Deformations of a plastic tube with concrete-infill under direct load

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Keywords

*Plastic tube;
Axial strain;
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Database;
Strain model.*

Abstract

Confinement of concrete columns can be an effective means of enhancing structural members' deformation—alternative materials such as uPVC tube show elastic-plastic behavior with considerable elongations at failure. The material ductility features significant deformations that usually considered to be belonging to the set of mechanical properties. The tube can be applied for encasing concrete, thereby influencing the deformability capacity of a column. The current work aims to evaluate the axial strain of plastic tubes with concrete-infill (PTCI) specimens tested under uniaxial compression load. A strain model was developed for PTCI specimens using a normalized confinement stiffness procedure, based on a database of experimental results from recent studies 2019-2020 and those of the present study. Five existing FRP-confined concrete models and the developed model were employed to predict PTCI columns' strain, and the predictions were compared with experimental results in the database. Three statistical indexes were used to evaluate the proposed and the three existing FRP-confined concrete strain models' performance. The indexes included: Average absolute relative error (AAE), Normalized root-mean-square error (NRMSE), and coefficient of correlation (R2). The comparison shows the proposed model to give more close prediction to the experimental test data and the comprehensive database to yield the lowest average absolute error (AAE). The root means square error (RMSE) compared with other models in the present study.

1. Introduction

Engineering plastics such as unplasticized polyvinyl chloride (uPVC) have been used in civil engineering and construction applications for several decades. However, there is a need to promote these new materials in civil engineering applications to protect and contain concrete elements. Based on its technological and economic advantages, the performance of these tubular elements under harsh environmental conditions has been established previously. Several studies recently explored the potential use of plastic tubes for structural concrete encasement, representing new trends in searching for alternative materials.

Composites like a concrete-filled steel tube (CFST) have shortcomings such as high cost and corrosion. PTCI was reported as a viable alternative for conventional steel tube for structural applications provided that appropriate design methodologies are employed. As a non-metallic pour-in form for concrete [1], the plastic tube can improve column constructability and enhance its resistance to environmental influences (chemical plants, large water tanks, and underground car parks). PTCI columns with an aspect ratio of two ($h/D=2$) were tested under compression load [2]. The post-peak stress-strain behavior of PTCI specimens proved to be affected by the total thickness/diameter ratio ($2t/D$). The absolute value of the slope decreased as the $2t/D$ proportion increased.

The aggregate characteristics were reported to be influential parameters that affected short PTCI columns' performance under applied load [3]. In experimental work, two series of slender PTCI

specimens were tested to assess the contribution of plastic tube (PT) in improving the ductility of concrete in PTCI specimens subjected to axial load [4]. The plastic tube was used in three low-cost composite systems for concrete construction [5]. The steel-reinforced hybrid systems demonstrated different rigidities that can ameliorate the deformation capacities and, in a similar manner, to a lesser extent the radial performance of the slender PTCI specimens. The increase in tube thickness was reported to affect steel-reinforced PTCI specimens' ductility when subjected to axial load [6]. To account for the individual load contribution of PTCI components under a compression load, concrete core, and outer PT jacket, a small gap of 1.2mm was introduced between the two [7]. The results showed the formation of two peak strains with a compression strain-softening in the falling branch. To predicate the plastic capacity of PTCI columns with two different mechanisms, composite mode and confining mode, two series of short PTCI specimens were tested, and material failure dominated the test results [8].

Double skin PTCI specimens under axial compression loads were investigated [9], showing considerable ductility enhancement. Drum type failure was the prevalent failure mode, with the internal tubes displaying local buckling. One of the plastic tube's primary deficiencies in the low modulus of elasticity can be overcome using fiber-reinforced polymers (FRP). From the above review, there is no strain model for PTCI, which includes the tube stiffness as one of the main input parameters. The present study's main objective is to adopt a normalized confinement stiffness procedure, which has been previously proposed for FRP [10], to predict a plastic tube's strain capacity with concrete-infill tested under uniaxial load. To achieve this goal, a database of test results of recently published papers 2019-

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2020 was compiled and combined with the current study's experimental results and used to develop a strain model for PTCI specimens tested under compression load.

3. Experimental program

3.1. Materials

3.1.1 Coarse aggregate

Graded crushed river aggregate from the Eski-kalak region north of the country was used as a coarse aggregate for making concrete. Natural river sand of a maximum aggregate size of 4.75mm with a fineness modulus of 2.78 was used as the fine aggregate. Both the fine and coarse aggregates were free from impurities. Two mixtures with target strength of 35 and 50MPa were investigated, and the ingredients were batched by weight, Table 1. To control the slump and have the desired workability, a superplasticizer (SP) was used as a water reducer admixture for the mix with the target strength of 50MPa.

