Journal of Sustainable Civil Engineering and Technology
e-ISSN: 2948-4294 | Volume 3 Issue 1 (March 2024), 114-132
https://joscetech.uitm.edu.my

Numerical Modelling of Bearing Strength of Concrete Strengthening with Carbon Fibre Reinforced Polymers (CFRP) Wrapping for Different Thickness of CFRP Sheet

Filzah Sofiya Kamaruzaman[1], Norrul Azmi Yahya[2]

[1]Iras Perunding (Civil and Structural Engineering, and Project Management Consultant) No. 20A, Taman Perkota, 75350 Melaka, Malaysia

[2]School of Civil Engineering, College of Engineering, MARA University of Technology (UiTM), Pasir Gudang, Johor, Malaysia

*Corresponding author: filzahsofiya98@gmail.com

Received: 30 January 2024/ Accepted: 18 March 2024 / Published online: 29 March 2024

Abstract

The bearing strength of concrete plays an important role in transmitting the bearing force into the structural supports, especially for buildings and infrastructure such as concrete footings, concrete bridges, column corbels and concrete connections. The structural behaviour of the concrete bearing is related to the confinement effect, in which the load is transmitted to the concrete surface through the contact interaction between the steel bearing plate. However, extreme penetration on the contact surface of the concrete blocks by the steel bearing plate leads to failure modes on the concrete block. This research study focuses on the performance of the bearing strength of the concrete when it is wrapped with carbon fiber-reinforced polymers (CFRP) as the strengthening method. This research also examines the bearing strength of concrete when it is wrapped with a single layer of different thicknesses of CFRP sheet, which range from 1mm to 4mm thick. In order to understand the concrete bearing performance, a finite element model (FEM) using ABAQUS/CAE software is developed. An optimum meshing with a size 12.5mm is used for the further nonlinear analysis of the concrete model to discuss the results, such as the model validation by comparing the bearing strength results from the FE model with the Australian Standard, the comparison of the load-displacement curve for different thicknesses of CFRP wrapping, as well as the structural response or visualization of the concrete model. From the results, it shows that the different thicknesses of the CFRP wrapping significantly have a positive impact on the bearing capacity of the concrete, where the bearing strength of the concrete increases up to 26.16% as the thickness of the CFRP wrapping increases to 4mm for the optimum meshing size of 12.5mm. The FE visualization also shows various structural responses of the concrete bearing in the context of the deformation shape, vertical displacement, vertical stress distribution and max and minimum principal stress distribution of the concrete bearing, which are further discussed in this report.

Keywords: Bearing strength; Concrete strengthening; CFRP; Structural response; Stress distribution

1. Introduction

The structural behaviour of the concrete bearing strength is related to the confinement effect, in which the load is transmitted to the concrete surface through the contact interaction between the steel bearing plate. By placing a steel plate on the top surface of the concrete block, as seen on a concrete bridge pedestal, the capacity of that concrete to support the load given to it is known as its load-bearing capacity. The bearing strength of concrete plays an important role in transmitting the bearing force in the structural supports, especially for buildings and infrastructure such as concrete footing, concrete bridges, column corbels, concrete connections, anchorage for prestressed post-tensioned members and others (Yahya et al., 2019; Raizamzamani Md Zain et al., 2019; Zain & Yahya, 2017).

Concrete's bearing capacity is an important factor in determining a structure's overall performance. However, during their service life, concrete structures may develop deficiencies that need strengthening and repair. An increase in traffic, blasts and explosions, damage that builds up over time from unintentional overloading, fires, earthquakes and functional modifications could result in the need for structural rehabilitation. In addition, changes to the design code, poor maintenance, changes to the structural system, and errors in the design or construction process could also become the main reasons for strengthening and repairing (Heiza et al., 2014). Thus, problems may arise in concrete bearings when structures are overloaded, such as an increase in load traffic due to heavy trucks or any vehicle. Localized failure, such as line cracking in concrete, is a critical issue affecting the overall stability of the bridge deck and reducing the structure's service life. A solution based on a replacement bearing is a difficult and costly process. The replacement process may take longer and affect the public transport system, which is a major concern for the public.

Strengthening has become the appropriate method for enhancing the load-carrying capacity and extending the service life of defective structures because replacing them requires significant financial investments as compared to the strengthening or repairing method, which is frequently the more cost-effective option.

Therefore, the application of carbon fibre reinforced polymer (CFRP) wrapping, or jacketing, is increasingly used, especially to strengthen and retrofit the existing reinforced concrete (RC) structures. It is because CFRP has high tensile strength, stiffness and strain capacity compared to the RC concrete itself. Other than that, CFRP is managed on-site, and it has easy fabrication (Scheffers & Ravindrarajah, 2009; Ye et al., 2002). Alotaibi & Galal (2018) also stated that the jacket's confinement is very useful in improving the axial capacity and ductility of the strengthened columns. However, there is still a lack of fundamental studies on concrete bearings being wrapped in CFRP sheets.

This enhancement may offer a better option for repairing buildings or bridges without interrupting the serviceability of the structures, rather than the replacement of a new member. Thus, this research study focuses on the structural response of the concrete bearings that are wrapped with CFRP sheet through numerical modelling and to evaluate the maximum bearing capacity of unreinforced concrete blocks wrapped with a single layer of different thicknesses of CFRP sheet subjected to vertical load.

1.1. Literature Review

There are numerous studies conducted by previous researchers on the importance of bearing strength of concrete as one of the design parameters, especially for transmitting load or bearing force to the structural concrete supports such as concrete footing, concrete bridges, column corbels, concrete connections, and many other related applications (Yahya et al., 2019; Raizamzamani Md Zain et al., 2019; Zain & Yahya, 2017). However, various failure patterns can be seen on the concrete when it is subjected to excessive penetration from the steel plate to the concrete surface, such as vertical cracks, inverse pyramid cracks, conical cracks, and radial cracks on the concrete block.

Therefore, in order to minimise the failure cracking on the concrete bearing and also to enhance the performance and strength of the concrete bearing, other alternatives need to be taken into consideration, such as confining the concrete with external fibre composites. Carbon Fiber Reinforced polymer (CFRP) has been widely used as a strengthening technology for reinforced concrete (RC) constructions in America, Canada, Japan, and Europe since the early 1990s (Ye et al., 2002).

This study also involved the comparison and discussion of the previous studies on the factors that may contribute to the performance of CFRP wrapping on concrete, such as its orientation, length, spacing and thickness. Therefore, this study was focused on the application of CFRP wrapping with a single layer of different thicknesses of CFRP sheet in order to strengthen the concrete-bearing structures.

1.1.1. Concrete Bearing Strength Concept

The bearing strength of concrete is one of the essential design criteria that is needed to transmit the load or the bearing force to the structural concrete supports. For instance, when designing transfer members such as concrete footings, it is crucial to assess the bearing strength characteristics of the concrete. It is because the failure of concrete bearing, especially at the support base, will negatively affect the stability of the concrete structure (N. A. Yahya et al., 2019).

According to Yahya et al. (2019), the performance of concrete bearings depends on the contact interaction between the steel bearing plate and the concrete surface. It is supported by Raizamzamani Md Zain et al. (2019), where the most important factors that affect the bearing strength of concrete are the ratio of the surface area of the concrete blocks to the area of the bearing plate, as shown in the equation below.

