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Analysis of CFRP Confined Concrete Cylinders by using ABAQUS Software

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ABSTRACT

The fiber-reinforced polymer (FRP) wrapping is widely used in concrete column strengthening, as it can enhance concrete strength and ductility. This study aims to develop finite element numerical model that can capture the behavior of the short cylinder column confined with CFRP. After validating the proposed finite element models with previous experimental works, a series of parametric studies have been conducted, including, CFRP number of layers, concrete grade, confinement configuration, and size of samples are investigated in terms of stress-strain curves, ductility, and volumetric strain. The results indicate a significant improvement in concrete strength after fully CFRP wrapping. However, the partial confinement records less improvement in concrete strength but considerable ductility. By increasing the specimen's size and maintaining the same confinement ratio, the strength enhancement was decreased. Based on this observation; it can be concluded that; by increasing the samples sizes, it should be escorted with more confining ratio than that of the small size. Moreover, it was concluded that as the number of layers increases the ductility increases whether it was full or partial confinement configuration. The CFRP confinement can control the specimen's dilation during the axial compression test thus presenting less volumetric strain. The proposed formula by (Lam & Teng, 2003) that can predict the stress-strain response of FRP full confined concrete cylinder was compared with the corresponding values. The results indicated that; a good matching was noticed only for the samples located in the same area that was studied by (Lam & Teng, 2003).

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تحليل الأسطوانات الخرسانية المطوقة بالألياف الكربونية باستخدام برنامج ال ABAQUS

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الخلاصة

ان تغليف الخرسانة باستخدام الياف البوليمر المسلحة FRP يستخدم بشكل كبير في زيادة قوة الاعمدة الخرسانية لما له من قابلية على تحسين عدة خواص في الخرسانة كالقوة والمطاوعة. يهدف هذا البحث الى تقديم نموذج عددي باستخدام طريقة العناصر المحددة لديه القابلية على محاكاة التصرف الحقيقي لأسطوانة خرسانة مقواه باستخدام الياف الكاربون المسلحة. بعد التحقق من صحة النموذج العددي المقترح وذلك عبر مقارنته بنتائج دراسات عملية سابقة، تم اعداد دراسة حدودية واسعه تشمل تأثير عدة عوامل بضمنها: عدد طبقات الCFRP ، قوة انضغاط الخلطة الخرسانية، طريقة تغليف ال FRP (كامل او جزئي) وحجم العينة على تصرف منحني الاجهاد والانفعال، المطاوعة والانفعال الحجمي. ان نتائج هذه الدراسة بينت تحسن عالي في قوة الخرسانة ذات الحجم الاعتيادي (150 ×300) ملم بعد تغليفها بشكل كامل سواءاً كانت بطبقة واحدة او اثنان او ثلاثة. اما عند تغليفها بشكل جزئي تم ملاحظة تحسن بمقدار اقل من نظيرتها المغلفة بشكل كلي. بزيادة حجم العينة مع المحافظة على نسبة الاحتضان بال FRP فأن تصرف بعض العينات ضعف عند مقارنة منحني الاجهاد والانفعال وبناءاً على هذه الملاحظة من الممكن الاستنتاج بأن زيادة حجم العينات يجب ان يرافق بزيادة نسبة الاحتضان بال FRP. في هذه الدراسة، قُيمت ايضاً مطاوعة النماذج والانفعال الحجمي. حيث لوحظ ان بزيادة عدد طبقات ال CFRP تزيد مقدار مطاوعة النماذج سواءاً كانت محوطة بشكل كامل او جزئي. من الممكن السيطرة على التوسع الجانبي للخرسانة والذي يحدث عند تعرضها لضغط محوري عند تغليفها باستخدام ألياف الكاربون المسلحة وعليه فأن الانفعال الحجمي للخرسانة يكون بشكل اقل. تم اجراء مقارنة بين منحنيات الاجهاد والانفعال المستخرجة من النموذج التحليلي المقدم من قبل (Lam & Teng, 2003) مع نظيرتها المستحصلة من هذه الدراسة للنماذج المحوطة بشكل كامل بال CFRP، حيث لوحظ وجود تطابق عالي فقط للنماذج التي تقع ضمن حدود دارسة (Lam & Teng, 2003).

الكلمات الدالة: الياف البوليمر المسلحة، قوه انضغاط الخرسانة، العناصر المحددة.

