Civil Engineering and Architecture 9(5A): 157-162, 2021
DOI: 10.13189/cea.2021.091318 http://www.hrpub.org

Bearing Strength of Concrete with Carbon Fibre Reinforced Plastic (CFRP) Wrapping Axially Loaded through Circular Plate

N. A. Yahya[1,*], N. Md Nor[2], M. R. Md Zain[1], C. L. Oh[1], S. W. Lee[3]

[1]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2]Faculty of Civil Engineering, Universiti Teknologi MARA, Pulau Pinang Campus, 13500 Permatang Pauh, Pulau Pinang, Malaysia
[3]Faculty of Civil Engineering, Universiti Teknologi MARA, Pasir Gudang Campus, 81750 Masai, Johor, Malaysia

Received December 11, 2020; Revised July 26, 2021; Accepted August 9, 2021

Cite This Paper in the following Citation Styles

(a): *[1] N. A. Yahya, N. Md Nor, M. R. Md Zain, C. L. Oh, S. W. Lee , "Bearing Strength of Concrete with Carbon Fibre Reinforced Plastic (CFRP) Wrapping Axially Loaded through Circular Plate," Civil Engineering and Architecture, Vol. 9, No. 5A, pp. 157 - 162, 2021. DOI: 10.13189/cea.2021.091318.*

(b): *N. A. Yahya, N. Md Nor, M. R. Md Zain, C. L. Oh, S. W. Lee (2021). Bearing Strength of Concrete with Carbon Fibre Reinforced Plastic (CFRP) Wrapping Axially Loaded through Circular Plate. Civil Engineering and Architecture, 9(5A), 157 - 162. DOI: 10.13189/cea.2021.091318.*

Abstract Bearing strength of concrete is strongly related to contact behaviour when the loaded bearing plate penetrate over limited area of concrete surface. The model of concrete bearing was examined using the three-dimensional (3D) nonlinear explicit finite element micro-model in the ABAQUS/Explicit. The contact interaction between the concrete surface and the steel bearing plate was modelled using Surface to Surface (S-to-S) contact model. For material nonlinearity, the Concrete Damage Plasticity Material Model (CDPM) was adopted to stimulate nonlinear behaviour of concrete. The main objective of this paper is to determine the effects of external reinforcement namely Carbon Fibre Reinforced Plastic (CFRP) wrapping in strengthening the bearing capacity of concrete blocks. The concrete block models are with three different bearing ratios of unloaded-loaded area 2, 4 and 6 were investigated. The FE results have shown that the structural performance of concrete bearing with CFRP external wrapped can increase the axial load capacity up to 30% than normal concrete block without CFRP wrapped. However, the effectiveness of CFRP wrapping is decreased as the concrete bearing ratio is increased. This indicates that the CFRP wrapping is effective for concrete blocks with high contact areas.

Keywords Bearing Strength, CFRP Wrapping, ABAQUS/Explicit, Concrete Damage Plasticity Material Model, Confinement Effect, Contact Interaction

1. Introduction

In building construction, concrete bearing or bearing strength of concrete is normally referred to the capacity of concrete to resist the concentrated of axial force over a limited area, popularly known as bearing area or loaded area. The vertical axial force is transferred through a steel bearing plate act as a medium of the force to the concrete surface. The steel bearing plate can significantly carry high concentrated load and avoid stress concentration on the concrete surface. Such system is which normally found in concrete support structures such as concrete corbel, concrete bearing, concrete footing and also post tension members for the anchorage. The structural mechanics of concrete bearing strength is strongly related to the confinement effect based on the compressive strength of material and the ratio of the concrete surface area to steel loaded area [1-6].

In concrete strengthening, wrapping concrete which also known as concrete jacketing provides alternative solution to structural replacement or using expensive repair materials, such as high early strength or high strength concrete. The concrete wrapping technique is widely used due to economical reason and sustainable proactive measure [7-10]. Meanwhile, advanced composite material such as carbon fibre reinforced polymer (CFRP) is widely used in the industrial fields for aerospace and marine. The CFRP provides lightweight, high strength, stiffness, durability, and good resistance against corrosion. The potential benefits of composite structural to overcome deterioration in civil structures and infrastructures are crucial [11-13]. The application of external wrapping technique becomes popular in concrete retrofitting and structural strengthening to enhance the structural performance and to maintain the service life of deteriorated structure members.

