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Strengthening of Reinforced Concrete Deep Beams with Large Openings Using Metal Plates

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Abstract:
Deep beams with large openings require innovative approaches to maintain strength and performance. To minimize the detrimental impacts of wide holes in reinforced concrete deep beams, effective reinforcing pro-cedures are essential. This paper presents a study on the use of metal plates for strengthening reinforced concrete deep beams with large openings. The Finite element modelling (FEM) software Abaqus is used to study the im-pact of various metal plate orientations on the structural behaviour and load-carrying capacity of the deep beams. The research includes an extensive sensitivity analysis and model calibration of the original model against exper-imental results, as well as four different examples of applying a load of 500 kN after validating the original beam against experimental results. The study found that case 3 exhibits the smallest deflection and have large load car-rying capacity, indicating its superior performance in minimizing deflection. However, case 4 is a more affordable choice due to the high cost of the metal plates used in case 3's design. Different grades of concrete were utilized on the same model after case 4 was chosen as the final one to examine the impact of concrete strength and deter-mine which was most cost-effective. Based on cost-effectiveness and performance, the proposed model has the ability to carry more load with less deflection, encouraging the development of practical and secure structural so-lutions

Keywords:
Deep beams; Finite element modelling; Abaqus; Metal plate; load-carrying capacity

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1. Introduction

In the field of structural engineering, the efficient reinforcing and strengthening of concrete com-ponents play a crucial role in ensuring the durability and structural integrity of civil infrastructure. Deep beams, known for their distinctive geometry and high load-carrying capacity, are widely used in a variety of applications such as bridge piers, transfer girders, and shear walls, particularly in industri-al and commercial structures, where large openings are necessary for service penetrations, such as elevators, staircases, and mechanical systems. But when these deep exhibit large openings, their struc-tural behavior becomes more complex and necessitates innovative approaches to maintain their strength and performance [1], [2].

Large openings in deep beams are often required to accommodate services such as ducts, pipes, and conduits, allowing for the smooth integration of various building systems. However, the structur-al implications of these openings cannot be overlooked. They tend to create stress concentrations, in-crease chances of shear failure, reduce the effective cross-sectional area, and lead to cracking, which may eventually compromise the integrity of the structure. Therefore, it becomes crucial to develop effective strengthening techniques that can mitigate the negative effects of large openings in reinforced concrete (RC) deep beams [3], [4].

Recently, metal plates have drawn attention as an alternative strengthening material for RC deep beams with large openings. Externally bonded metal plates, commonly made of steel or fiber-reinforced polymers (FRP), are attached to the tension face of the deep beam. Research by Bao et al. (2023) demonstrated that externally bonded steel plates significantly increased the flexural capacity and shear strength of deep beams with large openings [5] . The anchorage and bonding techniques are essential considerations to ensure proper load transfer between the plate and the concrete substrate. The utilization of Abaqus software in this research enables a comprehensive and reliable analysis of the structural behavior of deep beams with large openings, supporting the development of efficient and cost-effective rehabilitation strategies. Near-surface mounted (NSM) metal plates are embedded within grooves or slots in the concrete. NSM plates offer advantages such as improved corrosion re-sistance and better aesthetics compared to externally bonded plates. Mansour et al. (2021) conducted experimental investigations on deep beams strengthened with NSM steel plates and reported en-hancements in both flexural and shear performance [6].

Metal plates can be used to increase the shear capacity of RC deep beams by providing additional shear resistance. Research by Dang et al. (2021) investigated hybrid strengthening of deep beams with large openings using a combination of steel and FRP plates [7]. The study revealed significant im-provements in load-carrying capacity and ductility. Numerical modelling and analytical tools have played a crucial role in assessing the performance of deep beams strengthened with metal plates. Re-searchers have developed various analytical models to predict the behavior of strengthened beams and to establish design guidelines. Durability is a critical aspect of deep beam strengthening with metal plates, particularly in corrosive environments. Research by abed et al. (2023) investigated the long-term durability of FRP-strengthened deep beams and emphasized the importance of adequate protec-tion and maintenance. Metal plates can be attached to the beam soffit or web, or both [8]. The specif-ic configuration of the metal plates will depend on the specific beam geometry and loading condi-tions.