1. INTRODUCTION

In recent years, different techniques have been used and studied to increase concrete columns strength; the purpose was either to enhance the new construction member or to rehabilitate the existing one. The steel jacketing was used, as it can increase the concrete confinement pressure, hence increasing its strength, but nowadays the fiber-reinforced polymer (FRP) wrapping was widely utilized in the strengthening of concrete columns with promising results, as it is capable of improving both; concrete strength and ductility [1, 2].The FRP provides an increasing confining pressure to the concrete as the last dilate with loading, contrary to the steel confinement, which provides approximately constant pressure after its yielding point [3] . However, when concrete is subjected to laterally confining pressure, the uniaxial compressive strength f_{cc} and the corresponding strain $\varepsilon_{cc}$are much higher than unconfined concrete. Generally, the stress-strain curve of FRP wrapped concrete response in ascending bi-linear manner. In the FRP sufficiently confined concrete, the ultimate compressive strength and its corresponding ultimate strain occur coincide, thus both of them are significantly improved. On the other hand, if the FRP amount is less than that sufficient value, the stress-strain curve will exhibit a descending post-peak branch, where the sample's ultimate compressive strength reaches before an ultimate strain and FRP rapture. Furthermore, this type of behavior will separate into two cases depending on concrete stress at the ultimate strain. If the stress-strain response ends at stress f'_{cu} above the compressive strength of unconfined concrete f'_{co}. However, when the curve ends at a stress $f'_{cu} < f'_{co}$, the specimen should be treated as insufficiently confined, in which a slight increase in concrete strength can be achieved [4]. It has been known that in the steel-confined concrete, the unstable dilation happens when the periphery steel yield [5]. However, in the FRP-confined concrete, the FRP high hoop stress can restrain that dilation only if the amount of FRP is large enough. Mirmiran et al, 1998 [6] suggested that for FRP-confined circular specimens, enhancement in the compressive strength of confined concrete should not be expected if the following modified confinement ratio is less than 0.15; $f_l/f'_{co} < 0.15$ where f_l is the lateral pressure. On the other hand, Xiao et al, 2000 [7] suggested that for FRP-confined concrete with $E_{frp}t/Rf_{co}^2 < 0.2$, a post-peak descending branch could be expected. Many researchers have been studied the FRP confined concrete behavior under several conditions, such as Xiao et al, 2000 [7], where 27 concrete cylinders confined by carbon fiber reinforced polymer composite jackets were tested. The parameters included concrete compressive strength and the FRP jacket thickness. It was concluded that the CFRP wrapping could expressively improve the concrete compressive strength and ductility. The tests result showed that, in CFRP confined concrete, the most influential factors that can affect its stress-strain response are; the concrete strength and the lateral confining pressure. Campione et al, 2015 [8] studied the use of a new class of composites in addition to the normal CFRP, which was constituted by Basalt Fiber Reinforced Polymer (BFRP) bonded with epoxy resin to concrete specimens as an alternative confinement material for compressed concrete members with respect to carbon or glass fibers, the number and type of plies (full or partial wrapping), the type of loading (monotonic and cyclic actions) and the type of fiber (basalt and carbon) are the main variables investigated. The experimental results obtained from the compressive tests in terms of both stress-strain curves and failure modes showed the possibility of reducing the brittleness of unconfined concrete, resulting in significantly increased both the post-peak resistance and the axial strain of confined concrete corresponding to BFRP failure. Hany et al, 2015 [9] investigated the axial stress-strain response of eighteen carbon-fiber-reinforced polymers (CFRP) confined circular, square, and rectangular column specimens subjected to cyclic axial compression. Guided by these test results and other test data reported in the technical literature, a constitutive axial stress-strain material model of CFRP-confined concrete under generalized loading was developed by Hany et al, 2015 [9]. Further to the experimental studies, many attempts have been made to model FRP-confined concrete columns using the Finite Element (FE) method. The FE simulation can save cost and time. The main advantage of this method is its ability to deal with geometric non-linearity and the interactions of different materials. However, the main complexity of the FE modeling lies in the proper definition of the properties of the different materials. FRP laminates are usually modeled as linear elastic materials. Only the hoop properties are crucial when the fibers are in the hoop directions. On the other hand, many constitutive models were suggested to define concrete properties in FE software, especially for concrete subjected to confinement pressure [10]. More recently, Drucker-Prager (D-P) type available in ABAQUS was one of the most used types of plasticity models for modeling confined concrete [11]. Studies using the D-P type plasticity model reported good results when predicting the monotonic behavior of FRP confined concrete. Among these studies, Rousakis et al, 2012 [12] was the first approach proposing closed-form equations that interrelate all the parameters of the D-P model for concrete uniformly confined with FRP. These parameters included hardening/softening function, plastic potential function, dilation parameter, damage parameter. The numerical results predict the actual behavior with reasonable accuracy. Hany et al, 2016 [10] studied the influence of the different input parameters of the concrete damaged plasticity model (CDPM) on the monotonic behavior of FRP-confined concrete columns. As a result, a modified CDPM was proposed to accurately predict the monotonic axial stress-axial strain responses of actively confined and FRP confined concrete columns. The accuracy of the proposed model was validated against experimental results of different carbon fiber reinforced polymer (CFRP) confined concrete specimens showed a good agreement. Accordingly, it was used in this research to simulate the required models. The approach relies on calibrating the dilation angle and hardening/softening rule to predict the theoretical lateral dilation of FRP-confined in circular sections and the stress-strain curves of actively confined concrete. Raza, et al, 2020 [13] investigated the behavior of FRP reinforced concrete columns confined with FRP tubes subjected to axial load. Where the required models were simulated using the finite element package ABAQUS 6.14, the calibration depended on the previous experimental results. The results presented a good agreement between the numerical and experimental behavior. Furthermore, an empirical model was developed based on 685 FRP-confined concrete compression members found in the literature. Saberi et al, 2020 [14] developed a finite element model that can capture the concrete columns wrapped with FRP material under compression load by modifying the concrete damage evolution. The Miehe phase-field approach was employed to simulate the concrete and FRP damage during loading. The proposed model presented an excellent accuracy by comparing it with its corresponding experimental behavior. This study aims to develop finite element numerical model that can capture the CFRP confined concrete cylinder behavior in addition to the normal unconfined concrete. First, the proposed model will be validated with the existing experimental tests found in the literature. After that, the effect of CFRP number of layers, concrete grade, confinement configuration, and sample sizes can be investigated in terms of stress-strain curves, ductility, and volumetric strain.

2. METHODOLOGY

Two element types were implemented to the two main parts, i.e., the concrete core (cylinder) and the CFRP sheets. The 8-nodes continuum 3D solid hexahedra brick element with reduced integration (C3D8R) was chosen to represent the concrete as it can be used for linear analysis and for complex nonlinear analyses involving contact, plasticity, and large deformations with high accuracy if not distorted [15]. The 4-node thin rectangular shell element (S4R) was used to represent the CFRP sheets, as it has a small thickness compared with its other two dimensions (length and width) [16]. A mesh size of 15 mm was adopted with a total number of element equal to 480, shown in Fig. 1.

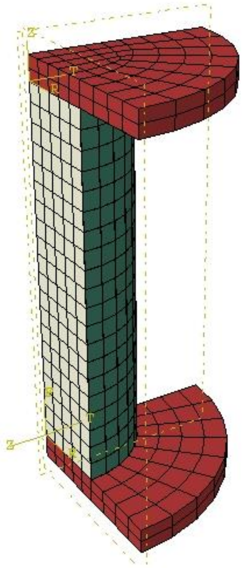

Fig. 1. Quarter model after meshing.

