INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 3 (2025) 23-33
https://publisher.uthm.edu.my/ojs/index.php/ijie

Effect of Specimen Shape on Bond Strength Between Deformed Steel Rebars and Normal Concrete

Nelly Majain[1,2]*, Muhd Fauzy Sulaiman[1,2], Ahmad Nurfaidhi Rizalman[2], Jodin Makinda[1]

[1] *Green Materials and Advanced Construction Technology, Faculty of Engineering, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, MALAYSIA*
[2] *Structures and Materials Research Team, Faculty of Engineering, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, MALAYSIA*

*Corresponding Author: nelly_mj@ums.edu.my
DOI: https://doi.org/10.30880/ijie.2025.17.07.003

Article Info

Received: 6 December 2024
Accepted: 30 September 2025
Available online: 23 December 2025

Keywords

Bond, pullout, bond strength

Abstract

The study of the bond between deformed steel rebar and concrete is essential in reinforced concrete structures, considering the assumption that rebar and concrete function as composite materials. Over the years, researchers have carried out bond testing, typically using the most common types of specimens, which are cube and cylinder specimens. Despite these advancements, an observation reveals the absence of studies exploring the effect of specimen shape on bond strength. Therefore, this study attempts to investigate the influence of specimen shape on the bond strength between rebar and normal concrete. The experimental work involves the preparation of cube pullout specimens measuring 200 mm × 200 mm × 200 mm, embedded with 16 mm and 20 mm rebars. The cube pullout specimens were then subjected to direct pullout testing using the RILEM pullout test standard. Subsequently, comparisons were made with previous experimental results employing cylindrical pullout specimens (100 mm diameter × 200 mm height), which were obtained by another researcher. The bond strength analysis uses normalised bond strength to minimise the effect of variations in concrete compressive strength. The results of the analysis indicate that bond strength is affected by the thickness of the concrete cover, which is influenced by the shape of the specimens.

1. Introduction

The study of bonds in reinforced concrete design is of vital importance as it is the basis for effective interaction between concrete and steel reinforcement, enabling them to function as a solid structural material. The bond formation in these composite materials required the transfer of load between the concrete and the reinforcement steel. Therefore, the bond can be described as a continuous distribution of stress that takes place throughout the interface of the steel and concrete [1]. Inadequate bond resistance can lead to the displacements or slips of the reinforcing rebar, resulting in the disruption of the composite action and ultimately causing failure, which is damaging to the overall structural system. Hence, the investigation of bond characteristics in reinforced concrete is of utmost importance, as it has the potential to impact the ultimate failure of reinforced concrete members.

Since the 1970s, various researchers have conducted quite extensively the bond study between rebars and normal concrete (NC) such as Orangun et al. [2], Eligehausen et al. [3], Ezeldin & Balaguru [4], and Reinhardt & Balázs [5]. The research shows that the bond strength between deformed steel rebar and concrete is significantly influenced by parameters such as concrete strength, rebar size, concrete cover, and confinement effect. Researchers also generally concur that the bond strength reduces as the diameter of the rebar increases. Contrary to this, Barbosa & Filho [6] found that the bond stress escalates as the size of rebar increases.

Over the years, various methods of bond testing have been developed by researchers, and the most common types of specimens used are cube and cylinder specimens. Rao et al. [7] used concrete cube specimens with dimensions of 150 mm x 150 mm x 150 mm embedded with 16 mm and 20 mm rebars. Meanwhile, Jansson et al. [8] carried out bond test using cube shape specimens having dimensions of 112 mm x 112 mm x 110 mm (depth), bonded with 16 mm diameter rebars and Fakoor & Nematzadeh [9] used 160 mm x 160 mm x 160 mm cube embedded with 12 mm and 16 mm rebars. Some researchers also prefer to use the diameter of rebar as a guideline to determine the size of the cube. For instance, Torre-Casanova et al. [10] used cube specimens with a dimension of 15 times the rebar diameter. Hence, different rebar sizes will have different cube sizes. Subsequently, Hameed et al. [11] and Garcia Taengua et al. [12] also used cube specimens with 200 mm length, width, and depth. The pullout test using the cube specimens was often conducted in accordance with the RILEM Standard [13], which specifies cubic specimens for testing having dimensions of not less than 200 mm.

