A Rational Approach toward Strain Efficiency Factor of Fiber-Reinforced Polymer-Wrapped Concrete Columns

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2 authors:


Pedram Sadeghian
Dalhousie University


Amir Fam
Queen's University

A Rational Approach towards Strain Efficiency Factor of FRP-Wrapped Concrete Columns

Pedram Sadeghian [1] and Amir Fam [2]

ABSTRACT

This paper aims at providing a rational approach to the concept of circumferential strain efficiency factor κ_ε of circular concrete columns wrapped with fiber reinforced polymer (FRP) jackets. κ_ε reflects the reduction in the FRP hoop rupture strain observed in experiments, relative to the true rupture strain of the FRP material obtained from standard coupon tests or manufacturer datasheets. Currently, ACI 440.2R-08 design guide uses a constant empirical κ_ε factor of 0.55 for any column, regardless of geometric or mechanical properties. A rational approach is proposed to calculate κ_ε. It employs a simplified Tsai-Wu interaction failure envelope of FRP laminates and acknowledges the bi-axial state of stresses in the jacket. A large database of 454 circular concrete specimens wrapped with unidirectional FRP fabrics has been compiled from literature and subjected to rigorous statistical evaluations. While the proposed model performed quite similar to the current ACI 440.2R-08, in that it did not lead to significant improvement in prediction, it has the advantage of offering analytical rational bases to the observed phenomenon. It also distinguishes between columns of different geometric and mechanical properties, leading to a variable κ_ε of 0.05 to 0.98 with a 0.65 average, which is consistent with experimental observations and more logical than the constant value of 0.55.

Keywords: Fiber reinforced polymer; Concrete; Column; Wrap; Confinement; Model; Strain efficiency factor; Design guideline.

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[1] Assistant Professor of Civil Engineering, Penn State Harrisburg, Middletown, PA, 17057; and Former Postdoctoral Fellow, Queen's University, Kingston, ON, K7L 3N6 Canada. E-mail: pedram@psu.edu

[2] Professor and Canada Research Chair in Innovative and Retrofitted Structures, Department of Civil Engineering, Queen's University, Kingston, ON, K7L 3N6 Canada. E-mail: fam@civil.queensu.ca **(Corresponding author)**

ACI Member **Pedram Sadeghian** is an Assistant Professor of Civil Engineering at Penn State Harrisburg, Middletown, PA. He is an associate member of ACI Committee 440 (Fiber Reinforced Polymer Reinforcement). Previously, he worked as a Postdoctoral Fellow at Queen's University, Canada. His research interests include the use of innovative materials and systems such as fiber reinforced polymer (FRP) composites for existing and new concrete structures.

ACI Member **Amir Fam** is a Professor and Canada Research Chair in Innovative and Retrofitted Structures at Queen's University, Canada. He is a voting member of ACI Committees 440 (Fiber Reinforced Polymer Reinforcement) and 335 (Hybrid and Composite). He is also the chair of ACI sub-committee 440-J (FRP Stay-in-Place Formwork). His research interests include applications of FRPs in new concrete construction and rehabilitation of existing structures.

INTRODUCTION

Fiber reinforced polymer (FRP) composites with continuous fibers, such as carbon and glass in the form of fabric sheets, are quite effective in wrapping concrete columns using wet layup techniques. The confinement effect of concrete and benefits gained for strength and ductility are well established and documented, including significant number of confinement models (Bisby et al., 2005) and design guides (for example, ACI 440.2R-08, 2008).

Failure of a circular FRP-wrapped concrete column is usually governed by rupture of the FRP jacket in the hoop direction. As such, the designer needs to know the circumferential strain or stress at which rupture of the FRP jacket occurs. It has been observed in experiments that considerable reduction, of significant variation, occurs in the measured hoop strains of the FRP jacket at failure. The reduction is measured relative to the ultimate values determined from flat coupon tests or split-disk tests, under uniaxial tension. The reduced rupture strain is required in most existing confinement models, usually in the form of a strain efficiency factor κ_ε, as proposed by Pessiki et al. (2001), which is the ratio of the reduced rupture strain to the full rupture strain from coupons. This factor may not be explicitly required in some models, but its concept is inherently included in the empirical coefficients of these models. (Chen et al., 2011)

Lam and Teng (2003) calibrated the κ_ε factor using 52 small-scale concrete cylinders wrapped with carbon-FRPs (CFRPs), and computed an average value of 0.586. Later, with adding 24 more specimens wrapped with high-modulus carbon, aramid, and glass FRPs, an average value of 0.632 was computed based on 76 specimens. Similarly, a database of 251 test results (Harries and Carey, 2003) computed a value of 0.58 for κ_ε, while other tests on medium- and large-scale columns resulted in values of 0.57 and 0.61, respectively (Carey and Harries, 2005).

The concept of strain efficiency factor κ_ε, as demonstrated in Eq. 1, has been implemented by the American Concrete Institute (2008) in the ACI 440.2R-08 guideline.

$$\varepsilon_{fe} = \kappa_\varepsilon \varepsilon_{fu} \qquad (1)$$

where ε_{fe} is the effective strain in FRP reinforcement attained at failure, ε_{fu} is the design rupture strain of FRP reinforcement, and κ_ε is equal to 0.55. The design guide offered some speculations on the reasons behind the reduction observed experimentally, including the multi-axial state of stress in the jacket, compared to the uniaxial state of stress in coupons. However, no rational approach was offered to express the hypothesis.

RESEARCH SIGNIFICANCE

ACI440.2R-08 design guide uses a single empirical strain efficiency factor of 0.55 for all cases of FRP-confined concrete columns, to account for a phenomenon observed experimentally, namely, the reduced FRP rupture hoop strain at ultimate. This paper proposes a simple rational analysis that can explain this phenomenon based on mechanics of composites under a biaxial state of stress. A database of 454 tests on cylindrical specimens, the largest to date, has been compiled and subjected to rigorous statistical analysis. All specimens wrapped with unidirectional FRP fabrics in hoop direction. The model clearly shows that strain efficiency factor is not a constant and indeed varies depending on geometric and mechanical properties of columns.

EXPERIMENTAL DATABASE

Significant number of experimental research programs has been conducted on FRP-wrapped concrete specimens under uniaxial compressive loading. In the present study, a database containing the test results of 454 FRP-wrapped concrete circular specimens was extracted from literature, as shown in Table 1. As noted in the table, the database includes specimens from the existing databases of Lam and Teng (2003); Carey and Harries (2003); and Realfonzo and Napoli (2011). The additional 295 data points were extracted from the literature by the authors. It should be mentioned that the current data base is unique and comprehensive because it contains 454 circular specimens with the required key parameters, such as hoop rupture strain of FRP wrap, being reported. The database is also unique in terms of the wide range it covers for each parameter as described next.

Statistical Evaluation of Database

The specimens included in the database are cylindrical and have diameter D ranging from 51 mm to 406 mm (2 to 16 in) with an average of 161 mm (6.3 in) and a standard deviation of 55 mm (2.2 in); and unconfined concrete strength f'_{co} of 19.7 to 169.7 MPa (2.9 to 24.6 ksi) with an average of 45.5 MPa (6.6 ksi) and a standard deviation of 22.0 MPa (3.2 ksi). All specimens were wrapped with unidirectional FRPs in the hoop direction. As shown in the column "Fiber type" in Table 1, 330 specimens were wrapped with carbon-FRP as indicated by "C", 8 specimens were wrapped with high modulus carbon-FRP as indicated by "HC", 109 specimens were wrapped with glass-FRP as indicated by "G", and 7 specimens were wrapped with aramid-FRP as indicated by "A". Most of the specimens are made of plain concrete (i.e. no internal reinforcements), but 26 specimens contain internal axial and transverse steel rebar as indicated by "R", and 6 specimens contain internal hollow steel tube as indicated by "T" in Table 1.

In the database, the sources of information on mechanical properties of FRPs are different. As shown in the last column of Table 1, the source of this information for 256 specimens is flat coupon tests as indicated by "F", for 110 specimens, is manufacturer data sheet as indicated by "M", for 6 specimens is split disk test as indicated by "S", and for 83 specimens some of the information is not available as indicated by "N". Based on literature, researchers have reported only elastic modulus E_f and ultimate tensile strength f_{fu} of FRP wraps in the hoop direction, where E_f varies from 11 to 663 GPa (1595 to 96157 ksi) with an average of 180 GPa (26107 ksi) and standard deviation of 129 GPa (18710 ksi); and f_{fu} varies from 220 to 4410 MPa (32 to 640 ksi) with an average of 2465 MPa (358 ksi) and standard deviation of 1416 MPa (205 ksi).

The true ultimate tensile strain ε_{fu} of FRP wrap parallel to the fibers can be calculated based on linear elastic behavior of FRPs, which varies from 0.26% to 4.62% with an average of 1.63% and standard deviation of 0.62%. The FRP wraps have thickness t ranging from 0.09 to 7.26 mm (0.0035 to 0.286 in) with an average of 0.92 mm (0.036 in) and standard deviation of 1.07 mm (0.042 in). It should be mentioned that some researchers have reported a nominal thickness of FRP wraps and the rest have reported the actual thickness. Most importantly is that the reported mechanical properties of FRP wraps are compatible and consistent with the reported thickness.

As shown in Table 1, the principal experimental results are ultimate axial strength of the confined concrete f'_{cc}, ranging from 31.4 to 303.6 MPa (4.6 to 44.0 ksi) with an average of 80.0 MPa (11.6 ksi) and a standard deviation of 36.7 MPa (5.3 ksi); ultimate axial strain of confined concrete ε_{ccu}, ranging from 0.23% to 6.20% with an average of 1.55% and a standard deviation of 0.93%; and FRP hoop rupture strain ε_{fe} ranging from 0.17% to 3.09% with an average of 1.06% and a standard deviation of 0.49%. Some of the test data reported by the researchers represent the average of two or three nominally identical physical specimens.

Experimental Strain Efficiency Factor

Experimental strain efficiency factor $\kappa_{\varepsilon,exp}$ can be calculated using Eq. 1 for each specimen of the database, as shown in Table 1. Overall, it varied from 0.12 to 1.22 with an average of 0.67 and a standard deviation of 0.23 for 454 specimens. In 36 cases (or 7.9% of all cases), $\kappa_{\varepsilon,exp}$ is larger than 1.0 (9% of CFRP-specimens, 4% of GFRP-specimens, and 14% of AFRP-specimens). This phenomenon may be explained by an error in the experimental measurement of ε_{fe} and/or an error in reporting ε_{fu}. Moreover, there is a chance not to have strain gauge at the failure position of the wrap for the case of specimens with few strain gauges, although in recent research programs this phenomenon has been minimized using many strain gauges or digital image correlation technique.

The distribution of $\kappa_{\varepsilon,exp}$ is as follows: for high-modulus CFRP it varied from 0.48 to 0.90 with an average of 0.78 and standard deviation of 0.14, for standard modulus CFRP varied from 0.13 to 1.22 with an average of 0.67 and standard deviation of 0.22; for GFRP varied from 0.12 to 1.13 with an average of 0.65 and standard deviation of 0.24; and for AFRP varied from 0.70 to 1.06 with an average of 0.86 and standard deviation of 0.12. This analysis shows that, except for high-modulus CFRP and AFRP wraps of limited number of specimens (8 and 7, respectively, i.e. 3.3% of all specimens), the experimental strain efficiency factors of carbon and glass wraps have almost identical statistical distributions. This means that there is no meaningful difference between carbon and glass wraps in terms of their strain efficiency factors.

Figure 1 shows the histogram of the experimental strain efficiency factors in 23 bins with the width of 0.05. The number of the bins was selected based on the square root of the number of data points. In addition to the histogram, a normal distribution based on the average of 0.67 and standard deviation of 0.23 is illustrated in Fig. 1 (the dotted curve). The relatively symmetric histogram and its compatibility with the normal distribution show that the specimens with $\kappa_{\varepsilon,exp}$

larger than 1.0 should be considered in data analysis and that $\kappa_{\varepsilon,exp}$ has an uncertain nature, where the uncertainty of $\kappa_{\varepsilon,exp}$ should be considered in development of analytical models and their verifications. If the specimens with $\kappa_{\varepsilon,exp}$ larger than 1.0 are eliminated from the database, the overall average and standard deviation of $\kappa_{\varepsilon,exp}$ in the modified database will be 0.63 and 0.20, respectively, instead of 0.67 and 0.23.

ANALYTICAL APPROACH FOR STRAIN EFFICIENCY FACTOR

This section proposes a rational analytical model for strain efficiency factor, which can be incorporated into confinement models or design guides such as ACI 440.2R-08 to predict the axial strength of FRP-confined concrete columns. The proposed model accounts for the biaxial state of stress in the FRP wrap and utilizes a biaxial strength failure criterion. In the following sections, the concept of biaxial state of stress in FRP wraps is explained, a rational analytical model for strain efficiency factor is derived, a simplified closed-form model is developed, and the model is examined using the experimental database discussed earlier.

Biaxial State of Stress in FRP Wraps

Failure of FRP-wrapped concrete columns subjected to axial compression occurs primarily due to tensile rupture of the FRP wrap in the hoop direction. As shown in Fig. 2(a), if the axial load is applied on the concrete core only and there is no bond or friction between the concrete core and the jacket, the jacket will be under uniaxial tensile stress in the hoop direction. In this hypothetical case, once the tensile hoop stress (σ_x) reaches the ultimate tensile strength of the wrap (σ_{xu}), hoop rupture occurs, leading to overall failure of the column. In this case the jacket is stressed due to confinement only. The jacket stress path of case (a), from zero to the failure point of $\sigma_x=\sigma_{xu}$ is shown in Fig. 3.

In practice, however, the wrap is adhesively bonded to concrete and also the compressive axial load may be applied on the entire section, including the jacket (Fig. 2(b)). In this case (case (b)), the wrap is axially loaded along with the concrete core and behaves as a biaxially loaded membrane under axial compressive and hoop tensile stresses. The presence of the axial compression reduces the strength of the wrap in the hoop direction, and a biaxial strength failure criterion must be adopted to account for the combined state of stress. The most widely used criterion for FRP composite laminates is the Tsai-Wu interactive tensor polynomial theory (Tsai and Wu, 1971), which provides an elliptical failure envelope in the biaxial stress plane. The quadrant relevant to the current problem is shown schematically in Fig. 3. In this case, at each axial strain level, the combination of stresses in the hoop direction (σ_x) and axial direction (σ_y) needs to be compared to the failure envelope. It is clear that under a biaxial state of stress, the stress path intersects the failure envelope at a point, where the hoop stress at ultimate (σ_x) is lower than the full hoop tensile strength (σ_{xu}) (case (b) in Fig. 3). The authors believe that this provides the rational basis for the reductions in hoop strain at failure observed by many experimentalists and hence led to the concept of strain efficiency factor.

Tsai-Wu Failure Criterion

The Tsai-Wu failure criterion for anisotropic composite materials can be expressed in the general form as follows (Tsai and Wu, 1971):

$$f_i \sigma_i + f_{ij} \sigma_i \sigma_j = 1 \qquad (2)$$

where the contracted notation is used; and i , j=1, 2, ... 6; σ_i and σ_j are stresses; and f_i and f_{ij} are strength tensors of the second and fourth rank, respectively. For an orthotropic FRP ply under plane state of stress, where the in-plane shear stress is zero, the criterion is reduced as follows (Daniel and Ishai, 1994):

$$f_1\sigma_1 + f_2\sigma_2 + f_{11}\sigma_1^2 + f_{22}\sigma_2^2 + 2f_{12}\sigma_1\sigma_2 = 1 \qquad (3)$$

where σ_1 and σ_2 are longitudinal (i.e. fiber direction) stress and transverse (i.e. matrix direction) stress of FRP ply, respectively. In the case of a unidirectional FRP wrap in the hoop direction, σ_1 and σ_2 will become σ_x and σ_y (shown in Figs. 2 and 3), respectively. The coefficients f_1, f_2, f_{11}, f_{22}, and f_{12} can be obtained for a unidirectional FRP ply using Eqs. 4 to 8 as follows:

$$f_1 = \frac{1}{F_{1t}} - \frac{1}{F_{1c}} \qquad (4)$$

$$f_2 = \frac{1}{F_{2t}} - \frac{1}{F_{2c}} \qquad (5)$$

$$f_{11} = \frac{1}{F_{1t}F_{1c}} \qquad (6)$$

$$f_{22} = \frac{1}{F_{2t}F_{2c}} \qquad (7)$$

$$f_{12} = -\frac{1}{2}\left(f_{11}f_{22}\right)^{1/2} \qquad (8)$$

where F_{1t} and F_{1c} are longitudinal tensile and compressive strengths of FRP ply, respectively; and F_{2t} and F_{2c} are transverse tensile and compressive strengths of FRP ply, respectively. These parameters are obtained using coupon tests or manufacturer data sheet.

This approach has been implemented by Fam and Rizkalla (2001) for concrete filled-FRP tubes with multi-directional fiber layers, using a multi-functional interaction failure envelopes which required an incremental numerical solution. However, in the case of FRP-wrapped columns with hoop fibers only, a rational closed-form solution with a single failure envelope (Fig. 3) is possible, as described next.

