Parametric Investigation Using Finite Element Analysis on Number of FRP Confinement Layers for Optimum Compressive Strength of Tin Slag Polymer Concrete Column

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Abstract

Tin slag polymer concrete (TSPC) is a recent progress in Polymer Concrete (PC) material which is composed of finely graded tin slag (TS) particles (<1mm) and Unsaturated Polyester Resin (UPR) with 1% Methyl Ethene Ketone Peroxide (MEKP). This study was performed to suggest the optimum number of GFRP and CFRP confinement layers on the TSPC core column for optimum compressive strength enhancement. Compression test on TSPC column samples consisting of unconfined TSPC, one and two layers of GFRP and CFRP confined TSPC shows strength measurements of 49.58 MPa, 85.48 MPa, 88.37 MPa, 108.77 MPa, and 132.52 MPa. Then a parametric study through the FEM model was performed to simulate the effect of FRP confinement on TSPC with the addition of FRP confinement layers to up to four layers. Results indicated that for both GFRP and CFRP confinement on TSPC column up to four layers, the percentage of strength enhancement was, for GFRP, 55.56 %, 82.47 %, 193.96 %, and 193.32 %, while, for CFRP, 85.27 %, 122.61 %, 177.81 %, and 151.65 %. For validation, a comparison has been made with an experimental result and data from literature which presents the effect of multiple layers of CFRP confinement on the TSPC column. Both the optimisation through parametric study and literature have provided a good match in a number of FRP confinement layers for optimum compressive strength enhancement of the TSPC column. For conclusion, three layers of FRP confinement was described as the most optimum number of FRP layers on the TSPC column for maximum performance.

Keywords: TSPC Column, Compressive Strength, GFRP & CFRP, Parametric Study, Optimisation

1.0 Introduction

Malaysia is one of the largest tin production countries in the world which makes Malaysia, also poses a massive amount of tin slag (TS) as an abundant potential resource. TS is a byproduct of the tin smelting industry and is primarily disposed of through dumping on a controlled land field which legalized for hazardous waste disposal sites [1], [2], [3], [4]. A review by Manda et al. [5] has reported that TS waste particles have a potential to be recycled by transforming into a tin slag polymer concrete (TSPC) material. In the study, the author has suggested that TSPC may be applied as structural materials as alternative to cement concrete as well as conventional polymer concrete materials. TSPC is a recent progress in Polymer Concrete (PC) material which is composed of finely graded TS particles (<1mm) and Unsaturated Polyester Resin (UPR) with 1% Methyl Ethene Ketone Peroxide (MEKP) (Faizal et al., 2018). According to the study, the optimum aggregates to resin ratio of TSPC was 70:30 representing fine TS particles as aggregates and MEKP resin as a matrix element. Then, most of the studies on TSPC after that have turned their focus on the strengthening of the TSPC column through externally constraining its lateral expansion during compressive loads. Some of the TSPC column strengthening studies were by [6] on glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) confinement, [7] on multiple layers of CFRP confinement, Manda et al. [8] on metallic material confinement, Manda et al. [9] on basalt (BFRP) and aramid fibre reinforced polymer (AFRP) confinement and Manda et al. [10] on hybrid FRP confinement. The compressive strength and behaviour of TSPC columns with varying magnitudes and failure patterns have been sufficiently studied in all of the research papers.

Numerical analysis using finite element method (FEM) has been performed by many researchers to evaluate various kind of structures [11], [12], [13], to name a few. This approach has been proven to provide the lowest cost and fastest results compared to the full-scale field test approach. Other than design investigation, FEM also allows optimisation through parametric study to predict the optimum performance of a structure by varying any of the pre-determined parameters. In addition to that, numerical investigation through finite element analysis (FEA) has also been performed on unconfined and FRP-confined TSPC columns under compression [14]. The study has provided enough details to allow the redevelopment of the numerical model with complete geometrical specification and property definition. Due to that extent, a parametric study on unconfined and confined TSPC under compression may be performed based on the numerical model that has been reported in the literature. The numerical model may be employed to optimise the TSPC performance under compressive loads. As a new material, TSPC has never undergone any optimisation studies, especially on the maximum strengthening limit with FRP confinement application. Therefore, to finalise the whole research findings, an optimisation study using finite element (FEM) model was done, particularly to suggest the optimum number of GFRP and CFRP confinement layers on the TSPC core column for optimum compressive strength.

2.0 Methodology

According to Manda et al. [9], the test samples of TSPC column confined GFRP and CFRP was prepared and tested under compression. The TSPC core column was composed of uniformly graded fine TS particles (<1 mm) with polyester resin and 1% methyl ethyl ketone peroxide (MEKP) as a catalyst. The wet mixture was then cast into a 50 mm diameter and 100 mm in height of cylindrical mould and cured for three days [15], [16]. After demoulding, GFRP and CFRP were wrapped on the TSPC core column specimen with epoxy Sikadur 330 part A:B (4:1) to provide strengthening by externally constraining its lateral expansion [17] during compressive loading application to delay the failure thus increasing the maximum compressive strength [16]. Figure 1 shows the test sample fabrication for the experimental test.