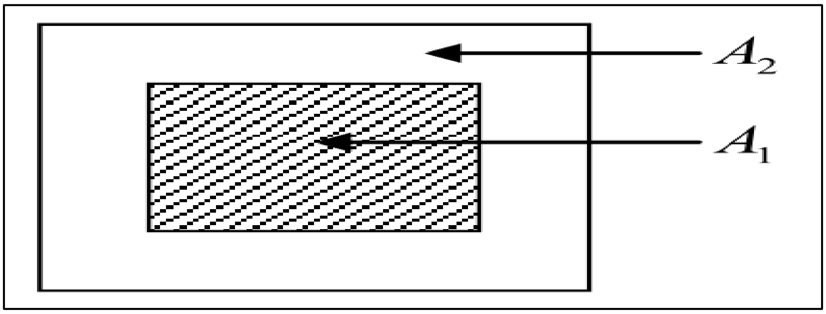


Figure 1. The bearing ratio of surface area of concrete blocks (A_2) to the area of the bearing plate (A_1).

$$Bearing\ ratio = \frac{A_2}{A_1} \tag{1}$$

Later, Australian Standard 3600 (2001) and ACI-318 (2005) developed a formulation for the concrete bearing strength of unconfined concrete. The equation stated that the compressive strength of the concrete and the ratio of unloaded to loaded area contributed to the bearing strength of unreinforced concrete. The formulation given also takes into account the factor of safety in order to take into consideration the allowable bearing stress of concrete. Therefore, the given formula for unconfined concrete stated in Australian Standard 3600 (2001) is:

$$f_b = \emptyset 0.85 f'_c \sqrt{\frac{A_2}{A_1}} \quad or\ \emptyset 2 f'_c \tag{1.1}$$

The formula for the bearing strength of unconfined concrete as stated in ACI-318 (2005), which supports the formulation stated in the Australian Standard 3600 (2001), is as follows:

$$f_b = \emptyset 0.85 f'_c \sqrt{\frac{A_2}{A_1}} \tag{1.2}$$

The formulations of concrete bearing strength developed by previous researchers were based on their observations of the formation of cracking in the form of an inverted pyramid under the loading bearing plate. However, most of the findings on the bearing strength of concrete were related to the relationship between the compressive strength of the concrete and the relative ratio of the area of the concrete surface to the bearing plate area. There were also studies conducted on the other factors that contribute to the bearing strength and the formation of failure patterns of concrete, such as the height of the concrete block, geometry, which is the size and shape of the steel plate, geometry, loading eccentricity and others (Yahya et al., 2019; Zain & Yahya, 2017; Ince & Arici, 2004). There is still a need for studies on the bearing strength strengthened with CFRP wrapping. Therefore, this study was conducted to focus on the strengthening of concrete bearings with different thicknesses of CFRP sheet.

1.1.2. Concrete Wrapping in RC Structural Strengthening

A structure may require rehabilitation and strengthening at any point from the start of construction to the end of its serviceable lifespan. It could happen while construction is underway due to design errors, inadequate production of concrete and poor implementation techniques. During its service life, structural rehabilitation might be needed due to natural disasters such as earthquakes, accidents such as collisions, fires, and explosions, situations involving changes in the structure's functionality and the development of more demanding code requirements (Júlio et al., 2003; Nuroji et al., 2020).

Therefore, the importance of structural rehabilitation and strengthening is growing as it plays a significant role in the construction industry. There are various approaches, each with different advantages and disadvantages. For example, in order to increase the capacity and stiffness of the structure's element, a commonly used strengthening technique involves superimposing external reinforcement, specifically steel plates or Fiber-Reinforced Polymers (FRP), at the member's tension zone surface.

Fibre-reinforced polymer (FRP) is defined as a composite material that consists of a form of fiber that is impregnated with saturated resin. FRP is commonly used as one of the retrofitting services for a building due to its advanced characteristics and performance. There are many types of fibre composites that were used, such as glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP). For instance, the application of externally bonded GFRP can improve the structural performance of concrete for service and ultimate load conditions (Achudhan et al., 2019).

Among the applications of FRP in concrete, concrete wrapping with FRP sheets is one of the ways to improve the ductility and enhance the strength of the concrete structure. FRP sheets can be wrapped around concrete structures such as beams and columns and are bonded to the concrete surface by using very high-strength adhesive in order to form FRP jackets (Alotaibi & Galal, 2018). It is crucial to ensure that the fibres are located perpendicular to the load axis of the concrete structure and aligned along the hoop direction.

Since the early 1990s, carbon fiber-reinforced polymers (CFRP) have been widely known and have been applied as one of the strengthening methods for reinforced concrete (RC) structures in America, Canada, Japan and Europe (Ye et al., 2002). The application of CFRP sheets had received global acceptance to be used in the strengthening and retrofitting of RC structures as well as in new concrete structures.

This is due to the advantages of CFRP, which has high tensile strength, stiffness and strain capacity compared to conventional structural concrete. Other than that, CFRP composites can increase the performance of structural concrete members in terms of ductility, performance under cyclic and fatigue loading and environmental durability (Li et al., 2006; Scheffers & Ravindrarajah, 2009). In addition, CFRP sheets also become favourable to be applied in strengthening and repairing RC structures because they are lightweight, easy to manage, handle and install, and have good resistance and abrasion to corrosion and chemical attack (Obaid et al., 2021). CFRP can be prefabricated at the factory, which may reduce the installation time required on site. Moreover, the lightweight characteristics of CFRP will reduce the transportation cost. Therefore, CFRP will have critical advantages for the overall life cycle costs (Täljsten, 2003).

Apart from that, Zhuang et al. (2018) found that the CFRP sheet can be used as external wrapping on marine structures such as RC piles in order to prevent reinforcement corrosion from occurring and to limit the crack growth on the concrete structure.

Previously, many studies had been conducted to investigate and evaluate the performance of shear, compressive, and flexural strengths of RC structures such as beams, columns and slabs with the application of CFRP sheets by using the wrapping technique on the structures (Täljsten, 2003; Ye et al., 2002; Obaid et al., 2021). However, the research on the behaviour and performance of concrete structures under the bearing load condition is still lacking. Therefore, this paper will discuss the bearing strength of concrete that is strengthened with a single layer of different thicknesses of CFRP sheet.

1.1.3. Factors Affecting the Concrete Wrapping in RC Structural Strengthening

There are many factors that will influence the characteristics and properties of CFRP composites, such as the type of fibre used, the fiber orientation, the shape and length of the fibres, as well as the resin matrix properties and the bonding interaction between the resin matrix and the fibres. Other than that, the spacing and thickness of the CFRP sheets may also play an important role in their effectiveness (Ye et al., 2002; Scheffers & Ravindrarajah, 2009).

