Ø12mm bars longitudinal reinforcement at the bottom, 2Ø10 mm bars at the top and Ø8mm stirrups at 200mm c/c. The ratio of the opening size is 0.66% out of the overall depth of the beam. The material properties used in this work are the same as those used in the experimental work conducted by Suresh et al [6] as shown in Table (1).

The beams were tested under two-point loading, the diameter of circular openings was 200mm at the shear and flexural zones. ABAQUS 6.12 software was used for modeling. The element type used in the model was C3D8 element (Three-dimensional continuum) and T3D2 element (Three-dimensional truss). C3D8 was used for concrete and steel plates. In addition, T3D2 element was used for steel reinforcement. For the interaction between the concrete and reinforcement steel, an embedded element was used. Moreover, the contact between the load plate and the surface of beam was defined, and the boundary conditions of the beam were defined as hinge and roller supports. Table 2 shows the details of the tested specimens.

Table 2: Details of the Tested Specimens

S.No	Specimen Details	Name of the Specimen	Opening size (mm)
1	Control beam	CB	-
2	Unstrengthened beams with openings in the shear zone	UBSH	D200
3	Unstrengthened beams with openings in the flexural zone	UBFLX	D200
4	Strengthened beams with openings in the shear zone	SBSH	D200
5	Strengthened beams with openings in the flexural zone	SBFLX	D200

3.1 Material Properties in ABAQUS Model:

3.1.1 Concrete:

ABAQUS offers several different models of inelastic behaviour to represent a wide range of potentially brittle materials, such as metals, soils, cast iron, and concrete. The concrete damage–plasticity (CDP) model is a continuum, plasticity-based, damage model for concrete. It provides a general capability for modeling concrete using concepts of isotropic damaged elasticity in

combination with isotropic tensile and compressive plasticity to represent the inelastic behaviour of concrete. It is designed to be used for applications in which the structure is subjected to monotonic, cyclic, or dynamic loading. It assumes that the main failure mechanisms are tensile cracking and compressive crushing of the concrete material. This model consists of a combination of non-associated multi-hardening plasticity and isotropic damaged elasticity to describe the irreversible damage occurring during the fracturing. The post-failure behaviour for direct straining is modelled with tension softening parameters which define the strain softening behaviour for cracked concrete. This behaviour also allows the effects of the reinforcement interaction with concrete to be simulated in a simple manner (ABAQUS Analysis User's Manual, 2006). The CDP model includes the dilation angle Ψ , flow potential eccentricity m , initial biaxial/uniaxial ratio σ_{c0}/σ_{b0} , the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian K_c , and the viscosity parameter μ . These parameters are related to the yield surfaces of the individual finite concrete elements. As mentioned previously, concrete has different yield stress in compression and tension; in essence, a yield surface attempts to envelope these stresses in order to create an interaction relationship. The yield surface of the concrete damage plasticity model is given in Figure 2 where the enclosed area represents the elastic states of stress.

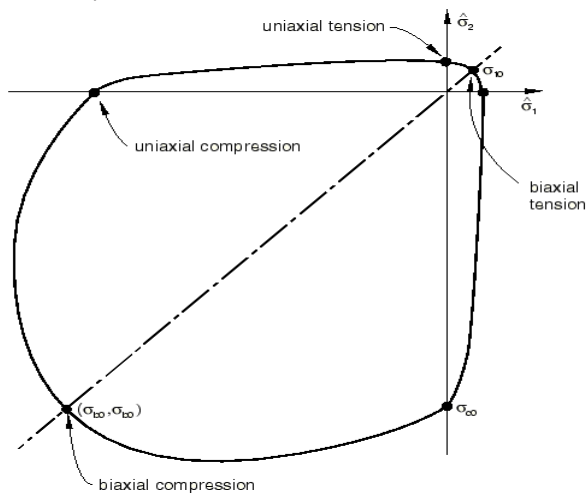


Figure 2: Bi-linear Yield Surface of Concrete
Source: (ABAQUS, 2006).