3.1.2 Plastic molds

Unplasticized polyvinyl chloride tubes with an external diameter of 110mm were cut into two groups, each with three different heights resulting in h/D ratios of 1 to 2 in an increment of 0.5. Group one had an average tube thickness of 4mm, whereas group two had an average tube thickness of 6mm.

Table 1 Properties of concrete mixes

Material properties		Batch 1	Batch 2
Water	(Kg)	170	150
Cement	(Kg)	355	400
Sand	(Kg)	680	700
Coarse aggregate	(Kg)	1350	1290
w/c ratio		0.51	0.41
Maximum aggregate size	(mm)	10	10
Slump	(mm)	100 $\pm$ 20	100 $\pm$ 20
The specific gravity of sand		2.7	2.7
The specific gravity of aggregate		2.72	2.72
The specific gravity of cement		3.15	3.15
Unit weight of concrete	Kg/m ³	2370	2400
Super-plasticizer	%	-	1
Target compressive strength	(MPa)	30	50

3.2 Mixing

All the ingredients were mixed in a rotary drum mixer with a capacity of 0.07m³ under indoor laboratory conditions. All the raw materials were loaded into the mixer and dry mixed for four minutes. Afterward, the water was added, and the mixing continued for another 3-4 minutes until a homogeneous mix was obtained. A standard slump cone was used to measure the workability of fresh concrete. Following the mixing, a part of the new concrete was used for the slump test. The concrete slump was computed as the drop in the height of the cone-shaped concrete. The plastic concrete was cast into the pre-prepared molds for confined and unconfined concrete specimens in two layers, and each layer was compacted for at least 30seconds. After casting, the specimens were covered with wet burlaps and polyethylene sheets for 28days. After that, the control specimens were de-molded by cutting the plastic tube longitudinally using an electric saw. All the details of mixes and specimen designations are summarized in Table 2. Specimens with series S1, S2, and S3 had infill concrete with compressive strength of 35MPa, whereas series S2, S4, and S6 had strength of 50MPa.

4. Tests

Uniaxial compression tests were carried out using a 2000KN universal testing machine. Two linear displacement transducers were used for the vertical displacement control case. The experimental tests were monitored at a speed of 0.2mm/s, and beyond the peak load, loading continued until a force of 50kN was reached to obtain the full stress-strain curves for PTCI specimens. The coupon test of the uPVC sample in tension was shown in Fig. (1), whereas the uPVC tubes' compression test was depicted in Fig. (2). PTCI stub columns, with h/D ratio equal to 0.75, tested under axial compression load displayed in Fig. (3). The specimen underwent gradual deformations, and Figs. 4(a) and (b) shows the deformation of columns at 50%, 70% of ultimate strain ϵ_{cu} . Fig.4(c) illustrates the column's excessive deterioration at 90% of ultimate strain before final failure.

5. Discussions

5.1 Stress-strain curve

5.1.1 Coupons

The coupons showed considerable flexibility with ductile failure in the post-peak plastic stage, reaching an elongation of more than 44% at ultimate failure. The stress-strain relationship of the PVC coupons is depicted in Fig. (5), which show four clear zones; elastic, post-yield; peak strain, and post-peak zone. The polymeric tubes offer no exact yield point, and the 0.2% strain method was used to determine the yield point of coupons and plastic tubes, Fig.(6).

Fig. (1) Coupon test of uPVC samples

Fig. (2) Failure of uPVC tubes due to local buckling.

5.1.2 CFPT specimens

The stress-strain relationship for the first series of PTCI specimens is demonstrated in Fig. (7). The behavior for the unconfined and confined specimens was similar in the elastic stage. The confined specimens started to deform locally at the ends and the mid-height. At these locations, the tube's color began to change from gray to a gray whitish color, which was a sign of permanent deformation in the tube's microstructure. With additional loading, the PTCI peaked at a corresponding strain much more significant than that for unconfined specimens. Beyond the peak load, PTCI stubs' resistance to the applied load started to deteriorate faster for specimens with high-strength concrete infill (S2-H4-1) than specimens with normal strength infill (S1-H4-1).

Fig. 3 PTCI stubs: (a) (S3-H2-1); (b) (S3-H2-1)

Fig. (4) Failure of PTCI stub columns (S3-H2-2) under axial compression load at (a) 50% of ϵ_{cu} ; (b) 70% of ϵ_{cu} ; (c) 90% of ϵ_{cu} .

Fig. 5 stress-strain relationship for the coupons tested in axial tension.

