

# NUMERICAL ANALYSIS FOR SHEAR STRENGTH OF COMPOSITE BOX STEEL-CONCRETE BEAM TRANSVERSE INTERMEDIATE TO LARGE OPENINGS

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## Abstract

This research paper presents a numerical analysis of composite box steel-concrete beams with transverse intermediate to large openings, conducted using the ABAQUS program. The study focused on various parameters, including opening size, shape, location, shear span to effective depth ratio, compressive strength, and diameter of rebars, to understand their effects on the shear load capacity of the beams. The results demonstrated a strong agreement with experimental data, with a correlation ranging from 0.927 to 1.023. Key findings include increasing the opening size from 90x90 mm to 110x110 mm and from 110x110 to 136x136 led to a 12.7% and 42.4% respectively decrease in shear load. Changing the shape of openings from square to circular decreased the shear load by 14.7% for 90 mm openings and 14.2% for 110 mm openings, while increased the shear load by 15.25% for 136 mm. Moving transverse openings closer to the loads by 126 mm reduced the shear load by 7.5% for 90x90 mm openings, 9.8% for 110x110 mm openings and 17.2% for 136x136 mm openings. The difference in shear load between the highest and lowest (a/d) ratios is 12.5% for 90x90 mm openings, 7.2% for 110x110 mm openings, and 0.8% for 136x136 mm openings. Beams with a compressive strength of 37.5 MPa showed higher shear loads compared to those with 30 MPa, with increases of slight change, and the shear load increased of slight change for beams with reinforcement (2Ø25-2Ø16) compared to those with (3Ø16) for 90x90 mm openings, 110x110 mm and 136x136 mm openings.

## Keywords:

Composite Beams;  
Steel-Concrete Beams;  
Transverse Openings;  
Shear Strength;  
Numerical Analysis;  
ABAQUS;  
Intermediate to Large  
Openings.

## 1 Introduction

In recent years, there has been a growing demand for buildings with high ceilings. However, installing ducts and openings for electro-mechanical systems within the clear heights underneath reinforced concrete beams is necessary. Most building systems use ceiling under beams to cover these ducts and pipes; this covering takes from floor height and creates dead space on each floor. The height of this space can add to the overall building height by passing pipes and ducts through the beams. Providing web openings in beams is considered the most practical solution in that case. Thus, several investigators exerted great efforts to study the behaviour of such beams and introduce reliable techniques for analysing and designing such beams[1]. Openings with square, circular, or nearly square shapes may be classified as tiny openings if the depth (or diameter) of the aperture is proportionate to the size of the beam, specifically less than 40% of the entire beam depth[2]. If such a situation occurs, beam activity will likely dominate. Hence, the analysis and design of a beam with tiny openings may be approached similarly to that of a solid beam. However, openings create interruptions or disruptions in the regular distribution of forces, resulting in the accumulation of stress and the formation of cracks in the vicinity of the opening. To avoid potential early failure of the beam, it is necessary to provide an adequate amount of specific reinforcement around the opening's perimeter to regulate crack widths, as with any discontinuity[3].

The position and size of any openings present often influence the deformation and strength of a beam. By carefully selecting the location, it is possible to create relatively big gaps in reinforced concrete beam constructions without compromising their final load-bearing capacity[4]. Nevertheless,

even little openings situated in an undesirable location might result in a significant reduction in the intensity of the beam. Therefore, it is essential to meticulously strategize the dimensions and positioning of the openings[5]. Nevertheless, the presence of the openings leads to interruptions or disruptions in the regular passage of stress, leading to a buildup of stress and the occurrence of cracks around the opening at an early stage. Hence, it is necessary to ensure sufficient reinforcement is placed in the opening area to effectively manage the breadth of cracks and prevent any potential early beam failure[6]. Vertical openings in reinforced concrete beams are utilized as an alternative to tiny openings in slabs, particularly in modest structures in both height and size (low-rise buildings). Frequently, the effect of tiny gaps on the structural behaviour of reinforced concrete slabs is disregarded since the structure can redistribute stresses [7].

Nevertheless, installing it will occupy valuable space and make the services more noticeable, which might not be aesthetically convenient. To address this, a suspended ceiling or specific decorating may be required to make it visually acceptable. However, to conceal most pipes and ducts, they are often routed via vertical openings in beams and remain concealed behind the partitions until they reach the designated position. This is why vertical openings in reinforced concrete (RC) beams have been widely utilized[8]. Like a beam with tiny openings, big openings may be described as openings that need more horizontal and vertical supports in the upper and lower sections of the beam[9]. The validity of Bernoulli's concept about the distribution of plane strain over the whole cross-section of a big aperture, is questionable. An opening is considered large when its depth ( $d$ ) or diameter ( $D$ ) exceeds 0.25 times the depth of the beam ( $h$ ) and its length ( $\ell$ ) is greater than its depth ( $d$ ). The presence of such openings decreases the strength of the beam, resulting in beam behaviour, as depicted in Figure 1, as described by Some and Corley[10].

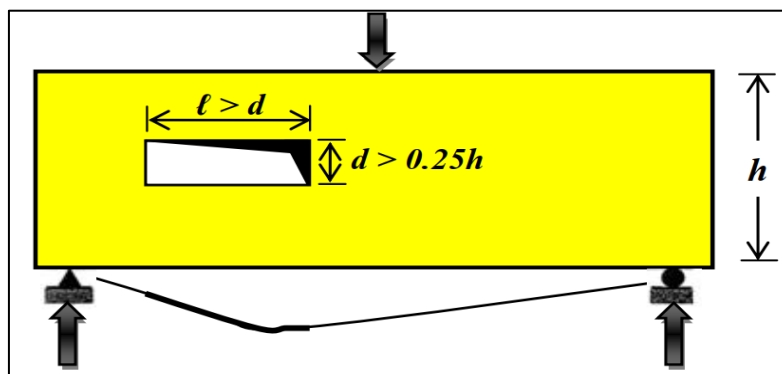


Fig. 1: large openings description based on structural reaction.

## 2 Literature Review

In recent years, there has been a considerable emphasis on steel-concrete composite structures due to their intricate properties and extensive application in engineering projects. Numerous scholars have acknowledged the importance of combining experimental and numerical studies in advanced construction engineering design. Numerical simulation tools, especially the finite element method, play a vital role in analysing the mechanical properties of concrete and steel composite structures. However, traditional composite beams are typically connected using steel shear studs, which can sometimes lead to stress concentration and cracking in the composite beam, thereby shortening its lifespan.

K. S. Hussein and N. H. Tu'ma in 2024[11] conducted experimental research in the structural members may have openings for utilizing passes and the necessary efforts should be taken to keep them structurally safe. The work focused on the behaviour of composite encased steel-concrete beams of longitudinal and transverse openings and investigated strengthening techniques for small and large transverse square openings. The experimental part includes poured nine (200×300×2100) mm specimens with transverse square openings in the shear span zone. Three beams attend as control beams, as well as one specimen without openings. The other two specimens had two openings located symmetrically at each shear span, At the opening zone with several methods six beams were strengthened by composite method and NSM CFRP bar. In NSM CFRP bars, Around the square openings two different configurations were installed (strengthening the specimens with a diamond strengthening scheme bar and diagonal strengthening scheme bars). Results have been

discussed in terms; first cracking load, ultimate load, maximum of deflection, modes of failure, crack of patterns, toughness value, ductility index, and crack with recognizing the best strengthening proposal opening. Test results indicate that the technique of strengthening large opening with CFRP bars diagonal strengthening scheme recorded an increase in the ductility, and toughness by about 59%, and 16%; respectively compared to the control beam with a large opening. Concerning the specimens strengthened by the composite method, the load capacity is almost equal to the control beam load capacity.

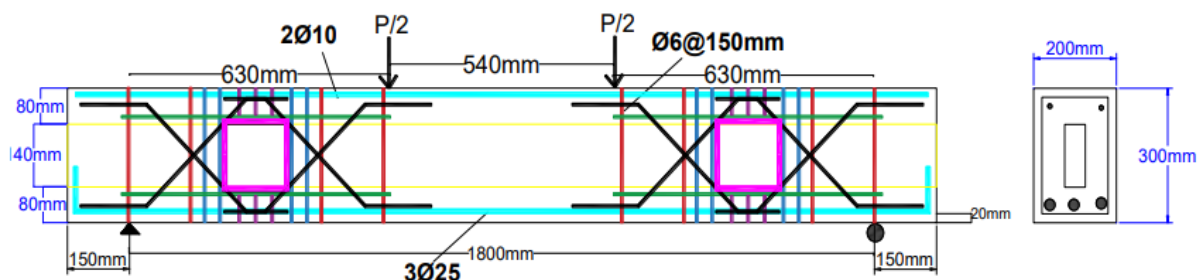


Fig. 2: Details of tested beams with web openings.

Yamada performed FE in 2019[12] studies and experiments on reinforced concrete (RC) beams having several openings in the shear spans. The study tested the effect of longitudinal reinforcement proportions on the beams' failure. The investigations focused on analysing several factors, such as the position of debonding fractures at the tension-reinforcing level, crack widths, and the opening location. The beams tested and studied had no shear reinforcement, and the openings were present throughout pouring the concrete. This research highlighted that the existence of openings has little effect on the strength of the beam. This is because the openings enhance the control of the arch mechanism in the beam rather than the beam mechanism.