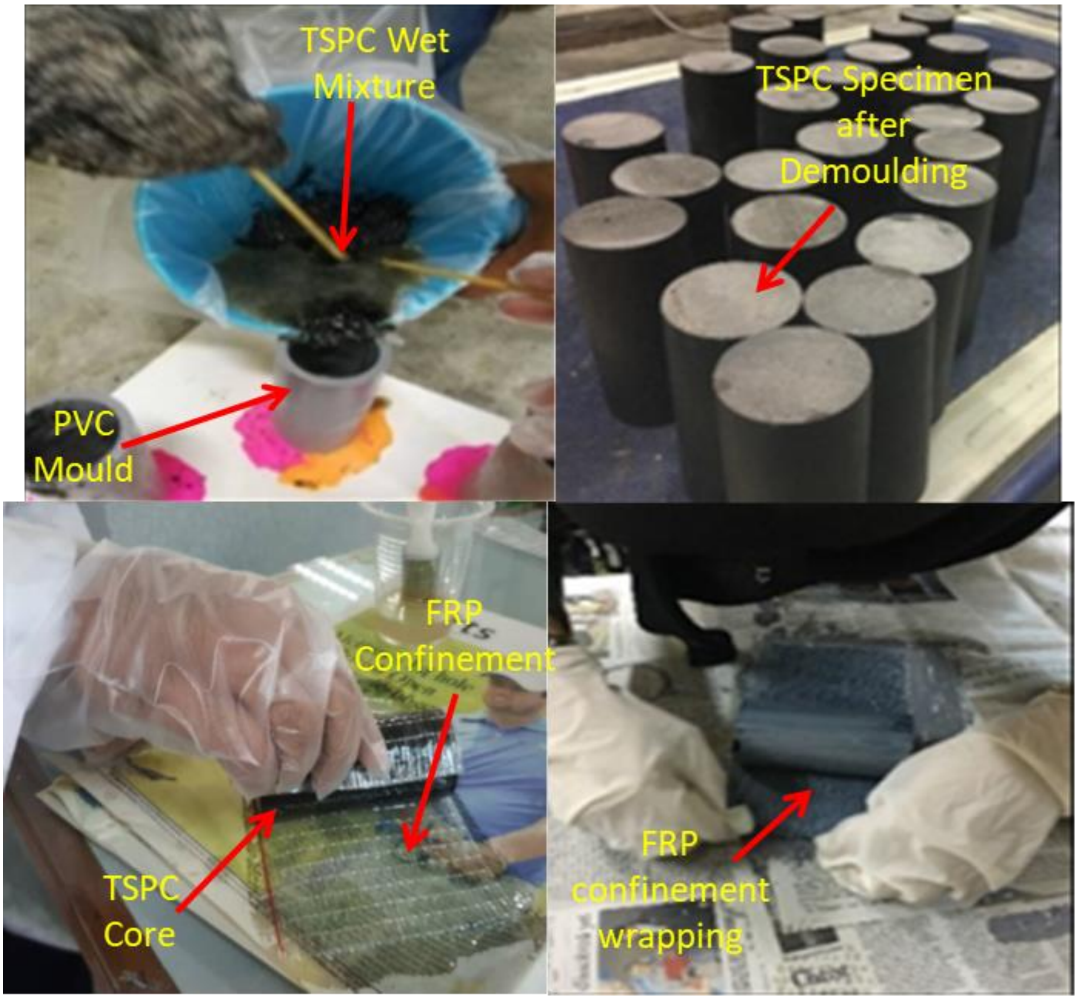

Figure 1: Test sample fabrication process

Then, the numerical model as reported by Manda et al. [14], has been developed using ABAQUS to perform a parametric study focusing on several FRP confinement layers for optimum strength enhancement. Figure 2 shows the geometrical development of the numerical model for the TSPC core column and the confinement element.

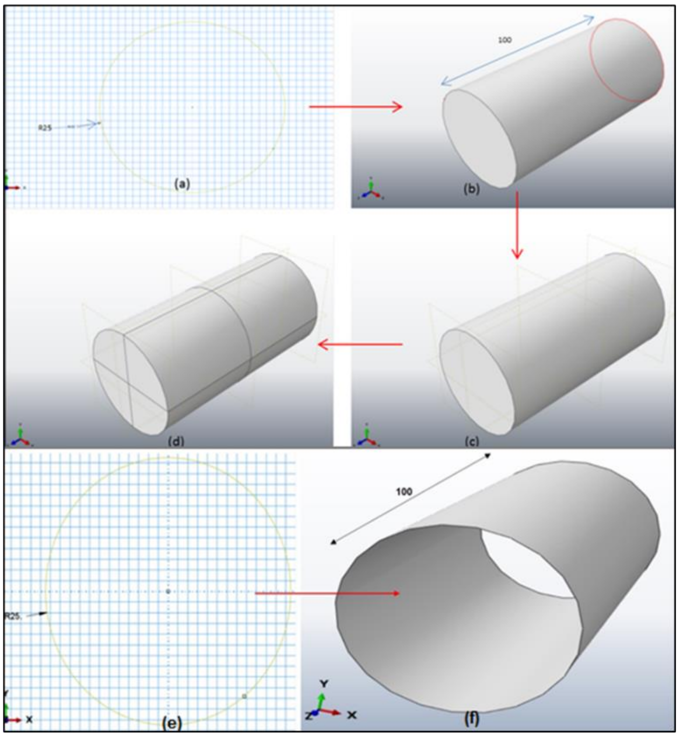

Figure 2: Model geometry of TSPC core column and confinement (a) Circular sketch solid. (b) 100 mm extrusion. (c) TSPC column model. (d) Partition definition. (e) Circular sketch shell. (f) Extrusion forming hollow shell cylindrical geometry

Figure 3 describes the boundary conditions and constraints on the FE model of the TSPC short-column samples. For initial condition, BC-1, the bottom surface of the model was set as encase which make it to remain static in all directions (X-axis, Y-axis, and Z-axis = 0) during compressive load application. Then for compression loads, the final boundary condition, BC-2, was set as displacement with 5 mm on the top surface of the model to represent compressive load application in vertical direction, Y-axis.