Both specimens underwent strain softening and continued to deform, and the ultimate strain (failure strain) reached values greater than 0.16, which was nearly 40 times greater than the strain at peak stress. 0.004 for column S1-H4-1.

Fig.6 0.2% strain used to determine the yield point of coupons.

Fig.7 Typical axial stress-strain relationship used for the tested columns

Such deformations beyond peak load are essential when considering the design of compression members in critical seismic zones where reinforced columns' failure is brittle.

5.1 Strain models

Three existing strain models for concrete were confined with the fiber-reinforced polymer used to predict PTCI specimens' strain. It includes the following models:

5.1.1. Ilki et al. [11]

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 20 \left(\frac{f_{lu}}{f_{co}} \right)^{0.5}$$

5.1.2. Wu et al. [12]

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 9.5 \left(\frac{f_{lu}}{f_{co}} \right)$$

5.1.3 Mohamed H, Masmoudi [13]

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 2 + 7.6 \left(\frac{f_{lu}}{f_{co}} \right)$$

5.1. Model development

Many existing stress and strain models for concrete confined with FRP are based on the model for steel-confined concrete developed by Richart et al. [14]:

$$\frac{f_{cc}}{f_{co}} = 1 + 4.1 \left(\frac{f_l}{f_{co}} \right)$$

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

where ε_{cc} = confined concrete strain, ε_{co} = unconfined concrete strain, f_{cc} = confined concrete strength, f_{co} = unconfined concrete strength, respectively. A large difference in failure strain of FRP-confined concrete has been reported, and values varied from 58 to 61% of the coupon test strains, mostly based on carbon FRP confinement results [10,15]. This behavior was ascribed to the FRP confinement device's multiaxial state of stress and possible stress concentrations throughout the concrete column's surface. For FRP-confined concrete, the confining pressure is given by:

$$f_l = \frac{2E_f t_f \varepsilon_{fe}}{D}$$

Where E_f = modulus of elasticity; t_f = total thickness; ε_{fe} = effective rupture strain; and D = concrete specimen diameter.

The effective strain value of FRP confinement is given by:

$$\varepsilon_{fe} = \kappa_e \varepsilon_{fu}$$

where κ_e = strain efficiency factor (a value of 0.55 is recommended for circular cross-sections) and ε_{fu} = ultimate tensile strain value of the FRP confinement material measured in coupon tests [10].

ACI 440.2R [16] recommends the confinement ratio (f_l/f_{co}) to be larger than 0.08 to avoid a post-peak descending branch based on the work of Lam and Teng [17,18].

$$\varepsilon_{cc} = \varepsilon_{co} \left(1.5 + 12 \frac{f_l}{f_{co}} \left(\frac{\varepsilon_{fe}}{\varepsilon_{co}} \right)^{0.45} \right)$$

Eq. (8) [16] for evaluating the axial strain of concrete corresponding to the maximum axial stress (ε_{cc}) but to avoid excessive cracking and maintain structural integrity, the value is restricted to a maximum of 0.01. By putting $\varepsilon_{co}=0.002$, $\varepsilon_{fu} = 0.0145$ (an average for carbon FRP

computed from a database of 85 specimens), and calculating ε_{fe} from Eq. (7), and putting $\varepsilon_{cc} = 0.01$ in Eq. (8) the lower and upper boundary for the confinement ratio (f_l/f_{co}) was determined by putting Eq. (9) [10]:

$$0.08 \leq f_l/f_{co} \leq 0.16$$

in practice, achieving passive confinement ratios (f_l/f_{co}) as large as 0.7 is quite tricky, considering the larger size of real concrete columns relative to test specimens and the cost of confinement materials and Yazici and Hadi [10] used a normalized confinement stiffness (K_N) given by Eq. (10) to express the confined concrete strain:

$$K_N = \frac{2E_f t_f}{D f_{co}} \quad (1)$$

The confinement ratio f_l/f_{co} can be expressed by:

$$\frac{f_l}{f_{co}} = \kappa_e \varepsilon_{fu} K_N \quad (2)$$

By substituting Eq. (7) into Eq. (5), and using $\kappa_e = 0.55$ (κ_e = strain efficiency factor, a value of 0.55 is recommended for circular cross-sections), the following expression for the strain of FRP-confined concrete [10] was obtained: (3)

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 0.16 K_N$$

The upper and lower limits of Eqn. (9) was also expressed in terms of K_N :

$$10 \leq K_N \leq 20 \quad (4)$$

5.2. Database

A database of recent works executed in the period 2019-2020 was compiled. The database comprises nine papers [1,2, 20, 3, 19, 4,5, 7, 14] related to PTCI directly or indirectly. The number of test data for the strain of PTCI specimens reported in the literature is limited and less than those for strength. Therefore, the database included only nine recent studies, and the entire test data are summarized in Table 2.