Another study done by Khalaf et al. (2021) to investigate experimentally and numerically the ef-fectiveness of using carbon fiber reinforced polymer (CFRP) strips to externally strengthen reinforced concrete continuous deep beams (RCCDBs) with large openings, three RCCDBs were tested under five-point bending [9]. Karimizadeh et al. (2022) investigated the use of carbon fiber-reinforced poly-mer (CFRP) composites and steel protective frames (SPFs) to strengthen reinforced concrete (RC) deep beams with square openings [10]. Rahim et al. (2020) investigated the strengthening of the structural behavior of web openings in RC deep beams using CFRP. They found that the CFRP layer wrapping technique increased the shear behavior of the reinforced concrete deep beams by 10-40% [11]. Al-khreisat et al. (2023) experimentally investigated the shear strengthening and repair of rein-forced concrete (RC) deep beams damaged by heat using near-surface mounted carbon fiber reinforced polymer (NSM-CFRP) ropes. The ultimate load capacity of the strengthened

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beams increased by 19-46%, while the repaired beams increased by 40.8-64.6% [12]. The study done by Jasim et al. (2020) found that CFRP sheets significantly enhanced the failure load capacity and flexural crack resistance of RC deep beams with large openings [13].

Metal plates provide considerable benefits over Carbon Fiber Reinforced Polymer (CFRP) in terms of their cost, ease of installation and mechanical characteristics, such as high strength, stiffness, and durability. The use of metal

plates as external reinforcement presents as opportunity to enhance the loading-carrying capacity, durability, and overall performance of deep beams in a cost-effective man-ner [14], [15]I. These advantages make metal plates a promising alternative to CFRP composites, par-ticularly for deep beams with large openings [16]–[19].

The aim of this paper is to investigate and present a comprehensive study on the strengthening of RC deep beams with large openings using metal plates, with a focus on the application of Abaqus software for accurate analysis and simulation. Abaqus, a widely adopted finite element analysis (FEA) tool, provides engineers with a powerful platform to simulate and evaluate complex structural behav-ior, enabling them to optimize reinforcement strategies and assess the performance of rehabilitated deep beams.

2. Methodology

2.1. Constitutive Modeling of Material

The Concrete Damaged Plasticity (CDP) model is a widely accepted method for simulating the in-elastic behavior of concrete and other quasi-brittle materials in finite element analysis (FEA) [20] . CDP can be implemented in numerical simulations to analyses reinforced concrete structures under different loading conditions [28]. The CDP model is a continuum damage plasticity model for con-crete that considers two critical failure mechanisms: compressive crushing and tensile cracking. The stress-strain relationships under uniaxial compression and tension loading are described by the follow-ing equations:

For tensile loading:

$$\sigma_t = (1 - d_t)E_o\,(\varepsilon_t - \varepsilon_t^{pl})$$

For compressive loading:

$$\sigma_c = (1 - d_c)E_o(\varepsilon_c - \varepsilon_c^{pl})$$

To control the evolution of the yield surface, two hardening parameters, ε_c^{pl} and ε_t^{pl}, are typically used. The compressive and tensile equivalent plastic strains, which represent the failure mechanisms under compression and tension loading, respectively, can vary from 0 to 1. A value of 0 indicates an undamaged material, while a value of 1 indicates a complete loss of strength.

The material stiffness is represented by E_o, which is the initial elastic stiffness of the undamaged material. The tension and compression damage variables are represented by d_t and d_c, respectively. The plastic flow parameters for the concrete material are adopted from previous research [21]–[23].

Concrete behavior in uniaxial stress-strain is typically divided into three distinct stages: hardening, linear elastic, and post-peak softening.

The linear elastic stage corresponds to the initial loading up to the elastic limit (20 MPa), as shown in Figure 1a.

The hardening stage of the stress-strain curve is defined by the ascending portion of the curve, starting from the elastic point (20 MPa) and extending up to the peak stress (27.8MPa).

After the peak stress, the post-peak softening stage corresponds to the initiation and progression of compressive damage in the concrete material until it reaches the ultimate compressive strain.

This characterization of concrete behavior is important for understanding failure mechanisms and predicting failure loads for concrete structures. In the CDP model, damage initiation in uniaxial compression is defined during the softening procedure, which begins at the peak compressive strength. As cracking strain increases, damage increases in a nonlinear manner, as shown in Figure 1b. This understanding of the relationship between cracking strain and damage is essential for a deeper understanding of concrete failure mechanisms and is invaluable in the analysis and design of concrete structures.

The uniaxial stress–strain behavior of concrete under tensile loading is simulated using a two-phase approach, as shown in Figure 1c. The first phase describes the linear elastic behavior of concrete until its tensile strength is reached. The second phase, which is characterized by the beginning and propagation of cracks in concrete, results in a nonlinear stress–strain relationship. This approach is important for improving concrete structure analysis and design because it allows for a more accurate prediction of

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the performance of concrete under tensile loading. The initiation of damage in uniaxial tension within the CDP model is defined at the point of tensile strength, as shown in Figure 1d.