In this study, the CDP model was adopted to simulate concrete behaviors. This model is a continuum, plasticity-based damage model for concrete. It assumes that the main two failure mechanisms are the concrete material's tensile cracking and compressive crushing [15]. The definition of the CDP model needs three features: tensile behavior, compressive behavior, and plasticity parameters. The plasticity parameters were set to the default values suggested by ABAQUS, 2017 [15] for the normal unconfined concrete. However, for the FRP confined concrete; Hany et al, 2015 [9] recommendations were adopted, as it is capable of capturing the actual behavior of FRP confined concrete. After defining the previous plasticity parameters, the compressive stress-strain relation for the unconfined concrete was expressed by adopting Mander et al, 1998 [17]. Special consideration should be conducted to simulate the response of FRP confined concrete samples. For FRP-confined concrete columns, the confining pressure provided to the concrete core is not constant during loading but increases as concrete dilation increases. Accordingly, a series of actively confined stress-strain relations should be introduced to Abaqus to simulate the actual FRP confined concrete behavior. In this study, the relations for modified actively confined concrete were utilized to drive the required data, each relation was obtained based on certain confinement pressure for actively confined concrete, such that; each concrete element in the numerical model can perform based on its confinement pressure during loading. The user subroutine (redefine field variables at a material point), or "USDFLD" was adopted in this study, which will allow customizing the concrete hardening based on any field variable required as suggested by Hany et al, 2015 [9]. The adopted tensile stress-strain relation in this study was proposed by Hsu, 2010 [18] for normal concrete. However, the maximum tensile strengths were entered based on the experimental tests data that had been conducted. Based on Hany et al, 2015 [9] findings; the damage parameters don't significantly affect FRP confined concrete; therefore, it can be neglected. The FRP sheets demonstrate linear elastic behavior at the beginning before failure, at the ultimate stress the material will suddenly rupture. In this work the FRP sheets properties are introduced by using "LAMINA" material type, where the elastic modulus E1 in the hoop direction is defined by the value provided by the experimental report been simulated; while E2; G12; G13, and G23 are assigned as a small value if it wasn't stated in the experimental tests program, where E2 is the elastic modulus in the second direction, G is the shear modulus which will be specified in each direction. The Hashin damage model available in Abaqus which is used for modeling fiber-reinforced composite material was selected to simulate the failure and rupture of FRP in this study as it is capable of assigning material strength in each direction as required [15]. The experimental work, which has been executed by previous researchers [8, 7, 19] were simulated in this study. first, the unconfined concrete was simulated. Next, the concrete samples that are confined with; one layer, two layers, three layers, and partial confinement were modeled, and its results were validated based on the above-mentioned experimental study. The model geometry was simulated based on its corresponding experimental work. Accordingly, a cylinder with 150mm in diameter and 300mm in height was conducted in ABAQUS; only one-quarter of the model was conducted, as shown in Fig. 2, by taking advantage of the symmetry around the two axes in the vertical plans (Y-X and Y-Z).

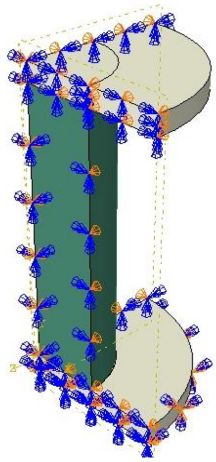

Fig. 2. Modeling quarter concrete cylinder.

Fig. 3 and Fig. 4 below present the behavior of the unconfined models, where the results showed a good agreement with the experimental work conducted by Campione, 2015 [8] and Xiao, 2000 [7], respectively.

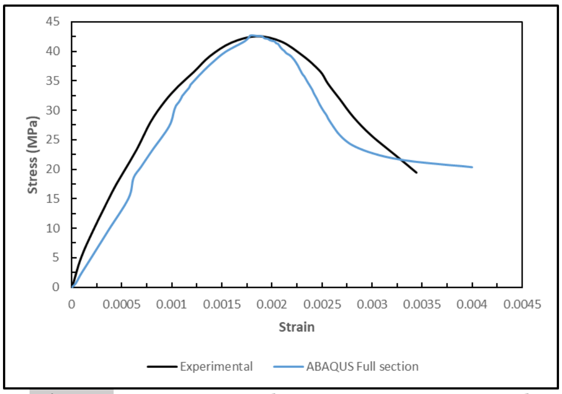

Fig. 3. Comparison between experimental work done by Campione, 2015 [8] and the proposed model for the unconfined concrete.

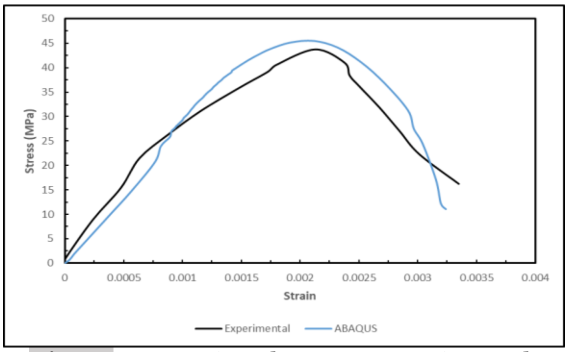

Fig. 4. Comparison between experimental work done by Xiao, 2000 [7] and the proposed model for the unconfined concrete.

The proposed finite element models for the cylinder concrete that are fully or partially confined by one, two, and three layers were compared with its corresponding experimental work that was tested by Campione, 2015 [8], Xiao, 2000 [7], and Zeng et al, 2018 [19]. A good agreement has been noticed for all samples, as shown in Fig. 5 through Fig. 8.

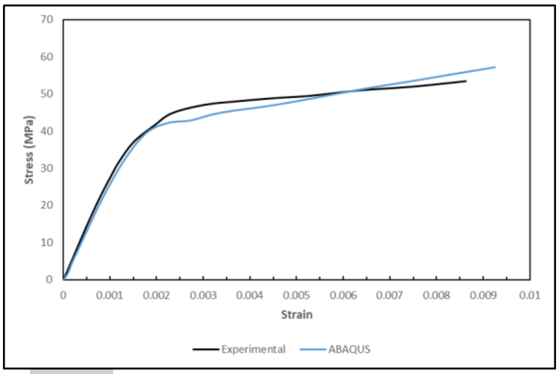

Fig. 5. Comparison between experimental work done by [8] and the proposed model for the confined concrete by one layer.

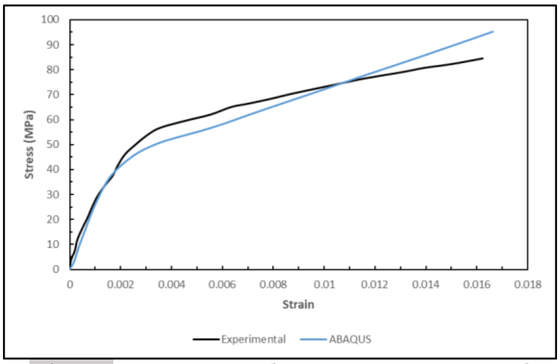

Fig. 6. Comparison between experimental work done by [7] and the proposed model for the confined concrete by two layers.