5.3. PTCI

For PTCI: a model proposed for the strain of concrete specimens with circular cross-sections confined with a plastic tube. In the present study, the average peak strain of PTCI specimens was calculated from Table 2 and was found to be $\varepsilon_{fu} = 0.00827$ and substituting in Eqn. (11): (6)

$$\frac{f_l}{f_{co}} = (0.00827) K_N$$

By substituting (14) into (4)

$$\frac{f_{cc}}{f_{co}} = 1 + 0.034 K_N \quad (7)$$

Eqn. (15) into (5):

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 0.17 K_N$$

With strain efficiency factor $\kappa_e = 1$ (value 0.55 recommended for circular cross-sections).

Recently Abdulla [19] proposed a model for the strain of PTCI specimens based on using a soft computing technique, artificial neural work (ANN): (8)

$$\left(\frac{\varepsilon_{cu}}{\varepsilon_{co}} \right)_{ANN} = 1.29 \left(\frac{f_l}{f_{co}} \right)^{-0.54}$$

By substituting Eqn. (14) into Eqn. (17):

$$\left(\frac{\varepsilon_{cu}}{\varepsilon_{co}}\right)_{ANN} = 1.29(0.00827K_N)^{-0.54}$$

K_{NPVC} was calculated from Eq.(10), and to account for premature failure of the plastic tube, a modifications factor was used and rendered it more effective in predicting the strength of PTCI.

$$10 \leq K_{NPVC} \leq 20$$

5.4 Statistical Indexes

Three statistical indexes were used to evaluate the proposed and the three existing FRP-confined concrete strain models' performance. The indexes included: Average absolute relative error (AAE), Normalized root-mean-square error (NRMSE), and coefficient of correlation (R^2):

$$AAE = \frac{\sum_{i=1}^N \left| \frac{model.i - exp.i}{exp.i} \right|}{N}$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^N (exp.i - model.i)^2}{N}}}{\sum_{i=1}^N exp.i}$$

Where (exp.i)= the experimental result; (model.i)=the model prediction; N= the total number of data. AAE's and NRMSE's small values show well model performance. Since most values of RMSE are smaller than those of AAE, the former is easier and more practical to use.

5.5 Predicted $\varepsilon_{cc}/\varepsilon_{coModel}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$

The Predicted $\varepsilon_{cc}/\varepsilon_{coModel}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$ using models 1, 2, and 3 are depicted in Figs 8 and 9. Model 2 by Wu et al. [12] shows a better fit of predicted results with the experimental results than models 1 and 3. Model 2 shows good predictions of test results for PTCI specimens with both normal and high strength concretes. However, model 2 displays poor predictions for PTCI columns with low strength. Predicted $\varepsilon_{cc}/\varepsilon_{coModel}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$ using models 12 and 13 are drawn in Fig.10. Nearly more than half of the predicted results fall within the 20% error lines. But the models show poor predictions for low strength concrete confined with the polymeric tube. Fig. 11 (a) and (b) shows the prediction of model 16 without and with the limit $10 \leq K_N \leq 20$. The predicted data fits within the upper and lower 20% boundaries, but it deviates from the best fitting line as the strength of concrete decreases. The limit $10 \leq K_N \leq 20$ has little influence on the fitting of predicted values with the test values. Model 17 shows low predictions of test data where there is a spread of data, Fig.12. Similar observations can be made for models 18 without and limit $10 \leq K_N \leq 20$, Fig.13.

5.6 Performance of models

The predictions by the FRP models and the proposed model are shown in Figs. 8 to 13. Two comparisons were made; one general that included all test results, and a second one for experimental results with K_N values between 10 and 20 according to ACI 440-2R (ACI 2008) [16] recommendations for stress strain limitations. The accuracy of the models was evaluated using statistical indexes, which were also used for comparison purposes. Ilki et al. [11], Eq. (1) could result in larger average absolute errors, 189%, $\varepsilon_{cc}/\varepsilon_{co}$ values, and a high RMSE value of 4.63. Wu et al. [12] model yielded reasonable predictions with AAE and RMSE values of 31.24% and 1.93, respectively.

The model by Mohamed and Masmoudi [13] produced higher errors with AAE and RMSE values of 41.34% and 1.6, respectively. Model 12 by Yazici and Hadi [10] made lower errors with AAE and RMSE of 31% and 1.57, respectively. The computed average absolute error for the proposed model 16 was similar to that of model 12 with an AAE of 31.7%. However, the RMSE value for the proposed model 16 was only 1.52, compared with 1.57 for model 12. The RMSE value for the proposed model 16 was the lowest among all models under discussion.