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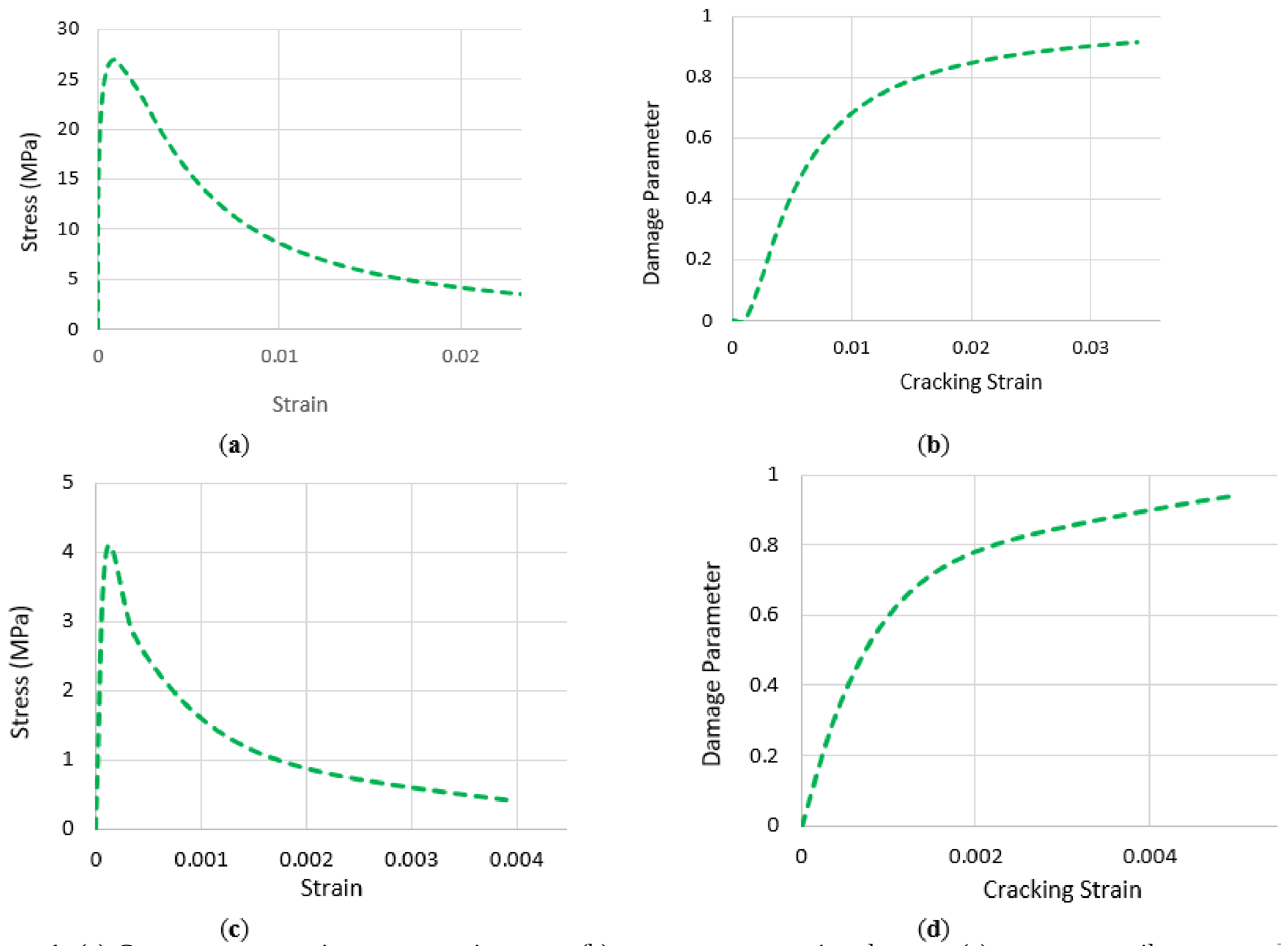

Figure 1. (a) Concrete compressive stress–strain curve; (b) concrete compression damage; (c) concrete tensile stress–strain curve; (d) concrete tension damage.

The behavior of steel was modeled using an elastic-plastic approach [24], [25]. Steel reinforcement exhibits both elastic and plastic behavior. The elastic behavior is characterized by Young's modulus, while the plastic behavior is defined by the post-yielding Young's modulus. The plastic phase is repre-sented by bilinear behavior, which resembles the typical stress-strain relationship of reinforcement. This behavior is integrated into the model, as shown in Figure 2.