2. Methodology

In the nonlinear analysis, the use of ABAQUS/implicit can cause incomplete analysis due to the convergence issues especially dealing with stress singularity. ABAQUS/explicit analysis particularly the nonlinear analysis [14] was employed in the study. It also incorporates high quality mesh control to prevent mesh distortion especially at the area that experience severe material deformation. It is also noted that the use of square mesh size improves the modelling results. The explicit algorithm is found to be suitable for quasi- static test although its main purpose is to model high velocity impact events such as earthquake or impact loading.

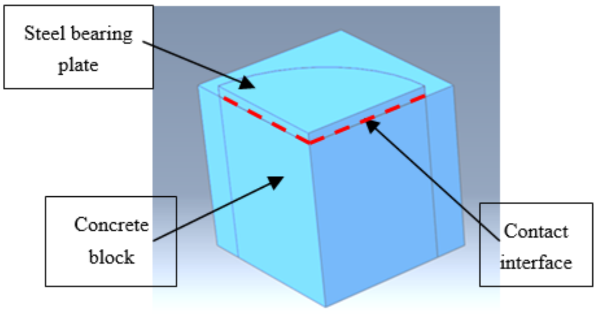

Figure 1. A 3D quarter size model of concrete bearing

For the FE modelling, the three dimensional (3D) linear and nonlinear analysis were developed in ABAQUS/ Explicit to investigate the structural performance of concrete bearing subjected to vertical circular bearing load with and without of CFRP wrapping in terms of its displacement and the concrete bearing capabilities. The nonlinearity of material was considered in the concrete damage plasticity model (CDPM) and was analysed in the explicit technique in order to capture the plasticity to failure behaviour of concrete bearing. By taking the advantages of symmetrical geometry and loading of the concrete bearing, only a quarter size of the model is considered in this research. The contact interaction [15] for surface-to-surface (S-to-S) contact has been used to stimulate the contact interface between the steel bearing plate and the concrete surface. For vertical direction, the contact surface is based on the “hard-contact” surface. For horizontal behaviour of contact surface, the typical value coefficient of frictional of 0.3 was used. The 3D model of the concrete bearing consists of square concrete block and circular steel bearing plate as shown in Figure 1.

In nonlinear analysis, the material properties of concrete are required for elastic and inelastic behaviours. For the elastic stage, two input parameters are required. The concrete grade 32 MPa was used with the elastic modulus and Poisson’s ratio of 26.48 GPa and 0.167 respectively. The tensile strength of concrete is 2.28 MPa based of 0.4 times the square roots of its compressive strength. In this study, Concrete Damage Plasticity Model (CDPM) is utilized to simulate the concrete non-linear behaviour. Under low confining pressure, concrete behave in a brittle manner in which the cracking and failure mechanism due to tension and compression.

The concrete damage plasticity model in ABAQUS uses a yield condition based on the yield function and this model also incorporates the modification to account for different evolution of strength under tension and compression as shown in Table 1 and 2 [16,17,19].

Table 1. The evolution of scalar damage parameter for CDPM

Compression damage		**Tension damage**	
Damage	**Crushing Strain**	**Damage**	**Cracking Strain**
0	0	0	0
0.1299	0.0004	0.30	0.0001
0.2429	0.0008	0.55	0.0003
0.3412	0.0012	0.70	0.0004
0.4267	0.0016	0.80	0.0005
0.5012	0.0020	0.90	0.0008
0.5660	0.0024	0.93	0.0010
0.7140	0.0036	0.95	0.0020
0.8243	0.0050	0.97	0.0030
0.9691	0.0100	0.99	0.0050

Table 2. Compression hardening and tension stiffening for CDPM

Compression Hardening		**Tension Stiffening**	
Stress (MPa)	**Crushing Strain**	**Stress (MPa)**	**Cracking Strain**
24.02	0	2.28	0
29.21	0.0004	1.46	0.0001
31.71	0.0008	1.11	0.0003
32.36	0.0012	0.96	0.0004
31.77	0.0016	0.80	0.0005
30.38	0.0020	0.54	0.0008
28.51	0.0024	0.36	0.0010
21.91	0.0036	0.16	0.0020
14.90	0.0050	0.07	0.0030
2.95	0.0100	0.04	0.0050

The tensile strength of concrete is determined based on the ratio of compressive strength of concrete. According to Australian Standard AS3600 [18], Clause 6.1.1.3 stated that the characteristic principal tensile strength of concrete can be taken as equal to 0.4 times the square root of compressive strength or determined by the indirect tensile test. In the present study, the typical value of tensile strength for grade 32 is taken as 2.28 MPa. For the inelastic material for CDPM, all parameters used in the current model were taken from the typical values that are available in ABAQUS documentation (2015). Some of parameters were obtained from various publications as tabulated in Table 3.

