FINITE ELEMENT MODELLING OF AXIAL COMPRESSION OF CONCRETE FILLED PLASTIC TUBES

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Abstract: In coastal regions the deterioration of concrete and corrosion of steel are the main causes for the failure of structures. Furthermore, due to the corrosion in the reinforcement loses its strength and turns ineffective. It is, therefore, concluded that concrete and reinforcement should be used in such a way that both should not remain in contact with the sea water. This can be done by providing an outer safety layer of such a material which has resistance against sea water and marine environment. Plastic tubes filled with concrete can be used as a structural element against marine environment with required durability. In the present study, a finite element model using ANSYS software was developed to study the behavior of concrete filled plastic tube. The results are verified against the experimental data of Wang Junyan and Yang Quanbing [10]. High density polyethylene pipes (HDPE) with nominal pressure of 0.6, 1.0 and 1.6 MPa of diameter 110 mm and length 220 mm were taken. The concrete filled HDPE tubes (CFHT) were subjected to axial compression to investigate their load compression behavior. Two empirical relationships on the basis of FEA are proposed, one between confining pressure ($f_l$) and outer diameter to thickness (D/t) and second between material degradation parameter ($k_3$) and D/t. It is shown that confining pressure ($f_l$) and material degradation parameter ($k_3$) increases as the (D/t) ratio decreases. It is also found that confining pressure is dependent upon the compressive strength of filled concrete.

Key words: high density polyethylene (HDPE) tubes, concrete filled HDPE tube (CFHT), confinement, finite element analysis (FEA).

1. Introduction

Plastics have exceptional properties, which make these materials attractive for different structural applications. Some of these properties include high resistance to severe environmental attacks, electromagnetic transparency and high strength to weight ratio. Therefore, plastic pipes can be used for construction of piles, overhead sign structures, light poles and bridge piers. There are two types of plastics: thermoplastic and thermosetting polymers. Thermoplastic polymers like HDPE / Poly Vinyl Chloride (PVC) are polymers used in the construction industries. This provides some main attributes that make it useful in the construction of certain structures exposed to corrosive environments. HDPE / PVC tubes are characterized by having light weight, which permits easy handling. They are impermeable to gases and fluids. Their service life goes beyond fifty years. Very few authors have studied the behavior of concrete filled plastic tubular columns.

Kurt C.E. conducted a theoretical analysis to study the interaction between the concrete core and plastic tube [5]. This analysis indicates that the effective pressure on the boundary between concrete core and pipe is proportional to the Poisson’s ratio of concrete and inversely proportional to the ratio of the modulus of elasticity of concrete and plastic. He also conducted experiments to see increase in strength of concrete core due to confinement and slenderness ratio in view of the ultimate strength of composite columns. Marzouck M. and Sennah K. conducted experimental study on concrete filled PVC tubes with 100 mm concrete core and 3 mm thickness.
of tube [7]. The lengths of tubes were 758, 562, 416 and 270 mm. They concluded that the PVC tube provides considerable lateral confinement to the concrete columns. They reported that as the slenderness ratio increases, the compressive strength of concrete filled PVC tube decreases. They found that tube exhibits large lateral deformation before failure. Wang Junyan and Yang Quanbing presented the experimental study on plastic pipe confined concrete (PPC) [10]. The plastic pipes were taken as HDPE pipes. They reported that the thickness and unconfined compressive strength of concrete affect the post-peak behavior of stress-strain curve and the ultimate strength of PPC. They also reported that the ductility ratio of PPC increases from 1.17 to 4.27 times that of common concrete (CC) and energy absorption of PPC increases from 10.7 to 26 times that of CC. Gupta P.K. with a research group tested twelve specimens of unplasticised poly vinyl chloride (UPVC) tubes filled with steel fiber concrete [2]. They showed the effect of diameter to thickness ratio and length to diameter ratio on the strength, confinement and ductility. They also concluded that the maximum displacement till complete failure of concrete core was around 4.5 mm while concrete filled UPVC tubes were not completely failed till 11 mm of compression.