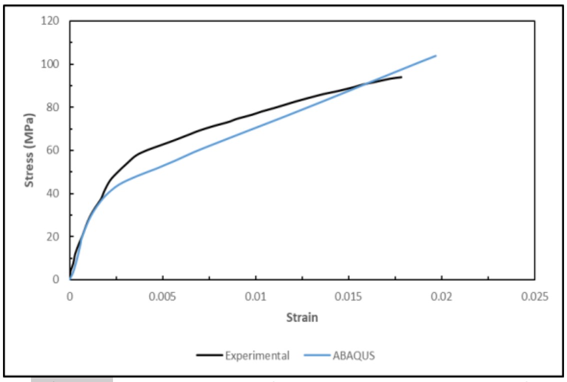

Fig. 7. Comparison between experimental work done by [7] and the proposed model for the confined concrete by three layers.

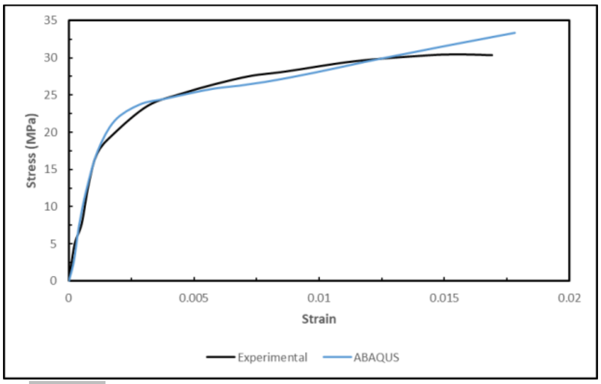

Fig. 8. Comparison between experimental work done by [19] and the proposed model for the partial confined concrete.

3. PARAMETRIC STUDY

A total of 36 CFRP- wrapped concrete cylinders were simulated. The effect of, CFRP layers, concrete compressive strength, confinement configuration (full or partial), and size of the specimen can be investigated in terms of stress-strain response, ductility, and volumetric strain. The specimens were categorized into three groups, each group has a specific size. The details of all samples are presented in Table 1. Moreover, the specimens were labeled to specify their properties. The first letter "S" followed by the number represents the size of the specimen: S1 means the first size; 150 x 300 mm cylinder, which has been chosen as the reference size based on ASTM C39 (compressive strength of cylindrical concrete specimens) [20], S2 means the second size; 300 x 600 mm cylinder, and S3 means the third size; 600 x 1200 mm cylinder. The second letter "C" followed by a number represents the concrete grade; C40 and C20 for 40MPa and 20MPa compressive strength, respectively. The third letter "L" followed by a number represents the CFRP number of layers; L1 for one layer, L2 for two layers, and L3 for three layers. Finally, the last letter "F or P" represents the confinement configuration, F for full confinement and P for partial confinement. The number of layers was assigned directly in ABAQUS as required and the concrete compressive strength. The confinement configuration for the partially wrapped cylinder was set by adjusting the width of the CFRP layers when the cylinder size needed to be changed and to fully explore the size effect on the CFRP-wrapped cylinder; the same confinement ratio (f_l/f_c) was carryout for each size, taking advantage of the ACI 440.2R-17 [21] expression of confinement pressure as shown in Eq. 1 below;

$$f_l = \frac{2E_f t_f n \varepsilon_f}{D} \qquad \textbf{Eq. 1}$$

Where f_l is the lateral confining pressure of FRP, E_f is the elastic modulus of FRP, t_f is the thickness of one FRP layer, n is the number of FRP layers, ε_f is the lateral strain of the FRP, and D is the sample diameter. By equalizing the confinement ratio and eliminating the constants for the investigated two sizes, the relation in Eq. 2 was obtained.

$$t_{f1}/D_1 = t_{f2}/D_2 \qquad \textbf{Eq. 1}$$

Table 1.
Specimens design parameters

	#	Specimen's label	Size (mm)	Compressive strength (MPa)	No. of CFRP layers	Confinement configuration	CFRP thickness t_f (mm)
Group S1	1	S1-C40-L1-F	150 X 300	40	1	Full	0.159
	2	S1-C40-L2-F	150 X 300	40	2	Full	0.318
	3	S1-C40-L3-F	150 X 300	40	3	Full	0.477
	4	S1-C20-L1-F	150 X 300	20	1	Full	0.159
	5	S1-C20-L2-F	150 X 300	20	2	Full	0.318
	6	S1-C20-L3-F	150 X 300	20	3	Full	0.477
	7	S1-C40-L1-P	150 X 300	40	1	Partial	0.159
	8	S1-C40-L2-P	150 X 300	40	2	Partial	0.318
	9	S1-C40-L3-P	150 X 300	40	3	Partial	0.477
	10	S1-C20-L1-P	150 X 300	20	1	Partial	0.159
	11	S1-C20-L2-P	150 X 300	20	2	Partial	0.318
	12	S1-C20-L3-P	150 X 300	20	3	Partial	0.477
Group S2	1	S2-C40-L1-F	300 X 600	40	1	Full	0.318
	2	S2-C40-L2-F	300 X 600	40	2	Full	0.636
	3	S2-C40-L3-F	300 X 600	40	3	Full	0.954
	4	S2-C20-L1-F	300 X 600	20	1	Full	0.318
	5	S2-C20-L2-F	300 X 600	20	2	Full	0.636
	6	S2-C20-L3-F	300 X 600	20	3	Full	0.954
	7	S2-C40-L1-P	300 X 600	40	1	Partial	0.318
	8	S2-C40-L2-P	300 X 600	40	2	Partial	0.636
	9	S2-C40-L3-P	300 X 600	40	3	Partial	0.954
	10	S2-C20-L1-P	300 X 600	20	1	Partial	0.318
	11	S2-C20-L2-P	300 X 600	20	2	Partial	0.636
	12	S2-C20-L3-P	300 X 600	20	3	Partial	0.954
Group S3	1	S3-C40-L1-F	600 X 1200	40	1	Full	0.636
	2	S3-C40-L2-F	600 X 1200	40	2	Full	1.272
	3	S3-C40-L3-F	600 X 1200	40	3	Full	1.908
	4	S3-C20-L1-F	600 X 1200	20	1	Full	0.636
	5	S3-C20-L2-F	600 X 1200	20	2	Full	1.272
	6	S3-C20-L3-F	600 X 1200	20	3	Full	1.908
	7	S3-C40-L1-P	600 X 1200	40	1	Partial	0.636
	8	S3-C40-L2-P	600 X 1200	40	2	Partial	1.272
	9	S3-C40-L3-P	600 X 1200	40	3	Partial	1.908
	10	S3-C20-L1-P	600 X 1200	20	1	Partial	0.636
	11	S3-C20-L2-P	600 X 1200	20	2	Partial	1.272
	12	S3-C20-L3-P	600 X 1200	20	3	Partial	1.908