Table 3. Inelastic material input parameters for CDPM

Material Parameters	**Typical Values**	**Values Used**
Ratio of initial equibiaxial compression yield stress to initial uniaxial compression yield stress, $(\sigma_{bo}/\sigma_{co})$	1.1 to 1.16 (Lubliner *et. al.*, 1989)	1.12
$\alpha = (\sigma_{bo}/\sigma_{co}) / 2 (\sigma_{bo}/\sigma_{co})$	0.08 to 0.12 (Lubliner *et. al.*, 1989)	0.12
Value for K_c for concrete	0.667 (ABAQUS default value)	0.666
Value of γ for concrete	3 (ABAQUS default value)	3
Dilation angle, ψ	30°(Starossek, 2008)	30°
Eccentricity, **E**	0.1 (ABAQUS)	0.1

The comparisons have been made of FE models to determine the accuracy of model in predicting the confinement effect of difference loaded sizes and bearing ratios for unconfined and confined as tabulated in Table 4.

Table 4. FE model dimensions

Model	**Confinement Conditions**	**Plate Size (mm dia.)**	**Bearing Ratio**
FE-1	Unconfined	320	2
FE-2	Unconfined	225	4
FE-3	Unconfined	185	6
FE-4	Confined	320	2
FE-5	Confined	225	4
FE-6	Confined	185	6

* Steel bearing shape is circular with 12.7mm thick
Concrete Block Dimension is 400mm x 400mm x 200mm
Unconfined is considered as plain concrete without CFRP
Confined is concrete bearing with external reinforcement of CFRP

The steel bearing plate with manufacture grade S420 for elastic modulus of 200 GPa, Poisson's ratio of 0.3 and yield stress of 400 MPa was used in all models. The carbon fibre reinforced polymer (CFRP) used for the external wrapping having elastic modulus of 240 GPa, Poisson's ratio of 0.3, ultimate tensile strain of 1.5% and ultimate tensile strength of 3800 MPa based on study [4]. The authors tested their specimen for bearing strength of concrete wrapping confined with two layers of unidirectional CFRP sheet in the hoop direction formed in a wet lay-up procedure. Their experimental work focused on the effect of additional confinement caused by CFRP strengthening system. However, no orientation effect of CFRP was considered in their study. The load-displacement control up to 0.4mm was applied on the top surface of steel bearing plate until it reached the failure as shown in Figure 2.

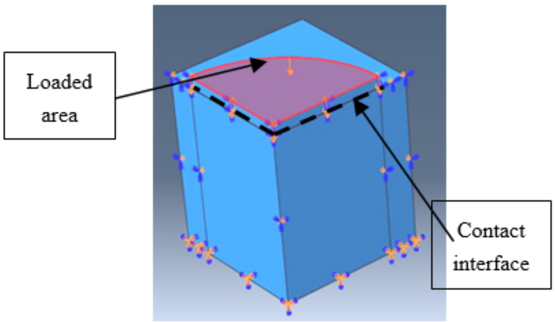

Figure 2. Load displacement control (on the top steel bearing plate surface)

For the meshing, four different mesh sizes, i.e., 7.5 mm, 10 mm, 15 mm and 20 mm were examined to determine the optimum mesh size. In mesh sensitivity studies, the linear analysis was carried out for the load-displacement control set to be 0.2 mm. In order to visualise the results of the convergence analysis, the axial load level and vertical stress at centre of loaded area for different mesh sizes were monitored and plotted in Figure 3 and 4 respectively.