Mastan et al. in 2023[13] adjust the design and location of the aperture to improve its structural performance. The composite steel-concrete beam was studied using ABAQUS v6.14, considering three shapes: triangle, rectangle, and circle. The optimal geometry is positioned at several locations between the span's support end and midpoint. The numerical analysis determined that the circular shape positioned at one-third of the span was useful in reducing stress concentration and maximizing stress strength. The beams' load-carrying capacity was estimated utilizing an artificial neural network (ANN) model. The accuracy of the predictions was assessed utilizing multiple mean square error (MSE) and coefficients of determination (R2). The MSE and R2 values for all the models were more than 0.09 and 0.94, respectively. This suggests that artificial neural networks (ANN) are suitable for analysing numerical data.

Jen et al. in 2020[14] conducted experimental research on reinforced concrete beams that included circular transverse openings. A four-point load test was performed to examine the effect of the opening's size and location on the beam's performance when subjected to shear and flexural stresses. Furthermore, three supplementary techniques for the introduction were tested. The beams were assessed based on their load-displacement responses, mechanical characteristics, deflections, and failure mechanisms. The presence of an aperture with a diameter that does not exceed 0.25 times the height of the beam reduces the beam strength by about 20% when no reinforcements are used at the entrance. The diagonal bar reinforcement technique successfully enhanced the beam's structural integrity when the opening size did not exceed one-third of the beam's height. The formula model suggested accurately predicting the maximum load-bearing capacity of the beam with a transverse aperture using a cautious approach.

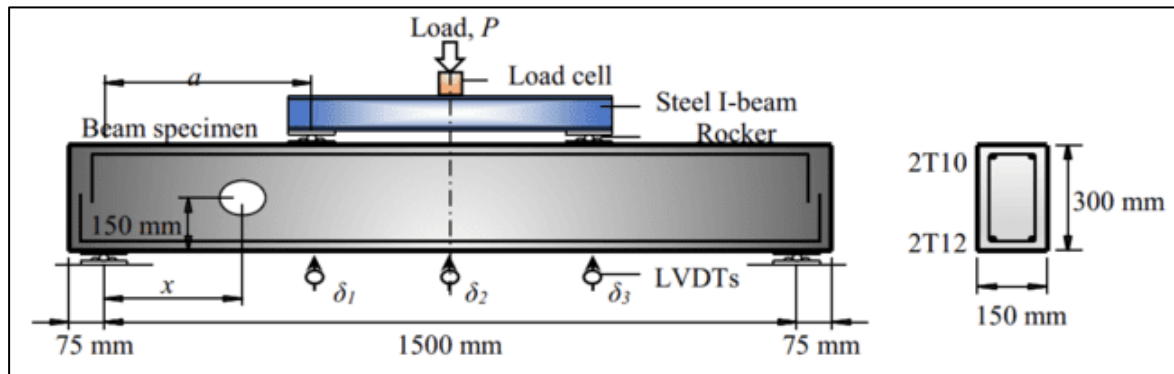


Fig. 4: Beam details and testing sketch.

Additionally, Jabbar et al. 2021[15] tested the behaviour of four reinforced concrete beams having a square cross-sectional area. These beams were subjected to three-point loads until they failed. Three beams were specifically constructed with tiny web openings of varying forms: circular, rectangular, and square. The goal of including a beam without any openings (the control beam) was to facilitate a comparison of the results. The load-deflection curves were satisfactorily produced for the samples that were tested. The findings showed that introducing tiny web gaps in reinforced concrete beams resulted in a marginal decrease in their maximum loads, corresponding to an increase in the maximum deflection. Furthermore, it was determined that the beams with circular web openings exhibited superior shear strength compared to the other chosen designs.

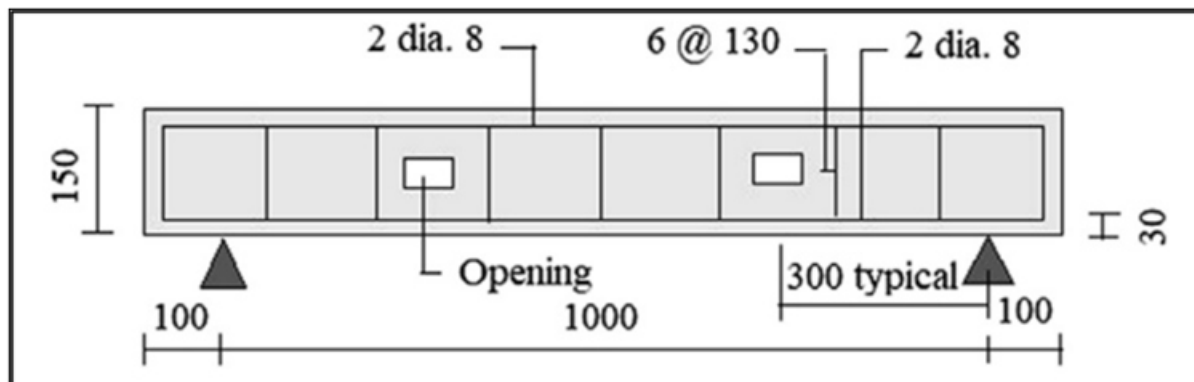


Fig. 4: Details of tested beams with web openings.

### 3 Research Significance

The purpose of this study is to provide numerical analyses about the behaviour of Composite Box Steel-Concrete beams with intermediate to large transverse openings (effect of locations, shape, and diameters) configurations to explain of the failure mechanism. Making openings reduces the materials used and makes them service facilities. In addition, study the effects of (a/d) ratio of the beams and compressive strength of concrete.

### 4 Description of Finite Element

#### 4.1 Geometry of Model

ABAQUS Finite Element (FE) software, was used to simulate Composite Box Steel-Concrete beams with transverse intermediate to large openings with width was 200 mm, depth was 300 mm, full length of 2100 mm, steel box 50\*140 mm welded by channel shear connectors 3 mm thickness to increase the bond between it and the concrete and the cover was 20 mm, The beam geometry, dimensions, and loading are shown in the Figure 5.

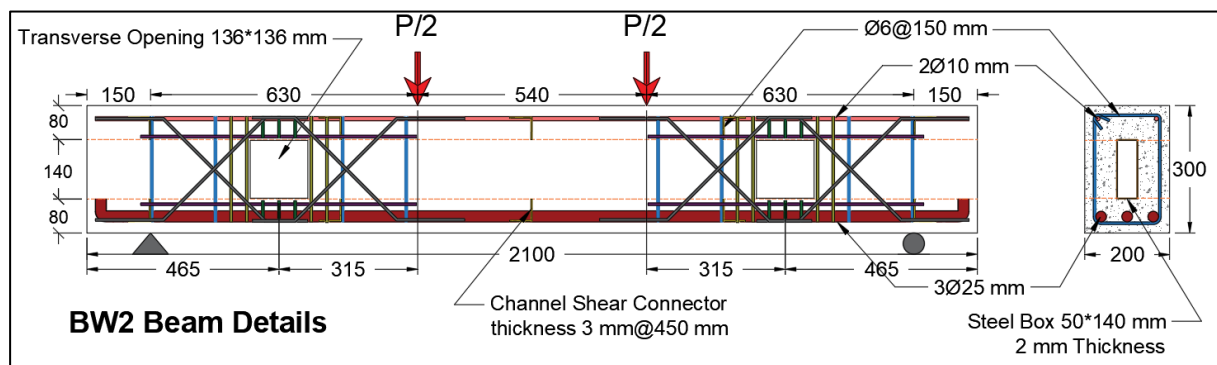


Fig. 5: Details of Modelled beams with openings.

## 4.2 Concrete Modelling

The Concrete Damage Plasticity (CDP) model in ABAQUS is widely used for simulating the behaviour of concrete structures under various load conditions. This model effectively captures concrete's non-linear response by incorporating both plasticity and damage mechanisms, accounting for irreversible deformations and crack formation. Stress-strain relationships are defined through constitutive equations, with material parameters obtained from various tests. The CDP model can predict crack initiation and propagation under different loading scenarios, making it an essential tool for analysing the stability of concrete structures such as buildings and bridges. ABAQUS offers resources to verify and ensure the accuracy of this model. In ABAQUS, the CDP model is implemented using parameters detailed in Table 1. The concrete beam was modelled using linear tetrahedral elements (C3D4), a three-dimensional 4-node mesh, as illustrated in Figure 6.