Husan-Teh Hu with a research group carried out a nonlinear finite element analysis (FEA) of concrete filled steel tubular (CFT) columns with circular section, square section and square section stiffened by reinforcing ties to study and analyze the behavior of CFT [4]. They reported that for circular tubes having smaller values of D/t (say D/t < 40) provides a greater confinement. They proposed an empirical relationship on the basis of FEA between confining pressure and D/t values for the two ranges of D/t values. The two ranges of D/t values were 21.7 to 47 and 47 to 150. On the basis of these equations, it is clear that as D/t increases, the confining pressure decreases.

From the literature review it can be concluded that only few researchers have studied the behavior of concrete filled plastic tubes as structural element. Study on the behavior of CFHT under axial compression can be performed with the help of computer modeling. In this paper a systematic computational study using Finite Element Analysis (FEA) has been conducted. With the help of this study it has been shown that the value of f₁ depends on D/t of tube and concrete compressive strength while post peak variation of load-compression curve depends on D/t ratio of HDPE tube.

2. Computer Modelling
2.1. Finite element model

A three dimensional Finite element model was developed using ANSYS software to simulate the concrete filled HDPE tube (CFHT) under axial compression. To model the concrete core, a three dimensional eight node solid element SOLID 65 was used. To model the HDPE tube, eight node solid element SOLID 45 was used. Mesh size was chosen from 6 mm to 10 mm for both HDPE tube and concrete core. Two rigid plates were modeled to simulate rigid cross heads of machine. Load was applied to the specimen through the top loading plate. In the compression test, direct contact exists between the end plates and end surface of the column; therefore a contact available in ANSYS was used to simulate the interaction between rigid plate and column end surface. The contact was defined as a surface to surface contact.

To activate the confinement of concrete core in finite element model, a contact surface pair comprised of the inner surface of the HDPE tube and the outer surface of concrete core was adopted. Flexible behavior in the normal direction was assumed with no penetration allowed between the surfaces. A friction factor of 0.2 was obtained and then adopted to achieve a quick convergence and to obtain accurate result. In finite element model, the lower rigid plate contacting the bottom of column was fixed in all six directions by reference node. The upper rigid plate at the top of the specimen was modeled fixed in five directions and only allowed movement in column axis at reference node. The load was applied as static uniform displacement at upper rig-
id plate through the reference node at the center of rigid plate. Fig. 1 shows a typical finite element model adopted for modeling of CFHT column.

2.2. Material model of HDPE tube

The material behavior of the HDPE tube is similar to PVC-U pipe and it can be simulated by an elastic-perfectly plastic model [11]. The Poisson’s ratio and elastic modulus of HDPE are taken 0.35 and 1000 MPa. Plastic deformation of HDPE tube during compression process is represented by the von Mises criterion. The parameter $F$ is used to define the elastic limit, which is written as:

$$F = \sqrt[3]{\frac{J_2}{2}} = \frac{1}{\sqrt{2}} \sqrt[(3)]{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \sigma_y,$$  

![Movement allowed only in (-y) direction](image), ![Meshed concrete core](image), ![Meshed HDPE hollow section](image)

where $J_2$ is the second stress invariant of the stress deviator tensor; $\sigma_1$, $\sigma_2$ & $\sigma_3$ are the principal stresses; $\sigma_y$ is the yield stress of HDPE pipe material in uniaxial tension. The stress-strain variation of HDPE pipe material is idealized as elastic-perfectly plastic.

2.3. Material model of concrete

The response of concrete is modeled by an elastic-plastic theory with associated flow rule and isotropic hardening rule. The concrete in CFHT column is usually subjected to triaxial compression stresses, the failure of concrete is dominated by compression failure. The Poisson’s ratio of concrete material is taken as 0.2.

