Universal Model to Predict Compressive Behavior of Confined Tin Slag Polymer Concrete Column

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Abstract

This study explores the application of analytical approach in predicting the compressive behavior of TSPC confined with FRP and metallic material based on previous studies on concrete structures. Experimental results on tensile strength of confinement materials and compressive strength of confined TSPC have been employed to obtain radial confining pressure and to validate the mathematical prediction. Tensile strength of confinement material was 169.51 MPa (GFRP), 199.89MPa (CFRP), 198.25 MPa (BFRP), 279.43 MPa (AFRP) and 485.20 MPa (mild steel). Unconfined TSPC column has maximum compressive strength of 59.19 MPa and the strength was enhanced with the application of confinement materials. The highest compressive strength enhancement was TSPC confined mild steel (TSPC-FM) with 131.84 MPa followed by TSPC confined AFRP (TSPC-AF), TSPC confined CFRP (TSPC-CF), TSPC confined GFRP (TSPC-GF) and TSPC confined BFRP (TSPC-BF) with 114.24 MPa, 108.77 MPa, 85.54 MPa and 81.52 MPa. Mathematical evaluation by Mander, Wei, Saadatmanesh, Lam & Teng and proposed model for compressive strength has provided different values for TSPC-GF (85.54 MPa, 89.54 MPa, 85.54 MPa, 92.29 MPa and 86.08 MPa), TSPC-CF (108.77 MPa, 120.54 MPa, 108.77 MPa, 79.42 MPa and 74.33 MPa), TSPC-BF (81.52 MPa, 89.33 MPa, 81.52 MPa, 89.29 MPa and 79.65 MPa), TSPC-AF (114.24 MPa, 120.52 MPa, 114.24 MPa, 114.24 MPa and 109.26) and TSPC-FM (131.84 MPa, 148.14 MPa, 131.84 MPa, 239.07 MPa and 131.03 MPa). Overall, the study suggested that Mander and proposed model have the capability to be adapted as universal model to represent confined TSPC column behavior under compression. The compressive behavior through stress versus strain curve as predicted by Mander and proposed models have shown closer match with experimental on all variant of test samples.

Keywords: TSPC, Confinement, Compression, Analytical, Stress vs strain

INTRODUCTION

Tin Slag Polymer Concrete (TSPC) is a newly found particulate composite material composed of fine Tin slag (TS) particles (<1 mm) as aggregates and Unsaturated Polyester Resin (UPR) with 1 % catalyst Methyl Ethyl Ketone Peroxide (MEKP). The optimum aggregate to resin ratio was 70:30 based on study by Faidzal et.al. (2018). Polymer concrete is an alternative concrete material with superior property compared to cement concrete in terms of curing time, strength, durability, chemical attack, and vibration damping (Bedi et. al., 2013). According to literature, there was limited study found on analytical analysis of polymer concrete behavior except by Toufigh et. al (2016). Moreover, the analytical prediction on TSPC column under compression has only been reported by Manda et. al (2022).

Therefore, to optimize the benefit from TSPC as new structural material particularly with fiber reinforced polymer (FRP) and metallic material reinforcement, complete understanding of its behavior is essential not only through experimental and finite element analysis (FEA), but also analytical model. TSPC has been studied experimentally for the past five years by Faidzal et al (2018) which reports the optimum composition, aggregate grading, and resin to aggregate ratio. Since then, study on TSPC gradually advances towards potential of strength enhancement through FRP and metallic material confinement as reports by Shakil & Hassan (2020), Hassan et. al. (2020), Abdullah (2021), Mandaa et. al. (2022), Amirnuddin et. al. (2022), Mandab et. al. (2023) and Mandac et. al. (2023). The analytical model evaluation on compressive behavior of unconfined TSPC has been reported by Mandad et. al. (2022) and in the study, Careira & Chu (1985) model has been found to be the best analytical model that may be employed to describe TSPC behavior under compression. The predicted shape of stress versus strain curve, elastic modulus, yield strength and maximum strength has shown good match with experimental data. However, mathematical evaluation on confined TSPC under compression has not yet been published in any of the previous literatures. Therefore, the purpose of this study is to explore the application of an analytical approach in predicting the compressive behavior of TSPC confined with FRP and metallic material based on previous studies on concrete structures. The results were compared to propose a new modified model that approximately suite to be universal model of confined TSPC behavior with closer match.

LITERATURE REVIEW

From literature, the earliest mathematical formula has been introduced by Richart et. al. (1929) which represents concrete structural strengthening through transverse steel confinement. Brief review indicates that the Richart model as shown in equation (1) has become the basis of analytical prediction in concrete structure strengthening behavior. Equation (1) shows, f_{cc} , confined concrete strength and the corresponding strain, ε_{cc}.

(1) $f_{cc} = f_{co} + k_1 f_1$

(2) $\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2 \frac{f_1}{f_{co}}\right)$

Where, f_{co} , unconfined concrete strength, ε_{co}, unconfined concrete strain, f_1, confining pressure, k_1 and k_2 , confinement coefficient based on material specifications. In experimental, Richart has reports that the value of both coefficient k_1 and $k_2$was, 4.1 and $k_2 = 5k_1$. The calculation for confining pressure is based on tensile strength of confinement material and concrete geometrical dimension as Equation (3) and (4).

(3) $f_1 = \frac{1}{2}\rho_s f_y$

(4) $\rho_s = \frac{4A_{sp}}{d_s s}$

Where, ρ_s, ratio of the volume of transverse confining steel to the volume of confined concrete core, f_y, yield strength of the transverse reinforcement, A_{sp}, area of transverse reinforcement bar and d_s, diameter of spiral between bar centers.

After that, Mander et. al. (1988) has proposed a new theoretical stress versus strain model for confined concrete particularly with metallic material confinement and the proposed equation has been adapted by American Society of Civil Engineers (ASCE) as codes and standards for construction in United States. Equation (5), (6), (7), (8), (9) and (10) present the newly proposed model by Mander et. al. (1988) and the predicted behavior as in Figure 1.

