

## **UNIAXIAL COMPRESSIVE STRENGTH OF DURABLE HYBRID PIER WITH UHPCC PERMANENT FORM**

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### **Abstract**

A hybrid pier made of Ultra High Performance Cementitious Composites (UHPCC) permanent form is proposed here. Uniaxial compression strength was analyzed theoretically. Circumferential cracking state is controlled and the loading capacity is derived. Ultimate strength of the hybrid pier is also derived theoretically. To verify the theoretical formula, numerical simulations were carried out. Short hybrid columns were tested to verify the numerical model. Comparison results show that the theoretical model predictions agree well with the numerical results and the hybrid effect is significant and cannot be ignored. The minimal wall thickness of UHPCC tube is proposed. Safety coefficients were proposed based on traditional structural design methods.

### **Résumé**

On propose dans cet article un concept de pieu hybride comportant un coffrage perdu en béton fibré à ultra-hautes performances (BFUP). On calcule théoriquement son comportement en compression uni-axiale. La maîtrise de la fissuration circonférentielle conduit à une limite de la capacité portante en service. La capacité portante à l'état limite ultime peut également être calculée. Des simulations numériques permettent de vérifier cette analyse théorique. Des poteaux hybrides courts ont été testés pour valider la modélisation numérique. La comparaison confirme la validité de l'analyse théorique par rapport aux simulations numériques et montre que la participation du coffrage perdu n'est pas négligeable. On propose une épaisseur minimale pour la paroi du tube en BFUP et des coefficients de sécurité issus des approches traditionnelles.

## **1. INTRODUCTION**

The construction of a gravity pier normally requires steel turnover formwork. However, installation and dismantlement of steel turnover formwork consumes significant work-hours.

Traditional steel formwork has a high cost due to materials and haulage. Additionally, in traditional gravity pier construction, concrete surfaces are exposed to the elements immediately after de-moulding. Traditional gravity pier durability properties are lower, especially for railway bridge piers. To address structural durability deterioration due to normal concrete cracking and low durability, Maalej and Li [1] proposed substituting the reinforced steel coat layer of normal concrete by strain hardening Engineered Cementitious Composites (ECC). Based on this design concept, a composites flexural beam with ECC coat layer was tested in their laboratory. To improve existing bridge pier service life, the Railway Transportation Management Centre of China (RTMCC) also proposed the design concept of pier protection plate, which has since been applied to existing railway bridge piers to improve structural durability [2]. However, these design concepts only concentrated on improving existing structural durability. ECC coat layer and pier protection plate has no significant contribution to the composites structural strength. The more reasonable material for high durability composites structure should possess high durability and high strength. Ultra High Performance Cementitious Composite (UHPCC) is proposed here for the advanced high durable hybrid pier design.

UHPCC is a new generation of engineering structural material that will replace normal strength concrete and normal high strength concrete in future designs. Recently, a number of researchers have carried out extensive research and engaged in international communication in the areas of material strain hardening behaviour, constitutive property behaviour of UHPCC [3], strength model [4], UHPCC behaviour under multi-axial compression [5], and interface performance of UHPCC hybrid elements [6, 7]. Some new types of structures employing UHPCC were developed recently, such as Shepherds Creek Bridge in Australia [8], Wapello Bridge in Iowa, USA [9], High Speed Bridge in Japan [10], and the Saint-Pierre-La-Cour hybrid bridge in France [11]. Design of hybrid pier with UHPCC permanent form is proposed by Wu *et al.* [12]. For this new type of hybrid pier, UHPCC permanent form acts as formwork during the bridge pier construction stage, and as protection plate post-construction, and also as a coat layer for the interior reinforced steel. UHPCC permanent form holds some characteristics such as high strength, high durability and light weight. Hence, this new form is named multifunctional permanent formwork.

