University of Wollongong

Research Online

Faculty of Engineering and Information
Sciences - Papers: Part B

Faculty of Engineering and Information
Sciences

2018

Compressive behaviour of partially FRP confined concrete: Experimental observations and assessment of the stress-strain models

Weiqiang Wang

University of Technology Sydney, ww674@uowmail.edu.au

M Neaz Sheikh

University of Wollongong, msheikh@uow.edu.au

Ali Qasim Al-Baali

University of Wollongong, aqlab865@uowmail.edu.au

Muhammad N. S Hadi

University of Wollongong, mhadi@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/eispapers1>

Part of the [Engineering Commons](#), and the [Science and Technology Studies Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Compressive behaviour of partially FRP confined concrete: Experimental observations and assessment of the stress-strain models

Abstract

This study provides new insight on the compressive behaviour of partially fibre reinforced polymer (FRP) confined concrete with either strain-hardening or strain-softening responses. Fully FRP confined concrete, partially FRP confined concrete with different strip gaps, and unconfined concrete were tested under axial compression. Four types of axial load-axial deformation behaviours were observed for specimens with different strip gaps. Even though a high volumetric ratio of FRP was applied, the confinement effectiveness was negligible when the strip gap exceeded the diameter of the specimens. Moreover, the axial stress-axial strain behaviours of wrapped and non-wrapped concrete were observed to be different, and significant strain localization was observed within the non-wrapped region. Based on the experimental observations and an extensive literature review, a confinement effectiveness coefficient was proposed for partially FRP confined concrete. A stress-strain model was then developed by considering the proposed confinement effectiveness coefficient. The developed stress-strain model provided better predictions than other existing stress-strain models.

Keywords

compressive, concrete, behaviour, experimental, observations, assessment, stress-strain, models, partially, frp, confined

Disciplines

Engineering | Science and Technology Studies

Publication Details

Wang, W., Sheikh, M. Neaz., Al-Baali, A. Q. & Hadi, M. N. S. (2018). Compressive behaviour of partially FRP confined concrete: Experimental observations and assessment of the stress-strain models. *Construction and Building Materials*, 192 785-797.

Compressive behaviour of partially FRP confined concrete: Experimental observations and assessment of the stress-strain models

Weiqliang Wang^a, M. Neaz Sheikh^b, Ali Q. Al-Baali^b, Muhammad N. S. Hadi^{b,*}

^a Centre for Built Infrastructure Research, School of Civil and Environmental Engineering,
University of Technology Sydney, NSW 2007, Australia

^b School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW
2522, Australia

* Corresponding author.

Weiqliang.Wang@uts.edu.au (W. Wang); msheikh@uow.edu.au (M.N. Sheikh);
aqlab865@uowmail.edu.au (A.Q. Al-Baali); mhadi@uow.edu.au (M.N.S. Hadi).

Compressive behaviour of partially FRP confined concrete: Experimental observations and assessment of the stress-strain models

Abstract: This study provides new insight on the compressive behaviour of partially fibre reinforced polymer (FRP) confined concrete with either strain-hardening or strain-softening responses. Fully FRP confined concrete, partially FRP confined concrete with different strip gaps, and unconfined concrete were tested under axial compression. Four types of axial load-axial deformation behaviours were observed for specimens with different strip gaps. Even though a high volumetric ratio of FRP was applied, the confinement effectiveness was negligible when the strip gap exceeded the diameter of the specimens. Moreover, the axial stress-axial strain behaviours of wrapped and non-wrapped concrete were observed to be different, and significant strain localization was observed within the non-wrapped region. Based on the experimental observations and an extensive literature review, a confinement effectiveness coefficient was proposed for partially FRP confined concrete. A stress-strain model was then developed by considering the proposed confinement effectiveness coefficient. The developed stress-strain model provided better predictions than other existing stress-strain models.

Keywords: FRP; Partial wrapping; Concrete; Strain localization; Stress-strain model.

1. INTRODUCTION

Due to the advantages of high strength and stiffness to weight ratios as well as superior corrosion resistance, fibre reinforced polymer (FRP) has been extensively used in recent years to improve the compressive, flexural, and shear behaviours of concrete members [1-6]. One popular application of FRP is to provide confinement to concrete columns [7-15]. Both experimental and analytical studies have proven that the FRP confinement can enhance the strength and ductility of concrete under compressive loadings. Several stress-strain models were developed for FRP confined concrete for circular or non-circular sections [1-2, 16-17], which led to an adequate understanding of the compressive behaviour of FRP confined concrete.

Even though many studies were conducted on fully FRP confined concrete, only a small number of studies focused on partially FRP confined concrete [11, 18-22]. Partial FRP wrapping onto concrete columns requires less FRP material and can be applied easier and faster than full FRP wrapping [20]. Also, for existing deficient concrete columns with sparse steel ties, the performance of the columns is expected to be improved by partial FRP wrapping in between the sparse steel ties, since the local buckling of longitudinal steel bars can be effectively constrained [21]. Moreover, partial FRP wrapping onto the deteriorated part of the existing concrete columns can significantly increase the ultimate capacities of the columns without the necessity of wrapping FRP throughout the whole column [23].

Even though partial FRP wrapping has been considered promising in some applications, there is a lack of knowledge on the compressive behaviour of partially FRP confined concrete. Most of the existing studies were mainly focused on the compressive behaviour of partially FRP confined concrete with relatively small FRP strip gaps, in which case a strain-hardening

response is more likely to occur. Only a few studies provided adequate information on partially FRP confined concrete with strain-softening response [11, 20-21]. On the other hand, it is widely accepted that the confinement effectiveness of partially FRP confined concrete is less than that of fully FRP confined concrete [20-21]. Several studies adopted a confinement effectiveness coefficient, k_e , to account for the reduced confinement effect for partially confined concrete [11, 18-21, 24, 25]. Different k_e values were suggested in several studies. The suggested k_e values were obtained mostly based on the regression analysis of test results from steel confined concrete [26-29]. Therefore, direct application of the suggested k_e values may be inappropriate for concrete confined with FRP. Moreover, the mainstream design standards regarding FRP confined concrete do not provide predictions of the ultimate strength and ultimate strain for partially FRP confined concrete [30-32]. The FIB [33] suggested a stress-strain model to predict the performance of partially FRP confined concrete, which was proposed by Spoelstra and Monti in 1999 [34]. Afterwards, a significant amount of research on FRP confinement was carried out in recent years and more accurate stress-strain models were proposed for fully FRP confined concrete [16]. On the other hand, research on stress-strain models for partially FRP confined concrete was limited [11, 20]. Therefore, research investigations for more precise stress-strain models are imperative for partially FRP confined concrete under compressive loading.

This study is concerned with the compressive behaviour of partially FRP confined concrete with either strain-hardening or strain-softening responses. An experimental program was first carried out to investigate the performance of partially FRP confined concrete with varying strip gaps. The axial load-axial deformation behaviour of specimens, axial stress-axial strain behaviours of both wrapped and non-wrapped concrete was investigated. Based on the

experimental investigations and an extensive review of literature, a confinement effectiveness coefficient, k_e , was proposed for partially FRP confined concrete. Afterwards, a stress-strain model was developed by considering the proposed confinement effectiveness coefficient, k_e . A new database was compiled from available literature and employed to assess the existing stress-strain models of partially FRP confined concrete.