4. THE RESULTS AND DISCUSSION

4.1. Comparison between ABAQUS program and Lam and Teng, 2003 [4] model

The proposed formula by Lam and Teng, 2003 [4] that can predict the stress-strain response of FRP full confined concrete cylinder was compared with the corresponding values obtained in this study for each model, for the S1 group. The results indicated that; a good matching was noticed for all samples located in the S1-C40 group, as shown in Fig. 9, were a maximum deviation of only 8.34% and 9.05% in the ultimate stress and strain respectively. However, the remaining samples in the S1 group that have unconfined strength of 20 MPa; were recorded more deviation. Where a max difference of 12.76% and 21.54% in the ultimate stress and strain respectively. this increment can be explained by the fact that; the formula proposed by Lam and Teng, 2003 [4] was tested on concrete samples with a compressive strength ranging from 26.2 MPa to 55.2 MPa only. A large gap has been noticed in the remaining S2 and S3 groups samples even for C40 concrete grade as shown in Fig. 10 and Fig. 11. This change in the responses can be explained by the fact that; the formula proposed by Lam and Teng, 2003 [4] was tested in concrete samples with a diameter ranging from 100mm to 200mm only. Taking into consideration that; the size of diameter was playing a major role in determining the ultimate strain in the Lam and Teng, 2003 [4] proposed formula, the gap will be increased as the samples size increase. The proposed formula by Lam and Teng, 2003 [4] that can predict the stress-strain response of FRP full confined concrete cylinder was compared with the corresponding values obtained in this study for each model, for the S1 group. The results indicated that; a good matching was noticed for all samples located in the S1-C40 group, as shown in Fig. 9, were a maximum deviation of only 8.34% and 9.05% in the ultimate stress and strain respectively. However, the remaining samples in the S1 group that have unconfined strength of 20 MPa; were recorded more deviation. Where a max difference of 12.76% and 21.54% in the ultimate stress and strain respectively. this increment can be explained by the fact that; the formula proposed by Lam and Teng, 2003 [4] was tested on concrete samples with a compressive strength ranging from 26.2 MPa to 55.2 MPa only. A large gap has been noticed in the remaining S2 and S3 groups samples even for C40 concrete grade as shown in Fig. 10 and Fig. 11. This change in the responses can be explained by the fact that; the formula proposed by Lam and Teng, 2003 [4] was tested in concrete samples with a diameter ranging from 100mm to 200mm only. Taking into consideration that; the size of diameter was playing a major role in determining the ultimate strain in the Lam and Teng, 2003 [4] proposed formula, the gap will be increased as the samples size increase.

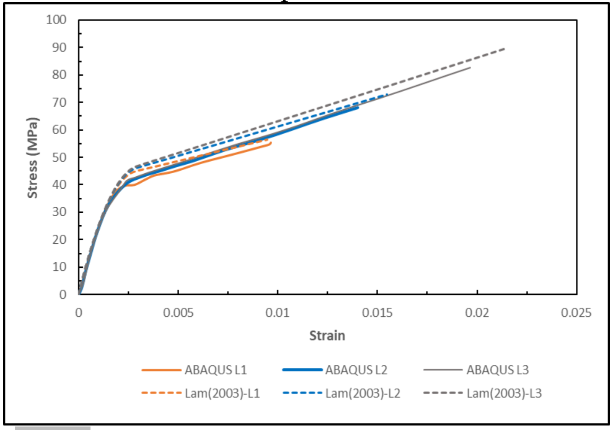

Fig. 9. Comparing the stress-strain response of S1 with (Lam & Teng, 2003) prediction.

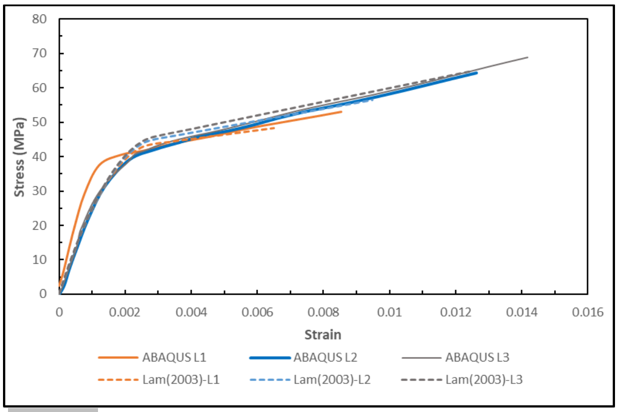

Fig. 10. Comparing the stress-strain response of S2 with (Lam & Teng, 2003) prediction.

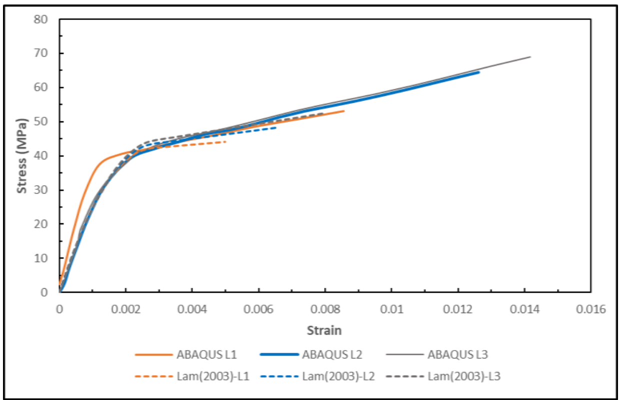

Fig. 11. Comparing the stress-strain response of S3 with (Lam & Teng, 2003) prediction.

4.2. Stress-strain curve

Increasing the number of layers on compressive strength for group S1 is presented in Table 2 by comparing it with the reference unconfined specimen, which records a compressive strength equal to 40.59 MPa and 20.67 MPa for the two concrete grades.