The proposed models 17 and 18 produced higher errors compared with the proposed model 16.

Fig. (8) Predicted $\varepsilon_{cc}/\varepsilon_{coModel}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$ using the model: (a) 1; (b) 2.

The model providing a smaller sum of squared errors was accepted as a better model than the other models. The average absolute error of 30% is not unfamiliar for $\varepsilon_{cc}/\varepsilon_{co}$ values, and several studies for FRP confined concrete have reported similar values [10].

Fig. (9) Predicted $\varepsilon_{cc}/\varepsilon_{coModel}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$ using model 3.

For K_N results between 10 and 20, only three models were considered: model 12, 16, and 18. Because of the parameter K_N , the other models were not applicable. The predicted $\varepsilon_{cc}/\varepsilon_{co}$ values for model 16 were closer to the experimental values over the given database. The

proposed model 16 was more accurate than the other two models 12 and 18,

Fig. (10) Predicted $\epsilon_{cc}/\epsilon_{coModel}$ versus $\epsilon_{cc}/\epsilon_{co-Exp}$ using the model: (a) 12; (b) 12 with the limit $10 \leq K_N \leq 20$.

Fig. (11) Predicted $\epsilon_{cc}/\epsilon_{coModel}$ versus $\epsilon_{cc}/\epsilon_{co-Exp}$ using the model: (a) 16; (b) 16 with the limit $10 \leq K_N \leq 20$.

Fig. (12) Predicted $\epsilon_{cc}/\epsilon_{coModel}$ versus $\epsilon_{cc}/\epsilon_{co-Exp}$ using model 17.

Table 2 Assembled database for CFPT from recent studies, 2019-2020.