2. EXPERIMENTAL PROGRAM

2.1 Design of Experiments

A total of 18 concrete specimens with 100 mm diameter and 200 mm height were cast and tested under axial compression. Fully FRP confined concrete, partially FRP confined concrete with different strip gaps in the middle of the specimens (strip gap $s = 25$ mm, 35 mm, 50 mm, 75 mm, 100 mm, 125 mm, and 150 mm), and unconfined concrete were tested. The detailed FRP wrapping configurations are shown in Fig. 1. It is noted that this partial FRP wrapping configuration was different from a typical implementation of partial FRP wrapping, where discrete or continuous FRP strips were wrapped around the circumference of specimens. However, this partial wrapping configuration was used in Campione et al. [19] and reliable experimental results were obtained. The volumetric ratio (ρ_f) of FRP was identical for both fully and partially FRP confined concrete, which was mainly to investigate the sole influence of strip gap on the confinement effectiveness of partially FRP confined concrete. For fully FRP confined concrete, three layers of carbon fibre reinforced polymer (CFRP) were wrapped with a volumetric ratio of 0.02. A high volumetric ratio of FRP was applied to ensure that the confinement effectiveness can be observed even for specimens with relatively large strip gaps. The CFRP was chosen since it can provide higher confinement than glass fibre reinforced polymer (GFRP) or aramid fibre reinforced polymer (AFRP). Also, to ensure higher

confinement, small specimens (100 mm × 200 mm) were chosen for the experiment. For each wrapping configuration, two identical concrete specimens were tested. Table 1 lists the specimens tested in this study. The specimens have been labelled as: (a) “S” and the number afterwards indicate the gap between the FRP strips; and (b) “I” or “II” indicates the order of the two identical specimens. For example, Specimen “S50-I” refers to the first specimen of partially FRP confined concrete with 50 mm strip gap.

2.2 Specimen Preparation and Material Properties Tests

The CFRP sheet used in this study was supplied by Nanjing Hitech Composites CO., LTD [35]. The original width of CFRP sheet was 100 mm and the thickness was 0.167 mm per layer. In order to obtain the required width of CFRP strip, each CFRP strip was precisely cut from the original CFRP sheet using a pair of scissors. First, the total number of fibre strands in the original width of CFRP sheet was counted (37 fibre strands). Second, the width of each fibre strand was calculated as the total width divided by the total number of fibre strands (2.70 mm per fibre strand). Third, the required number of fibre strands was cut from the CFRP sheet along the fibre direction based on the required width of CFRP strip. The cutting of CFRP strip from the original CFRP sheet was conducted carefully to ensure that the fibre strands along the cutting edge would not get damaged during the cutting. A measuring tape was then used to measure the required length of CFRP strip. It is noted that for specimens with large strip gaps, the required length of CFRP strips was quite large (e.g., 12 layers of CFRP strip was wrapped onto specimens with 150 mm strip gap).

Normal strength concrete with a design compressive strength of 30 MPa was used for casting the specimens. The concrete was supplied by a local concrete provider with a maximum aggregate size of 10 mm. After 28 days of standard curing, the concrete specimens were

142 wrapped with different layers of FRP strips. A mixture of epoxy resin and hardener at a ratio
143 of 5:1 was used as the adhesive. Before the first layer of CFRP strip was wrapped, the adhesive
144 was evenly spread onto the surface of the specimen and then CFRP strip was wrapped onto the
145 surface with the fibres oriented in the hoop direction. After the first layer was wrapped, the
146 adhesive was evenly spread onto the surface of the first layer of CFRP strip and the second
147 layer was continuously wrapped. The remaining layers of CFRP strips were wrapped in an
148 equivalent manner. An overlap of 100 mm was ensured in the last layer of CFRP strips.

149
150 Compression tests at 28 days showed that the average compressive strength of the concrete was
151 32 MPa. The tensile properties of CFRP were tested according to ASTM D7565 [36]. Five
152 CFRP coupons with 25 mm width and 250 mm length were prepared and tested. For each
153 coupon, three layers of CFRP were glued together using epoxy resin. The coupons were capped
154 at both ends by aluminium plates. Detailed description of the test can be found in Pham et al.
155 [20]. The average nominal thickness of the coupons was 1.18 mm, and the average tensile
156 strength of CFRP was 1674 MPa with an average ultimate strain of 0.016.

157 158 2.3 Test Setup and Instrumentation

159 To investigate the axial and hoop strain distributions of the FRP strips, strain gauges were
160 attached onto the middle of the FRP strips and evenly distributed away from the overlap zone.
161 The gauge length of the strain gauges was 5 mm. Two pairs of strain gauges were used for each
162 specimen and each pair contained two strain gauges, one was attached in the axial direction
163 and the other one was attached in the hoop direction. For fully FRP wrapped specimens, two
164 pairs of strain gauges were attached onto the mid-height of the specimens with one pair 180°
165 away from the other pair (Fig. 1(a)). While for partially FRP wrapped specimens, one pair of

strain gauges were attached onto the middle of the upper FRP strip and the other pair of strain gauges were attached onto the middle of the bottom FRP strip (Figs. 1(b)-(h)).

The compression tests for all the specimens were conducted using the Denison 5000 kN testing machine. The specimens were capped with high-strength plaster on the top end to ensure uniform loading. Calibration was carried out to ensure that the specimens were placed at the centre of the testing machine. Two LVDTs were used to measure the deformation of the specimens in this study, as shown in Fig. 2. The tests were conducted as deflection controlled with a rate of 0.3 mm/min. The readings of the load, LVDTs, and strain gauges were recorded every second using a data logging system and were subsequently saved into a computer.

3 Experimental Results and Analyses

3.1 Failure Modes

The failure modes of specimens with varying strip gaps are shown in Fig. 3. For fully wrapped specimens as well as partially wrapped specimens with relatively small strip gaps ($s = 25$ mm, and 35 mm), the failures were caused by the rupture of FRP. While for partially wrapped specimens with relatively large strip gaps ($s \geq 50$ mm), the failures were caused by the crushing of concrete within the non-wrapped region. Inclined shear cracks were observed for partially wrapped specimens with 125 mm and 150 mm strip gaps. For partially wrapped specimens, the non-wrapped concrete began to crack and spall off after the unconfined compressive strength was approached. The non-wrapped concrete was continuously crushed, which resulted in a smaller gap between the FRP strips (Fig. 3(c)). It is also noted that for partially wrapped specimens with more than 35 mm strip gaps, the upper part of specimens could be easily removed from the specimens after the test, which indicated extensive concrete crushing within the non-wrapped region. However, the crushing of non-wrapped concrete for partially wrapped

specimens with 25 mm strip gap was not significant and remained almost intact after the failure of the specimens, which indicated sufficient confinement provided by the FRP strips to the non-wrapped concrete.

3.2 Axial Load-Axial Deformation Behaviour of Specimens

Table 2 reports the test results of all specimens, where the peak load P_u , peak stress f_{cc} , corresponding axial deformation Δ_u and axial strain ε_{cc} , as well as the corresponding hoop strain of FRP strips $\varepsilon_{h,frp}$, are presented. Figs. 4 (a) and (b) show the axial load-axial deformation ($P-\Delta$, where P indicates the axial load and Δ indicates the axial deformation) behaviours of all specimens. With the increase of strip gap, the performance of partially FRP confined concrete was significantly decreased. When the strip gap was more than 50 mm, the partially FRP confined concrete experienced a strain-softening response, which indicated insufficient confinement. Furthermore, when the strip gap exceeded the diameter of the specimens ($s = 100$ mm), the confinement effectiveness was negligible, as also can be seen in Figs. 4 and 5. This observation can be validated by the readings of strain gauges at the peak load for specimens with large strip gaps ($s \geq 100$ mm), as shown in Table 2. The axial and hoop strains of FRP strips at peak loads were around 0.2% and 0.04%, respectively, for specimens with 100 mm, 125 mm, and 150 mm strip gaps. As a result, the confinement effect was marginal and could not contribute to the increase in the strength. When the strip gaps were equal to or less than 50 mm, the partially FRP confined concrete experienced a strain-hardening response, and the peak load increased significantly with the decrease of strip gaps. Fully FRP confined concrete obtained the highest peak load, while Specimen “S35-I” obtained the largest axial deformation at peak load.

