Structural Behaviour of Putra Block Under Axial Load Using FEM

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ABSTRACT

Interlocking hollow block (IHB) system is a new building technology which eliminates the mortar layer and instead provides a key connection (protrusions and grooves) to interconnect the blocks. With respect to the mortarless feature of the system, it will shorten the construction period, reduce labour and cost, and is environmental friendly. This study covers the modelling and the analysis of Putra Block which is an interlocking hollow block system developed by the Housing Research Centre at Universiti Putra Malaysia (UPM) under axial compression load using Finite Element Method (FEM). The block units comprise of a stretcher block, a corner block and a half block. The aims of this research were to develop the Putra Block prism model using ABAQUS software and to study the structural behaviour of these prisms under axial load using finite element analysis. The Putra Block prism consists of three layers of blocks where the top and bottom layer are made of stretcher block where the middle layer are made of two half blocks placed side by side. Before proceeding with the simulation study, validation of the Putra Block prisms was conducted by using results from previous experimental research work. It was found that the ultimate load between experimental and simulation results had slight differences with an error of 2.56%. The small variations justify the ability of ABAQUS to predict the structural behaviour of elements under axial compression load with good accuracy level. Based on the FEA study, higher compressive stress value was observed on the face-shell of the block whilst higher tensile stress occurred at the webs. The failure of the prisms was mainly due to extensive tensile cracks induced at the web-shell interaction and middle of the block. Further parametric study reveals that by increasing the height of the individual blocks lead to the reduction of its ultimate load. Consequently, the use of higher concrete grade block indicated an improvement in the prism strength and stability under axial load.

Keywords: ABAQUS, FEM, Interlocking Hollow Block System, Prism, Putra Block.

1.0 INTRODUCTION

In Malaysia, the demand for a sustainable, affordable and high quality housing have increased over the past two decades. Due to the ever increasing of population and the growing numbers of young workers, different types of housing are in greater demand. Hence, in the recently launched 11th Malaysia Plan [1] various housing schemes had been introduced by the government. To fulfil this demand and supply of houses, a fast and rapid industrialised building system is required by the construction industry. The construction system must fulfil all the basic building requirement, such as structurally stable, workability and is environmental friendly.

Interlocking hollow block (IHB) system is a new alternative construction system to the more traditional bonded masonry system where the mortar layer is required to integrate the block into the wall. The interlocking hollow block system has no mortar layer and instead provided key connection (protrusions and grooves) to interconnect the blocks. It is believed that the invention of the interlocking hollow block system will bring forward lots of advantages to the construction field. Thus, with respect to mortarless feature of the system, it will reduce the construction period, reduce labour and cost, and is environmental friendly.

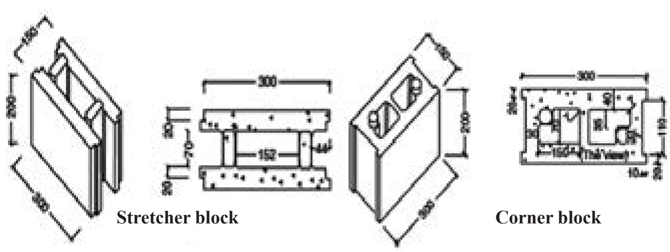
In 2000, an interlocking block building system called Putra Block was developed by the Housing Research Centre (HRC) at University Putra Malaysia (UPM) [2] [3]. The Putra Block was designed for the construction of load bearing walls of up to 3 metres in height. The dimension of Putra Block meets the modular coordination requirement and is a self-aligned construction system to ensure rapid and precise construction. There are three different configurations of block units, these are the stretcher block, corner block and half block [4]. Further understanding towards the structural behaviour of grouted and ungrouted Putra Block prism was experimentally conducted by *Jaafar et al.,* [5].