Uniaxial compressive strength of the UHPCC hybrid pier is studied theoretically in this paper including the ultimate and cracking states. Numerical simulations validated by the short hybrid column test were used to validate the accuracy of the theoretical model and formulas proposed in this paper. Comparisons of the ultimate strength between UHPCC hybrid piers and reinforced NC piers with the same geometrical dimensions show that the loading capacity of the UHPCC hybrid piers is considerably improved and the hybrid effect cannot be ignored. The minimal wall thickness of UHPCC tube is proposed and finally a proposed application of UHPCC hybrid piers is illustrated.

## 2. THEORETICAL ANALYSIS

A UHPCC hybrid pier is composed of a UHPCC circular tube and core reinforced NC element as shown in Figure 1(a). The geometrical parameters relation can be written as

$$R - t = r \quad (1)$$

in which,  $R$  is the radius of the hybrid pier,  $r$  is the radius of the core NC element, and  $t$  is the thickness of UHPCC tube.

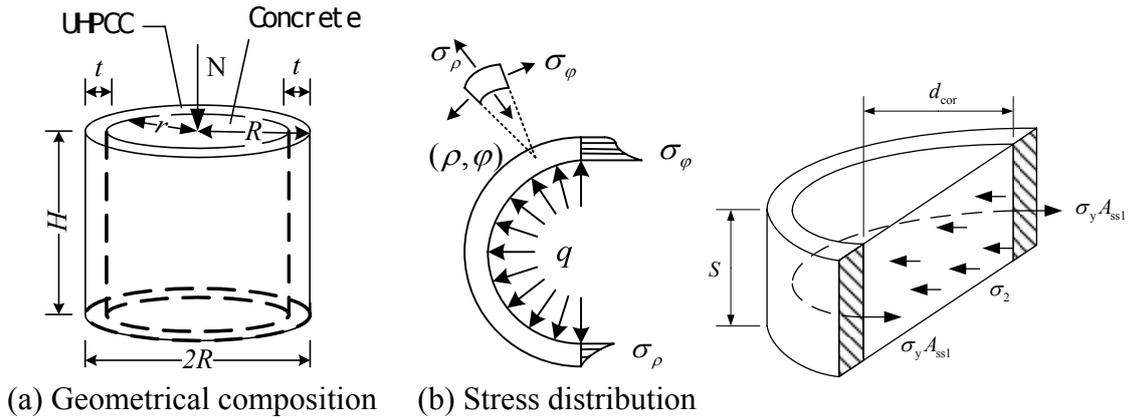


Figure 1: UHPCC hybrid pier and stress distribution

Figure 2 Lateral stress distribution

Because of UHPCC high tensile strength and ductile behaviour, the NC is constrained circumferentially by the UHPCC tube and the core NC element is compressed in three dimensions. Thus, the core NC element loading capacity can be improved. The failure processes of the hybrid piers under uniaxial loading can be divided into three stages: (1) quasi-elastic stage from initial loading to the first cracking, (2) from the first cracking to ultimate state of core NC, and (3) failure stage from ultimate compression of core NC to yielding state of RC. To improve hybrid pier durability, crack development should be controlled. The first cracking state is the key mechanism which should be controlled for high durability design of UHPCC hybrid piers. Based on cracking strength, ultimate strength of UHPCC hybrid pier is also analyzed in this paper.

## 2.1 Cracking strength analysis under uniaxial compression

The following five assumptions are considered in the analysis: (1) axial load is considered a concentrated load and acts on the upper surface; (2) the influences of micro non-uniformity of UHPCC and NC on mechanics behaviour are ignored; (3) radial displacements between core NC and UHPCC tube are compatible with each other and tangential stress at the interface is ignored; (4) the radial strain resulting from gravity and loading can be superposed linearly; and (5) cross section analysis of the pier is considered as plane strain state. A cross section with distance which is far enough from the acting surface will be analyzed as follows. When loading, UHPCC tube is acted on with distributed stress  $q$  by the core NC element as shown in Figure 1(b). From the Lamé solution of elasticity theory, radial stress and circumferential stress at any point  $(\rho, \varphi)$  of UHPCC tube can be written as:

$$\sigma_{\rho} = -q \left( \frac{R^2}{\rho^2} - 1 \right) / \left( \frac{R^2}{r^2} - 1 \right), \quad \sigma_{\varphi} = q \left( \frac{R^2}{\rho^2} + 1 \right) / \left( \frac{R^2}{\rho^2} - 1 \right) \quad (2)$$

in which,  $\rho$  is the radial coordinate  $[r, R]$ ,  $\varphi$  is the circumferential coordinate  $[0, \pi]$ ,  $\sigma_{\rho}$  is the radial stress at coordinate  $\rho$ ,  $\sigma_{\varphi}$  is the circumferential stress at coordinate  $\rho$ , and  $q$  is the compressive stress from the core NC element (absolute value). When  $\rho = r$ , the absolute values of  $\sigma_{\rho}$  and  $\sigma_{\varphi}$  are at maximum. The first cracking state can be expressed as:

$$\sigma_{\varphi}|_{\rho=r} = f_{U_t,1st} = q \left( \frac{R^2}{r^2} + 1 \right) / \left( \frac{R^2}{r^2} - 1 \right) \quad (3)$$

$$\sigma_{\rho}|_{\rho=r} = -q \quad (4)$$

Here,  $f_{U_t,1st}$  is the cracking strength of UHPCC (MPa). From equation (3), the radial stress  $q$  at this state can be written as:

$$q = f_{U_t,1st} \left( \frac{R^2}{r^2} - 1 \right) / \left( \frac{R^2}{r^2} + 1 \right) \quad (5)$$

The corresponding circumferential strain can be written as:

$$\varepsilon_{\varphi} = \frac{1 - \mu_U^2}{E_U} \left( \sigma_{\varphi} - \frac{\mu_U}{1 - \mu_U} \sigma_{\rho} \right) \quad (6)$$

where  $\varepsilon_{\varphi}$  is the circumferential strain at radius  $\rho$ ,  $\mu_U$  is the Poisson's ratio of UHPCC,  $E_U$  is the elastic modulus of UHPCC. By substituting (3 - 5) into (6), equation (6) can be written as:

$$\varepsilon_{\varphi}|_{\rho=r} = \frac{1 - \mu_U^2}{E_U} \left( f_{U_t,1st} + \frac{\mu_U}{1 - \mu_U} \cdot \left( \frac{R^2}{r^2} - 1 \right) / \left( \frac{R^2}{r^2} + 1 \right) f_{U_t,1st} \right) \quad (7)$$

According to the geometrical relation of plane axial symmetrical problem of elasticity theory, the relation between radial displacement and circumferential strain can be expressed as:

$$u_{\rho} = \rho \varepsilon_{\varphi} \quad (8)$$

where  $u_{\rho}$  is the radial displacement at radius  $\rho$ . By substituting (7) into (8), the radial displacement of point  $\rho = r$  at the interface of the UHPCC tube can be obtained as:

$$u_{\rho}|_{\rho=r} = r \cdot \frac{1 - \mu_U^2}{E_U} \left( f_{U_t,1st} + \frac{\mu_U}{1 - \mu_U} \cdot \left( \frac{R^2}{r^2} - 1 \right) / \left( \frac{R^2}{r^2} + 1 \right) f_{U_t,1st} \right) \quad (9)$$

Based on Assumption (4), the radial displacement of the core NC element is also equal to  $u_{\rho}|_{\rho=r}$ . Then, concrete Poisson's ratio can be expressed as:

$$\mu_c = \left| \varepsilon_c' / \varepsilon_c \right| \quad (10)$$

where  $\varepsilon_c'$  is the lateral linear strain of core NC,  $\varepsilon_c$  is the longitudinal linear strain of the core NC element, and  $\mu_c$  is the Poisson's ratio of the NC core. The lateral linear strain of the core NC element can be simplified as:

$$\varepsilon_c' = u_{\rho}|_{\rho=r} / r \quad (11)$$

By substituting (11) into (10), the expression can be written as:

$$\varepsilon_c = \frac{u_{\rho}|_{\rho=r}}{r \mu_c} = \frac{1 - \mu_U^2}{\mu_c E_U} \left( f_{U_t,1st} + \frac{\mu_U}{1 - \mu_U} \cdot \left( \frac{R^2}{r^2} - 1 \right) / \left( \frac{R^2}{r^2} + 1 \right) f_{U_t,1st} \right) \quad (12)$$