Table 1: Input Parameters of Concrete Damage Plasticity Model.

| Parameter                                                                                                | Value   |
|----------------------------------------------------------------------------------------------------------|---------|
| Compressive Strength [MPa]                                                                               | 23.5    |
| Concrete Tensile ft [MPa]                                                                                | 2.7     |
| Modulus of elasticity [GPa]                                                                              | 23.5    |
| Poisson Ratio [v]                                                                                        | 0.2     |
| The Ratio of Biaxial Compressive Strength to Uniaxial Compressive Strength [ $\sigma_{bo}/\sigma_{co}$ ] | 1.16    |
| The Shape of The Failure Surface [Kc]                                                                    | 2/3     |
| Dilation Angle [ $\psi$ ]                                                                                | 36°     |
| Eccentricity [e]                                                                                         | 0.1     |
| Viscosity Parameter [v]                                                                                  | 0.00375 |
| Modulus of elasticity [GPa]                                                                              | 23.5    |
| Poisson Ratio [v]                                                                                        | 2.7     |

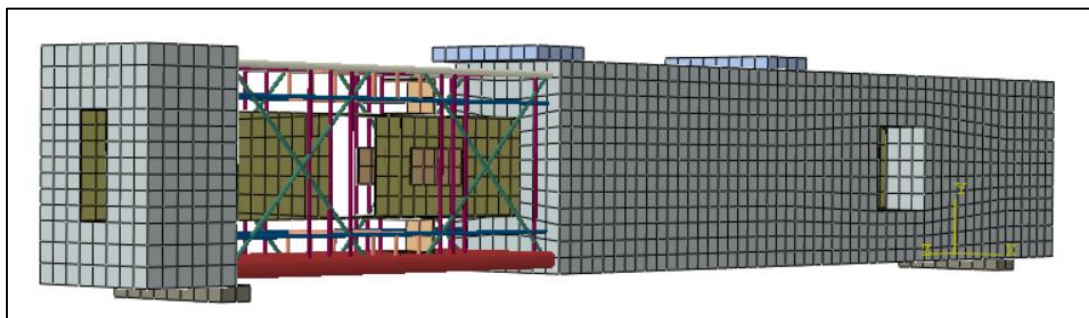


Fig. 6: Element Types of Composite Box Steel-Concrete beam Model.

### 4.3 Steel Modelling

The steel bars are modelled as bilinear, isotropic materials with a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. The material properties are defined using an elastic-perfectly plastic model, with parameters such as yield stress and ultimate strength detailed in Table 2. These

parameters are derived from the experimental study referenced as [11]. For the reinforcement modelling, truss mesh elements (T3D2) were employed.

Table 2: Properties of Steel Bars.

| Bar size (mm) | Yield Strength (MPa) | Ultimate Strength (MPa) |
|---------------|----------------------|-------------------------|
| 6             | 378.57               | 424.5                   |
| 10            | 416.34               | 618.567                 |
| 25            | 585.89               | 693.36                  |

#### 4.4 Design for Flexural and Shear Strengths

To guarantee shear failure, the overall shear strength must be lower than the beam's flexural strength. The flexural capacity of each beam was determined using a derived equation, which identifies the point at which significant reinforcement begins to yield and calculates the compressive force. This compressive force is divided into two components: a rectangular uniform compressive pressure of  $0.65 \times f_c'$ , and a triangular compressive pressure of the same magnitude. The tensile force is comprised of two parts: the force from the reinforcing bars and the uniform pressure in the tensile zone, extending from the neutral axis to the extreme tensile fibres, with an intensity of  $0.4 \times \sqrt{f_c'}$ .

The design process followed the model of the method used by Naser[16], Shear reinforcement was calculated using either conventional or normal concrete techniques. Flexural strength was predicted using the mid-cross section of the beams, and the shear design for concrete and fibre components adhered to the guidelines set by the Japan Society of Civil Engineers JSCE[17].

#### 4.5 Boundary Conditions

Boundary conditions in ABAQUS are crucial specifications that determine how a finite element model interacts with its external environment. They include directives like forces, displacements, velocities, temperatures, or other physical quantities applied to the model's boundaries or surfaces. Engineers use these conditions to simulate real-world loading scenarios, such as structural loads or environmental effects, to accurately represent the system being analyzed. These boundary conditions are essential in predicting the model's behavior and obtaining valuable insights into structural, thermal, or fluid dynamics within ABAQUS simulations, the boundary condition of the composite beam is simply supported, two-point loading were investigated in this study. The load was displacement controlled.

#### 4.6 Constraint and Interaction Conditions

When using ABAQUS, constraints and interactions play essential roles in controlling the behavior and connections in finite element models. Constraints limit the movement of nodes or elements, either by fixing specific areas or by linking components together. These constraints are vital for accurately depicting real-world limitations, like fixed supports or connected interfaces, which help maintain the stability and integrity of the analysis. On the other hand, interaction conditions simulate how different sections of the structure interact with each other or with the environment. In this study used different types of constraint such as: tie constraint between the upper surfaces of supports and lower surface of composite beam and use this type of constraint between the lower surfaces of load plates and upper surface of composite beam, also used the embedded region constraint between steel rebars and concrete beam.

Contact interactions in ABAQUS allow engineers to mimic friction, separation, or adherence between surfaces, as well as enforce tie constraints to ensure displacements between connected regions are compatible. By specifying constraint and interaction conditions, engineers can accurately model complex behaviors and phenomena, facilitating realistic simulations of mechanical, thermal, or multi-physics systems, in this study use surface to surface contact interaction between steel box outside surface and beam inside surface.

### 5 Results and Discussion

#### 5.1 Experimental - Numerical Comparative Analysis

In this study, the structural behaviour of simply supported composite box steel-concrete beams was simulated based on the experimental tests detailed in reference [11]. The experimental work involved fifteen reinforced concrete beams, which were divided into five groups and tested under two-point loading. For validation purposes, eight of these composite beams were used.

The first group comprised beams CB and CW2, which featured small transverse openings. The second group included C1S2, where the variable was the extruded encasing around the openings. The third group, R1S2, tested the effect of adding diagonal bars on either side of the web opening. The fourth group, ECS2 and ECW2, investigated the strengthening effect of CFRP, utilizing a fully wrapped system and diagonal strengthening sheets around the square openings. The fifth group, ECR2 and ECR4, looked at the strengthening effect of NSM CFRP bars arranged in two different patterns around the square openings, including rhombus shapes and diagonal bars. As illustrated in Table 3.

Table 3: Details of Experimental Beams Compared.

| Group No.       | Beam name | Transverse opening | Strengthening type             |
|-----------------|-----------|--------------------|--------------------------------|
| 1 <sup>st</sup> | CB        | ---                | ---                            |
|                 | CW2       | (136×136) mm       | ---                            |
| 2 <sup>nd</sup> | C1S2      | (136×136) mm       | extruded encasing transversely |
| 3 <sup>rd</sup> | R1S2      | (136×136) mm       | Reinforcement arrangement      |
| 4 <sup>th</sup> | ECS2      | (136×136) mm       | CFRP fully wrapping sheets     |
|                 | ECW2      | (136×136) mm       | CFRP diagonal sheets           |
| 5 <sup>th</sup> | ECR2      | (136×136) mm       | CFRP diagonal bars             |
|                 | ECR4      | (136×136) mm       | CFRP bars rhombus shape        |

For verification, the study analyzed shear load-deflection curves, crack patterns, and strain distribution. As shown in Table 4, the predicted rates varied between 0.927 and 1.023. Figure 8 illustrates the comparison of experimental and numerical shear strength-deflection responses for the developed beams. The numerical model successfully predicted beam responses with high accuracy, aligning closely with experimental results, and all specimens exhibited similar flexural stiffness behavior. The failure mode of beam CW2 is depicted in Figure 7.

Table 4: Comparison Between the Numerical and Experimental Results.

| Group No. | Beam ID | Shear Strength (MPa) |        |         |
|-----------|---------|----------------------|--------|---------|
|           |         | EXP                  | FEA    | EXP/FEA |
| 1st       | CB      | 295.4                | 295.75 | 0.998   |
|           | CW2     | 153.9                | 159.13 | 0.967   |
| 2nd       | C1S2    | 127                  | 136.92 | 0.927   |
| 3rd       | R1S2    | 143.4                | 149.96 | 0.956   |
| 4th       | ECS2    | 176                  | 171.96 | 1.023   |
|           | ECW2    | 154.1                | 153.23 | 1.005   |
| 5th       | ECR2    | 155.7                | 164.60 | 0.945   |
|           | ECR4    | 135.2                | 140.99 | 0.958   |