Description of the Analytical Model

For FRP-wrapped concrete columns, axial and hoop stresses in the wrap can be given as follows:

$$\sigma_x = \frac{E_x}{1-\nu_{xy}\nu_{yx}}\left(\varepsilon_x + \nu_{yx}\varepsilon_y\right) \tag{9}$$

$$\sigma_y = \frac{E_y}{1-\nu_{xy}\nu_{yx}}\left(\varepsilon_y + \nu_{xy}\varepsilon_x\right) \tag{10}$$

where σ_x and σ_y are the hoop and axial stresses in the wrap, respectively (Fig. 2(b)); ε_x and ε_y are the hoop and axial strains in the wrap; E_x and E_y are the hoop and axial elastic modulus of the wrap; and ν_{xy} and ν_{yx} are the major and minor Poisson's ratios of the wrap, respectively. The elastic modulus and Poisson's ratios can be obtained using the classical lamination theory, coupon tests, or from manufacturer data sheet.

In the case of a unidirectional FRP wrap in the hoop direction, Eqs. 9 and 10 can be plugged in Eq. 3, where $\sigma_x=\sigma_1$ and $\sigma_y=\sigma_2$, thus the following equation is derived:

$$\begin{aligned} & f_1 E_x\left(1-\nu_{xy}\nu_{yx}\right)\left(\varepsilon_x+\nu_{yx}\varepsilon_y\right)+f_2 E_y\left(1-\nu_{xy}\nu_{yx}\right)\left(\varepsilon_y+\nu_{xy}\varepsilon_x\right)+f_{11}E_x^2\left(\varepsilon_x+\nu_{yx}\varepsilon_y\right)^2+ \\ & f_{22}E_y^2\left(\varepsilon_y+\nu_{xy}\varepsilon_x\right)^2+2f_{12}E_xE_y\left(\varepsilon_x+\nu_{yx}\varepsilon_y\right)\left(\varepsilon_y+\nu_{xy}\varepsilon_x\right)=\left(1-\nu_{xy}\nu_{yx}\right)^2 \end{aligned} \tag{11}$$

which can be rearranged in terms of ε_x as the following quadratic:

$$a\varepsilon_x^2 + b\varepsilon_x + c = 0 \tag{12}$$

Equation 12 can be solved for a given ε_y as follows:

$$\varepsilon_x = \frac{1}{2a}\left(-b+\sqrt{b^2-4ac}\right) \tag{13}$$

where

$$a = f_{11}E_x^2 + 2\nu_{xy}f_{12}E_xE_y + \nu_{xy}^2 f_{22}E_y^2 \tag{14}$$

$$b = \left(f_1+\nu_{yx}f_2\right)\left(1-\nu_{xy}\nu_{yx}\right)E_x + 2\left(\nu_{xy}f_{22}E_y^2+\nu_{yx}f_{11}E_x^2+\nu_{xy}^2 f_{12}E_x^2+f_{12}E_xE_y\right)\varepsilon_y \tag{15}$$

$$c = \left(f_{22}+\nu_{xy}^2 f_{11}+2\nu_{xy}f_{12}\right)E_y^2\varepsilon_y^2 + \left(\nu_{xy}f_1+f_2\right)\left(1-\nu_{xy}\nu_{yx}\right)E_y\varepsilon_y - \left(1-\nu_{xy}\nu_{yx}\right)^2 \tag{16}$$

Knowing the reduced hoop strain at failure (ε_x) using Eq. 13, and knowing the ultimate hoop strain ε_{xu} using coupon tests or manufacturer data sheet, the analytical strain efficiency factor $\kappa_{\varepsilon,m}$ can be obtained as follows:

$$©_{£,m} = \frac{b}{2a£_{xu}}\left(\sqrt{1-4ac/b^2}-1\right) \tag{17}$$

To demonstrate the model, a concrete column wrapped with a unidirectional CFRP in the hoop direction with the following typical set of CFRP mechanical properties (Daniel and Ishai, 1994) is considered: E_x=142 GPa (20595 ksi), E_y=10.3 GPa (6895 ksi), ν_{xy}=0.27, F_{1t}=2280 MPa (330.7 ksi), F_{2t}=57 MPa (8.3 ksi), F_{1c}=1440 MPa (208.8 ksi), and F_{2c}=228 MPa (33.1 ksi). Figure 4 shows the variation of $\kappa_{\varepsilon,m}$ with the level of axial compressive strain ε_y (i.e. perpendicular to the fiber direction). At axial stress σ_y in the jacket equal zero (i.e. pure tensile hoop stress), the axial compressive strain is 0.43% (i.e. $\nu_{xy}\varepsilon_{xu}$). Thus, $\kappa_{\varepsilon,m}$ equals 1.0. With increasing the axial stress, $\kappa_{\varepsilon,m}$ decreases. At an axial stress equal to the ultimate compressive strength σ_{yu} (i.e. F_{2c}=228 MPa (33.1 ksi)), $\kappa_{\varepsilon,m}$ equals zero. Between the two extreme conditions, $\kappa_{\varepsilon,m}$ depends on the level of axial strain. For example, at ε_y of 1.5%, $\kappa_{\varepsilon,m}$ is 0.77.

The proposed analytical model for $\kappa_{\varepsilon,m}$ is able to predict strain efficiency factor for all types of FRP-wrapped concrete columns, but this model needs a large number of parameters for mechanical properties of FRP wraps, which in practice may not be available. In addition, the model is not a single equation, which is not favorable for design purposes. Therefore, in the next section, a simplified model is developed.

Description of the Simplified Model

The Tsai-Wu failure criterion for an orthotropic unidirectional FRP lamina under plane state of stress takes the form of an inclined ellipse, as shown in Fig. 3 for one quadrant. A simplified parabolic failure envelope which only needs the two parameters F_{1t} (σ_{xu}) and F_{2c} (σ_{yu}) is proposed. The new parabolic failure envelope has a vertex point at the ultimate hoop tensile strength σ_{xu}, as shown in Fig. 3. The proposed envelope is plotted for typical unidirectional FRP laminates adopted from Daniel and Ishai (1994) and compared with the original Tsai-Wu envelope, as shown in Fig. 5. The figure shows that the proposed simplified parabolic envelope has a good agreement with Tsai-Wu envelope. Moreover, the proposed envelope is located inside the Tsai-Wu's safe region. As such, models based on this parabolic approximation would lead to a safe design. The proposed parabolic failure envelope can be expressed as follows:

$$\frac{\sigma_x}{\sigma_{xu}} + \left(\frac{\sigma_y}{\sigma_{yu}}\right)^2 = 1 \qquad (18)$$

Substituting the hoop stress σ_x and the axial stress σ_y from Eqs. 9 and 10 in Eq. 18, leads to the following expression:

$$\frac{E_x}{(1-\nu_{xy}\nu_{yx})\sigma_{xu}}\left(\varepsilon_x + \nu_{yx}\varepsilon_y\right) + \left[\frac{E_y}{(1-\nu_{xy}\nu_{yx})\sigma_{yu}}\left(\varepsilon_y + \nu_{xy}\varepsilon_x\right)\right]^2 = 1 \qquad (19)$$

Equation 19 can be rearranged in terms of hoop strain ε_x as follows:

$$A\varepsilon_x^2 + B\varepsilon_x + C = 0 \qquad (20)$$

which has the following solution:

$$\varepsilon_x = \frac{1}{2A}\left(-B + \sqrt{B^2 - 4AC}\right) \qquad (21)$$

where

$$A = \left(\frac{E_y}{\sigma_{yu}}\right)^2 \qquad (22)$$

$$B = \left(1-\nu_{xy}\nu_{yx}\right)\frac{E_x}{\sigma_{xu}} + 2\nu_{xy}\varepsilon_y A \qquad (23)$$

$$C = A\varepsilon_y^2 + \nu_{yx}\left(1 - \nu_{xy}\nu_{yx}\right)\frac{E_x}{\sigma_{xu}}\varepsilon_y - \left(1 - \nu_{xy}\nu_{yx}\right)^2 \tag{24}$$

By calculating the actual hoop strain ε_x from Eq. 21 and given the ultimate hoop strain ε_{xu} from coupon tests or from manufacturer data sheets, a simplified analytical strain efficiency factor $\kappa_{\varepsilon,sm}$ can be expressed as follows:

$$\kappa_{\varepsilon,sm} = \frac{B}{2A\varepsilon_{xu}}\left(\sqrt{1 - 4AC/B^2} - 1\right) \tag{25}$$

The parameters ε_y and σ_{yu} are negative, while in practice they are usually considered as positive numbers. Thus, in order to be consistent with common practice, they shall be considered as follows: $\varepsilon_y=-\varepsilon_{ccu}$ and $\sigma_{yu}=-\sigma_{yu}$, where ε_{ccu} is the ultimate axial strain of the FRP-wrapped concrete column (+ve); E_x and σ_{xu} are the elastic modulus and ultimate tensile strength of FRP in the hoop direction of the column (i.e. in the fiber direction), which are the same as E_1 and F_{1t}, respectively; E_y and σ_{yu} are the elastic modulus and ultimate compressive strength (+ve) of the FRP in the axial direction of the column (i.e. transverse to the fiber direction), which are the same as E_2 and F_{2c}, respectively; and ν_{xy} is the major Poisson's ratio of FRP.

Similar to the original analytical model (Eq. 17), the simplified analytical model (Eq. 25) is applied for a typical unidirectional CFRP wrap in the hoop direction. Figure 4 shows the variation of $\kappa_{\varepsilon,sm}$ at different levels of axial compressive strain. Using the simplified model at a given level of axial strain of $\varepsilon_y=1.5\%$, $\kappa_{\varepsilon,sm}$ is 0.72, which is only 6.5% lower than the 0.77 value from the original model (i.e. on the safe side).

Prediction of Strain Efficiency Factors using Simplified Model

The simplified analytical model was used to predict the strain efficiency factors of the experimental specimens presented in Table 1. Three required parameters including the major

Poisson's ratio ν_{xy}, the transverse elastic modulus E_y, and the transverse compressive strength σ_{yu} of the FRP wraps are adopted from Daniel and Ishai (1994) for typical FRP materials and are recommended to be used in the model unless more accurate values are available to designers. For the three types of fibers (i.e. carbon, glass, and aramid) ν_{xy} is 0.27, 0.28, and 0.34; E_y is 10.5, 4.3, and 5.5 GPa (1523, 624 and 798 ksi); and σ_{yu} is 237, 128, and 158 MPa (34, 19 and 23 ksi), respectively. The predicted $\kappa_{\varepsilon,sm}$ for each specimen is shown in Table 1.

The experimental values of the axial strain ε_{ccu} at failure for 58 of the 454 specimens are larger than the values used in the model for ultimate compressive strains of FRP wraps in the transverse direction. As a result, the model could not predict their strain efficiency factors, as marked in Table 1. Figure 6 shows the predicted $\kappa_{\varepsilon,sm}$ in comparison to the experimental factors. While the data shows an obvious scatter, the results clearly show that strain efficiency factor is indeed a variable and not a constant value of 0.55 as used in the current ACI 440.2R-08 design guide. The average value of the predicted $\kappa_{\varepsilon,sm}$ is 0.65 which is quite close to the average value of 0.67 for the experimental factors. The standard deviation of the predicted values is 0.17 which is less than that of the experimental values of 0.23. In the next section, the predicted confinement ratios (f'_{cc}/ f'_{co}) using ACI440.2R-08 with both the original 0.55 constant κ_{ε} and the variable factor $\kappa_{\varepsilon,sm}$ based on the simplified model, are compared to experimental values and assessed statistically.

There is a concern about the scalability of findings based on small-scale specimens for large-scale columns in practice. In the data base with 454 specimens, there are 50 specimens with a diameter equal to or larger than 200 mm (7.9 in) including 10 specimens with 406 mm (16.0 in) diameter, 3 specimens with 400 mm (15.7 in) diameter, and 37 specimens with a diameter between 200 mm (7.9 in) and 305 mm (12.0 in). The average of $\kappa_{\varepsilon,exp}$ for these 50 medium-scale specimens is 0.73, which is slightly higher than the average of 0.66 for the rest of specimens. The average of $\kappa_{\varepsilon,sm}$ for these 50 specimens is 0.81, which is slightly higher than the average of 0.76 for the rest of specimens. This shows that the experimental and analytical strain efficiency factors of medium-scale specimens are averagely 10.6% and 6.6% higher than small-scale specimens, respectively; and there is an agreement between analytical model and experimental date base in this regards.

Significant researches have been performed by Toutanji et al. (2010), Lignola et al. (2010), and Luca et al. (2011) to identify the behavior of large-scale columns with rectangular section. Toutanji et al. (2010) have developed a model for large-scale columns with rectangular section, which accurately predicts the axial ultimate strength of the columns at hand and, when applied to the small-scale columns studied by other investigators, produces reasonable results. Based on this investigation on large-scale rectangular sections, it can be concluded that the models developed based on small- and medium-scale circular sections can be applicable for large-scale circular sections as well, although more research is needed. The model developed in the current study is definitely applicable for circular columns up to 400 mm (15.7 in) diameter.

Prediction of Confinement Ratio based on Simplified Model

Figures 7 and 8 show the variation of confinement ratios (f'_{cc}/f'_{co}) using ACI440.2R-08 with the experimental values from the database. In Fig. 7, κ_{ε} is the original constant factor of 0.55 of ACI 440.2R-08, whereas in Fig. 8, $\kappa_{\varepsilon,sm}$ is calculated using the proposed simplified model for each individual sample. In this case, in order to calculate $\kappa_{\varepsilon,sm}$ the axial strains at ultimate (ε_{ccu}) are needed, and were calculated using ACI 440.2R-08 without applying the upper limit of 0.01. This quite restricted limit for ε_{ccu} (and accordingly for f'_{cc}) has been merely set as an upper limit for the level of achievable strength and ductility increased due to the confinement provided by FRP wrap. In fact, 69% of specimens in the entire data base have experimental ε_{ccu} values larger than 0.01.

In order to evaluate the effect of κ_ε on the predicted confinement ratios, two statistical indices, namely the R-squared (R^2) and Root Mean Square Error (RMSE) are used. R^2 is the square of the correlation coefficient, and is calculated from the following equation:

$$R^2(X,Y) = \left(\frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \right)^2 \qquad (26)$$

where X and Y are the vectors of experimental and predicted values, respectively; x and y are experimental and predicted values, respectively; and $\bar{x}$ and $\bar{y}$ are the averages of experimental and predicted values, respectively. R^2 ranges from zero to 1.0, with 1.0 indicating a perfect correlation between predicted and experimental values, and zero indicating no correlation. It is important to note, however, that an R^2 value of 1.0 does not necessarily indicate a perfect prediction. It only shows that there is a linear correlation between predicted and experimental values. Thus, R^2 is not the best index for this kind of evaluations. The RMSE which is the square root of the variance of the residuals is better suited for this analysis, and is defined as follows:

$$\text{RMSE} = \sqrt{\frac{\sum (x-y)^2}{n}} \qquad (27)$$

where n is the number of data points. RMSE indicates how close the predicted values (i.e. y) to experimental values (i.e. x). While R^2 is a relative measure of fit, RMSE is an absolute measure of fit. Lower values of RMSE indicate a better fit, with zero indicating a perfect prediction. There is no upper limit for RMSE. It should be noted that ten out of the 454 data points of the database have significant variance from the values predicted by ACI 440.2R-08 original model. Thus, these data points are eliminated, given the uncertainty of accuracy of the experimental points, to have a meaningful RMSE index and to prevent its saturation with the square of error values (i.e. $(x-y)^2$) in Eq. 27.

By comparing Figures 7 and 8, it can be seen that the RMSE values are 0.431 and 0.329, respectively. This indicates that the simplified model provides predictions that are not weaker, but perhaps slightly better, than the existing ACI 440.2R-08 with the constant $\kappa_\varepsilon = 0.55$. If the samples that could not be included in Fig. 8, as explained earlier, are also eliminated from Fig. 7, and the results are plotted in a new Fig. 9 that has the same number of samples as Fig. 8, the RMSE would be 0.345, which is not better than that of the proposed simplified model.

DESIGN EXAMPLE

A 400 mm (15.7 in) diameter circular concrete column is wrapped with five plies of a unidirectional CFRP sheets in the hoop direction. The unconfined concrete strength f'_{co} is 45 MPa (6.5 ksi). The thickness of each layer is 1 mm (0.039 in), the tensile strength f_{fu} is 1500 MPa (217.6 ksi), and the elastic modulus E_f is 100 GPa (14503 ksi). It is required to calculate the confined concrete strength f'_{cc} and strain ε_{ccu} using ACI 440.2R-08 guideline based on the proposed simplified model for FRP strain efficiency factor.

Based on the linear behavior of CFRP and the assumptions stated earlier, the CFRP ultimate longitudinal strain ε_{fu} is 0.015, major Poisson's ratio ν_{xy} is 0.27, transverse elastic modulus E_y is 10.5 GPa (1523 ksi), and transverse compressive strength σ_{yu} is 237 MPa (34.4 ksi). In order to use Eq. 25, ε_{ccu} is required. Thus, $\kappa_{\varepsilon,sm}$ is first assumed for the iterative process (a 0.67 representing the average value from the experimental database may be assumed). Using ACI 440.2R-08 guideline, ε_{ccu} is calculated as 0.043 in the first trial. After three iterations, the process converges to a ε_{ccu} of 0.0184. Then using Eqs. 22, 23, and 24; the parameters A, B, and C can be calculated as 1962.8, 45.6, and -0.355, respectively. By plugging these parameters into

Eq. 25, $\kappa_{\varepsilon,sm}$ can be calculated as 0.404, and f'_{cc} is 92.5 MPa (13.4 ksi). If the upper limit of 0.01 imposed by ACI 440.2R-08 for ultimate axial strain, is used in lieu of the 0.0184 established above, a lower value of f'_{cc} can be interpolated according to the procedure described in ACI 440.2R-08.