According to a study conducted by Li et al. (2006), the researcher claims that the number of layers and length of the CFRP sheet will have a significant effect on the failure patterns, ductility, and stiffness of the RC concrete. Therefore, experimental and numerical testing were conducted on rectangular RC concrete beams, which were strengthened by the CFRP sheets. They found that the number of layers and length can improve the crack patterns of the RC concrete beams and enhance the initial cracking loads and ultimate loads, as well as the stiffness and ductility of the concrete beams, as shown in Figures 2 and 3. Täljsten (2003) found that the fibre can be utilised efficiently when thinner fibre is applied, and the fibre is placed perpendicularly to the shear crack in order to achieve better strain measurement.

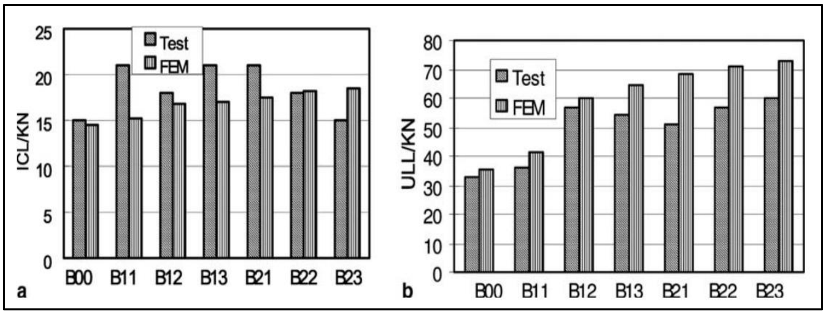


Figure 2. The comparison of loading results between experimental testing and simulation for beams with single layer and double layer strengthening; a) initial cracking loads; b) ultimate loads. (Li et al., 2006)

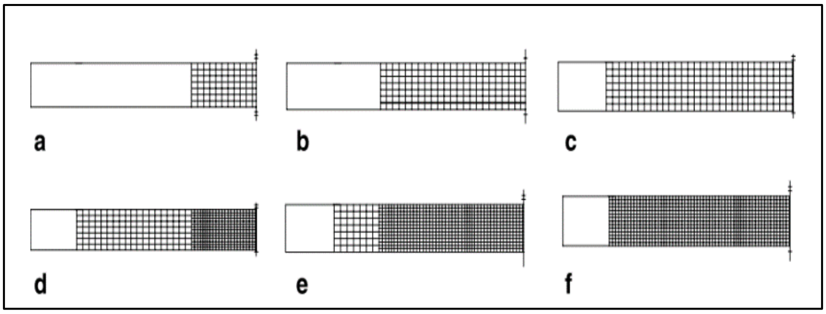


Figure 3. The different number of layers and length of the CFRP being applied to the concrete beam. (Li et al., 2006)

Where,

Single layer strengthening;

a) B11 : 0.6m CFRP
b) B12 : 1.2m CFRP
c) B13 : 1.6m CFRP

Double layer strengthening (with 1.6m CFRP for the 1st layer);

d) B21 : 2nd layer of 0.6m CFRP
e) B22 : 2nd layer of 1.2m CFRP
f) B23 : 2nd layer of 1.6m CFRP

In CFRP concrete wrapping, the in situ wet application of CFRP strips is the most frequent method to be used in the construction industry. The strip is impregnated with high-adhesive resin before being wrapped around the concrete structure in a perpendicular direction to the axis of the concrete structure (Chalioris et al., 2017). Apart from that, in another study conducted by Nikoloutsopoulos et al. (2018), the researchers conducted an experiment to study the effect of different shear strengthening techniques on the concrete beams by using CFRP. It is important to identify the most effective technique to be applied, either by using strip, jacket or rope techniques.

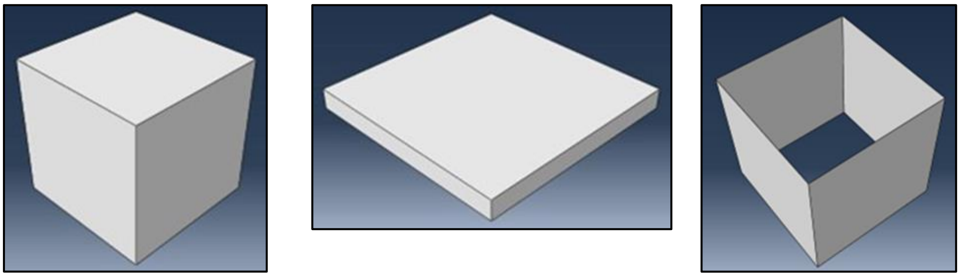
Apart from that, Baggio et al. (2014) also conducted an experimental study on shear strengthening with CFRP by using the strip techniques in the U-strengthening method, which were located perpendicular to the axis of the specimen with a single rope anchoring on the beam. As a result, the use of CFRP strips significantly improved the shear capacity and the CFRP anchoring techniques also enhanced the shear capacity as well as the failure ductility even more.

From the previous studies conducted, there are many factors that may contribute to the performance of concrete when it is strengthened with CFRP wrapping. For instance, the type of FRP utilised, their orientation, shape, and length, as well as the resin matrix qualities and the bonding interaction between the resin matrix and the CFRP. Aside from that, the spacing and thickness of CFRP sheets may have a significant impact on the effectiveness of CFRP sheets. They are all elements that determine the characteristics and properties of CFRP composites. However, these studies are focused on strengthening the shear and flexural performance of concrete structures such as beams, columns and foundations. There is still a lack of studies conducted on the application of CFRP wrapping, especially for the strengthening of concrete bearings. Therefore, this study was conducted to further discuss the effect of different thicknesses of CFRP sheet in order to strengthen and enhance the concrete bearing capacity as well as to improve the overall performance of concrete bearing.

2. Methods

In this study, finite element modelling (FEM) using ABAQUS software is developed. The finite element analysis is used to analyse the comparison of the maximum bearing strength of the concrete model with different thicknesses of CFRP sheet being wrapped around the concrete. It is also used to evaluate the structural response of the concrete bearing that is wrapped in CFRP sheet. As for the control model, there is no CFRP wrapped around the concrete block, which was the reference model for this study.

In model development, the purpose of the analysis is to predict and evaluate the structural response of the concrete block subjected to the loading applied in the vertical loading direction through the steel bearing plate. There are four (4) important steps in the model development process, which are the selection of element types, contact interaction, loading displacement control and meshing sensitivity analysis. The 200mm x 200mm x 200mm concrete model and the 100mm x 100mm x 10mm thick steel plate model were both produced. The model was also developed in full scale in order to analyse its deformation. As for the CFRP model, the element is created in a four-sided continuous jacket (full wrap) by using a shell extrusion element with a single layer of different thicknesses, which are 1mm, 2mm, 3mm and 4mm and these parts were created separately in different parts before they were assembled in the instance section.



a) Concrete b) Steel Plate c) CFRP

Figure 4. The model developed by using Abaqus software.

The contact interface between the concrete surface and the steel plate surface is created by using a surface-to-surface contact interface. This surface-to-surface discretization considered both the master surface (concrete surface) and the slave surface (steel plate surface) in the area where contact limitations exist. As for the contact interface between the concrete surface and the CFRP, a tie-constraint was applied. This constraint allows the merging of two areas together, even if the meshes built on the regions' surfaces are different. Figure 5 shows the contact interface between the concrete surface and the steel plate, as well as between the concrete surface and CFRP.