Concrete Element SOLID 65
HDPE Element SOLID 45
Three degree of freedom at each node i.e. translation in $X$, $Y$ and $Z$ directions

Fig. 1. Typical Finite Element Model for CFHT Column
2.4. Stress-Strain model for concrete confined by HDPE tube

Fig. 2 shows the uniaxial stress-strain curve for unconfined and confined concrete. The maximum stress of concrete $f_{cc}$ confined by HDPE tube and corresponding strain $\varepsilon_{cc}$ have been proposed by Mander J.B. [6]. The equations are given as:

$$f_{cc} = f_k + k_1 f_i; \quad (2)$$

$$\varepsilon_{cc} = \varepsilon_k (1 + k_2 \frac{f_i}{f_k}); \quad (3)$$

where $f_{ck}$ is the unconfined compressive cylinder strength of concrete; $k_1$ and $k_2$ are the constant, generally taken as 4.1 and 20.5 [8]; $f_i$ is the lateral confining stress induced due to confinement provided by HDPE tube and depends upon $D/t$ and ultimate tensile strength of tube material ($f_u$); the value of $\varepsilon_{ck}$ for confined concrete may be taken as 0.003 as per ACI-318 [1].

The first part of stress-strain curve shown in Fig. 2 defines the linear property of confined concrete and the proportional limit stress can be assumed to be 0.5$f_{cc}$ [3]. The initial Young’s Modulus of the confined concrete as per ACI-318 is given by $E_{cc} = 4700 \sqrt{f_{cc}}$. The Poisson’s ratio may be taken as 0.2.

The second part of the stress-strain curve is the nonlinear portion, starts from the proportional limit stress 0.5$f_{cc}$, ends at the confined strength $f_{cc}$. This part was proposed by Saenz L.P. [9] and is given as:

$$f = \frac{E_{cc} \varepsilon}{1 + (R + R_E - 2) \left(\frac{\varepsilon}{E_{cc}}\right) - (2R - 1) \left(\frac{\varepsilon}{E_{cc}}\right)^2 + R \left(\frac{\varepsilon}{E_{cc}}\right)^3}, \quad (4)$$

where

$$R_E = \frac{E_{cc} E_{cc}}{f_{cc}}, \quad R = \frac{E_{cc}(R - 1)}{(R - 1)^2} - \frac{1}{R_E}, \quad (5)$$

the values of $R_e$ & $R_e = 4$ [4].

The third part of the curve starts from $f_{cc}$ and ends at $f_u = k_3 f_{cc}$ with the corresponding strain $\varepsilon_u = 11 \varepsilon_{cc}$ [3]. The reduction factor $k_3$ depends upon $(D/t)$ values of tube. They approximate values of $f_i$ and $k_3$ are determined by matching the numerical results with experimental results.

![Stress-strain curves for unconfined concrete and concrete confined by HDPE tube](image)

Fig. 2. Stress-strain curves for unconfined concrete and concrete confined by HDPE tube
3. Simulation results of concrete filled HDPE tube

Table 1 shows the geometrical and material properties of CFHT specimens. The geometrical and material properties were taken from the literature [10]. The outer diameter and length of pipes are taken as constant and equals to 110 mm and 220 mm respectively.

The thickness of HDPE pipes varies from 4.61 mm to 10.3 mm. The HDPE pipes which were used in the specimens fall under the category of nominal pressure of 0.6 MPa, 1.0 MPa and 1.6 MPa. Three grades of concrete i.e. C30, C45 and C60 have been used to fill the HDPE pipes to obtain different specimens in the study. The variables which affect the confining pressure ($f_l$) are the grade of concrete, ultimate tensile strength of tube material ($f_u$) and diameter to thickness ratio while the value of D/t affects the material degradation parameter ($k_3$). The results of numerical simulations for concrete filled HDPE tubes are given in Table 2. From finite element analysis, strength of concrete filled HDPE tubes varied from 24.05 MPa to 44.58 MPa. The stress-strain curves are plotted against the experimental data of Wang Junyan and Yang Quanbing in Fig. 3 [10]. The stress-strain variations up to peak stress for all specimens were almost similar and started from zero and increases linearly to achieve peak stress. On the other hand the stress-strain variations for different specimens have different post-peak variation. For specimens having lower thickness HDPE tubes have very sharp declining post-peak behavior. Contrary to that the specimens having higher thickness HDPE tubes showed flat post-peak variation. Fig. 3(j) shows the typical deformed shapes of concrete filled HDPE tubes obtained from experimental study and FE simulation. The deformed shapes obtained from experiment and simulations are quite similar in nature. It can be claimed that the numerical results of stress-strain variations and mode of deformation shown in Fig. 3 are in good agreement with their experimental counterparts.