The axial load-axial deformation behaviours of partially FRP confined concrete can be categorized into four types. For Specimens “S25-I, II”, an initial parabolic ascending branch, followed by a linear second ascending branch until failure, was observed (Type A). For Specimens “S35-I, II”, after the initial parabolic ascending branch, a linear second ascending branch was observed. Afterwards, a smooth descending branch occurred, which was mainly due to the strength degradation of non-wrapped concrete. The descending branch was then followed by a linear third ascending branch until FRP rupture (Type B). One possible interpretation for the linear third ascending branch was that the non-wrapped concrete was seriously crushed and spalled off and hence the upper and bottom parts of the wrapped concrete were closer to each other, as evidenced by Fig. 3 (c). As a result, the confinement effect became more prominent due to the reduced strip gap, thus a strain-hardening response was observed again. For specimens with Types A and B behaviours, the failures were caused by the rupture of FRP strips.

For Specimens “S50-I, II”, the axial load-axial deformation behaviour was similar to that of Specimens “S35-I, II” until reaching the peak load, after which a continuous descending branch until failure was observed (Type C). In this case, the non-wrapped concrete lost all the strength before the FRP strips could take effect again. While for specimens with relatively large strip gaps ($s \geq 75$ mm), a steep descending branch until failure was observed after the initial ascending branch (Type D). Moreover, with the decrease of strip gap, the descending branch became more gradual. The occurrence of strain-softening response indicated that the confinement provided by the FRP strips could not be activated if the strip gap was larger than 75 mm. For specimens with Types C, D behaviours, the failures were caused by the crushing of non-wrapped concrete.

It should be noted that the size of the tested specimens was relatively small compared to the sizes of real columns. Although the size effect on FRP confined concrete was found insignificant in several previous studies [37-39], Jamatia and Deb [40] reported the existence of size effect on the behaviour of FRP confined concrete under axial compression. Hence, the experimental results presented in this study should be translated with caution for large-size FRP confined concrete columns. Moreover, the slenderness ratio of the specimens was 2 and the specimens were categorized as short columns. As a result, the influence of the slenderness ratio was not reflected in the test results.

3.3 Axial Stress-Axial Strain Behaviour of Wrapped and Non-Wrapped Concrete

The axial load-strain relationships for specimens with varying strip gaps ($s = 0$ mm, 25 mm, 35 mm, 50 mm, 75 mm, and 100 mm) are shown in Fig. 6. The strain distributions for specimens with more than 100 mm strip gaps were not shown in Fig. 6, as the strain distributions of those specimens ($s > 100$ mm) were very similar to those of unconfined concrete. Moreover, only one pair of strain gauge readings were shown in Fig. 6, since some strain gauges were damaged during the test. All the strain gauges were attached onto the middle of FRP strips to investigate the strain distributions within the wrapped region.

Except for specimens with Type A behaviour ($s = 0$ mm, and 25 mm), unloading occurred within the wrapped region for specimens with Types B, C, and D behaviours ($s = 35$ mm, 50 mm, 75 mm, and 100 mm). The slope for the unloading path was almost equal to the slope of the initial ascending curve, which indicated a linear unloading path. With the increase of strip gaps, both the axial and hoop strains within the wrapped region were significantly decreased, thus less amount of confinement could be provided by FRP strips. For specimens with Types A, B, and C behaviours ($s = 0$ mm, 25 mm, 35 mm, and 50 mm), the axial and hoop strains of

FRP strips continued to increase beyond the unconfined compressive strength, indicating that sufficient confinement was provided for a strain-hardening response. In addition, the wrapped concrete was reloaded for specimens with 35 mm strip gap after the unloading (Fig. 6 (c)). For specimens with Type D behaviour ($s = 75$ mm, 100 mm), the axial and hoop strains within the wrapped region were slightly increased or continuously decreased after the peak load (Figs. 6 (e) and (f)). Therefore, the confinement was insufficient to sustain a strain-hardening response.

The average axial strain of the specimen was continuously increased during the test (deflection controlled). Therefore, if decrease of axial strain due to unloading was observed within the wrapped region, the axial strain within the non-wrapped region must continue to increase so that the average axial strain of the specimen can experience an overall increase. Based on the above observations, the axial stress-axial strain behaviour of partially FRP confined concrete (both wrapped and non-wrapped concrete) can be divided into four distinct categories based on the types of axial load-axial deformation behaviours. For specimens with Type A axial load-axial deformation behaviour, the axial stress-axial strain curve represented a typical stress-strain curve which was similar to that of fully FRP confined concrete with strain-hardening response (Fig. 7 (a)). For specimens with Type B axial load-axial deformation behaviour, the wrapped concrete experienced an unloading and then reloading. The non-wrapped concrete experienced a continuous decrease in the stress (Fig. 7 (b)). Moreover, due to the strip gap reduction as mentioned above, the confinement effect was higher and thus a higher peak stress was obtained for the specimen. For specimens with Types C and D axial load-axial deformation behaviours, the wrapped concrete was unloaded while the non-wrapped concrete experienced a continuous strain softening after the peak stress. In these cases, the axial strains within the wrapped region and non-wrapped region began to vary significantly after the peak stress (Figs. 7 (c) and (d)).

290 With the increase of FRP strip gaps, the axial stress-axial strain curves changed from Type A
291 to D behaviours. Moreover, it was apparent that significant strain localization occurred within
292 the non-wrapped region for specimens with Types B to D behaviours. Due to the lack of
293 sufficient data, the possibility of strain localization for specimens with Type A behaviour was
294 not verified. However, it is believed that strain localization also occurred for specimens with
295 Type A behaviour. This can be qualitatively described by the fact that after the unconfined
296 concrete strength was reached, non-wrapped concrete began to crack and spall off; therefore,
297 the effective cross section area of non-wrapped concrete was decreased. On the other hand, the
298 applied load was equal throughout the height of the specimen due to the force equilibrium. As
299 a result, the axial stress of the non-wrapped concrete (σ_2) was higher than that of wrapped
300 concrete (σ_1), as shown in Fig. 7 (a). The difference continued to increase since more and more
301 non-wrapped concrete spalled off. Thus, a smaller cross-sectional area remained. With the
302 assumption of the same stress-strain path as shown in Fig. 7 (a), the axial strain of non-wrapped
303 concrete was higher than that of wrapped concrete. Therefore, stress localization occurred
304 within non-wrapped region for all types of partially FRP confined concrete.

305

306 **4 Discussions on Confinement Effectiveness**

307 Many studies adopted a confinement effectiveness coefficient, k_e , to account for the reduced
308 confinement effect for partially confined concrete. The confinement effectiveness coefficient
309 was found to be different in different studies and was obtained mostly based on the regression
310 analysis of test results from steel confined concrete [26-27, 41-44]. Iyengar et al. [41] studied
311 the stress-strain behaviour of normal strength concrete confined with steel spirals. The
312 confinement was found to be effective only when the pitch of spirals was less than the diameter

of the confined concrete. Afterwards, Martinez et al. [42] stated that the conclusion was also applicable for high strength concrete confined with steel spirals. A confinement effectiveness coefficient $(1 - s/d)$ was suggested, in which s indicates the vertical spacing between neighbouring steel spirals, and d indicates the diameter of confined concrete [42]. By using this coefficient, a linear relationship exists between the strength increase and spacing to diameter ratio (s/d) . Nevertheless, several studies revealed that the strength increase is not proportional to the s/d ratio for both actively and passively confined concrete [43-44]. As a result, inaccurate predictions could be obtained by using this confinement effectiveness coefficient. Ahmad and Shah [26] later investigated the influence of vertical steel hoop spacing on the stress-strain behaviour of concrete. It was observed that the confinement was negligible when the vertical spacing exceeded 1.25 times the diameter of the confined concrete, and a confinement effectiveness coefficient $(1 - \sqrt{s/1.25d})$ was suggested.