On the other hand, some researchers preferred to use the cylinder type of specimen for the pullout testing. For example, Choi et al. [14] used cylinder specimens with a diameter of 100 mm and a length of 200 mm to conduct the bond study. These pullout specimens were embedded with 22 mm diameter of rebars. Other studies that used cylinder pullout specimens can be found in the work of Yeih et al. [15], which also used 100 mm diameter and 200 mm length. These researchers proposed to use the ASTM C-234-86 standard [16]. Subsequently, various other researchers have also used cylinder type of specimens to conduct the bond study using the pullout testing method [17]-[19].

Based on these existing studies, it was observed that none of the studies conducted discussed the effect of the specimen shape on the bond strength. The specimen shape will determine the concrete cover, which is imperative as the thickness of the concrete cover will affect the extent of the bond strength between rebar and the surrounding concrete. Based on the sizes of specimens used in the existing studies, it showed that the cube specimens would provide a much larger concrete cover as compared to the cylinder specimens.

Therefore, in this study, attempts will be made to compare the results of bond strength between pullout specimens cast in cube shape and pullout specimens cast in cylindrical shape. The cube pullout specimens were prepared in this study, whereas the cylinder pullout specimens will use the data provided by the study of Zaini [19]. This particular study was selected due to the similarity in terms of materials and mix proportions used in this study, as it was produced from the same laboratory. The main difference is the shape of the pullout specimens in which the current study used cube pullout specimens, whereas the previous study used cylinder pullout specimens. To compare the effect of concrete cover confinement and steel fibre confinement, the cube specimens were cast using plain concrete. These cube specimens will then be compared with cylinder specimens cast using plain and steel fibre concrete.

The following section entails the research methodology, which focuses on the materials and mix proportions used for the preparation of the cube pullout specimens. Subsequently, the preparation of the cube pullout specimens was also discussed, and the method of pullout testing was elaborated at the end of the research methodology. Afterwards, the results and discussion were presented, which mainly discussed the results from the cube pullout specimen. These results will then be compared with the results from previous study using the cylinder specimens. The results are expected to show the effect of concrete cover towards the bond strength of rebar and concrete, which is due to the shape of specimens.

2. Materials and Method

In this study, a total of six (6) cube pullout specimens were prepared. These cube specimens were cast using plain normal concrete and tested using the direct pullout testing method. The results were then compared with the pullout testing results derived from other study conducted by Zaini [19] that used cylinder pullout specimens. The following sections describe the materials used and the preparation and testing of the pullout specimens, which includes mechanical properties and direct pullout testing.

2.1 Materials and Mix Proportions

The mix design proportions for the normal concrete (NC) adopt the methodology specified by the Department of Environment (DOE). The DOE method, a concrete mix design technique, originated in the United Kingdom in 1975 and underwent revisions in 1988. The DOE method was chosen due to its suitability for normal-weight concrete, which may be produced using solely Portland cement or by mixing with other cementitious materials [20]. The NC mixes were developed to achieve a compressive strength of 40 N/mm^2 after 28 days of curing. This grade of concrete is similar to the grade of concrete used in the cylinder pullout specimens designed by Zaini [19]. The concrete materials and mix proportions are shown in Table 1. As seen in this table, the content of the constituent materials for both types of specimens are comparable, and the water/cement ratio is identical for both types of mixes. As also seen in Table 1, the cylinder specimens were added with 1% and 1.5% of 35 mm hooked-end steel fibres. These specimens will be compared with the cube specimens to study the effect of steel fibre confinement and concrete cover confinement.

The NC mixing procedure for cube pullout specimens begins by combining the dried coarse aggregate and fine aggregate for a duration of 30 seconds. Subsequently, half of the entire water volume was poured into the combined aggregate and mixed for an additional duration of 1 minute. Afterwards, cement and half of the remaining water were added, and the mixing process proceeded for an additional 2 minutes.