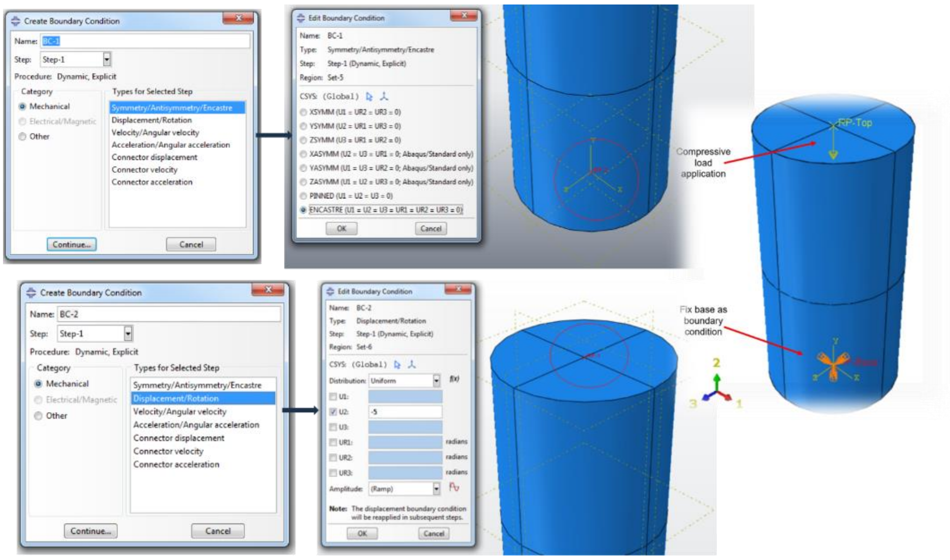

Figure 3. Boundary condition and constraint of the FE model

Then, the optimisation process was performed through the FEM model simulation by varying the FRP confinement layers parameter. The results were validated through an experimental study by Hassan et al. [6], which presented the compression behaviour of TSPC-confined CFRP with multiple numbers of CFRP confinements. In the study, an additional confinement layer was added to TSPC using both CFRP and GFRP material to observe its effect on the maximum compressive strength that could be achieved. Figure 4 shows the FEM model for both TSPC core column and confinement element with confinement material lamina property definition to simulate 1 layer, 2 layers and up to 4 layers of FRP wrapping.

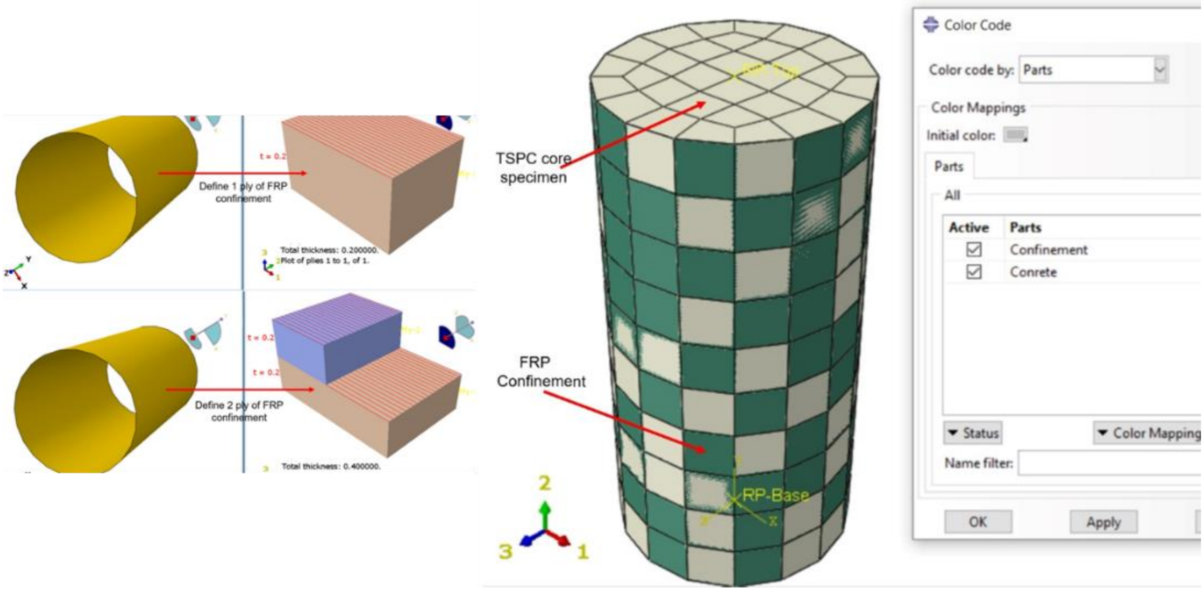

Figure 4: FEA model for TSPC core column and confinement element

3.0 Results and Discussion

3.1 Mechanical properties from experimental

Table 1 has listed some quantitative data from experimental results to describe TSPC performance under compression especially with the introduction of FRP material confinement. For unconfined TSPC, the maximum load is 100.48 kN with 3.111mm longitudinal deformation before crushing failure. Then, with the application of CFRP confinement, the load bearing application has enhanced up to 222.23 kN and 275.85 kN each for 1 layer and 2 layers of CFRP wrapping. Meanwhile, with the application of GFRP confinement, the load bearing application has been enhanced to 175.73 kN and 181.79 kN for 1 layer and 2 layers of GFRP wrapping. This improvement also occurred on maximum deformation, maximum stress, maximum strain, and yield stress which follow the same trend as the maximum load. For 1-layer CFRP, 2-layer CFRP, 1-layer GFRP and 2-layer GFRP confinement on TSPC specimens, the longitudinal deformation measured are 3.899 mm, 5.671 mm, 4.426 mm and 4.572 mm. Then the maximum stress measured is 108.77 MPa, 132.52 MPa, 85.48 MPa and 88.37 MPa compared to only 49.58 MPa for unconfined TSPC.