Sheikh and Uzumeri [27] assumed that the reduced confinement effect between neighbouring transverse reinforcement can be considered through the arching action assumption: a parabola is assumed to separate the effectively confined concrete and ineffectively confined concrete, as shown in Fig. 8. The ineffectively confined concrete is assumed to receive no confinement, while the effectively confined concrete is assumed to be uniformly confined. Based on this assumption, a confinement effectiveness coefficient $(1 - s \cdot \tan \theta / 2d)^2$ was suggested for concrete confined by steel hoops. The arching angle θ was considered to be 45° , which was developed by the regression analysis of the experimental results. It is clear that the variation of arching angle θ can significantly influence the confinement effectiveness coefficient, especially for concrete confined with sparse transverse reinforcement [45]. Moreover, in addition to the arching angle θ , the three other parameters $(\alpha, \gamma$ and $\beta)$ were also proposed in the regression

analysis. Even though good prediction results could be obtained, the accuracy of this confinement effectiveness coefficient cannot be fully verified, since the close prediction may be achieved because of counteracting errors in the four different parameters [45]. By using this confinement effectiveness coefficient, the confinement could be neglected when the vertical spacing of transverse reinforcement is more than two times the diameter of confined concrete [43].

Few analytical studies also focused on the influence of spacing to diameter ratio (s/d) on the confinement effectiveness of concrete columns [43-44, 46-48]. An elastic analytical solution was developed by Chen and Mau [46] for circular concrete columns with transverse reinforcement. The confinement effectiveness is quantified as a function of spacing to radius ratio (s/r , in which r indicates radius of confined concrete). The confinement effectiveness is virtually negligible when the vertical spacing between neighbouring transverse reinforcement is as large as the diameter of the confined concrete. Elastoplastic analysis was later carried out by Eid and Dancygier [43] to investigate the confinement effectiveness of circular columns with transverse reinforcement. It was reported that the confinement effectiveness can be observed only if the vertical spacing between neighbouring transverse reinforcement is less than the diameter of the confined concrete. Also, the comparisons between the analytical and experimental results indicate that the empirical arch assumption is limited to the practical range of vertical spacing between neighbouring transverse reinforcement on which it is based [43].

Based on the experimental observations as well as the review of existing literature, it is suggested that the widely used empirical arch assumption can also be adopted for partially FRP confined concrete [29, 43]. However, a confinement effectiveness coefficient needs to be

proposed to represent the behaviour of passively/FRP confined concrete [43-44, 47-48]. In this study, a confinement effectiveness coefficient $(1-s/d)^2$ is suggested for partially FRP confined concrete. The confinement effectiveness can only be observed when the spacing is less than the diameter of the confined concrete ($s < d$), while the confinement effect would be negligible when the spacing is not less than the diameter of the confined concrete ($s \geq d$), which conforms with previous experimental results (as proved in Figs. 4 and 5) and analytical investigations [47-48].

5 Proposed Stress-Strain Model

The proposed stress-strain model is an extension of Lam and Teng model [1] with the introduction of the suggested confinement effectiveness coefficient $(1-s/d)^2$. Lam and Teng [1] model is one of the widely used models for the prediction of the ultimate capacity of FRP confined concrete and has been extended for square and rectangular FRP confined concrete [2, 16]. The ACI 440.2R-08 [30] has adopted Lam and Teng [1-2] models for the prediction of the ultimate capacities of circular and noncircular FRP confined concrete. Based on the Lam and Teng [1] model, the following equation is proposed to calculate the ultimate strength of partially FRP confined concrete:

$$\frac{f_{cc}}{f_{co}} = 1 + 3.3k_f \frac{f_{l,a}}{f_{co}} \quad (1)$$

$$f_{l,a} = \frac{1}{2} \rho_f E_f \varepsilon_{h,rup} \quad (2)$$

where f_{cc} is the ultimate compressive strength of confined concrete; f_{co} is the unconfined compressive strength of concrete; k_f is the confinement effectiveness coefficient, which can be expressed as $(1-s/d)^2$ for partially FRP confined concrete; $f_{l,a}$ is the actual lateral

381 confining pressure; ρ_f is the volumetric ratio of FRP; E_f is the elastic modulus of FRP; and
 382 $\varepsilon_{h,rupt}$ is the actual hoop rupture strain of FRP.

383 The ultimate strain model in Lam and Teng [1] is also extended to partially FRP confined
 384 concrete by introducing the proposed confinement effectiveness coefficient k_e :

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1.75 + 12k_e \left(\frac{f_{l,a}}{f_{co}} \right) \left(\frac{\varepsilon_{h,rupt}}{\varepsilon_{co}} \right)^{0.45} \quad (3)$$

385 where ε_{cc} is the ultimate compressive strain of confined concrete; and ε_{co} is the unconfined
 386 compressive strain of concrete.

387

388 **6 Assessment of Stress-strain Models**

389 **6.1 Experimental Database**

390 A database containing test results of 76 partially FRP confined concrete was compiled (Table
 391 3). It is noted that for the short specimens tested in this study, the wrapping scheme was
 392 different from the typical wrapping scheme. Moreover, the test results may be influenced by
 393 the end constraints. Therefore, the current test data were not used in developing and assessing
 394 the stress-strain models in the subsequent section. In this database, the concrete and FRP
 395 properties, amount of FRP, FRP strip gap, FRP strip width, peak axial stress, and corresponding
 396 axial strain were included. The diameter of the specimens varied from 100 to 200 mm. The
 397 unconfined concrete strengths varied from 23 to 54 MPa. All specimens were not internally
 398 reinforced. Types of FRP included CFRP, GFRP and Basalt Fibre Reinforced Polymer (BFRP),
 399 while 67 specimens were confined with CFRP. In all cases, the FRP was wrapped onto the
 400 specimens with the fibres in the hoop direction. During these tests, 62 specimens experienced
 401 strain-hardening response, while 14 specimens experienced strain-softening response.

6.2 FRP Hoop Rupture Strain

Fig. 9 shows the relationship between the strain efficiency factor ($\varepsilon_{h,rupt} / \varepsilon_{frp}$) and the actual confinement ratio ($k_f \cdot f_{l,a} / f_{co}$). A large scatter of the data was observed. The average strain efficiency factor was calculated to be 0.594, which was close to the strain efficiency factor of 0.55 that was suggested by ACI 440.2R-08 [30]. Moreover, for lightly partially FRP confined concrete, premature hoop rupture is more likely to occur with much lower hoop strains than the nominal ultimate tensile strain. For example, the three specimens with less amount of FRP confinement failed with a maximum strain efficiency factor of 0.34 only.

6.3 Statistical Methods of Verification

The performance of the proposed stress-strain model was compared with the existing models listed in Table 4. As for the model proposed by Barros and Ferreira [11], only unconfined concrete strength within 16 MPa to 32 MPa can be evaluated. Therefore, Barros and Ferreira [11] model was evaluated by using the available test results (16-32 MPa) of the database. The accuracy was evaluated by using two statistical indicators: average absolute error (AAE) and mean square error (MSE). The AAE and MSE indicators are determined by Equations (4) and (5), respectively:

$$AAE = \frac{\sum_{i=1}^N \left| \frac{pre_i - exp_i}{exp_i} \right|}{N} \quad (4)$$

$$MSE = \frac{\sum_{i=1}^N \left(\frac{pre_i - exp_i}{exp_i} \right)^2}{N} \quad (5)$$

A total of 62 data points were plotted to assess the performance of existing strength models and the proposed strength model. Fig. 10 shows the comparisons between these selected strength models. Based on the two statistical indicators, the proposed strength model provides

the best ultimate strength prediction, followed by the models of Pham et al. [20] and FIB [33]. It can also be seen that un-conservative predictions are obtained by using other existing models, while a conservative prediction is obtained by using the proposed model. Based on the comparison results, it is evident that the Lam and Teng [1] model can be successfully extended to provide accurate ultimate strength predictions for partially FRP confined concrete, when appropriate confinement effectiveness coefficient is included.