Table 1 *NC materials compositions for concrete in cube and cylinder specimens (1 m^3 volume)*

Component	Content (kg/m^3)	
	Cube Pullout Specimen	Cylinder Pullout Specimen [19]
Cement	444	485
Fine aggregate	813	810
Coarse aggregate	954	810
Water	213	235
Water/Cement	0.48	0.48
Superplasticiser	0	1.2
Steel Fibre	0	1% and 1.5%

2.2 Pullout Specimens

In order to examine the mechanical properties of the hardened concrete, some samples were prepared using the same batch of concrete used in the cube pullout specimens. These samples were cubic samples of 100 mm × 100 mm × 100 mm, specifically prepared for the compressive strength test. The preparation of these samples followed the guidelines outlined in the BS EN 12390-3 standard [21]. The specimens used for the splitting tensile strength test have dimensions of 100 mm in diameter and 200 mm in height. These specimens were prepared in accordance with the BS EN 12390-6 standard [22]. In this study, only the 28-day results of concrete compressive strength and splitting tensile strength were presented, as the direct pullout testing was only conducted 28 days after curing.

(a) **(b)**

Fig. 1 *Pullout specimens: (a) cube pullout specimens with 16 mm and 20 mm rebars; and (b) cylinder pullout specimens with 16 mm and 20 mm rebars [19]*

A total of six (6) cube pullout specimens were prepared in this study. Some of the cast cube pullout specimens are as shown in Fig. 1(a). The cube specimen can be identified using the following designation, CB-NC-16-B35-3Ø, which represents a cube specimen (CB), normal concrete (NC), with a rebar diameter of 16 mm (16), located at the bottom with a concrete cover of 35 mm (B35), and an embedment length that is three times the rebar diameter (3Ø). Meanwhile, the cylinder pullout specimen selected in the previous study is as shown in Fig. 1(b). Similar to the total number of cube specimens, six (6) cylindrical specimens were selected for the investigation. The cylinder specimen can be identified using this abbreviation, CY-SF-16-1, which represents a cylinder specimen (CY), steel fibre reinforced concrete (SF), with a rebar diameter of 16 mm (16) and added with 1% of steel fibre volume fractions (1). Both the cube and cylinder specimens were embedded with 16 mm and 20 mm deformed steel rebars, which are high-yield rebars with characteristics yield strength of 460 MPa. The comparison of both cube and cylinder pullout specimens in terms of embedment length, thickness of concrete cover and position of rebar is shown in Table 2.

Table 2 *Comparison of cube and cylinder pullout specimens*

Specimen	Rebar Size, Ø (mm)	Embedment Length, l_d (mm)	Min. Concrete Cover, c_{min} (mm)	Max. Concrete Cover, c_{max} (mm)	Position of rebar
Cube					
CB-NC-16-92-3Ø	16	48	92	92	Middle
CB-NC-16-B35-3Ø		48	35	149	Bottom
CB-NC-16-T35-3Ø		48	35	149	Top
Cylinder [18]					
CY-NC-16 (0% steel fibres)	16	65	47	47	Middle
CY-SF-16-1 (1.0% steel fibres)		65	47	47	Middle
CY-SF-16-1.5 (1.5% steel fibre)		65	47	47	Middle
Cube					
CB-NC-20-90-3Ø	20	60	90	90	Middle
CB-NC-20-B35-3Ø		60	35	145	Bottom
CB-NC-20-T35-3Ø		60	35	145	Top
Cylinder [18]					
CY-NC-20 (0% steel fibres)	20	65	45	45	Middle
CY-SF-20-1 (1.0% steel fibres)		65	45	45	Middle
CY-SF-20-1.5 (1.5% steel fibre)		65	45	45	Middle

The concrete cover for the cube pullout specimens varies according to the position of the embedded rebars. Fig. 2 shows the position of the rebar, which affects the thickness of the concrete cover. The placement of rebars at both the top and bottom of the pullout specimen is to resemble the positioning of rebars in concrete structures such as beams. It is anticipated that the bond between the top and bottom rebars may vary due to the casting direction.