Sourceofdata	Specimens	tP mm	Dex mm	Ap mm ²	Ac mm ²	H mm	H/D	fyp MPa	fcc/ fcoex	E MPa	K _N	10≤K _N ≤20	fl/ fco
Abdulla(2019)[1]	1-SF	4	75	892.57	4419.	150	2	48	1.22	3900	13.21	13.21	0.11
	2-SF	4.5	90	1209.	6364.	180	2	48	1.17	3900	12.56	12.56	0.1
	3-SF	5	110	1650	9507.	220	2	48	1.19	3900	11.57	11.57	0.1
Woldemariam etal.(2019)[2]	C1P1H1	2.5	68	514.64	3633.1	136	2	41	2.36	3580	27.45	20	0.23
	C1P2H1	3	96	876.86	7241.	192	2	41	2.23	3580	23.06	20	0.19
	C1P3H1	3	116	1065.	10573	232	2	41	2.13	3580	18.87	18.87	0.16
	C1P4H1	3	146	1348.3	16748	292	2	41	2.03	3580	14.82	14.82	0.12
	C2P1H1	2.5	68	514.64	3633.1	136	2	41	1.99	3580	20.6	20	0.17
	C2P2H1	3	96	876.86	7241.	192	2	41	1.94	3580	17.31	17.31	0.14
	C2P3H1	3	116	1065.	10573	232	2	41	1.81	3580	14.16	14.16	0.12
	C2P4H1	3	146	1348.3	16748	292	2	41	1.72	3580	11.13	11.13	0.0
	C3P1H1	2.5	68	514.64	3633.1	136	2	41	1.7	3580	16.82	16.82	0.14
	C3P2H1	3	96	876.86	7241.	192	2	41	1.69	3580	14.13	14.13	0.12
	C3P3H1	3	116	1065.4	10573	232	2	41	1.6	3580	11.56	11.56	0.1
	C3P4H1	3	146	1348.3	16748	292	2	41	1.45	3580	9.08	10	0.0
	C4P1H1	2.5	68	514.64	3633.1	136	2	41	1.6	3580	14.11	14.11	0.12
	C4P2H1	3	96	876.86	7241.	192	2	41	1.52	3580	11.86	11.86	0.1
	C4P3H1	3	116	1065.4	10573	232	2	41	1.47	3580	9.701	10	0.0
	C4P4H1	3	146	1348.3	16748	292	2	41	1.39	3580	7.622	10	0.0
	C5P1H1	2.5	68	514.64	3633.1	136	2	41	1.44	3580	11.78	11.78	0.1
	C5P2H1	3	96	876.86	7241.	192	2	41	1.42	3580	9.895	10	0.0
	C5P3H1	3	116	1065.4	10573	232	2	41	1.36	3580	8.09	10	0.0
	C5P4H1	3	146	1348.3	16748	292	2	41	1.28	3580	6.361	10	0.0
Lu2019[20]	PVC-RACO	3.2	110	1074.1	9507.	300	2.7	37	1.43	3500	7.305	10	0.0
Abdulla(2020)[3]	CT-A1	3.8	110	1268.3	9507.	200	1.8	40	1.22	400	7.671	10	0.0
	CT-A2	3.8	110	1268.3	9507.	200	1.8	40	1.25	400	7.671	10	0.0
	CT-A3	3.8	110	1268.3	9507.	200	1.8	40	1.23	400	7.671	10	0.0
	CT-B1	3.8	110	1268.3	9507.	200	1.8	40	1.24	400	7.981	10	0.0
	CT-B2	3.8	110	1268.3	9507.	200	1.8	40	1.25	400	7.981	10	0.0
	CT-B3	3.8	110	1268.3	9507.	200	1.8	40	1.28	400	7.981	10	0.0
	CT-C1	3.8	110	1268.3	9507.	200	1.8	40	1.29	400	8.555	10	0.0
	CT-C2	3.8	110	1268.3	9507.	200	1.8	40	1.28	400	8.555	10	0.0
	CT-C3	3.8	110	1268.3	9507.	200	1.8	40	1.32	400	8.555	10	0.0
	CT-D1	3.8	110	1268.3	9507.	200	1.8	40	1.26	400	9.02	10	0.0
	CT-D2	3.8	110	1268.3	9507.	200	1.8	40	1.39	400	9.02	10	0.0
	CT-D3	3.8	110	1268.3	9507.	200	1.8	40	1.35	400	9.02	10	0.0
Abdulla(2020)JSC[19]	CT-E1	3.8	110	1268.3	9507.	200	1.8	40	1.37	400	9.22	10	0.0
	CT-E2	3.8	110	1268.3	9507.	200	1.8	40	1.4	400	9.22	10	0.0
	CT-E3	3.8	110	1268.3	9507.	200	1.8	40	1.39	400	9.22	10	0.0
	CT-F1	3.8	110	1268.3	9507.	200	1.8	40	1.36	400	9.515	10	0.0
	CT-F2	3.8	110	1268.3	9507.	200	1.8	40	1.41	400	9.515	10	0.0
	CT-F3	3.8	110	1268.3	9507.	200	1.8	40	1.43	400	9.515	10	0.0
	CT-G1	3.8	110	1268.3	9507.	200	1.8	40	1.4	400	10.38	10.38	0.0
	CT-G2	3.8	110	1268.3	9507.	200	1.8	40	1.43	400	10.38	10.38	0.0
	CT-G3	3.8	110	1268.3	9507.	200	1.8	40	1.41	400	10.38	10.38	0.0
	CT-H4	3.8	110	1268.3	9507.	200	1.8	40	1.48	400	11.64	11.64	0.1
	CT-H5	3.8	110	1268.3	9507.	200	1.8	40	1.51	400	11.64	11.64	0.1
	CT-H6	3.8	110	1268.3	9507.	200	1.8	40	1.45	400	11.64	11.64	0.1
	CT-I1	3.8	110	1268.3	9507.	200	1.8	40	1.54	400	14.55	14.55	0.12
	CT-I2	3.8	110	1268.3	9507.	200	1.8	40	1.59	400	14.55	14.55	0.12
	CT-I3	3.8	110	1268.3	9507.	200	1.8	40	1.57	400	14.55	14.55	0.12
	CT-J4	3.8	110	1268.3	9507.	200	1.8	40	1.64	400	15.46	15.46	0.13
	CT-J5	3.8	110	1268.3	9507.	200	1.8	40	1.64	400	15.46	15.46	0.13
	CT-J6	3.8	110	1268.3	9507.	200	1.8	40	1.69	400	15.46	15.46	0.13
	CT-K1	3.8	110	1268.3	9507.	200	1.8	40	1.76	400	17.78	17.78	0.15
	CT-K2	3.8	110	1268.3	9507.	200	1.8	40	1.79	400	17.78	17.78	0.15
	CT-K3	3.8	110	1268.3	9507.	200	1.8	40	1.75	400	17.78	17.78	0.15
	CT-L4	3.8	110	1268.3	9507.	200	1.8	40	1.86	400	18.21	18.21	0.15
	CT-L5	3.8	110	1268.3	9507.	200	1.8	40	1.84	400	18.21	18.21	0.15
	CT-L6	3.8	110	1268.3	9507.	200	1.8	40	1.82	400	18.21	18.21	0.15
Abdulla(2020)KSCE[5]	1	4	90	1081.1	6364.	180	2	40	1.22	3950	12.31	12.31	0.1
	2	5	110	1650	9507.	220	2	40	1.18	3950	12.62	12.62	0.1
Abdulla(2020)[4]jordan	1-10s	4	75	892.57	4419.	150	2	41	1.22	400	15.76	15.76	0.13
	1-11s	4.5	90	1209.	6364.	180	2	41	1.13	400	14.72	14.72	0.12
	1-13s	5	110	1650	9507.	220	2	41	1.28	400	13.33	13.33	0.11