Since the thickness of the tube is relatively small, deformation conditions can be assumed as:

$$\varepsilon_s = \varepsilon_U = \varepsilon_c \quad (13)$$

Based on the equilibrium condition:

$$N = \sigma_c A_c + \sigma_s A_s + \sigma_U A_U \quad (14)$$

and three dimension compression results from the NC cylinder, the three stresses conform to:

$$\sigma_1 = \sigma_{c\perp} + 4\sigma_2 \quad (15)$$

in which,  $\sigma_{c\perp}$  is the stress of NC under uni-axial compression.

$$\sigma_{c\perp} = E_c \varepsilon_c \quad (16)$$

Considering the structure reinforced by a stirrup, the stress distribution of the region between stirrups with height  $S$  is shown in Fig. 2. The equilibrium relation can be written as:

$$\sigma_2 S d_{cor} = 2\sigma_y A_{ss1} + 2\sigma_{Ut} S t_U \quad (17)$$

in which  $A_{ss1}$  is the cross section area of the stirrup,  $S$  is the spacing between stirrups,  $d_{cor}$  is the diameter of the stirrup hoop,  $\sigma_{Ut}$  is the circumferential tensile stress of the UHPCC element,  $t_U$  is the thickness of the UHPCC element, and  $\sigma_y$  is the stirrup stress.

$$N_c = \sigma_{c\perp} A_c + 8\sigma_y A_{ss1} A_c / (S d_{cor}) + 8\sigma_{Ut} S t_U A_c / (S d_{cor}) + \sigma'_s A'_s + \sigma_{Uc} A_U \quad (18)$$

Here, stress components  $\sigma_y$ ,  $\sigma_{Ut}$ ,  $\sigma'_s$  and  $\sigma_{Uc}$  are unknown and these unknown components will be determined according to analysis at different stages. When UHPCC cracking occurs, equations (3) and (12) can be obtained. Derivation of (12) is based on the cracking condition of UHPCC in which the hoop of UHPCC element on the core NC element is already considered, i.e. the effects of the UHPCC tube on the core NC are already included in the expression  $\varepsilon_c$ . The effects of UHPCC on the core NC element are not considered again. But effects of the stirrup should be considered.

$$\sigma_2 = 2\sigma_y A_{ss1} / (S d_{cor}) \quad (19)$$

For different  $\varepsilon_c$ , (18) can thus be written as:

$$N_c = \begin{cases} \sigma_{c\perp} A_c + 8E_s \varepsilon_c \left|_{\rho=r} A_{ss1} A_c / (S d_{cor}) + E_y \varepsilon_c A'_s + E_{Uc} \varepsilon_c A_U & \varepsilon_c < \varepsilon_{y0} \\ \sigma_{c\perp} A_c + 8E_s \varepsilon_c \left|_{\rho=r} A_{ss1} A_c / (S d_{cor}) + f_y A'_s + E_{Uc} \varepsilon_c A_U & \varepsilon_{y0} \leq \varepsilon_c < \varepsilon_0 \\ \sigma_c A_c + 8E_s \varepsilon_c \left|_{\rho=r} A_{ss1} A_c / (S d_{cor}) + f_y A'_s + f_{Uc} A_U & \varepsilon_0 \leq \varepsilon_c < \varepsilon_{Ucu} \end{cases} \quad (20)$$

$N_u$  in Formula (20) is the load of cracking of the hybrid pier.

