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Finite Element Modelling of CFRP wrapped Concrete Specimens Subjected to Localised Axial Compression

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ABSTRACT

The strengthening and rehabilitation of reinforced concrete structures using Carbon Fibre Reinforced Polymer (CFRP) wrapping is most common. Recently, this method was used in the rehabilitation of deteriorated reinforced concrete columns, the pier of girder bridges and corbels that are subjected to localised axial compression. The numerical simulation which is verified by experimental works minimizes the time and cost to get the internal behaviours of structures. This study is an attempt to numerically investigate the performance of CFRP wrapped concrete specimens subjected to localised compressive loading conditions. The finite element modelling by ABAQUS software was used in the simulation of adopted specimens in this study. The FEM results show good agreement with the experimental data. The performance of adopted specimens and the behaviour of the concrete core and CFRP wrapping were extensively studied. The FEM results indicated that the CFRP wrapping improves the load carrying capacity and increases the dissipation of energy by increasing the deformation capacity and subsequently the wrapped specimens behave more ductile. The fully wrapped cylinder subjected to a smaller area of loading exhibits higher capacity (119%) of exposed specimen, while the wrapped cube subjected to area of loading (size:75 mm) exhibits higher load carrying capacity about(52%) than the exposed cube.

Keywords: CFRP Wrapping; Finite Element Modelling; Localised Axial Compression; Strengthening and Rehabilitation; Concrete Confinement.

INTRODUCTION

Deterioration of reinforced concrete (RC) structural members such as beams and columns happens due to cracking and spalling off the concrete cover and reinforcement corrosion. Concrete spalling off caused strength decreasing as well as local buckling of rebars (Toutanji et al. 2002). The widespread methods of retrofitting of damaged RC members are; cross-sectional enlargement, steel jacketing and wrapping by CFRP (Ballinger and Graig 1997). The cross-sectional enlargement needs formwork, a considerable increase in the weight, and the cross-section of the support members (Park et al 2008).

The steel jacketing is conventional and widely used in retrofitting the damaged RC members. However, the erosion of exposed material and the possibility of exposure to fires reduce the application of this technique (Chun and Park 2002). The CFRP wrapping is the most effective technique in the strengthening and rehabilitation of reinforced concrete structures due to lightweight, high stiffness or strength-to-weight ratios, etc. Fibre reinforced polymer (FRP) composite materials have been widely applied to buildings and bridge columns to retrofit and enhance the axial load capacity and ductility (Liu et al. 2020 and Prabhua & Sundarraja 2013). The application of CFRP wrapping as a strengthening manner of reinforced concrete structures has been widely carried out and reported in the last few decades (Shehata et al. 2002, Mukherjee et al. 2004, Zhong et al. 2007, Zhong & Han 2007 and (Choi & Xiao 2010).

The phenomena of loading a partial area can be encountered in any structural supports such as concrete foundations, corbels, piers of bridge, anchorage zone in post-tension members. The bearing strength of concrete is strongly dependent on the resistance of concrete blocks loaded through a steel bearing plate (Scheffers and Ravindrarajah 2009). Most of the existing formulas in the American Concrete Institute (ACI) and the AASHTO (LFRD) for predicting the concrete bearing capacity depend on concrete compressive strength and ratio of the concrete-to-steel area (Ravindrarajah and Reinaldy 2010).

Many studies have been conducted to investigate the performance of exposed concrete parts subjected to localised axial compression (Hawkins 1968, Niyogi 1973 and Chen 1971). Few studies have been taken of the confined concrete members subjected to this loading condition. Han et al (2008) conducted experimental and theoretical research to investigate the behaviour of concrete filled steel tubular stub columns subjected to axially local compression. The results showed that the bearing resistance is affected by the thickness of the walled tube and the bearing plate.

Ravindrarajah and Reinaldy (2010) experimentally investigated the bearing behaviour of CFRP wrapped concrete. The parameters of the study were the bearing strength ratio and bearing shape ratio. Results showed that the bearing strength of concrete is enhanced due to CFRP wrapping, as well as, it was depicted that the shape of the bearing area had a minor effect on the bearing capacity of concrete.

Mai et al (2019) conducted an experimental investigation on square and circularised square RC columns intermittently wrapped with CFRP under different load cases. The test results proved that the intermittent confining enhances the strength and ductility of square columns, as well as, the circularisation and intermittent confining significantly improve the ductility and load capacity of columns.

Shen and others (2019) numerically investigated the performance of circular concrete filled steel tubular stub columns partially wrapped using CFRP belts. Two design formulas were suggested to assess the axial compressive capacity of partially wrapped columns in compliance with the tubed concrete method and the unified theory.

Zheng et al. (2018) presented an experimental investigation on the axial compressive behaviour of partially FRP wrapped circular reinforced concrete columns. The test results were compared with existing representative stress-strain models to check the reliability and accuracy of these models.

Abdullah and others (2020) conducted an experimental study to investigate the effect of CFRP wrapping length on the bearing resistance of confined concrete specimens. The results appeared to show that the full wrapping has little effect on the bearing resistance of specimens applied to small areas of loading.

Finite element modelling (FEM) is a familiar tool within the field of structural engineering. It reduces the time and cost to obtain initial estimates of the structure's performance. FEM is used to generate numerical data which then provides a basis for validating experimental analyses (Liu et al. 2011, Abdullah 2010 and Hibbitt et al. 2006).

In the last few decades, there is a growing number of sophisticated FEM commercial software. ABAQUS is appropriate software used in structural modelling which was adopted in the current study to simulate the experimental performance of CFRP wrapped concrete specimens subjected to different localised areas of axial loading. In the present study, the performance of CFRP wrapped standard cylinders and cubes subjected to localised axial compression is numerically investigated. The main objectives of this research are folded into three aims: first, to develop a numerical model using FEM to simulate the CFRP wrapped specimens under a localised axial compression and verify it using recent experimental data; second, to analyze the influences of several parameters, such as the shape of specimens, the ratio of localised compressive area on the behaviour of CFRP wrapped specimens; and third, to analyze the mechanism of simulated specimens subjected to localised axial compression using stress distribution in constructional parts of specimens (i.e. the concrete core and CFRP wrapping).

DATA COLLECTIONS

This study took the performance of concrete elements strengthened using CFRP wrapping into considerations. The experimental results of a recent study were taken to verify the accuracy of the developed model herein (Abdullah et al. 2020). The details of adopted specimens are summarised in Table 1; further, the testing procedure of the simulated specimens was conducted according to the scheme shown in Figure 1.

FINITE ELEMENT MODELLING

A nonlinear three-dimensional (3D) FEM using ABAQUS software (Abdullah 2010 and Hibbitt et al. 2006) was utilized in simulating the performance of localised axial compression of CFRP wrapped concrete specimens. The types of elements were carefully selected to simulate the parts of the adopted specimens to get an accurate model. The elements' types and descriptions are summarised in Table 2 and the scheme of Figure 2. The concrete core was solid which was confined by lateral CFRP wrapping consisting of one layer with overlap length (100 mm). The mesh size of elements was taken 25 mm for all specimens.