In addition to that, the subsequence strain rate measurement has shown 0.03899, 0.05838, 0.04426 and 0.04572 compared to unconfined TSPC strain rate which just 0.03111. Compressive modulus however does not follow similar trend in increment between confined and unconfined TSPC except for GFRP confinement. The compressive modulus for unconfined TSPC is 2.73 GPa and with 1 GFRP to 2 GFRP wrapping, the compressive modulus increases to 3.77 GPa and 4.66 GPa. Vice versa for CFRP confinement, even the compressive modulus has also shown an increase compared to unconfined TSPC, with 1 CFRP wrapping, the compressive modulus is 4.82 GPa while with 2 CFRP wrapping, it's decreased to 3.64 GPa. These findings indicate the difference in specimen stiffness with the application of CFRP and GFRP confinement. By applying CFRP confinement, additional confinement layer may reduce the stiffness while for GFRP; additional confinement layer may increase the stiffness. Although, the stiffness value does not affect maximum stress achievement as both CFRP and GFRP additional confinement layers on TSPC core column has results in proportional increased of maximum stress.

Table 1: Mechanical properties of confined and unconfined TSPC from experimental

Specimens	Max. Load (kN)	Max. Deformation (mm)	Max. Stress (MPa)	Max. Strain (mm/mm)	Compressive Modulus (GPa)	Yield Stress (MPa)	Strength Increment (%)
Unconfined TSPC	100.48	3.111	49.58	0.03111	2.73	40.08	-
1-CFRP Confinement	222.23	3.899	108.77	0.03899	4.82	65.91	119.38
2-CFRP Confinement	275.85	5.671	132.52	0.05671	3.64	64.03	167.29
1-GFRP Confinement	175.73	4.426	85.48	0.04426	3.77	48.72	72.41
1-GFRP Confinement	181.79	4.572	88.37	0.04572	4.66	61.97	78.24

For strength enhancement percentages, experimental results have revealed that 1 and 2 CFRP confinement layers on the TSPC column have provided 119.38 % and 167.29 % of strength enhancement compared to unconfined TSPC. For samples with GFRP confinement, the results indicate 72.41 % and 78.24 % of strength enhancement percentages for 1 and 2 layers respectively.

3.2 Effect of Additional CFRP Confinement

The finite element model (FEM) of TSPC confined CFRP was parametrically studied and in the composite layup definition, additional CFRP confinement layers are defined for the model. The simulation result shows that strength increased to 83.5 MPa and 100.33 MPa for one and two layers of CFRP confinement on the TSPC column. Then, with 3 layers of CFRP confinement, the strength was further increased to 125.21 MPa. However, with the addition of the 4th CFRP layer, the strength decreased to 113.42 MPa. This shows that the CFRP confinement is optimal using up to 3 layers. After that, the confinement reaches saturation, and further addition of CFRP confinement layers may either reduce or maintain the maximum compressive strength.

Figure 5 shows the stress-strain curve obtained from the FEM simulation of the parametric study. Figure 6 shows a quantitative comparison of maximum strength increased due to additional CFRP confinement layers.

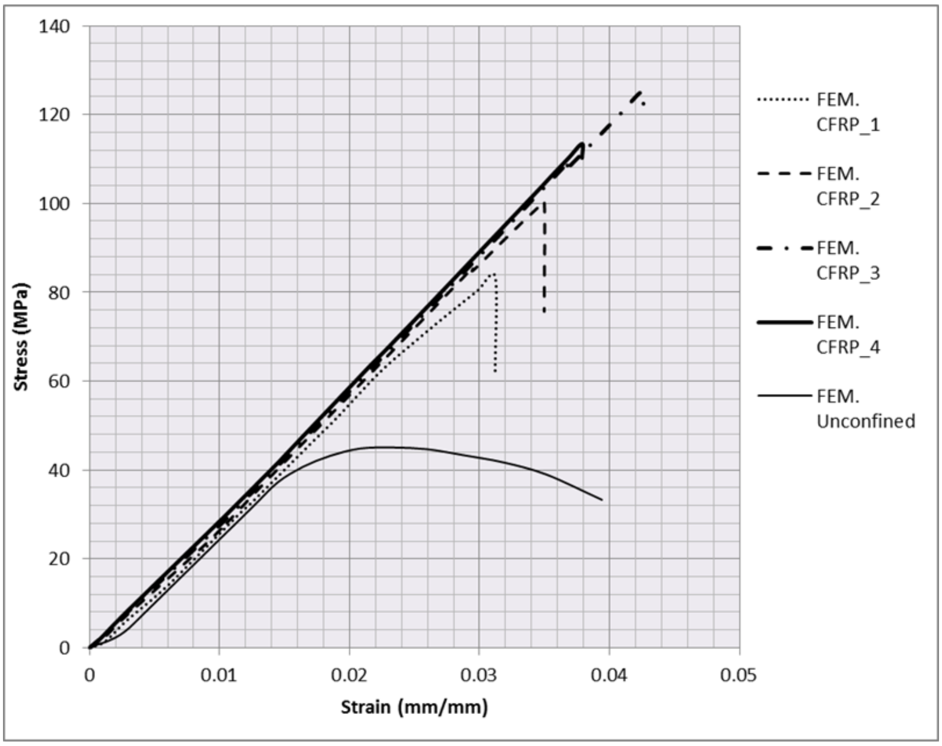

Figure 5: Stress versus strain curves with variation in additional CFRP confinement