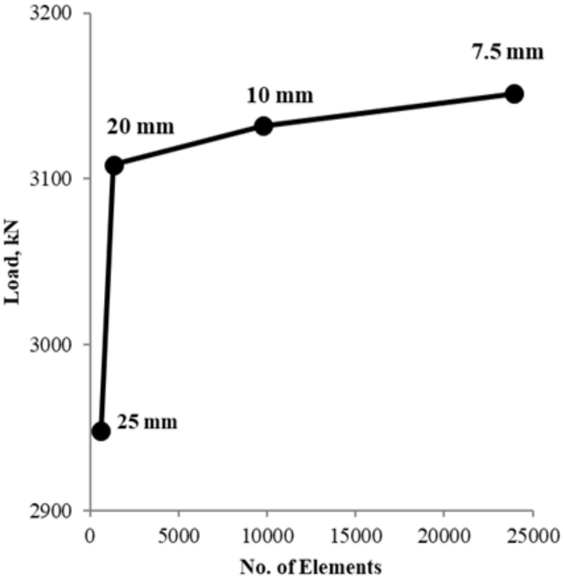

Figure 3. The load levels in different mesh sizes

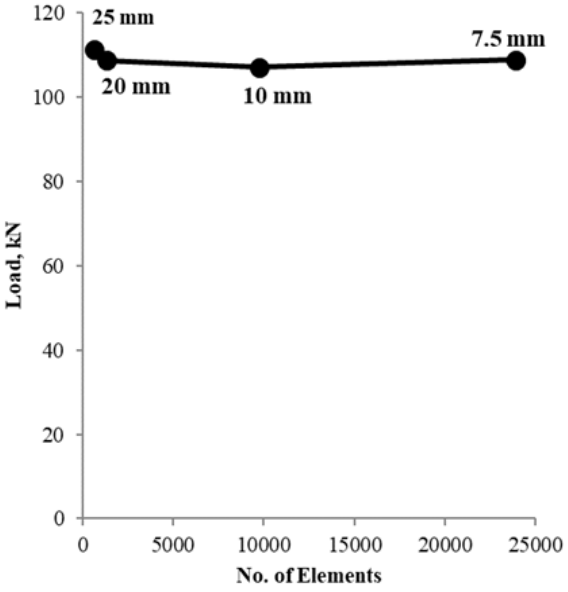

Figure 4. The vertical stress at centre for different mesh sizes

Figure 3 shows the maximum axial load is 2948.25 kN, 3108.65 kN, 3132.1 kN and 3151.3 kN for 25 mm, 20 mm, 10 mm and 7.5 mm mesh size respectively. The maximum axial load started to converge when the axial load achieved between 10 mm and 7.5 mm meshing. The percentage difference of axial load for 10 mm and 7.5 mm is less than 1%. Thus, the optimum mesh size for all model is 10 mm. For vertical stresses, the stress levels are considered quite consistent at ±109 MPa for all mesh sizes.

3. Results and Discussions

The model validation is presented deal with confinement of concrete bearing of a defined height due to dimension of steel bearing plate. The confinement of concrete is a crucial benchmark for validation work to ensure the FE model capable of predicting the confinement level for different steel plate surface areas. In this validation, the result of ultimate load from the nonlinear FE model was compared with the theoretical for bearing strength of concrete in accordance to Australian standard [18] based on concrete compressive strength and ratio of unloaded to loaded area. The results of FE modelling and theoretical are shown in Table 5a and 5b respectively. The load displacement for FE model and theoretical prediction is provided in Figure 5 and 6 respectively.

$$f_b = \emptyset\, 0.85\sqrt{A/A'}\; f_c' \le 1.19 f_c' \qquad (1)$$

Table 5. FE model result

Ultimate Bearing Load FE Model (kN)	Bearing Capacity FE Model (N/mm^2)
2947.96	36.65

Table 6. Theoretical prediction model [20, 21, 22]

Ultimate Bearing Load Theory (kN)	Bearing Capacity Theory (N/mm^2)
3085.68	38.36

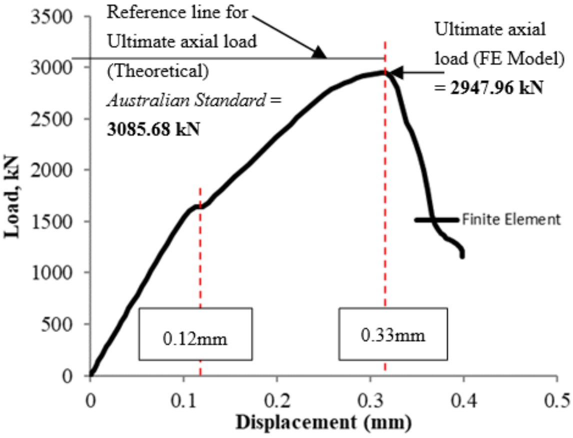

Figure 5. The load-displacement for FE model of unwrapped concrete bearing and theoretical prediction model