The CDP model requires compressive and tensile input parameters to accurately model the material behaviour. The uniaxial compressive response

is linear-elastic until the value of initial yield, σ_{c0} , is reached. The material experiences a hardening effect, ultimately reaching a maximum compressive stress, σ_{cu} , followed by a softening branch. If the concrete specimen is unloaded from any point on the strain-softening branch, of the stress strain curve, the unloading response is weakened. The elastic stiffness of the material is considered damaged, as some residual stress remains present (Figure 3).

The uniaxial tensile stress-strain response is initially linear-elastic, with the same modulus of elasticity as in compression. As the tensile failure stress, σ_{t0} , is reached, cracking initiates in the concrete. The uniaxial loading concrete response for tension shown in Figure 3.

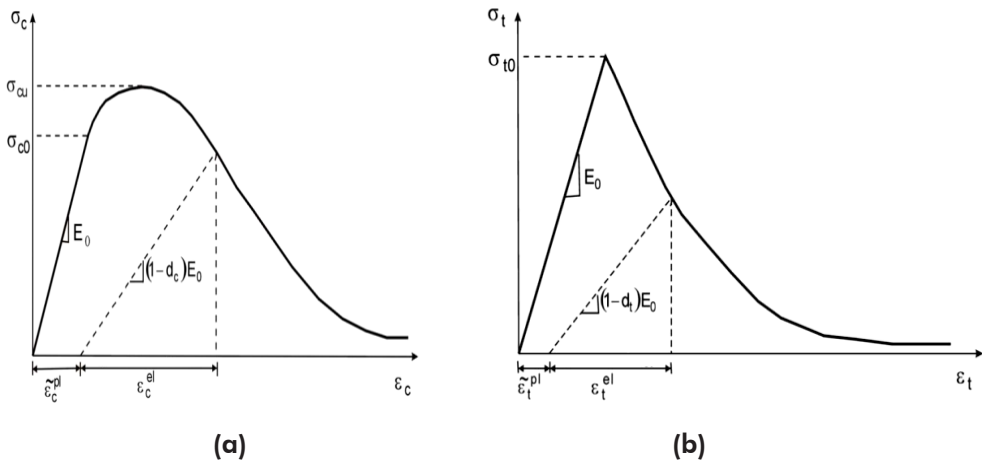


Figure 3: Uniaxial Loading Concrete Response (a) Compression and (b) Tension
Source: (ABAQUS, 2006).

In this study, it was desirable to capture the material behaviour up to and past the peak loading and so the concrete damage plasticity model, which exhibits a non-linear ascending curve followed by a softening post peak response, was chosen. The default finite element CDP model parameters were used in this analysis and are summarized in Table 3. The first two parameters (dilatation angle and eccentricity) control the plastic straining response of the material and since the later segment analyses will be unrestrained, there should be little change with the dilatation angle and eccentricity. The next two parameters (σ_{c0}/σ_{b0} and K_c) determine the shape and size of the bi-linear yield surface. Since the response of the segments will be predominately uniaxial, it is not anticipated that there will be significant changes to the analyses by varying

these parameters. The viscosity has been set to zero and this assumes that there are no strain rate effects.

Table 3: Material and Concrete Damage Plasticity (CDP) Parameters

CDP Parameters	Value
Dilation angle (Ψ)	36.31°
Viscosity Parameter (μ)	0
Eccentricity (m)	0.1
σ_0/σ_b0	1.16
K_c	0.67

3.1.2 Reinforcement Bars:

Reinforcement was represented by two-nodded truss element embedded anywhere within a concrete element along local coordinate lines. Perfect bond between the concrete and the steel existed. Full compatibility between the bar and basic concrete element was assured. The yield stress of reinforcement bars was taken as 415 N/mm² and the Young Modulus E was taken as 2 x 10⁵ N/mm². Stress-strain curve is shown in Figure 4.