Table 2.
Results summary for the group S1:

#	Specimen's label	The percentage of enhancement in compressive strength compared with control specimen (%)
1	S1-C40-L1-F	36.41
2	S1-C40-L2-F	67.85
3	S1-C40-L3-F	103.84
4	S1-C20-L1-F	66.33
5	S1-C20-L2-F	129.27
6	S1-C20-L3-F	209.29
7	S1-C40-L1-P	1.38
8	S1-C40-L2-P	26.44
9	S1-C40-L3-P	38.33
10	S1-C20-L1-P	15.09
11	S1-C20-L2-P	51.72
12	S1-C20-L3-P	80.31

4.2.1. The effect of the number of layers on fully confinement configuration

The influence of the number of layers has a significant effect on strength. Accordingly, as the number of layers increases the ultimate strength of the specimen increases. As shown in Fig. 12, the unconfined reference concrete with strength equal to 40.59 MPa was improved by 36.41%, 67.85%, and 103.84% when the samples were wrapped with one, two, and three layers respectively, as the number of layers increases the confining pressure to the concrete core will be increased. Therefore, the concrete strength will be improved further.

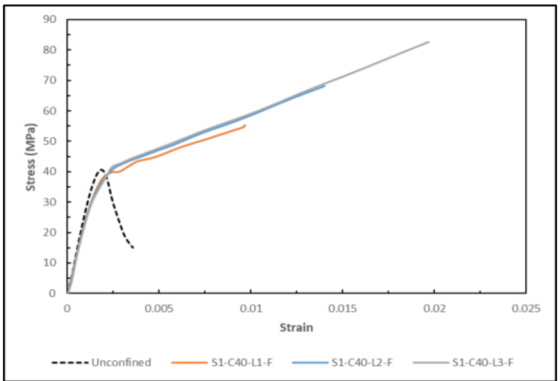

Fig. 12. CFRP-wrapped concrete samples response (C40).

The same behavior has been noticed in the concrete samples with grade C20. Comparing with the unconfined model; an enhancement of 66.33%, 129.27%, and 209.29% has been noticed when the samples were wrapped with one, two, and three layers respectively as shown in Fig. 13.

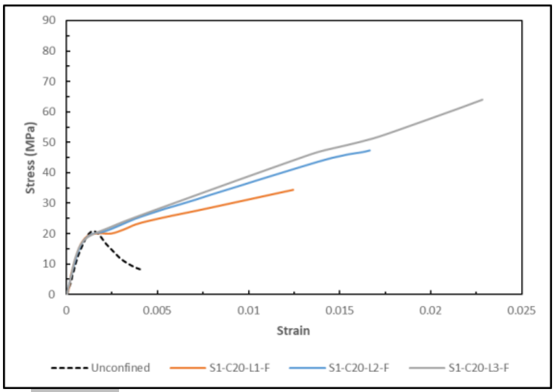

Fig. 13. CFRP-wrapped concrete samples response (C20).

4.2.2. The effect of the number of layers on partial confinement configuration

In the partial confinement samples, an increasing number of layers was recorded less improvement than that of the full confinement. As shown in Fig. 14 compared with the reference sample; an enhancement in the compressive strength of only 1.38%, 26.44%, and 38.33% when the samples were wrapped with one, two, and three layers respectively for the concrete of grade (C40). However, the improvement in concrete strength with grade (C20) was only 15.09%, 51.72%, and 80.31% when the samples were wrapped with one, two, and three layers, respectively, as shown in Fig. 15. The stress-strain curves imply that the one CFRP layer provides a low confinement pressure to the concrete core and this observation is in agreement with Oliveira et al, 2019 [22]. However, even if the partial wrapping didn't significantly improve strength, it enhanced the concrete ductility and coincided with previous studies investigating the responses with low confining pressure [23], as illustrated in the ductility section.

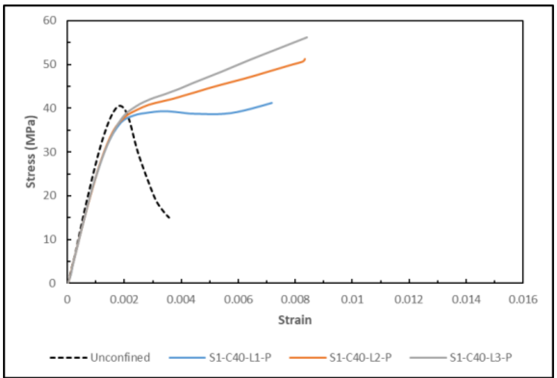

Fig. 14. CFRP-partial-wrapped concrete samples response (C40).

In group S2, the results of this study point out that; by increasing the sample size and providing the same confinement ratio; the stress capacity decreased a little for the CFRP wrapped with one layer by 4.24%, and also a strength decreased in the partial confinement specimens by 2.48%, 8.37% and 8.1% for the samples that were wrapped with one, two and three layers respectively. However, the full confinement configuration with two and three layers shows a small improvement in its ultimate stress capacity by 1.64% and 2.78% respectively. A similar result was obtained in the S3 group, where an average deviation in the stress enhancement percentages was only 1.1% between the S2 and S3 groups. In general, these results coincided with previous studies conducted by [24], where they study different specimens' sizes with a diameter of (51, 101, and 149) mm; their results reported that; a not significant effect in the CFRP wrapping samples size. On the other hand; other researchers such as [25] pointed out that the size effect could improve the samples strength by 10% for the CFRP confined square concrete columns when the samples size increase from (200 x 200 x 600) mm to (400 x 400 x 1200) mm, then it was drop down by 3.14% by increasing the size to (600 x 600 x 1800)mm. However, all of the prementioned studies didn't investigate the samples with large diameters used in this study (i.e., 300mm and 600mm) with such deep investigation in the CFRP layers, concrete grade, and confinement configuration. The concluded remarks based on this work is that; increasing the samples sizes, should be escorted with a more confining ratio than that of the small size to further improve the model stress capacity.

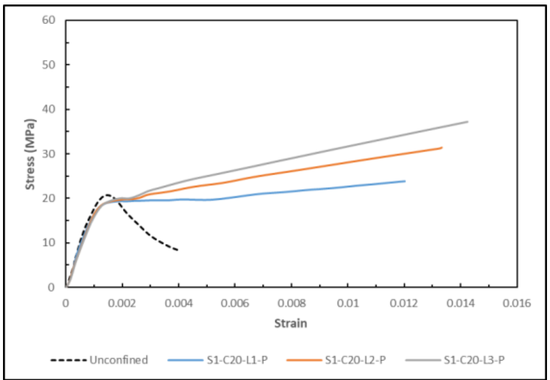

Fig. 15. CFRP-partial-wrapped concrete samples response (C20).