Most researchers are aware that conducting full scale research by experimental and laboratory works is an expensive exercise. Hence, to overcome such circumstances, studies using Finite element method (FEM) or also known as Finite Element Analysis (FEA) are a preferable choice. It has been stated that FEM, as a numerical tool, has the ability to conduct various analytical work with high precision results. It is also known that FEM has the ability to analyse all types of structures and continua. Large structures or components are divided into smaller and simpler elements called finite elements. This technique is widely used to solve complicated structures or components with different types of load conditions and material properties in the engineering field. The FEM solves the problem through generating and calculating simultaneous algebraic equations using digital computers. The final results may not show the ‘exact’ output required, but these errors can be reduced by processing more equations, and the suitable results for engineering purposes can be obtained at a reasonable time and cost [6].

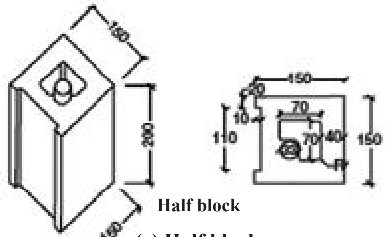
ABAQUS [7] is one of the FEM software which is available in the market nowadays. ABAQUS is a general purpose simulation tool based on the finite element method and can be used for a set of applications ranging from the modelling of civil engineering structures to acoustics. It can be applied to address combinations of static and dynamic, linear and nonlinear problems [8]. The Concrete Damage Plasticity model is used for modelling of the damage properties (crushing and cracking) of the Putra Block prisms in ABAQUS.

2.0 LITERATURE REVIEW

Interlocking hollow block (IHB) system is introduced as a new building technology that may result in a rapid and economical construction. Putra block was invented by the Housing Research Centre (HRC) of University Putra Malaysia (UPM). It is an innovative hollow block system that have the interlocking load bearing function and developed to meet the modular coordination requirement as stated in the Industrialized Building System (IBS) concept [9]. The primary feature of Putra Block is the elimination of the mortar layers as the blocks are interconnected through the provision of protrusions and grooves [10]. The system consists of three types of block, namely as a stretcher, half and corner blocks as shown in Figure 1 (a), (b) and (c).



(a) Stretcher block **(b) Corner block**



(c) Half block

Figure 1: Putra Block units [11]

Jaafar et al., [5] conducted an experimental study into the dry-joint contact behaviour of masonry and the behaviour of interlocking mortarless hollow blocks for grouted and ungrouted prisms under axial compression. Table 1 shows the compression test results for three ungrouted prisms. The ungrouted prisms presented an average compressive strength (f_m) of 11.2 N/mm^2, and the average stress at which web cracks (f_{wc}) will be initiated was measured at 6.4 N/mm^2. *Safiee et al.,* [9] carried out a compression test to determine the compressive strength of the individual block. Table 2 presents the compressive strength of the different block types.

Table 1: Test results of compressive strength and web splitting loads of prisms [5]

Type of prism	Specimen	Maximum load (kN)	Compressive strength, f_m (N/mm^2)	Web splitting load (kN)	Web splitting stress, f_{wc} (N/mm^2)
Ungrouted	PR1	216.1	9.0	122.8	5.1
	PR2	299.5	12.5	171.9	7.2
	PR3	289.6	12.1	164.1	6.8
	Ave	268.4	11.2	152.9	6.4

Table 2: Compressive strength of individual block units [11]

Block types	Density, ρ (kg/m^3)	Compressive strength, f_m (N/mm^2)	Tensile strength, f'_t, (N/mm^2)
Stretcher	2042.24	18.62	2.06
Corner	2014.8	18.02	2.79
Half	1936.66	17.03	2.16

3.0 MATERIALS AND METHODS

The proposed models of Putra Block prism were three dimensional non-linear material models. The models were developed and analysed by using ABAQUS/Explicit software through concrete damage plasticity model. The material properties of the Putra Block used in this research was in accordance with the previous research work conducted by *Thanoon et al.,* [9]. Table 3 shows the detailed material properties of Putra Block used in the research. The constitutive parameters used in concrete damaged plasticity model for both compressive and tensile behaviour of Putra Block were presented in Table 4.