Figure 5 shows the axial load versus the vertical displacement relationship curve for FE model. The reference line is also added in the figure to indicate the limit of ultimate axial load (theoretical) that calculated based on bearing strength of concrete in accordance to Australian Standard AS3600. It is clearly seen that the FE model is able to simulate nonlinear behaviour of concrete bearing and capture the axial load of 2947 kN. The ultimate axial load from FE model is only 5 % difference from the predicted axial load (3085 kN). The confinement effect is exhibited due to the contact interaction between circular steel bearing plate and concrete surface. The external confinement in this context refers to the CFRP wrapping of concrete. The performance of unwrapped and CFRP concrete bearing are presented in Table 7 and 8 respectively.

Table 7. Unwrapped concrete bearing (Unconfined condition)

Model	Bearing Ratio	Ultimate Load, F_{ult} (kN)	Bearing Strength (N/mm^2)	Confinement Effect
FE-1	2	2947.96	36.65	1.20
FE-2	4	1997.36	50.23	1.70
FE-3	6	1538.50	57.23	2.07

Table 7 indicates that the ultimate load for model 1, 2 and 3 are 2947.6 kN, 1997.36 kN and 1538.60 kN for bearing ratio of 2, 4 and 6, respectively. For the bearing strength, results obtained are 36.65 N/mm^2 for FE-1, 50.23 N/mm^2 for FE-2 and 57.23 N/mm^2 for FE-3. As far the confinement effect taking into consideration, the ratio of concrete bearing strength to compressive strength yielded at 1.20, 1.70 and 2.07 for FE-1, FE-2 and FE-3 respectively. This also indicates that the concrete blocks with smaller plate exhibited greater confinement effects compared to a larger steel plate. However, the ultimate load for smaller plate is low due to smaller contact area.

Table 8. CFRP wrapped concrete bearing (Confined condition)

Model	Bearing Ratio	Ultimate Load, F_{ult} (kN)	Bearing Strength (N/mm^2)	Confinement Effect
FE-4	2	4333.88	53.88	1.68
FE-5	4	2561.77	64.42	2.01
FE-6	6	1906.87	70.93	2.22

In Table 8, the CFRP wrapped concrete bearing for the ultimate load for FE-4, FE-5 and FE-6 are 4333.88 kN, 2561.77 kN and 1906.87 kN and calculated bearing pressure are 53.88 N/mm^2, 64.42 N/mm^2 and 70.93 N/mm^2 respectively. The confinement effects are yielded at 1.68, 2.01 and 2.22 for these models, respectively. The presence of external CFRP wrapping of concrete has improved the behaviour and properties of unwrapped concrete bearing. The result of unwrapped concrete blocks and CFRP wrapped concrete blocks are presented in Table 9.

Table 9. Structural performance of unwrapped and CFRP wrapped concrete bearing

FE Model	Bearing Ratio	Without CFRP	With CFRP	Percentage Diff. of Bearing Capacity (%)
		Bearing Capacity (N/mm^2)		
FE-1, FE-4	2.0	36.65	53.88	31.98
FE-2, FE-5	4.0	50.23	64.42	22.03
FE-3, FE-6	6.0	57.23	70.93	19.32

The results in Table 9 show the comparison both the plain concrete and CFRP wrapped concrete. It shows the ultimate load for all the CFRP wrapped concrete has better bearing capacity as expected due to confinement effect of CFRP wrapping. For concrete with bearing ratio of 2, it showed that the external CFRP wrapping increase the ultimate load and bearing strength of the concrete block by 32 % followed by 22.03 % and 19.32 % for ratio 4 and 6 respectively. The presence of external CFRP confinement can increase the ability to increase concrete bearing strength, the effectiveness of external CFRP wrapping on concrete also improving the strength and ductility. These trends are also similar to [4, 8, 10, 23, 24] where the presence of CFRP wrapping can increase the structural performance of concrete. However, this study found that the effectiveness of CFRP wrapping decreased when the concrete bearing ratio increased. This study suggests that the CFRP wrapping is more effective in concrete blocks with higher contact areas such as concrete-column connection, concrete footing or concrete bridge pedestals. For the post-tensioned member for anchorage is not suitable for CFRP wrapping as its smaller contact area.