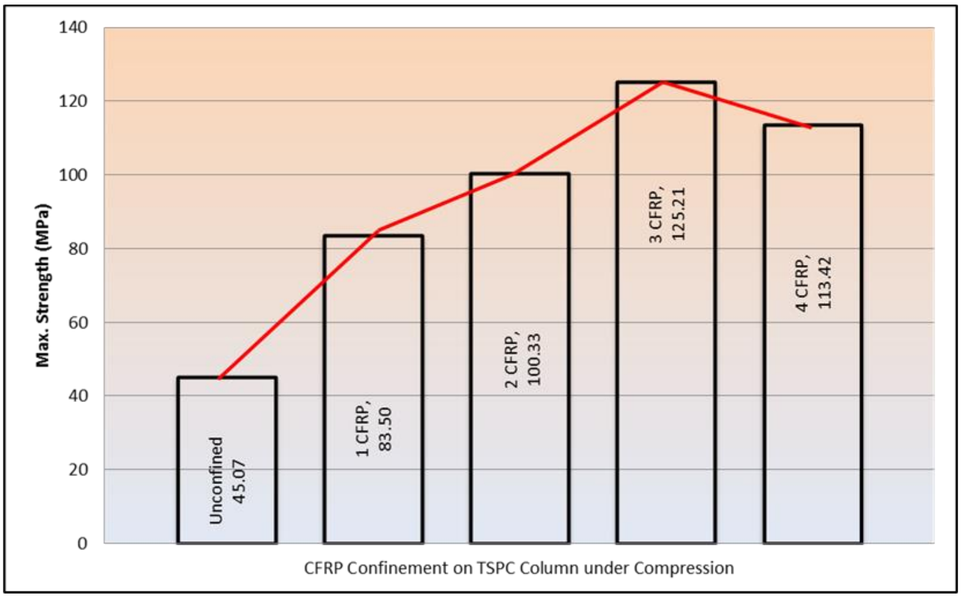

Figure 6: Quantitative comparison of maximum strength increased due to additional CFRP confinement layers

Figure 7 presents the maximum compressive stress for each test specimen for the TSPC column with CFRP confinement indicated by colour contour from FEM simulation. For TSPC with one layer of CFRP confinement, early failure has occurred measured at 83.50 MPa and with two layers of CFRP confinement, the maximum strength increased to 100.3 MPa. Then, for test specimens with three layers of CFRP confinement, the strength increased to 125.21 MPa and the domination of red colour from simulation indicated the stress intensity. For test specimens with four layers of CFRP confinement, the strength show decreased to 113.42 MPa. The strength enhancement percentages were calculated as 85.27 %, 122.61 %, 177.81 %, and 151.65 %.

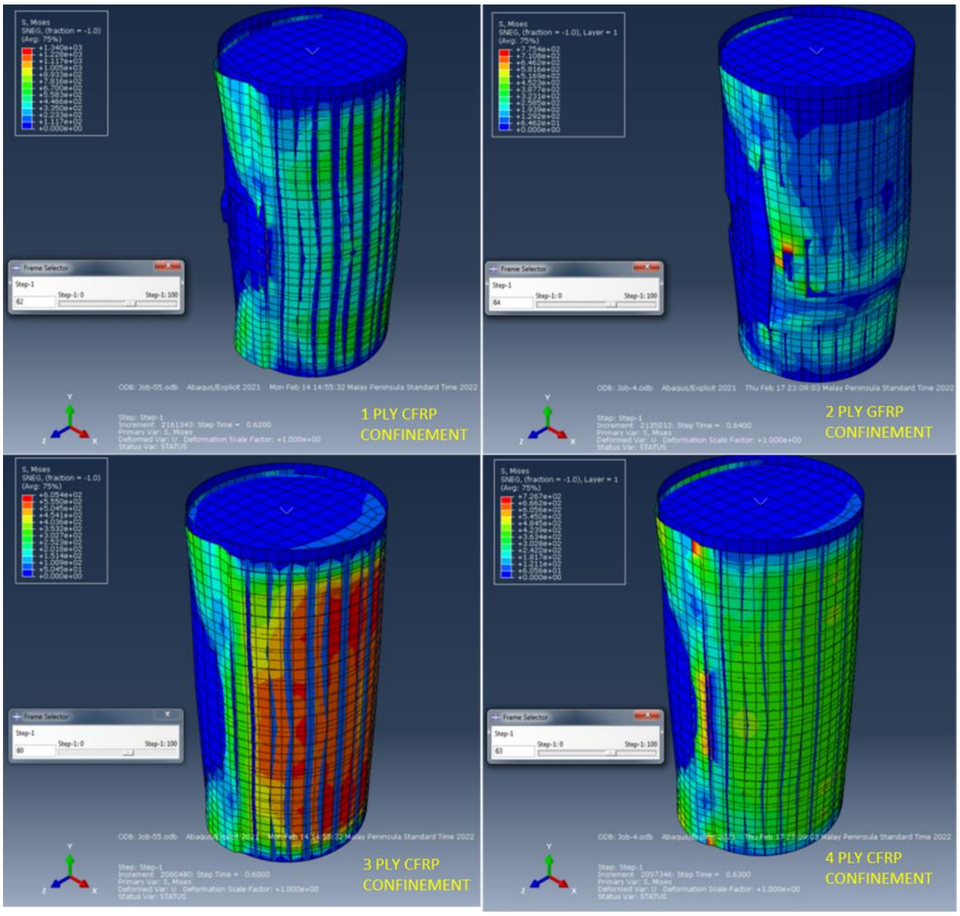

Figure 7: Maximum stress simulation before failure for each test specimen (CFRP confined TSPC)