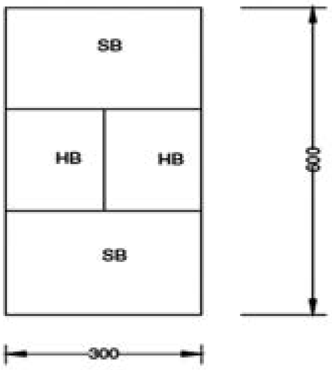
Table 3: Material properties of Putra Block unit [9]

Materials	Properties
Putra Block	• Consists of ordinary Portland cement, coarse aggregates having 10 mm nominal maximum size and fine aggregates (quarry dust).
	• Water cement ratio = 0.45.
	• Young’s Modulus, E = 11 GPa.
	• Cube compressive strength at 28 days, f_{cu} = 22 MPa.
	• Tensile strength, f_t = 1.98 MPa
	• Poisson ratio, υ = 0.20
	• Material parameter = 8
	• Density, ρ = 2000 kg/m^3

The prism models were assembled from two stretcher block units and two half-block units. Hence, the Putra Block prism with a total height of 600mm (3 x 200mm) and thickness of 150mm was computationally modelled by ABAQUS software and simulation study of the prisms was conducted under axial loading. The Putra Blocks prism was also designed to be in compliance with ASTM C1314-11 [12]. According to ASTM C1314-11 [12], the test prism shall have a minimum of two units high with a height-to-thickness ratio, h_p / t_p between 1.3 and 5.0. The full designation and dimension of the Putra Block prism were demonstrated in Figure 2.

Table 4: Concrete damaged plasticity of Putra Block unit

Density (kg/m^3)	**2000**		**The parameter of CDP model**		
			Dilation angle, ψ	32	32
Concrete elasticity			Eccentricity	0.1	0.1
			f_{bo} / f_{co}	1.16	1.16
E (GPa)	11		k	0.67	0.67
ν	0.2		Viscosity	0.001	0.001
Compressive behaviour from experiment			Tensile behaviour from experiment		
Yield stress (MPa)	Inelastic strain	Damage parameter	Yield stress (MPa)	Cracking strain	Damage parameter
16.96	0	0	1.8	0	0
21.24	0.0005078	0	1.5	0.0001	0.16667
22	0.0013542	0	1	0.0003	0.44444
16.96	0.0026122	0.2290909	0.7	0.0005	0.61111
9.5	0.0055439	0.5681818	0.5	0.0008	0.72222
5.2	0.0080831	0.7636363	0.2	0.0015	0.88889
2.5	0.0103684	0.8863636	-	-	-
1.23	0.0124844	0.9440909	-	-	-



SB-Stretcher Block Unit = 2
HB-Half Block Unit = 2

Figure 2: Detailed of the Putra Block prism (all units in mm)

In the validation process, the Putra Block prism with a dimension of 600mm x 300mm x 150mm assembled by two stretcher blocks (200 x 300 x 150mm) and two half blocks (200 x 150 x 150mm) was simulated under axial load. The simulation results were compared with the experimental results by *Jaafar et al.,* [5] and the variation of result was expected to have a difference of ±10%. A parametric study was conducted on five prisms which the thickness and width of blocks was fixed, but the height of the block varies from 100mm to 300mm. Moreover, three prisms with fixed block dimension and compressive strength of blocks varied from 18MPa to 28MPa was also studied.

4.0 RESULTS AND DISCUSSIONS

4.1 Convergence Study of Putra Block Prism

FEA is a method that used to solve complex problems by disintegrated the rigid body into small discrete regions known as finite elements. The arising of discretization error in the FEA indicated the essential of convergence study. Increasing the number of elements in the model illustrated a finer mesh is used. Thus, the solution is approached to the analytical solution and the discretization error is reduced. At some point, further mesh refinement yields little or no change in the solution, and also required longer solution processing time. The mesh is assumed to converge when the solution yields little or no change.

In the study, convergence study had been conducted by several element sizes as stated in Table 5 to choose the most suitable mesh size for the consequence analysis process. Same material properties were used for the different mesh sizes. A graph of ultimate load versus total elements was plotted as shown in Figure 3 to show the results of the convergence study. Based on the results, the ultimate load, P_u FEA converged to a near constant value or had a small percentage difference with the experimental results when the total elements reached 100000. Therefore, the suitable mesh sizes chosen for the consequence simulation and parametric study were global size 6 to 5 or about 100000 to 170000 elements.