Fig. 11 shows the comparisons between different ultimate strain models. In general, the prediction accuracy on the ultimate strain is significantly lower than the prediction accuracy on the ultimate strength. The proposed ultimate strain model provides the best ultimate strain prediction, followed by the FIB [33] model and Barros and Ferreira [11] model. Even though reasonable accuracy can be obtained by using FIB [33] model, it may not be appropriate to use this model for ultimate strain prediction, since the effective hoop rupture strain was not taken into consideration in the model, as shown in Table 4. Moreover, the existing ultimate strain models failed to capture the unique characteristic of partially FRP confined concrete, that is, strain localization within the non-wrapped regions. It is recommended that a more accurate ultimate strain model be proposed to account for the non-uniform strain distribution along the height of the partially FRP confined concrete.

7 Conclusions

Based on the experimental and analytical investigations presented in this study, the following conclusions can be drawn:

1. The failure modes of partially FRP confined concrete differ with different strip gaps. For specimens with relatively small strip gaps, the failures are caused by the rupture of FRP strips.

For specimens with relatively large strip gaps, the failures are caused by the crushing of non-wrapped concrete.

2. The performance of partially FRP confined concrete significantly decreases with the increase of the strip gap. When the strip gap exceeds the diameter of the specimens, the confinement effectiveness becomes negligible even though a high FRP volumetric ratio is applied.

3. Based on the value of the FRP strip gap, the axial load-axial deformation behaviours of partially FRP confined concrete can be categorized into four different types. Moreover, the axial stress-axial strain behaviours of wrapped and non-wrapped concrete are different. Stress unloading occurs within the wrapped region for specimens with relatively large strip gaps, and significant strain localization can be observed within the non-wrapped region.

4. A confinement effectiveness coefficient is proposed based on the experimental observations and an extensive literature review. Afterwards, a stress-strain model is developed by considering the proposed confinement effectiveness coefficient into the widely used Lam and Teng [1] model. The developed stress-strain model has been found to provide better predictions than other existing models.

References

[1] Lam, L., and Teng, J. G. Design-oriented stress-strain model for FRP-confined concrete. *Construction and Building Materials* 2003; 17(6–7): 471–489.

[2] Lam, L., and Teng, J. G. Design-oriented stress-strain model for FRP-confined concrete in rectangular columns. *Journal of Reinforced Plastics and Composites* 2003; 22(13): 1149-1186.

[3] Hawileh, R. A., Nawaz, W., Abdalla, J. A., and Saqan, E. I. Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams. *Composite Structures* 2015; 122: 468-476.

- 468 [4] Nawaz, W., Hawileh, R. A., Saqan, E. I., and Abdalla, J. A. Effect of longitudinal carbon
469 fiber-reinforced polymer plates on shear strength of reinforced concrete beams. *ACI Structural*
470 *Journal* 2016; 113(3): 577-586.
- 471 [5] Meyer, M. R., Friedman, R. J., Del Schutte, H., Jr., and Latour, R. A., Jr. Long-term
472 durability of the interface in FRP composites after exposure to simulated physiologic saline
473 environments. *Journal of Biomedical Materials Research* 1994; 28(10): 1221-1231.
- 474 [6] Hawileh, R. A., Rasheed, H. A., Abdalla, J. A., and Al-Tamimi, A. K. Behavior of
475 reinforced concrete beams strengthened with externally bonded hybrid fiber reinforced
476 polymer systems. *Materials & Design* 2014; 53: 972-982.
- 477 [7] Shahawy, M., Mirmiran, A. and Beitelman, T. Tests and modeling of carbon-wrapped
478 concrete columns. *Composites Part B: Engineering* 2000; 31(6): 471-480.
- 479 [8] Wang, W., Sheikh, M. N., Hadi, M. N. S., Gao, D., and Chen, G. Behaviour of concrete-
480 encased concrete-filled FRP tube (CCFT) columns under axial compression. *Engineering*
481 *Structures* 2017; 147: 256-268.
- 482 [9] Wang, W., Sheikh, M. N., and Hadi, M. N. S. Experimental study on FRP tube reinforced
483 concrete columns under different loading conditions. *Journal of Composites for Construction*
484 2016; 20(5): 04016034.
- 485 [10] Wang, W., Sheikh, M. N., and Hadi, M. N. S. Behaviour of perforated GFRP tubes under
486 axial compression. *Thin-Walled Structures* 2015; 95: 88-100.
- 487 [11] Barros, J., and Ferreira, D. Assessing the efficiency of CFRP discrete confinement systems
488 for concrete cylinders. *Journal of Composites for Construction* 2008; 12(2): 134-148.

489 [12] Wang, W., Martin, P. R., Sheikh, M. N., and Hadi, M. N. S. Eccentrically loaded FRP
 490 confined concrete with different wrapping schemes. *Journal of Composites for Construction*
 491 2018: accepted on 15th June 2018.

492 [13] Wang, W., Wu, C., Liu, Z., and Si, H. Compressive behavior of ultra-high performance
 493 fiber-reinforced concrete (UHPFRC) confined with FRP. *Composite Structures* 2018; 204:
 494 419-437.

495 [14] Hadi, M. N. S., and Widiarsa, I. B. R. Axial and flexural performance of square RC
 496 columns wrapped with CFRP under eccentric loading. *Journal of Composites for Construction*
 497 2012; 16(6): 640–649.

498 [15] Hadi, M. N. S., Wang, W., and Sheikh, M. N. Axial compressive behaviour of GFRP tube
 499 reinforced concrete columns. *Construction and Building Materials* 2015; 81: 198–207.

500 [16] Ozbakkaloglu, T., Lim, J. C., and Vincent, T. FRP-confined concrete in circular sections:
 501 review and assessment of the stress-strain models. *Engineering Structures* 2013; 49: 1068–
 502 1088.

503 [17] Lim, J., and Ozbakkaloglu, T. Confinement model for FRP confined high-strength
 504 concrete. *Journal of Composites for Construction* 2014; 18(4): 04013058-1–04013058-19.

505 [18] Park, T. W., Na, U. J., Chung, L., and Feng, M. Q. Compressive behaviour of concrete
 506 cylinders confined by narrow strips of CFRP with spacing. *Composites Part B: Engineering*
 507 2008; 39(7-8): 1093-1103.

508 [19] Campione, G., La Mendola, L., Monaco, A., Valenza, A., and Fiore, V. Behaviour in
 509 compression of concrete cylinders externally wrapped with basalt fibres. *Composites Part B:*
 510 *Engineering* 2015; 69: 576-586.