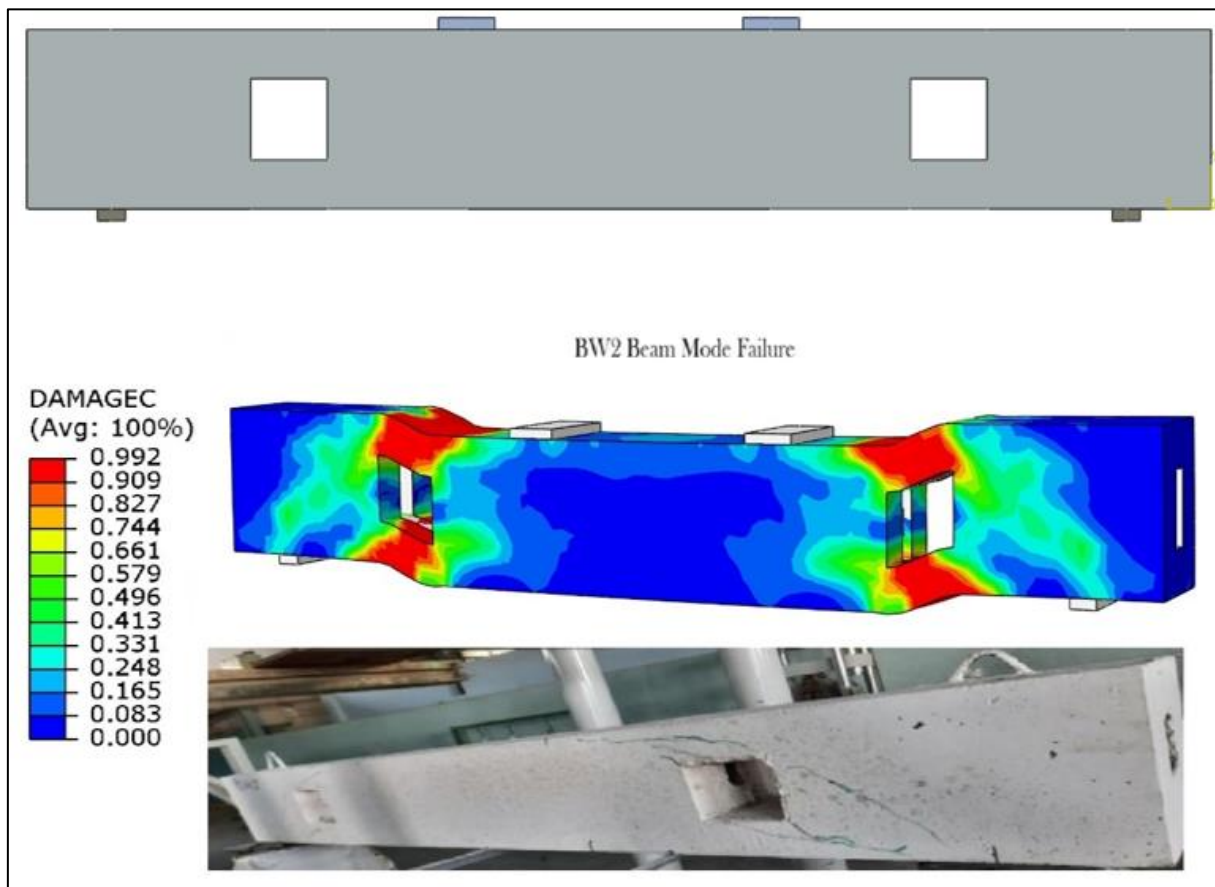
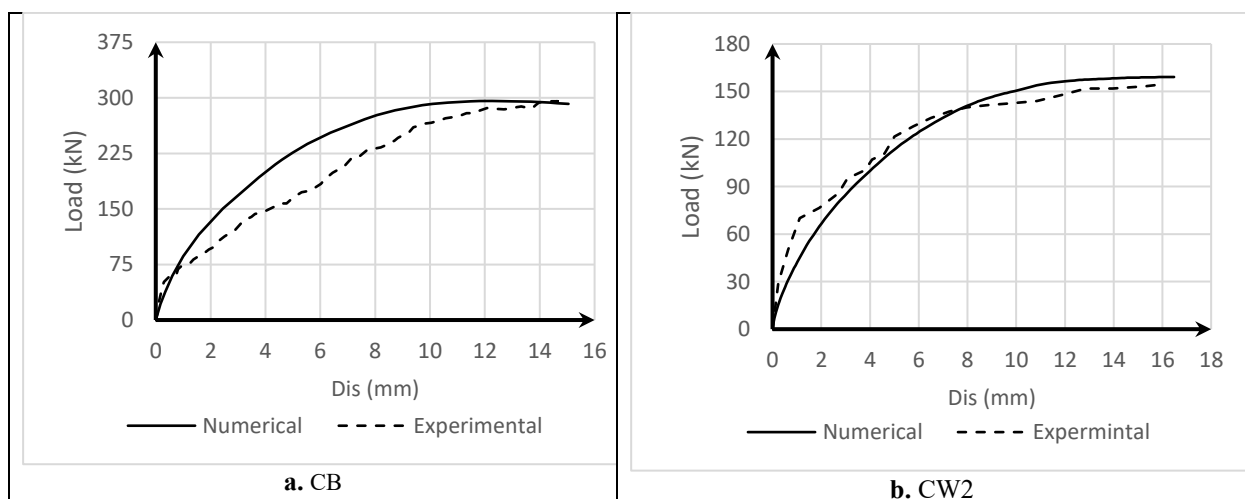


Fig. 7: Failure Mode and Strain Distribution for Experimental-Numerical of CW2.



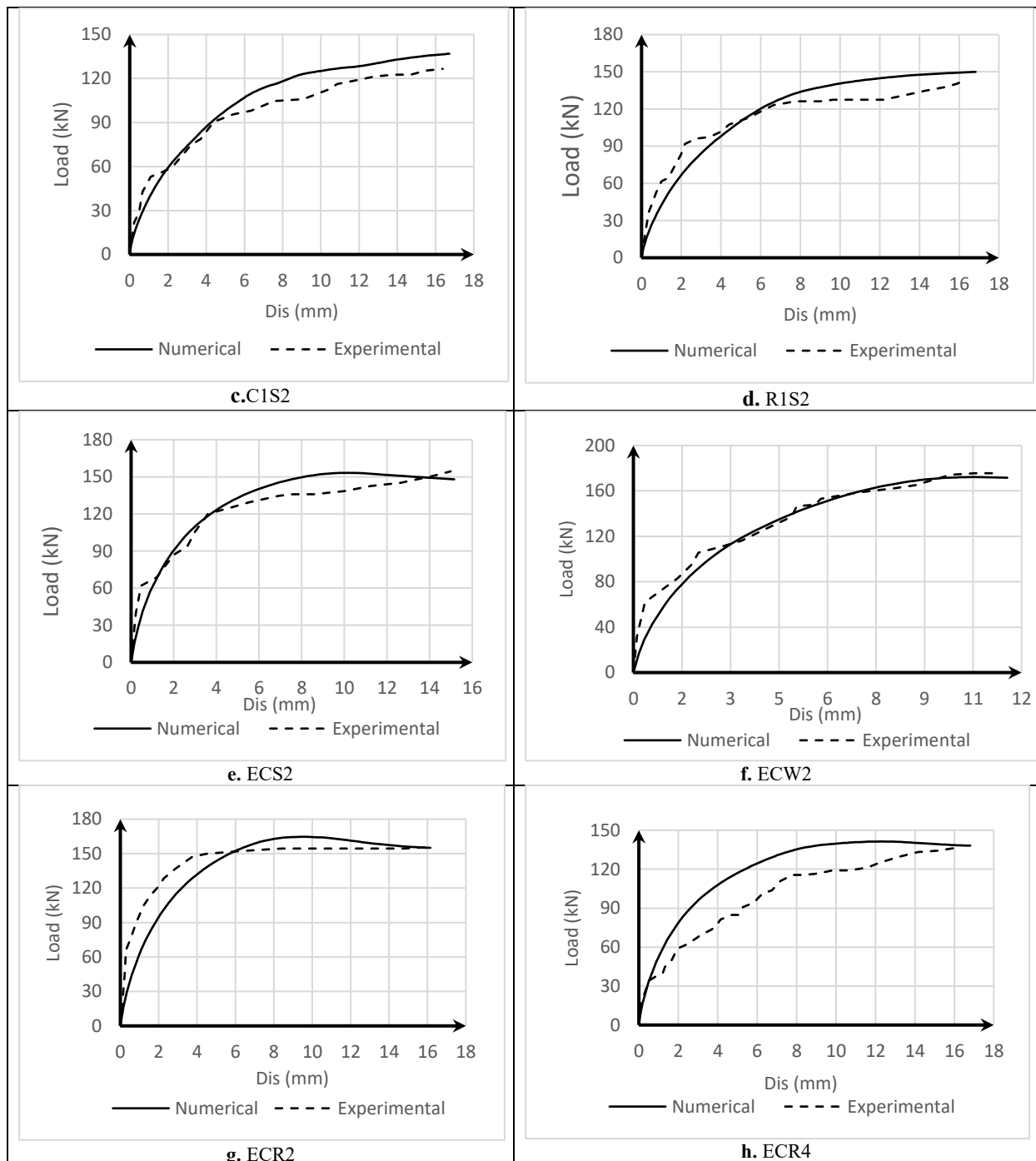


Fig. 8: Comparison of the Experimental-Numerical Load-Displacement

## 5.2 Parametric Study

In this study, thirty parameters were investigated, focusing on various variables modelled and tested to failure under two-point loading conditions. The composite box steel-concrete beams had fixed dimensions, with a depth of 300 mm and a width of 200 mm. The primary variables considered included the ( $a/d$ ) ratio, the size and location of transverse openings by moving the openings to the left and right from the centre of shear span by ( $a/5$ ) equal to 126 mm, concrete compressive strength, and the diameter of the tensile rebars. Based on these variables, the twenty composite beams were categorized into six groups. All beams, except those in the last group, were equipped with three tensile rebars of ( $3\phi 25$ ). The final group featured configurations of ( $3\phi 16$ ) and ( $2\phi 25-2\phi 16$ ). Details of the specimens are provided in Table 5.