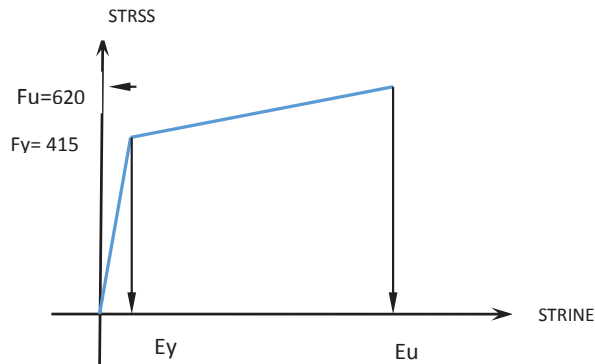


Figure 4: Reinforcing Steel Material Stress-Strain Curve

3.2 Model Set-Up:

In the first step, the parts of model were drawn and gathered. Then the materials' properties from the experimental study of Suresh et al [6] were defined in order to make the modeling calibration and verification. The constructed load is shown in Figure 5. The simulation tests were carried out at a constant load increment of 5 KN up to the failure. The applied load and the deflection at the mid span of the beams were measured.

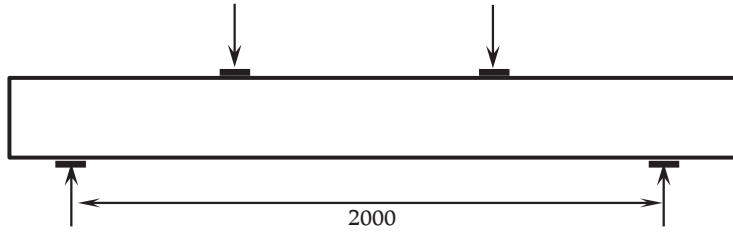


Figure 5: Constructed and Gravity Loads

3.3 Verification of the Finite Element Model:

The results of the finite element analysis of the RC beam without openings (control beam) were compared with the experimental results. The experimental and numerical load-deflection curves of the RC beams without openings were shown in Figure 6. The experimental and numerical (FEM) deflections of the RC beams without openings were 8.8 mm and 8.5 mm, respectively. A good agreement between the experimental and numerical results was observed. The difference between the experimental and numerical deflections was 2.4%. The numerical deflection pattern of the control beam is shown in Figure 7.

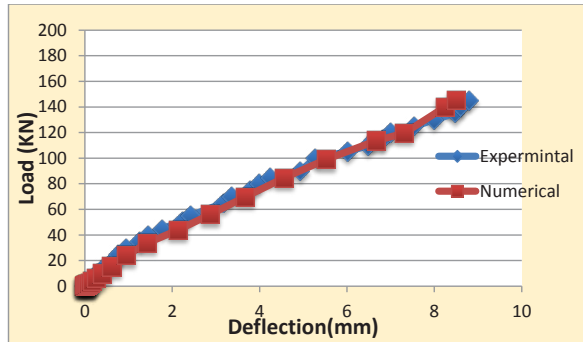


Figure 6: Comparison between the Load-Deflection Curve of the Beam without Openings (Control Beam) and the Experimental Beams without Opening

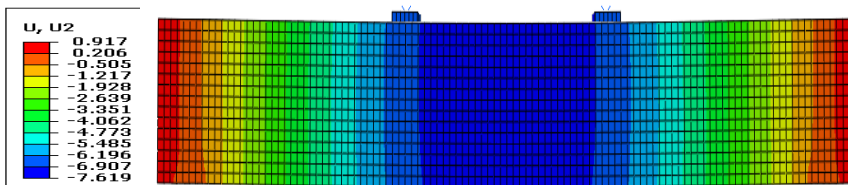


Figure 7: Deflection Pattern of the Beam without Openings (Numerical Beam)

3.4 Simulation Approach:

3.4.1 RC Beams Simulation in ABQUS Model:

Five different specimens of RC beams were simulated. The first specimen was solid without openings (control beam). The second and third specimens were with circular openings in the shear and flexural zones and without strengthening steel plates. The last two specimens were with circular openings in the shear and flexural zones, and they were strengthened by 4mm steel plates surrounding the openings. Figures 8–12 show the finite element models.