CONCLUSIONS

The concept of strain efficiency factor κ_ε of FRP-wrapped circular concrete columns was studied with the objective of providing a rational analytical approach to this factor, in lieu of the constant empirical value of 0.55 used in ACI 440.2R-08. A large database including 423 circular concrete specimens wrapped with unidirectional FRP fabrics was established from literature, and rigorous statistical evaluations were performed. This database is the largest reported to date on the subject. Statistical evaluation showed that experimental κ_ε values varied significantly, from 0.12 to 1.22, with 8% of the database showing values higher than 1.0, which can only be explained by inaccuracies in the values reported for hoop strain at rupture of the wrap or the ultimate FRP tensile strain. The average experimental κ_ε is 0.67 with a standard deviation of 0.23.

A rational analytical approach to explain the observed reduction in ultimate hoop strain has been established and used to develop a model which enables the calculation of κ_ε for each individual case. The approach is based on the concept of biaxial state of stress and Tsai-Wu interaction failure envelope of FRP laminates. The analytical model requires several mechanical parameters of the FRP wrap which may not be readily available to designers. As such, a simplified model based on a parabolic approximation of Tsai-Wu interaction failure envelope, which requires only a few input parameters, was developed. The predicted κ_ε ranged from 0.05 to 0.98 with an average of 0.65 and a standard deviation of 0.17.

The confinement ratios (f'_{cc}/f'_{co}) using ACI 440.2R-08 guideline, based on both, the original constant κ_ε value of 0.55, and κ_ε calculated using the proposed model, were predicated for the database and compared to the experimental values. Statistical analyses used to assess the quality of correlation to experimental values in both cases showed that the proposed model provides very similar level of correlation as the existing ACI 440.2R-08. The key advantage then of the proposed model is that it offers analytical rational bases to an experimentally observed phenomenon, and distinguishes between columns of different geometric and mechanical properties, leading to a variable κ_ε, which is more logical than the current constant of 0.55. In fact, the proposed factor by ACI 440 (i.e. 0.55) is lower than the average of experimental data (i.e. 0.67) and analytical model (i.e. 0.65). In addition, the analytical model is definitely applicable for circular columns up to 400 mm (15.7 in) diameter, although for large-scale columns more research is needed.

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NOTATION

a, b, c = parameters of second order equation for analytical model;

A, B, C = parameters of second order equation for simplified analytical model;

E_f = elastic modulus of FRP in fiber direction;

E_x = elastic modulus of FRP wrap in hoop direction;

E_y = elastic modulus of FRP wrap in axial direction;

f_i , f_{ij} = strength tensors of the second and fourth rank where *i* and *j* varies from 1 to 6;

f'_{cc} = confined concrete strength;

f'_{co} = unconfined concrete strength;

f_{fu} = ultimate tensile strength of FRP in fiber direction;

f_l = confinement pressure;

F_{1t} = longitudinal tensile strength of FRP ply;

F_{1c} = longitudinal compressive strength of FRP ply;

F_{2t} = transverse tensile strength of FRP ply;

F_{2c} = transverse compressive strength of FRP ply;

n = number of data points;

x = experimental values;

$\bar{x}$ = average of experimental values;

X = vector of experimental values;

y = predicted values;

$\bar{y}$ = average of predicted values;

Y = vector of predicted values;

κ_ε = FRP strain efficiency factor;

$\kappa_{\varepsilon,exp}$ = experimental strain efficiency factor;

$\kappa_{\varepsilon,m}$ = analytical strain efficiency factor;

$\kappa_{\varepsilon,sm}$ = simplified analytical strain efficiency factor;

ν_{xy} = major Poisson's ratio of FRP wrap;

ν_{yx} = minor Poisson's ratio of FRP wrap;

ε_{ccu} = ultimate axial strain of concrete column;

ε_{fe} = effective strain level in FRP reinforcement attained at failure;

ε_{fu} = design rupture strain of FRP reinforcement;

ε_x = hoop strain in FRP wrap;

ε_{xu} = ultimate hoop strain in FRP wrap;

ε_y = axial strain in FRP wrap;

σ_1 = longitudinal stress in FRP ply;

σ_2 = transverse stress in FRP ply;

σ_i , σ_j = stress components where *i* and *j* varies from 1 to 6;

σ_x	=	hoop stress in FRP wrap;
σ_{xu}	=	tensile hoop strength of FRP wrap;
σ_y	=	axial stress in FRP wrap;
σ_{yu}	=	compressive axial strength of FRP wrap; and
ψ_f	=	FRP strength reduction factor.

REFERENCES

Abdelrahman, K., and El-Hacha, R. (2012). "Behavior of large-scale concrete columns wrapped with CFRP and SFRP sheets." *Journal of Composites for Construction*, 16 (4), 430-439.

Aire, C., Gettu, R., and Casas, J. R. (2001). "Study of the compressive behavior of concrete confined by fiber reinforced composites." *Proc., International Conference on Composites in Constructions*, A.A. Balkema Publishers, Lisse, The Netherlands, 239–243.

Almusallam, T. H. (2007). "Behavior of normal and high-strength concrete cylinders confined with E-glass/epoxy composite laminates." *Composites Part B: Engineering*, 38(5-6), 629–639.

American Concrete Institute. (2008). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures." ACI 440.2R-08, Farmington, MI.

Benzaid, R., Mesbah, H., and Chikh, N. E. (2010). "FRP-confined concrete cylinders: axial compression experiments and strength model." *Journal of Reinforced Plastics and Composites*, 29(16), 2469–2488.

Berthet, J. F., Ferrier, E., and Hamelin, P. (2005). "Compressive behavior of concrete externally confined by composite jackets. Part A: experimental study." *Construction and Building Materials*, 19(3), 223–232.

Bisby, L., Dent, A. and Green, M (2005) "Comparison of Confinement Models for Fiber-Reinforced Polymer-Wrapped Concrete", ACI Structural Journal, 102(1):62-72

Bullo, S. (2003). "Experimental study of the effects of the ultimate strain of fiber reinforced plastic jackets on the behavior of confined concrete." *Proc., International Conference on Composites in Construction*, Cosenza, Italy, 465–470.

Carey, S. A. (2002). "Behavior of variably confined concrete." Honors thesis, University of South Carolina, Columbia, SC.

Carey, S. A., and Harries, K. A. (2003). "The effects of shape, 'gap', and scale on the behavior and modeling of variably confined concrete." *Report No. ST03-05*, University of South Carolina, Columbia, SC.

Carey, S. A., and Harries, K. A. (2005). "Axial behavior and modeling of small-, medium-, and large-scale circular sections confined with CFRP jackets." *ACI Structural Journal*, 102(4), 596–604.

Chen, J. F., Li, S. Q., Bisby, L. A., and Ai, J. (2011). "FRP rupture strains in the split-disk test." *Composites Part B: Engineering*, 42(4), 962–972.

Cui, C., and Sheikh, S. A. (2010). "Experimental study of normal- and high-strength concrete confined with fiber-reinforced polymers." *Journal of Composites for Construction*, 14(5), 553–561.

Daniel, I. M., and Ishai, O. (1994). "Engineering mechanics of composite materials." Oxford University Press, New York, NY.

De Lorenzis, L., Micelli, F., and La Tegola, A. (2002). "Influence of specimen size and resin type on the behavior of FRP-confined concrete cylinders." *Proc., 1st International Conference on Advanced Polymer Composites for Structural Applications in Construction*, Thomas Telford, London, UK, 231–239.

Demers, M., and Neale, K. W. (1994). "Strengthening of concrete columns with unidirectional composite sheets." *Proc., 4th International Conference on Short and Medium Span Bridges*, Montreal, Canada, 895–905.

Dias da Silva, V., Santos, J. M. C. (2001). "Strengthening of axially loaded concrete cylinders by surface composites." *Proc., International Conference on Composites in Constructions*, A.A. Balkema Publishers, Lisse, The Netherlands, 257–262.

Fam, A .Z., and Rizkalla, S. H. (2001). "Confinement model for axially loaded concrete confined by FRP tubes." *ACI Structural Journal*, 98(4), 251–461.

Harmon, T. G., and Slattery, K. T. (1992). "Advanced composite confinement of concrete." *Proc., 1st International Conference on Advanced Composite Materials in Bridges and Structures*, Canadian Society for Civil Engineering, Sherbrooke, Canada, 299–306.

Harries, K. A., and Carey, S. A. (2003). "Shape and 'gap' effects on the behavior of variably confined concrete." *Cement and Concrete Research*, 33(6), 881–890.

Howie, I., and Karbhari, V. M. (1995). "Effect of tow sheet composite wrap architecture on strengthening of concrete due to confinement. I: experimental studies." *Journal of Reinforced Plastics and Composites*, 14(9), 1008–1030.

Jiang, T., and Teng J. G. (2007). "Analysis-oriented models for FRP-confined concrete: a comparative assessment." *Engineering Structures*, 29(11), 2968–2986.

Kharel, G. (2001). "Behavior and modeling of variably confined concrete." M.S. thesis, University of South Carolina, Columbia, SC.

Kono, S., Inazumi, M., and Kaku, T. (1998). "Evaluation of confining effects of CFRP sheets on reinforced concrete members." *Proc., 2nd International Conference on Composites in Infrastructure*, University of Arizona, Tucson, AZ, 343–355.

Kshirsagar, S., Lopez-Anido, R. A., and Gupta, R. K. (2000). "Environmental aging of fiber-reinforced polymer-wrapped concrete cylinders." *ACI Materials Journal*, 97(6), 703–712.

Lam, L, Teng, J. G., Cheung, C. H., and Xiao, Y. (2006). "FRP-confined concrete under axial cyclic compression." *Cement and Concrete Composites*, 28(10), 949–958.

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

Lam, L., and Teng, J. G. (2004). “Ultimate condition of fiber reinforced polymer-confined concrete.” *Journal of Composites for Construction*, 8(6), 539–548.

Lignola, G. P., Nardone, F., Prota, A., Luca, A. D., Nanni, A. (2010). “Analysis of RC Hollow Columns Strengthened with GFRP.” *Journal of Composites for Construction*, 15(4), 545-556.

Luca, A. D., Nardone, F., Matta, F., Nanni, Lignola, G. P., Prota A. (2011). “Structural evaluation of full-scale FRP-confined reinforced concrete columns.” *Journal of Composites for Construction*, 15(1), 112-123.

Marquesa, P. F., and Chastre, C. (2012). “Performance analysis of load–strain models for circular columns confined with FRP composites.” *Composite Structures*, 94 (11), 3115–3131.

Mastrapa, J. C. (1997). “The effect of construction bond on confinement with FRP composites.” M.S. thesis, University of Central Florida, Orlando, FL.

Matthys, S., Taerwe, L., and Audenaert, K. (1999). “Test on axially loaded concrete columns confined by fiber reinforced polymer sheet wrapping.” *Proc., 4th International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-4)*, NO. SP-188, American Concrete Institute, Farmington, MI, 217–229.

Micelli, F., Myers, J. J., and Murthy, S. (2001). “Effect of environmental cycles on concrete cylinders confined with FRP.” *Proc., International Conference on Composites in Constructions*, A.A. Balkema Publishers, Lisse, The Netherlands, 317–322.

Modarelli, R., Micelli, F., and Manni, O. (2005). “FRP-confinement of hollow concrete cylinders and prisms.” *Proc.,* 7th *International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-7)*, NO. SP-230, American Concrete Institute, Farmington, MI, 1029–1046.

Pessiki, S., Harries, K. A., Kestner, J., Sause, R., and Ricles, J. M. (2001). "The axial behavior of concrete confined with fiber reinforced composite jackets." *Journal of Composites for Construction*, 5(4), 237–245.

Picher, F., Rochette, P., and Labossiere, P. (1996). "Confinement of concrete cylinders with CFRP." *Proc., 1st International Conference on Composites for Infrastructures*, University of Arizona, Tucson, AZ, 829–841.

Purba, B. K., and Mufti, A. A. (1999). "Investigation of the behavior of circular concrete columns reinforced with carbon fiber reinforced polymer (CFRP) jackets." *Canadian Journal of Civil Engineering*, 26(5), 590–596.

Realfonzo, R., and Napoli, A. (2011). "Concrete confined by FRP systems: confinement efficiency and design strength models." *Composites Part B: Engineering*, 42(4), 736–755.

Rochette, P., and Labossiere, P. (2000). "Axial testing of rectangular column models confined with composites." *Journal of Composites for Construction*, 4(3), 129–136.

Rousakis, T., and Tepfers, R. (2004). "Behavior of concrete confined by high E-modulus carbon FRP sheets, subjected to monotonic and cyclic axial compressive load." *Nordic Concrete Research Journal*, 31(1), 73–82.

Shahawy, M., Mirmiran, A., and Beitelman, A. (2000). "Test and modeling of carbon-wrapped concrete columns." *Composites Part B: Engineering*, 31(6-7), 471–480.

Shehata, I. A. E. M., Carneiro, L. A. V., and Shehata L. C. D. (2002). "Strength of short concrete columns confined with CFRP sheets." *Materials and Structures*, 35(1), 50–58.

Silva, M. A. G., and Rodrigues, C. C. (2006). "Size and relative stiffness effects on compressive failure of concrete columns wrapped with glass FRP." *Journal of Materials in Civil Engineering*, 18(3), 334–342.

Smith, S. T., Kim, S. J., and Zhang, H. (2010). "Behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders." *Journal of Composites for Construction*, 14(5), 573–582.

Teng, J. G., Yu, T., Wong, Y. L, and Dong, S. L. (2007). “Hybrid FRP-concrete-steel tubular columns: Concept and behaviour.” *Construction and Building Materials*, 21(4), 846–854.

Toutanji, H. A. (1999). “Stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets.” *ACI Materials Journal*, 96(3), 397–404.

Toutanji, H., and Deng, Y. (2001). “Performance of concrete columns strengthened with fiber reinforced polymer composite sheets.” *Advanced Composites and Materials*, 10(2-3), 159–168.

Toutanji, H., Han, M., Gilbert, J., and Matthys, S. (2010). “Behavior of large-scale rectangular columns confined with FRP composites.” *Journal of Composites for Construction*, 14(1), 62-71.

Tsai, S. W., and Wu, E. M. (1971). “A general theory of strength for anisotropic materials.” *Journal of Composite Materials*, 5(1), 58–80.

Wang, L. M., and Wu, Y. F. (2008). “Effect of corner radius on the performance of CFRP-confined square concrete columns: Test.” *Engineering Structures*, 30(2), 493–505.

Wang, P., and Cheong, K. K. (2001). “RC columns strengthened by FRP under uniaxial compression.” *Proc., International Conference on FRP Composites in Civil Engineering*, Elsevier Science Ltd, Oxford, UK, 327–334.

Wang, Z., Wang, D., Smith, S. T., and Lu, D. (2012). “Experimental testing and analytical modeling of CFRP-confined large circular RC columns subjected to cyclic axial compression.” *Engineering Structures*, 40, 64-74.

Watanable, K., Nakamura, H., Honda, T., Toyoshima, M., Iso, M., Fujimaki, T., Kaneto, M., and Shirai, N. (1997). “Confinement effect of FRP sheet on strength and ductility of concrete cylinders under uniaxial compression.” *Proc., 3rd International Symposium on Non-Metallic FRP Reinforcement for Concrete Structures*, Japan Concrete Institute, Sapporo, Japan, Vol. 1, 233–240.

Xiao, Y., and Wu, H. (2000). "Compressive behavior of concrete confined by carbon fiber composite jackets." *J. Mater. Civ. Eng.*, 12(2), 139–146.

Youssef, M. N. (2003). "Stress strain model for concrete confined by FRP composites." doctoral dissertation, University of California-Irvine, Irvine, CA.