Table 5: Results of mesh refinement study of Putra Block Prism

Mesh size	**Total Element**	**Ultimate Load, P_u (kN)**		**Percentage Differences (%)**
		FEA	**Experimental**	
GB 5	166048	297	299.5	-0.83
GB 6	106474	297	299.5	-0.83
GB 8	45900	292	299.5	-2.50
GB 10	22972	283	299.5	-5.51
GB 14	7396	232	299.5	-22.54
GB 20	3704	195	299.5	-34.89
GB 24	1940	192	299.5	-35.89

Note: GB = global size for mesh density in ABAQUS

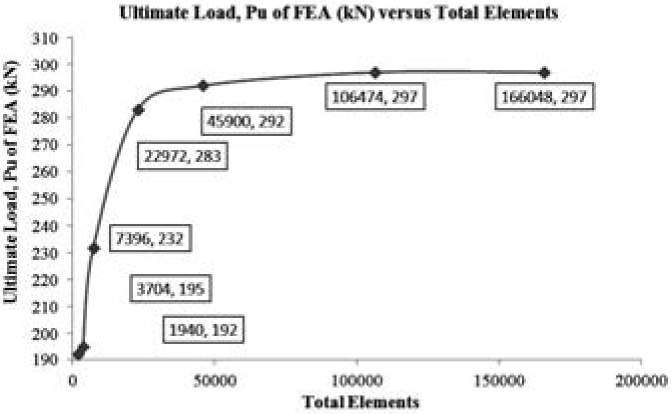
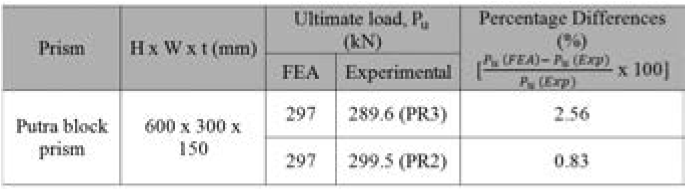


Figure 3: Convergence study of FEA

4.2 Validation

The validation of the FEA by using the concrete damaged plasticity model is done by comparing the simulation results with the experimental data from *Jaafar et al.,* [5]. The ultimate load from the experiment and the FEA were tabulated in Table 6.

Table 6: Comparison on ultimate load carrying capacity of Putra Block Prism under axial load for experimental and FEA method



Prism	H x W x t (mm)	Ultimate load, P_u (kN)		Percentage Differences (%) $[\frac{P_u\ (FEA) - P_u\ (Exp)}{P_u\ (Exp)} \times 100]$
		FEA	Experimental	
Putra block prism	600 x 300 x 150	297	289.6 (PR3)	2.56
		297	299.5 (PR2)	0.83

The FE model predicted the local capacity within acceptable range of ±10%, which was 0.83% and 2.56% respectively. Therefore, it was indicated that the concrete damaged plasticity model and material properties used were able to model the Prism under axial loading.

4.3 Simulation Study

Based on the simulation process, the structural behaviour of Putra Block prism subjected to axial load was studied. Outputs such as ultimate load, crack patterns, stress distribution, strain distribution and load-deflection profile of Putra Block Prism were determined and discussed.

4.3.1 Load-deflection Profile of Putra Block Prism

The ability of Putra Block Prism in sustaining the applied load can be studied by referring to the graph of compressive load versus vertical displacement as shown in the Figure 4. Besides that, the experimental result from *Jaafar et al.,* [10] was plotted in order to compare with the FEA result.