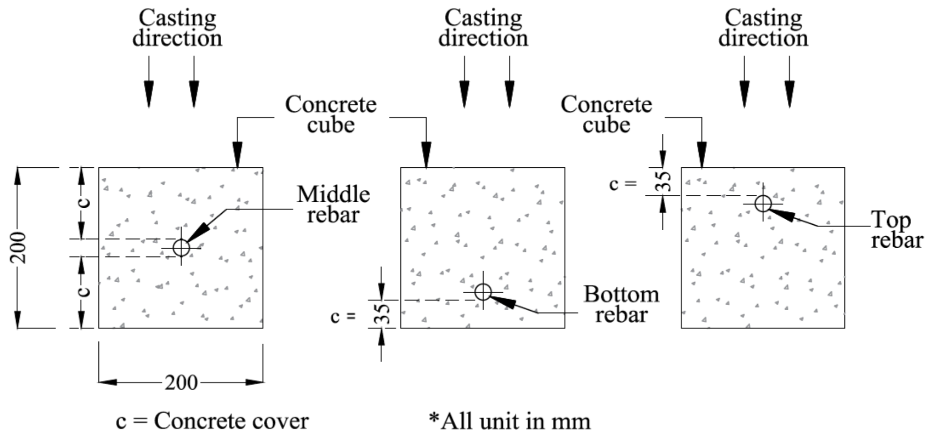
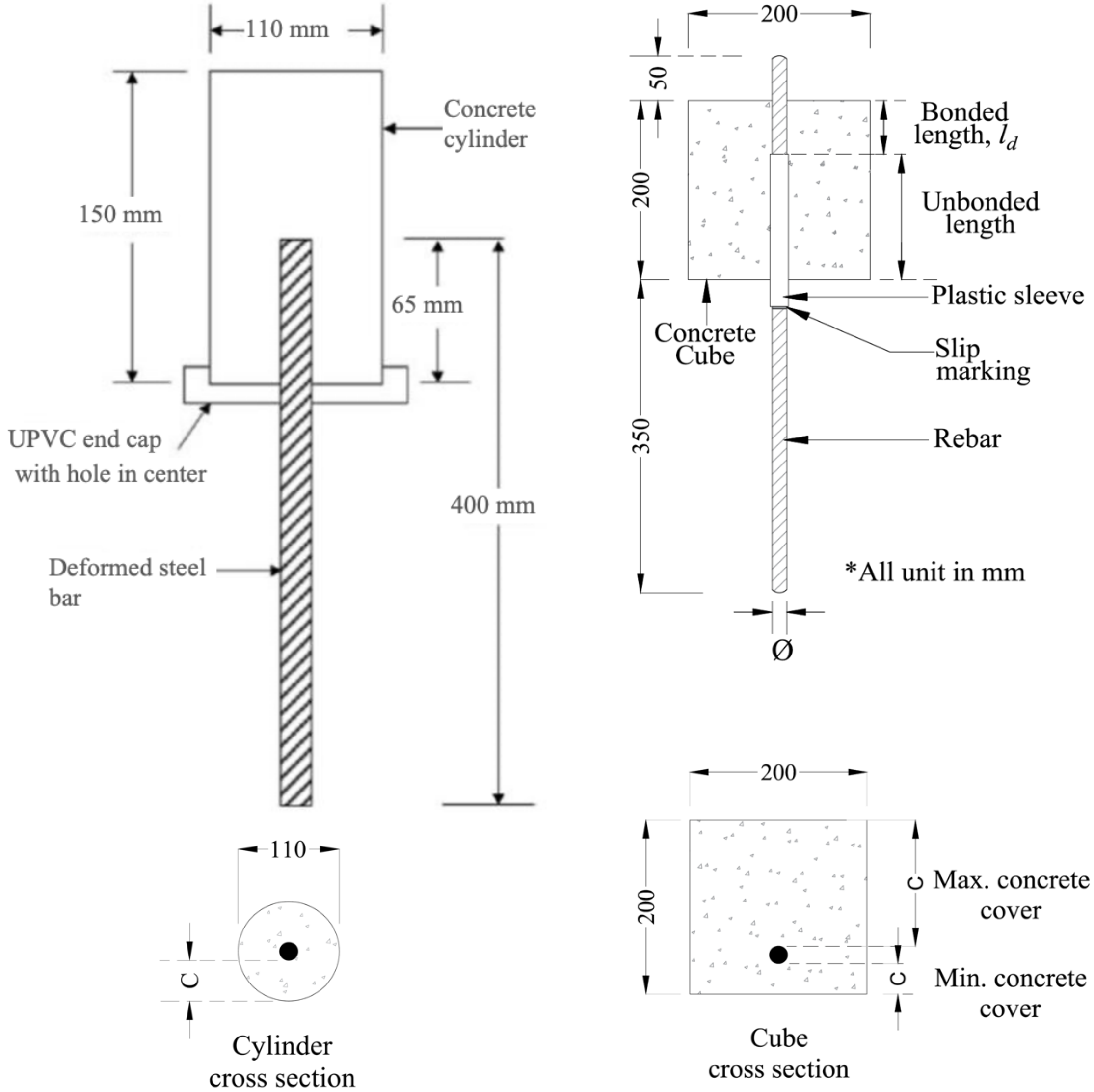