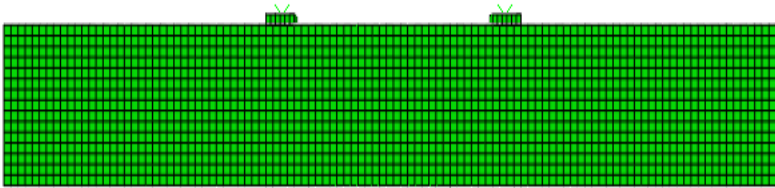


Figure 8: ABAQUS Model of Solid Beam without Openings (Control Beam)

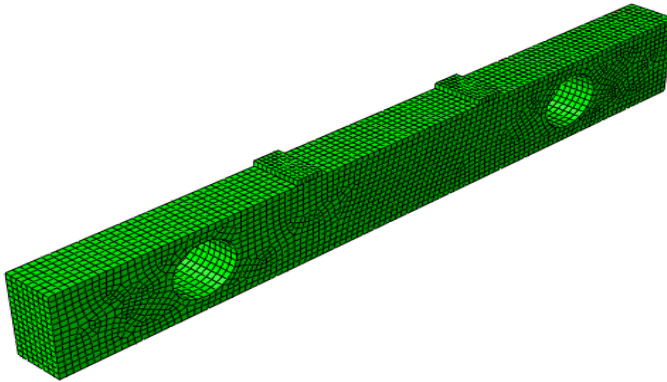


Figure 9: ABAQUS Model of Beam with Circular Openings in the Shear Zone without Strengthening Steel Plates

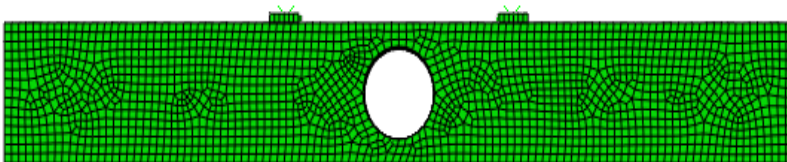


Figure 10: ABAQUS Model of Beam with Circular Openings in the Flexural Zone without Strengthening Steel Plates

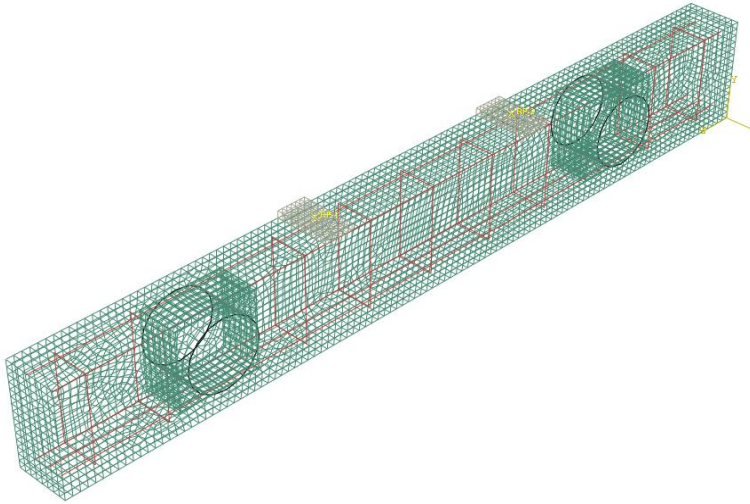


Figure 11: ABAQUS Model of Beam with Circular Openings in the Shear Zone with Strengthening Steel Plates