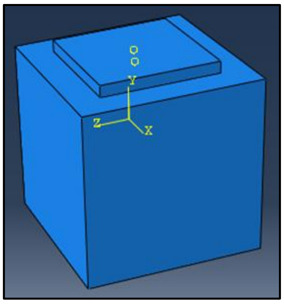


Figure 5 (a). Concrete bearing (Control model-without CFRP)

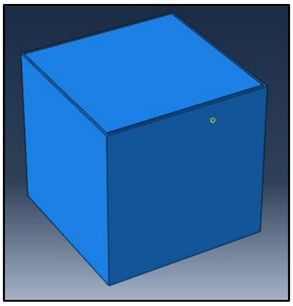


Figure 5 (b). Concrete bearing wrapped with single layer of different thicknesses of CFRP sheet ranging from 1mm, 2mm, 3mm and 4mm thick.

In order to stimulate the concrete's non-linear behaviour, the concrete damage plasticity model (CDPM) was applied. Concrete behaves in a brittle manner under low confining pressures, which will cause cracking in tension and crushing in compression as the principal failure mechanisms. In addition, as shown in Figure 4.0 below, the bottom surface of the concrete cube was thus restrained in all directions, implying that the model is not moving vertically. As a result, the Encastre property was selected. The displacement control at the steel plate's centre up to a maximum movement of 0.3mm is used and the vertical load generated is the real load due to the model analysis being done in full size. Figure 6 shows the illustration for the boundary condition and the displacement control of the concrete model.

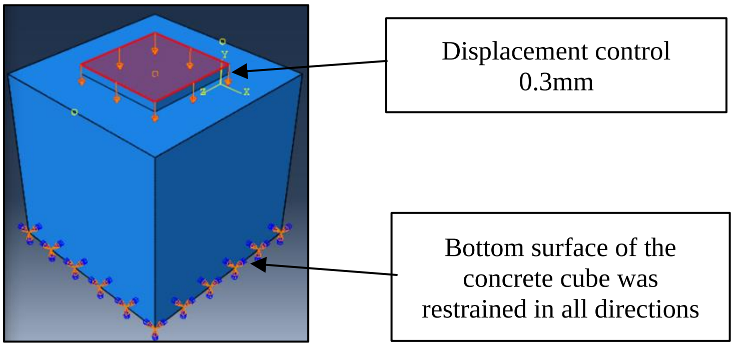


Figure 6. The boundary condition and displacement control of the model.

In the mesh sensitivity analysis, the linear analysis of the control model without the CFRP wrapping is conducted with four (4) different meshings, which are 5.5mm, 8.5mm, 12.5mm, and 25mm. According to Yahya (2017), the FE model was discretized for multiple mesh sizes in mesh sensitivity studies to discover the optimal mesh size that minimises the computing time. The percentage difference on the load of different mesh sizes was calculated and the results obtained are summarised in Figure 7.

Meshing size (mm)	25mm	12.5mm	8.5mm	5.5mm
No of element	512	4096	13824	46656
Compressive load (kN)	7153.79	7244.34	7285.85	7367.91
Percentage difference of the load	-	1.27	1.85	2.99
Vertical stress at middle section (MPa)	415.84	424.86	425.16	428.60
Percentage difference of the load	-	2.17	2.24	3.07
Displacement (mm)	2.07	2.01	1.97	1.97

Figure 7. The summary of mesh sensitivity analysis.

In addition, these findings were plotted as shown in Figures 8 and 9, respectively, to clearly illustrate the influence of mesh size on compressive load and vertical stress at the middle section of the concrete block.

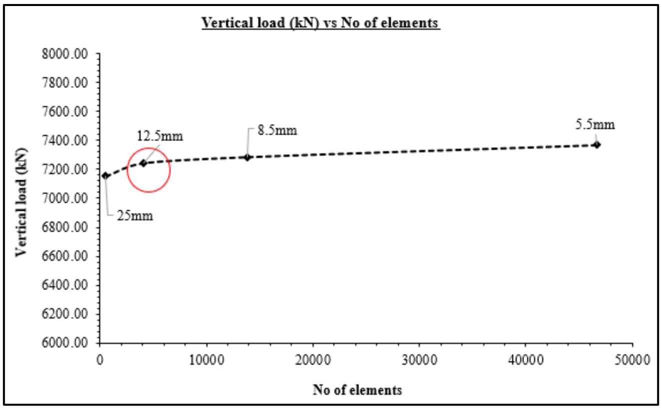


Figure 8. Vertical load for different mesh sizes.

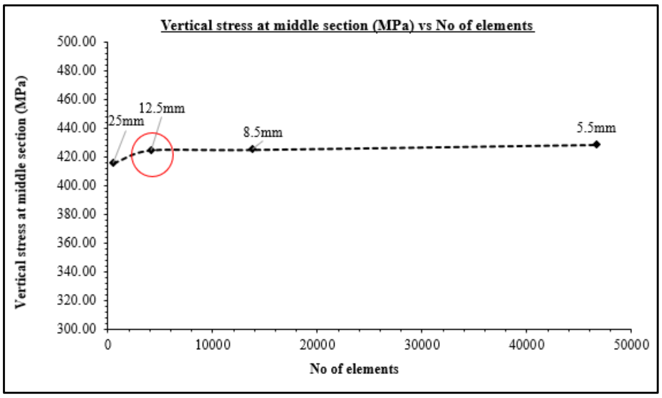


Figure 9. Vertical stress at middle section for different mesh sizes.

Based on Figure 7, the coarsest mesh size of 25 mm contained 512 elements, while the finest mesh size of 5.5 mm contained 46656 elements. From Figures 5.0 and 5.1, it is shown that the vertical load and the vertical stress at the middle section increase when the meshing sizes decrease from 25 mm to 12.5 mm. Then, the value level is almost consistent, starting from mesh size 12.5 mm to 5.5 mm. Therefore, based on the tabulated results, the optimum meshing size of 12.5 mm was selected. By choosing the optimum meshing size of 12.5 mm, the computational time to analyse the results in the ABAQUS software was reduced while obtaining an almost similar result with the finest meshing size of 5.5 mm.

For model validation, the optimum meshing size obtained in the linear analysis is further analysed in the non-linear analysis and the results obtained are compared with the predicted ultimate load from the Australian Standard AS3600 to examine the accuracy of finite element results. The sample calculations for the predicted ultimate bearing load are as follows:

Formula for bearing strength of concrete (based on AS3600):

$$f_b = \emptyset \times 0.85 \times f'_c \times \sqrt{\frac{Ac}{As}}$$

$$Fult\ (Predicted\ ultimate\ bearing\ load) = fb \times As \tag{2}$$

As shown in Figure 10 and 11, it demonstrates that the results from the FE model for the optimised mesh size model of 12.5mm considerably predict the loading of 336.89 kN, which was almost accurate when it was compared with the expected load with only a 3.11% difference.

.