3.3 Effect of Additional GFRP Confinement

The finite element model (FEM) of TSPC-confined GFRP was parametrically studied and in the composite layup definition, additional GFRP layers are defined for the model. Unconfined TSPC has indicated a compressive strength of 45.07 MPa. The simulation result shows that strength increased to 70.11 MPa and 82.24 MPa for one and two layers of GFRP confinement on the TSPC column. Then, with 3 layers of GFRP confinement, the strength was further increased to 132.49 MPa. However, with the addition of the 4th GFRP layer, the strength shows a slight decrease to 132.10 MPa. This shows that the GFRP confinement is optimal using 3 layers. After that, the confinement reaches saturation, and further addition of GFRP confinement layers may either reduce or maintain the maximum compressive strength. Figure 8 shows the stress-strain curve obtained from the FEM simulation of the parametric study. Figure 9 shows a quantitative comparison of maximum strength increased due to additional GFRP confinement layers.

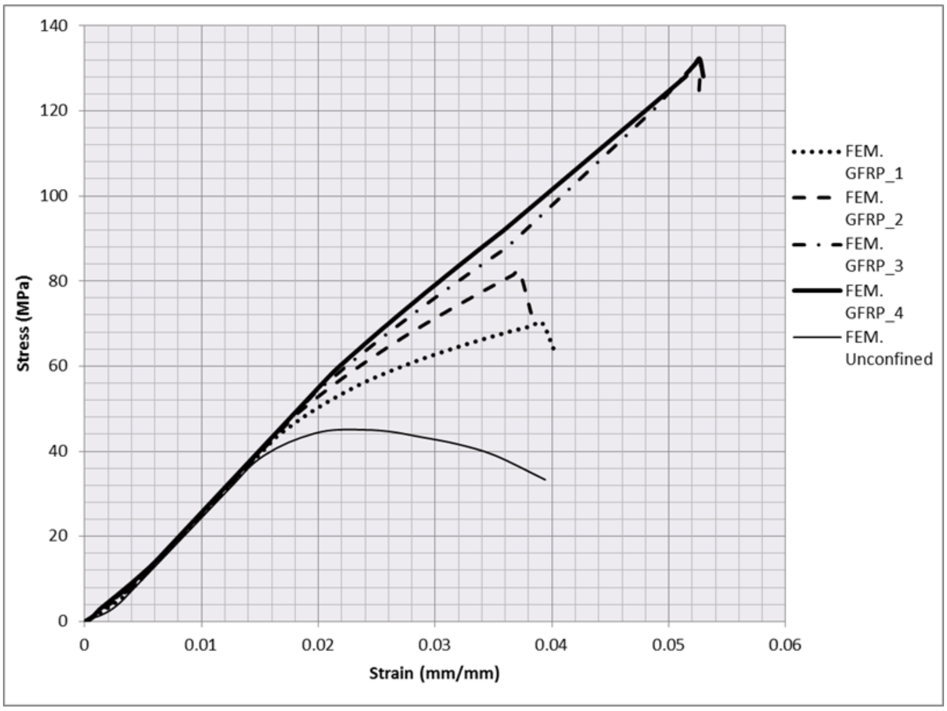

Figure 8: Stress versus strain curves with variation in additional GFRP confinement layers

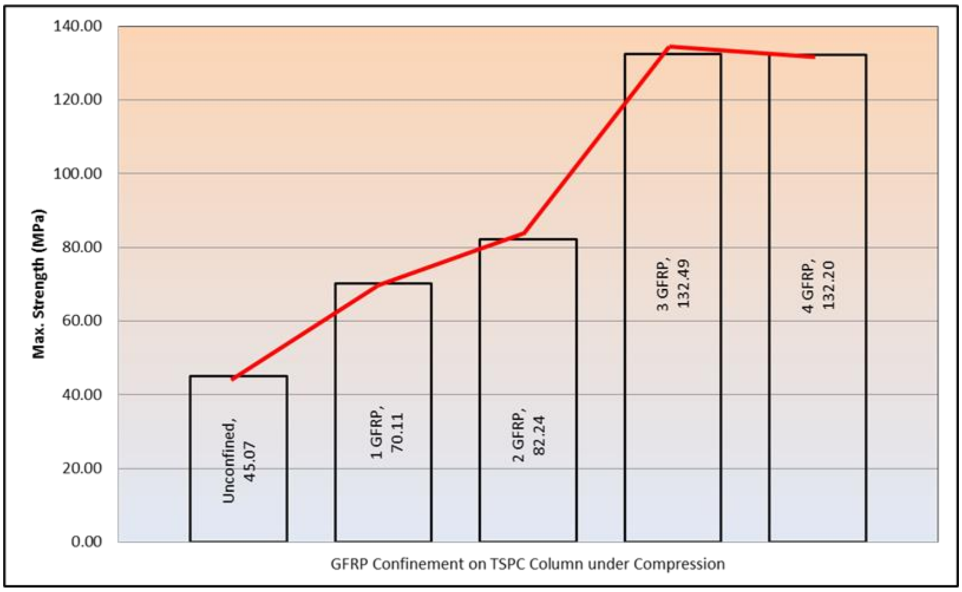

Figure 9: Quantitative comparison of maximum strength increased due to additional GFRP confinement layers

Figure 10 presents the maximum compressive stress for each test specimen for the TSPC column with GFRP confinement indicated by colour contour from FEM simulation. For TSPC with one layer of GFRP confinement, early failure has occurred measured at 70.11 MPa and with two layers of GFRP confinement, the maximum strength increased to 82.24 MPa. Then, for test specimens with three layers of GFRP confinement, the strength has increased to 132.49 MPa and the domination of red colour from simulation indicated the stress intensity. For test specimen with four layers of GFRP confinement, the strength show decreased to 132.20 MPa and failure can be observed at the third layer where the stress is barely transfer to the fourth layer to further enhanced the maximum compressive strength of the test specimen. The strength enhancement percentages were calculated as 55.77 %, 82.72 %, 194.36 %, and 193.71 %.