4. Conclusions

The main aim of this study is to examine the effect of using Carbon Fibre Reinforced Polymer (CFRP) wrapping as an external reinforcement to increase bearing capacity of concrete block in the structural support system. To date, in spite all issues dealing in designing concrete bearing, there is limited fundamental studies have been focused on CFRP wrapped concrete bearing using FEA. For this study, the finite element method was carried out in four main stages namely mesh sensitivity analysis, model validation, model analysis and parametric studies focused on different plate sizes under confined and unconfined conditions. Based on the FE analysis carried out and data presented, the following conclusions and recommendation are drawn:

1. The effects of concrete compressive strength, concrete-to-loaded area ratio and external CFRP wrapping has significant effects on the confinement effects, bearing capacity and structural ductility in designing concrete bearing.
2. Use of confinement can improve the ultimate load and improve the load bearing capacity. The effectiveness of CFRP wrapping in strengthening plain concrete block is significant where the bearing strength with external CFRP capacity was increased up to 31%.
3. The nonlinear FE model successfully simulate the behaviour of CFRP wrapping concrete bearing for different loaded steel plate sizes on the concrete surface. However, the results show that the effectiveness of CFRP wrapping reduces when the concrete bearing ratio increases from 2 to 6. This also indicates that the CFRP wrapping is more effective in concrete blocks with higher contact area such as bridge pedestal or corbel. However, it was found less significant for anchorage strengthening in repairing of post tension member.

Hence, the increase of confining pressure improves the ductility and stiffness of concrete bearing. As the confining pressure increases, the concrete bearing becomes more ductile with increased its stiffness. Therefore, this present study suggests that the future design of concrete bearing needs to incorporate with confining pressure that can improve the confinement effect of concrete bearing.

Acknowledgements

This research was funded by the Universiti Teknologi MARA under grant BESTARI PERDANA Research Grant (600-IRMI/DANA 5/3/BESTARI (P) (060/2018)). Authors would also like to thank especially to Mr.

Nazreen and Mr. Hazlan who directly involved in this research works for the master dissertation project. Also, to all laboratory staffs in Concrete, Fabrication and Heavy Structures Laboratories, Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Shah Alam for their support in the laboratory testing.

REFERENCES

[1] R. Bonetti, C. L. Roberts-Wollmann, J. T. Santos, Bearing Strength of Confined Concrete, ACI Structural Journal, Vol. 111(6) 1317, 2014.

[2] D. E. Lehman, C. W. Roeder, R. A. Larsen, Design of Cotton Duck Bridge Bearing Pads, Journal of Bridge Engineering, Vol. 10(5), 555-563, 2005.

[3] K. Mounir, L. C. Montedor, J. B. de Hanai, Compression Tests of Cement-Composite Bearing Pads for Precast Concrete Connections, Cement and Concrete Composites, Vol. 28 621-629, 2006.

[4] C. A. Scheffers, R. S. Ravindrarajah, R. Reinaldy. Bearing Strength of CFRP Confined Concrete, Proceeding of the 5th International Conference on FRP Composites in Civil Engineering, Sep 27–29, Beijing, China. 2011.

[5] R. S. Ravindrarajah. Bearing Strength of Concrete Containing Polystyrene Aggregate, Proceeding the RILEM 8th International Conference. Durability of Building Materials and Components, Vancouver, Canada. 1999.

[6] C. L. Roberts-Wolimann, T. Banta, R. Bonetti, F. Charney. Bearing Strength of Lightweight Concrete, ACI Materials Journal, Vol. 103(6), 459. 2006.

[7] G. P. Lignola, A. Prota, G. Manfredi. Simplified Modeling of Rectangular Concrete Cross-Sections Confined by External FRP Wrapping, Polymers, Vol. 6(4), 1187-1206, 2014.

[8] G. Ganesh Prabhu M. C. Sundarraja, Behaviour of Concrete Filled Steel Tubular (CFST) Short Columns Externally Reinforced using CFRP Strips Composite, Construction and Building Materials, Vol. 47, 1362-1371, 2013.