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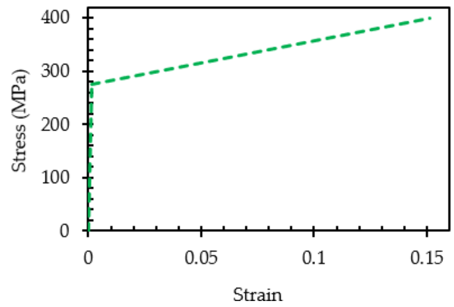

Figure 2. Typical stress–strain behavior of steel introduced to the numerical mode.

The material information for concrete and steel are listed in Table 1. While Table 2 contains the plastic flow parameters of the CDP model.

Table 1. Material information for concrete and steel [29].

Details	Concrete	Steel
Density (Kg/m^3)	2,400	7,850
Compressive strength (MPa)	27.8	300
Tensile strength (MPa)	2.39	450
Poisson's Ratio	0.2	0.3
Modulus of elasticity (MPa)	25,805	200,000

Table 2. Plasticity flow parameters for CDP model [29].

Parameters	Values
Dilation angle (ψ)	40 (Calibrated)
Eccentricity (e)	0.1
Ratio of biaxial to uniaxial compressive yield stress (σ_{bo}/σ_{co})	1.16
Coefficient determining the shape of the deviatoric cross-section (K)	0.66
Viscosity parameter (μ)	0.01(Calibrated)

2.2. Geometric Details

This study utilizes the experimental data from a large-scale test conducted by University of Malaysia for CFRP [28]. The model was designed to meet the the ACI and ASTM construction codes and standards and was constructed using the Abaqus software. The model has a rectangular cross-section with dimensions of 2400 mm × 600 mm having thickness of 120mm. It has two circular openings with a diameter of 270 mm each. The tension reinforcement consists of two 16 mm diameter bars, while the compression reinforcement includes two 10 mm diameter bars. Shear reinforcement is provided by 6 mm diameter bars spaced at 300 mm vertically and 150 mm horizontally [29]. The inclusion of the circular openings allows for the examination of the challenges associated with strengthening deep beams with large openings using metal plates. Figure 5 provides a visual representation of the beam's configuration and the location of openings.

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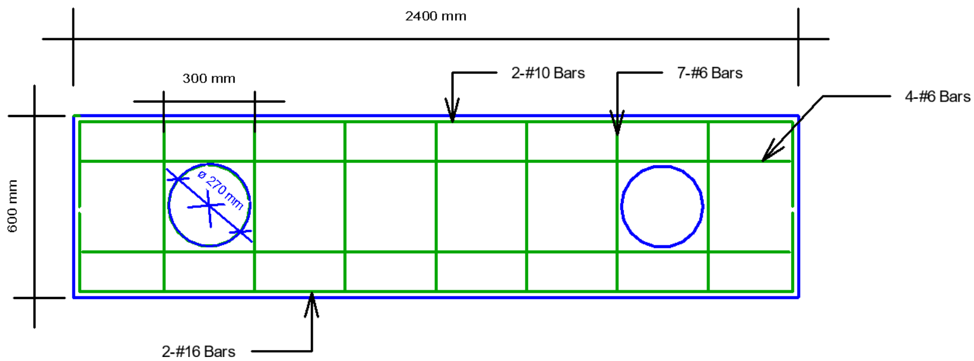

Figure 1. Assembly of deep beam and reinforcement cage

2.3. Loading, boundary conditions and interactions

To ensure the experimental setup, the test consists of a four-point loading configuration with a magnitude of 500 KN. The ENCASTRE boundary condition is used to simulate fixed supports in Abaqus. This boundary condition restricts all translational and rotational degrees of freedom. The embedded region method is used to account for the bond between concrete and steel. A tie connection is used between steel plates and the beam. The tie constraint creates a rigid connection between the two surfaces. Figure 4(a) shows the loading, and boundary conditions applied to the model.

2.4. Meshing

The concrete elements were meshed with a uniform size of 50 mm. The steel and concrete elements were discretized into distinct sections. The reinforcing elements were represented by 3D wire elements, while the concrete components were modeled using 3D solid elements. Mesh convergence analysis was carried out to choose the mesh size. The meshed geometry of the model is shown in Figure 4(b). The results of mesh sensitivity analysis are discussed in the next section.