It can be observed that the value of $f_l$ and $k_3$ decrease with the increase in diameter to thickness ratio (D/t). As a result the value of $f_l$ varies from 1.18 to 3.0 for CFHT when HDPE pipes with nominal pressure 0.6 MPa to 1.6 MPa were filled with C30 grade concrete. On the

### Geometrical and material properties of CFHT specimens

| Specimen | Dimensions (mm) | Ratios | Material Properties (MPa) | Tested by |
|----------|-----------------|--------|---------------------------|-----------|
|          | Outer diameter (D) | Thickness (t) | D/t | L/D | $f_c$ | $f_u$ |         |           |
| PE0.6-C30 | 110 | 4.61 | 220 | 23.86 | 2.0 | 23.38 | 26.0 | Wang and Yang (2010) |
| PE1.0-C30 | 110 | 7.35 | 220 | 14.97 | 2.0 | 23.38 | 26.0 |
| PE1.6-C30 | 110 | 10.3 | 220 | 10.68 | 2.0 | 23.38 | 26.0 |
| PE0.6-C45 | 110 | 4.61 | 220 | 23.86 | 2.0 | 38.86 | 26.0 |
| PE1.0-C45 | 110 | 7.35 | 220 | 14.97 | 2.0 | 38.86 | 26.0 |
| PE1.6-C45 | 110 | 10.3 | 220 | 10.68 | 2.0 | 38.86 | 26.0 |
| PE0.6-C60 | 110 | 4.61 | 220 | 23.86 | 2.0 | 50.18 | 26.0 |
| PE1.0-C60 | 110 | 7.35 | 220 | 14.97 | 2.0 | 50.18 | 26.0 |
| PE1.6-C60 | 110 | 10.3 | 220 | 10.68 | 2.0 | 50.18 | 26.0 |
other hand it varies from 0.6 to 1.5 MPa when higher grade of concrete C45 and C60 were used. The values of confining pressure for higher grade of concrete say C45 & C60 are half of the values for normal grade of concrete C30. The higher grade of concrete loses its strength before getting full confinement. In the present case the degradation parameter (k₃) varies from 0.3 to 0.4 and depends on the value of D/t. From equations (6) and (7), it can be seen that the confining pressure depends on the ultimate strength of HDPE tube, compressive strength of concrete and the value of D/t. From Table 2 it can be seen that error in the results obtained from simulation is within 5%.

Figs 4(a) & 4(b) show the variations of (a) confinement ratio (fᵢ/fₜ) and (b) degradation parameter k₃ with D/t ratio. Using these variations three empirical relations equations (6), (7) and (8) are proposed for getting the values of fᵢ and k₃. These equations can be used for the range of D/t from 10 to 25. The equations (6) to (8) can be used to find load carrying capacity of columns prepared by filling HDPE pipes with concrete having compressive strength between 30 and 60 MPa.

\[
\frac{f_i}{f_u} = 0.0004 \left(\frac{D}{t}\right)^2 - 0.0194 \left(\frac{D}{t}\right) + 0.2758 \quad (10 \leq \frac{D}{t} \leq 25) \text{ for C30 concrete} \quad (6)
\]

\[
\frac{f_i}{f_u} = 0.0002 \left(\frac{D}{t}\right)^2 - 0.0098 \left(\frac{D}{t}\right) + 0.1388 \quad (10 \leq \frac{D}{t} \leq 25) \text{ for C45 & C60 concrete} \quad (7)
\]

For the parameter k₃ another empirical relation may be proposed as follows

\[
k_3 = 0.0005 \left(\frac{D}{t}\right)^2 - 0.0234 \left(\frac{D}{t}\right) + 0.5976 \quad (10 \leq \frac{D}{t} \leq 25) \quad (8)
\]