4.3. Ductility

Based on [26] [27], the ductility index (μ) of a confined specimen can be obtained by using the following expression:

$$\mu = \frac{\Delta u}{\Delta y} \quad \textbf{Eq. 3}$$

Where Δu is the ultimate axial displacement, Δy is the yield axial displacement. The ultimate axial displacement could be found in the displacement corresponding to a 20 % drop of the ultimate axial load, and the yield displacement is the displacement corresponding to the intercept of the two blue lines shown in Fig. 16.

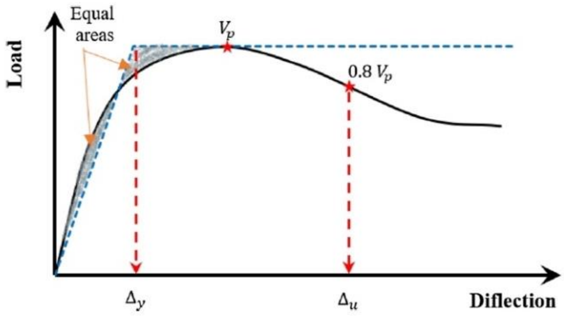

Fig. 16. ductility ratio definition [28].

The ductility for all specimens is presented in Table 3. The results indicated that as the number of layers increased the sample's ductility increased either full or partial confinement configuration. Increasing the number of layers provides more load-carrying capacity as well as its corresponding axial displacement. Moreover, it was noticed that the samples with lower concrete compressive strength present more ductility, as the FRP provides a large lateral constrain which will allow large axial deformation before failure. When the specimens with partial configuration were tested, it presents lower ductility than that of the full confinement samples, as the partial confinement provide less confinement pressure to the concrete core.

4.4. Volumetric strain

The unconfined concrete cylinders in axial compression experience a rapid volumetric explanation or dilation after peak stress [29]. When the CFRP is used in concrete wrapping; it will curtail the dilation. Therefore, the volumetric strain will not exhibit an unstable response after the peak stress [4]. Under axial compression, the volumetric strain for confined concrete can be expressed as [30];

$$\varepsilon_v = \varepsilon_c + \varepsilon_{ci} + \varepsilon_l \quad \textbf{Eq. 4}$$

Where ε_v is the volumetric strain, ε_c is axial strain, ε_l is the lateral strain. The axial stress versus volumetric strain graphs for group S1 are presented through Fig. 17 to Fig. 20 similar to that obtained by Rousakis et al, 2003 [31]. Where a positive volumetric strain indicates compressive strain and a negative value corresponds to dilation. The results indicated that; for the unconfined sample a rapid increase in the dilation strain after the peak stress has been noticed. After the peak, the stress exhibits a softening behavior with volumetric strain reaching up to 0.8% and 0.7% for C40 and C20 respectively. This softening can be restricted, where a stress stiffening was observed by adding the CFRP layers. However, as the confining pressure increase due to wrapping layers, the dilation strain will be decreased. where a remarkable lateral constrain was provided when the sample are fully wrapped with three layers. The volumetric strain records a value of 0.19% and 0.09% for C40 and C20 respectively when the samples were wrapped with three layers. On the other hand, the partial confinement didn't add a significant reduction to the volumetric strain, but it also provides stress stiffening behavior as that of the full confinement configuration. A similar result was noticed for the S2 and S3 groups.

Table 3.Ductility Index.

	#	Specimen's label	Ductility (Î¼)
Group S1	1	S1-C40-L1-F	5.27
	2	S1-C40-L2-F	5.90
	3	S1-C40-L3-F	8.18
	4	S1-C20-L1-F	10.36
	5	S1-C20-L2-F	12.19
	6	S1-C20-L3-F	14.89
	7	S1-C40-L1-P	3.9
	8	S1-C40-L2-P	4.35
	9	S1-C40-L3-P	4.37
	10	S1-C20-L1-P	8.78
	11	S1-C20-L2-P	9.31
	12	S1-C20-L3-P	9.36
Group S2	1	S2-C40-L1-F	4.25
	2	S2-C40-L2-F	6.61
	3	S2-C40-L3-F	8.19
	4	S2-C20-L1-F	9.45
	5	S2-C20-L2-F	11.54
	6	S2-C20-L3-F	14.14
	7	S2-C40-L1-P	3.14
	8	S2-C40-L2-P	3.43
	9	S2-C40-L3-P	3.83
	10	S2-C20-L1-P	5.78
	11	S2-C20-L2-P	7.21
	12	S2-C20-L3-P	7.60
Group S3	1	S3-C40-L1-F	4.91
	2	S3-C40-L2-F	6.67
	3	S3-C40-L3-F	7.96
	4	S3-C20-L1-F	10.96
	5	S3-C20-L2-F	11.19
	6	S3-C20-L3-F	13.57
	7	S3-C40-L1-P	4.66
	8	S3-C40-L2-P	4.41
	9	S3-C40-L3-P	3.88
	10	S3-C20-L1-P	5.51
	11	S3-C20-L2-P	7.11
	12	S3-C20-L3-P	7.21

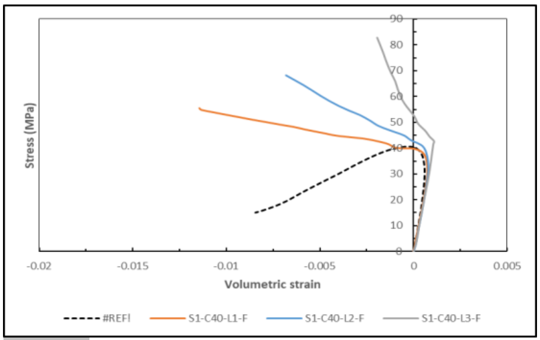

Fig. 17. Volumetric strain for the unconfined and one, two, and three layers of S1-C40-F.

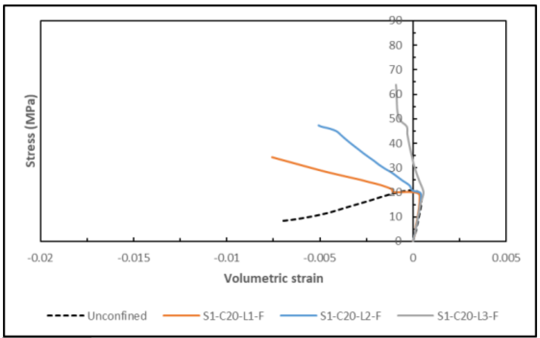

Fig. 18. Volumetric strain for the unconfined and one, two, and three layers of S1-C20-F.