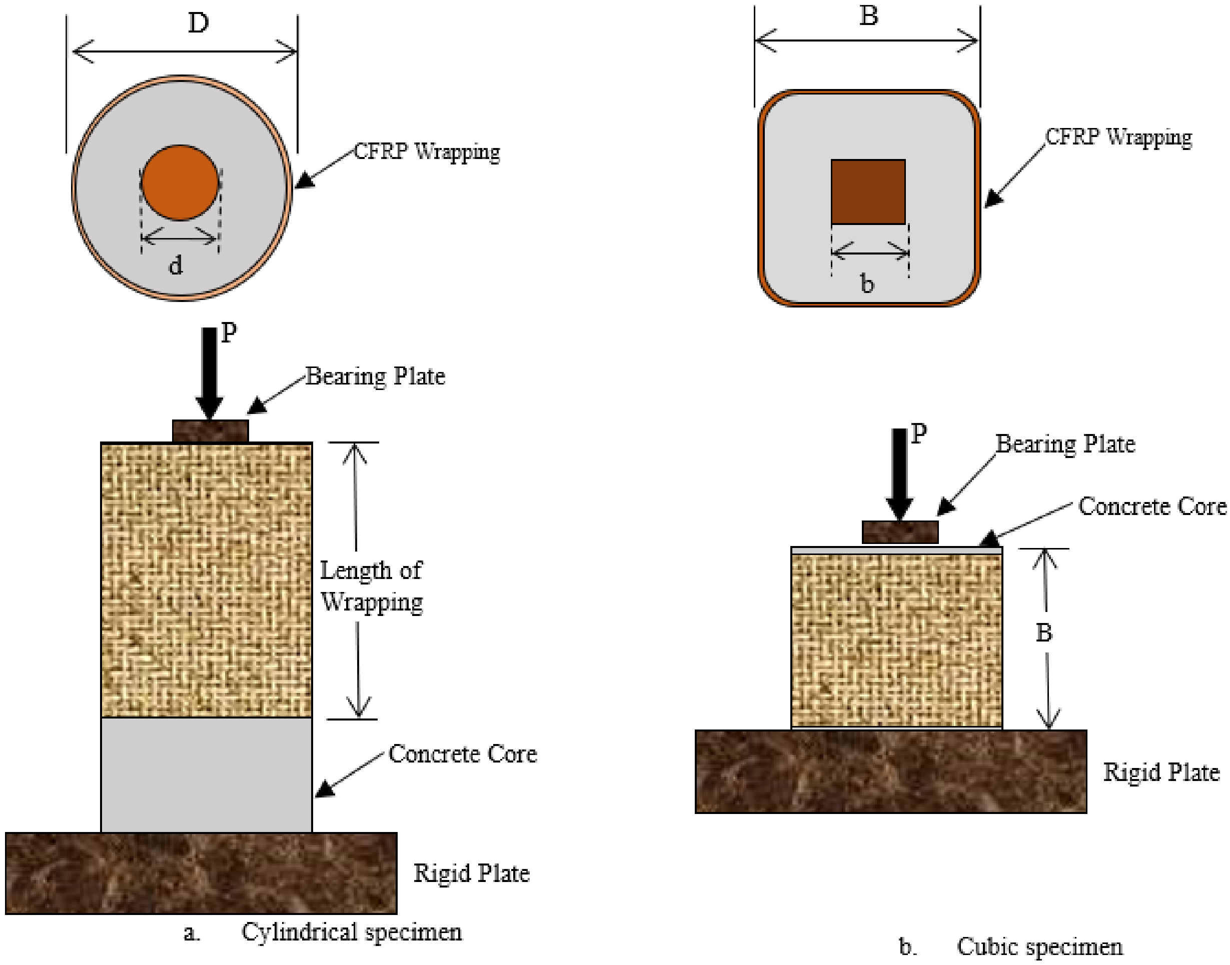


FIGURE 1. Adopted specimens test scheme.

TABLE 1. Details of Tested Specimens.

Group	Specimen	Type of specimen	fc' (MPa)	Size of bearing plate (mm)	Length of wrapping (mm)
Group-1	CYN-50-A	Cy. 150×300 mm	36.8	50	0
	CYN-50-B				100
	CYN-50-C				200
	CYN-50-D				300
Group-2	CYN-100-A	Cy. 150×300 mm	36.8	100	0
	CYN-100-B				100
	CYN-100-C				200
	CYN-100-D				300
Group-3	CYN-150-A	Cy. 150×300 mm	36.8	150	0
	CYN-150-B				100
	CYN-150-C				200
	CYN-150-D				300
Group-4	CYH-100-A	Cy. 150×300 mm	52.6	100	0
	CYH-100-B				100
	CYH-100-C				200
	CYH-100-D				300
Group-5	CYH-150-A	Cy. 150×300 mm	52.6	150	0
	CYH-150-B				100

continue...

...continued

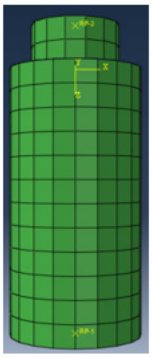
	CYH-150-C				200
	CYH-150-D				300
Group-6	CUN-50-A	Cube 150 mm	36.8	50	0
	CUN-50-B				150
Group-7	CUN-75-A	Cube 150 mm	36.8	75	0
	CUN-75-B				150
Group-8	CUN-100-A	Cube 150 mm	36.8	100	0
	CUN-100-B				150
Group-9	CUN-150-A	Cube 150 mm	36.8	150	0
	CUN-150-B				150

The boundary conditions and the applied loading process of the developed model were simulated by following the testing procedure as depicted in Figure 1. The localised axial load was applied incrementally using the General Solution Method (GSM) available in the software. ABAQUS generally uses Newton's method as a numerical technique for solving the nonlinear equilibrium equations. Monotonic localised axial load similar to that in the tests was subjected using the displacement control at nodes of the bearing plate surface. The time increment of loading did not exceed 10% of the total displacement.

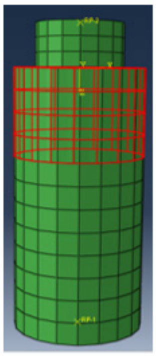
In the developed model, the damaged plasticity model was used to simulate the concrete behaviour. The CFRP wrapping behaves Elastic-Plastic in tension only. The steel bearing plate was modelled as an elastic material to implement the rigid behaviour of loading applied to the concrete core. The materials' modelling is summarised in Table 2 and Figure 3. For concrete, the compressive and tensile behavior is shown in Figure 3-a. The compressive strength (fc'), tensile strength (ft), the modulus of Elasticity (Ec) and the Poisson's ratio (μ) were taken from experimental results. The tensile behaviour of CFRP is depicted in Figure 3-b. The modulus of Elasticity (ECFRP), the Poisson's ratio (μCFRP) and thickness (t) of CFRP were taken from a data sheet provided by the manufacturer company. The modulus of Elasticity (Es) and Poison's ratio (μs) of the bearing plate was inputted as depicted in Table 2.

TABLE 2. Element Type and material modeling of the developed model.

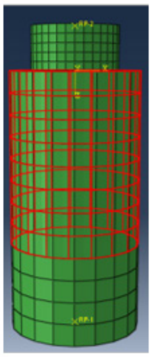
Part	Element Type	Material Model
Concrete Core	C3D8: 3-D isoparametric solid element	the concrete damaged plasticity (Figure 3). Ec=28512 MPa, μ=0.2 (Normal Concrete). Ec=34305 MPa, μ=0.15 (High strength Concrete) (Caldarone 2009).
CFRP Wrapping	M3D4R: 4-node quadrilateral membrane, reduced integration, hourglass control element	Elastic-Plastic in tension only (Figure 3) σCFRP=4300 MPa ECFPR=238000MPa μCFRP=1×10-7 ≈ 0 t=0.131 mm
Bearing Plate	C3D8: 3-D isoparametric solid element	Elastic material Es=200 GPa μs=0.3
Concrete to CFRP Connection	The interface element	
Bearing Plate to Concrete Connection	Hard Contact.	



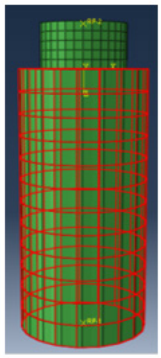
a. Exposed cylinder.