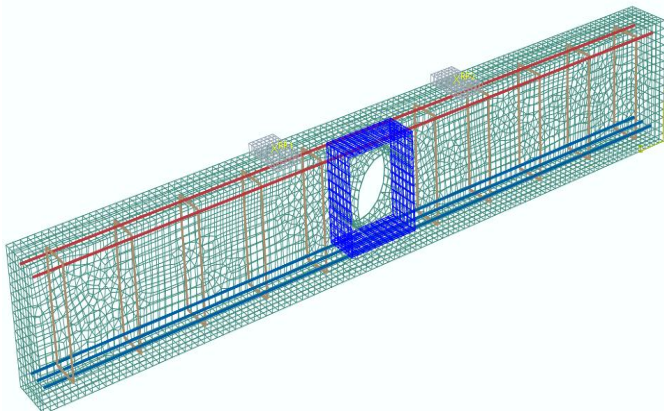


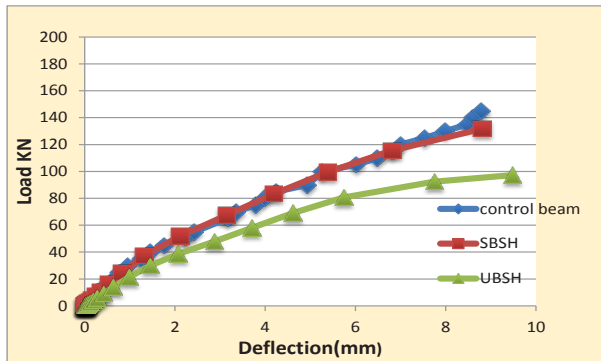
Figure 12: ABAQUS Model of Beam with Circular Openings in the Flexural Zone with Strengthening Steel Plates

4. Results and Discussion:

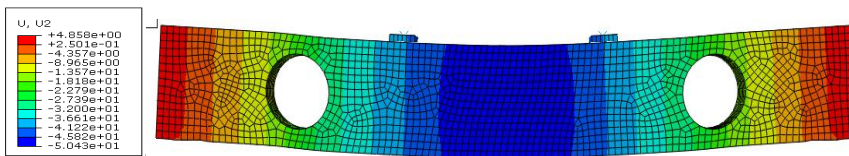
A comparison between the numerical and the experimental results was performed for the calibration and verification of the finite element model. While the comparison between the simulated circular openings of the RC beams in the shear and flexural zones with and without strengthening steel plates were conducted to investigate the possibility of using the same strengthening method for the whole beams at the shear and flexural zones.

4.1 Comparison between the RC beams with circular openings in the shear zone with and without strengthening steel plates and with the control beam:

The load-deflection behavior of the RC beam with circular openings in the shear zone strengthened by steel plates are shown in Figure 13. When the openings of the RC beam were strengthened by steel plates, the ultimate load carrying capacity increased by 26.2% and the deflection decreased by 7.9% when compared to the UBSH. While the load carrying capacity decreased by 9.1% but the deflection had the same result when compared to the control beam. Also can be illustrated that the load carrying capacity of the RC beam with circular openings in the shear zone without strengthening steel plates decreased by 33% and the deflection was increased by 7.4% when compared to the RC beam without openings.



(a)

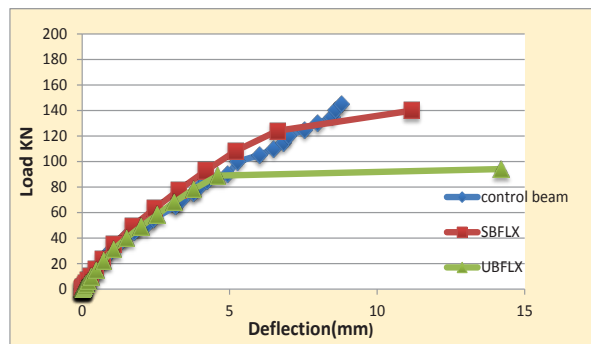


(b)

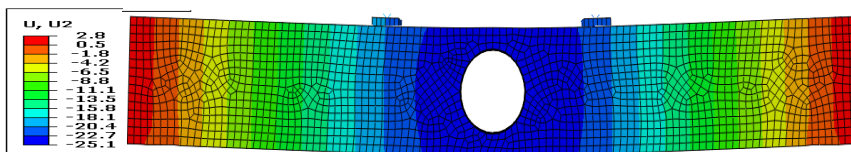
Figure 13: Results of the Beam with Circular Openings of D200mm in the Shear Zone with Strengthening Steel Plates (a) Load-Deflection Curves (b) Failure Pattern

4.2 Comparison between the RC beams with circular openings in the flexural zone with and without strengthening steel plates and with the control beam:

The load-deflection behavior of the RC beam with a circular opening in the flexural zone strengthened by a steel plate is shown in Figure 14. The load-deflection curve is shown in Figure 13(a). For the SBFLX, there was an increase in the ultimate load carrying capacity by 32.7%, and decrease in the deflection by 19% when compared to the UBFLX while for the SBFLX, there was also a little decrease in the load carrying capacity by 3.5% and an increase in the deflection by 23.5% when compared to the control beam. Also can be observed that the load carrying capacity of the RC beam with a circular opening in the flexural zone without a strengthening steel plate decreased by 35%, and the deflection increased by 38% when compared to the control beam.