### Table 2

| Specimen | Ultimate Strength (MPa) | % Error | fᵢ | fᵢ/fᵤ | K₃ |
|----------|-------------------------|---------|----|-------|----|
|          | Experiment | Analysis |        |       |    |
| PE0.6-C30 | 23.009     | 24.05    | 4.52 | 1.18  | 0.0454 | 0.30 |
| PE1.0-C30 | 24.976     | 26.02    | 4.18 | 2.0   | 0.077  | 0.35 |
| PE1.6-C30 | 27.088     | 28.22    | 4.18 | 3.0   | 0.1154 | 0.40 |
| PE0.6-C45 | 28.775     | 30.07    | 4.50 | 0.6   | 0.0231 | 0.30 |
| PE1.0-C45 | 30.002     | 30.90    | 2.99 | 1.0   | 0.0385 | 0.35 |
| PE1.6-C45 | 29.536     | 30.57    | 3.50 | 1.5   | 0.0577 | 0.40 |
| PE0.6-C60 | 42.900     | 44.58    | 3.92 | 0.6   | 0.0231 | 0.30 |
| PE1.0-C60 | 39.004     | 39.66    | 1.68 | 1.0   | 0.0385 | 0.35 |
| PE1.6-C60 | 36.551     | 37.46    | 2.49 | 1.5   | 0.0577 | 0.40 |
Fig. 3. Comparison of experimental and numerical stress-strain curves and deformed shapes.
Conclusion

The paper presents a finite element analysis model to numerically investigate the compression process of concrete filled HDPE pipes subjected to axial compression. The developed FE model is validated by comparing stress-strain variations and associated mode of deformation of different specimens presented in previous research done by Wand and Yang [10]. The following points can be concluded on the basis of results obtained from present study:

1. The developed FEA model is capable to predict the compression process of concrete filled HDPE pipes subjected to axial compression;
2. The confinement contribution increases with decrease of D/t value. The confining pressure is half for higher grade of concrete compared to normal grade of concrete. In the present case the confining pressure varies from 0.6 MPa to 3.0 MPa;
3. The material degradation parameter, k₃ increases with decreasing of D/t value;
4. The enhancement in concrete strength is not significant in concrete filled HDPE pipe subjected to axial compression, but it improves the ductility of filled concrete. Furthermore, the outer HDPE pipe provides a protective layer to the filled concrete against the chemical attack and makes it suitable for marine construction.

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КОНЕЧНО-ЭЛЕМЕНТНОЕ МОДЕЛИРОВАНИЕ ОСЕВОГО СЖАТИЯ ПЛАСТИКОВЫХ ТРУБ, ЗАПОЛНЕННЫХ БЕТОНОМ

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Аннотация: В прибрежных районах основными причинами разрушения конструкций являются износ бетона и коррозия стали. Кроме того, из-за коррозии арматура теряет прочность и становится малоэффективной. Поэтому, можно сделать вывод, что бетон и арматура должны использоваться таким образом, чтобы они не находились в контакте с морской водой. Это может быть сделано путем обеспечения внешнего защитного слоя из такого материала, который имеет устойчивость к морской воде и морской среде. Пластиковые трубы, заполненные бетоном, могут использоваться в качестве структурного элемента, противостоящего морской среде, с требуемой долговечностью. В настоящем исследовании была разработана конечно-элементная модель с использованием программного комплекса ANSYS для изучения поведения пластиковой трубы, заполненной бетоном. Результаты сопоставлены с экспериментальными данными исследований Ю. Вонга и К. Янга [10]. В работе использовались трубы из полиэтилена высокой плотности (HDPE) с номинальным давлением 0.6, 1.0 и 1.6 МПа диаметром 110 мм и длиной 220 мм. HDPE трубы, заполненные бетоном (CFHT), подвергались осевому сжатию для исследования их поведения под воздействием сжимающей нагрузки. Были предложены две эмпирические зависимости на основе конечно-элементного анализа: одна между боковым давлением (f) и отношением наружного диаметра к толщине (D/t), а вторая — между параметром разрушения материала (k) и D/t. Определено, что боковое давление (f) и параметр разрушения материала (k) увеличиваются по мере уменьшения отношения (D/t). Также установлено, что боковое давление зависит от прочности на сжатие бетона.

Ключевые слова: трубы из полиэтилена высокой плотности (HDPE), HDPE трубы, заполненные бетоном (CFHT), ограничение, конечно-элементный анализ (FEA).