Concrete surface dimensions, Ac (mm x mm)	Steel plate surface dimensions, As (mm x mm)	Compressive strength of concrete, f'c (MPa)	Predicted bearing strength of concrete by Australian Standard AS3600, f_b (MPa)	Predicted ultimate bearing load, *Fult* (kN)	Ultimate bearing load from FEA (kN)	Percentage difference of ultimate load (%)
200x200	100 x 100	32	32.64	326.4	336.89	3.11

Figure 10. Summary of results for optimum meshing size 12.5mm

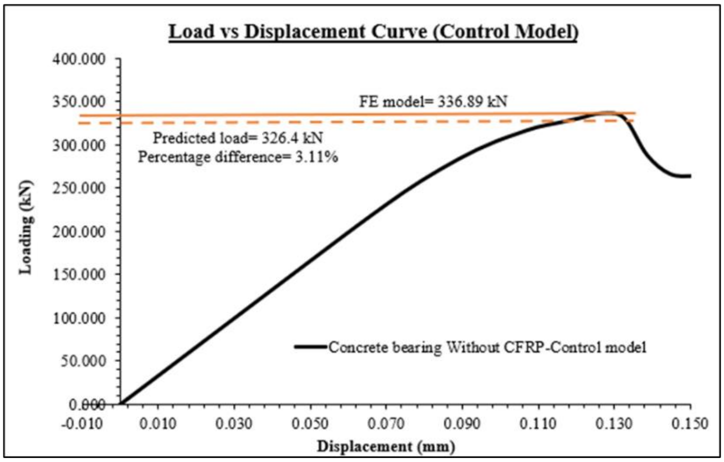


Figure 11. Load-displacement curve for the control model.

3. Results and Discussion

3.1 Comparison load-displacement curve

The findings of the finite element analysis for a full-scale model of a 200 mm high cube concrete block as the control model with a compressive strength of 32 MPa are used, and it is further examined for different thicknesses of the CFRP sheet, i.e., 1mm, 2 mm, 3mm, and 4mm thick. In this study, the comparison of the load displacement curve for different thicknesses of CFRP wrapping as well as the structural response or visualization of the concrete model obtained from the FE model were evaluated.

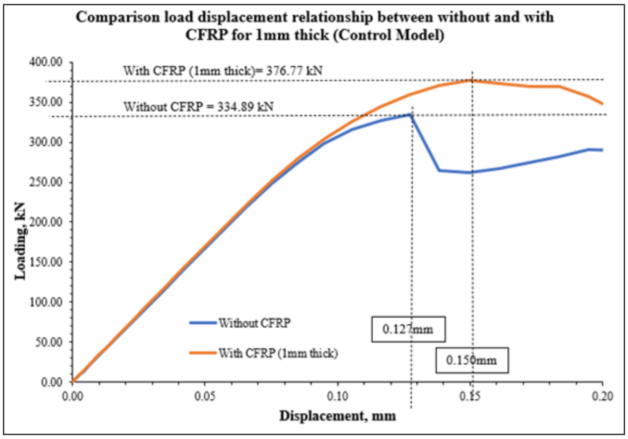


Figure 12. Comparison-load displacement relationship between without and with CFRP for 1mm thick.

By referring to Figure 12, it shows that the ultimate load of the FE model increases from 334.89 kN for the control model (without CFRP) to 376.77 kN for the concrete model with CFRP (1mm thick). It was found that adding CFRP wrapping as lateral confinement to the concrete block had a substantial impact on its strength and ability to increase its ductility when subjected to bearing stress.

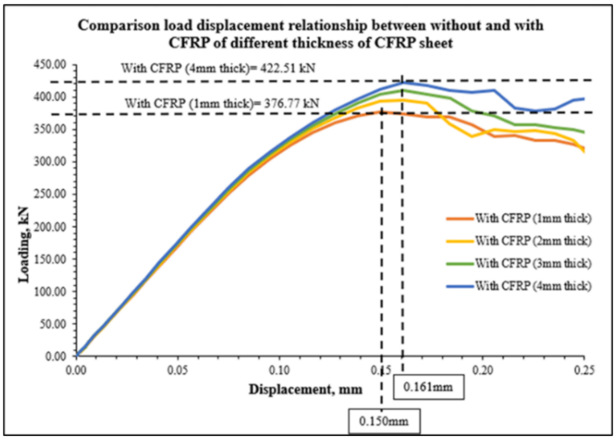


Figure 13. Comparison load-displacement relationship between without and with CFRP wrapping of different thicknesses of CFRP sheet.

Figure 13 demonstrates that the ultimate load of the FE model rises significantly from 376.77 kN to 422.51 kN when the concrete model has increased the thickness of CFRP wrapping from 1mm to 4mm thick. In addition, it was shown that the concrete model wrapped with 4 mm of CFRP has a higher ductility, as the displacement was delayed to 0.161mm when it reached its ultimate load, compared to the displacement of 0.15mm for the concrete model wrapped with 1mm of CFRP. The outcomes of the FE analysis of the concrete model were further examined, and the results are displayed in Figure 14.

Thickness of CFRP wrapping	Displacement at max. load (mm)	Ultimate load (kN)	Percentage increased (%)	Vertical stress at the sharp edge (MPa)
Without CFRP	0.127	334.886	-	47.337
1mm	0.150	376.772	12.51	35.258
2mm	0.161	395.178	18.00	40.125
3mm	0.161	409.577	22.30	44.142
4mm	0.161	422.507	26.16	45.065

Figure 14. Structural performance of concrete blocks wrapped with different thicknesses of CFRP under bearing force.

Figure 14 demonstrates that the ultimate load for the concrete model with 4mm thick CFRP wrapping was increased by up to 26.16%. Next, as for the concrete model without CFRP wrapping, the vertical stress at the sharp edge is 47.337 MPa, which is significantly reduced to 35.258 MPa for the concrete model wrapped with 1 mm of CFRP.

Additionally, this study continues to explore how the confinement effect is impacted by the bearing strength of concrete wrapped in various CFRP wrapping thicknesses. From Figure 15, it can be seen that the confinement effect increased as the thickness of CFRP increased. The confinement effect is formulated by the dimensionless unit of the bearing strength of concrete, fb, over the concrete compressive strength, fcu. Therefore, as shown in the table below, when the thickness of the CFRP wrapping that confined the concrete model increases, the bearing strength of the concrete model also increases. Thus, it resulted in an increase in the confinement effect.

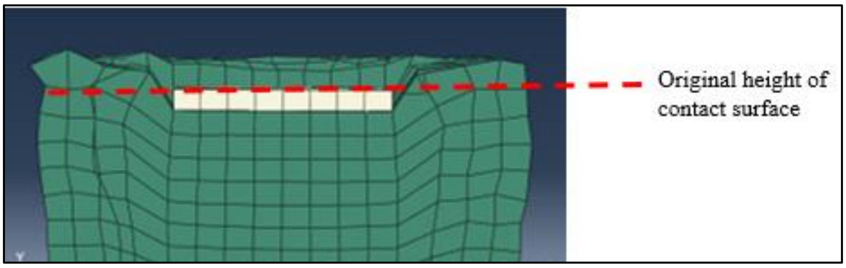
Sample (FE Model)	Concrete surface dimensions (mm x mm)	Steel plate surface dimensions (mm x mm)	Concrete surface area, Ac (mm^2)	Steel plate surface area, As (mm^2)	Ac/As	Ultimate load, Fult (kN)	Bearing strength, fb= Fult/As (MPa)	Concrete compressive strength, fcu (MPa)	Confinement effect, fb/fcu
No CFRP						334.8856	33.48856		1.047
CFRP 1mm						376.7717	37.67717		1.177
CFRP 2mm	200 x 200	100 x 100	40000	10000	4	395.1784	39.51784	32	1.235
CFRP 3mm						409.5767	40.95767		1.280
CFRP 4mm						422.5066	42.25066		1.320

Figure 15. Summary of the confinement effect of different thicknesses of CFRP wrapping.