## 2.2 Ultimate strength analysis under axial compression

For appropriate reinforcement of the cross section, the ultimate state can be defined as the state with the yielding of longitudinal and stirrup bars, full cracking of UHPCC ( $\sigma_{Ut} = 0$ ), and compressive failure of the core NC element. Then the ultimate strength of the UHPCC hybrid pier can be obtained by superposition of each component contribution.

$$N_u = f_c A_c + 8f_y A_{ss1} A_c / (S d_{cor}) + f'_y A'_s + f_{Uc} A_U \quad (21)$$

### 3. NUMERICAL SIMULATIONS

To verify the theoretical formula, numerical analysis of the hybrid column is done here. Short hybrid columns are tested here to validate the numerical model. The theoretical results are compared with the numerical results finally.

#### 3.1 Test validation for the numerical model

Mix composition of UHPCC in this test is shown in Table 1. Fine silica sand is substituted by normal sand from the Songhua River in Harbin to reduce the material cost. The steel fibre content is 2%. Precise information of the composite material and mixing technique of UHPCC can be obtained from [12].

Table 1: Mix compositions of UHPCC (kg/m<sup>3</sup>)

Cement	Silica fume	Filling powder	Fine sand	Super-Plast.	Water	Expansive agent	Defoamer	Steel fiber
789.75	197.44	157.95	868.72	31.59	197.44	3.95	3.95	102.41

Four groups of specimens are designed in Harbin Institute of Technology laboratory. Each specimen is named as UN(H)-t with the information of the specimen height(H) and thickness(t). The geometrical dimensions of the hybrid specimens are listed in the Table 2 in which OR, IR, H and t represent the outside radius, inside radius, height and thickness of the UHPCC tube, respectively. The test results of the cracking capacity and ultimate loading capacity are also listed in Table 2. Loading process of the specimen is shown in Photos 1.

Table 2: Test specimen of the short hybrid column

Specimen	OR (mm)	IR (mm)	H (mm)	t (mm)	$N_c$ (kN)	$N_u$ (kN)
UN(400)-15	96	81	400	15	900	1707
UN(400)-32	96	64	400	32	1200	2635
UN(400)-42	96	54	400	42	1500	3200
UN(300)-23	77	54	300	23	990	1401



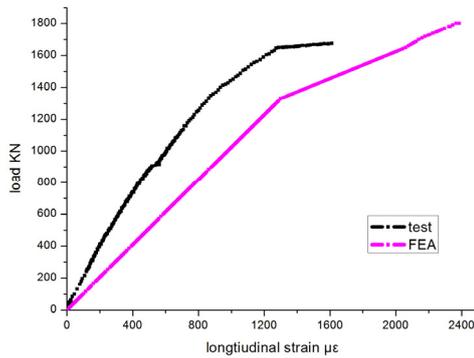
Photos 1: Loading test of UHPCC-NC hybrid column

Smearred cracking models were selected for UHPCC, NC and steel bar. Material parameters for the simulation are listed in Table 3. Element C3D8R was selected for the simulation. Pin-fixed boundary conditions were selected for the interface between UHPCC and NC sections. According to the first cracking strain of UHPCC, the first cracking load can be determined and corresponding loading value can be obtained.

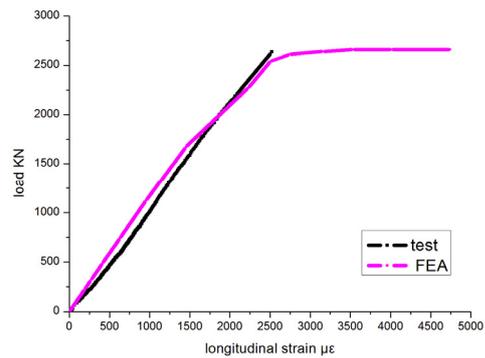
Table 3: Material parameters

Material	Poisson's ratio	E (GPa)	Ultimate compress. strain	Comp. strength (MPa)	Cracking strain	Cracking strength (MPa)	Ultimate tensile strain	Bending strength (MPa)
UHPCC	0.18	50	0.0043	135	0.00016	8.1	0.01	18
NC	0.2	30	0.0036	30	0.00012	1.8	0.00014	
Steel bar	0.3	200					0.01	