Fig. 2 *Thickness of concrete cover and position of rebar in cube pullout specimen*

Subsequently, the comparison of dimensions between cube and cylinder pullout specimens can be referred to in Fig. 3. As seen in this figure, the cylindrical specimen has a diameter of 110 mm and a height of 150 mm. The rebar was inserted into the concrete at a depth of 65 mm, and the concrete cover, denoted as *c*, measures 47 mm and 45 mm for the 16 mm and 20 mm diameter rebar, respectively. On the other hand, the cube specimen measures 200 mm in length, breadth, and height. The minimum thickness of concrete required to cover the rebar positioned in the middle of the specimen is 92 mm and 90 mm for the rebar with diameters of 16 mm and 20 mm, respectively. The minimum concrete cover for the rebar positioned at the top and bottom of the specimen is 35 mm. The required length of embedment for both sizes of rebars is three times the diameter of the rebar.



Cylinder specimen [19]

- Diameter: 110 mm
- Height: 150 mm
- Concrete Type: NC and steel fibre reinforced concrete (1.0 and 1.5% steel fibres)
- Concrete Grade: 40

Cube specimen

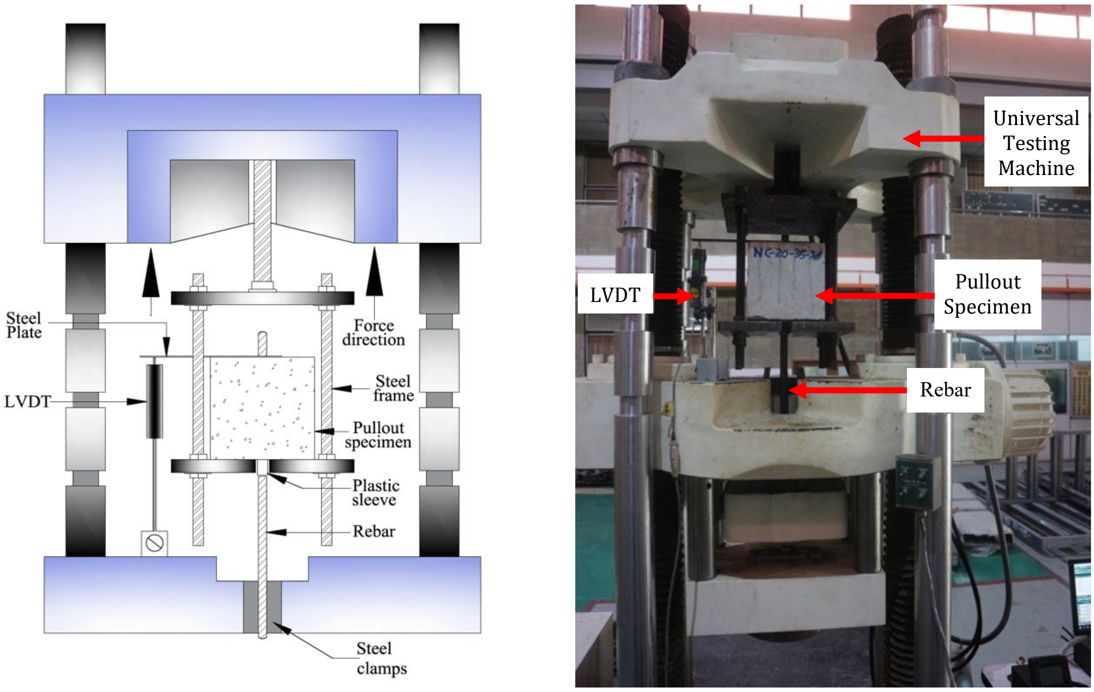
- Length, width and height: 200 mm
- Concrete Type: NC (without steel fibres)
- Concrete Grade: 40