(5) $f_c = \frac{f_{cc} x r}{r - 1 + x^r}$

(6) $x = \frac{\varepsilon_c}{\varepsilon_{cc}}$

(7) $\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$

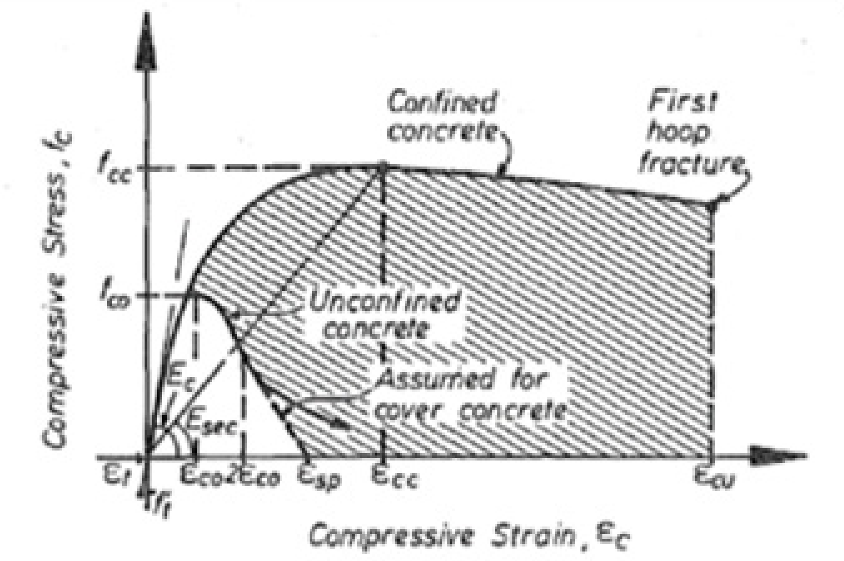

Figure 1: Stress versus strain model of confined concrete strength based on Mander et. al. (1988)

(8) $r = \frac{E_c}{E_c - E_{sec}}$

(9) $E_c = 5000\sqrt{f_{co}}\,MPa$

(10) $E_c = \frac{f_{cc}}{\varepsilon_{cc}}$

In 1994, Saadatmanesh et. al. (1994) has proposed an equation (11) to represent, f_1, confining pressure from FRP wrapping. The model by Mander[c] et al (1988) has been modified and new model has been introduced as in equation (12) which is applied to define f_{cc} value as in equation (5) and (7).

(11) $f_1 = \frac{2 t f_{frp}}{d}$

(12) $f_{cc} = \left[2.254 * \sqrt{1 + 7.94 * \frac{f_1}{f_{co}}} - 2 * \frac{f_1}{f_{co}} - 1.254\right] * f_{co}$

Where, E_c, first linear portion of compressive modulus, E_{sec}, second linear portion of compressive modulus, t, thickness of confinement material, f_{frp}, tensile strength of confinement material, and d, diameter of the circular concrete column. In the study, for calculation of confined concrete strain, equation (7) is still employed by Saadatmanesh (Figure 2).

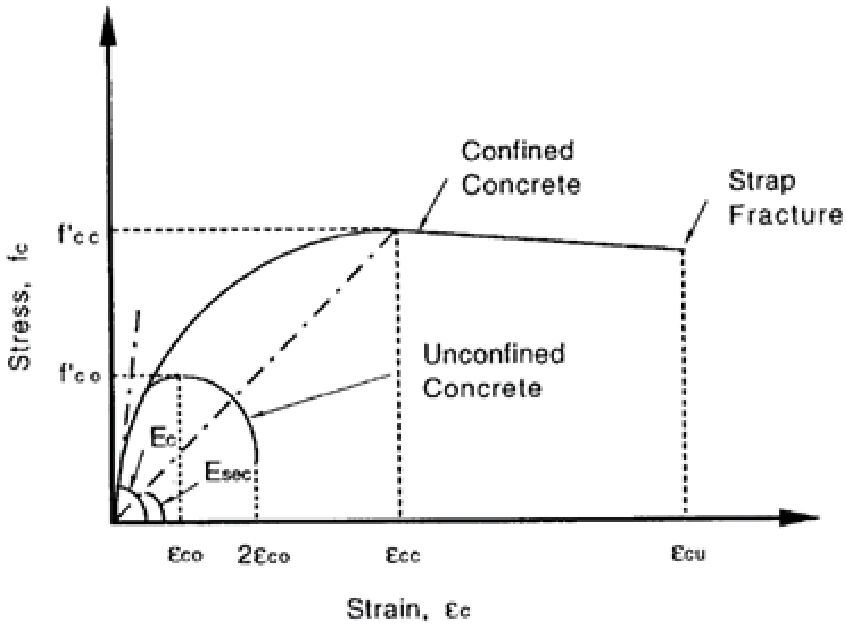

Figure 2: Stress versus strain model of confined concrete strength based on Saadatmanesh

Later in 2003, Lam & Teng (2003) proposed a design-oriented stress versus strain which provides several modifications to improved deficiencies in previous model based on Figure 3.

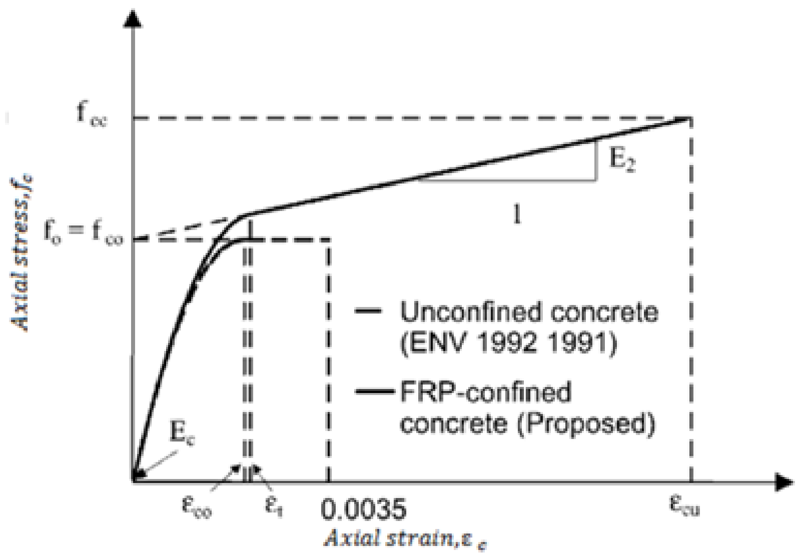

Figure 3. Stress versus strain model of confined concrete strength based on Lam & Teng (2003)

The Lam & Teng model are as the following equations (13), (14), (15) and (16).

(13) $f_c = E_c\varepsilon_c - \frac{(E_c-E_2)^2}{4f_o} * \varepsilon_c{}^2 \qquad for\ (0 \le \varepsilon_c \le \varepsilon_t)$

(14) $f_c = E_2\varepsilon_c \qquad for\ (\varepsilon_t \le \varepsilon_c \le \varepsilon_{cu})$

(15) $\varepsilon_t = \frac{2f_o}{(E_c-E_2)}$

(16) $E_2 = \frac{f_{cc}-f_o}{\varepsilon_{cu}}$

Review of research articles for the last 5 years has found that in 2018, Surepally and Prakash (2018) has proposed an improved mathematical model for concrete column confinement which adopted from previous equation. Equation (17), (18), (19), and (20) shows the proposed model.