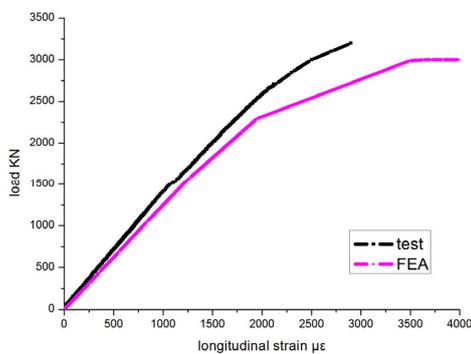
Numerical and test results of the specimens are shown in Figure 3 including the variations of the load with circumferential strain and longitudinal strain. The comparisons indicate that the numerical model results agree well with the test results.



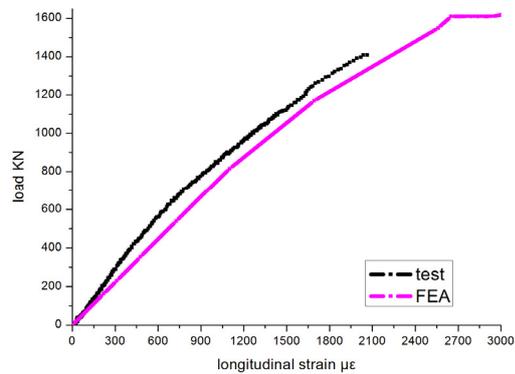
(a) Results of specimen UN(400)-15



(b) Results of specimen UN(400)-32



(c) Results of specimen UN(400)-42



(d) Results of specimen UN(300)-23

Figure 3 Comparisons of the numerical model and test results

### 3.2 Numerical calculations of the large size hybrid pier

Using this finite element model, the hybrid pier structures with length 10 m, diameter 1.5 m and tube thicknesses 20 mm, 30 mm, 40 mm, 50 mm, 100 mm, 150 mm and 200 mm are simulated and analyzed. Smearred cracking models are selected for UHPCC, NC and steel bar. Material parameters for the simulation are listed in Table 4. Element C3D8R is selected for the simulation. One end of the structure is given fixed boundary conditions and the other end is subjected to a concentrated load. The UHPCC tube is divided into one layer elements when tube thickness is less than 20 mm. The UHPCC tube is divided into two layer elements when tube thickness equals 20 mm. Numerical results are listed in Table 4.

Table 4: Results of theoretical and numerical analysis

t (mm)	Cracking strength			Ultimate strength			
	T (kN)	N (kN)	D (%)	T (kN)	N (kN)	D (%)	Improvement percentage (%)
20	17372	19302	10.00	59494	58510	1.68	11.63
30	18358	20413	10.07	62681	61629	1.71	17.58
40	19337	21446	9.83	65823	64825	1.54	23.68
50	20309	22450	9.53	68923	67690	1.82	29.15
100	25072	25392	1.26	83760	82170	1.94	56.77
150	29665	27628	-7.37	97497	95946	1.62	83.06
200	34079	34963	2.53	110136	108350	1.65	106.72

In this table ‘t’ is the UHPCC tube thickness, ‘T’ and ‘N’ represent theoretical prediction and numerical simulation results, respectively, and ‘D’ means the difference between theoretical and numerical results.

### 3.3 Comparisons and analysis of the large size hybrid pier results

Comparisons between theoretical results and numerical results are drawn in Figure 4 and Figure 5 for cracking strength and ultimate strength, respectively. It should be emphasized ahead that the tests validate the model in the 15-50 mm-range. For thicker UHPCC cylindrical elements the model and comparisons clearly are extrapolated, which may require specific care because fiber orientation may be less favorable compared to thin UHPCC tube.