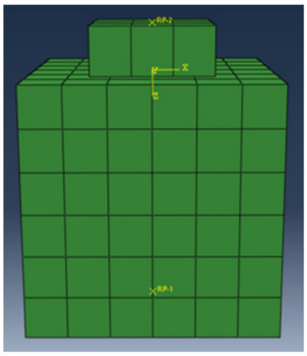
b. Wrapped 100 mm.



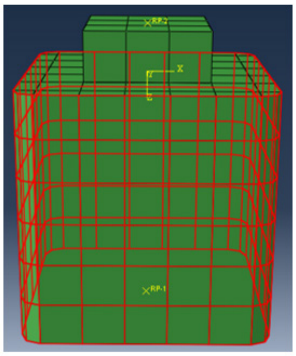
c. Wrapped 200 mm.



d. Wrapped 300 mm.

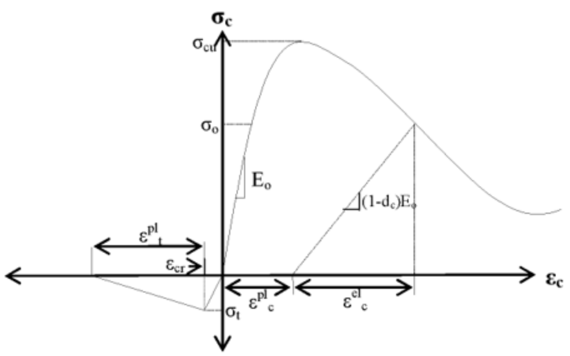


e. Exposed cube.



f. Full depth wrapped cube

FIGURE 2. Mesh generation of simulated specimens.



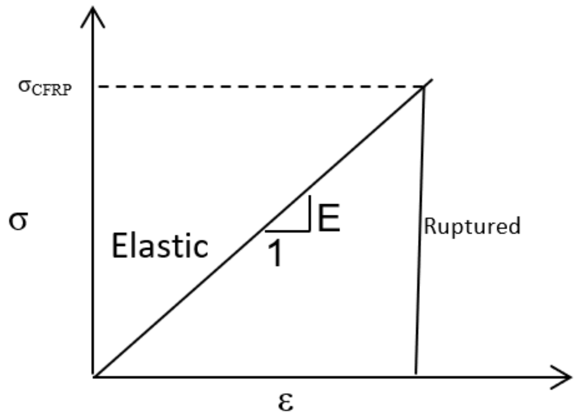


FIGURE 3. Materials Model (Abdullah 2010).

VERIFICATION OF FEM AND RESULTS' DISCUSSION

Table 3 and Figure 4 show the verification of the developed model of simulated specimens. As depicted in the table, the mean value of Experimental to FEM load carrying capacity (P^{EXP}/P^{FEM}) ratio of simulated specimens is 1.07 and the correlation factor (R) is 0.97 while the standard deviation (SDV) is 0.11. The signed values by a star were excluded from the test of the correlation due to differences between the experimental results and reasonable FEM results. The statistical values indicate that an excellent matching is achieved between the experimental results and others obtained from the developed model. The comparison between the experimental and FEM load carrying capacity is depicted in Figure 4. The figure also shows great matching between them. Figure 5 shows the comparison of experimental failure modes and numerical plastic strain of concrete cores which boosts the good correlation between the experimental and the FEM results. The ratio of load carrying capacity of wrapped specimen to that exposed specimen ($P^{Wrp.}/P^{Exp.}$) is presented in Table 3. The ratio proves the improvement of load carrying capacity of specimens in the presence of wrapping. The wrapped cylinders subjected to a smaller area of loading exhibited higher capacity (119%) for specimens with a full length of wrapping. While the wrapped specimens subjected to the full area of loading exhibited lower capacity about (23%). In addition, the wrapped cubes subjected to bearing area of loading (size: 75 mm) exhibited higher load carrying capacity about (52%) than others.

TABLE 3. Verifications of FEM results against EXP data.

Group	Specimen	*fc'* (MPa)	P^{EXP} (kN)	P^{FEM} (kN)	(P^{EXP}/ P^{FEM})	($P^{Wrp.}$/ $P^{Exp.}$)
Group-1	CYN-50-A	36.8	300	218	1.38*	1.00
	CYN-50-B	36.8	320	280	1.14	1.28
	CYN-50-C	36.8	420	402	1.04	1.84
	CYN-50-D	36.8	300	477	0.63*	2.19
Group-2	CYN-100-A	36.8	310	384	0.81	1.00
	CYN-100-B	36.8	500	509	0.98	1.33
	CYN-100-C	36.8	430	582	0.74*	1.52
	CYN-100-D	36.8	500	530	0.94	1.38
Group-3	CYN-150-A	36.8	650	633	1.03	1.00
	CYN-150-B	36.8	690	654	1.06	1.03
	CYN-150-C	36.8	850	737	1.15	1.16
	CYN-150-D	36.8	920	778	1.18	1.23
Group-4	CYH-100-A	52.6	500	507	0.99	1.00
	CYH-100-B	52.6	780	650	1.20	1.28
	CYH-100-C	52.6	810	757	1.07	1.49
	CYH-100-D	52.6	810	658	1.23	1.30
Group-5	CYH-150-A	52.6	930	900	1.03	1.00
	CYH-150-B	52.6	1010	925	1.09	1.03
	CYH-150-C	52.6	1100	1000	1.10	1.11
	CYH-150-D	52.6	1200	1060	1.13	1.18
Group-6	CUN-50-A	36.8	300	304	0.99	1.00
	CUN-50-B	36.8	400	366	1.09	1.20
Group-7	CUN-75-A	36.8	400	340	1.18	1.00
	CUN-75-B	36.8	570	518	1.10	1.52
Group-8	CUN-100-A	36.8	750	656	1.14	1.00
	CUN-100-B	36.8	1000	840	1.19	1.28
Group-9	CUN-150-A	36.8	900	1072	0.84	1.00
	CUN-150-B	36.8	1200	1220	0.98	1.14
Mean Value = 1.07						
Correlation Factor (R) = 0.96						
Standard Deviation = 0.11						
* poor correlation						

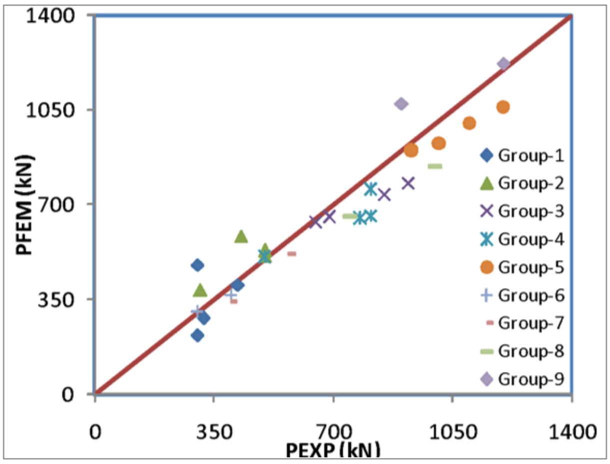
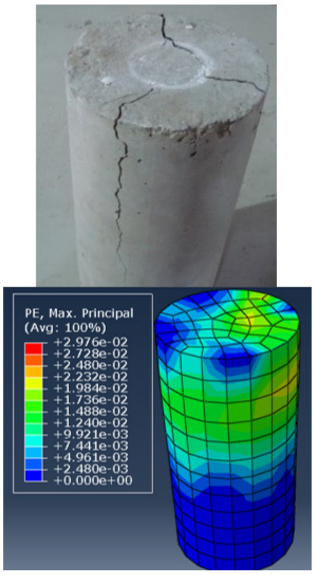
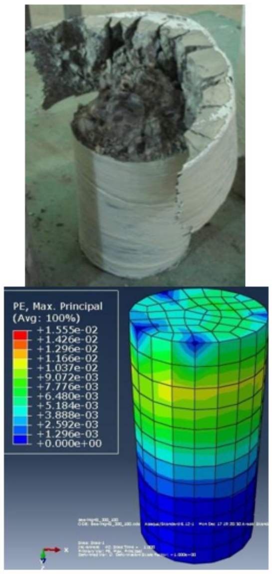


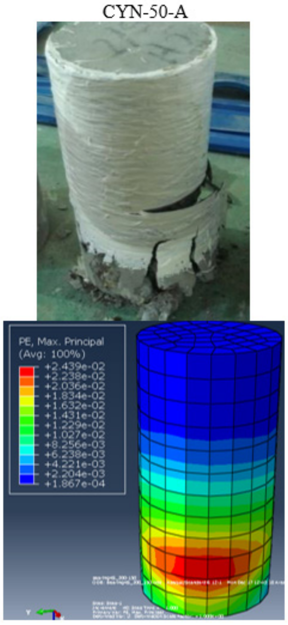
FIGURE 4. Comparison between experimental and numerical load capacity of tested specimens.