- 511 [20] Pham, T. M., Hadi, M. N. S., and Youssef, J. Optimized FRP wrapping schemes for
512 circular concrete columns under axial compression. *Journal of Composites for Construction*
513 2015; 19(6): 04015015, 1-10.
- 514 [21] Triantafyllou, G. G., Rousakis, T. C., and Karabinis, A. I. Axially loaded reinforced
515 concrete columns with a square section partially confined by light GFRP straps. *Journal of*
516 *Composites for Construction* 2015; 19(1): 04014035, 1-15.
- 517 [22] Saljoughian, A., and Mostofinejad, D. Axial-flexural interaction in square RC columns
518 confined by intermittent CFRP wraps. *Composites Part B: Engineering* 2016; 89: 85-95.
- 519 [23] Wei, H., Wu, Z., Guo, X., and Yi, F. Experimental study on partially deteriorated strength
520 concrete columns confined with CFRP. *Engineering Structures* 2009; 31(10): 2495-2505.
- 521 [24] Saadatmanesh, H., Ehsani, M. R., and Li, M. W. Strength and ductility of concrete
522 columns externally reinforced with fibre composite straps. *ACI Structural Journal* 1994; 91(4):
523 434-447.
- 524 [25] Wang, W., Sheikh, M. N., and Hadi, M. N. S. Axial compressive behaviour of concrete
525 confined with polymer grid. *Materials and Structures/Materiaux et Constructions* 2016; 49(9):
526 3893-3908.
- 527 [26] Ahmad, S. H., and Shah, S. P. Stress-strain curves of concrete confined by spiral
528 reinforcement. *ACI Journal Proceedings* 1982; 79(6): 484-490.
- 529 [27] Sheikh, S., and Uzumeri, S. M. Analytical model for concrete confinement in tied columns.
530 *Journal of the Structural Division* 1982; 108(ST12): 2703-2722.
- 531 [28] Mander, J. B., Park, R., and Priestley, M. J. N. Theoretical stress-strain model for confined
532 concrete. *Journal of Structural Engineering* 1988; 114(8): 1804–1826.

533 [29] Teng, J. G., Xiao, Q. G., Yu, T., and Lam, L. Three-dimensional finite element analysis
534 of reinforced concrete columns with FRP and/or steel confinement. *Engineering Structures*
535 2015; 97: 15-28.

536 [30] ACI. Guide for the design and construction of externally bonded FRP systems for
537 strengthening concrete structures. ACI 440.2 R-08 2008; Farmington Hills, MI.

538 [31] GB. Technical code for infrastructure application of FRP composites. GB 50608-10 2010;
539 Beijing, China.

540 [32] TR. Design guidance for strengthening concrete structures using fibre composite materials.
541 TR 55 2012; Concrete Society, Camberley, England.

542 [33] FIB (Fédération internationale du béton). Externally bonded FRP reinforcement for RC
543 structures. *Bulletin* 2001; 14, 138.

544 [34] Spoelstra, M. R., and Monti, G. FRP-confined concrete model, *Journal of Composites for*
545 *Construction* 1999; 3(3): 143-150.

546 [35] Nanjing Hitech Composites Co.,Ltd. CFRP. ([http://www.hitechfrp.com/goods-show-](http://www.hitechfrp.com/goods-show-919.htm)
547 [919.htm](http://www.hitechfrp.com/goods-show-919.htm)) (Assessed on 1st Jun 2018).

548 [36] ASTM. Standard test method for tensile properties of fibre reinforced polymer matrix
549 composites used for strengthening of civil structures. ASTM D7565 2010; West Conshohocken,
550 PA.

551 [37] Carey, S. A., and Harries, K. A. Axial behavior and modeling of confined small-, medium-
552 and large scale circular sections with carbon fiber-reinforced polymer jackets. *ACI Structural*
553 *Journal* 2005; 102(4): 596–604.

554 [38] Elsanadedy, H. M., Al-Salloum, Y. A., Alsayed, S. H., and Iqbal, R. A. Experimental and
555 numerical investigation of size effects in FRP-wrapped concrete columns. *Construction and*
556 *Building Materials* 2012; 29: 56-72.

557 [39] Thériault, M., Neale, K. W., and Claude, S. Fiber-Reinforced Polymer-Confined Circular
558 Concrete Columns: Investigation of Size and Slenderness Effects. *Journal of Composites for*
559 *Construction* 2004; 8(4): 323-331.

560 [40] Jamatia, R., and Deb, A. Size Effect in FRP-Confined Concrete under Axial Compression.
561 *Journal of Composites for Construction* 2017; 21(6): 04017045.

562 [41] Iyengar, K. T. S. R., Desayi, P., and Reddy, K. N. Stress-strain characteristics of concrete
563 confined in steel binders. *Magazine of Concrete Research* 1970; 22(72): 173-184.

564 [42] Martinez, S., Nilson, A. H., and Slate, F. O. Spirally reinforced high-strength concrete
565 columns. *Journal of the American Concrete Institute* 1984; 81(5): 431-442.

566 [43] Eid, R., and Dancygier, A. N. Confinement effectiveness in circular concrete columns.
567 *Engineering Structures* 2006; 28(13): 1885-1896.

568 [44] Eid, R., Dancygier, A. N., and Paultre, P. Elastoplastic confinement model for circular
569 concrete columns. *Journal of Structural Engineering* 2007; 133(12): 1821-1831.

570 [45] Wang, Y. C., and Restrepo, J. I. Investigation of concentrically loaded reinforced concrete
571 columns confined with glass fibre-reinforced polymer jackets. *ACI Structural Journal* 2001;
572 98(3): 377-385.

573 [46] Chen, B., and Mau, S. T. Numerical simulation of behaviour of spirally reinforced
574 columns. *Journal of Structural Engineering* 1990; 116(10): 2842-2861.

- [47] Eid, R., Dancygier, A. N., and Paultre, P. Stress-strain curve for concrete in circular columns based on elastoplastic analysis. *Materials and Structures/Materiaux et Constructions* 2010; 43(1-2): 63-79.
- [48] Eid, R., and Paultre, P. Plasticity-based model for circular concrete columns confined with fibre-composite sheets. *Engineering Structures* 2007; 29(12): 3301-3311.
- [49] Wang, J. W. Test study on mechanical performance of C50 concrete cylinders confined by CFRP under axial load. Master thesis 2010; Yanbian University, Yanbian, China.
- [50] Yang, Y. W. Experimental research on durability of FRP confined load-bearing short columns. Master thesis 2010; Shenzhen Graduate School of Harbin Institute of Technology, Shenzhen, China.
- [51] Wu, G., Lü, Z. T., and Wu, Z. S. Strength and ductility of concrete cylinders confined with FRP composites. *Construction and Building Materials* 2006; 20(3): 134-148.

596

597

598

599

600

601

602

603

604 **List of Tables**

605 **Table 1.** Test Matrix

606 **Table 2.** Experimental Results

607 **Table 3.** Collected Test Results of Partially FRP Confined Concrete

608 **Table 4.** Summary of Existing Stress-Strain Models for Partially FRP Confined Concrete

609

610

611

612

613

614

615

616

617

618

619

620

621

622

623

624 **List of Figures**

625 **Fig. 1.** Wrapping configurations

626 **Fig. 2.** Test setup

627 **Fig. 3.** Failure modes

628 **Fig. 4.** Axial load-axial deformation behaviour of specimens

629 **Fig. 5.** Influence of s/D ratio on the ultimate load (Note: s/D indicates spacing to diameter
630 ratio, and $P2/P1$ indicates load enhancement ratio)

631 **Fig. 6.** Axial load-strain relationships (strain gauges readings were taken from FRP strips)

632 **Fig. 7.** Axial stress-axial strain behaviours

633 **Fig. 8.** Partial confinement mechanism

634 **Fig. 9.** Hoop rupture strain of FRP with different effective confinement ratio

635 **Fig. 10.** Performance of models on ultimate strength prediction

636 **Fig. 11.** Performance of models on ultimate strain prediction

Table 1. Test Matrix

Specimen	Strip width w	Strip gap s	s / d	Number of FRP layers	FRP volumetric ratio ρ_f
S0-I, II	100.0	0	0	3	0.02
S25-I, II	87.5	25	0.25	4	0.02
S35-I, II	82.5	35	0.35	4	0.02
S50-I, II	75.0	50	0.50	4	0.02
S75-I, II	62.5	75	0.75	5	0.02
S100-I, II	50.0	100	1.00	6	0.02
S125-I, II	37.5	125	1.25	8	0.02
S150-I, II	25.0	150	1.50	12	0.02
S200-I, II	0.0	200	2.00	0	0.00

Note: d is the diameter of specimen, and s is the gap between FRP strips.