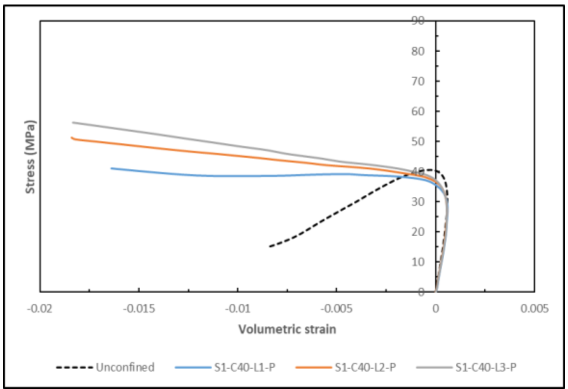

Fig. 19. Volumetric strain for the unconfined and one, two, and three layers of S1-C40-P.

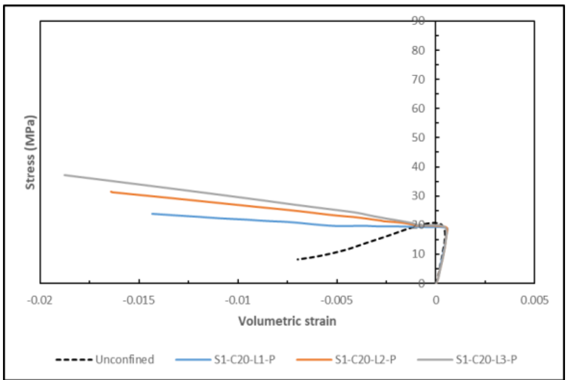

Fig. 20. Volumetric strain for the unconfined and one, two, and three layers of S1-C20-P.

4.5. *Size effect discussion of CFRP wrapped concrete*

By changing the size of the cylinder from (150 x 300) to (300 x 600) and to (600 x 1200); the stress-strain responses show a small change as stated earlier. When the samples size was increased from S1 to S2 sizes and had the same confinement ratio, the stress capacity decreases a little for the specimens fully wrapped with one layer, as well as the partially confined samples by one, two, and three layers for the two concrete grades. the remaining samples that were fully wrapped with two and three layers, present a small enhancement in their ultimate strength. The cylinders samples in the S3 group that have the same confinement ratio, present a stress-strain response so close to that of the previous S2 cylinder. The summary of these is presented in Table 4, by taking the size of S1 as a controlled size.

Table 4.
Size effect summary by taking S1 size as a reference.

#	Specimen's label	The percentage of change in compressive strength compared with control size (%)
1	S2-C40-L1-F	-4.24
2	S2-C40-L2-F	1.64
3	S2-C40-L3-F	2.78
4	S2-C20-L1-F	-1.86
5	S2-C20-L2-F	2.55
6	S2-C20-L3-F	0.91
7	S2-C40-L1-P	-2.48
8	S2-C40-L2-P	-8.37
9	S2-C40-L3-P	-8.10
10	S2-C20-L1-P	-19.29
11	S2-C20-L2-P	-12.05
12	S2-C20-L3-P	-12.69
13	S3-C40-L1-F	-3.12
14	S3-C40-L2-F	1.61
15	S3-C40-L3-F	2.71
16	S3-C20-L1-F	-1.89
17	S3-C20-L2-F	0.32
18	S3-C20-L3-F	0.91
19	S3-C40-L1-P	-2.94
20	S3-C40-L2-P	-5.11
21	S3-C40-L3-P	-5.29
22	S3-C20-L1-P	-14.96
23	S3-C20-L2-P	-12.09
24	S3-C20-L3-P	-12.72

Regarding the sample's ductility and Volumetric strain, no large influence has been noticed due to changing the size samples. As the different sizes used in this study, presents approximately similar behavior when the ductility and volumetric strain been measured.

5. CONCLUSION

The proposed finite element model that adopts the modified concrete damage plasticity theory to simulate the plastic deformation of concrete, can predict the unconfined and CFRP warped concrete cylinder behavior is subjected to an axial compression test, with high accuracy. Based on this study finding, wrapping the concrete specimens with CFRP improve its strength, as the number of layers increases the concrete strength increases. Furthermore, as the number of layers increases the ductility increase whether it was a full or partial confinement configuration. The volumetric strain exhibited a rapid increase in the dilation strain after the peak stress for the unconfined sample, this dilation can be reduced by the CFRP confinement. where a remarkable lateral constrain was provided when the sample was fully wrapped with three layers. Similar stress-strain responses were observed for the CFRP confined samples with bigger sizes with small deviations. When the samples size was increased to the size of the S2 group and had the same confinement ratio, a small decrease in the stress capacity has been noticed for the specimens fully wrapped with one layer, and for all partially confined samples in the two concrete grades. In the remaining samples (wrapped with two and three layers), a small improvement in the ultimate strength was recorded. Moreover, the cylinders samples in the S3 group that have the same confinement ratio, present a stress-strain response so close to that of the S2 cylinder. The concluded remark here is that, if a bigger size sample are intended to use, it should be escorts with more confining ratio than that of the small size to further improve the specimens ultimate stress capacity. No large influence has been noticed in the specimen's ductility and volumetric strain due to changing the samples size. The proposed formula by (Lam & Teng, 2003) that can predict the stress-strain response of FRP full confined concrete cylinder was compared with the corresponding values obtained in this study for each specimen. The results indicated that; a good matching was noticed for all samples located in the S1-C40 group only. However, the remaining samples have recorded some deviation in their behavior, this increment can be explained by the fact that; the formula proposed by (Lam & Teng, 2003) where tested on concrete samples that has a compressive strength ranging from 26.2 MPa to 55.2 MPa and diameter ranging from 100mm to 200mm only.

6. RECOMMENDATION

For future studies, the following points are recommended to be investigated further:

1. More experimental studies should be considered in samples with large sizes that are wrapped by FRP. Therefore, more realistic finite element models can be proposed.

2. The effect of other FRP types on the confined concrete, need to studied.
3. Study the shape of the sample (square, rectangle) effect.
4. Investigate adding steel fibers to the concrete core and how it will influence the enhancement percentages by changing the number of layers and samples size.

Conflict of interest

The authors do not have any personal financial interests related to the subject matters discussed in this manuscript.

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