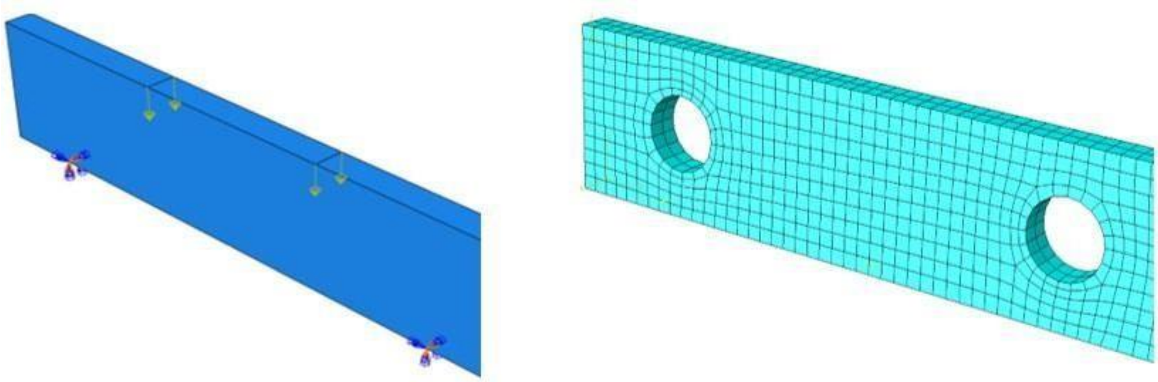

Figure 2. (a) load and boundary conditions; (b) Meshing of RC deep beam

3. Results and Discussion

3.1. Model Validation

A comprehensive investigation was conducted to explore the factors that influence the constitutive equations of the CDP model and to accurately calibrate the model. The authors performed a sensitivity analysis of the mesh and flow parameters in their numerical model of concrete flow to validate their numerical model by comparing the results to the

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experimental one obtained from. The investigation included examining and determining the effect of varying the viscosity parameter and dilation angle on the behavior of the model under different loading conditions.

Concrete expands under triaxial stress conditions, resulting in inelastic strain. This phenomenon is called dilatancy. When connection joints in specimens are subjected to lateral simulated loads, a complex stress state highly sensitive to dilatancy is created in the analytical model due to high shear stress in the joint core. Previous studies [30], [31] have shown that a dilation angle of 30° to 42° is suitable for modeling concrete. Figure 5a shows that a dilation angle of 40° accurately reproduces the load-deformation curve. To investigate the effects of visco-plastic regularization on the constitutive equations of the CDP model, the viscosity parameter was included in the FEM calibration process. Figure 5b compares the predicted and observed results, demonstrating the importance of the viscosity parameter in accurately calibrating the FEM model. The results show that a relatively low viscosity parameter of 0.01 is required for accurate numerical results to match the experimental data, even with an invariant mesh size.

Table 3. Mesh sensitivity analysis

Mesh Name	Mesh Size(mm)		
	Con-crete	Longitudinal Re-bar	Distribution bar
Mesh-1	20	20	20
Mesh-2	30	30	30
Mesh-3	40	40	40
Mesh-4	50	50	50

Mesh sensitivity analysis showed that decreasing the mesh size beyond 30 mm had a negligible impact on the predicted results and model behavior, as shown in Figure 5c. This indicates that a mesh size of 30 mm is sufficient for accurate analysis. To evaluate the performance of RC beam-column joints using FEA results, it is essential to validate the FE model against experimental data. This can be done by comparing the force-deformation backbone curves of the computational model and the experimental test specimen subjected to reverse cyclic loading. As shown in Table 4, the experimental and FEM results show a strong correlation, especially for the ultimate and failure load and defor-mation. Mesh size of 40 gave the closest results to the experimental results as shown in Figure 5(c). Figure 5(d) below shows the comparison of experimental vs numerical results.

Table 4. Comparison of Peak loads obtained from FEM and experimental results.

Experimental Results	FEM Results	Percentage Difference
Peak Load (KN)	Peak Load (KN)	
410	430	0.04

The crack pattern graph obtained from [28] serves as a crucial reference in validating the findings of the current study. The observed crack pattern, depicted in Figure 6, provides visual evidence of the structural behavior and failure mode of the RC deep beams without additional strengthening measures. The presence of diagonal cracks in the shear region, as shown in [28] (Figure 6(b)), aligns with 6(b) generated from Abaqus software, reinforcing the consistency between the experimental ob-servations and numerical simulations.

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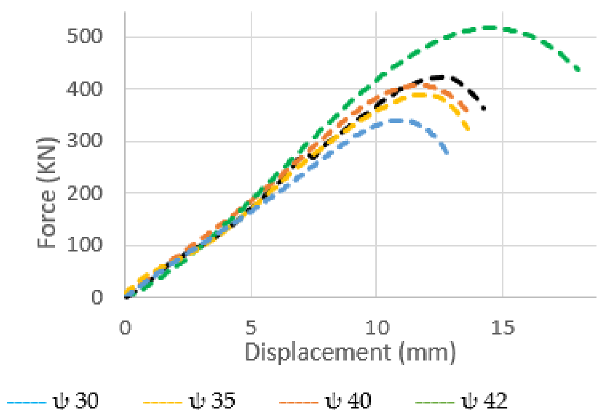