Table 5: Details of The Specimens of Composite Box Steel-Concrete Beams.

| Group Number | Beam ID | Opening Size (mm) | Opening Shape | Location Opening      | (a/d) | Compressive Strength of Concrete (MPa) | Dia. Of bars (mm) |
|--------------|---------|-------------------|---------------|-----------------------|-------|----------------------------------------|-------------------|
| Group 1      | BOS2    | 90*90             | Square        | Centre the shear span | 2.4   | 23.5                                   | 3Ø25              |
|              | BOS3    | 110*110           |               |                       |       |                                        |                   |
|              | BW2     | 136*136           |               |                       |       |                                        |                   |
| Group 2      | BOD3    | Ø90               | Circular      | Centre the shear span | 2.4   | 23.5                                   | 3Ø25              |
|              | BOD4    | Ø110              |               |                       |       |                                        |                   |
|              | BOD5    | Ø136              |               |                       |       |                                        |                   |
| Group 3      | BOL3    | 90*90             | Square        | Left the shear span   | 2.4   | 23.5                                   | 3Ø25              |
|              | BOL4    | 110*110           |               |                       |       |                                        |                   |
|              | BOL5    | 136*136           |               |                       |       |                                        |                   |
|              | BOL8    | 90*90             |               | Right the shear span  |       |                                        |                   |
|              | BOL9    | 110*110           |               |                       |       |                                        |                   |
|              | BOL10   | 136*136           |               |                       |       |                                        |                   |
| Group 4      | BAD3    | 90*90             | Square        | Centre the shear span | 2     | 23.5                                   | 3Ø25              |
|              | BAD4    | 110*110           |               |                       |       |                                        |                   |
|              | BAD5    | 136*136           |               |                       |       |                                        |                   |
|              | BAD8    | 90*90             |               |                       | 2.8   |                                        |                   |
|              | BAD9    | 110*110           |               |                       |       |                                        |                   |
|              | BAD10   | 136*136           |               |                       |       |                                        |                   |
| Group 5      | BFC3    | 90*90             | Square        | Centre the shear span | 2.4   | 30                                     | 3Ø25              |
|              | BFC4    | 110*110           |               |                       |       |                                        |                   |
|              | BFC5    | 136*136           |               |                       |       |                                        |                   |
|              | BFC8    | 90*90             |               |                       |       | 37.5                                   |                   |
|              | BFC9    | 110*110           |               |                       |       |                                        |                   |
|              | BFC10   | 136*136           |               |                       |       |                                        |                   |
| Group 6      | BDB3    | 90*90             | Square        | Centre the shear span | 2.4   | 23.5                                   | 3Ø16              |
|              | BDB4    | 110*110           |               |                       |       |                                        |                   |
|              | BDB5    | 136*136           |               |                       |       |                                        |                   |
|              | BDB8    | 90*90             |               |                       |       |                                        |                   |
|              | BDB9    | 110*110           |               |                       |       |                                        |                   |
|              | BDB10   | 136*136           |               |                       |       |                                        | 2Ø25&2Ø16         |

### 5.3 Geometry of Openings

#### 5.3.1 Openings Dimension and Shape

This study aimed to investigate the shear strength of composite box steel-concrete beams featuring intermediate to large transverse square openings. The modelling simulations were used to determine the shear strength of beams with transverse openings measuring 90×90 mm, 110×110 mm, and 136×136 mm. The dimensions, shape, and location of the opening's centre between the loads and supports were varied, while the composite beam's cross-sectional area and reinforcement ratio remained constant. All beams utilized concrete with a compressive strength of 23.5 MPa. The results, presented in Table 6, indicated that increasing the size of the opening led to a decrease in the ultimate shear strength. Specifically, beams with various configurations of 90 mm square openings exhibited lower ultimate shear strengths compared to other transverse opening's beams. The ultimate shear strength improved as the size of the opening decreased. Beams with two square openings of 90 mm or 110 mm dimensions achieved better optimization than those with circular openings. However, beams with a 136 mm diameter circular opening demonstrated greater shear load capacity than those with 136 mm two square openings, as illustrated in Figures 6.a and 6.b and summarized in Table 9.

From the results, we find that the behaviour of the composite beam with a steel box inside it greatly affected the ultimate shear strength with the change in the opening shape, and this can be compared through the stresses in the failure mode as shown in Figure 10.

Table 6: Effect of Openings Dimensions, Location and Shape on Composite Beam

| Beam ID | Opening Size (mm) | Location Opening      | Opening Shape | Shear Strength (kN) | Ultimate Deflection (mm) |
|---------|-------------------|-----------------------|---------------|---------------------|--------------------------|
| BOS2    | 90*90             | Centre the shear span | Square        | 259.40              | 17.60                    |
| BOS3    | 110*110           |                       |               | 230.15              | 18.60                    |
| BW2     | 136*136           |                       |               | 161.60              | 17.50                    |
| BOD1    | Ø90               | Centre the shear span | Circular      | 226.10              | 15.65                    |
| BOD2    | Ø110              |                       |               | 201.60              | 14.80                    |
| BOD2    | Ø136              |                       |               | 186.25              | 16                       |

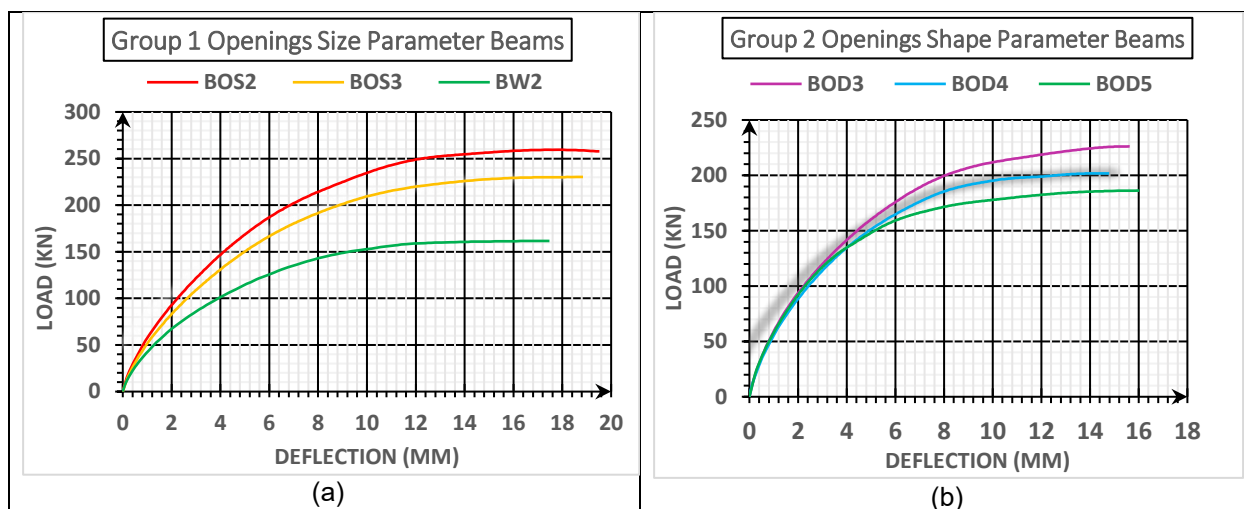


Fig. 9: (a) Load-Displacement for Square Transvers Openings in Composite Beam; (b) Load-Displacement for Circular Transvers Openings in Composite Beam.

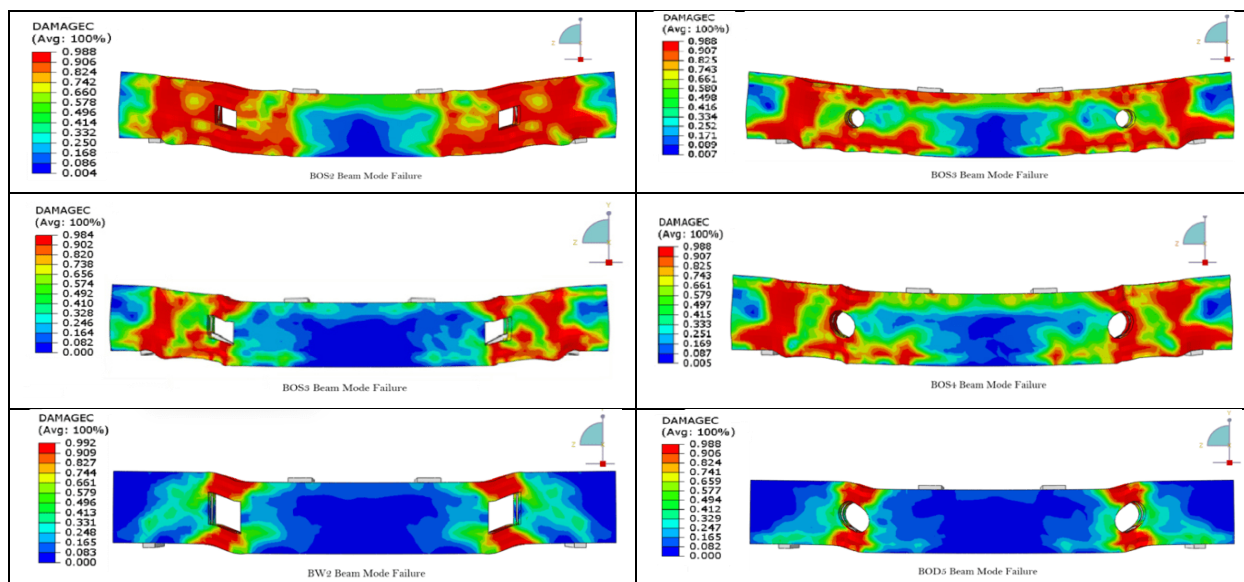


Fig. 10: Mode Failure for Square and Circular Transvers Openings in Composite Beams.