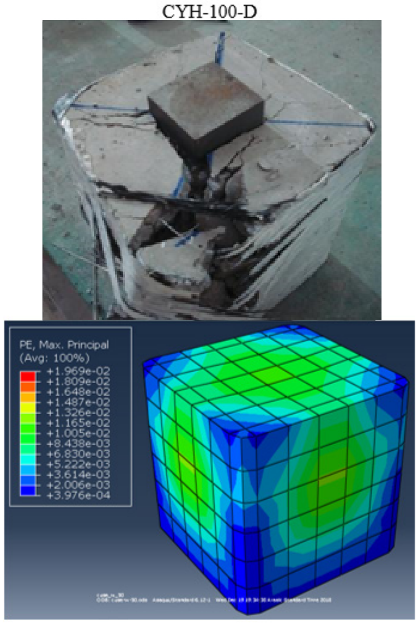
CYN-50-A



CYH-100-D



CYH-150-C



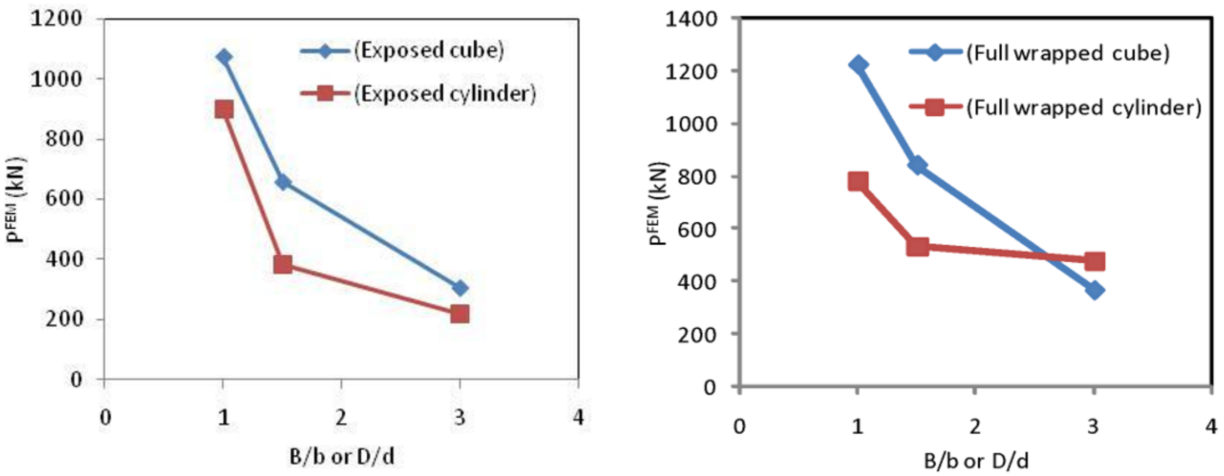
CUN-50-B

FIGURE 5. Comparison of experimental failure shape and numerical plastic strain (Max. Principal) of concrete.

Table 4 and Figure 6 depict the comparison of the localised axial load capacity of both cubic and cylindrical specimens for exposed and full wrapped cases. The table and figure indicate that the strength of wrapped specimens progresses better than those exposed as bearing area increases. While the wrapped cylindrical specimen which was subjected to a smaller loading area presented better performance and higher localised axial load capacity than cubic due to the better confinement of specimen against a small area of loading.

TABLE 4. Comparison of cubic and cylindrical exposed and full depth CFRP wrapped specimens.

Bearing Plate Size (mm)	B/b or D/d	P^{FEM} (kN) (Exposed cube)	P^{FEM} (kN) (Exposed cylinder)	P^{cube}/P^{cy} Exposed	P^{FEM} (kN) (Full rapped cube)	P^{FEM} (kN) (Full wrapped cylinder)	P^{cube}/P^{cy} Full wrapped
50	3	304	218	1.4	366	477	0.8
100	1.5	656	384	1.7	840	530	1.6
150	1	1072	900	1.2	1220	778	1.6



a. Exposed Specimens.

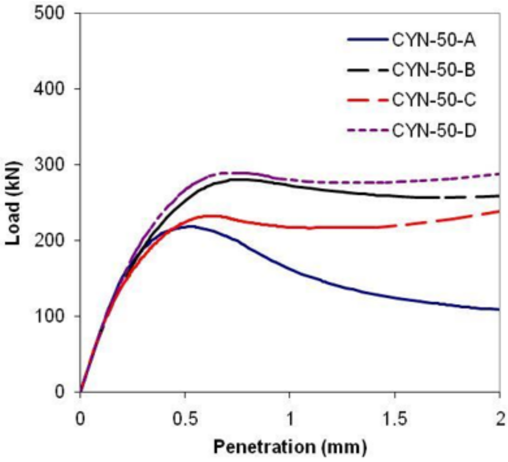
b. CFRP wrapped Specimens.

FIGURE 6. Comparison of load caring capacity for cubic and cylindrical specimens.

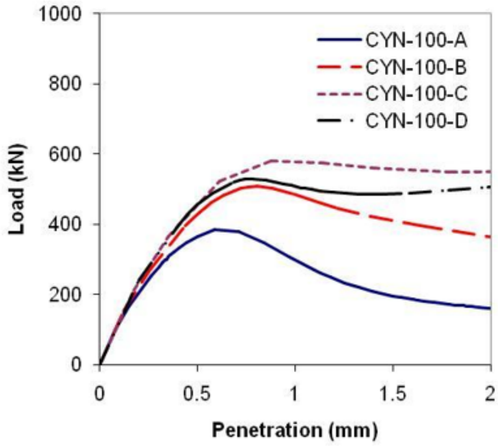
Depending on the obtained results from FEM, Figure 7 shows the localised axial load versus the penetration of the bearing plate in the concrete core. Figure 7(a, b and c) depict the axial behaviours of specimens prepared using normal concrete. Each figure shows the axial behaviour of one of the group specimens that were tested in the same conditions except the length of wrapping. As depicted in the figures, the group subjected to a smaller area of axial loading behaves more ductile than others due to the large dissipation of energy of specimens at the test, as well as, the figures indicate that the CFRP wrapping improves the localised loading capacity of the confined specimens while the length of the wrapping is ineffective especially with specimens tested using the small bearing area. Figures 7(d and e) show the axial bearing behaviour of specimens prepared of high strength concrete. Figure 7 (d) depicts the localised axial behaviour of the specimens subjected to the small area of loading. The figure proves that the load and deformation capacities of the specimens improved due to the presence of the CFRP wrapping, while the length of wrapping doesn't give any indication, which confirms that the full wrapping of specimens isn't necessary. Figure 7 (e) shows the axial behaviour of specimens subjected to the full area of loading. The figure proves that the presence of CFRP wrapping and the increasing of its length enhance the load carrying capacity of the simulated specimens which behave more ductile.