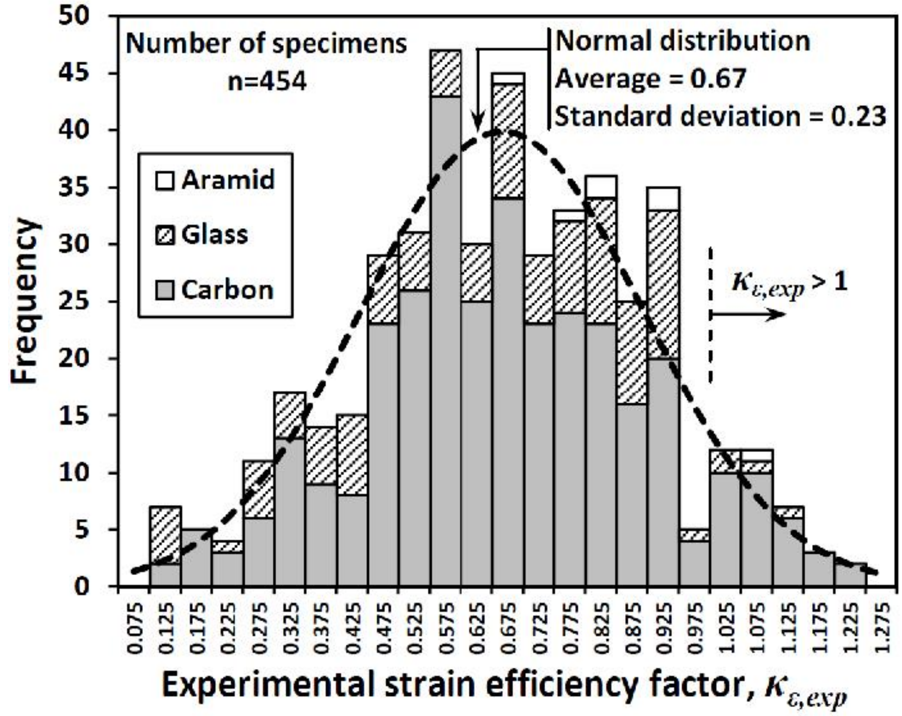

Figure 1. Histogram of experimental strain efficiency factor for the experimental database

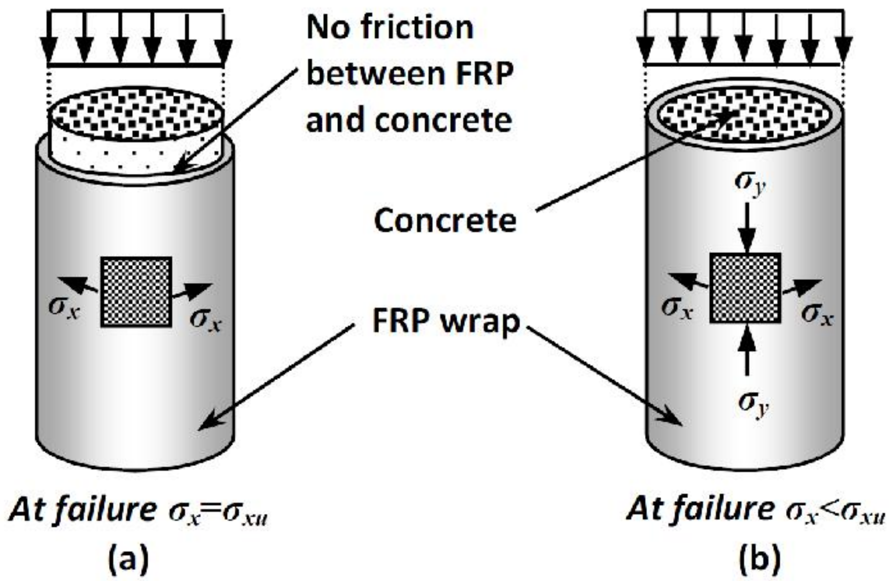

Figure 2. Possible conditions of state of stress in the FRP jacket: (a) only core is axially loaded, hence, FRP wrap is under uniaxial hoop stress; and (b) both core and FRP wrap are axially loaded, hence, the wrap is under biaxial stress

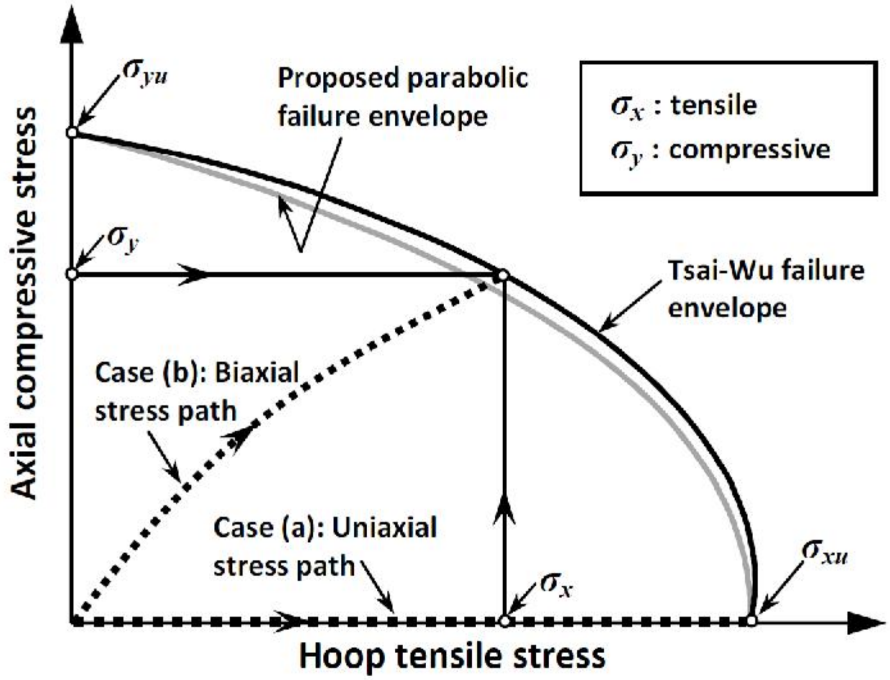

Figure 3. Effect of axial loading conditions on strength of FRP wrap using a bi-axial strength failure envelope: (a) only core is axially loaded and FRP wrap is under uniaxial hoop stress; and (b) both core and FRP wrap are axially loaded and the wrap is under biaxial stress

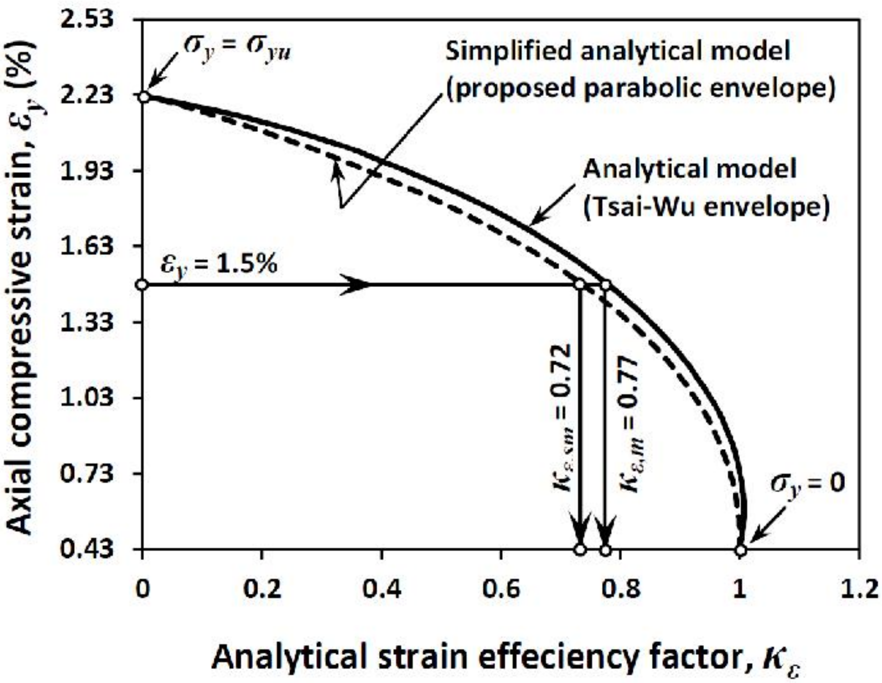

Figure 4. Performance of the analytical models for a typical unidirectional CFRP wrap with fibers oriented in the hoop direction

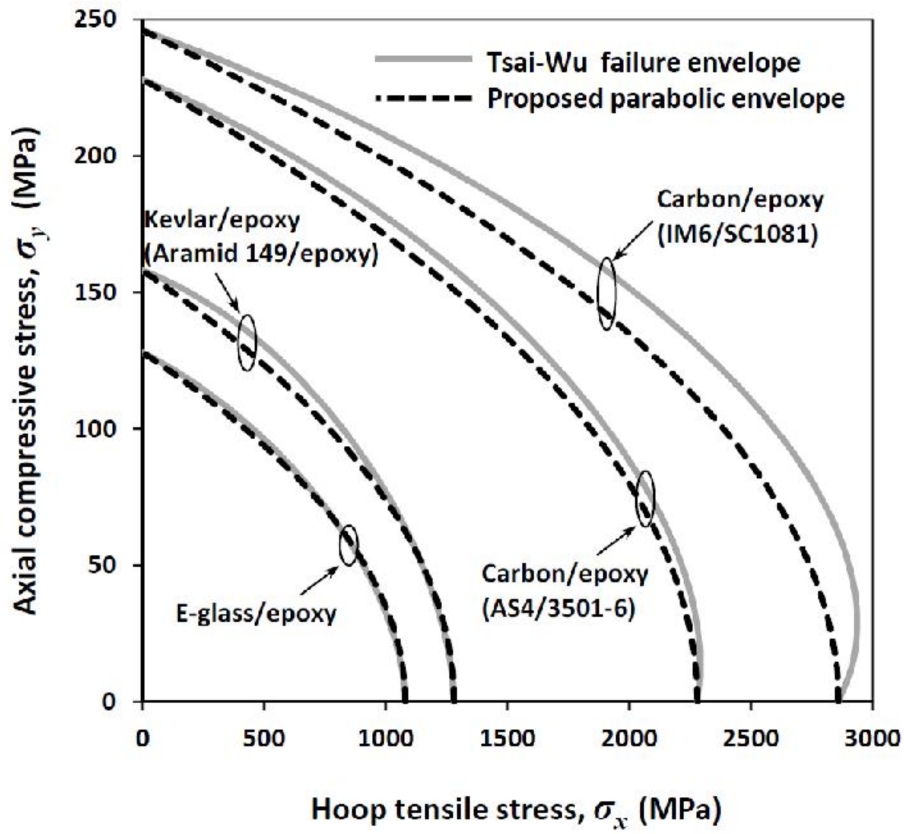

Figure 5. Comparison of the proposed simplified parabolic failure envelope with Tasi-Wu failure envelope for typical unidirectional FRP materials adopted from Daniel and Ishai (1994) (1ksi =6.895 MPa)

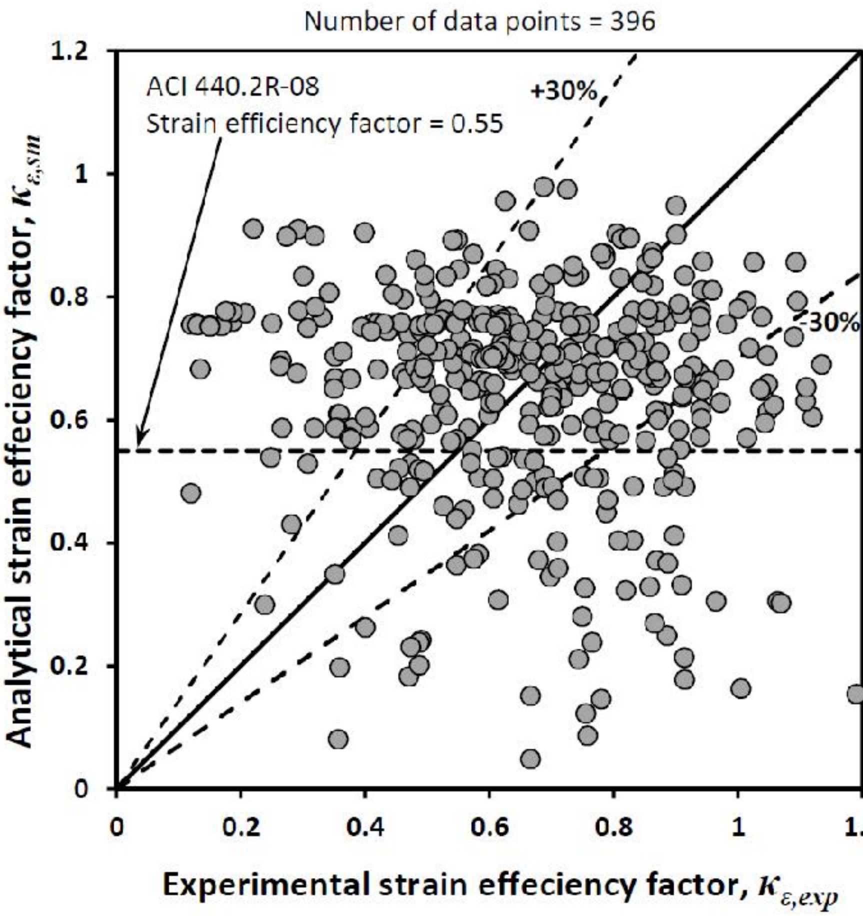

Figure 6. Variation of analytical strain efficiency factor based on the proposed simplified model as well as current ACI 440.2R-08 with experimental values

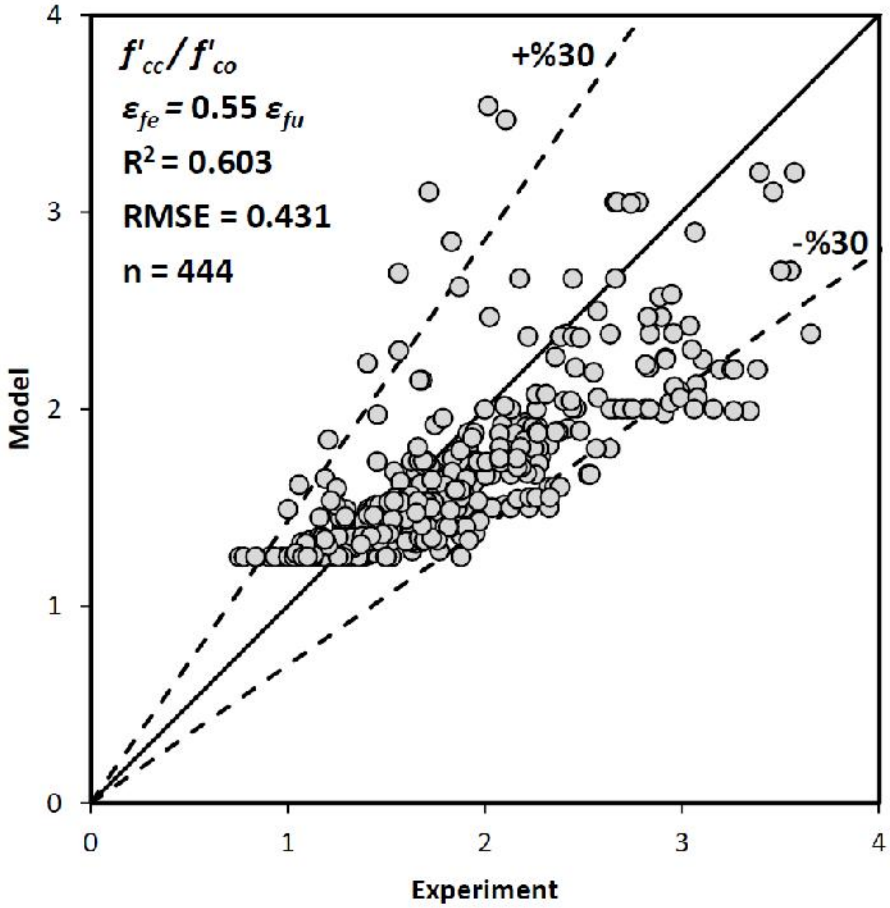

Figure 7. Predicted confinement ratio (f'_{cc}/f'_{co}) using ACI 440.2R-08 based on κ_ε = 0.55 (ψ_f = 0.95 and f_l/f'_{co}>0.08) vs. experimental (f'_{cc}/f'_{co}).

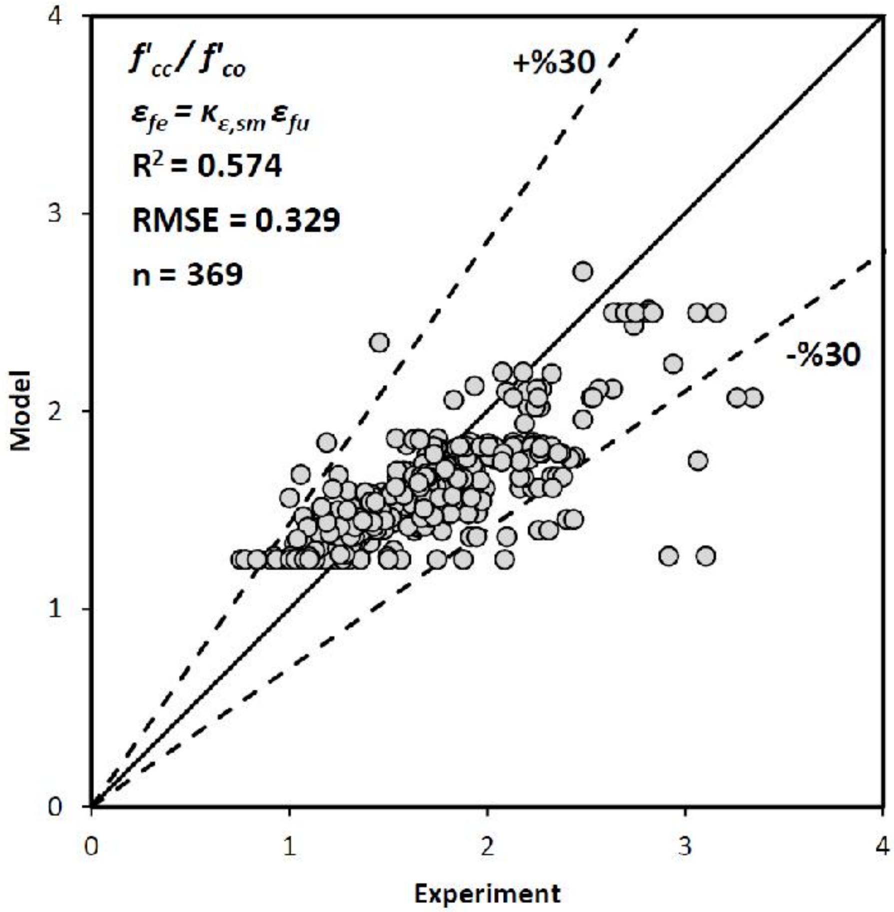

Figure 8. Predicted confinement ratio (f'_{cc}/f'_{co}) using ACI 440.2R-08 based on κ_{ε} from the proposed simplified model (ψ_f = 0.95 and f_l/f'_{co}>0.08) vs. experimental (f'_{cc}/f'_{co}).