It can be seen from Fig. 4 that the results based on theoretical formula proposed in this paper generally agree well with the numerical simulations. For cracking strength, the differences are 9.5 % and 7.4 % for UHPCC tube with thickness less than 50 mm and equal to 150 mm. When UHPCC tube thickness is 100 mm and 200 mm, the theoretical results agree well with the numerical simulations with differences of only 1.3 % and 2.5 %, respectively. The differences result from the elements selection, since cracks in each UHPCC FEM element may not occur simultaneously. Some elements at the maximum circumferential stress zone may fracture first and arrive at an idealized plasticity deformation region. Other elements will fracture one after another. This is multiple cracking behaviour of UHPCC. In the numerical simulation process, the first cracking element is selected based on the maximum stress zone distribution. Some safety coefficient should be considered for the reliability or conservative consideration of the theoretical formula. According to long-term loading experiments and

existing guidelines for UHPFRC [13], related safety coefficient regarding design margins of the hybrid pier under compression can be proposed.

It can be seen from Figure 5 that the results of the theoretical formula proposed in this paper for the ultimate strength agree very well with the numerical simulations. The average difference is only 1.7 %. Some safety coefficient should also be considered for the reliability or conservative consideration of the theoretical formula.

The ultimate strength of the pier with the same length and cross section made by reinforced NC material is 52.4 MN according to calculation. For the minimal tube thickness of 20 mm, the capacity increase reaches 11.63 %. When UHPCC tube is 50 mm, the ultimate loading capacity is improved to about 29.15 % compared to traditional design. The improvement percentages for other UHPCC hybrid pier compared to reinforced normal concrete pier are listed in the last column in Table 4.

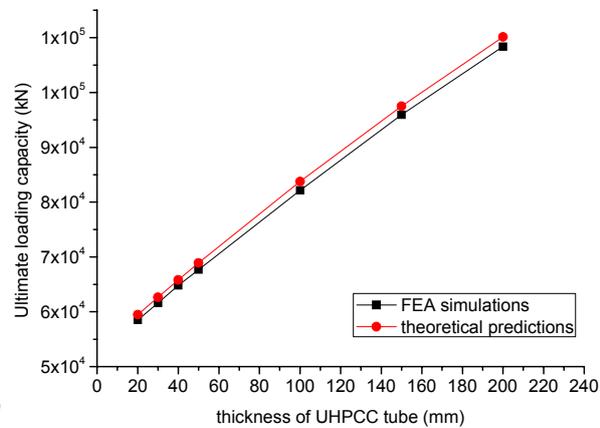
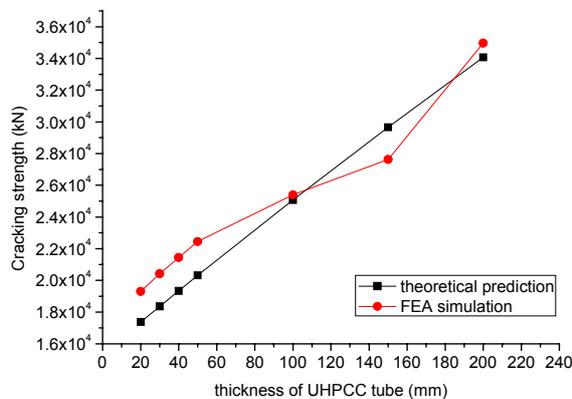


Figure 4: Comparisons of cracking strength      Figure 5 : Comparisons of the ultimate strength

#### 4. CONCLUSIONS

The theoretical formula to predict the ultimate strength of UHPCC hybrid piers was proposed in this paper. Theoretical predictions agree very well with nonlinear numerical simulation results. To ensure the durability of UHPCC hybrid piers, the cracking state is controlled. Theoretical formulas to predict the first circumferential cracking strength were developed. Theoretical results agree generally well with the numerical simulation results.

Comparisons of the ultimate limit loading capacities between UHPCC hybrid piers and reinforced NC piers with the same geometrical dimensions show that the loading capacity of the hybrid pier was improved from 11.63 % to 106.27 % for different tube thicknesses. We propose that the UHPCC tube minimum thickness should be no less than 20 mm, which takes into consideration the coat layer requirement for the inside reinforced bar coat layer. This is a considerable improvement. Based on this superior performance, the structure can be optimized at various loading capacities.

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