Figure 8 depicts the relation of a localised load of simulated cubes versus the penetration of the bearing plate in the concrete core. All the specimens were prepared using normal strength concrete. The figures reveal that the presence of CFRP wrapping enhances the load carrying capacity and increases the dissipation of energy by increasing the deformation capacity and subsequently the wrapped specimens behave more ductile.

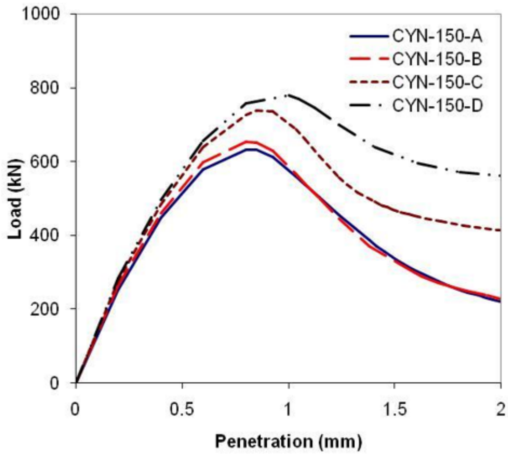
Figures (9-11) show the relationships of Von Mises (VM) stress of CFRP wrapping versus the applied load of wrapped specimens. Figure 9 depicts the VM stress behaviour of cylindrical wrapping for specimens prepared using normal concrete and different wrapping lengths. These relationships indicate that the CFRP wrapping is ruptured at peak load only for the specimens applied to the localised loading area with a size equal to (50 mm) and length of wrapping (200 and 300 mm). Figure 10 shows the VM stress behaviours of cylindrical wrapping of specimens prepared using high strength concrete. These curves reveal that the CFRP wrapping isn't ruptured at peak load, while it tends to fail after peak load, which can be attributed to the smaller Poisson's ratio compared to that of normal concrete. Figure 11 depicts the VM stress behaviour of the CFRP wrapping of cubic specimens prepared using normal concrete. The figure shows that the specimens applied to larger areas of loading (100 and 150 mm) show high VM stress at the peak load point and still oscillate around the half value of the tensile strength of the CFRP (4300 MPa), while, the specimens applied to smaller loading areas (50 and 75 mm) show less than a quarter of the tensile strength of the CFRP at peak load point.



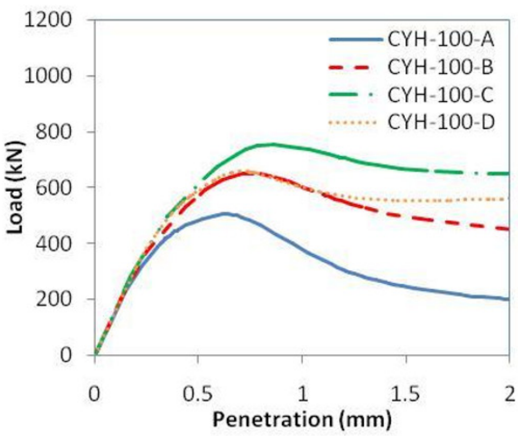
a. Bearing plate size=50 mm (Normal Concrete)



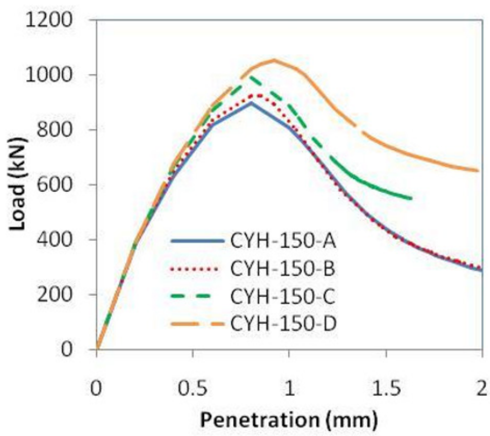
b. Bearing plate size=100 mm (Normal Concrete)



c. Bearing plate size=150 mm (Normal Concrete)

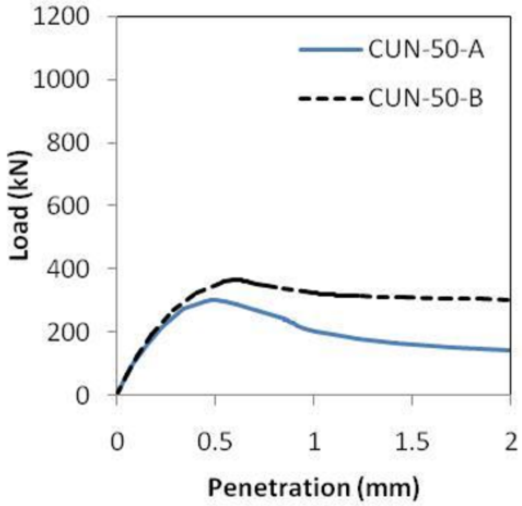


d. Bearing plate size=100 mm (High Strength Concrete)

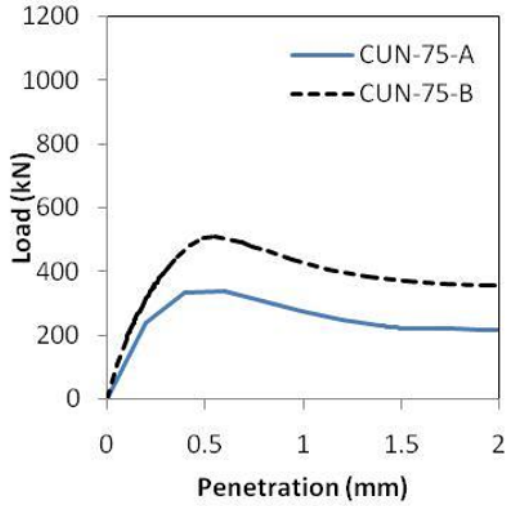


e. Bearing plate size=150 mm (High Strength Concrete)

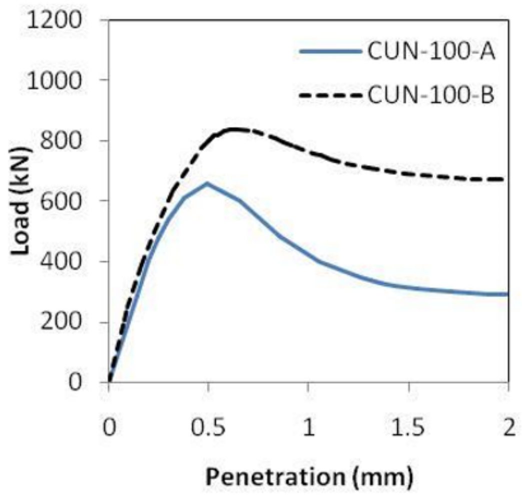
FIGURE 7. Localised Axial Load-Penetration curves of tested cylinders for normal and high strength concrete.