Table 2 Assembled database for CFPT from recent studies, 2019-2020.(Continued)

Sourceofdata	Specimens	tP mm	Dex mm	Ap mm ²	Ac mm ²	H mm	H/D	fyp MPa	fcc/ fcoex	E MPa	K _N	10≤K _N ≤20	fl/ fco
Askerietal.[7]	C40-6-0#1	3	110	1008.	9507.	220	2	48	1.15	320	5.715	10	0.05
	C40-6-0#2	3	110	1008.	9507.	220	2	48	1.18	320	5.672	10	0.05
	C40-6-1#1	3.1	110	1041.5	9507.	220	2	48	1	320	4.684	10	0.0
	C40-6-1#2	3.1	110	1041.5	9507.	220	2	48	1.15	320	5.142	10	0.0
	C40-6-3#1	3.1	110	1041.5	9507.	220	2	48	1.04	320	5.176	10	0.0
	C40-6-3#2	3.1	110	1041.5	9507.	220	2	48	1.19	320	5.562	10	0.05
	C40-10-0#1	4.9	110	1618.5	9507.	220	2	48	1.1	320	9.689	10	0.0
	C40-10-0#2	4.7	110	1555.4	9507.	220	2	48	1.22	320	9.186	10	0.0
	C40-10-1#1	4.6	110	1523.8	9507.	220	2	48	0.95	320	7.157	10	0.0
	C40-10-1#2	4.6	110	1523.8	9507.	220	2	48	1.11	320	7.856	10	0.0
	C40-10-3#1	4.7	110	1555.4	9507.	220	2	48	1	320	8.097	10	0.07
	C40-10-3#2	4.7	110	1555.4	9507.	220	2	48	1.14	320	8.7	10	0.07
	C50-6-0#1	3.3	110	1106.6	9507.	220	2	48	1.09	320	4.69	10	0.0
	C50-6-0#2	3.1	110	1041.5	9507.	220	2	48	1.2	320	4.761	10	0.0
	C50-6-1#1	3.1	110	1041.5	9507.	220	2	48	1.06	320	3.926	10	0.03
	C50-6-1#2	3.1	110	1041.5	9507.	220	2	48	1.2	320	4.289	10	0.0
	C50-6-3#1	3.1	110	1041.5	9507.	220	2	48	1.08	320	4.198	10	0.03
	C50-6-3#2	3	110	1008.	9507.	220	2	48	1.13	320	4.05	10	0.03
	C50-10-0#1	4.5	110	1492.1	9507.	220	2	48	1.05	320	6.55	10	0.05
	C50-10-0#2	4.5	110	1492.1	9507.	220	2	48	1.17	320	7.102	10	0.0
	C50-10-1#1	4.8	110	1587	9507.	220	2	48	1.01	320	6.284	10	0.05
	C50-10-1#2	4.8	110	1587	9507.	220	2	48	1.02	320	6.867	10	0.0
	C50-10-3#1	4.5	110	1492.1	9507.	220	2	48	1.03	320	6.262	10	0.05
	C50-10-3#2	4.5	110	1492.1	9507.	220	2	48	1.02	320	6.262	10	0.05
Abdulla(2020)structures[21]	A-0-1	3.9	110	1300.5	9507.	220	2	41	1.34	400	11.31	11.31	0.0
	A-0-2	3.9	110	1300.5	9507.	220	2	41	1.3	400	10.56	10.56	0.0
	A-0-3	3.9	110	1300.5	9507.	220	2	41	1.29	400	10.31	10.31	0.0
	A-1-1	3.9	110	1300.5	9507.	220	2	41	1.21	400	8.722	10	0.07
	A-1-2	3.9	110	1300.5	9507.	220	2	41	1.22	400	8.926	10	0.07
	A-1-3	3.9	110	1300.5	9507.	220	2	41	1.19	400	8.527	10	0.07
	B-1-1	3.9	110	1300.5	9507.	220	2	41	1.16	400	7.828	10	0.0
	B-1-2	3.9	110	1300.5	9507.	220	2	41	1.15	400	7.594	10	0.0
	B-1-3	3.9	110	1300.5	9507.	220	2	41	1.14	400	7.428	10	0.0
	C-1-1	3.9	110	1300.5	9507.	220	2	41	1.13	400	7.269	10	0.0
	C-1-2	3.9	110	1300.5	9507.	220	2	41	1.11	400	6.891	10	0.0
	C-1-3	3.9	110	1300.5	9507.	220	2	41	1.09	400	6.551	10	0.05
	D-1-1	3.9	110	1300.5	9507.	220	2	41	1.08	400	6.282	10	0.05
	D-1-2	3.9	110	1300.5	9507.	220	2	41	1.09	400	6.495	10	0.05
	D-1-3	3.9	110	1300.5	9507.	220	2	41	1.09	400	6.50	10	0.05
	E-1-1	3.9	110	1300.5	9507.	220	2	41	1.07	400	6.18	10	0.05
	E-1-2	3.9	110	1300.5	9507.	220	2	41	1.07	400	6.09	10	0.05
	E-1-3	3.9	110	1300.5	9507.	220	2	41	1.08	400	6.269	10	0.05
Presentstudy	S1-H1-1	4.1	110	1364.6	9507.	110	1	40	1.32	3950	7.837	10	0.0
	S1-H1-2	4.0	110	1339	9507.	110	1	40	1.33	3950	7.787	10	0.0
	S2-H1-1	6.0	110	1976.5	9507.	110	1	40	1.15	3950	9.353	10	0.0
	S2-H1-2	6.1	110	1998.1	9507.	110	1	40	1.13	3950	9.261	10	0.0
	S3-H2-1	4.2	110	1396.6	9507.	165	1.5	40	1.29	3950	8.417	10	0.07
	S3-H2-2	4	110	1332.6	9507.	165	1.5	40	1.32	3950	8.328	10	0.07
	S4-H2-1	6.1	110	1995	9507.	165	1.5	40	1.11	3950	9.493	10	0.0
	S4-H2-2	6.0	110	1982.7	9507.	165	1.5	40	1.1	3950	9.237	10	0.0
	S5-H3-1	4.0	110	1345.4	9507.	220	2	40	1.29	3950	9.665	10	0.0
	S5-H3-2	4.0	110	1335.8	9507.	220	2	40	1.24	3950	9.799	10	0.0
	S6-H3-1	6.1	110	2010.	9507.	220	2	40	1.05	3950	9.749	10	0.0
	S6-H3-2	6.1	110	1991.9	9507.	220	2	40	1.04	3950	9.777	10	0.0