Table 2. Experimental Results

Specimens	P_u (kN)	f_{cc} (MPa)	Δ_u (mm)	ε_{cc} (%)	$\varepsilon_{h,frp}$ (%)	$P-\Delta$ relationship
S0-I	1126	143.4	11.06	3.74	1.54	A
S0-II	1036	131.9	11.41	3.51	1.52	A
S25-I	871	110.1	10.52	2.52	1.20	A
S25-II	825	105.0	10.54	2.30	1.21	A
S35-I	695	88.5	31.45	1.46	1.23	B
S35-II	643	81.9	28.90	1.62	1.24	B
S50-I	367	46.7	3.26	0.31	0.20	C
S50-II	392	49.9	3.78	0.42	0.29	C
S75-I	326	41.5	1.10	0.21	0.05	D
S75-II	346	44.1	0.96	0.20	0.06	D
S100-I	332	42.3	0.76	0.24	0.04	D
S100-II	315	40.1	0.81	0.17	0.03	D
S125-I	319	40.6	0.98	0.32	0.05	D
S125-II	323	41.1	0.95	0.17	0.04	D
S150-I	313	39.9	0.75	0.25	0.04	D
S150-II	306	39.0	0.81	0.19	0.04	D
S200-I	278	35.4	0.83	-	-	D
S200-II	286	36.4	0.88	-	-	D

663 Note: P_u is the peak axial load; f_{cc} is the peak axial stress; Δ_u is the axial deformation at peak
664 load P_u ; ε_{cc} is the axial strain of FRP strips at peak stress f_{cc} ; $\varepsilon_{h,frp}$ is the hoop strain of FRP
665 strips at peak stress f_{cc} ; P is the axial load; and Δ is the axial deformation.

Table 3. Collected Test Results of Partially FRP Confined Concrete

Number of specimens	Source of data	H	d	f_{co}	ε_{co} (%)	Fibre type	t	f_{frp}	E_{frp}	ε_{frp} (%)	$\varepsilon_{h,rup}$ (%)	w	s	$\frac{f_{cc}}{f_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$	$\frac{f_{cu}}{f_{co}}$
1	Pham et al. [20]	300	150	54	0.23	GFRP	1.40	582	29.5	1.97	1.59	25	25	1.02	5.43	1.02
2	Pham et al. [20]	300	150	54	0.23	GFRP	1.40	582	29.5	1.97	1.61	25	25	0.98	5.48	0.98
3	Pham et al. [20]	300	150	54	0.23	GFRP	1.40	582	29.5	1.97	1.34	25	25	0.95	4.43	0.95
4	Pham et al. [20]	300	150	54	0.23	CFRP	1.80	2157	133	1.62	1.18	25	25	1.59	6.87	1.59
5	Pham et al. [20]	300	150	54	0.23	CFRP	1.80	2157	133	1.62	1.18	25	25	1.76	8.91	1.76
6	Pham et al. [20]	300	150	54	0.23	CFRP	1.80	2157	133	1.62	1.42	25	25	1.78	9.22	1.78
7	Pham et al. [20]	300	150	54	0.23	CFRP	2.70	2157	133	1.62	1.21	25	25	2.09	13.91	2.09
8	Pham et al. [20]	300	150	54	0.23	CFRP	2.70	2157	133	1.62	1.29	25	25	2.19	14.13	2.19
9	Pham et al. [20]	300	150	54	0.23	CFRP	2.70	2157	133	1.62	1.39	25	25	2.17	14.3	2.17
10	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.18	3250	230	1.46	0.80	15	285	1.17	1.2	0.85
11	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.35	3250	230	1.46	0.80	15	285	1.19	1.32	0.85
12	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.80	15	285	1.2	1.12	0.85
13	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.70	3250	230	1.46	0.80	15	285	1.2	1.4	0.85
14	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.06	3250	230	1.46	0.80	15	285	1.24	1.4	0.85
15	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.17	3250	230	1.46	0.45	15	85	1.3	1.6	0.85
16	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.35	3250	230	1.46	0.40	15	85	1.32	1.64	0.85
17	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.70	15	85	1.3	1.72	0.85
18	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.70	3250	230	1.46	0.70	15	85	1.3	1.8	0.85

19	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.06	3250	230	1.46	0.80	15	85	1.35	1.68	0.85
20	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.18	3250	230	1.46	0.80	15	45	1.22	1.56	0.85
21	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.35	3250	230	1.46	0.80	15	45	1.23	3.08	0.85
22	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.80	15	45	1.38	3.44	1.38
23	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.70	3250	230	1.46	0.80	15	45	1.49	4	1.49
24	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.06	3250	230	1.46	0.80	15	45	1.63	4.8	1.63
25	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	1.30	30	70	1.61	10.8	1.61
26	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	0.75	30	70	1.87	10.8	1.87
27	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.23	3250	230	1.46	0.75	30	70	1.83	9.52	1.83
28	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.74	30	45	2.48	9.2	2.48
29	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	1.00	30	45	2.83	8.24	2.83
30	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.80	45	30	3.91	9.6	3.91
31	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	0.77	45	30	3.11	11	3.11
32	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.23	3250	230	1.46	0.80	45	30			
33	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	1.20	60	40	2.89	10.8	2.89
34	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	0.65	60	40	3.46	11	3.46
35	Barros and Ferreira [11]	300	150	23	0.25	CFRP	1.23	3250	230	1.46	0.64	60	40	3.61	11.4	3.61
36	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.34	3539	232	1.53	0.77	45	30	1.66	5.07	1.66

37	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.57	3539	232	1.53	0.75	45	30	2.09	7.2	2.09
38	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.34	3539	232	1.53	0.64	60	40	1.64	5.46	1.64
39	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.57	3539	232	1.53	0.84	60	40	2.08	8.48	2.08
40	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.53	3250	230	1.46	0.80	45	30	3.17	12.21	3.17
41	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.88	3250	230	1.46	0.86	45	30	3.96	16	3.96
42	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.53	3250	230	1.46	1.02	60	40	2.62	12.15	2.62
43	Barros and Ferreira [11]	300	150	16	0.24	CFRP	0.88	3250	230	1.46	0.86	60	40	3.51	20.08	3.51
44	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.34	3539	232	1.53	0.67	45	30	1.37	3.14	1.37
45	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.57	3539	232	1.53	0.73	45	30	1.81	4.55	1.81
46	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.34	3539	232	1.53	0.79	60	40	1.38	3.21	1.38
47	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.57	3539	232	1.53	0.78	60	40	1.6	4.22	1.6
48	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	0.70	45	30	1.84	7.24	1.84
49	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	0.63	45	30	2.33	8.45	2.33
50	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.53	3250	230	1.46	1.07	60	40	1.65	8.32	1.65
51	Barros and Ferreira [11]	300	150	23	0.25	CFRP	0.88	3250	230	1.46	0.60	60	40	1.98	8.36	1.98
52	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.05	2100	90	2.8	1.54	100	60	1	1.13	0.85
53	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.05	2100	90	2.8	1.54	100	60	0.94	1.1	0.85
54	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.05	2100	90	2.8	1.54	100	60	0.91	1	0.85