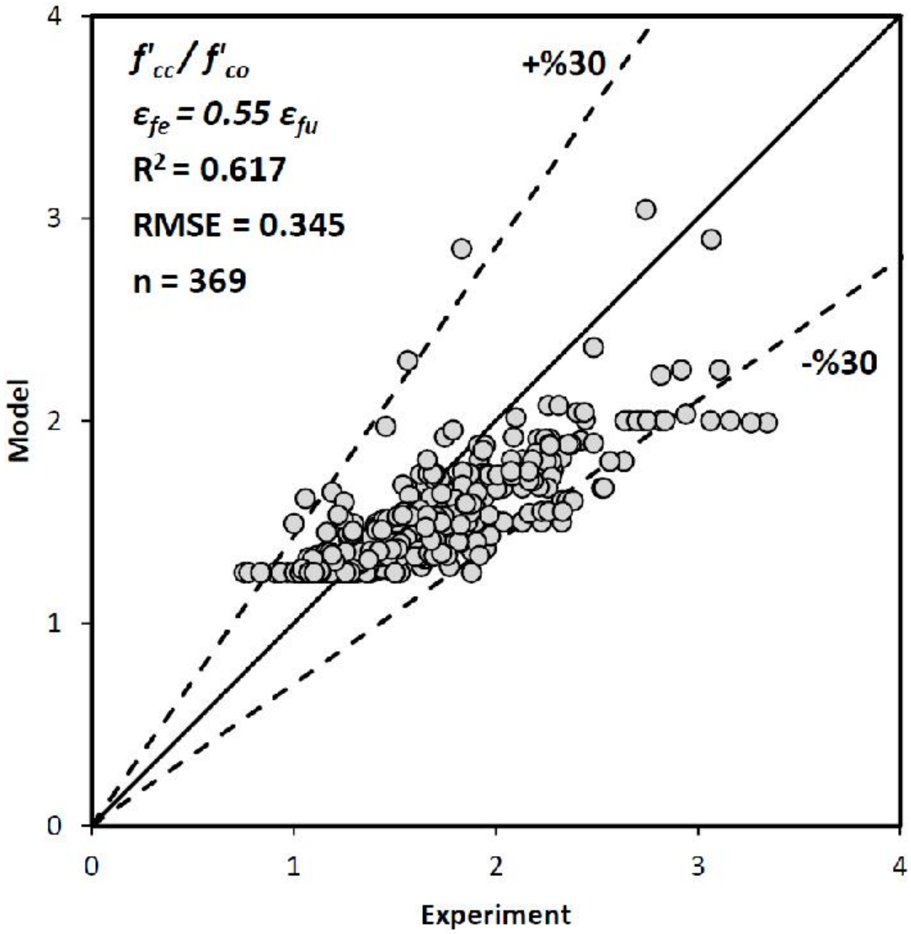

Figure 9. Predicted confinement ratio (f'_{cc}/f'_{co}) using ACI 440.2R-08 based on $\kappa_\varepsilon = 0.55$ (ψ_f = 0.95 and f_l/f'_{co}>0.08) vs. experimental (f'_{cc}/f'_{co}) for the 369 data points used in the simplified model.

Table 1. Database and comparison of experimental and analytical strain efficiency factors (1 ksi = 6.895 MPa, 1 in = 25.4 mm)

No.	Source of data	Fiber type	D (mm)	t (mm)	f'_{co} (MPa)	f'_{cc} (MPa)	ε_{ccu} (%)	ε_{fe} (%)	f_{fu} (MPa)	E_f (Gpa)	ε_{fu} (%)	$\kappa_{\varepsilon,exp}$	$\kappa_{\varepsilon,sm}$	Source of FRP data
1	Watanable et al. (1997)[a]	HC	100	0.14	30.2	41.7	0.57	0.230	1563	612	0.255	0.90	0.58	F
2	Watanable et al. (1997)[a]	HC	100	0.28	30.2	56.0	0.88	0.220	1563	612	0.255	0.86	*	F
3	Watanable et al. (1997)[a]	HC	100	0.42	30.2	63.3	1.30	0.220	1563	612	0.255	0.86	*	F
4	Matthys et al. (1999)[a]	HC	150	0.24	34.9	41.3	0.40	0.190	1100	420	0.262	0.73	0.95	F
5	Matthys et al. (1999)[a]	HC	150	0.24	34.9	40.7	0.36	0.180	1100	420	0.262	0.69	0.87	F
6	Dias da Silva and Santos (2001)[a]	HC	150	0.17	28.2	41.5	0.75	0.370	3000	390	0.769	0.48	0.71	M
7	Dias da Silva and Santos (2001)[a]	HC	150	0.33	28.2	65.6	1.81	0.690	3000	390	0.769	0.90	0.76	M
8	Dias da Silva and Santos (2001)[a]	HC	150	0.50	28.2	79.4	1.69	0.640	3000	390	0.769	0.83	0.78	M
9	Matthys et al. (1999)[a]	C	150	0.12	34.9	44.3	0.85	1.150	2600	200	1.300	0.88	0.98	F
10	Matthys et al. (1999)[a]	C	150	0.12	34.9	42.2	0.72	1.080	2600	200	1.300	0.83	0.98	F
11	Watanable et al. (1997)[a]	C	100	0.17	30.2	46.6	1.51	0.940	2749	225	1.224	0.77	0.68	F
12	Watanable et al. (1997)[a]	C	100	0.50	30.2	87.2	3.11	0.820	2749	225	1.224	0.67	0.96	F
13	Watanable et al. (1997)[a]	C	100	0.67	30.2	104.6	4.15	0.760	2749	225	1.224	0.62	0.51	F
14	Matthys et al. (1999)[b]	C-R	400	0.59	37.3	59.4	1.12	0.690	3900	260	1.500	0.46	0.54	N
15	Matthys et al. (1999)[b]	C-R	400	0.94	37.3	59.4	0.43	0.250	2650	663	0.400	0.63	0.62	N
16	Rochette and Labossiere (2000)[a]	C	100	0.60	42.0	73.5	1.65	0.890	1265	83	1.530	0.58	0.66	F
17	Rochette and Labossiere (2000)[a]	C	100	0.60	42.0	73.5	1.57	0.950	1265	83	1.530	0.62	0.60	F
18	Rochette and Labossiere (2000)[a]	C	100	0.60	42.0	67.6	1.35	0.800	1265	83	1.530	0.52	0.65	F
19	Xiao and Wu (2000)[a]	C	152	0.38	33.7	47.9	1.20	0.840	1577	105	1.502	0.56	0.50	F
20	Xiao and Wu (2000)[a]	C	152	0.38	33.7	49.7	1.40	1.150	1577	105	1.502	0.77	0.05	F
21	Xiao and Wu (2000)[a]	C	152	0.38	33.7	49.4	1.24	0.870	1577	105	1.502	0.58	0.15	F
22	Xiao and Wu (2000)[a]	C	152	0.76	33.7	64.6	1.65	0.910	1577	105	1.502	0.61	*	F
23	Xiao and Wu (2000)[a]	C	152	0.76	33.7	75.2	2.25	1.000	1577	105	1.502	0.67	*	F
24	Xiao and Wu (2000)[a]	C	152	0.76	33.7	71.8	2.16	1.000	1577	105	1.502	0.67	0.71	F
25	Xiao and Wu (2000)[a]	C	152	1.14	33.7	82.9	2.45	0.820	1577	105	1.502	0.55	0.76	F
26	Xiao and Wu (2000)[a]	C	152	1.14	33.7	95.4	3.03	0.900	1577	105	1.502	0.60	0.76	F
27	Xiao and Wu (2000)[a]	C	152	0.38	43.8	54.8	0.98	0.810	1577	105	1.502	0.54	0.54	F
28	Xiao and Wu (2000)[a]	C	152	0.38	43.8	52.1	0.47	0.760	1577	105	1.502	0.51	0.61	F
29	Xiao and Wu (2000)[a]	C	152	0.38	43.8	48.7	0.37	0.280	1577	105	1.502	0.19	0.50	F
30	Xiao and Wu (2000)[a]	C	152	0.76	43.8	84.0	1.57	0.920	1577	105	1.502	0.61	0.46	F
31	Xiao and Wu (2000)[a]	C	152	0.76	43.8	79.2	1.37	1.000	1577	105	1.502	0.67	0.49	F
32	Xiao and Wu (2000)[a]	C	152	0.76	43.8	85.0	1.66	1.010	1577	105	1.502	0.67	0.45	F
33	Xiao and Wu (2000)[a]	C	152	1.14	43.8	96.5	1.74	0.790	1577	105	1.502	0.53	0.75	F
34	Xiao and Wu (2000)[a]	C	152	1.14	43.8	92.6	1.68	0.710	1577	105	1.502	0.47	0.76	F
35	Xiao and Wu (2000)[a]	C	152	1.14	43.8	94.0	1.75	0.840	1577	105	1.502	0.56	0.76	F
36	Xiao and Wu (2000)[a]	C	152	0.38	55.2	57.9	0.69	0.700	1577	105	1.502	0.47	0.66	F
37	Xiao and Wu (2000)[a]	C	152	0.38	55.2	62.9	0.48	0.620	1577	105	1.502	0.41	0.73	F

38	Xiao and Wu (2000)[a]	C	152	0.38	55.2	58.1	0.49	0.190	1577	105	1.502	0.13	0.59	F
39	Xiao and Wu (2000)[a]	C	152	0.76	55.2	55.2	1.21	0.740	1578	106	1.489	0.50	0.59	F
40	Xiao and Wu (2000)[a]	C	152	0.76	55.2	77.6	0.81	0.830	1577	105	1.502	0.55	0.67	F
41	Xiao and Wu (2000)[a]	C	152	1.14	55.2	106.5	1.43	0.760	1577	105	1.502	0.51	0.73	F
42	Xiao and Wu (2000)[a]	C	152	1.14	55.2	108.0	1.45	0.850	1577	105	1.502	0.57	0.78	F
43	Xiao and Wu (2000)[a]	C	152	1.14	55.2	103.3	1.18	0.700	1577	105	1.502	0.47	0.78	F
44	De Lorenzis et al. (2002)[a]	C	120	0.30	43.0	58.5	1.16	0.700	1028	91	1.128	0.62	0.66	F
45	De Lorenzis et al. (2002)[a]	C	120	0.30	43.0	65.6	0.95	0.800	1028	91	1.128	0.71	0.69	F
46	De Lorenzis et al. (2002)[a]	C	150	0.45	38.0	62.0	0.95	0.800	1028	91	1.128	0.71	0.75	F
47	De Lorenzis et al. (2002)[a]	C	150	0.45	38.0	67.3	1.35	0.800	1028	91	1.128	0.71	0.66	F
48	Picher et al. (1996)[a]	C	152	0.36	39.7	56.0	1.07	0.840	1266	83	1.525	0.55	*	M
49	Purba and Mufti (1999)[a]	C	191	0.22	27.1	53.9	0.58	0.670	3483	231	1.511	0.44	*	M
50	Aire et al. (2001)[a]	C	150	0.12	42.0	46.0	1.10	0.950	3900	240	1.625	0.58	0.75	M
51	Aire et al. (2001)[a]	C	150	0.35	42.0	77.0	2.26	1.050	3900	240	1.625	0.65	0.24	M
52	Aire et al. (2001)[a]	C	150	0.70	42.0	108.0	3.23	1.060	3900	240	1.625	0.65	*	M
53	Dias da Silva and Santos (2001)[a]	C	150	0.11	28.2	31.4	0.39	0.260	3700	240	1.542	0.17	0.86	M
54	Dias da Silva and Santos (2001)[a]	C	150	0.22	28.2	57.4	2.05	1.180	3700	240	1.542	0.77	0.41	M
55	Dias da Silva and Santos (2001)[a]	C	150	0.33	28.2	69.5	2.59	1.140	3700	240	1.542	0.74	0.49	M
56	Micelli et al. (2001)[a]	C	102	0.16	37.0	60.0	1.02	1.200	3790	227	1.670	0.72	0.67	M
57	Micelli et al. (2001)[a]	C	152	1.00	26.2	50.6	1.44	0.810	580	38	1.522	0.53	0.61	M
58	Micelli et al. (2001)[a]	C	152	2.00	26.2	64.0	1.65	0.720	580	38	1.522	0.47	0.53	M
59	Wang and Cheong (2001)[a] **	C	200	0.36	27.9	82.8	1.52	0.850	4400	235	1.872	0.45	0.52	M
60	Wang and Cheong (2001)[a]	C	200	0.36	27.9	81.2	1.43	1.070	4400	235	1.872	0.57	0.55	M
61	Shehata et al. (2002)[a]	C	150	0.17	29.8	57.0	1.23	1.230	3550	235	1.511	0.81	0.65	M
62	Shehata et al. (2002)[a]	C	150	0.33	29.8	72.1	1.74	1.190	3550	235	1.511	0.79	0.45	M
63	Wang and Wu (2008)	C	150	0.17	30.9	55.8	2.50	1.110	4364	219	1.993	0.56	*	F
64	Wang and Wu (2008)	C	150	0.17	52.1	67.9	3.36	1.110	4364	219	1.993	0.56	*	F
65	Wang and Wu (2008)	C	150	0.33	52.1	99.3	2.00	1.440	3788	197	1.923	0.75	0.28	F
66	Toutanji (1999)	C	76	0.22	30.9	95.0	2.45	1.250	3485	231	1.512	0.83	*	F
67	Toutanji (1999)	C	76	0.33	30.9	94.0	1.55	0.550	2940	373	0.789	0.70	0.57	F
68	Lam and Teng (2004)	C	152	0.17	35.9	50.4	1.27	1.147	4217	259	1.629	0.70	0.62	F
69	Lam and Teng (2004)	C	152	0.17	35.9	47.2	1.11	0.969	4217	259	1.629	0.59	0.66	F
70	Lam and Teng (2004)	C	152	0.17	35.9	53.2	1.29	0.981	4217	259	1.629	0.60	0.62	F
71	Lam and Teng (2004)	C	152	0.33	35.9	68.7	1.68	0.988	4217	259	1.629	0.61	0.47	F
72	Lam and Teng (2004)	C	152	0.33	35.9	69.9	1.96	1.001	4217	259	1.629	0.61	0.31	F
73	Lam and Teng (2004)	C	152	0.33	34.3	71.6	1.85	0.949	4217	259	1.629	0.58	0.38	F
74	Lam and Teng (2004)	C	152	0.50	34.3	82.6	2.05	0.799	4217	259	1.629	0.49	0.24	F
75	Lam and Teng (2004)	C	152	0.50	34.3	90.4	2.41	0.884	4217	259	1.629	0.54	*	F
76	Lam and Teng (2004)	C	152	0.50	34.3	97.3	2.52	0.968	4217	259	1.629	0.59	*	F
77	Lam and Teng (2004)	C	152	0.17	34.3	50.3	1.02	0.908	4217	259	1.629	0.56	0.68	F
78	Lam and Teng (2004)	C	152	0.17	34.3	50.0	1.08	0.890	4217	259	1.629	0.55	0.67	F
79	Lam and Teng (2004)	C	152	0.17	34.3	56.7	1.17	0.927	4217	259	1.629	0.57	0.65	F
80	Shahawy et al. (2000)	C	152	0.50	19.7	33.8	1.59	0.740	3654	207	1.765	0.42	0.50	M
81	Shahawy et al. (2000) **	C	152	1.00	19.7	46.4	2.21	0.630	3654	207	1.765	0.36	0.08	M