(17) $f_c = 1.3f_{cc}\left[2\left(\frac{\varepsilon_c}{\varepsilon_1}\right) - \left(\frac{\varepsilon_c}{\varepsilon_1}\right)^2\right]^{\frac{1}{1+2K}}$

(18) $\varepsilon_2 = \varepsilon_1 + (\varepsilon_{s2} - \varepsilon_{s1})$

(19) $\varepsilon_{s1} = 0.0022K_s$

(20) $\frac{\varepsilon_{s2}}{\varepsilon_o} = 1 + \left\{\frac{0.81}{c}\left[1 - 5\left(\frac{s}{B}\right)^2\right] + 0.25\sqrt{\frac{B}{C}}\right\}\frac{\rho_t f_{yt}}{\sqrt{f_{co}}}$

Where, f_c, confined stress, ε_c, calculated confined strain, f_{cc}, maximum confined strength, K, ratio of confined to unconfined strength, ε_1, strain at maximum confined strength, ε_2, strain at maximum confined strength before strength reduction, ε_o, strain of unconfined concrete, C, distance between support longitudinal bars in lateral direction, B,core size center to center or perimeter tie, s, tie spacing, ρ_t,ratio of tie steel to core volume, f_{yt}, yield strength of transverse steel, f_{co}, unconfined concrete strength and K_s, effective confinement coefficient.

All the past analytical models presented so far have been applied to describe the compressive behavior of cement based concrete column externally strengthen by FRP and metallic material confinement. In terms of structural geometry, most of the models involve circular columns with varying diametric value ranging from 50 mm to 300 mm and double the diametric value on height of the column to avoid buckling. Among the earliest mathematical characterizations on polymer concrete confinement were reports by Wei et. al. (1992) which is based on experimental. In the study, Wei introduced passive confinement on circular polymer concrete column with thickness variation of Aluminum ring to expand the potential of polymer concrete through strength enhancement. The proposed mathematical models for stress and strain are as equation (21), (22), (23), (24), (25) and (26) as follows.

(21) $\frac{f'_{cc}}{f'_{co}} = 1 + 3.5 * \left(\frac{f_c}{f'_{co}}\right)$

(22) $\frac{f_c}{f'_{cc}} = \frac{\left[\varepsilon_c/\varepsilon'_{cc}\right]}{(1-p-q)+q*\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)+p*\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^s}$

(23) $\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1 + 5.5 * \left(\frac{f_c}{f'_{co}}\right)$

(24) $p = 4.5 * \left(\frac{f_c}{f'_{co}}\right) - 0.2$

(25) $q = -4.0 * \left(\frac{f_c}{f'_{co}}\right) + 0.8$

(26) $s = \frac{(1-q)}{p}$

Where, f'_{cc}, ultimate strength of confined polymer concrete and f'_{co}, ultimate strength of unconfined polymer concrete, while f_c, strength of confined polymer concrete, ε'_{cc}, ultimate strain of confined polymer concrete and ε'_{co}, ultimate strain of unconfined polymer concrete.

METHODOLOGY

The study involves analytical prediction and validation of TSPC confined FRP and metallic material under compression through experimental. According to Figure 4, the study on mathematical evaluation of confined TSPC start with experimental work to obtained tensile strength data for confinement material and compression test on confined TSPC to evaluate radial confining pressure as well as observation on actual compressive behavior of TSPC under confinement. After that, analytical study continues based on selected mathematical models to describe the compressive behavior of confined TSPC column.

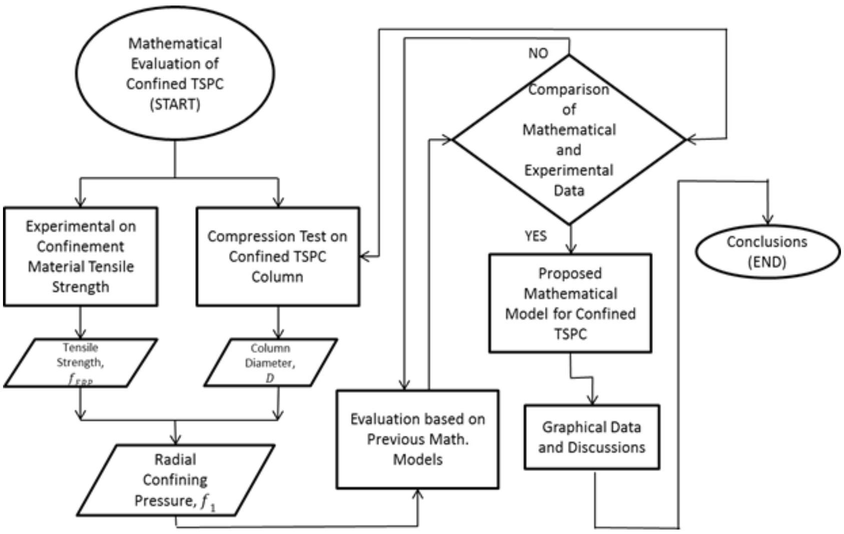

Figure 4: Flow chart of mathematical evaluation on confined TSPC behavior under compressive load

Selected mathematical equation as in Table 1 has been applied to evaluate the compressive behavior of TSPC confined FRP and metallic materials. The selection was based on closer test sample specification of selected models as well as parameters employed which includes circular shape concrete core column, external constraint of test sample by passive confinement and less complex model. Experimental to evaluate tensile property of confinement materials and compressive behavior of TSPC circular column confinement has also been performed for mathematical model validation. The final parts involved a proposed model based on modification of previous mathematical model that provide closer approximation to TSPC confinement.

The proposed model has been produced from Lam and Teng model by neglecting the secant modulus thus the corresponding compressive strain on TSPC behavior with confinement was based on initial strain up to ultimate strain. The mathematical equation of the proposed model was as equation (27).

(27) $f_c = E_c\varepsilon_c - \frac{(E_c - E_2)^2}{4f_o} \times \varepsilon_c^{\,2} \qquad for\ (0 \le \varepsilon_c \le \varepsilon_{cu})$

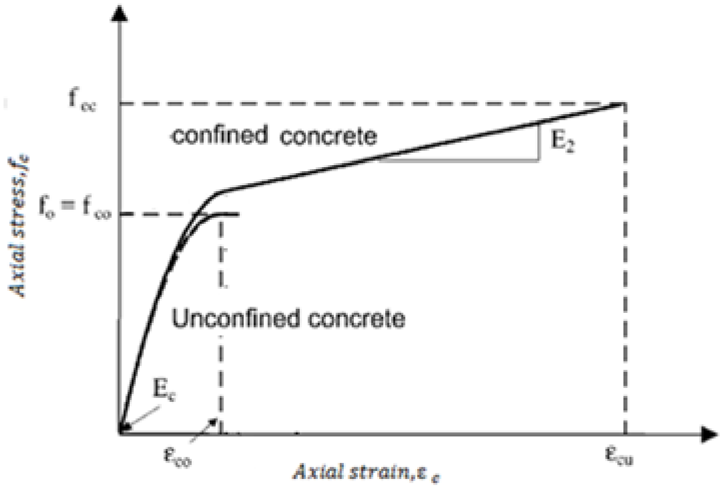

Figure 5: Proposed relationship of stress versus strain model of confined concrete