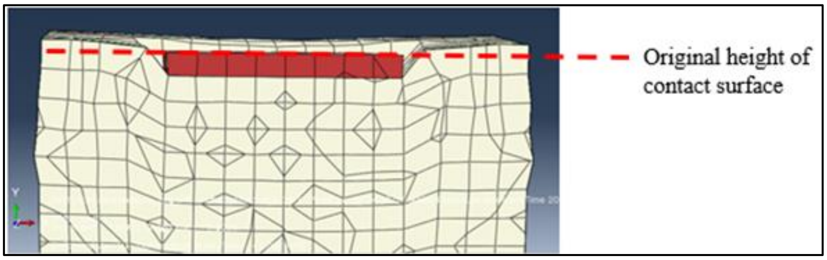
3.2 Structural Response of Concrete Bearing

3.2.1 Deformation Shape of Concrete

The load-displacement control compressed the concrete surface at the contact area between the concrete surface and the steel plate surface downward, causing the outer section of the concrete edge to deform upward.



(a) Deformed shape of control model without CFRP wrapping.

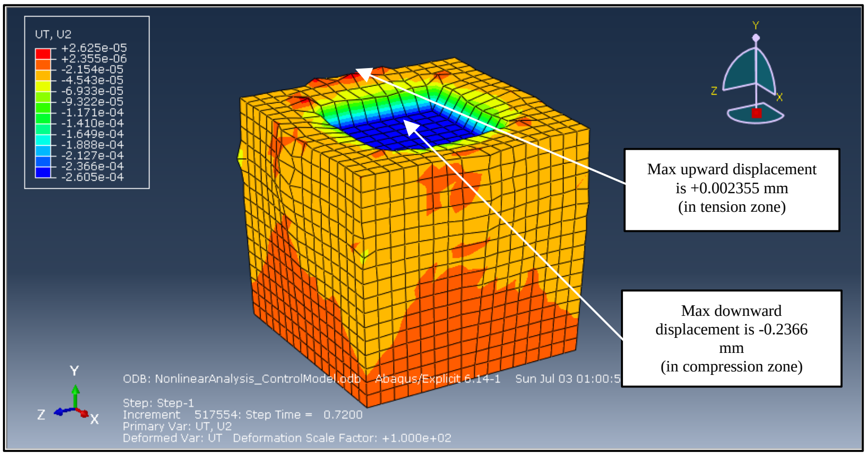


(b) Deformed shape of control with 1mm thick CFRP wrapping.
Figure 16. Deformation shape of control concrete model

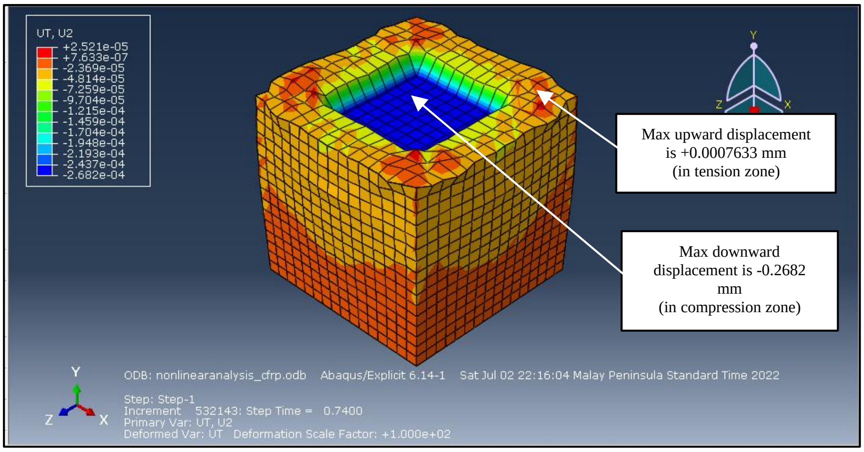
Following the steps in Figure16, the deformation of the concrete model without CFRP wrapping is shown in Figure 16 (a). This model has a bigger bulging effect than Figure 16 (b), which is because the outer edge of the concrete surface deforms upward more. This is due to the fact that the fact that the concrete model was strengthened by the confinement of the CFRP wrapping, which reduced the deformation effect of the concrete model.

3.2.2 Vertical Displacement of Concrete (U2)

The vertical displacement of the concrete has been compared between the control model, which is shown in Figure 17 (a), the control concrete model without CFRP wrapping and Figure 17 (b), the model wrapped with 1 mm of CFRP. Finding the maximum upward displacement (in tension) and the maximum downward displacement (in compression) on the concrete surface will help to discuss the vertical displacement.



(a) Control model without CFRP



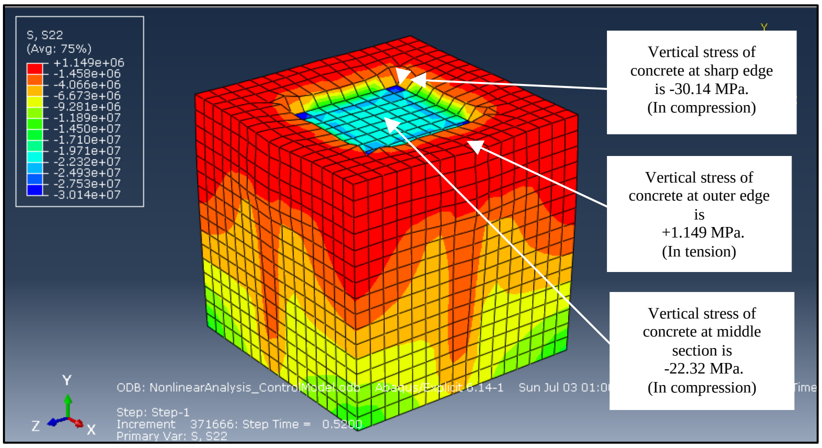
(b) Control model with 1mm CFRP thickness

Figure 17. Visualization of the vertical displacement (U2) of the concrete model;
(a) Control model without CFRP wrapping; (b) Control model with 1mm CFRP thickness.