Fig. 3 *Dimensions of the cylindrical and cube pullout specimens*

2.3 Direct Pullout Testing

The direct pullout testing for the cube specimens was conducted using the RILEM RC6 Part 2 standard [13], while the pullout testing for the cylinder specimens was carried out in accordance with the specification of ASTM C-234-86 [16]. The direct pullout testing setup for the cube specimen can be seen in Fig. 4(a) and Fig. 4(b). Once the cube specimen was positioned in the testing frame, the machine control system exerted forces on it, while maintaining deformation at a steady rate of 0.01 mm/s. The progressive forces exerted caused the steel frame to move up, resulting in an upward displacement of the concrete cube. The test is conducted until failures, which might occur due to splitting or pullout failures. Consequently, the maximum load at failure was recorded and analysed. The procedure for testing and acquiring data for the cylinder specimen is essentially identical to that of the cube specimen. Based on the load acquired in the testing of the cube specimens, the bond stresses were calculated using Eq. (1). In this equation, τ is the bond stress in MPa, P is the applied load in Newton (N), Ø is the rebar diameter in mm, and l_d is the embedment length in mm. Subsequently, the bond strength, τ_u is the maximum bond stress in N/mm^2, corresponding to the peak load recorded.

$$\tau = \frac{P}{\pi.\varnothing.l_d} \tag{1}$$



(a) **(b)**

Fig. 4 *Pullout testing: (a) Details of direct pullout testing setup for cube pullout specimen; and (b) Direct pullout testing using universal testing machine*

3. Results and Discussion

The pullout test results for the cylindrical and cube specimens are shown in Table 3. The comparison of the bond strength is using the normalised bond strength so that the effect in the variation of concrete compressive strength can be minimised. The normalised bond strength is frequently employed for comparative examination of various concrete types and strengths. The research work of Orangun et al. [2] has been referred to in ACI Code 318 and FIB Bulletin No. 1. These sources define the normalised bond strength as the ratio of bond strength to the square root of the concrete compressive strength. Comparing the bond strength behaviour of different concrete strengths can be done equally by applying the normalised bond strength. Eq. (2) shows the normalised bond strength (τ_n) which is bond strength (τ_u) divided by the square root of concrete compressive strength, $\sqrt{f_{cu}}$. Subsequently, some figures are also shown to illustrate in detail the comparison of cracks between the cubic and cylindrical specimens.

$$\tau_n = \frac{\tau_u}{\sqrt{f_{cu}}} \tag{2}$$

3.1 Specimens With 16 mm Diameter Rebars

As depicted in Fig. 5(a), the mode of failure for the cylindrical specimen CY-NC-16 is splitting failure, due to the absence of steel fibre. The normalised bond strength is also very low, which is only 0.97. On the other hand, the normalised bond strength of the cube specimen, CB-NC-16-92-3Ø, is 3.40, and no cracks were observed, as shown in Fig. 5(b). It is imperative to observe that the minimum concrete cover in the cube specimen is 92 mm, which is about double the thickness of the concrete cover of the cylinder specimen (47 mm). Hence, doubling the thickness of the concrete cover resulted in a 3.5 times improvement in bond strength of the cube specimen as compared to the cylinder specimen.

The normalised bond strength of CY-SF-16-1 with 1.0% steel fibres is 1.95, and the mode of failure is pullout failure with no sign of cracks, as depicted in Fig. 5(c). Meanwhile, the cube specimen, CB-NC-16-T35-3Ø, shown in

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Fig. 5(d), has a bond strength of 1.82, which is comparable to CY-SF-16-1 with 1.0% steel fibres. It was also observed that the bond strength of cube specimen CB-NC-16-T35-3Ø was greatly reduced as compared to the CB-NC-16-92-3Ø specimen. This is due to the small concrete cover of the CB-NC-16-T35-3Ø, in which the rebar is positioned 35 mm below the top surface of the cube specimen. Furthermore, as a result of the casting orientation, the positioning of the rebar also rendered it susceptible to cracks. This occurred because, at the beginning of the curing process, the upper layer of the fresh concrete in the cube specimen tends to bleed, which may reduce the bond strength between the top rebar and the concrete. However, the bond strength of the cube specimen remains comparable to that of the cylinder specimen, which is greatly reinforced with 1.0% steel fibres. This finding implies that the maximum concrete cover, located 149 mm below the top rebar, has a substantial effect in enhancing the bond strength of the cube specimen. It appears that this effect is similar to the impact of adding 1.0% of steel fibres in concrete with a concrete cover thickness of 47 mm.