Table 1: Mathematical expression of previous analytical model on confined concrete circular column under compression

Study	Analytical models	Eq.
Mander et. al. (1988)	$f_c = \frac{f_{cc} x r}{r - 1 + x^r}$	(8)
	$x = \frac{\varepsilon_c}{\varepsilon_{cc}}$	(9)
	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$	(10)
Wei et. al. (1992)	$\frac{f'_{cc}}{f'_{co}} = 1 + 3.5 * \left(\frac{f_c}{f'_{co}}\right)$	(21)
	$\frac{\varepsilon'_{cc}}{\varepsilon'_{co}} = 1 + 5.5 * \left(\frac{f_c}{f'_{co}}\right)$	(22)
	$\frac{f_c}{f'_{cc}} = \frac{\left[{}^{\varepsilon_c}/_{\varepsilon'_{cc}}\right]}{(1 - p - q) + q * \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right) + p * \left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^s}$	(23)
Saadatmanesh et. al. (1994)	$f_{cc} = \left[2.254 * \sqrt{1 + 7.94 * \frac{f_1}{f_{co}}} - 2 * \frac{f_1}{f_{co}} - 1.254\right] * f_{co}$	(12)
	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$	(7)
Lam & Teng (2003)	$f_c = E_c\varepsilon_c - \frac{(E_c - E_2)^2}{4f_o} * \varepsilon_c^2 \quad for\ (0 \le \varepsilon_c \le \varepsilon_t)$	(13)
	$f_c = E_2\varepsilon_c \quad for\ (\varepsilon_t \le \varepsilon_c \le \varepsilon_{cu})$	(14)
	$\varepsilon_t = \frac{2f_o}{(E_c - E_2)}$	(15)
	$E_2 = \frac{f_{cc} - f_o}{\varepsilon_{cu}}$	(16)

RESULTS AND DISCUSSION

Mechanical Test Results

Table 2 presents the summary of mechanical test results on of TSPC circular column under FRP and Metallic Material confinement based on experimental. The compressive strength of unconfined TSPC column (TSPC-UC) was 59.19 MPa. With the application of lateral confinement, the compressive strength has enhanced depending on the type of confinement materials employed. The highest compressive strength enhancement was TSPC confined mild steel (TSPC-FM) with 131.84 MPa which indicates 122.74% of strength increment compared to TSPC-UC. The following strength enhancement on other variation of test samples from highest to lowest were TSPC confined AFRP (TSPC-AF), TSPC confined CFRP (TSPC-CF), TSPC confined GFRP (TSPC-GF) and TSPC confined BFRP (TSPC-BF) with 114.24 MPa, 108.77 MPa, 85.54 MPa and 81.52 MPa. The equivalent percentages of strength enhancement from TSPC-UC for TSPC-AF, TSPC-CF, TSPC-GF, and TSPC-BF were 93.00%, 83.76%, 44.52% and 37.73%. The findings have shown that strength enhancement of confined TSPC depends on tensile strength of confinement materials through coupon test where mild steel (485.20 MPa) has the highest tensile strength followed by AFRP (279.43 MPa) and CFRP (199.89 MPa).

A little bit different from that, for GFRP and BFRP, the pattern has shown that the compressive strength of TSPC-GF was higher than TSPC-BF despite coupon test have indicated that tensile strength of BFRP (198.25 MPa) was larger than GFRP (169.51 MPa). These conditions are probably due to errors in either compression test, tensile test, or samples fabrication for both tests. However, the general findings regarding the relevance on compressive strength of confined TSPC and tensile strength of confinement materials were maintained as both GFRP and BFRP were both in the same class of FRP materials in term of mechanical properties and specification.

Table 2: Compression test results of TSPC under FRP and Metallic Material confinement based on experimental

Bil	Samples	Designation	Maximum Load (kN)	Maximum Deformation (mm)	Compressive Strength (MPa)	Compressive Strain	Compressive Modulus (GPa)	Yield Stress (MPa)	Percentage of Strength Enhancement	Confinement Thickness (mm)	Tensile Strength of Confinement Material (MPa)
1	Unconfined TSPC	TSPC-UC	116.22	2.997	59.19	0.0300	3.32	46.55	0.00%	-	-
2	TSPC confined GFRP	TSPC-GF	167.95	4.527	85.54	0.0453	3.65	51.25	44.50%	1.00	169.51
3	TSPC confined CFRP	TSPC-CF	213.56	3.977	108.77	0.0398	4.69	67.57	83.75%	0.85	199.89
4	TSPC confined BFRP	TSPC-BF	160.06	3.356	81.52	0.0356	4.32	57.21	37.70%	1.18	198.25
5	TSPC confined AFRP	TSPC-AF	224.31	6.654	114.24	0.0665	3.23	80.71	93.00%	1.80	279.43
6	TSPC confined Mild Steel	TSPC-FM	258.86	2.872	131.84	0.0287	7.68	125.33	122.74%	2.95	485.20

Stress versus Strain Curves

Figure 6a shows the stress versus strain curves of unconfined TSPC as well as TSPC confined GFRP through experimental and prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The linear portion of stress versus strain curves by Mander, Lam & Teng and proposed model was approximately in parallel with experimental curves. Compressive modulus as predicted by Wei and Saadatmanesh model indicating that the test sample was stiffer than actual test samples. The yielding pattern of all models shows similar trends with experimental except for Wei model. Maximum compressive strength as predicted by Saadatmanesh, Mander and proposed model indicated exact point as compressive strength on experimental curve. Failure behavior of experimental curve appeared as strain softening similar as Wei and proposed model. However, the other models have shown failure with a little horizontal line after reaching maximum compressive strength except for Lam & Teng which stop exactly on maximum point.

Figure 6b shows the stress versus strain curves of unconfined TSPC as well as TSPC confined CFRP through experimental and prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The linear portion of stress versus strain curves by Mander, Lam & Teng and proposed model was approximately in parallel with experimental curves. The yielding pattern of proposed model and saadatmanesh shows similar trends with experimental but with different magnitudes compared with others. Maximum compressive strength as predicted by Saadatmanesh and Mander indicated exact point as compressive strength on experimental curve. Failure behavior of experimental curve appeared nearly vertical downward line while failure curves as predicted by wei and proposed model shows strain softening behavior. However, the other models have shown failure approximately just after reaching maximum compressive strength.