55	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.16	2100	90	2.8	1.54	100	60	1.05	1.05	1.05
56	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.16	2100	90	2.8	1.54	100	60	0.98	1.1	0.98
57	Campione et al. [19]	300	150	43.75	0.2	BFRP	0.16	2100	90	2.8	1.54	100	60	0.94	1.05	0.94
58	Wang [49]	400	200	35.35	0.28	CFRP	0.17	4330	237	1.7	0.59	30	30	1.17	2.04	0.85
59	Wang [49]	400	200	35.35	0.28	CFRP	0.17	4330	237	1.7	0.59	30	30	1.17	2.04	0.85
60	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.12	30	30	1.56	1.88	1.56
61	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.12	30	30	1.56	1.88	1.56
62	Wang [49]	400	200	35.35	0.28	CFRP	0.50	4330	237	1.7	1.23	30	30	2.03	2.43	1.56
63	Wang [49]	400	200	35.35	0.28	CFRP	0.50	4330	237	1.7	1.23	30	30	2.03	2.43	1.56
64	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.18	40	40	1.56	4.07	1.56
65	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.18	40	40	1.56	4.07	1.56
66	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.05	50	30	1.7	1.08	1.56
67	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.05	50	30	1.7	1.08	1.56
68	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.03	60	90	1.21	1.19	0.85
69	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.03	60	90	1.21	1.19	0.85
70	Wang [49]	400	200	35.35	0.28	CFRP	0.17	4330	237	1.7	0.77	70	80	1.21	1.63	0.85
71	Wang [49]	400	200	35.35	0.28	CFRP	0.17	4330	237	1.7	0.77	70	80	1.21	1.63	0.85
72	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.16	70	80	1.33	1.04	1.33
73	Wang [49]	400	200	35.35	0.28	CFRP	0.33	4330	237	1.7	1.16	70	80	1.33	1.04	1.33
74	Wang [49]	400	200	35.35	0.28	CFRP	0.50	4330	237	1.7	1.15	70	80	1.51	0.78	1.51
75	Wang [49]	400	200	35.35	0.28	CFRP	0.50	4330	237	1.7	1.15	70	80	1.51	0.78	1.51
76	Yang [50]	450	150	27.4	0.2	CFRP	0.17	3400	240	1.8	1.12	50	50	1.66	3.97	1.66
77	Yang [50]	450	150	27.4	0.2	CFRP	0.17	3400	240	1.8	1.10	50	50	1.68	3.85	1.68

Note: H is the specimen height; d is the specimen diameter; f_{co} is the unconfined concrete strength; ε_{co} is the corresponding axial strain at unconfined concrete

strength; t is the thickness of FRP jacket; f_{frp} is the ultimate tensile strength of FRP determined by coupon test; E_{frp} is the elastic modulus of FRP; ε_{frp} is the

ultimate tensile strain of FRP determined by coupon test; $\varepsilon_{h,frp}$ is the actual hoop rupture strain of FRP; w is the FRP strip width; s is the FRP strip gap; f_{cc} is the peak strength of confined concrete; ε_{cc} is the corresponding axial strain at peak strength; and f_{cu} is the strength at ultimate strain.

Table 4. Summary of Existing Stress-Strain Models for Partially FRP Confined Concrete

Model	k_e	Ultimate strength	Ultimate strain	Effective hoop rupture strain
Saadatmanesh et al. [24]	$\left(1 - \frac{s}{2d}\right)^2$	$\frac{f_{cc}}{f_{co}} = -1.254 + 2.254 \sqrt{1 + \frac{7.94k_e f_l}{f_{co}}} - 2 \frac{k_e f_l}{f_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 5 \left(\frac{f_{cc}}{f_{co}} - 1 \right)$	No
FIB [33]	$\left(1 - \frac{s}{2d}\right)^2$	$\frac{f_{cc}}{f_{co}} = 0.2 + 3 \left(\frac{k_e f_l}{f_{co}} \right)^{0.5}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 2 + 1.25 \left(\frac{E_c}{f_{co}} \right) \left(\frac{k_e f_l}{f_{co}} \right)^{0.5} \varepsilon_{frp}$	No
Wu et al. [51]	No	$\frac{f_{cc}}{f_{co}} = 0.745 + 3.357 \frac{f_l}{f_{co}} - 1.053 \left(\frac{f_l}{f_{co}} \right)^2$	$\varepsilon_{cu} = \frac{\varepsilon_{frp}}{0.56k_1 \left(\frac{f_l}{f_{co}} \right)^{-0.66}}$	No
		or $\frac{f_{cc}}{f_{co}} = 1 + 2 \frac{f_l}{f_{co}}$	$k_1 = 1$ if $E_{frp} \leq 250$ GPa $k_1 = \sqrt{\frac{250}{E_{frp}}}$ if $E_{frp} > 250$ GPa	
Barros and Ferreira [11]	$\left(1 - \frac{s}{2d}\right)^2$	$\frac{f_{cc}}{f_{co}} = 1 + k_1 \frac{k_e f_{l,a}}{f_{co}} \quad k_1 = a \left(\frac{k_e f_{l,a}}{f_{co}} \right)^{-b}$ the values of a and b vary with f_{co}	$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + k_2 \left(\frac{f_{cc}}{f_{co}} - 1 \right)$ values of k_2 vary with f_{co} for C16 and $0.0025 \leq \rho_f \leq 0.0176$: $k_2 = [555 - 29006(\rho_f - 0.0025)] \varepsilon_f + 2.0$ for C32 and $0.0025 \leq \rho_f \leq 0.0176$: $k_2 = [600 - 28695(\rho_f - 0.0025)] \varepsilon_f + 1.0$	Yes
		for C16 and $0.0025 \leq \rho_f \leq 0.0176$: $a = 2.9 + 72.848(\rho_f - 0.0025)$ $b = 0.2177$ for C32 and $0.0025 \leq \rho_f \leq 0.0176$:		

		$a = 2.0 + 125.828(\rho_f - 0.0025)$		
		$b = 0.42 - 7.947(\rho_f - 0.0025)$		
Pham et al. [20]	$\left(1 - \frac{s}{2d}\right)^2$	$\frac{f_{cc}}{f_{co}} = 1 + 3.3k_e \frac{f_{l,a}}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co} + \frac{2ktf_{fe}\varepsilon_{h,rup}}{D(f_{co} + k_e f_{cc})}$	Yes

Note: f_l is the nominal lateral confining pressure; $f_{l,a}$ is the actual lateral confining pressure; and f_{fe} is the actual rupture strength of FRP.

Fig. 1. Wrapping configurations (all units in mm)

Fig. 2. Test setup

(a) S0

(b) S25

Phase 1

Phase 2
(c) S35

Phase 3

(d) S50

(e) S75

(f) S100

(g) S125

(h) S150

Fig. 3. Failure modes

(a) First specimen in each group (Specimen I)

(b) Second specimen in each group (Specimen II)

Fig. 4. Axial load-axial deformation behavior of specimens

Fig. 5. Influence of s/D ratio on the P_2/P_1 ratio (Note: s/D indicates spacing to diameter ratio; P_2/P_1 indicates load enhancement ratio, in which P_1 and P_2 indicate the ultimate loads for confined and unconfined concrete specimens, respectively)

(a) S0

(b) S25

(c) S35

(d) S50

(e) S75

(f) S100

(g) S150

Fig. 6. Axial load-strain relationships (strain gauge readings were taken from FRP strips)

(a) Specimens with Type A behavior

(b) Specimens with Type B behavior

(c) Specimens with Type C behavior

(d) Specimens with Type D behavior

Fig. 7. Axial stress-axial strain behaviors of wrapped and non-wrapped concrete (**1** indicates the stress-strain behavior of wrapped concrete, and **2** indicates the stress-strain behavior of non-wrapped concrete; σ_1 and σ_2 indicate the axial stress of wrapped and non-wrapped concrete, respectively, at the same time)

Fig. 8. Partial confinement mechanism

Fig. 9. Hoop rupture strain of FRP with different effective confinement ratio

Fig. 10. Performance of models for ultimate strength prediction

Fig. 11. Performance of models for ultimate strain prediction