82	Shahawy et al. (2000) **	C	152	1.50	19.7	62.6	2.58	0.570	3654	207	1.765	0.32	*	M
83	Shahawy et al. (2000) **	C	152	2.00	19.7	75.7	3.56	0.590	3654	207	1.765	0.33	*	M
84	Shahawy et al. (2000) **	C	152	2.50	19.7	80.2	3.42	0.600	3654	207	1.765	0.34	*	M
85	Shahawy et al. (2000)	C	152	0.50	49.0	59.1	0.62	0.620	3654	207	1.765	0.35	0.70	M
86	Shahawy et al. (2000)	C	152	1.00	49.0	76.5	0.97	0.620	3654	207	1.765	0.35	0.67	M
87	Shahawy et al. (2000)	C	152	1.50	49.0	98.8	1.26	0.630	3654	207	1.765	0.36	0.61	M
88	Shahawy et al. (2000)	C	152	2.00	49.0	112.7	1.90	0.620	3654	207	1.765	0.35	0.35	M
89	Berthet et al. (2005)	C	160	0.17	25.0	42.8	1.63	0.957	3200	230	1.391	0.69	0.51	M
90	Berthet et al. (2005)	C	160	0.17	25.0	37.8	0.93	0.964	3200	230	1.391	0.69	0.73	M
91	Berthet et al. (2005)	C	160	0.17	25.0	45.8	1.67	0.960	3200	230	1.391	0.69	0.49	M
92	Berthet et al. (2005)	C	160	0.33	25.0	56.7	1.73	0.899	3200	230	1.391	0.65	0.46	M
93	Berthet et al. (2005)	C	160	0.33	25.0	55.2	1.58	0.911	3200	230	1.391	0.65	0.54	M
94	Berthet et al. (2005)	C	160	0.33	25.0	56.1	1.68	0.908	3200	230	1.391	0.65	0.49	M
95	Berthet et al. (2005)	C	160	0.11	40.1	49.8	0.55	1.015	3200	230	1.391	0.73	0.78	M
96	Berthet et al. (2005)	C	160	0.11	40.1	50.8	0.66	0.952	3200	230	1.391	0.68	0.77	M
97	Berthet et al. (2005)	C	160	0.11	40.1	48.8	0.61	1.203	3200	230	1.391	0.86	0.77	M
98	Berthet et al. (2005)	C	160	0.17	40.1	53.7	0.66	0.880	3200	230	1.391	0.63	0.77	M
99	Berthet et al. (2005)	C	160	0.17	40.1	54.7	0.62	0.853	3200	230	1.391	0.61	0.77	M
100	Berthet et al. (2005)	C	160	0.17	40.1	51.8	0.64	1.042	3200	230	1.391	0.75	0.77	M
101	Berthet et al. (2005)	C	160	0.22	40.1	59.7	0.60	0.788	3200	230	1.391	0.57	0.77	M
102	Berthet et al. (2005)	C	160	0.22	40.1	60.7	0.69	0.830	3200	230	1.391	0.60	0.76	M
103	Berthet et al. (2005)	C	160	0.22	40.1	60.2	0.73	0.809	3200	230	1.391	0.58	0.76	M
104	Berthet et al. (2005)	C	160	0.44	40.1	91.6	1.44	0.924	3200	230	1.391	0.66	0.59	M
105	Berthet et al. (2005)	C	160	0.44	40.1	89.6	1.36	0.967	3200	230	1.391	0.70	0.62	M
106	Berthet et al. (2005)	C	160	0.44	40.1	86.6	1.17	0.885	3200	230	1.391	0.64	0.68	M
107	Berthet et al. (2005)	C	160	0.99	40.1	142.4	2.46	0.989	3200	230	1.391	0.71	*	M
108	Berthet et al. (2005)	C	160	0.99	40.1	140.4	2.39	1.002	3200	230	1.391	0.72	*	M
109	Berthet et al. (2005)	C	160	1.32	40.1	166.3	2.70	0.999	3200	230	1.391	0.72	*	M
110	Berthet et al. (2005)	C	160	0.33	52.0	82.6	0.83	0.934	3200	230	1.391	0.67	0.75	M
111	Berthet et al. (2005)	C	160	0.33	52.0	82.8	0.70	0.865	3200	230	1.391	0.62	0.76	M
112	Berthet et al. (2005)	C	160	0.33	52.0	82.3	0.77	0.891	3200	230	1.391	0.64	0.76	M
113	Berthet et al. (2005)	C	160	0.66	52.0	108.1	1.14	0.667	3200	230	1.391	0.48	0.69	M
114	Berthet et al. (2005)	C	160	0.66	52.0	112.0	1.12	0.871	3200	230	1.391	0.63	0.69	M
115	Berthet et al. (2005)	C	160	0.66	52.0	107.9	1.12	0.882	3200	230	1.391	0.63	0.69	M
116	Berthet et al. (2005)	C	70	0.33	112.6	141.1	0.45	0.712	3200	230	1.391	0.51	0.78	M
117	Berthet et al. (2005)	C	70	0.33	112.6	143.1	0.49	0.738	3200	230	1.391	0.53	0.78	M
118	Berthet et al. (2005)	C	70	0.82	112.6	189.5	0.72	0.754	3200	230	1.391	0.54	0.76	M
119	Berthet et al. (2005)	C	70	0.82	112.6	187.9	0.70	0.728	3200	230	1.391	0.52	0.76	M
120	Berthet et al. (2005)	C	70	0.33	169.7	186.4	0.67	0.459	3200	230	1.391	0.33	0.77	M
121	Berthet et al. (2005)	C	70	0.99	169.7	296.4	1.02	0.799	3200	230	1.391	0.57	0.72	M
122	Rousakis and Tepfers (2004)	C	150	0.17	25.2	41.6	1.44	0.700	4410	377	1.170	0.60	0.61	M
123	Rousakis and Tepfers (2004)	C	150	0.17	25.2	38.8	1.21	0.580	4410	377	1.170	0.50	0.69	M
124	Rousakis and Tepfers (2004)	C	150	0.17	25.2	44.1	1.53	0.640	4410	377	1.170	0.55	0.57	M
125	Rousakis and Tepfers (2004)	C	150	0.34	25.2	60.1	1.88	0.640	4410	377	1.170	0.55	0.36	M

126	Rousakis and Tepfers (2004)	C	150	0.34	25.2	55.9	2.10	0.550	4410	377	1.170	0.47	0.18	M
127	Rousakis and Tepfers (2004)	C	150	0.34	25.2	61.6	2.08	0.570	4410	377	1.170	0.49	0.20	M
128	Rousakis and Tepfers (2004)	C	150	0.51	25.2	67.0	2.45	0.450	4410	377	1.170	0.38	*	M
129	Rousakis and Tepfers (2004)	C	150	0.51	25.2	67.3	2.43	0.370	4410	377	1.170	0.32	*	M
130	Rousakis and Tepfers (2004)	C	150	0.51	25.2	70.0	2.44	0.440	4410	377	1.170	0.38	*	M
131	Rousakis and Tepfers (2004)	C	150	0.17	51.8	78.7	0.75	0.540	4410	377	1.170	0.46	0.80	M
132	Rousakis and Tepfers (2004)	C	150	0.17	51.8	72.8	0.66	0.400	4410	377	1.170	0.34	0.81	M
133	Rousakis and Tepfers (2004)	C	150	0.17	51.8	79.2	0.68	0.520	4410	377	1.170	0.44	0.81	M
134	Rousakis and Tepfers (2004)	C	150	0.34	51.8	95.4	1.05	0.550	4410	377	1.170	0.47	0.74	M
135	Rousakis and Tepfers (2004)	C	150	0.34	51.8	90.7	1.00	0.360	4410	377	1.170	0.31	0.75	M
136	Rousakis and Tepfers (2004)	C	150	0.34	51.8	90.3	1.02	0.510	4410	377	1.170	0.44	0.74	M
137	Rousakis and Tepfers (2004)	C	150	0.51	51.8	110.5	1.29	0.440	4410	377	1.170	0.38	0.67	M
138	Rousakis and Tepfers (2004)	C	150	0.51	51.8	103.6	1.20	0.310	4410	377	1.170	0.27	0.70	M
139	Rousakis and Tepfers (2004)	C	150	0.51	51.8	117.2	1.53	0.560	4410	377	1.170	0.48	0.57	M
140	Rousakis and Tepfers (2004)	C	150	0.85	51.8	112.7	1.59	0.290	4410	377	1.170	0.25	0.54	M
141	Rousakis and Tepfers (2004)	C	150	0.85	51.8	126.7	1.61	0.360	4410	377	1.170	0.31	0.53	M
142	Rousakis and Tepfers (2004)	C	150	0.85	51.8	137.9	1.81	0.530	4410	377	1.170	0.45	0.41	M
143	Harmon and Slattery (1992)[b]	C	51	0.09	41.0	86.0	1.15	1.130	3500	235	1.489	0.76	0.67	N
144	Harmon and Slattery (1992)[b]	C	51	0.18	41.0	120.5	1.57	1.000	3500	235	1.489	0.67	0.53	N
145	Harmon and Slattery (1992)[b] **	C	51	0.34	41.0	158.4	2.50	0.750	3500	235	1.489	0.50	*	N
146	Harmon and Slattery (1992)[b] **	C	51	0.69	41.0	241.0	3.60	0.250	3500	235	1.489	0.17	*	N
147	Harmon and Slattery (1992)[b]	C	51	0.18	103.0	131.1	1.10	0.200	3500	235	1.489	0.13	0.68	N
148	Harmon and Slattery (1992)[b]	C	51	0.34	103.0	193.2	2.05	0.725	3500	235	1.489	0.49	0.24	N
149	Harmon and Slattery (1992)[b]	C	51	0.69	103.0	303.6	3.45	0.550	3500	235	1.489	0.37	*	N
150	Howie and Karbhari (1995)[b]	C	152	0.33	42.5	44.9	1.10	0.447	3500	227	1.542	0.29	0.68	N
151	Howie and Karbhari (1995)[b]	C	152	0.66	42.5	59.7	1.35	0.553	3500	227	1.542	0.36	0.61	N
152	Howie and Karbhari (1995)[b]	C	152	0.99	42.5	77.7	2.10	0.553	3500	227	1.542	0.36	0.20	N
153	Howie and Karbhari (1995)[b]	C	152	1.32	42.5	89.5	2.29	0.342	3500	227	1.542	0.22	*	N
154	Kono et al. (1998)[b]	C	100	0.17	34.3	61.2	0.95	0.880	3820	235	1.626	0.54	0.69	N
155	Kono et al. (1998)[b]	C	100	0.17	32.3	59.2	1.07	0.795	3820	235	1.626	0.49	0.67	N
156	Kono et al. (1998)[b]	C	100	0.33	32.3	80.2	1.75	0.890	3820	235	1.626	0.55	0.44	N
157	Kono et al. (1998)[b]	C	100	0.50	32.3	88.5	1.62	0.720	3820	235	1.626	0.44	0.50	N
158	Kono et al. (1998)[b]	C	100	0.17	34.8	54.7	0.99	0.803	3820	235	1.626	0.49	0.68	N
159	Kono et al. (1998)[b]	C	100	0.33	34.8	82.1	2.06	0.770	3820	235	1.626	0.47	0.23	N
160	Kono et al. (1998)[b]	C	100	0.50	34.8	106.7	2.43	0.855	3820	235	1.626	0.53	*	N
161	Toutanji and Deng (2001)[b]	C	76	0.57	31.8	140.9	2.05	1.545	2059	118	1.745	0.89	0.25	N
162	Toutanji and Deng (2001)[b]	C	76	0.24	31.8	60.8	1.53	1.624	1519	73	2.092	0.78	0.51	N
163	Toutanji and Deng (2001)[b]	C	76	0.22	31.8	95.0	2.45	1.260	3485	231	1.512	0.83	*	N
164	Toutanji and Deng (2001)[b]	C	76	0.33	31.8	94.0	1.55	0.542	2940	373	0.789	0.69	0.57	N
165	Youseff (2003)[b]	C	406	1.17	29.4	45.9	0.63	0.816	1246	105	1.184	0.69	0.81	N
166	Youseff (2003)[b]	C	406	2.34	29.4	64.8	1.16	1.206	1246	105	1.184	1.02	0.72	N
167	Youseff (2003)[b]	C	406	3.51	29.4	85.9	1.56	1.202	1246	105	1.184	1.01	0.57	N
168	Youseff (2003)[b]	C	406	5.84	29.4	126.4	2.84	1.240	1246	105	1.184	1.05	*	N
169	Youseff (2003)[b]	C	153	0.58	44.1	86.1	1.90	1.029	1246	105	1.184	0.87	0.37	N

170	Youseff (2003)[b]	C	153	1.17	44.1	96.6	1.99	1.260	1246	105	1.184	1.06	0.31	N
171	Youseff (2003)[b]	C	153	1.75	44.1	130.7	2.83	0.967	1246	105	1.184	0.82	*	N
172	Youseff (2003)[b]	C-R	406	2.34	45.6	79.5	1.68	0.892	1246	105	1.184	0.75	0.51	N
173	Youseff (2003)[b]	C-R	406	2.34	38.3	73.1	1.05	0.964	1246	105	1.184	0.81	0.74	N
174	Carey and Harries (2003, 2005)	C	152	0.20	33.5	47.0	0.97	1.075	3500	250	1.400	0.77	0.72	N
175	Carey and Harries (2003, 2005)	C	152	0.20	33.5	47.6	0.88	1.136	3500	250	1.400	0.81	0.74	N
176	Carey and Harries (2003, 2005)	C	254	1.00	38.9	54.2	0.99	0.508	875	73	1.207	0.42	0.76	N
177	Carey and Harries (2003, 2005)	C	153	0.10	32.1	32.9	0.60	0.823	3500	250	1.400	0.59	0.77	N
178	Carey and Harries (2003, 2005)	C	153	0.20	32.1	41.7	0.86	1.043	3500	250	1.400	0.75	0.74	N
179	Carey and Harries (2003, 2005)	C	153	0.30	32.1	52.2	1.38	1.230	3500	250	1.400	0.88	0.61	N
180	Bullo (2003)[c]	C	150	0.17	32.5	52.6	0.83	0.470	3000	390	0.769	0.61	0.84	N
181	Bullo (2003)[c]	C	150	0.17	32.5	56.6	0.93	0.524	3000	390	0.769	0.68	0.82	N
182	Bullo (2003)[c]	C	150	0.17	32.5	61.1	0.83	0.424	3000	390	0.769	0.55	0.84	N
183	Bullo (2003)[c]	C	150	0.50	32.5	97.3	1.82	0.639	3000	390	0.769	0.83	0.40	N
184	Bullo (2003)[c]	C	150	0.50	32.5	83.8	1.27	0.439	3000	390	0.769	0.57	0.71	N
185	Bullo (2003)[c]	C	150	0.50	32.5	100.2	1.69	0.539	3000	390	0.769	0.70	0.49	N
186	Demers and Neale (1994)[c]	C	152	1.00	43.7	48.4	0.97	1.275	375	25	1.500	0.85	0.73	M
187	Demers and Neale (1994)[c]	C	152	3.00	43.7	75.2	1.83	1.065	375	25	1.500	0.71	0.47	M
188	Demers and Neale (1994)[c]	C	152	3.00	43.7	73.4	1.83	1.185	375	25	1.500	0.79	0.47	M
189	Demers and Neale (1994)[c]	C	152	1.00	32.2	41.1	1.41	1.365	375	25	1.500	0.91	0.64	M
190	Jiang and Teng (2007)	C	152	0.68	38.0	110.1	2.55	0.977	3615	241	1.502	0.65	*	F
191	Jiang and Teng (2007)	C	152	0.68	38.0	107.4	2.61	0.965	3615	241	1.502	0.64	*	F
192	Jiang and Teng (2007)	C	152	1.02	38.0	129.0	2.79	0.892	3615	241	1.502	0.59	*	F
193	Jiang and Teng (2007)	C	152	1.02	38.0	135.7	3.08	0.927	3615	241	1.502	0.62	*	F
194	Jiang and Teng (2007)	C	152	1.36	38.0	161.3	3.70	0.872	3615	241	1.502	0.58	*	F
195	Jiang and Teng (2007)	C	152	1.36	38.0	158.5	3.54	0.877	3615	241	1.502	0.58	*	F
196	Jiang and Teng (2007)	C	152	0.11	37.7	48.5	0.90	0.935	3900	260	1.500	0.62	0.72	F
197	Jiang and Teng (2007)	C	152	0.11	37.7	50.3	0.91	1.092	3900	260	1.500	0.73	0.72	F
198	Jiang and Teng (2007)	C	152	0.11	44.2	48.1	0.69	0.734	3900	260	1.500	0.49	0.74	F
199	Jiang and Teng (2007)	C	152	0.11	44.2	51.1	0.89	0.969	3900	260	1.500	0.65	0.72	F
200	Jiang and Teng (2007)	C	152	0.22	44.2	65.7	1.30	1.184	3900	260	1.500	0.79	0.63	F
201	Jiang and Teng (2007)	C	152	0.22	44.2	62.9	1.03	0.938	3900	260	1.500	0.63	0.70	F
202	Jiang and Teng (2007)	C	152	0.33	47.6	82.7	1.30	0.902	3900	260	1.500	0.60	0.63	F
203	Jiang and Teng (2007)	C	152	0.33	47.6	85.5	1.94	1.130	3900	260	1.500	0.75	0.33	F
204	Jiang and Teng (2007)	C	152	0.33	47.6	85.5	1.82	1.064	3900	260	1.500	0.71	0.40	F
205	Lam et al. (2006)	C	152	0.17	41.1	52.6	0.90	0.810	3800	250	1.520	0.53	0.72	F
206	Lam et al. (2006)	C	152	0.17	41.1	57.0	1.21	1.080	3800	250	1.520	0.71	0.65	F
207	Lam et al. (2006)	C	152	0.17	41.1	55.4	1.11	1.070	3800	250	1.520	0.70	0.68	F
208	Lam et al. (2006)	C	152	0.17	41.1	60.2	1.34	1.320	3800	250	1.520	0.87	0.61	F
209	Lam et al. (2006)	C	152	0.17	41.1	56.8	1.17	1.030	3800	250	1.520	0.68	0.66	F
210	Lam et al. (2006)	C	152	0.17	41.1	56.5	1.20	1.130	3800	250	1.520	0.74	0.65	F
211	Lam et al. (2006)	C	152	0.33	38.9	76.8	1.91	1.060	3800	250	1.520	0.70	0.35	F
212	Lam et al. (2006)	C	152	0.33	38.9	79.1	2.08	1.130	3800	250	1.520	0.74	0.21	F
213	Lam et al. (2006)	C	152	0.33	38.9	65.8	1.25	0.790	3800	250	1.520	0.52	0.64	F