Fig. (13) Predicted $\varepsilon_{cc}/\varepsilon_{co}$ versus $\varepsilon_{cc}/\varepsilon_{co-Exp}$ using the model: (a) 18; (b) 18 with the limit $10 \leq K_N \leq 20$.

respectively. For the overall database of $\varepsilon_{cc}/\varepsilon_{co}$ values, for K_N values between 10 and 20, the proposed model 16 with AAE and RMSE values of 32.38% and 1.5, was better than the predictions by model 12 for the strain of FRP-confined concrete [10] with AAE and RMSE values of 40.55% and 1.6, respectively. The proposed model 16 can estimate maximum axial strain values with accuracy similar to the accuracy produced by model 12 or better for K_N values between 10 and 20. The proposed model yielded the best predictions on the overall database, with an average absolute error of 32% compared with 35.67% for model 12 [10].

6. CONCLUSIONS

A normalized confinement stiffness procedure used to develop models to evaluate the axial strain of PTCI specimens tested in the present work and those tested in very recent studies. The following conclusions can be drawn:

- 1- The available few strain models for PTCI specimens are based on a limited number of experimental data.
- 2- Using a normalized confinement stiffness procedure, three models proposed to determine the axial strain of PTCI specimens tested in the present work and those tested in very recent studies based on a comprehensive database of experimental test results.
- 3- The computed average absolute error of 31.7% for the proposed model 16 was similar to that of model 12 for predicting FRP-confined concrete's strain, with AAE of 30.8%.
- 4- For the overall database of $\varepsilon_{cc}/\varepsilon_{co}$ values, for K_N values between 10 and 20, the proposed model 16 with AAE and RMSE values of 32.38% and 1.5 was better than model 12 AAE and RMSE values of 40.55% and 1.6, respectively.
- 5- For the overall database, the proposed model yielded the best predictions with an average absolute error of 32% compared with 35.67% for model 12, for the strain of FRP-confined concrete.

Engineering plastic is a new class of construction materials that can be used in infrastructure applications such as piers and bridge columns. Its several advantages include reducing the brittleness of concrete and providing additional shear and compressive capacity. With proper design methodologies, PTCI specimens can be used for structural applications with economic and technical advantages. There is no available design guideline for uPVC tube confined concrete columns. More research is needed to narrow the gap between recent research and the use of PTCI in practice.

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Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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