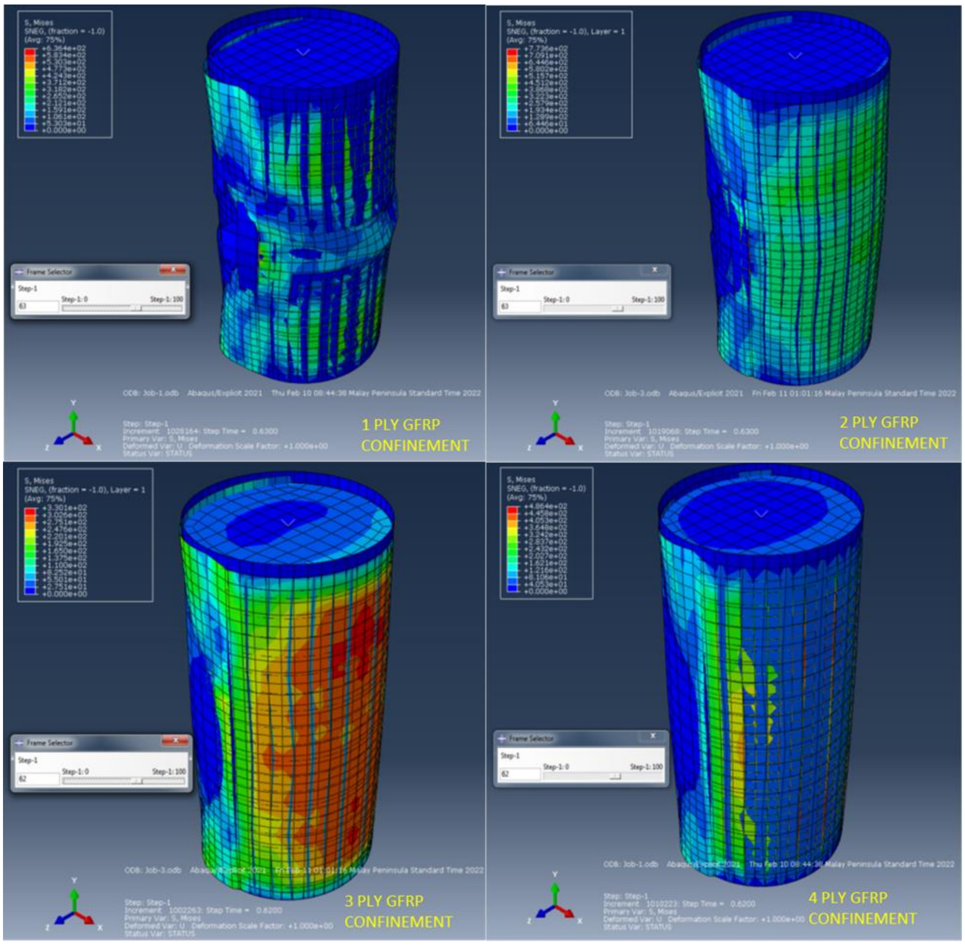

Figure 10: Maximum stress simulation before failure for each test specimen (GFRP confined TSPC)

3.4 Comparison between GFRP and CFRP Confinement on TSPC Core

An experimental study was performed on the effect of FRP material confinement on the TSPC column, as well as FEM simulation studies and parametric studies. The findings have shown that the TSPC column strength has been successfully enhanced with the addition of FRP material confinement to a certain extent. That extent indicates saturation, where the addition of further confinement does not increase the compressive strength of the TSPC core. The worst situation may also occur where the addition of more FRP confinement layers has decreased the compressive strength of the specimen. This finding has been reported in a parametric study with the addition of a 4th layer of FRP confinement material. Figure 11 shows the comparison between GFRP and CFRP confinement on the TSPC column under compression for an experimental study, an FEM study, and a parametric study.