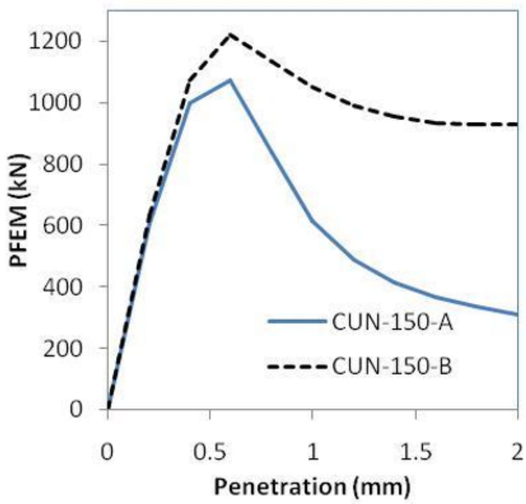
a. Bearing plate size=50 mm



b. Bearing plate size=75 mm

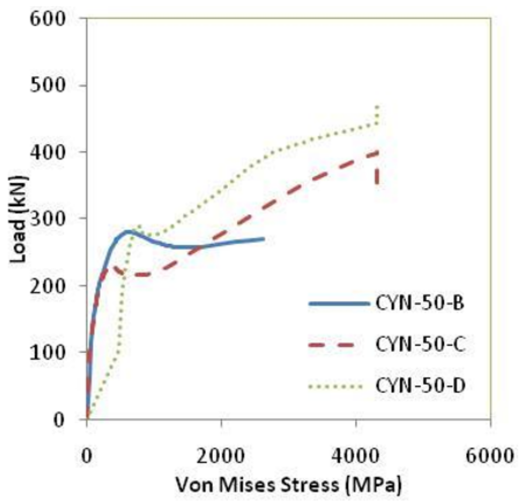


c. Bearing plate size=100 mm

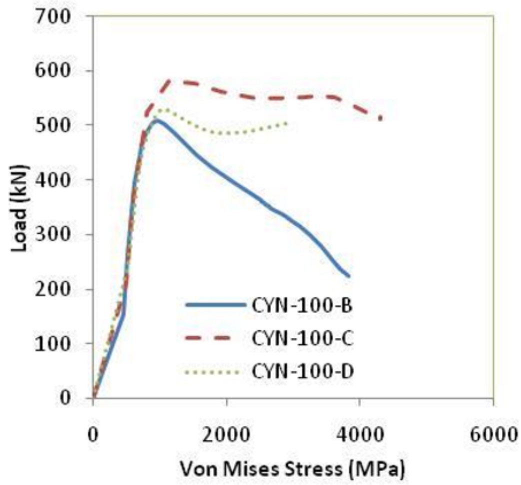


d. Bearing plate size=150 mm

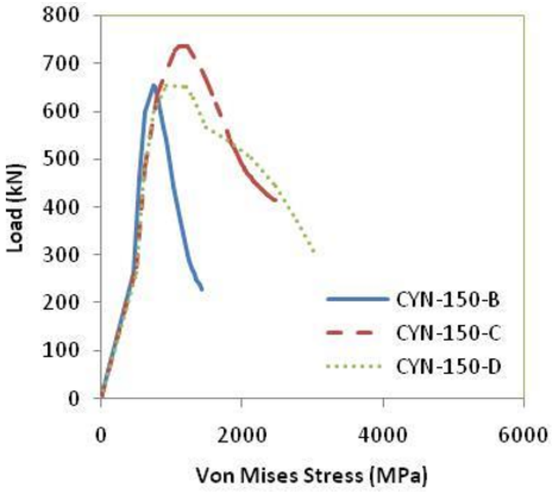
FIGURE 8. Load-Penetration curves of Tested cubes for normal concrete.



a. Bearing plate size=50 mm

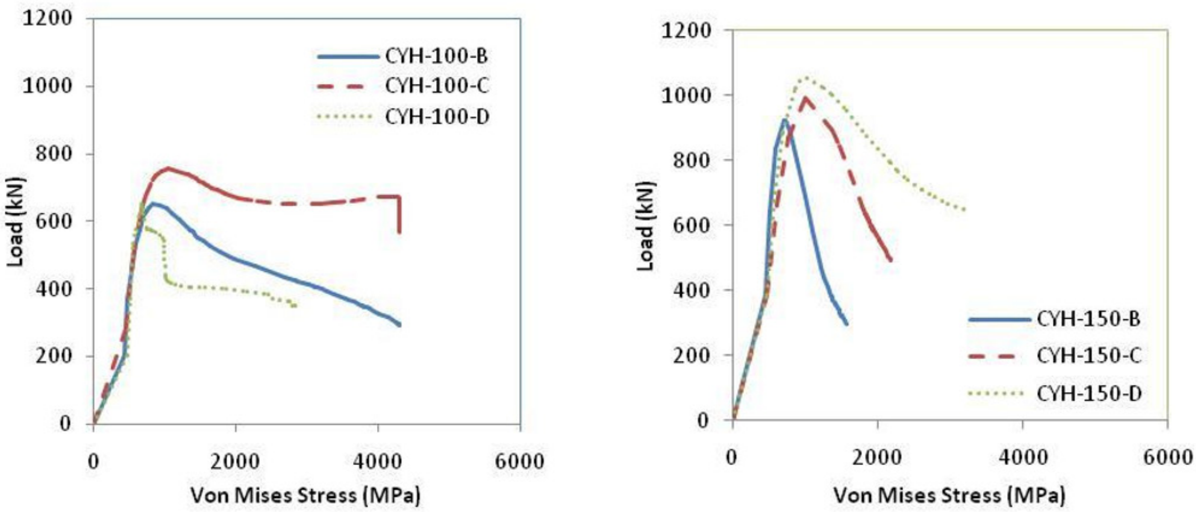


b. Bearing plate size=100 mm



c. Bearing plate size=150 mm

FIGURE 9. Von-Mises stress of CFRP Vs. Applied load (Cylinders with Normal Concrete).



a. Bearing plate size=100 mm

b. Bearing plate size=150 mm

FIGURE 10. Von-Mises stress of CFRP Vs. Applied load (cylinders with High Strength Concrete).

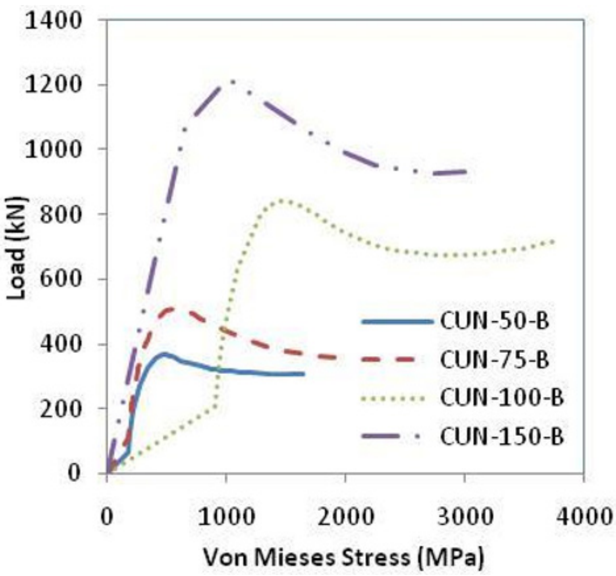
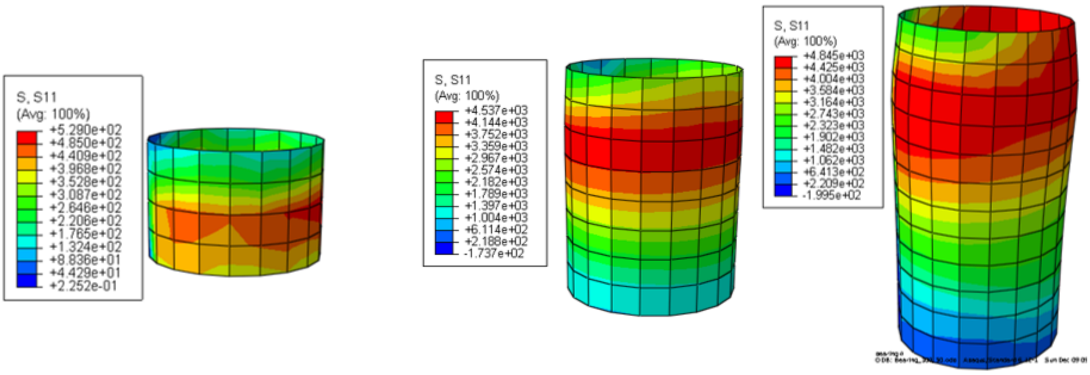