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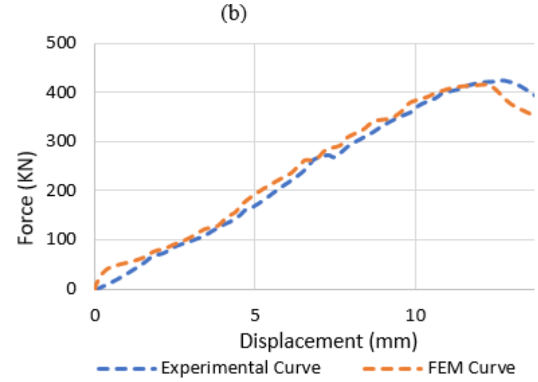
(b)



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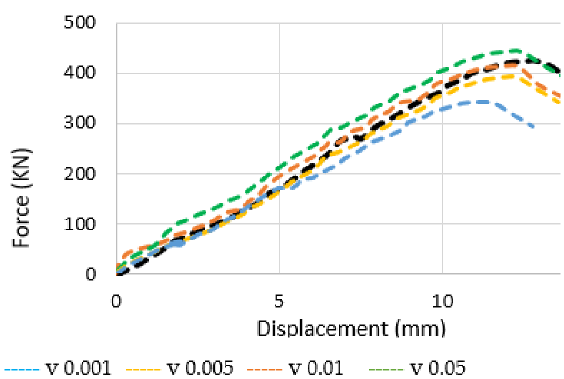

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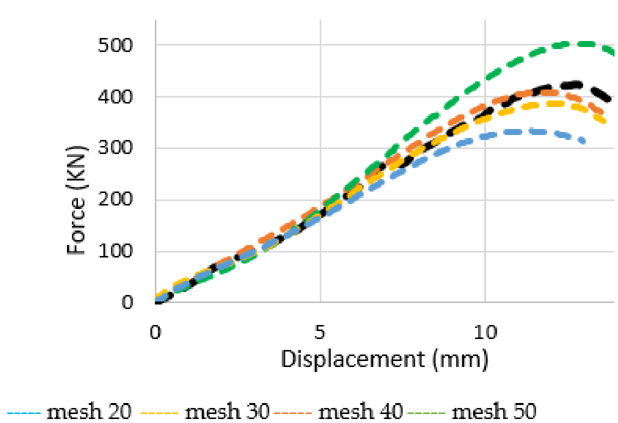

(c)

Figure 5. (a) Force deflection curve of FEM for various ψ values; (b) FEM's force deflection curve for various v (c) Force deflection curve of FEM for various Mesh sizes; (d) Comparison of experimental vs numerical results

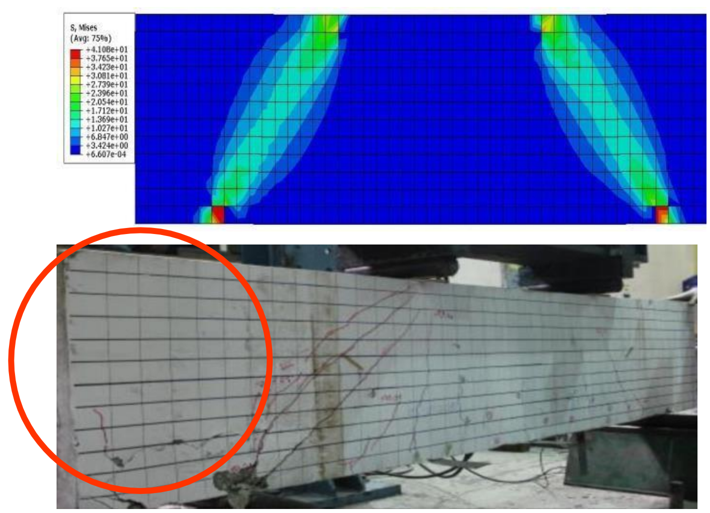

Figure 6. (a) FEM Damage contour. (b) Experimental crack pattern [28].

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3.2. Implementation of Metal Plates

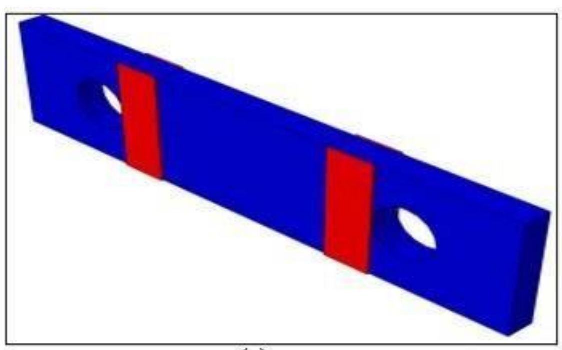
After validating the model with the experimental results, the metal plate is employed for strength-ening the RC deep beams with large openings, employing a 10 mm thickness in different orienta-tions. These orientations are divided into four distinct cases, each exploring different configurations for strengthening the RC deep beams with large openings.