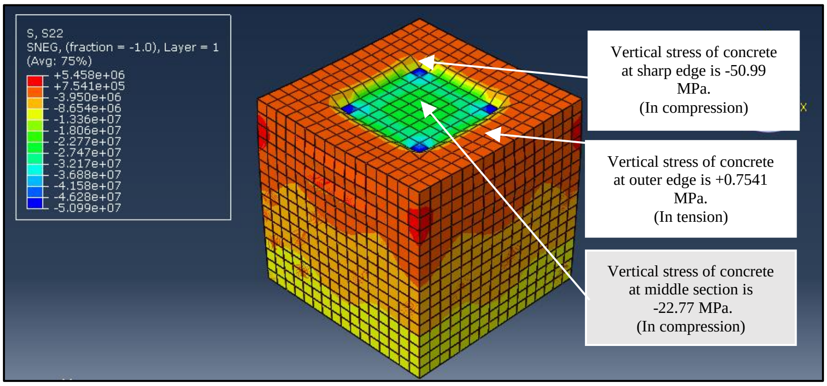
Figure 17 shows that the maximum upward displacement is located at the outer edge of the concrete surface, which is in the tension zone, and it can also be seen as bulging on the concrete surface. Moreover, as the excessive plate penetrates at the centre of the concrete surface, the maximum downward displacement is in the compression zone, which is at the contact surface between the steel plate and the concrete surface. As illustrated in the figure above, the maximum upward displacement of concrete for the control model without the CFRP wrapping is +0.00235 mm, as shown in Figure 10(a), which is slightly higher compared to the control model wrapped with 1 mm of CFRP, as shown in Figure 10(b), with a value of +0.000763mm.

3.2.3 Vertical Stress Distribution (S22): Stress Distribution at the Middle and Edge Section

By referring to Figure 18, it can be observed that the vertical stress distribution of the concrete surface at the sharp edge and at the middle section acted in compression, where the sharp edge resulted in a concentrated stress value compared to the uniform stress distribution at the middle section on the concrete surface. However, at the outer edge of the concrete surface, the vertical stress distribution at that location gradually reduced to tension related to concrete bulging that can affect concrete spalling.



(a) Concrete model without CFRP wrapping (Control)



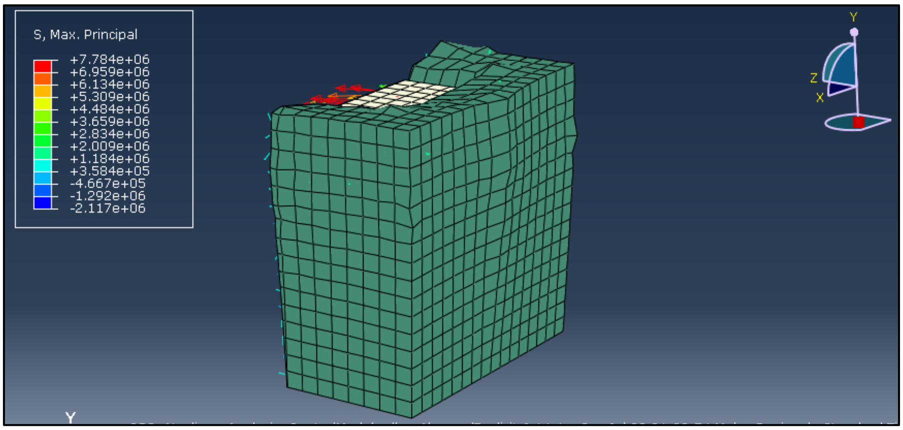
(b) Concrete model wrapped with 1mm CFRP (Control)

Figure 18. The vertical stress distribution (S22) of the concrete model, where (a) Concrete model without CFRP wrapping (Control) and (b) Concrete model wrapped with 1mm CFRP thick (Control)

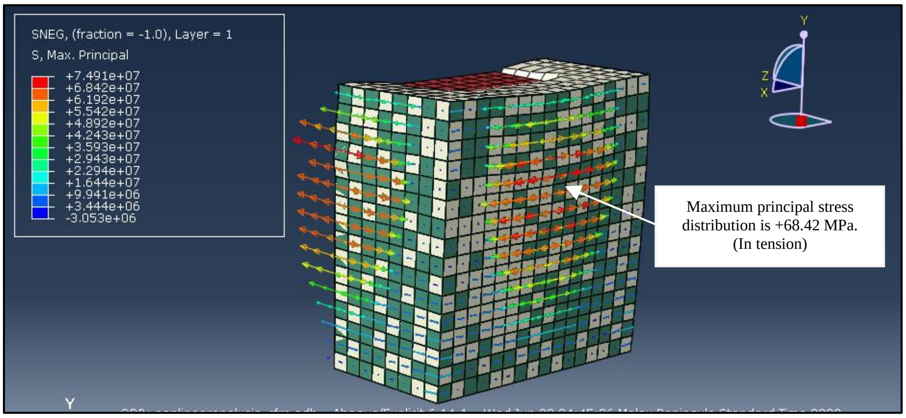
Besides, as can be seen in Figure 18, the vertical stress distribution at the sharp edge and at the middle section was higher for the concrete model wrapped with 1mm thick CFRP, as shown in Figure 18 (b) compared to the concrete model without CFRP in Figure 18 (a). For instance, the concrete model in Figure 18 (b) resulted in a stress distribution of -50.99 MPa for the sharp edge and -22.77 MPa for the middle section, which were higher compared to the results in Figure 11(a) with the stress levels of -30.41 MPa and -22.32 MPa, respectively. However, the stress level at the outer edge of the concrete surface for the concrete model without the CFRP wrapping, as shown in Figure 11(a), resulted in a higher stress level in tension with a value of +1.149 MPa, which is slightly higher than +0.7541 MPa, as stated in Figure 18 (b).

3.2.4 Max Principal Stress Distribution (maximum tension in all planes)

The maximum principal stress distribution is crucial because it has a direct impact on the damages inflicted on the concrete blocks due to the bulging of the concrete outer surface under high tensile force. As illustrated in Figure 19 (b), the maximum principal stress distribution for the concrete model wrapped with 1 mm of CFRP is +68.42 MPa, which is higher than the concrete model without CFRP wrapping with only +7.784 MPa, as shown in Figure 19 (a).



(a) Concrete model without CFRP wrapping (Control)



(b) Concrete model wrapped with 1mm CFRP (Control)

Figure 19. The maximum principal stress distribution of the concrete model, where (a) is the concrete model without CFRP wrapping and (b) is the concrete model wrapped with 1 mm of CFRP.

In addition, concrete bulging and spalling are both caused by steel plate penetration into the concrete surface and are considered critical along the outside perimeter edge of the contact region and the side edge of the concrete block. Thus, the tensile force was higher on the outside perimeter of the CFRP wrapping, as can be seen in Figure 12.0(b), where the CFRP-confined concrete blocks undergo excessive tension in a hoop direction during the bearing strength failure of the concrete blocks to resist the load exceeding the failure of the concrete core.

4. Conclusion

In this study, finite element modelling (FEM) using ABAQUS/CAE software was used to develop a concrete bearing model wrapped with CFRP sheet subjected to different thicknesses of CFRP sheet.

i. It was shown by the developed finite element model that the concrete bearing wrapped in CFRP sheet significantly affects the bearing strength of the concrete. By comparing the load displacement relationship between the control model of concrete without and with CFRP wrapping, it shows that the ultimate load of the FE model increases from 334.89 kN for the control model without the CFRP wrapping to 376.77 kN for the concrete model with CFRP wrapping that is 1mm thick.
ii. The concrete block wrapped with 1mm CFRP sheet has reached the ultimate load, which was delayed by 0.15mm as compared to the concrete block without the CFRP wrapping, whose displacement was 0.127mm.
iii. The ultimate load for the concrete model with the 4mm thick CFRP wrapping was increased by up to 26.16% when compared to the control specimen (without CFRP).
iv. The deformation of the concrete model without CFRP wrapping shows a greater bulging effect, which is due to the upward deformation at the outer edge of the concrete surface.
v. The vertical stress distribution at the sharp edge and in the middle section was higher for the concrete model wrapped with 1mm of CFRP compared to the concrete model without CFRP.
vi. As the thickness of CFRP that wraps the concrete bearing increases, the ultimate bearing load also increases. For instance, the ultimate load of the FE model rises significantly from 376.77 kN to 422.51 kN when the concrete model increases the thickness of CFRP wrapping from 1mm to 4mm.