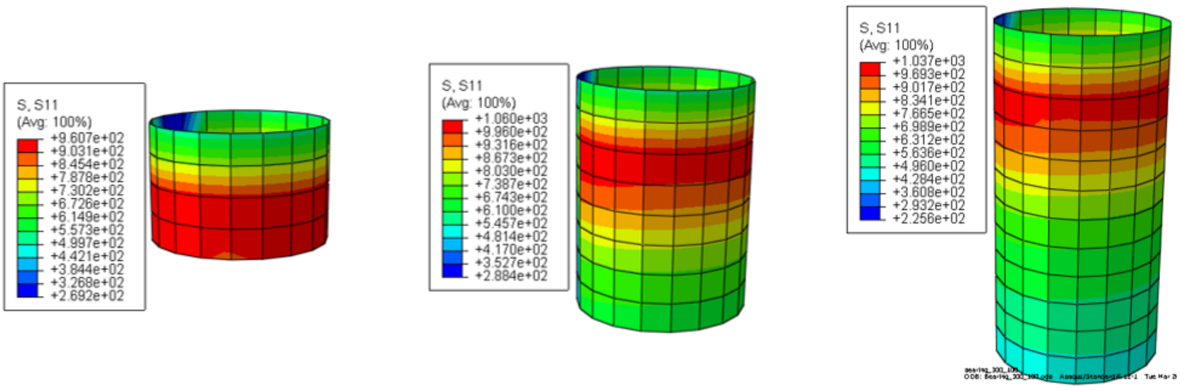
FIGURE 11. Von-Mises stress of CFRP Vs. Applied load (Cubes with Normal Concrete).

Figures 12 and 13 show respectively the lateral tensile stress of CFRP wrapping and VM stress of concrete core at peak load for specimens subjected to different sizes of the loading area. As well known, the lateral tension of CFRP indicates the efficiency of confinement. Figures 12 & 13 (a) depict that the higher lateral tension of CFRP wrapping and concrete stress lie at the upper third of specimens, revealing that the full wrapping is not necessary with the small area of loading. In addition, Figures 12 & 13 (b & c) show the lateral tension of wrapping and concrete stress of specimens' applied to the bearing plate with size (100 mm) and the full area of loading, respectively. As shown in the figures, the higher lateral tension of CFRP wrapping and concrete stress lie near the mid height of specimens which indicates that the full wrapping provides better confinement.



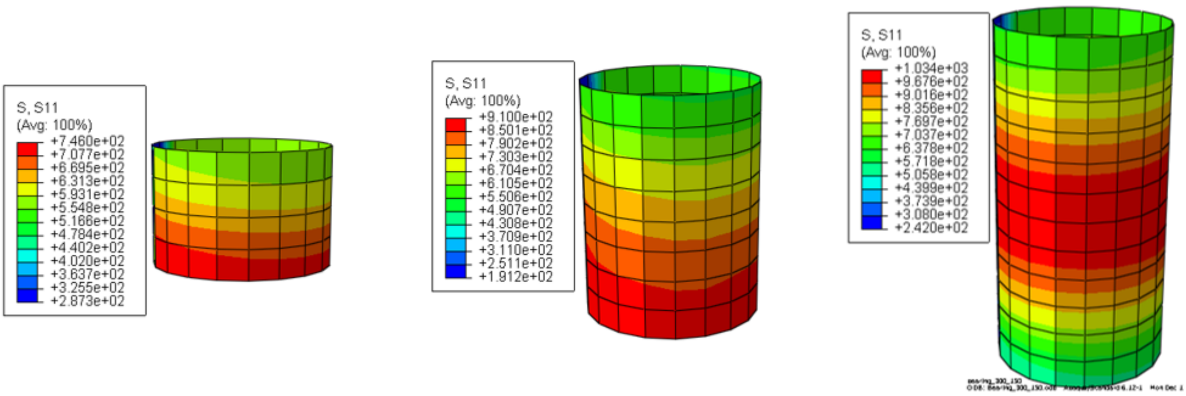
Length of wrapping =100 mm Length of wrapping =200 mm Length of wrapping =300 mm

a. Bearing plate size 50 mm



Length of wrapping =100 mm Length of wrapping =200 mm Length of wrapping =300 mm

b. Bearing plate size 100 mm



Length of wrapping =100 mm Length of wrapping =200 mm Length of wrapping =300 mm

c. Bearing plate size 150 mm

FIGURE 12. Tensile stress is applied to the CFRP wrapping.

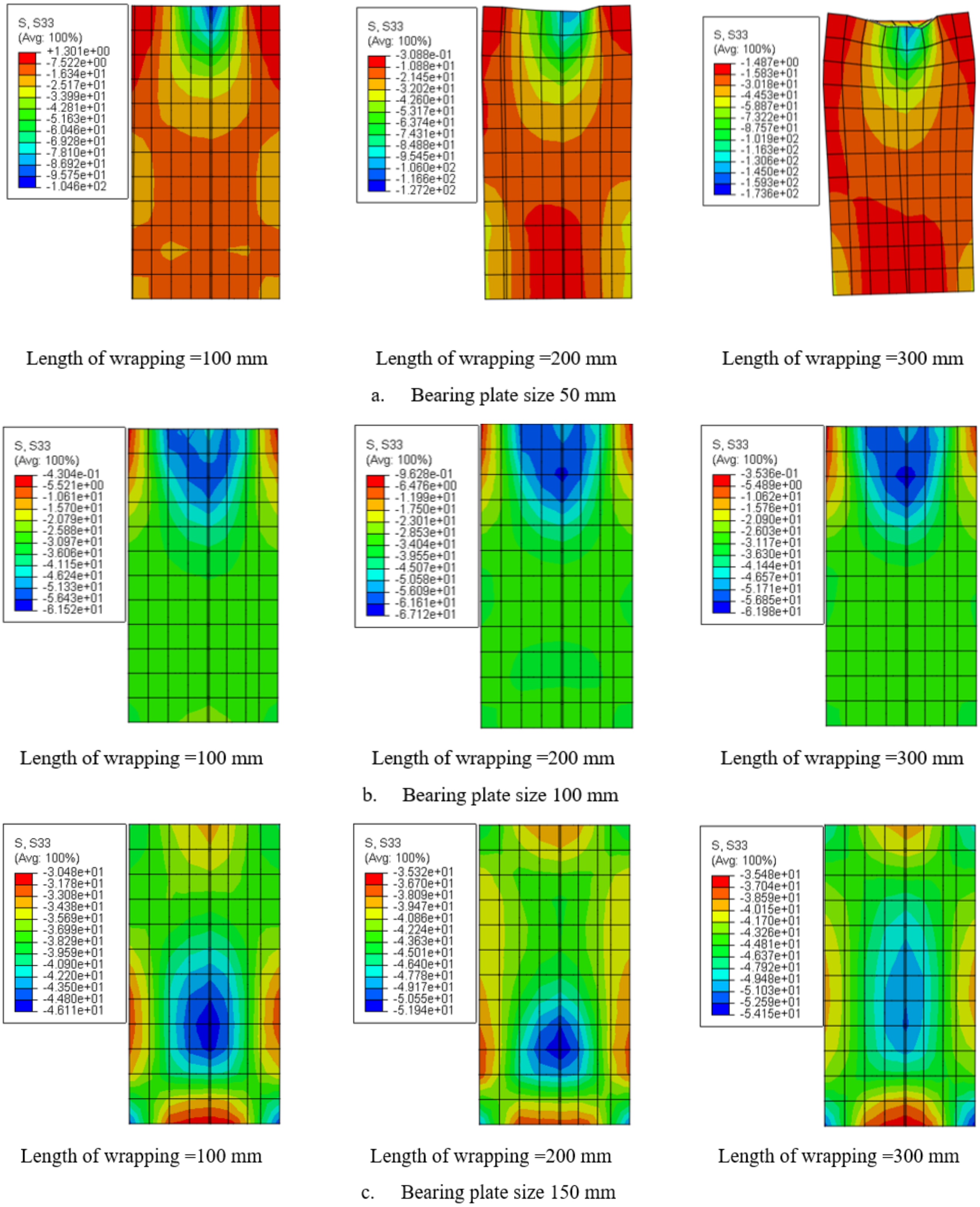


FIGURE 13. Compressive stress applied to the concrete core.