### 5.3.2 Openings Location

The presence of openings along and across the transverse axis of a beam significantly reduces both compression and tensile strengths, thereby diminishing flexural and shear strength. This study aims to identify the optimal position for openings to enhance shear force while also facilitating the

passage of service utilities and reducing the beam's self-weight. Six composite beams were tested: BOL3 with two 90×90 mm BOL4 with two 110×110 mm and BOL5 with two 136×136 mm square openings ( $a/5=126$  mm) near the loads, BOL8 with two 90×90 mm, and BOL9 with two 110×110 mm and BOL10 with two 136×136 mm square openings ( $a/5=126$  mm) near the supports as shown in the figure 12.

The dimensions of the openings in this study were 90 mm, 110 mm and 136 mm. Results and analyses of the opening dimensions and their locations are summarized in Table 6. The beam with two 90×90 mm openings near the supports (BOL8) demonstrated superior shear strength compared to other configurations, showing a 7.5% increase in shear strength relative to the beam with two 90×90 mm openings near the loads. This is illustrated in Figures 11.a and 7.b, which show shear strength versus deflection. Additionally, the beam with two 110×110 mm openings near the supports (BOL9) exhibited a 9.8% increase in shear strength compared to the beam with two 110×110 mm openings near the loads. And the beam with two 136×136 mm openings near the supports (BOL10) increase in shear strength compared to the beam with two 136×136 mm openings near the loads by 17.2%. This indicates that placing square openings near the supports results in higher shear strength compared to placing them near the loads, as detailed in Table 7.

Table 7: Effect of Openings Location on Composite Beam.

| Beam ID | Opening Size (mm) | Location Opening | Shear Strength (kN) | Ultimate Deflection (mm) |
|---------|-------------------|------------------|---------------------|--------------------------|
| BOL3    | 90*90             | Near Loads       | 221.05              | 18.7                     |
| BOL4    | 110*110           |                  | 197.80              | 17.65                    |
| BOL5    | 136*136           |                  | 135.35              | 16.25                    |
| BOL8    | 90*90             | Near Supports    | 237.55              | 16                       |
| BOL9    | 110*110           |                  | 217.15              | 18.8                     |
| BOL10   | 136*136           |                  | 158.65              | 17.7                     |

Scientifically speaking, these findings relate to shear force distributions within the beam since shear forces are greatest towards its supports. Such regions consequently expectance disruption in load path leading to higher stresses concentration thereby causing significant decreases in shear capacity. When placed near applied loads on the other hand where there are less shear forces more shear strength is retained by beam thereby enabling it to sustain even heavier ultimate shear loads compared to those having openings located elsewhere. This indicates the need for consideration of where transversal openings are incorporated when designing beams for instance under high amount of shearing stresses-based structures should pay careful attention on their placement too.

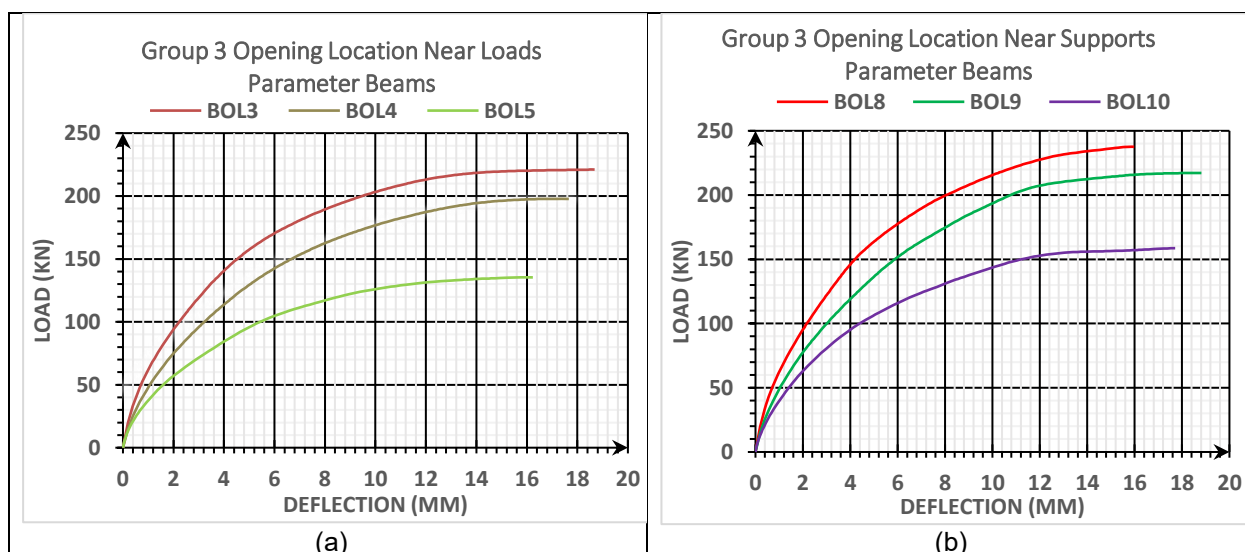


Fig. 11: (a) Load-Displacement for Square Transvers Openings Near Loads in Composite Beam; (b) Load-Displacement for Square Transvers Openings Near Supports in Composite Beam.

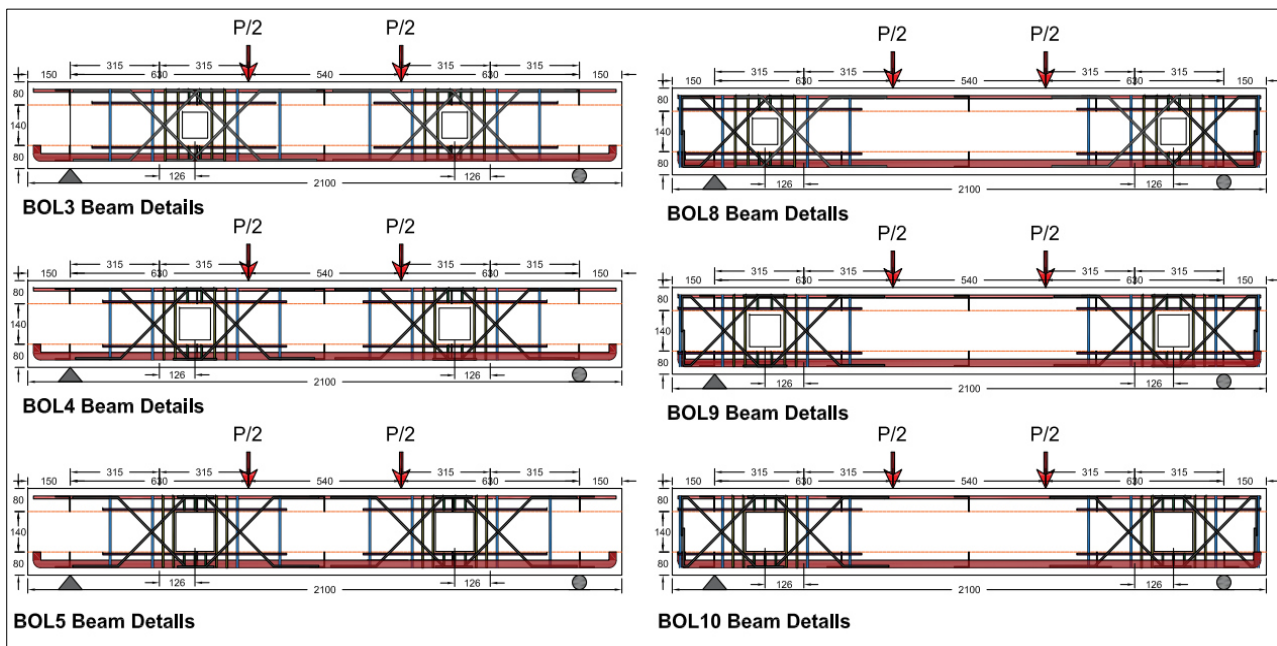


Fig. 12: Details of Locations for Square Transvers Openings in Composite Beams.

#### 5.4 Shear Span to Effective Depth (a/d) Ratio

Six shear span-to-depth ratios ( $a/d$ ) of 2 and 2.8 were considered to inspect section shear strength and understand various stress distribution modes. Specimens BAD3, BAD4, and BAD5 have an ( $a/d$ ) ratio of 2, while specimens BAD8, BAD9, and BAD10 have an ( $a/d$ ) ratio of 2.8, as shown in the figure 14. Table 5 provides the geometric descriptions of the adopted specimen sets, and Table 7 presents the related results analysis. The analysis in Table 8 indicates that varying the shear span alters the stress distribution modes, with ( $a/d$ ) ratios of 2 and 2.8, respectively. Figures 8.a and 8.b show the load-deflection response for specimens with different shear spans. Specimen BAD3, which is dominated by a shear failure mode, exhibits a ductile response. As the load approaches the support, the deflection decreases. Specimen BAD8 also shows an acceptable ductile response characteristic of the shear failure mode. However, as the ( $a/d$ ) ratio increases, the shear strength decreases. This decrease in shear strength may be due to the direct compression strut between the load and the support, as illustrated in Table 8.

Through an examination of how increased shear spans reduce stress on and cause failure in beams, we find the scientific rationale behind these outcomes. Furthermore, smaller openings increase stress concentration while being more influenced by alterations of ( $a/d$ ) ratio; in contrast, larger ones have already affected inbuilt beam structure hence there is no change when span-length is raised.