[9] H. Bouchelaghem, A. Bezazi, F. Scarpa, Compressive Behaviour of Concrete Cylindrical FRP-Confined Columns Subjected to A New Sequential Loading technique. Composites Part B: Engineering, Vol. 42(7), 1987-1993. 2011.

[10] I. A. Shehata, L. A. Carneiro, l. C. Shehata, Strength of Short Concrete Columns Confined with CFRP Sheets. Materials and Structures, Vol. 35(1), 50-58. 2002.

[11] G. Campione, L. La Mendola, A. Monaco, A. Valenza, V. Fiore, Behavior in Compression of Concrete Cylinders Externally Wrapped with Basalt Fibers. Composites Part B: Engineering, Vol. 69, 576-586, 2015.

[12] J. F. Berthet, E. Ferrier, P. Hamelin, Compressive Behavior of Concrete Externally Confined by Composite Jackets. Part A: Experimental Study, Construction and Building Materials, Vol. 19(3), 223-232, 2005.

[13] M. N. S. Hadi, J. Li, External Reinforcement of High Strength Concrete Columns, Composite Structures, Vol. 65, 279-287, 2004.

[14] S. Yena, N. Pochai. Numerical Treatment of a Two-Dimensional Vertically-Averaged Groundwater Flow Model Using Alternating Direction Explicit Methods. Civil Engineering and Architecture, Vol. 8, No. 2, pp. 144 - 153, 2020. DOI: 10.13189/cea.2020.080212.

[15] Z. Zenasni, M. Haterbouch, K. Nasri, M. Zenasni, R. Addou, K. Hannawid, W. P. Agbodjand. Numerical Simulation of Residual Behavior of Steel Concrete Interface after High Temperature Exposure. Civil Engineering and Architecture, Vol. 9, No. 3, pp. 625 - 633, 2021. DOI: 10.13189/cea.2021.090306.

[16] N. A. Yahya. Strategies for Mitigation of the Failure of Concrete Pedestals Supporting Bridge Girder Bearings. Doctoral dissertation, Queensland University of Technology, 2017.

[17] N. A. Yahya, M. Dhanasekar. Explicit Finite Element Modelling of Bridge Girder Bearing Pedestals, The 23rd Australasian Conference on the Mechanics of Structures and Materials, Southern Cross University, Byron Bay, Australia, Vol 1, 849-853, 2014.

[18] Australia Standard for Concrete Structures: AS3600, Standards Australia Limited, 2009.

[19] M. R. M Zain, N. A. Yahya, Experimental Study on Bearing Strength of Concrete Blocks under Concentric Compression Load. Pertanika Journal of Science and Technology, Vol 25, 67-76. 2017.

[20] M. R. M. Zain, N. A. Yahya, L. S. Wee, O. C. Lian, A. S. A. Rahman, M. Dhanasekar, Bearing Strength Behaviour of Bridge Concrete Pedestal with Confined Reinforcements, Journal of Mechanical Engineering, Vol. 16(2), 167-181. 2019.

[21] N. A Yahya, N. M. Amin, M. R. M. Zain, O. C. Lian, L. S. Wee, Bearing Strength of Concrete Blocks with External Wrapping of Carbon Fibre Reinforced Plastic (CFRP). In *ICSDEMS 2019* (pp. 249-257). Springer, Singapore. 2019.

[22] N. A. Yahya, M. Dhanasekar, H. A. Hamid, Localised Failure Mechanism of Concrete Pedestals under Bridge Bearing, Australian Journal of Civil Engineering, 1-12. 2020.

[23] N. A. Yahya, N. M. Nor, R. M. Zain, C. L. Oh, S. W. Lee, Bearing Strength of Circular Concrete Blocks Varies in Heights Subjected to Concentrically Circular Loaded Bearing Plate. In IOP Conference Series: Earth and Environmental Science, IOP Publishing. Vol. 498(1), 012049, 2020.

[24] N. A. Yahya, M. Dhanasekar, M. R. M. Zain, C. L. Oh, S. W. Lee, Numerical Modelling of Concrete Bearing Strength for Different Heights of Concrete Blocks. In IOP Conference Series: Materials Science and Engineering, IOP Publishing. Vol. 513(1), 012031, 2019.