Case 1. The metal plate is applied between the two circular openings on both sides of the deep beam. The metal plate covers a height of 600 mm and a length of 200 mm as shown in Figure 7(a).

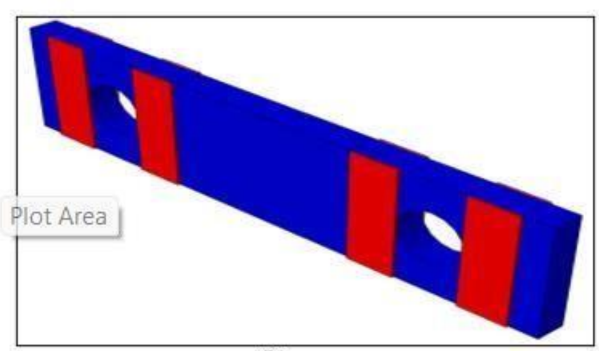
Case 2. Here the metal plate is applied on the left and right sides of both circular openings in the deep beam as shown in Figure 7(b).

Case 3. The metal plate is applied directly on the two circular openings of the deep beam, covering a length of 670 mm and a height of 600 mm while excluding the circular opening themselves as shown in Figure 7(c).

Case 4. The metal plate is applied both above and below the circular opening on both sides of the deep beam. This configuration covers a height of 165 mm and a length of 670 mm as shown in Figure 7(d).



(a)



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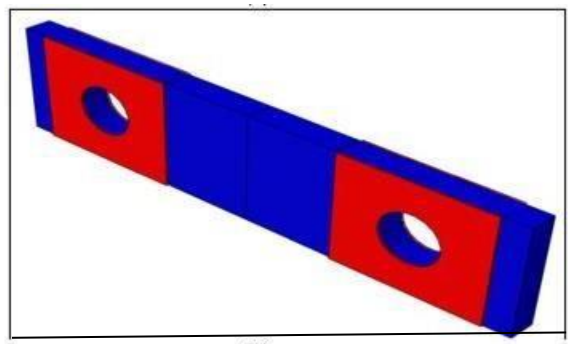

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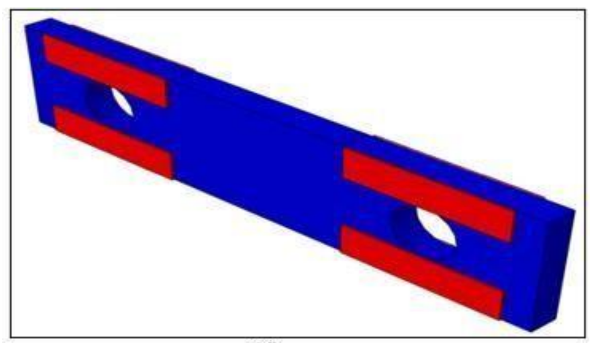

(d)

Figure 7. (a) Case 1 metal plates orientation; (b) Case 2 metal plates orientation (c) Case 3 metal plates orientation; (d) Case 4 metal plates orientation

3.3. Load-Deflection Curve

The deflection characteristics of the original model and the different cases can be observed in the Figure 8 below. The original model deflects by approximately 12 mm under a load of 400 kN, while the model with holes and no steel plate deflects by 7 mm under a load of 200 kN as shown in Figure 8(b). In case 1, the deflection reduces to approximately 1 mm, while in case 2, it reduces to around 0.83 mm. Case 3 shows the lowest deflection of approximately 0.45 mm, and case 4 has a deflection of about 0.61 mm as shown in Figure 8(a). All of these deflections were measured under the same load of 500 kN. An analysis of the graph shows that case 3 has a significantly smaller deflection than the other cases. However, it is worth noting that case 3, despite its superior performance in terms of deflection, involves a higher cost due to the use of a larger metal plate. Therefore, case 1 is a more fa-vorable option due to its relatively lower cost, while still yielding satisfactory results compared to the original model. Case 1 can be used to strengthen the design of deep beams.