Meanwhile, the bond strength of the cylinder specimen CY-SF-16-1.5, which has 1.5% steel fibres, is 3.13, as depicted in Fig. 5(e). As seen in this figure, the mode of failure is still pullout failure, with some hairline cracks observed near the rebar. Subsequently, the bond strength of the plain cube specimen CB-NC-16-B35-3Ø, as illustrated in Fig. 5(f), is 3.59, which is higher than the normalised bond strength of the cylindrical specimen. There are also some hairline cracks observed on this cube specimen. These findings indicate that the concrete confinement in the cube specimen seems to be effective in enhancing the bond strength. It was also observed that despite the heavy confinement of the cylinder specimen with 1.5% steel fibres, the bond strength was comparatively lower than that of the cube specimen without steel fibre confinement. Hence, it can be considered that the primary factor contributing to the bond strength enhancement in the cube specimen is the maximum concrete cover, which is 149 mm thick from the top of the bottom rebar.

3.2 Specimens With 20 mm Diameter Rebars

Some findings in specimens with 16 mm rebars were also similar to specimens embedded with 20 mm diameter rebars. According to the results presented in Table 3, the cube specimen CB-NC-20-90-3Ø has a normalised bond strength of 2.92, while the cylinder specimen (CY-NC-20) is 0.81. This shows that the bond strength of the cube specimen is 3.6 times greater than that of the cylinder specimen with 0% steel fibres. This is undoubtedly due to the larger concrete cover thickness of the cube specimen. The increased thickness of the concrete cover in the cube specimen, which measures 90 mm, makes it two times as thick as the concrete cover of the cylinder specimen, which contributes to the increase in bond strength.

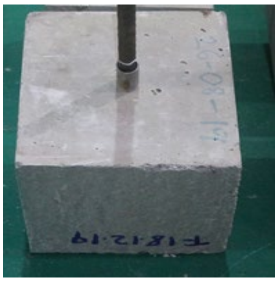
Meanwhile, the cube specimen, CB-NC-20-T35-3Ø, has a normalised bond strength of 1.61, which is comparable to the cylinder specimen CY-SF-20-1 (with 1.0% steel fibres), with a normalised bond strength of 1.73. The mode of failure for the cube specimen is pullout failure with a hairline crack, as stated in Table 3. Similar to the cube specimen embedded with 16 mm top rebar, the hairline crack is due to the casting orientation, in which the positioning of the top rebar makes it susceptible to cracks and hence reduce the bond strength. Subsequently, the normalised bond strength of the cube specimen CB-NC-20-B35-3Ø is close to that of the cylindrical specimen CY-SF-20-1.5 with 1.5% steel fibres, which are 2.35 and 2.36, respectively. This demonstrates the significant contribution of the maximum concrete cover of the cube specimen, which is 145 mm from the top of the bottom rebar. The thicker concrete cover in the cubic specimen contributes to improving the bond strength, making it equivalent to the bond strength of a cylindrical specimen reinforced with 1.5% steel fibres.

These findings clearly indicate that the bond strength was affected by the thickness of the concrete cover because of the shape of the specimens. While cylindrical specimens ensure uniform concrete cover thickness around the rebar, this may not accurately reflect the actual bond strength between the rebar and concrete. This is because, in structural members like beams, the concrete cover thickness varies depending on whether the rebar is positioned at the top or bottom of the specimen. Hence, the bond strength derived from a cylindrical specimen reinforced with steel fibres may underestimate the actual strength of the bond due to the exclusion of the contribution of the maximum concrete cover. On the other hand, it is estimated that the bond strength of the cube specimen will be significantly enhanced by employing the same volume of fibres applied in the cylinder specimen, owing to the synergistic effects of steel fibres and the confinement effects of the concrete cover.