214	Lam et al. (2006)	C	152	0.33	38.9	81.5	2.44	1.220	3800	250	1.520	0.80	*	F
215	Lam et al. (2006)	C	152	0.33	38.9	78.2	1.89	1.080	3800	250	1.520	0.71	0.36	F
216	Lam et al. (2006)	C	152	0.33	38.9	85.6	2.34	1.220	3800	250	1.520	0.80	*	F
217	Modarelli et al. (2005)[c]	C	150	0.17	28.0	55.3	0.90	1.526	3094	221	1.400	1.09	0.74	N
218	Modarelli et al. (2005)[c]	C	150	0.17	38.0	62.7	0.48	1.316	3094	221	1.400	0.94	0.78	N
219	Cui and Sheikh (2010)	C	152	1.00	48.1	80.9	1.51	1.052	849	85	1.004	1.05	0.61	F
220	Cui and Sheikh (2010)	C	152	1.00	48.1	86.6	1.53	1.124	849	85	1.004	1.12	0.60	F
221	Cui and Sheikh (2010)	C	152	2.00	48.1	109.4	2.01	0.968	849	85	1.004	0.96	0.31	F
222	Cui and Sheikh (2010)	C	152	2.00	48.1	126.7	2.66	1.221	849	85	1.004	1.22	*	F
223	Cui and Sheikh (2010)	C	152	3.00	48.1	162.7	3.09	1.158	849	85	1.004	1.15	*	F
224	Cui and Sheikh (2010)	C	152	3.00	48.1	153.6	2.89	1.035	849	85	1.004	1.03	*	F
225	Cui and Sheikh (2010)	C	152	1.00	48.1	84.2	1.55	1.047	849	85	1.004	1.04	0.60	F
226	Cui and Sheikh (2010)	C	152	1.00	48.1	87.9	1.69	1.216	849	85	1.004	1.21	0.52	F
227	Cui and Sheikh (2010)	C	152	2.00	48.1	123.3	2.37	1.062	849	85	1.004	1.06	*	F
228	Cui and Sheikh (2010)	C	152	2.00	48.1	108.2	1.93	0.890	849	85	1.004	0.89	0.37	F
229	Cui and Sheikh (2010)	C	152	3.00	48.1	156.5	3.13	1.089	849	85	1.004	1.09	*	F
230	Cui and Sheikh (2010)	C	152	3.00	48.1	157.0	2.84	1.136	849	85	1.004	1.13	*	F
231	Cui and Sheikh (2010)	C	152	1.00	79.9	90.9	0.53	1.097	849	85	1.004	1.09	0.86	F
232	Cui and Sheikh (2010)	C	152	1.00	79.9	105.3	0.74	0.917	849	85	1.004	0.91	0.83	F
233	Cui and Sheikh (2010)	C	152	2.00	79.9	142.1	1.13	0.985	849	85	1.004	0.98	0.76	F
234	Cui and Sheikh (2010)	C	152	2.00	79.9	140.8	0.97	1.099	849	85	1.004	1.10	0.79	F
235	Cui and Sheikh (2010)	C	152	3.00	79.9	172.9	1.48	0.975	849	85	1.004	0.97	0.63	F
236	Cui and Sheikh (2010)	C	152	3.00	79.9	181.8	1.47	1.113	849	85	1.004	1.11	0.63	F
237	Cui and Sheikh (2010)	C	152	1.00	110.6	107.3	0.52	1.029	849	85	1.004	1.03	0.86	F
238	Cui and Sheikh (2010)	C	152	1.00	110.6	116.6	0.55	0.855	849	85	1.004	0.85	0.85	F
239	Cui and Sheikh (2010)	C	152	3.00	110.6	198.4	0.84	0.867	849	85	1.004	0.86	0.82	F
240	Cui and Sheikh (2010)	C	152	3.00	110.6	182.3	0.73	0.746	849	85	1.004	0.74	0.84	F
241	Cui and Sheikh (2010)	C	152	0.11	45.6	57.7	1.21	1.678	3649	241	1.512	1.11	0.65	F
242	Cui and Sheikh (2010)	C	152	0.11	45.6	55.4	1.31	1.599	3649	241	1.512	1.06	0.62	F
243	Cui and Sheikh (2010)	C	152	0.22	45.6	78.0	1.97	1.616	3649	241	1.512	1.07	0.30	F
244	Cui and Sheikh (2010)	C	152	0.22	45.6	86.8	2.14	1.801	3649	241	1.512	1.19	0.15	F
245	Cui and Sheikh (2010)	C	152	0.33	45.6	106.5	2.90	1.786	3649	241	1.512	1.18	*	F
246	Cui and Sheikh (2010)	C	152	0.33	45.6	106.0	2.83	1.798	3649	241	1.512	1.19	*	F
247	Cui and Sheikh (2010)	C	152	0.11	45.6	56.3	1.23	1.573	3649	241	1.512	1.04	0.65	F
248	Cui and Sheikh (2010)	C	152	0.11	45.6	58.8	1.19	1.584	3649	241	1.512	1.05	0.66	F
249	Cui and Sheikh (2010)	C	152	0.22	45.6	81.9	1.87	1.027	3649	241	1.512	0.68	0.37	F
250	Cui and Sheikh (2010)	C	152	0.22	45.6	82.8	2.17	1.142	3649	241	1.512	0.76	0.12	F
251	Cui and Sheikh (2010)	C	152	0.33	45.6	107.3	2.86	1.152	3649	241	1.512	0.76	*	F
252	Cui and Sheikh (2010)	C	152	0.33	45.6	108.6	2.78	1.148	3649	241	1.512	0.76	*	F
253	Cui and Sheikh (2010)	C	152	0.11	85.6	64.4	0.44	0.823	3649	241	1.512	0.54	0.76	F
254	Cui and Sheikh (2010)	C	152	0.11	85.6	66.6	0.44	0.758	3649	241	1.512	0.50	0.76	F
255	Cui and Sheikh (2010)	C	152	0.22	85.6	78.9	0.56	0.736	3649	241	1.512	0.49	0.75	F
256	Cui and Sheikh (2010)	C	152	0.22	85.6	86.1	0.58	0.763	3649	241	1.512	0.50	0.75	F
257	Cui and Sheikh (2010)	C	152	0.44	85.6	125.4	1.00	0.886	3649	241	1.512	0.59	0.70	F

258	Cui and Sheikh (2010)	C	152	0.44	85.6	126.5	0.99	0.924	3649	241	1.512	0.61	0.70	F
259	Cui and Sheikh (2010)	C	152	0.22	111.8	101.1	0.32	0.937	3649	241	1.512	0.62	0.76	F
260	Cui and Sheikh (2010)	C	152	0.22	111.8	94.3	0.48	0.825	3649	241	1.512	0.55	0.76	F
261	Cui and Sheikh (2010)	C	152	0.56	111.8	152.1	0.50	0.753	3649	241	1.512	0.50	0.76	F
262	Cui and Sheikh (2010)	C	152	0.56	111.8	145.3	0.58	0.597	3649	241	1.512	0.39	0.75	F
263	Cui and Sheikh (2010)	C	152	0.16	45.7	67.5	1.11	0.789	3325	438	0.760	1.04	0.77	F
264	Cui and Sheikh (2010)	C	152	0.16	45.7	64.1	1.03	0.769	3325	438	0.760	1.01	0.79	F
265	Cui and Sheikh (2010)	C	152	0.33	45.7	84.2	1.33	0.642	3325	438	0.760	0.84	0.68	F
266	Cui and Sheikh (2010)	C	152	0.33	45.7	83.1	1.23	0.634	3325	438	0.760	0.83	0.72	F
267	Cui and Sheikh (2010)	C	152	0.49	45.7	99.7	1.56	0.603	3325	438	0.760	0.79	0.57	F
268	Cui and Sheikh (2010)	C	152	0.49	45.7	94.9	1.43	0.546	3325	438	0.760	0.72	0.64	F
269	Cui and Sheikh (2010)	C	152	0.16	45.7	65.8	0.97	0.716	3325	438	0.760	0.94	0.81	F
270	Cui and Sheikh (2010)	C	152	0.16	45.7	65.9	1.03	0.770	3325	438	0.760	1.01	0.79	F
271	Cui and Sheikh (2010)	C	152	0.33	45.7	88.1	1.42	0.692	3325	438	0.760	0.91	0.64	F
272	Cui and Sheikh (2010)	C	152	0.33	45.7	82.0	1.23	0.609	3325	438	0.760	0.80	0.72	F
273	Cui and Sheikh (2010)	C	152	0.65	45.7	103.2	1.53	0.362	3325	438	0.760	0.48	0.58	F
274	Cui and Sheikh (2010)	C	152	0.65	45.7	105.6	1.86	0.437	3325	438	0.760	0.58	0.37	F
275	Cui and Sheikh (2010)	C	152	0.16	85.7	91.5	0.42	0.303	3325	438	0.760	0.40	0.90	F
276	Cui and Sheikh (2010)	C	152	0.16	85.7	94.5	0.54	0.417	3325	438	0.760	0.55	0.89	F
277	Cui and Sheikh (2010)	C	152	0.33	85.7	117.7	0.71	0.436	3325	438	0.760	0.57	0.87	F
278	Cui and Sheikh (2010)	C	152	0.33	85.7	117.5	0.55	0.411	3325	438	0.760	0.54	0.89	F
279	Cui and Sheikh (2010)	C	152	0.65	85.7	161.6	1.02	0.383	3325	438	0.760	0.50	0.80	F
280	Cui and Sheikh (2010)	C	152	0.65	85.7	162.6	0.95	0.377	3325	438	0.760	0.50	0.82	F
281	Cui and Sheikh (2010)	C	152	0.33	111.8	139.1	0.32	0.222	3325	438	0.760	0.29	0.91	F
282	Cui and Sheikh (2010)	C	152	0.33	111.8	123.3	0.31	0.167	3325	438	0.760	0.22	0.91	F
283	Cui and Sheikh (2010)	C	152	0.82	111.8	176.4	0.49	0.242	3325	438	0.760	0.32	0.90	F
284	Cui and Sheikh (2010)	C	152	0.82	111.8	172.5	0.50	0.208	3325	438	0.760	0.27	0.90	F
285	Smith et al. (2010)	C	250	0.26	35.0	43.0	0.36	0.692	3182	211	1.512	0.46	0.76	F
286	Smith et al. (2010)	C	250	0.26	35.0	50.0	0.42	0.893	3182	211	1.512	0.59	0.76	F
287	Smith et al. (2010)	C	250	0.26	35.0	57.0	0.68	1.218	3182	211	1.512	0.81	0.74	F
288	Smith et al. (2010)	C	250	0.26	35.0	59.0	0.54	1.311	3182	211	1.512	0.87	0.75	F
289	Smith et al. (2010)	C	250	0.26	35.0	56.0	0.45	1.149	3182	211	1.512	0.76	0.76	F
290	Benzaid et al. (2010)	C	160	1.00	29.5	50.6	1.59	1.315	476	34	1.400	0.94	0.57	F
291	Benzaid et al. (2010)	C	160	1.00	29.5	49.2	1.48	1.316	476	34	1.400	0.94	0.62	F
292	Benzaid et al. (2010)	C	160	3.00	29.5	70.8	2.22	1.406	476	34	1.400	1.00	0.16	F
293	Benzaid et al. (2010)	C	160	3.00	29.5	71.9	2.37	1.242	476	34	1.400	0.89	*	F
294	Benzaid et al. (2010)	C	160	1.00	25.9	39.6	1.28	1.312	476	34	1.400	0.94	0.68	F
295	Benzaid et al. (2010)	C	160	3.00	25.9	66.1	1.52	1.318	476	34	1.400	0.94	0.60	F
296	Benzaid et al. (2010)	C	160	1.00	58.2	75.8	0.74	1.317	476	34	1.400	0.94	0.77	F
297	Benzaid et al. (2010)	C	160	1.00	58.2	79.2	0.94	1.316	476	34	1.400	0.94	0.74	F
298	Benzaid et al. (2010)	C	160	3.00	58.2	101.5	1.37	1.320	476	34	1.400	0.94	0.65	F
299	Benzaid et al. (2010)	C	160	3.00	58.2	99.4	1.34	1.317	476	34	1.400	0.94	0.66	F
300	Benzaid et al. (2010)	C	160	1.00	49.5	52.8	0.25	0.290	476	34	1.400	0.21	0.77	F
301	Benzaid et al. (2010)	C	160	3.00	49.5	82.9	0.73	1.315	476	34	1.400	0.94	0.77	F

302	Benzaid et al. (2010)	C	160	1.00	63.0	78.0	0.46	0.779	476	34	1.400	0.56	0.78	F
303	Benzaid et al. (2010)	C	160	1.00	63.0	74.4	0.29	0.261	476	34	1.400	0.19	0.78	F
304	Benzaid et al. (2010)	C	160	3.00	63.0	94.9	0.39	0.410	476	34	1.400	0.29	0.78	F
305	Benzaid et al. (2010)	C	160	3.00	63.0	94.7	0.85	0.715	476	34	1.400	0.51	0.76	F
306	Benzaid et al. (2010)	C	160	1.00	61.8	62.7	0.33	0.246	476	34	1.400	0.18	0.78	F
307	Benzaid et al. (2010)	C	160	3.00	61.8	93.2	1.05	1.289	476	34	1.400	0.92	0.73	F
308	Wang et al. (2012)	C	305	0.17	24.5	35.0	1.85	1.602	4340	244	1.779	0.90	0.90	F
309	Wang et al. (2012)	C	305	0.33	24.5	55.3	3.26	1.615	4340	244	1.779	0.91	0.77	F
310	Wang et al. (2012)	C-R	305	0.17	24.5	41.5	1.82	1.431	4340	244	1.779	0.80	0.90	F
311	Wang et al. (2012)	C-R	305	0.17	24.5	43.1	1.96	1.446	4340	244	1.779	0.81	0.89	F
312	Wang et al. (2012)	C-R	305	0.33	24.5	52.2	2.68	1.249	4340	244	1.779	0.70	0.84	F
313	Wang et al. (2012)	C-R	305	0.33	24.5	61.8	3.22	1.554	4340	244	1.779	0.87	0.78	F
314	Wang et al. (2012)	C-R	305	0.17	24.5	47.0	2.32	1.398	4340	244	1.779	0.79	0.87	F
315	Wang et al. (2012)	C-R	305	0.33	24.5	62.1	3.30	1.520	4340	244	1.779	0.85	0.77	F
316	Wang et al. (2012)	C	204	0.17	24.5	46.1	2.45	1.678	4340	244	1.779	0.94	0.86	F
317	Wang et al. (2012)	C	204	0.17	24.5	42.3	1.94	1.469	4340	244	1.779	0.83	0.90	F
318	Wang et al. (2012)	C	204	0.17	24.5	46.5	2.40	1.398	4340	244	1.779	0.79	0.86	F
319	Wang et al. (2012)	C	204	0.33	24.5	65.2	3.66	1.453	4340	244	1.779	0.82	0.72	F
320	Wang et al. (2012)	C	204	0.33	24.5	66.8	3.82	1.357	4340	244	1.779	0.76	0.69	F
321	Wang et al. (2012)	C	204	0.33	24.5	64.6	3.41	1.085	4340	244	1.779	0.61	0.75	F
322	Wang et al. (2012)	C-R	204	0.17	24.5	52.1	2.31	1.387	4340	244	1.779	0.78	0.87	F
323	Wang et al. (2012)	C-R	204	0.17	24.5	49.9	2.38	1.534	4340	244	1.779	0.86	0.86	F
324	Wang et al. (2012)	C-R	204	0.17	24.5	45.6	1.73	1.181	4340	244	1.779	0.66	0.91	F
325	Wang et al. (2012)	C-R	204	0.17	24.5	54.5	2.72	1.308	4340	244	1.779	0.74	0.83	F
326	Wang et al. (2012)	C-R	204	0.33	24.5	66.1	3.41	1.306	4340	244	1.779	0.73	0.75	F
327	Wang et al. (2012)	C-R	204	0.33	24.5	68.9	3.39	1.328	4340	244	1.779	0.75	0.75	F
328	Wang et al. (2012)	C-R	204	0.33	24.5	67.4	3.19	1.522	4340	244	1.779	0.86	0.78	F
329	Wang et al. (2012)	C-R	204	0.33	24.5	77.4	3.89	1.738	4340	244	1.779	0.98	0.68	F
330	Wang et al. (2012)	C-R	204	0.17	24.5	52.2	2.54	1.306	4340	244	1.779	0.73	0.85	F
331	Wang et al. (2012)	C-R	204	0.17	24.5	57.0	2.81	1.504	4340	244	1.779	0.85	0.82	F
332	Wang et al. (2012)	C-R	204	0.33	24.5	69.5	3.41	1.298	4340	244	1.779	0.73	0.75	F
333	Wang et al. (2012)	C-R	204	0.33	24.5	75.0	4.03	1.538	4340	244	1.779	0.86	0.66	F
334	Abdelrahman and El-Hacha (2012)	C	300	0.38	40.1	51.0	0.23	0.438	895	65.4	1.369	0.32	0.78	M
335	Abdelrahman and El-Hacha (2012)	C-R	300	0.38	38.3	72.0	0.41	0.944	895	65.4	1.369	0.69	0.79	M
336	Marques and Chastre (2012)	C-R	150	0.33	38.0	84.1	1.31	0.900	3339	226	1.477	0.61	0.63	F
337	Marques and Chastre (2012)	C-R	250	0.35	35.2	76.2	1.55	0.930	3937	241	1.634	0.57	0.53	F