Figure 6c shows the stress versus strain curves of unconfined TSPC as well as TSPC confined BFRP through experimental and prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The linear portion of stress versus strain curves by all models was approximately in parallel with experimental curves except for Wei model. Compressive modulus as predicted by Wei model indicating that the test sample was stiffer than actual test samples. The yielding pattern of all models shows similar trends with experimental except for Wei model. Maximum compressive strength as predicted by all models indicated exact point as compressive strength on experimental curve except for Wei model. Failure behavior of experimental curve appeared as strain softening as well as failure as predicted by Mander and proposed model. Lam & Teng and Saadatmanesh model shows horizontal line after reaching maximum compressive strength while Wei model has predicted secondary strain hardening behavior before failed at second point of maximum strength.

Figure 6d shows the stress versus strain curves of unconfined TSPC as well as TSPC confined AFRP through experimental and prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. Linear portion of stress versus strain curves by Mander have shown close approximation with experimental curves. Others, includes the proposed models have provided larger deviation on linear behavior prediction of the test samples compared to experimental. The yielding pattern of Manders and Saadatmnanesh model exhibit similar trends with experimental. Then, for maximum compressive strength, the prediction of all models indicates close approximation with experimental except for Wei model which presents larger difference in compressive strength prediction. Failure behavior of experimental curve appeared as sudden drop in strength at constant strain, but all models indicate sudden failure at maximum strength. In general, in terms of curves pattern, Manders, Saadatmanesh and proposed model have shown good replication of experimental curve except for failure behavior.

Figure 6e shows the stress versus strain curves of unconfined TSPC as well as TSPC confined metallic material (mild steel tube) through experimental and prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. Mander and proposed model have shown closer match on linear behavior with experimental curve. In terms of yielding, all models exhibit yielding patterns approaching the pattern of experimental curve. After yielding, all curves have shown strain hardening behavior up to maximum compressive strength. Other than Lam & Teng, all the models have predicted the maximum compressive strength in close match which experimental according to observation on every curve in the stress versus strain diagram. Finally, the experimental curve has exhibited strain softening which indicates ductile failure as results of metallic material confinement. Failure curves of Mander and proposed model have shown good match with experimental but Wei and Saadatmanesh model provide horizontal line during failures. Lam & Teng produce straight upward line and stop at maximum strength.

Universal Model for Confined TSPC Column

Table 3a presents the mechanical properties of TSPC confined GFRP (TSPC-GF) sample under experimental and mathematical prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The mechanical property involves are compressive modulus, yield strength, maximum strength, and corresponding strain as well as the percentage of deviation between experimental and mathematical prediction particularly on maximum compressive strength achieved. Experimental study on unconfined TSPC (TSPC-UC) and GFRP confined TSPC (TSPC-GF) have results in the improvement of mechanical property from 3.32 GPa to 3.65 GPa for compressive modulus, 46.55 MPa to 51.25 MPa for yield strength, 59.19 MPa to 85.54 MPa for maximum compressive strength and 0.0300 to 0.0453 for the corresponding strain. The application of previous mathematical models on confined circular concrete column under compression to predict the TSPC-GF property have revealed that for compressive modulus, Saadatmanesh model have provided closer match with 3.46 GPa. On the other hand, the predictions for yield strength by Lam & Teng and proposed model have shown closer approximation with 60.63 MPa compared to experimental (51.25 MPa). Then, in term of maximum experimental results, 85.54 MPa which also involves the corresponding strain with 0.0454 and 0.0453. Comparison based on the deviation percentage of maximum compressive strength between experimental and mathematical model predictions indicate that Mander and Saadatmanesh, 0.00 %, Wei, 4.68 %, Lam & Teng, 7.89 % and proposed model, 0.63 %. In general, observation and evaluation on experimental and mathematical prediction have indicated that Mander, Saadatmanesh and proposed model have shown good compatibility to represent actual TSPC-GF compressive behavior considering both stress versus strain (Figure 6a) and mechanical properties (Table 3a).