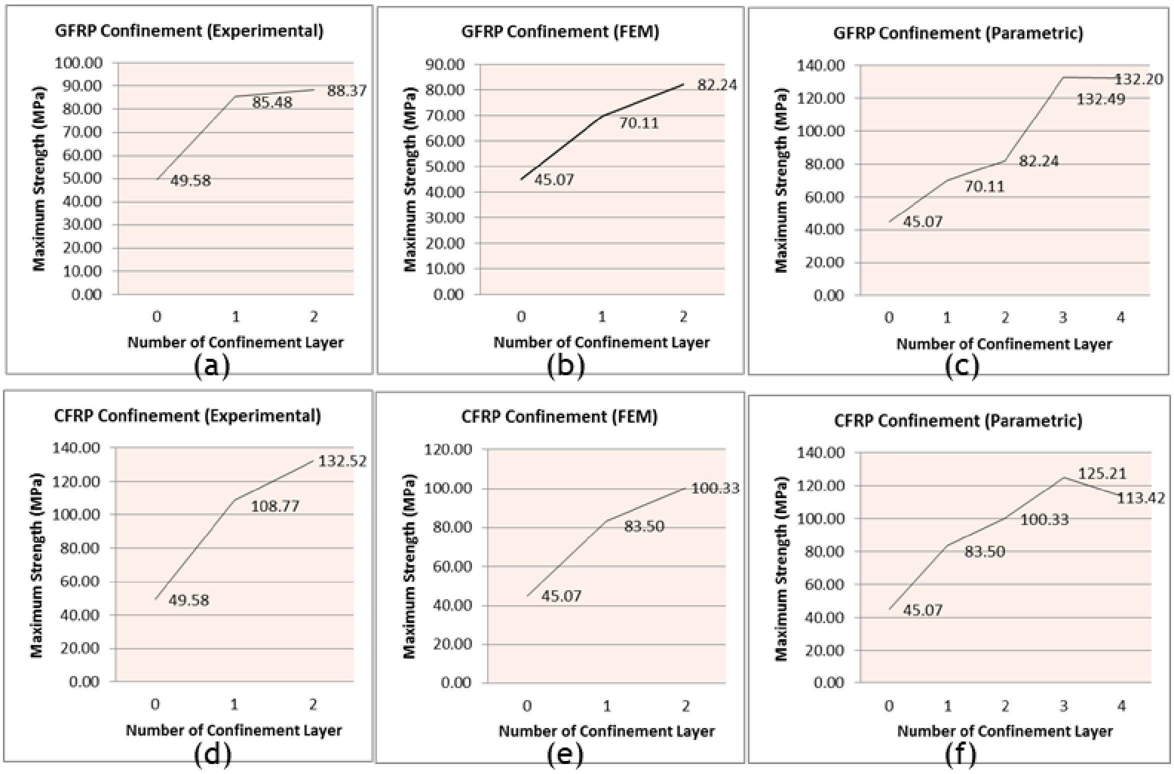

Figure 11: Comparison between the effect of GFRP and CFRP confinement layers on TSPC core. (a) Experimental 1–2-layer GFRP confinement on TSPC column. (b) FEA was developed based on experimental data. (c) Addition of GFRP layers to simulate strength enhancement. (d) Experimental 1–2-layer CFRP confinement on TSPC column. (e) FEA was developed based on experimental data. (f) Addition of CFRP layers to simulate strength enhancement

The experimental and FEM studies revealed the potential to enhance the compressive strength of TSPC columns by wrapping up to two layers of confinement with FRP material. A parametric study on the potential for further strength enhancement with additional FRP confinement layers has shown that three layers of GFRP and CFRP wrapping have provided the optimum strength enhancement to the TSPC core column. To validate the optimisation process that has been performed through numerical analysis results from an experimental study by [18] have been compared. Hassan has reported that with the addition of three layers of CFRP confinement in an experimental study, the strength has been enhanced, but the percentages of strength enhancement from the unconfined condition to each layer of confinement application have shown an approximately similar trend with numerical results. Table 2 shows the comparison of numerical, experimental and literature results on compressive strength enhancement percentage, where the highest was within the first confinement layer (85.27%, 119.38%, 103.02%). For the second layer of CFRP confinement on the TSPC column, the strength enhancement percentage starts to decrease, as indicated by only 20.16%, 21.84%, and 14.83% increases from 1 layer to 2 layers. With the application of 3 layers, the numerical study has shown only a further 24.80%, while the literature result has shown 13.67% of strength enhancement percentages.

Table 2: Comparison of Numerical and experimental results on compressive strength enhancement percentage (Hassan et al., 2020)

Test Samples	Numerical Results		Experimental Results		Literature Results	
	Max. Strength (MPa)	% of Strength Enhancement	Max. Strength (MPa)	% of Strength Enhancement	Max. Strength (MPa)	% of Strength Enhancement
Unconfined TSPC	45.07	-	49.58	-	59.2	-
TSPC-1CFRP	83.5	85.27	108.77	119.38	120.19	103.02
TSPC-2CFRP	100.33	20.16	132.52	21.84	138.01	14.83
TSPC-3CFRP	125.21	24.80	-	-	156.88	13.67
TSPC-4CFRP	113.42	-9.42	-	-	-	-

For 4 layers of CFRP confinement, the numerical result shows a decrease in strength enhancement, with -9.42%, indicating that the confinement layer has reached saturation. Therefore, for optimisation of confined TSPC compressive strength through the number of confinement layers in general, 1 layer of confinement has provided large percentages of strength enhancement. The strength will be enhanced with the application of confinement layers up to 3 layers before it reaches saturation. TSPC confinements beyond 3 layers were not suggested based on the evaluation of results from experimental and numerical studies.

4.0 Conclusion

An optimisation study on TSPC strength enhancement was performed, particularly to examine the maximum number of CFRP confinement layers on the TSPC column to efficiently enhance the TSPC strength before the confinement layers reach saturation. The study was performed using the parametric method by employing the FE model of TSPC with CFRP and GFRP confinement in ABAQUS software. The number of FRP confinement layers was multiplied from 1 layer to 2 layers, 3 layers, and 4 layers. The findings indicate that at the 4th layer, the strength enhancement either remains constant or shows a little drop. The experimental and proposed FEM using the ABAQUS commercial software package have shown similarity in strength enhancement with the application of GFRP and CFRP confinement on the TSPC column through the stress-strain curve produced. In addition to that, the failure observation from experimental and FEM simulations has also shown an acceptable match. However, the exact values of compressive strength, yield strength, and compressive modulus have shown some deviation between FEM and experimental. A parametric study using FEM has revealed that 3 layers of FRP composite confinement on the TSPC column were likely to be the number of saturation layers of FRP confinement materials for maximum compressive strength enhancement.

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Author Contributions
M.S. Manda: Conceptualization, Methodology, Writing- Original Draft Preparation; **M.R.M. Rejab**: Data Curation, Validation; **S.A. Hassan**: Research Lead, Validation, Supervision; **N.S. Md Jaafar**: Software, Writing- Reviewing and Editing.

Conflicts of Interest
The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

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