Table 8: Effect of shear span to effective depth ( $a/d$ ) ratio.

| Beam ID | Opening Size (mm) | ( $a/d$ ) Ratio | Shear Strength (kN) | Ultimate Deflection (mm) |
|---------|-------------------|-----------------|---------------------|--------------------------|
| BAD3    | 90*90             | 2               | 278.30              | 18.2                     |
| BAD4    | 110*110           |                 | 233.35              | 15.85                    |
| BAD5    | 136*136           |                 | 158.10              | 16.6                     |
| BAD8    | 90*90             | 2.8             | 247.30              | 18.35                    |
| BAD9    | 110*110           |                 | 217.55              | 18.6                     |
| BAD10   | 136*136           |                 | 156.80              | 16.25                    |

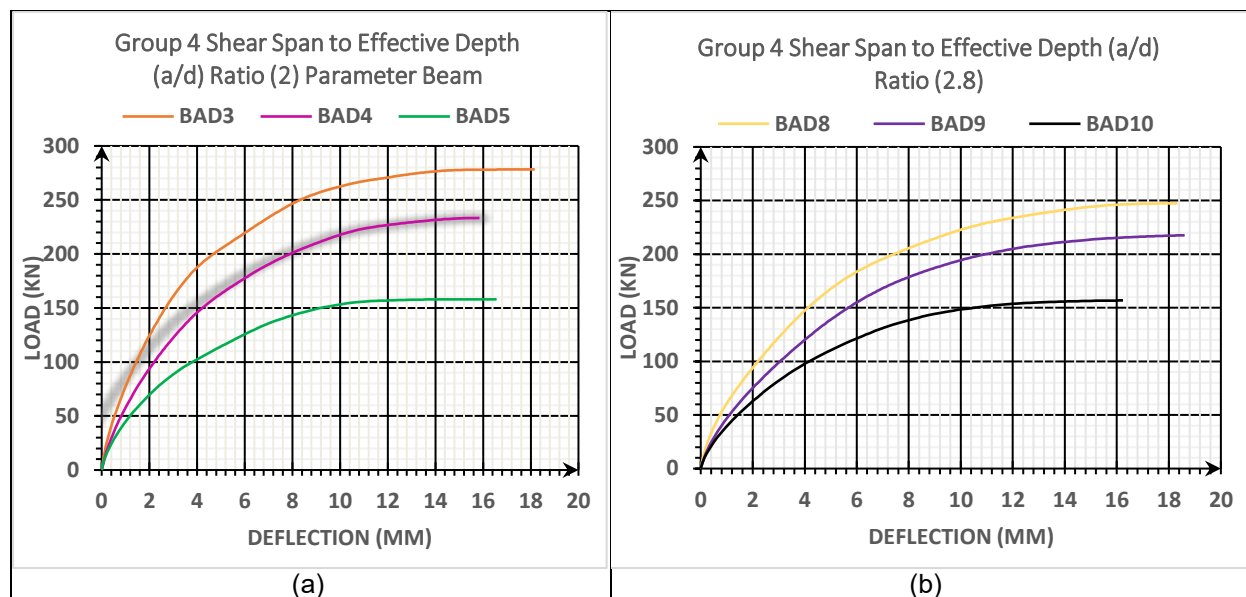


Fig. 13: (a) Load-Displacement for (a/d) Ratio (2) of Beams; (b) Load-Displacement for (a/d) Ratio (2.8) of Beams.

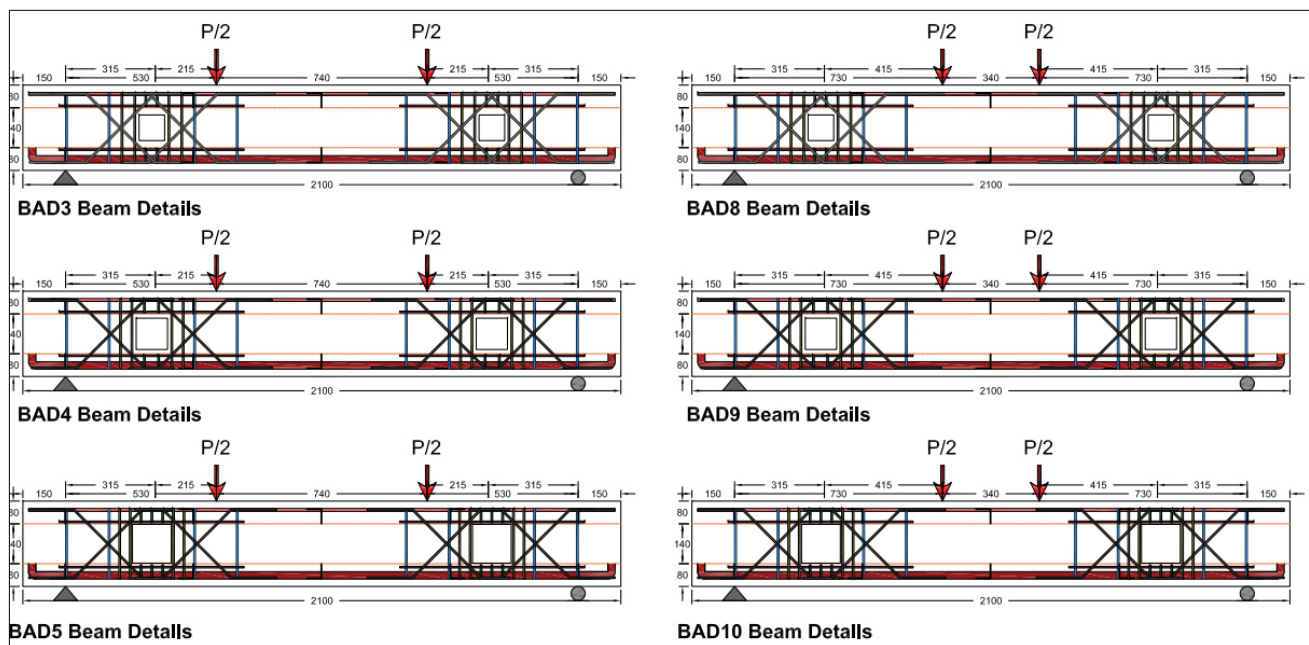


Fig. 14: Details of Shear Span to Effective Depth for Square Transvers Openings in Composite Beams.

### 5.5 Compressive Strength

Different compressive strengths of concrete were evaluated to understand their effect on the shear strength and ductility of developed composite beams. The dimensions, shapes, and locations of openings in the specimens are detailed in Table 5, while the corresponding results are presented in Table 9. Figures 15.a and 9.b illustrate the influence of various compressive strengths on the shear strength-deflection response. Beam BFC8, with a concrete compressive strength of 37.5 MPa and two 90x90 mm square openings, exhibited a 1.5% higher shear load compared to beam BFC3, which had a concrete compressive strength of 30 MPa and identical openings. Similarly, specimen BFC9, with two 110x110 mm square openings and a concrete compressive strength of 37.5 MPa, showed a 1.4% higher shear load than beam BFC4, which also had a concrete compressive strength of 30 MPa and the same opening dimensions. Additionally, specimen BFC10, with two 136x136 mm square openings and a concrete compressive strength of 37.5 MPa, exhibited a 3.9% higher shear load compared to

beam BFC5, which had a compressive strength of 30 MPa and the same opening dimensions. These results indicate that while an increase in concrete compressive strength does lead to an increase in shear load, the effect is relatively small, as shown in Table 9.

Table 9: Effect of Compressive Strength of concrete on Composite Beam.

| Beam ID | Opening Size (mm) | Compressive Strength (kN) | Shear Strength (kN) | Ultimate Deflection (mm) |
|---------|-------------------|---------------------------|---------------------|--------------------------|
| BFC3    | 90*90             | 30                        | 280.30              | 16.8                     |
| BFC4    | 110*110           |                           | 240.15              | 14.55                    |
| BFC5    | 136*136           |                           | 161.50              | 12.65                    |
| BFC8    | 90*90             | 37.5                      | 284.45              | 16.35                    |
| BFC9    | 110*110           |                           | 243.55              | 14.65                    |
| BFC10   | 136*136           |                           | 167.80              | 11.7                     |

These increases can be attributed to greater material strength provided by higher compression concrete that enhances the beam's ability to resist shear forces acting upon it. Specifically, improved shear resistance results from superior strength and lower crack widths from use of high compressive strength concrete enabling better load distribution and consequently improved structural performance. Also, it can be seen that taking into consideration all the variables that affect the ultimate shear strength, the shear strength of large openings is half the shear strength of large openings. Also, when changing the compressive strength of concrete from 23.5 MPa to 30 MPa, the shear strength is affected relatively little.