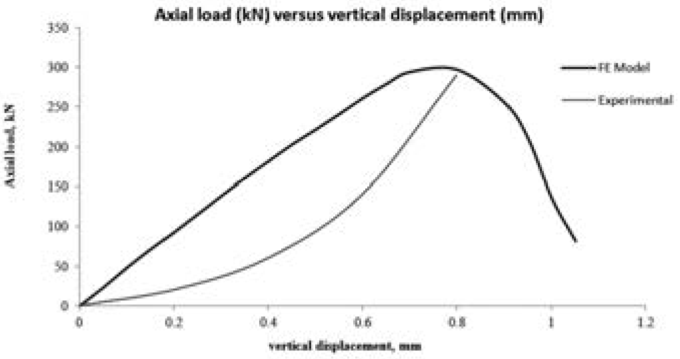


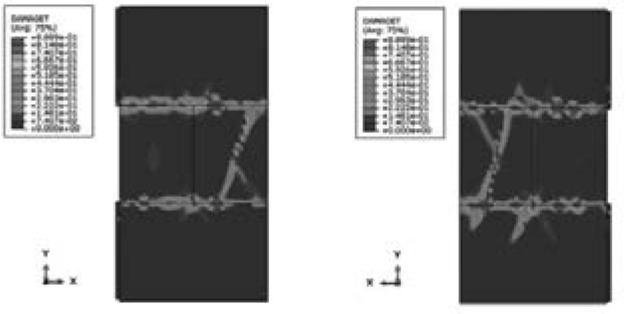
Figure 4: Load-deflection profile for prism

The ultimate load and vertical displacement at ultimate load from FEA was 297.33kN and 0.8mm. Figure 4 shows that there are differences between the FEA and experimental result. Since the prism used in the FEA is considered as a perfectly geometrical model, it should in most cases have variations from the experimental study prism which may have imperfections occurred during the test. Moreover, the study of the interlocking joint behaviour between block (key and protrusion) was not included in this research that may cause the FEA result to differ from the experimental result. Thus the difference occurred between the experimental and FEA study was in the acceptable range.

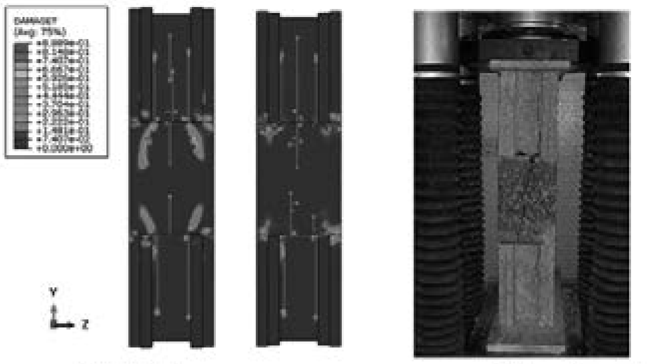
From close observation of the FEA results, the Von Mises stress distribution of the block indicated that the crack will be occur at web-shell intersection and middle of block webs. Based on the stress distribution, it found that higher tensile stress was occurring at webs of block and higher compressive stress was occurring in the face - shell of a block. Therefore, the Von Mises stress of the prism can be used to visualize the damage zone of the Prism.

4.3.2 Failure Mode of Putra Block Prism

The behaviour of Putra Block Prism when subjecting to incremental compressive load until failure is presented. Prior to failure, various cracking patterns were observed. The main vertical cracks occurred at the middle web and shell-web intersection of the upper stretcher block. More severe cracks were observed at the lower stretcher block, left half block and right half block of the prisms. Simultaneously, diagonal cracks in the half block shell was also detected. These crack patterns are clearly illustrated in Figures 5(a), 5(b) and 5 (c). The FEA results show good agreement with the crack patterns from the experimental work as shown in Figure 5 (d).