CONCLUSIONS

The CFRP wrapped cylindrical and cubic concrete molds were simulated using finite element modelling to investigate the performance of twenty eight specimens subjected to localised compressive loading. The ABAQUS software was utilized in the simulation of the specimens tested recently. Three dimensional nonlinear FEM was developed to simulate the bearing behaviour of adopted specimens. The FEM results were extensively analyzed and the following findings can be mentioned:

1. The results of the developed model showed excellent matching to those experimentally obtained. The mean value of the ratio (P^{EXP}/ P^{FEM}) of adopted specimens is (1.07) and the correlation factor (R=0.96) while the standard deviation (SDV=0.12).
2. The FEM results indicate that the CFRP wrapping improves the load and deformation capacities of the confined specimens while the length of the wrapping is ineffective especially with specimens loaded using a small bearing area.
3. The comparison of the localised axial load capacity of both cubic and cylindrical specimens for those exposed and fully wrapped reveals that the strength of wrapped specimens progresses better than that of exposed as bearing area increases.
4. The axial behaviour of specimens subjected to the full area of loading is enhanced due to the presence of CFRP wrapping, as well as, the increasing of the wrapping length leads to increasing the load and deformation capacities of the tested specimens which behave more ductile.
5. The CFRP wrapping enhances the load capacity of cubic specimens and increases the dissipation of energy by increasing the deformation capacity and subsequently the wrapped specimens behave more ductile.
6. The CFRP wrapping is ruptured only for the specimens subjected to localised compressive load with a small area of loading and the full length of wrapping.
7. As known, the lateral tensile stress of CFRP wrapping indicates the efficiency of confinement. The upper third of wrapping was subjected to high lateral tension for specimens applied to a small area of loading, which indicates the full wrapping is not necessary. While the fully wrapped specimens applied to the full area of loading showed high lateral tension of wrapping and the concrete stress near the mid-height of specimens which indicates that the better confining of the concrete core happens with full wrapping.

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REFERENCES

Abdullah, J. A. 2010. Behavior of square tubed reinforced concrete and steel reinforced concrete short columns. Ph.D. Dissertation, Harbin Institute of Technology.

Abdullah, J. A. Awad, S. Y. & Salih, O. A. 2020. Bearing resistance of cfrp wrapped concrete. *Journal of University of Duhok (Pure and Eng. Sciences)* 23(2): 788-799.

Abdullah, J. A. Zhang, S. M. & Liu J. P. 2010. Shear strength and behavior of tubed reinforced and steel reinforced concrete (TRC and TSRC) short columns. *Thin-Walled Structures* 48(3): 191–199.

Ballinger, A. C. & Graig. P. E. 1997. Infrastructure repair and retrofit strengthening with external FRP system. *Composite Fabrication* 10: 18-22.

Caldarone, M, A. 2009. High-Strength Concrete A practical guide, Taylor & Francis, New York: USA, Taylor & Francis.

Chen, W. F. 1971. Bearing strength of concrete blocks. Special Topics report for M. S. degree for Siciliano.

Choi, K. K. & Xiao, Y. 2010. Analytical model of circular CFRP confined concrete-filled steel tubular columns under axial compression, *J Composite Construction* 14(1): 125-133.

Chun, S. S. & Park, H. C. 2002. Load carrying capacity and ductility of RC columns confined by carbon fiber reinforced polymer. *In Proc., 3rd Int. Conf. on Composites in Infrastructure,* San Francisco: Univ. of Arizona.

Han, L. H. Liu, W. & Yang, Y. F. 2008. Behaviour of concrete-filled steel tubular stub columns subjected to axially local compression. *Journal of Constructional Steel Research* 64: 377–387.

Hawkins, N. M. 1968. The Bearing Strength of Concrete Loaded Through Rigid Plates. *Magazine of Concrete Research* 20(62): 31-40.

Hibbitt, H. D. Karlsson, G.I. & Sorensen, E.P. 2006. ABAQUS Standard User's Manual Inc. Vol. 1, 2 and 3, Version 6.6, , USA.

Liu, J. P. Abdullah, J. A. & Zhang S. M. 2011. Hysteretic behavior and design of square tubed reinforced and steel reinforced concrete (STRC and/or STSRC) short columns. *Thin-Walled Structures* 49(7): 874–888.

Liu, J. Chen, H. M. Wang, Z. H. & Du, X. L. 2020. Size effect on axial compressive failure of CFRP-wrapped square concrete columns: Tests and simulations. *Composite Structures* 254: 112843.

Mai, A. D. Sheikh, M. N. & Hadi, M. N. 2019. Performance evaluation of intermittently CFRP wrapped square and circularised square reinforced concrete columns under different loading conditions. *Structure and Infrastructure Engineering* 15(5):696-710.

Mukherjee, A. Boothby, T. E. Bakis, C. E. Joshi, M. V. & Maitra, S. R. 2004. Mechanical behavior of fibre-reinforced polymer-wrapped concrete columns-complicating effects. *Journal of Composite Construction* 8(2): 97–103.

Niyogi, S. K. 1973. Bearing Strength of Concrete – Geometric Variations. *Journal of the Structural Division* 99(ST7): 1471-1490.

Park, T. W. Na, U. J. Chung, L. & Feng, M. Q. 2008. Compressive behavior of concrete cylinders confined by narrow strips of CFRP with spacing. *Composites: Part B* 39:1093-1103.

Prabhua, G. G. & Sundarraja, M. C. 2013. Behaviour of concrete filled steel tubular (CFST) short columns externally reinforced using CFRP strips composite. *Construction and Building Materials* 47: 1362–1371.

Ravindrarajah, R. S. & Reinaldy, R. 2010. Bearing Strength of CFRP Confined Concrete. *The 5th International Conference on FRP Composites in Civil Engineering CICE, Beijing, China:* 603-606.

Scheffers, C. A. & Ravindrarajah R. S. 2009. Bearing Strength of Concrete with and without FRP Confinement. *24th Biennial Conference of the Concrete Institute of Australia, Concrete Solutions.*

Shehata, I. A. E. M. Carneiro, L. A. V. & Shehata, L. C. D. 2002. Strength of short concrete columns confined with CFRP sheets. *Materials and Structures/ Materiaux et Constructions* 35: 50-58.

Shen, Q. Wang, J. Wang, Y. & Wang, F. 2019. Analytical modelling and design of partially CFRP-wrapped thin-walled circular NCFST stub columns under axial compression. *Thin-Walled Structures* 144:106276.

Toutanji, H. & Saafi M. 2002. Stress-strain behavior of concrete columns confined with hybrid composite materials. *Materials and Structures/Materiaux et Constructions* 35: 338-347.

Zeng, J. J. Guo, Y. C. Gao, W. Y. Chen, W. P. & Li, L. J. 2018. Stress-strain behavior of concrete in circular concrete columns partially wrapped with FRP strips. *Composite Structures* 200:.810-828.

Zhong, T. & Han, L. H. 2007. Behaviour of fire-exposed concrete-filled steel tubular beam columns repaired with CFRP wraps. *Thin Walled Structures* 45:63–76.

Zhong, T. Han, L. H. & Wang. L. L. 2007. Compressive and flexural behavior of CFRP-repaired concrete-filled steel tubes after exposure to fire. *Journal of Constructional Steel Research* 63:1116–1126.