(a)



(b)

Figure 14: Results of the Beam with a Circular Opening of D200mm in the Flexural Zone with a Strengthening steel plate (a) Load-Deflection Curves (b) Failure Pattern

The study results were summarized in Figures 15 (a,b) as follow:

The load carrying capacity of the beam with openings in the shear zone without strengthening steel plates decreased by 33% and the deflection increased by 7.4% when compared to the control beam. While the ultimate load carrying capacity of the beam with openings in the shear zone strengthened by steel plates increased by 26.2% and the deflection decreased by 7.9% when compared without strengthening.

The load carrying capacity of the beam with openings in the flexural zone without strengthening steel plates decreased by 35% and the deflection increased by 38% when compared to the control beam. While the ultimate load carrying capacity the beam with openings in the flexural zone strengthened by steel plates increased by 32.7% and the deflection decreased by 19% when compared without strengthening steel plates.

In brief, the effect of openings of the beams was more in the flexural zone than in the sheer zone but the overall result of this study demonstrated that, same steel plates can be used for opening strengthening the beams in shear and flexural zones effectively.

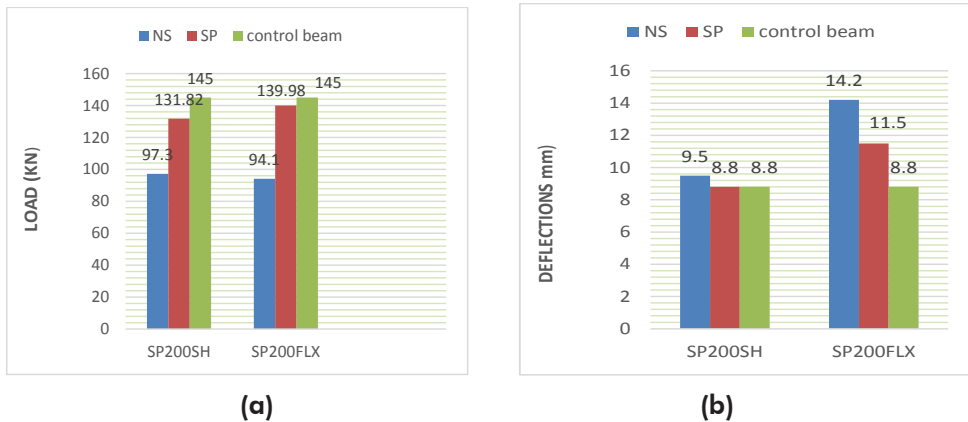


Figure 15: Comparison of the Ultimate Loads and the Deflections of RC Specimens

(a) Comparison of Ultimate Loads

(b) Comparison of Deflections

5. Conclusion:

In the current study, a numerical study was conducted to investigate the structural behavior of the RC beams having openings in the shear and flexural zones strengthened by steel plates around the openings. The numerical results revealed that the following:

- The difference between the experimental and numerical analysis was 2.4%.
- The load carrying capacity of the UBSH decreased by 33% and the deflection increased by 7.3% when compared to the control beam, while the ultimate load carrying capacity of the SBSH increased by 26.2% and the deflection decreased by 7.4% when compared to the UBSH.
- The load carrying capacity of the UBFLX decreased by 35% and the deflection increased by 38% when compared to the control beam, while the ultimate load carrying capacity of the SBFLX increased by 32.7% and the deflection decreased by 23.4% when compared to the UBFLX.
- The effect of openings of the beams was more in the flexural zone than in the shear zone. There is a possibility of using one strengthening method for the beams having circular openings in both zones; shear and flexural.
- The finite element models are able to simulate the behavior of RC beams with and without openings in a predictably suitable and accurate degrees.

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