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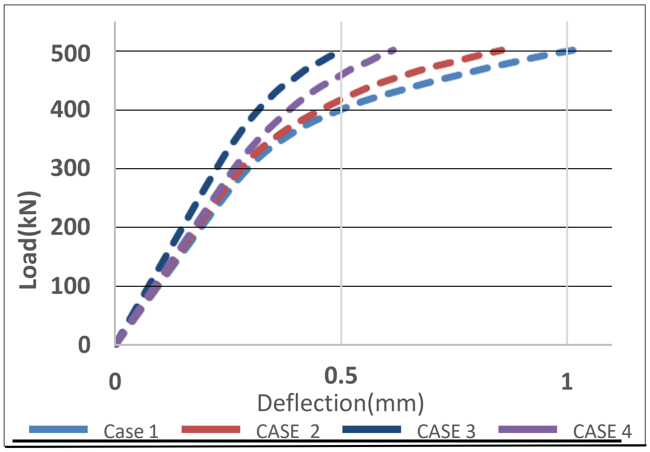

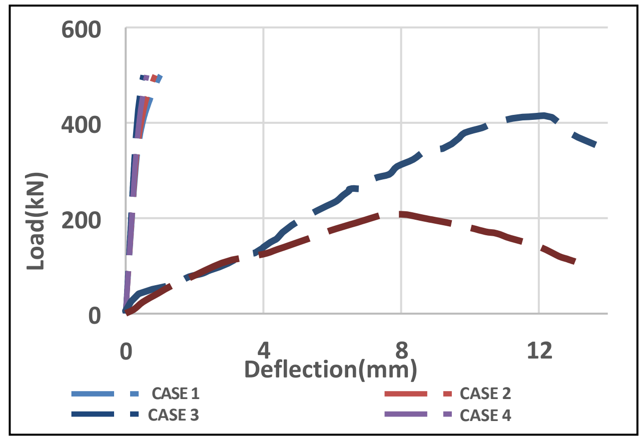

Figure 8. (a) comparison of load-Deflection curve of all 4 cases; (b) comparison of load-Deflection curve of all 4 cases and the original beam with and without the circular holes

3.4 Parametric study:

After obtaining the numerical results for all cases and selecting case 4 as the final design option, a parametric analysis was performed to determine the most cost-effective deep beam design with metal plates.

1. Effect of concrete f'c on load carrying capacity and deflection of beam:

Different concrete grades were considered for the study and their CDP properties were obtained us-ing the equations discussed in Section 2.1. For all grades, it can be seen from Figure 9 that increasing the grade increases the capacity and decreases the deflection of the beam. However, the economical and most suitable design concrete grade is 25 MPa.

Table 5. Concrete properties for different f'c [30], [32]–[36].

f'c	Elastic Modu-lus (MPa)	Pois-son's ra-tio	Yield Strengt h (MPa)	Tensile Strengt h (MPa)
15	21590	0.2	4.5	1.21
20	23700	0.2	6.89	1.27
25	23953	0.2	7.5	2.3
30	23410	0.2	9	3
35	25244	0.2	10.5	3.4
40	27208	0.2	12	4

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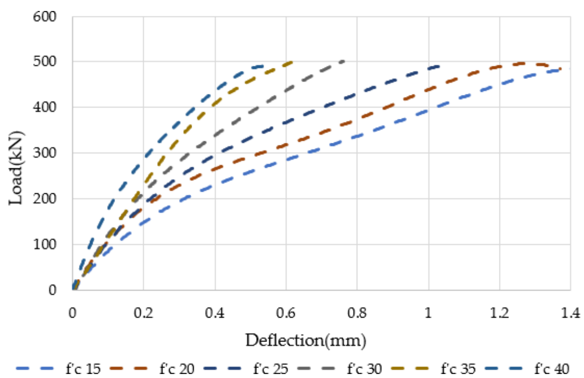

Figure 9. load vs deflection curve for different concrete grades

5. Conclusions

This study investigated the use of metal plates to strengthen RC deep beams with large openings. The numerical analysis using Abaqus software showed that metal plates can significantly increase the load-carrying capacity and stiffness of deep beams, providing enhanced resistance against shear and flexural failure. The results also showed that the specific metal plate orientation is important for op-timizing structural performance. The study found that case 3 had the smallest deflection among the investigated cases, but it was also the most expensive. Case 1, 2, and 4 were more cost-effective alter-natives that still achieved significant reductions in deflection. Of all the cases, case 4 is the most eco-nomical and least deflective design option for deep beams with openings.

Based on the findings, the study identified several directions for future research and development:

Dynamic load behavior: Investigating the performance of strengthened deep beams under dynamic loads (e.g., earthquakes, impact events).

Different plate configurations: Exploring the effects of varying plate thickness, arrangements, and connections on structural behavior.

Robustness against extreme loads: Assessing the strength of strengthened deep beams under ex-treme loading conditions (e.g., blast loads, progressive collapse).

Conflicts of Interest: The authors declare no conflict of interest.

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