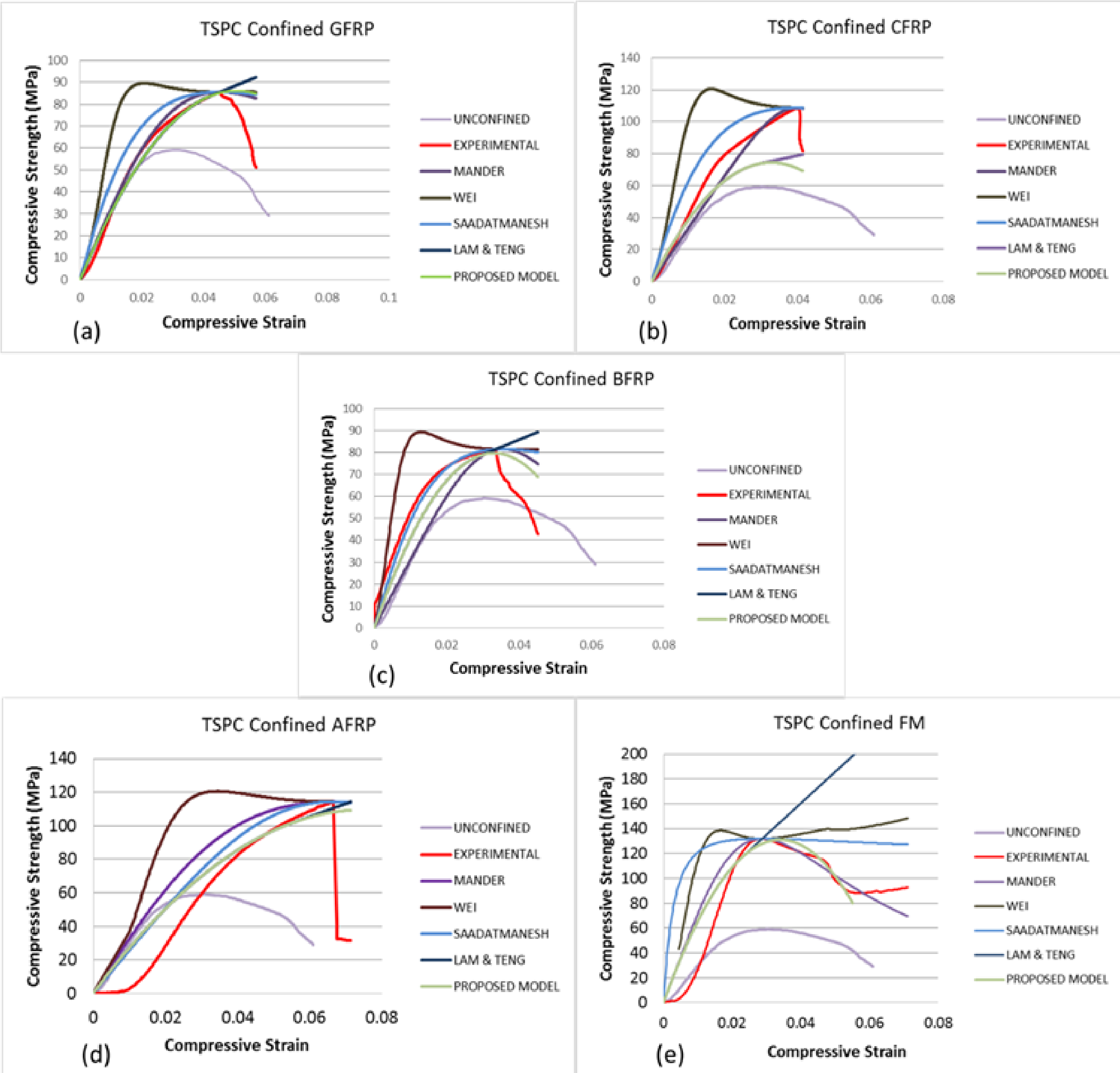

Figure 6: Stress versus strain curve of experimental and mathematical prediction
(a) TSPC confined GFRP (TSPC-GF); (b) TSPC confined CFRP (TSPC-CF); (c) TSPC confined BFRP (TSPC-BF); (d) TSPC confined AFRP (TSPC-AF); (e) TSPC confined mild steel tube (TSPC-FM)

Table 3b presents the mechanical properties of TSPC confined CFRP (TSPC-CF) sample under experimental and mathematical prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The mechanical property involves are compressive modulus, yield strength, maximum strength, and corresponding strain as well as the percentage of deviation between experimental and mathematical prediction particularly on maximum compressive strength achieved. Experimental study on unconfined TSPC (TSPC-UC) and CFRP confined TSPC (TSPC-CF) have results in the improvement of mechanical property from 3.32 GPa to 4.69 GPa for compressive modulus, 46.55 MPa to 67.57 MPa for yield strength, 59.19 MPa to 108.77 MPa for maximum compressive strength and 0.0300 to 0.0398 for the corresponding strain. The application of previous mathematical models on confined circular concrete column under compression to predict the TSPC-CF property have revealed that for compressive modulus, Mander and Saadatmanesh model have provided closer match with 3.31 GPa and 5.81 GPa (experimental 4.69 GPa). On the other hand, the predictions for yield strength by Lam & Teng and proposed model have shown closer approximation with 68.89 MPa compared to experimental (67.57 MPa). Then, in term of maximum compressive strength, the evaluation through Mander and Saadatmanesh models have shown exact match with experimental results, 108.77 MPa which also involves the corresponding strain with both 0.0398. Comparison based on the deviation percentage of maximum compressive strength between experimental and mathematical model predictions indicate that Mander and Saadatmanesh, 0.00 %, Wei, 10.82 %, Lam & Teng, 26.89 % and proposed model, 31.66 %. In general, observation and evaluation on experimental and mathematical prediction have indicated that Mander and Saadatmanesh model have shown good compatibility to represent actual TSPC-CF compressive behavior considering both stress versus strain (Figure 6b) and mechanical properties (Table 3b).

Table 3c presents the mechanical properties of TSPC confined BFRP (TSPC-BF) sample under experimental and mathematical prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The mechanical property involves are compressive modulus, yield strength, maximum strength, and corresponding strain as well as the percentage of deviation between experimental and mathematical prediction particularly on maximum compressive strength achieved. Experimental study on unconfined TSPC (TSPC-UC) and BFRP confined TSPC (TSPC-BF) have results in the improvement of mechanical property from 3.32 GPa to 3.65 GPa for compressive modulus, 46.55 MPa to 50.21 MPa for yield strength, 59.19 MPa to 81.52 MPa for maximum compressive strength and 0.0300 to 0.0356 for the corresponding strain. These findings indicated that TSPC-GF and TSPC-BF have provided almost similar confinement effect on TSPC strength enhancement except for compressive strain where GFRP (0.0453) has produced larger strain compared to BFRP (0.0356). The application of previous mathematical models on confined circular concrete column under compression to predict the TSPC-BF property have revealed that for compressive modulus, Saadatmanesh, Lam & Teng and proposed model have provided closer match with 3.87 GPa, 3.17 GPa and 3.17 GPa (experimental, 3.65 GPa). On the other hand, the predictions for yield strength by proposed model have shown closer approximation with 63.70 MPa compared to experimental (50.21 MPa). Then, in terms of maximum compressive strength, the evaluation through Mander and Saadatmanesh models have shown exact match with experimental results, 81.52 MPa which also involves the corresponding strain with 0.03556. Comparison based on the deviation percentage of maximum compressive strength between experimental and mathematical model predictions indicate that Mander and Saadatmanesh, 0.00 %, Wei, 9.58 %, Lam & Teng, 9.53 % and proposed model, 2.29 %. In general, observation and evaluation on experimental and mathematical prediction have indicated that Mander, and proposed model have shown good compatibility to represent actual TSPC-GF compressive behavior considering both stress versus strain (Figure 6c) and mechanical properties (Table 3c).

Table 3d presents the mechanical properties of TSPC confined AFRP (TSPC-AF) sample under experimental and mathematical prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The mechanical property involves are compressive modulus, yield strength, maximum strength, and corresponding strain as well as the percentage of deviation between experimental and mathematical prediction particularly on maximum compressive strength achieved. Experimental study on unconfined TSPC (TSPC-UC) and AFRP confined TSPC (TSPC-AF) have results in the improvement of mechanical property from 3.32 GPa to 3.65 GPa for compressive modulus, 46.55 MPa to 80.71 MPa for yield strength, 59.19 MPa to 114.24 MPa for maximum compressive strength and 0.0300 to 0.0665 for the corresponding strain. The application of previous mathematical models on confined circular concrete column under compression to predict the TSPC-AF property have revealed that for compressive modulus, Mander model have provided closer match with 2.92 GPa. On the other hand, the predictions for yield strength by Lam & Teng and proposed model have shown closer approximation with 88.90 MPa and 86.70 MPa compared to experimental (80.71 MPa). Then, in term of maximum compressive strength, the evaluation through Mander, Saadatmanesh and Lam & Teng models have shown exact match with experimental results, 114.24 MPa which also involves the corresponding strain with 0.0665, 0.0665 and 0.01752. Comparison based on the deviation percentage of maximum compressive strength between experimental and mathematical model predictions indicate that Mander, Saadatmanesh and Lam & Teng, 0.00 %, Wei, 5.50 %, and proposed model, 4.36 %. In general, observation and evaluation on experimental and mathematical prediction have indicated that all models except Wei model have shown good compatibility to represent actual TSPC-AF compressive behavior considering both stress versus strain (Figure 6d) and mechanical properties (Table 3d).