(a) Front view (b) Rear view



(c) Side View (d) Experimental

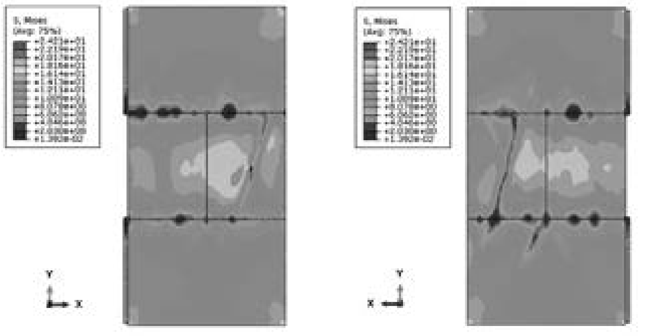
Figure 5: Failure mode of prism

4.3.3 Stress Distribution Across Depth of Prism

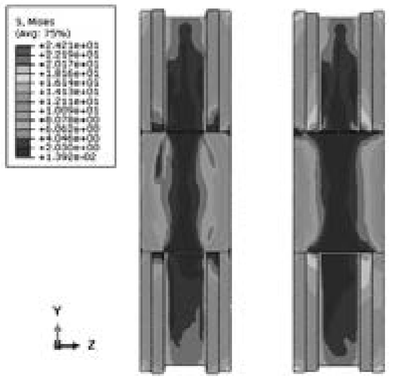
The Von Mises stress distribution of prism is an important parameter that can used to predict potential yielding of the block prism under axial loading condition. As illustrated in Figure 6, the Von Mises stress distribution of the block indicates that cracks will occur in the web-shell intersection and middle of block webs. The stress contour as shown in the Figure 6 represented the highest stress zone of a panel when achieving its ultimate load carrying capacity. The prism failed through cracking at the middle zone of the block web and web-shell intersection. Similar observation was evidently shown by the failure mode of prism in the experimental study, see Figure 5(d).

4.3.4 Strain Distribution Across Prism Thickness

Strain distribution across the thickness of the prism is also an important parameter to identify the structural behaviour of the block. The strain distribution across the thickness of the prism at top height of web-shell intersection at different load stages were illustrated in Figure 7 and Figure 8. It is shown that the strain was varied along the thickness of the prism at top height. Besides that, the increment of negative strain was proven that when the axial load applied to the panel increased, the vertical strain of prism increased. Thus, it indicated the prism was displaced in the vertical down direction. Moreover, it's shown that the strain distribution at left web-shell intersection was quite similar with right web-shell interaction.



(a) Front View (b) Rear view



(c) Side view

Figure 6: Stress distribution across depth of prism

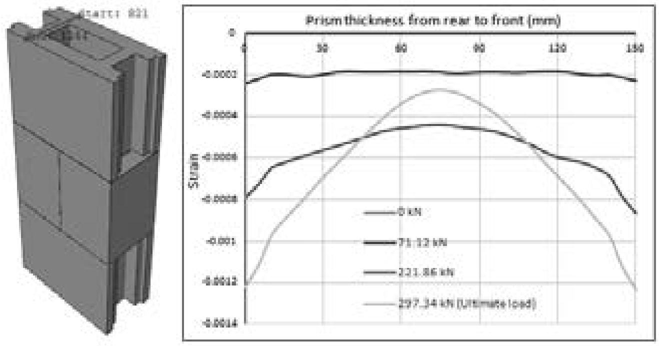


Figure 7: Vertical strain across the thickness of Prism at the top of left web-shell intersection

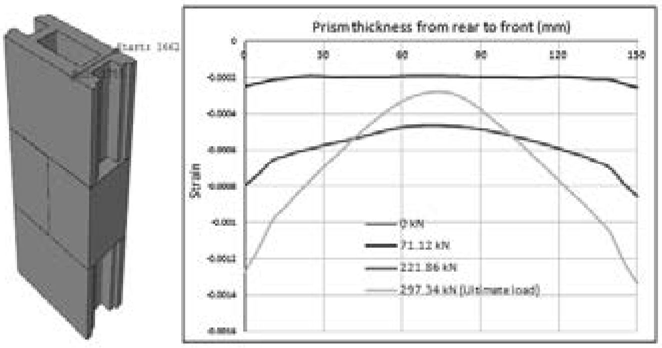


Figure 8: Vertical strain across the thickness of Prism at the top of right web-shell intersection

4.4 Parametric study: Block Height and Compressive Strength

A parametric study was carried out using the prism with constant thickness of 150mm but with increasing block height. By subjecting the prisms with axial compressive load until failure, the results of the parametric study are as illustrated in Figure 9 and Figure 10. By observing Figure 9, it was evident that when the height of the block increases, the ultimate load carrying capacity subsequently decreased.

Figure 10 illustrates the effect of changing the cube compressive strength of the block. As the strength increases, the ultimate load carrying capacity of the prism was also increased as shown. An increment of 181.5% in ultimate load was observed when the cube compressive strength increases from 18MPa (PR6) to 28MPa (PR8) as stated in Table 6. Thus, the higher concrete grade block will have greater ability to resist the higher axial loading.