Table 3 *Comparison of pullout testing results for cube and cylinder specimens*

Specimen	Rebar Size, Ø (mm)	Embed-ment Length, l_d (mm)	Min. Concrete Cover, c_{min} (mm)	Max. Concrete Cover, c_{max} (mm)	Position of rebar	Average Compre-ssive Strength, f_{cu} (MPa)	Average Splitting Tensile Strength, f_{cts} (MPa)	τ_u (MPa) Eq. (1)	$\tau_n = \tau_u/\sqrt{f_{cu}}$	Mode of Failure (P-O: Pullout, S: Splitting)
Cube										
CB-NC-16-92-3Ø		48	92	92	Middle	49.77	4.47	23.99	3.40	P-O
CB-NC-16-B35-3Ø	16	48	35	149	Bottom	56.94	5.33	27.06	3.59	P-O (hairline cracks)
CB-NC-16-T35-3Ø		48	35	149	Top	57.30	3.95	13.80	1.82	P-O
Cylinder [19]										
CY-NC-16 (0% steel fibres)		65	47	47	Middle	53.11	5.57	7.04	0.97	S
CY-SF-16-1 (1.0% steel fibres)	16	65	47	47	Middle	49.85	7.64	13.77	1.95	P-O
CY-SF-16-1.5 (1.5% steel fibres)		65	47	47	Middle	48.34	6.45	21.73	3.13	P-O (hairline cracks)
Cube										
CB-NC-20-90-3Ø		60	90	90	Middle	49.77	4.47	20.58	2.92	P-O
CB-NC-20-B35-3Ø	20	60	35	145	Bottom	56.94	5.33	17.72	2.35	S- Premature
CB-NC-20-T35-3Ø		60	35	145	Top	57.30	3.95	12.17	1.61	P-O (hairline cracks)
Cylinder [19]										
CY-NC-20 (0% steel fibres)		65	45	45	Middle	53.11	5.57	5.88	0.81	S
CY-SF-20-1 (1.0% steel fibres)	20	65	45	45	Middle	49.85	7.64	12.24	1.73	P-O
CY-SF-20-1.5 (1.5% steel fibres)		65	45	45	Middle	48.34	6.45	16.40	2.36	P-O

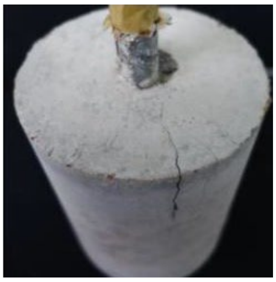
CY-NC-16
(0% steel fibres)
τ_u = 7.04 MPa, τ_n = 0.97
(a)



CB-NC-16-92-3Ø
τ_u = 23.99 MPa
τ_n = 3.40
(b)

CY-SF-16-1
(1.0% steel fibres)
τ_u = 13.77 MPa, τ_n = 1.95
(c)

CB-NC-16-T35-3Ø
τ_u = 13.80 MPa
τ_n = 1.82
(d)



CY-SF-16-1.5
(1.5% steel fibres)
τ_u = 21.73 MPa, τ_n = 3.13
(e)

CB-NC-16-B35-3Ø
τ_u = 27.06 MPa
τ_n = 3.59
(f)

Fig. 5 *Comparison of the mode of failure between cylinder specimens [19] and cube specimens embedded with 16 mm diameter rebar*

4. Conclusion

This study investigates the effect of specimen shape on the bond strength between deformed steel rebar and normal concrete. The comparison of the specimen shape involves the cube specimen against the cylinder specimen. Due to the shape of the specimens, the concrete cover may vary for both cubic and cylindrical specimens. Based on the analysis of the normalised bond strength, it was observed that the bond strength is affected by the thickness of the concrete cover as a result of the shape of the specimen. It was also observed that despite the heavy confinement of the cylinder specimen with 1.5% steel fibres, the bond strength was comparatively lower than that of the cube specimen without steel fibre confinement. Consequently, it can be considered that the primary factor contributing to the bond strength enhancement in the cube specimen is the maximum concrete cover. Therefore, the bond strength derived from a cylindrical specimen may underestimate the true value of the bond since it does not account for the maximum concrete cover contribution.

Acknowledgement

The authors would like to express their deepest gratitude to the Ministry of Higher Education Malaysia (MOHE), Universiti Teknologi Malaysia (UTM), Research Grant Votes No. 14H69 for making this study possible and also to Green Materials and Advanced Construction Technology (GMACT) Research Unit and Structure and Material

Research Group (SMART) of the Faculty of Engineering, Universiti Malaysia Sabah (UMS) for their continuous support and assistance.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Nelly Majain;* ***Data collection:*** *Nelly Majain;* ***Analysis and interpretation of results:*** *Nelly Majain, Muhd Fauzy Sulaiman;* ***Draft manuscript preparation:*** *Nelly Majain, Muhd Fauzy Sulaiman, Ahmad Nurfaidhi Rizalman, Jodin Makinda. All authors reviewed the results and approved the final version of the manuscript.*

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