Table 3e presents the mechanical properties of TSPC confined mild steel (TSPC-FM) sample under experimental and mathematical prediction using Mander et. al. (1988), Wei et. al. (1992), Saadatmanesh et. al. (1994), Lam & Teng (2003) and proposed model. The mechanical property involves are compressive modulus, yield strength, maximum strength, and corresponding strain as well as the percentage of deviation between experimental and mathematical prediction particularly on maximum compressive strength achieved. Experimental study on unconfined TSPC (TSPC-UC) and mild steel tube confined TSPC (TSPC-FM) have results in the improvement of mechanical property from 3.32 GPa to 7.68 GPa for compressive modulus, 46.55 MPa to 125.33 MPa for yield strength, 59.19 MPa to 131.84 MPa for maximum compressive strength and 0.0300 to 0.0287 for the corresponding strain. The application of previous mathematical models on confined circular concrete column under compression to predict the TSPC-FM property have revealed that for compressive modulus, Mander, Lam & Teng and proposed model have provided closer match with 7.13 GPa, 6.31 GPa and 6.31 GPa. On the other hand, the predictions for yield strength by Wei model have shown closer approximation with 125.67 MPa compared to experimental (125.33 MPa). Then, in term of maximum compressive strength, the evaluation through Mander and Saadatmanesh models have shown exact match with experimental results, 131.84 MPa which also involves the corresponding strain with 0.02872 and 0.02906. Comparison based on the deviation percentage of maximum compressive strength between experimental and mathematical model predictions indicate that Mander and Saadatmanesh, 0.00 %, Wei, 12.36 %, Lam & Teng, 81.33 % and proposed model, 0.61 %. In general, observation and evaluation on experimental and mathematical prediction have indicated that Mander and proposed model have shown good compatibility to represent actual TSPC-FM compressive behavior considering both stress versus strain (Figure 6e) and mechanical properties (Table 3e).

Table 3: Mechanical properties by experimental and mathematical prediction
(a) TSPC confined GFRP (TSPC-GF); (b) TSPC confined CFRP (TSPC-CF); (c) TSPC confined BFRP (TSPC-BF); (d) TSPC confined AFRP (TSPC-AF); (e) TSPC confined mild steel tube (TSPC-FM)

Mathematical Model	Compressive Modulus (GPa)	Yield Strength (MPa)	Maximum Strength (MPa)	Corresponding Strain	Max. Strength Deviation (%)
Unconfined TSPC	3.32	46.55	59.19	0.03	-
Exp. GFRP Confinement	3.65	51.25	85.54	0.0453	-
Mander et. al (1988)	2.78	61.1	85.54	0.0454	0.00%
Wei et. al (1992)	7.62	79.85	89.54	0.0205	4.68%
Saadatmanesh et. al (1994)	3.46	64.7	85.54	0.0453	0.00%
Lam & Teng (2003)	2.35	60.63	92.29	0.0569	7.89%
Proposed Model	2.35	60.63	86.08	0.0505	0.63%

(a)

Mathematical Model	Compressive Modulus (GPa)	Yield Strength (MPa)	Maximum Strength (MPa)	Corresponding Strain	Max. Strength Deviation (%)
Unconfined TSPC	3.32	46.55	59.19	0.03	-
Exp. CFRP Confinement	4.69	67.57	108.77	0.0398	-
Mander et. al (1988)	3.31	88	108.77	0.0398	0.00%
Wei et. al (1992)	11.89	102.93	120.54	0.0165	10.82%
Saadatmanesh et. al (1994)	5.81	90.2	108.77	0.0398	0.00%
Lam & Teng (2003)	2.82	68.89	79.42	0.0414	26.98%
Proposed Model	2.82	68.86	74.33	0.0328	31.66%

(b)

Mathematical Model	Compressive Modulus (GPa)	Yield Strength (MPa)	Maximum Strength (MPa)	Corresponding Strain	Max. Strength Deviation (%)
Unconfined TSPC	3.32	46.55	59.19	0.03	-
Exp. BFRP Confinement	3.65	50.21	81.52	0.0356	-
Mander et. al (1988)	2.94	68.08	81.52	0.03556	0.00%
Wei et. al (1992)	11.11	81.71	89.33	0.0129	9.58%
Saadatmanesh et. al (1994)	3.87	68.15	81.52	0.03556	0.00%
Lam & Teng (2003)	3.17	72.68	89.29	0.04524	9.53%
Proposed Model	3.17	63.7	79.65	0.03306	2.29%

(c)

Mathematical Model	Compressive Modulus (GPa)	Yield Strength (MPa)	Maximum Strength (MPa)	Corresponding Strain	Max. Strength Deviation (%)
Unconfined TSPC	3.32	46.55	59.19	0.03	-
Exp. AFRP Confinement	3.65	80.71	114.24	0.0665	-
Mander et. al (1988)	2.92	102.33	114.24	0.06654	0.00%
Wei et. al (1992)	6.35	106.68	120.52	0.0345	5.50%
Saadatmanesh et. al (1994)	2.46	97.82	114.24	0.06654	0.00%
Lam & Teng (2003)	2.22	88.9	114.24	0.07152	0.00%
Proposed Model	2.22	86.7	109.26	0.07152	4.36%

(d)

Mathematical Model	Compressive Modulus (GPa)	Yield Strength (MPa)	Maximum Strength (MPa)	Corresponding Strain	Max. Strength Deviation (%)
Unconfined TSPC	3.32	46.55	59.19	0.03	-
Exp. Metal Confinement	7.68	125.33	131.84	0.0287	-
Mander et. al (1988)	7.13	120.12	131.84	0.02872	0.00%
Wei et. al (1992)	13.96	125.67	148.14	0.07106	12.36%
Saadatmanesh et. al (1994)	26.02	105.42	131.84	0.02906	0.00%
Lam & Teng (2003)	6.31	114.09	239.07	0.07106	81.33%
Proposed Model	6.31	123.04	131.03	0.03388	0.61%

(e)

In order to investigate the model which capable to be proposed as universal model to represent the compressive behavior of confined TSPC regardless of confinement materials employed, the curve of each sample for both experimental and mathematical prediction (TSPC-UC, TSPC-GF, TSPC-CF, TSPC-BF, TSPC-AF, and TSPC-FM) was plotted together based on every model. Figure 7 shows the curve for each model to evaluate the curve lines concentration where dotted lines represent experimental curve and solid lines represent mathematical model curve. In this evaluation, lines of any models (Mander, Saadatmanesh, Wei, Lam & Teng or proposed model) that appears as more concentrated and narrowed have a higher level of accuracy and precision to represent as universal mathematical model which capable to describe the compressive behavior of confined TSPC. Manders model in Figure 7a shows that all variation of confinement material application on TSPC samples (GFRP, CFRP, BFRP, AFRP and FM) have provide good pattern with its corresponding experimental curves. Then, in Figure 7b, Saadatmanesh model have also capable of replicating experimental response of every test samples but not on metallic material confinement (FM), where the experimental and predicted curve have shown significance different. Figure 7c which presents the prediction of Wei model on stress versus strain curve in comparison with experimental curve have indicate the different pattern on each samples resulting in less concentrated and narrowed lines on the graphical figure. At a glance, Lam & Teng model in Figure 7d look as it were exhibited concentrated and narrowed lines but if observed closely, the curve of metallic material application on TSPC confinement has diverged in a large different with experimental curve making it incapable of becoming universal model to describe compressive behavior of confined TSPC. The proposed model in Figure 16e have shown approximately similar behavior as Mander except for CFRP where the predicted curve provide lower peak strength then experimental curve. However, the pattern is still in approximately similar pattern as experimental pattern and the different was not too large. Overall, the study suggested that Mander and proposed model have the capability to be adapted as universal model to represent confined TSPC under compression. Compressive behavior through stress versus strain curve as predicted by Mander (Figure 7a) and proposed models (Figure 7e) have shown closer match with experimental on all variation of test samples.