338	Marques and Chastre (2012)	C-R	400	0.59	34.3	59.4	1.15	0.730	2356	198	1.190	0.61	0.71	F
339	Kshirsagar et al. (2000)[a]	G	102	1.42	38.0	57.0	1.73	1.740	363	20	1.824	0.95	0.66	F
340	Kshirsagar et al. (2000)[a]	G	102	1.42	39.4	63.1	1.60	2.070	363	20	1.824	1.13	0.69	F
341	Kshirsagar et al. (2000)[a]	G	102	1.42	39.5	60.4	1.79	1.890	363	20	1.824	1.04	0.65	F
342	Aire et al. (2001)[a]	G	150	0.15	42.0	41.0	0.73	0.550	3000	65	4.615	0.12	0.48	M
343	Aire et al. (2001)[a]	G	150	0.45	42.0	61.0	1.74	1.300	3000	65	4.615	0.28	0.43	M
344	Aire et al. (2001)[a]	G	150	0.89	42.0	85.0	2.50	1.100	3000	65	4.615	0.24	0.30	M
345	Micelli et al. (2001)[a]	G	102	0.35	32.0	52.0	1.25	1.250	1520	72	2.111	0.59	0.70	M
346	Pessiki et al. (2001)[a]	G	152	1.00	26.2	38.4	1.30	1.150	383	22	1.773	0.65	0.74	M
347	Pessiki et al. (2001)[a]	G	152	2.00	26.2	52.5	1.82	1.240	383	22	1.773	0.70	0.65	M
348	Toutanji (1999)	G	76	0.24	30.9	60.8	1.53	1.630	1518	73	2.091	0.78	0.66	F
349	Lam and Teng (2004)	G	152	1.27	38.5	51.9	1.32	1.442	490	22	2.182	0.66	0.69	F
350	Lam and Teng (2004)	G	152	1.27	38.5	58.3	1.46	1.885	490	22	2.182	0.86	0.67	F
351	Lam and Teng (2004)	G	152	2.54	38.5	75.7	2.46	1.762	490	22	2.182	0.81	0.40	F
352	Lam and Teng (2004)	G	152	2.54	38.5	77.3	2.19	1.674	490	22	2.182	0.77	0.51	F
353	Silva and Rodrigues (2006)	G	150	2.54	27.4	91.6	2.61	1.985	465	21	2.183	0.91	0.33	F
354	Silva and Rodrigues (2006)	G	150	2.54	27.4	89.4	2.72	1.890	465	21	2.183	0.87	0.27	F
355	Berthet et al. (2005)	G	160	0.33	25.0	42.8	1.70	1.655	2500	74	3.378	0.49	0.52	M
356	Berthet et al. (2005)	G	160	0.33	25.0	42.3	1.69	1.643	2500	74	3.378	0.49	0.52	M
357	Berthet et al. (2005)	G	160	0.33	25.0	43.1	1.71	1.671	2500	74	3.378	0.49	0.52	M
358	Berthet et al. (2005)	G	160	0.22	40.1	44.8	0.53	1.369	2500	74	3.378	0.41	0.59	M
359	Berthet et al. (2005)	G	160	0.22	40.1	46.3	0.47	1.246	2500	74	3.378	0.37	0.59	M
360	Berthet et al. (2005)	G	160	0.22	40.1	49.8	0.50	1.075	2500	74	3.378	0.32	0.59	M
361	Berthet et al. (2005)	G	160	0.33	40.1	50.8	0.63	0.900	2500	74	3.378	0.27	0.59	M
362	Berthet et al. (2005)	G	160	0.33	40.1	50.8	0.58	1.281	2500	74	3.378	0.38	0.59	M
363	Berthet et al. (2005)	G	160	0.33	40.1	51.8	0.64	1.197	2500	74	3.378	0.35	0.59	M
364	Berthet et al. (2005)	G	160	0.55	40.1	66.7	1.05	1.546	2500	74	3.378	0.46	0.58	M
365	Berthet et al. (2005)	G	160	0.55	40.1	68.2	1.24	1.817	2500	74	3.378	0.54	0.56	M
366	Berthet et al. (2005)	G	160	0.55	40.1	67.7	1.17	1.582	2500	74	3.378	0.47	0.57	M
367	Berthet et al. (2005)	G	160	0.50	52.0	64.7	0.53	1.190	2500	74	3.378	0.35	0.59	M
368	Berthet et al. (2005)	G	160	0.50	52.0	75.1	1.13	1.265	2500	74	3.378	0.37	0.57	M
369	Berthet et al. (2005)	G	160	0.50	52.0	76.1	1.17	1.274	2500	74	3.378	0.38	0.57	M
370	Youseff (2003)[b]	G	406	1.68	29.4	44.1	0.73	0.835	425	18	2.300	0.36	0.71	N
371	Youseff (2003)[b]	G	406	3.35	29.4	49.5	0.93	1.532	425	18	2.300	0.67	0.70	N
372	Youseff (2003)[b]	G	406	4.47	29.4	55.2	1.18	0.604	425	18	2.300	0.26	0.69	N
373	Youseff (2003)[b]	G	406	7.26	29.4	73.1	1.45	1.397	425	18	2.300	0.61	0.66	N
374	Youseff (2003)[b]	G	153	1.68	44.1	65.5	1.32	1.712	425	18	2.300	0.74	0.67	N
375	Youseff (2003)[b]	G	153	2.24	44.1	80.5	1.51	1.869	425	18	2.300	0.81	0.65	N
376	Youseff (2003)[b]	G	153	3.35	44.1	91.8	2.01	2.086	425	18	2.300	0.91	0.55	N
377	Carey (2002)[b]	G	153	0.51	31.8	37.2	0.65	1.212	906	61	1.495	0.81	0.83	N
378	Carey (2002)[b] **	G	153	1.53	31.8	53.2	0.95	1.433	906	61	1.495	0.96	0.81	N
379	Kharel (2001)[b]	G	153	0.17	32.1	36.3	0.26	0.449	906	61	1.495	0.30	0.83	N
380	Kharel (2001)[b]	G	153	0.34	32.1	35.6	0.35	0.648	906	61	1.495	0.43	0.84	N
381	Kharel (2001)[b]	G	153	0.51	32.1	34.3	0.45	0.741	906	61	1.495	0.50	0.84	N

382	Kharel (2001)[b]	G	153	1.02	32.1	38.2	0.57	0.794	906	61	1.495	0.53	0.83	N
383	Kharel (2001)[b]	G	153	1.53	32.1	46.7	0.68	0.942	906	61	1.495	0.63	0.83	N
384	Kharel (2001)[b]	G	153	2.04	32.1	50.2	0.82	0.907	906	61	1.495	0.61	0.82	N
385	Kharel (2001)[b]	G	153	2.55	32.1	60.0	0.87	0.890	906	61	1.495	0.60	0.82	N
386	Kharel (2001)[b]	G	153	0.40	32.1	44.4	1.18	1.501	1520	101	1.501	1.00	0.78	N
387	Kharel (2001)[b]	G	153	0.80	32.1	62.1	1.71	1.281	1520	101	1.501	0.85	0.67	N
388	Bullo (2003)[c]	G	150	0.46	32.5	72.4	3.73	2.148	1703	65	2.620	0.82	*	N
389	Bullo (2003)[c]	G	150	0.46	32.5	73.6	3.93	2.175	1703	65	2.620	0.83	*	N
390	Bullo (2003)[c]	G	150	0.46	32.5	75.8	2.85	2.044	1703	65	2.620	0.78	0.15	N
391	Bullo (2003)[c]	G	150	1.15	32.5	118.8	4.28	1.965	1703	65	2.620	0.75	*	N
392	Bullo (2003)[c] **	G	150	1.15	32.5	130.2	4.04	1.913	1703	65	2.620	0.73	*	N
393	Bullo (2003)[c] **	G	150	1.15	32.5	135.8	4.84	1.808	1703	65	2.620	0.69	*	N
394	Cui and Sheikh (2010)	G	152	1.25	47.7	59.1	1.35	2.020	496	21	2.310	0.87	0.67	F
395	Cui and Sheikh (2010)	G	152	1.25	47.7	59.8	1.15	2.143	496	21	2.310	0.93	0.69	F
396	Cui and Sheikh (2010)	G	152	2.50	47.7	88.9	2.21	2.032	496	21	2.310	0.88	0.49	F
397	Cui and Sheikh (2010)	G	152	2.50	47.7	88.0	2.21	2.114	496	21	2.310	0.92	0.49	F
398	Cui and Sheikh (2010)	G	152	3.75	47.7	113.2	2.85	2.112	496	21	2.310	0.91	0.18	F
399	Cui and Sheikh (2010)	G	152	3.75	47.7	112.5	2.80	2.110	496	21	2.310	0.91	0.21	F
400	Cui and Sheikh (2010)	G	152	1.25	47.7	63.4	1.51	2.179	496	21	2.310	0.94	0.65	F
401	Cui and Sheikh (2010)	G	152	1.25	47.7	62.4	1.35	2.116	496	21	2.310	0.92	0.67	F
402	Cui and Sheikh (2010)	G	152	2.50	47.7	89.7	2.14	2.074	496	21	2.310	0.90	0.51	F
403	Cui and Sheikh (2010)	G	152	2.50	47.7	88.3	2.05	2.049	496	21	2.310	0.89	0.54	F
404	Cui and Sheikh (2010)	G	152	3.75	47.7	108.0	2.62	1.893	496	21	2.310	0.82	0.32	F
405	Cui and Sheikh (2010)	G	152	1.25	79.9	66.7	0.76	2.018	496	21	2.310	0.87	0.71	F
406	Cui and Sheikh (2010)	G	152	1.25	79.9	74.7	0.88	2.418	496	21	2.310	1.05	0.70	F
407	Cui and Sheikh (2010)	G	152	2.50	79.9	92.5	0.86	1.389	496	21	2.310	0.60	0.71	F
408	Cui and Sheikh (2010)	G	152	2.50	79.9	94.1	0.78	1.694	496	21	2.310	0.73	0.71	F
409	Cui and Sheikh (2010)	G	152	3.75	79.9	120.8	1.26	2.008	496	21	2.310	0.87	0.68	F
410	Cui and Sheikh (2010)	G	152	3.75	79.9	126.1	1.18	1.916	496	21	2.310	0.83	0.69	F
411	Cui and Sheikh (2010)	G	152	2.50	79.9	106.3	0.67	1.192	496	21	2.310	0.52	0.71	F
412	Cui and Sheikh (2010)	G	152	2.50	79.9	100.3	0.46	1.080	496	21	2.310	0.47	0.71	F
413	Cui and Sheikh (2010)	G	152	5.00	79.9	174.6	0.95	1.398	496	21	2.310	0.61	0.70	F
414	Cui and Sheikh (2010)	G	152	5.00	79.9	172.9	1.28	1.538	496	21	2.310	0.67	0.68	F
415	Demers and Neale (1994)[c]	G	152	1.05	32.2	48.3	2.04	1.650	220	11	2.095	0.79	0.58	M
416	Demers and Neale (1994)[c]	G	152	1.05	32.2	48.3	1.97	1.826	220	11	2.095	0.87	0.60	M
417	Jiang and Teng (2007)	G	152	0.17	33.1	42.4	1.30	2.080	1826	80	2.280	0.91	0.67	F
418	Jiang and Teng (2007)	G	152	0.17	33.1	41.6	1.27	1.758	1826	80	2.280	0.77	0.68	F
419	Jiang and Teng (2007)	G	152	0.17	45.9	48.4	0.81	1.523	1826	80	2.280	0.67	0.71	F
420	Jiang and Teng (2007)	G	152	0.17	45.9	46.0	1.06	1.915	1826	80	2.280	0.84	0.70	F
421	Jiang and Teng (2007)	G	152	0.34	45.9	52.8	1.20	1.639	1826	80	2.280	0.72	0.68	F
422	Jiang and Teng (2007)	G	152	0.34	45.9	55.2	1.25	1.799	1826	80	2.280	0.79	0.68	F
423	Jiang and Teng (2007)	G	152	0.51	45.9	64.6	1.55	1.594	1826	80	2.280	0.70	0.64	F
424	Jiang and Teng (2007)	G	152	0.51	45.9	65.9	1.90	1.940	1826	80	2.280	0.85	0.57	F
425	Mastrapa (1997)	G	153	0.61	29.8	33.7	0.25	2.059	565	19	2.945	0.70	0.62	S

426	Mastrapa (1997)	G	153	1.84	31.2	67.5	2.95	2.233	565	19	2.945	0.76	0.09	S
427	Mastrapa (1997)	G	153	1.84	31.2	64.7	3.15	1.972	565	19	2.945	0.67	*	S
428	Mastrapa (1997)	G	153	3.07	31.2	91.0	3.80	1.798	565	19	2.945	0.61	*	S
429	Mastrapa (1997)	G	153	3.07	31.2	96.9	6.20	1.769	565	19	2.945	0.60	*	S
430	Teng et al. (2007)	G-T	152	0.17	39.6	41.5	0.83	1.869	1825.5	80	2.279	0.82	0.71	F
431	Teng et al. (2007)	G-T	152	0.17	39.6	40.8	0.94	1.609	1825.5	80	2.279	0.71	0.70	F
432	Teng et al. (2007)	G-T	152	0.34	39.6	54.6	2.13	2.040	1825.5	80	2.279	0.90	0.50	F
433	Teng et al. (2007)	G-T	152	0.34	39.6	56.3	1.83	2.061	1825.5	80	2.279	0.90	0.58	F
434	Teng et al. (2007)	G-T	152	0.51	39.6	65.7	2.56	1.955	1825.5	80	2.279	0.86	0.33	F
435	Teng et al. (2007)	G-T	152	0.51	39.6	60.9	1.79	1.667	1825.5	80	2.279	0.73	0.59	F
436	Almusallam (2007)[c]	G	150	1.30	47.7	56.7	1.50	0.840	540	27	2.000	0.42	0.68	N
437	Almusallam (2007)[c]	G	150	3.90	47.7	100.1	2.72	0.800	540	27	2.000	0.40	0.26	N
438	Almusallam (2007)[c]	G	150	1.30	50.8	55.5	1.21	1.000	540	27	2.000	0.50	0.72	N
439	Almusallam (2007)[c]	G	150	3.90	50.8	90.8	1.88	0.800	540	27	2.000	0.40	0.60	N
440	Almusallam (2007)[c]	G	150	1.30	60.0	62.4	0.50	0.500	540	27	2.000	0.25	0.76	N
441	Almusallam (2007)[c]	G	150	3.90	60.0	99.6	1.67	0.700	540	27	2.000	0.35	0.65	N
442	Almusallam (2007)[c]	G	150	1.30	80.8	88.9	0.36	0.240	540	27	2.000	0.12	0.75	N
443	Almusallam (2007)[c]	G	150	3.90	80.8	100.9	0.63	0.860	540	27	2.000	0.43	0.76	N
444	Almusallam (2007)[c]	G	150	1.30	90.3	97.0	0.32	0.260	540	27	2.000	0.13	0.75	N
445	Almusallam (2007)[c]	G	150	3.90	90.3	110.0	0.93	0.820	540	27	2.000	0.41	0.74	N
446	Almusallam (2007)[c]	G	150	1.30	107.8	116.0	0.29	0.300	540	27	2.000	0.15	0.75	N
447	Almusallam (2007)[c]	G	150	3.90	107.8	125.2	0.26	0.300	540	27	2.000	0.15	0.75	N
448	Watanable et al. (1997)[a]	A	100	0.15	30.2	39.0	1.58	2.360	2654	91	2.916	0.81	0.58	F
449	Watanable et al. (1997)[a]	A	100	0.29	30.2	68.5	4.75	3.090	2654	91	2.916	1.06	*	F
450	Watanable et al. (1997)[a]	A	100	0.43	30.2	92.1	5.55	2.650	2654	91	2.916	0.91	*	F
451	Rochette and Labossiere (2000)[a]	A	150	1.27	43.0	47.3	1.11	1.530	230	14	1.691	0.90	0.79	F
452	Rochette and Labossiere (2000)[a]	A	150	2.56	43.0	58.9	1.47	1.390	230	14	1.691	0.82	0.75	F
453	Rochette and Labossiere (2000)[a]	A	150	3.86	43.0	71.0	1.69	1.330	230	14	1.691	0.79	0.72	F
454	Rochette and Labossiere (2000)[a]	A	150	5.21	43.0	74.4	1.74	1.180	230	14	1.691	0.70	0.71	F
Ave.												0.67	0.65	

[a] Lam and Teng (2003), [b] Carey and Harries (2003), [c] Realfonzo and Napoli (2011)
HC: high modulus carbon, C: carbon, G: glass, A: aramid, R: internal axial and transverse steel rebars, T: internal hollow steel tube
F: flat coupon test, M: manufacturer data sheet, S: split disc coupon test, N: not available
* the analytical model cannot predict these cases
** the data point is not considered in prediction and evaluation of confinement ratio