5. Recommendations

There are various recommendations that can be taken into consideration in order to improve the performance of the concrete bearing for further research in the future. The recommendations were attained as follows:

i. Conducting more samples with different key parameters in experimental work together with the numerical analysis for more accurate results and for good validation purposes.
ii. The use of high-strength concrete can be proposed for future studies to examine the confinement effect, which can be taken as bearing strength over compressive strength of the concrete (fb/fcu), especially for bridge pedestals that use higher grade (50 MPa).
iii. Different dimensions of the concrete blocks, such as different heights of the blocks, can be considered to evaluate the slenderness effect on the concrete bearing.

Acknowledgements

The authors would like to extend my gratitude to the School of Civil Engineering, College of Engineering, Universiti Teknologi MARA for providing the necessary facilities for this research.

Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

References

Achudhan, Deepavarsa, Vandhana, & Shalini. (2019). ScienceDirect Strengthening and Retrofitting of RC Beams Using Fiber Reinforced Polymers. *Materials Today: Proceedings*, *16*, 361–366. https://doi.org/10.1016/j.matpr.2019.05.102

Alotaibi, K. S., & Galal, K. (2018). Experimental study of CFRP-confined reinforced concrete masonry columns tested under concentric and eccentric loading. *Composites Part B: Engineering*, *155*(March), 257–271. https://doi.org/10.1016/j.compositesb.2018.08.024

Heiza, K., Nabil, A., Meleka, N. N., & M, T. (2014). Strengthening of Reinforced Concrete Structures – Different Strengthening Techniques. *Sixth International Conference on Nano-Technology in Construction*, *March*.

Ince, R., & Arici, E. (2004). Size effect in bearing strength of concrete cubes. *Construction and Building Materials*, *18*(8), 603–609. https://doi.org/10.1016/j.conbuildmat.2004.04.002

Júlio, E. S., Branco, F., & Silva, V. D. (2003). Structural rehabilitation of columns with reinforced concrete jacketing. *Progress in Structural Engineering and Materials*, *5*(1), 29–37. https://doi.org/10.1002/pse.140

Li, L. J., Guo, Y. C., Liu, F., & Bungey, J. H. (2006). An experimental and numerical study of the effect of thickness and length of CFRP on performance of repaired reinforced concrete beams. *Construction and Building Materials*, *20*(10), 901–909. https://doi.org/10.1016/j.conbuildmat.2005.06.020

Md Zain, M. R., Yahya, N. A., Dhanasekar, M., Zain, M., Oh, C. L., & Lee, S. W. (2018). Bearing strength of concrete for difference heights of concrete blocks. *IOP Conference Series: Materials Science and Engineering*, *431*(7). https://doi.org/10.1088/1757-899X/431/7/072011

Nikoloutsopoulos, N., Passa, D., Gavela, S., & Sotiropoulou, A. (2018). Comparison of shear strengthening techniques of reinforced concrete beams with carbon fibre reinforced polymers (CFRPs). *Procedia Structural Integrity*, *10*, 141–147. https://doi.org/10.1016/j.prostr.2018.09.021

Nuroji, Hung, C. C., Prasetya, B. H., & Han, A. (2020). The behavior of reinforced concrete members with section enlargement using self-compacting concrete. *International Review of Civil Engineering*, *11*(3), 121–126. https://doi.org/10.15866/irece.v11i3.18574

Obaid, W. A., AL-asadi, A. K., & Shaia, H. (2021). Repair and strengthening of concrete beam materials using different CFRP laminates configuration. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2021.09.532

Raizamzamani Md Zain, M., Azmi Yahya, N., Siong Wee, L., Lian, O. C., & Md Yunus, B. (2019). Experimental study on the bearing capacity of concrete blocks loaded through square and circular steel plates. *IOP Conference Series: Materials Science and Engineering*, *513*(1). https://doi.org/10.1088/1757-899X/513/1/012032

Scheffers, C. A., & Ravindrarajah, R. S. (2009). *Concrete Solutions 09 Bearing Strength of Concrete with and without FRP Confinement f Paper 4b-4*. *September 2009*, 1–10.

Täljsten, B. (2003). Strengthening concrete beams for shear with CFRP sheets. *Construction and Building Materials*, *17*(1), 15–26. https://doi.org/10.1016/S0950-0618(02)00088-0

Yahya, N. A. (2017). *Strategies for mitigation of the failure of concrete pedestals supporting bridge girder bearings*. 240.

Yahya, N. A., Dhanasekar, M., Md Zain, M. R., Oh, C. L., & Lee, S. W. (2019). Numerical modelling of concrete bearing strength for different heights of concrete blocks. *IOP Conference Series: Materials Science and Engineering*, *513*(1). https://doi.org/10.1088/1757-899X/513/1/012031

Yahya, N. A., Nor, N. M., Zain, R. M., Oh, C. L., & Lee, S. W. (2020). Bearing Strength of Circular Concrete Blocks Varies in Heights Subjected to Concentrically Circular Loaded Bearing Plate. *IOP Conference Series: Earth and Environmental Science*, *498*(1). https://doi.org/10.1088/1755-1315/498/1/012049

Yahya, Norrul Azmi. (2017). Strategies for Mitigation of the Failure of Concrete Pedestals Supporting Bridge Girder Bearings. *School of Civil Engineering and BUilt Environment Science and Engineering Faculty, Queensland University of Technology*, 240.

Ye, L., Yue, Q., Zhao, S., & Li, Q. (2002). Shear Strength of Reinforced Concrete Columns Strengthened with Carbon-Fiber-Reinforced Plastic Sheet. *Journal of Structural Engineering*, *128*(12), 1527–1534. https://doi.org/10.1061/(asce)0733-9445(2002)128:12(1527)

Zain, M. R. M., & Yahya, N. A. (2017). Experimental study on bearing strength of concrete blocks under concentric compression load. *Pertanika Journal of Science and Technology*, *25*(S7), 67–76.

Zain, M. R. M., Yahya, N. A., Wee, L. S., Lian, O. C., Rahman, A. S. A., & Dhanasekar, M. (2019). Bearing strength behaviour of bridge concrete pedestal with confined reinforcements. *Journal of Mechanical Engineering*, *16*(2), 167–181.

Zhuang, N., Dong, H., Zhou, Y., & Chen, D. (2018). Cracking behavior of reinforced concrete piles externally bonded with carbon fiber reinforced polymer in a marine environment. *Construction and Building Materials*, *190*, 1154–1162. https://doi.org/10.1016/j.conbuildmat.2018.09.185