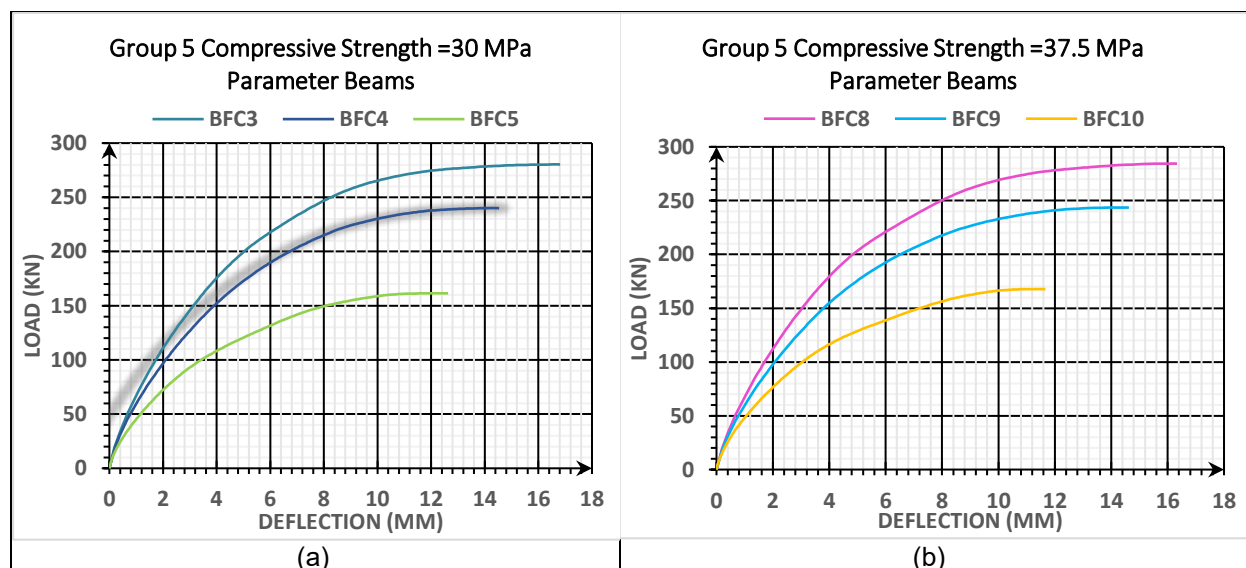


Fig. 15: (a) Load-Displacement for Compressive Strength (30); (b) Load-Displacement Compressive Strength (37.5).

## 5.6 Diameter of Bars

Shear strength encompasses several mechanical effects, including shear stress, dowel action, arch action, aggregate interlock, and residual tensile stress. This study focuses on the effect of bar diameter on dowel action behaviour. Table 9 presents the relevant results, while Table 4 details the dimensions, shapes, and locations of openings, along with shear span-to-effective depth ratios ( $a/d$ ) and the compressive strength of concrete for the adopted specimens.

Beam BDB8, featuring two 90×90 mm square openings and reinforcement bars (2Ø25-2Ø16), exhibited a 5.8% higher shear load compared to beam BDB3, which had the same opening dimensions but different reinforcement (3Ø16). Similarly, specimen BDB9, with two 110×110 mm square openings and reinforcement (2Ø25-2Ø16), showed a 6.5% higher shear load than beam BDB4, which had the same opening dimensions and reinforcement (3Ø16). Additionally, beam BDB10, with two 136×136 mm square openings and reinforcement (2Ø25-2Ø16), exhibited a 4.2% higher shear

load compared to beam BDB5, which had the same dimensions and reinforcement ( $3\phi 16$ ). These results are illustrated in Table 9 and Figures 16.a and 16.b.

Table 10: Effect of Bars Diameter on Composite Beam.

| Beam ID | Opening Size (mm) | (a/d) Ratio         | Shear Strength (kN) | Ultimate Deflection (mm) |
|---------|-------------------|---------------------|---------------------|--------------------------|
| BDB3    | 90*90             | $3\phi 16$          | 232.10              | 19.7                     |
| BDB4    | 110*110           |                     | 193.90              | 22.75                    |
| BDB5    | 136*136           |                     | 141.80              | 18.1                     |
| BDB8    | 90*90             | $2\phi 25-2\phi 16$ | 245.50              | 16.4                     |
| BDB9    | 110*110           |                     | 206.60              | 21.1                     |
| BDB10   | 136*136           |                     | 147.75              | 17.75                    |

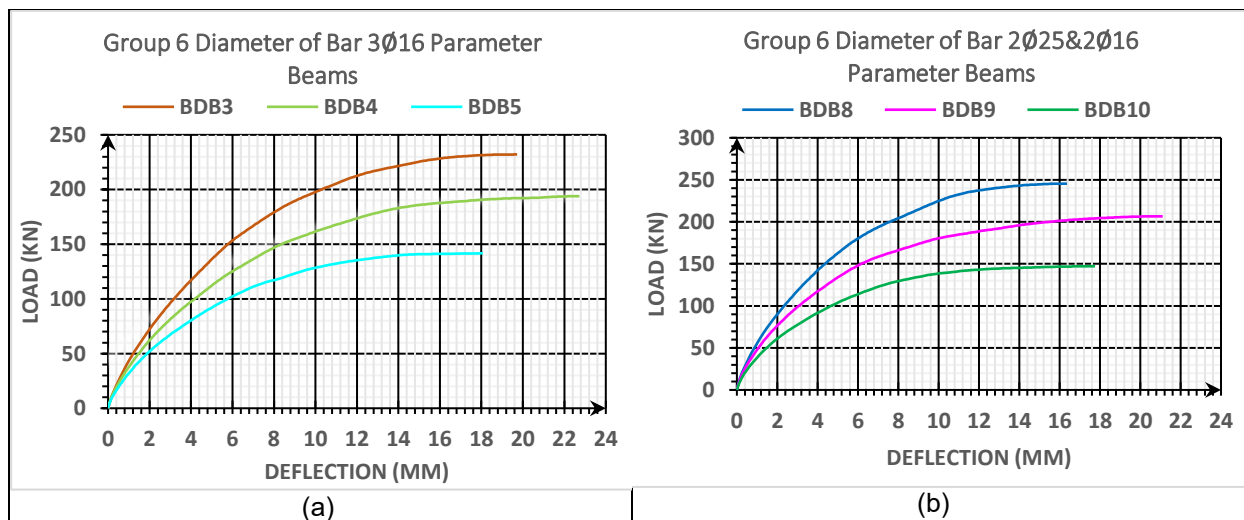


Fig. 16: (a) Load-Displacement for Diameter of Bar ( $3\phi 16$ ); (b) Load-Displacement Diameter of Bar ( $2\phi 25 \& 2\phi 16$ ).

## 6 Conclusion

The current numerical study investigates the behaviour of composite box steel-concrete beams using the Abaqus program for finite element analysis (FEM). By comparing the numerical results with previous experimental data, the structural behaviour of the composite box steel-concrete beam models can be reasonably predicted. Several factors significantly influence the overall behaviour of the beam at failure, and these effects can be summarized as follows:

1) Increasing size of the openings does affect shear strength and deflection. Whereas, when the size of the transverse openings was changed from 90\*90 mm to 110\*110 mm the shear load decreased by 12.7%, And when changed the size of the transverse openings from 110\*110 mm to 136\*136 mm the shear load decreased by 42.4%, Also the deflection will be effect as results.

2) Using two circular transverse openings in beams reduces shear strength. However, changing the shape of the largest opening can increase the shear load. Specifically, altering the shape of transverse openings from square to circular decreased the shear load by 14.7% for 90 mm and by 14.2% for 110 mm openings. In contrast, changing the shape from square to circular increased the shear load by 15.25% for 136 mm openings.

3) The location of the openings affects shear loads and deflection. Moving the transverse openings 125 mm closer to the applied loads, as opposed to near the supports, decreases the shear load by 7.5% for 90\*90 mm openings, 9.8% for 110\*110 mm openings, and 17.2% for 136\*136 mm openings.

4) As the (a/d) ratio increases, the shear strength decreases, and conversely, as the (a/d) ratio decreases, the shear load increases. The difference in shear load between the highest and lowest

(a/d) ratios is 12.5% for 90×90 mm openings, 7.2% for 110×110 mm openings, and 0.8% for 136×136 mm openings.

5) Increasing the compressive strength of concrete leads to a slight increase in shear load. For beams with two 90×90 mm square transverse openings, a compressive strength of 37.5 MPa results in a 1.5% higher shear load compared to a compressive strength of 30 MPa. Similarly, for beams with 110×110 mm openings, the shear load increases by 1.4%, and for beams with 136×136 mm openings, the shear load increases by 3.9% when the compressive strength is raised from 30 MPa to 37.5 MPa.

6) The diameter of the reinforcing bars affects the shear load. For a beam with reinforcement of (2Ø25-2Ø16) and two 90×90 mm square openings, the shear load is 5.8% higher compared to a beam with (3Ø16) reinforcement and the same openings. For beams with 110×110 mm openings, the shear load is 6.5% higher, and for beams with 136×136 mm openings, the shear load is 4.2% higher when reinforced with (2Ø25-2Ø16) compared to (3Ø16).

### Acknowledgement

I would like to express my sincere gratitude to [Assist. Prof. Dr. Nasser Hakeem Tu'ma], my research advisor, for their unwavering support, guidance, and invaluable insights throughout the course of this study. Their expertise and encouragement have been instrumental in shaping this work.

I also wish to extend my appreciation to [University of Misan/Collage of Engineering] for providing the necessary resources and facilities that made this research possible. Special thanks to my colleagues and friends, whose discussions and feedback have enriched this study.

Finally, I would like to acknowledge my family for their constant support and encouragement, which has been a source of strength throughout this journey.

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