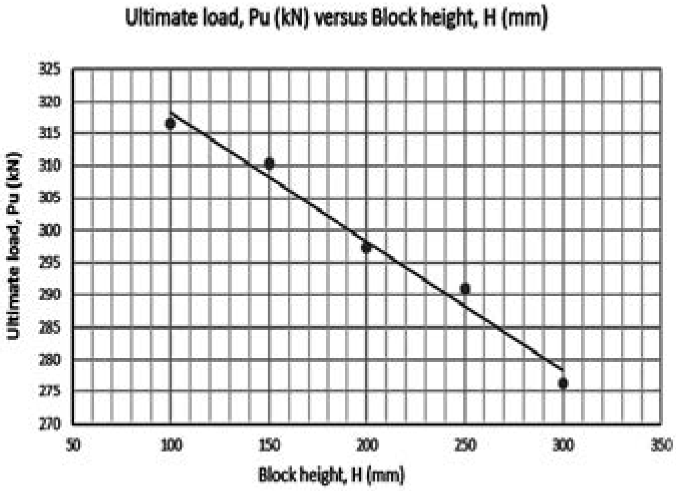


Figure 9: Ultimate load carrying capacity versus block height

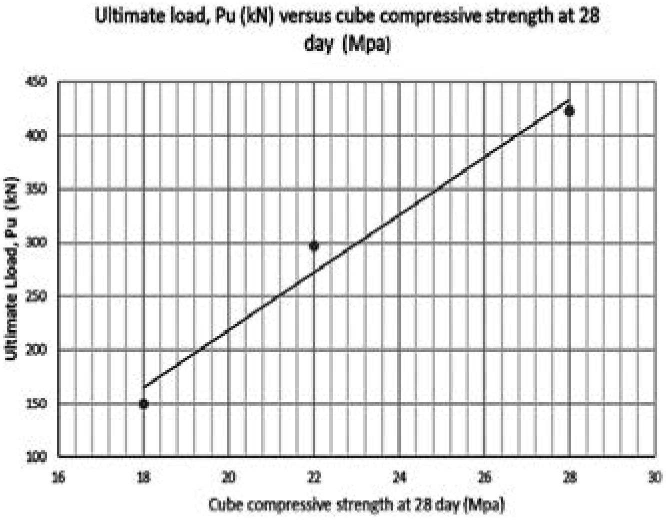
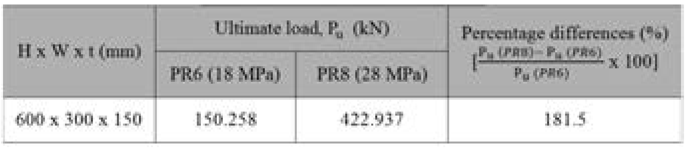


Figure 10: Ultimate load Carrying capacity versus cube compressive strength at 28 days

Table 7: Comparison on ultimate load carrying capacity of PR6 (18MPa) and PR8 (28 MPa) under axial load



H x W x t (mm)	Ultimate load, P_u (kN)		Percentage differences (%) $[\frac{P_u\ (PR8) - P_u\ (PR6)}{P_u\ (PR6)} \times 100]$
	PR6 (18 MPa)	PR8 (28 MPa)	
600 x 300 x 150	150.258	422.937	181.5

5.0 CONCLUSIONS

Based on the study, it can be concluded that the aims of this study have achieved. Hence, the results were summarized as follows:

1. The Putra Block prism was successfully modelled by the ABAQUS Finite Element Software to study its structural behaviour under axial compression load. It was validated with previous experimental result from *Jaafar et al.,* [5] with more than 97% accuracy level.
2. Von Mises stress distribution and load deflection of prism were able to predict the potential failure zone of Putra Block accurately.
3. Higher compressive stress was observed in the face-shell of the block, but the highest tensile stress was occurring on the web. The failure of prisms was due to tensile cracks induced at the web-shell interaction and middle of the web.
4. From the parametric study, by increasing the block height reduces the ultimate load carrying capacity of the Putra Block prisms. However, by increasing the concrete grade of the FEM prisms will ultimately increase its load carrying capacity.

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