CONCLUSION AND FUTURE RESEARCH

This study has presented a brief evaluation on confined TSPC under compression by employing both experimental and analytical approach. The comparison of five mathematical models has brought to a proposition on which models were capable to be applied in predicting the confined TSPC behavior particularly as a universal model. According to results and discussions, Mander model have shown good match to describe compressive behavior of confined TSPC followed by proposed model as proved by comparison between experimental and analytical study that have been done. Mander model was introduced in 1988 and it has been developed to evaluate stress versus strain behavior of cement concrete column under steel confinement in transverse direction subjected to uniaxial compression. On the other hand, proposed model was adapted from Lam & Teng model, where secant modulus of elasticity was neglected to modify failure curve of the model to suite TSPC behavior. The reason was that Lam & Teng model in particular have been assigned to describe compressive behavior of cement concrete column with FRP material confinement, while TSPC was a polymer concrete material which certainly need for the modification moreover with FRP and metallic material confinement. The remaining model have failed to satisfy the stress versus strain behavior of experimental results as a universal model but can be highlighted if assigned to a specific confinement specification, for instances, Saadatmanesh model have succeeded in representing experimental results for all variant of FRP material confinement on TSPC but failed to predict metallic material confinement application on TSPC. Different from that, Lam & Teng model can describe the confined TSPC compressive behavior on linear relationship up to maximum strength. The failure curve for each sample cannot be predicted by Lam & Teng model as it stops suddenly without any downward line. Another model, Wei has shown obvious differences with experimental results for all variants of test samples whereas, Wei model was the only one which specifically introduced to describe compressive behavior of confined polymer concrete. However, Wei developed the model based on experimental of polymer concrete column confined with Aluminum rings under compression. Finally, the performance of Mander and proposed model as universal model to represent compressive behavior of confined TSPC column may be further investigated with the application of larger database of confinement material specifications.

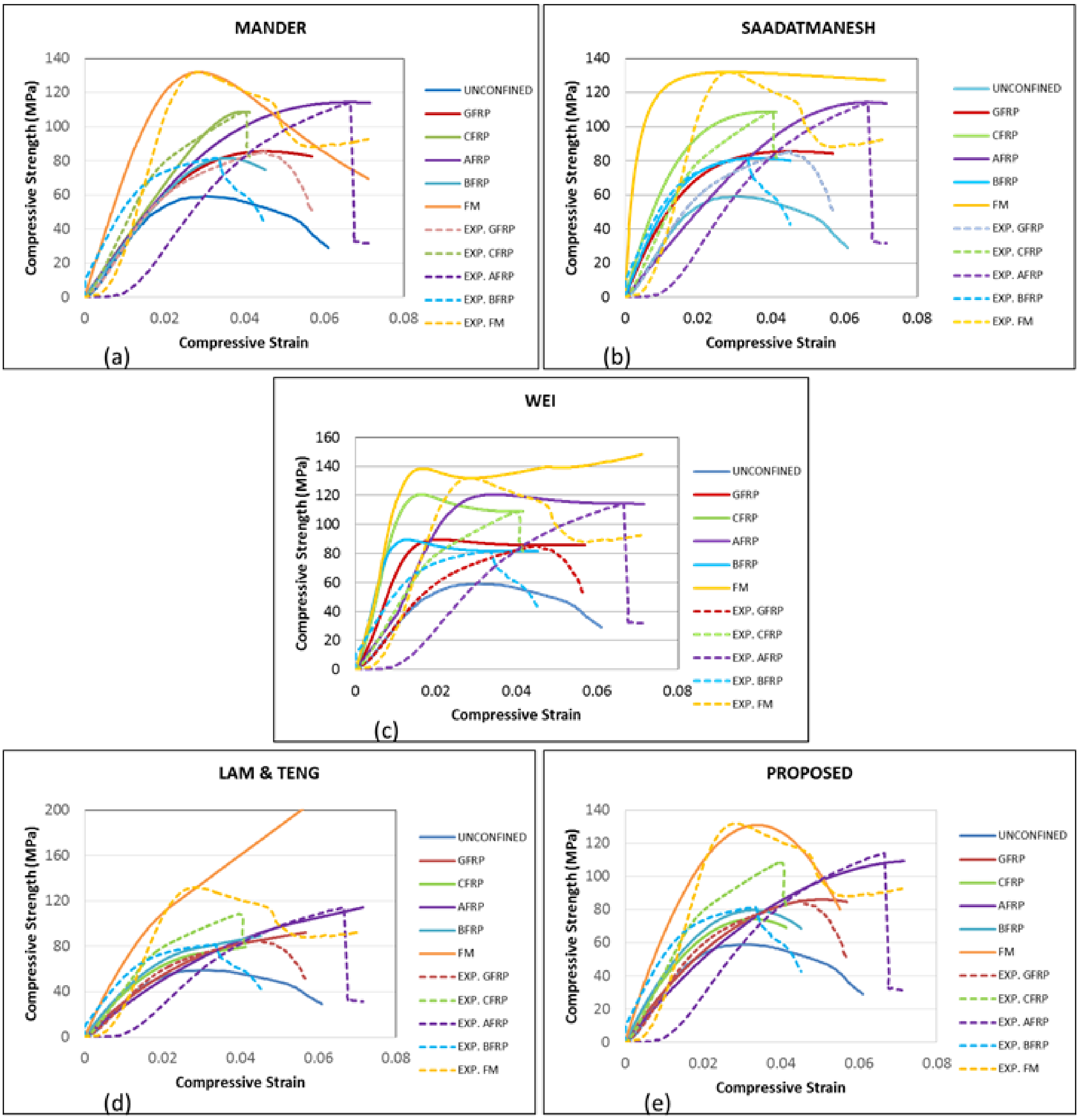

Figure 7: Stress versus strain curve of all confined TSPC samples by experimental and mathematical prediction
(a) Mander model; (b) Saadatmanesh model; (c) Wei model; (d) Lam & Teng model; (e) Proposed model

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