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# Analytical model for CFRP strengthened circular RC column under elevated temperature

Raizal S.M. Rashid[*1] and Riyad S. Aboutaha[2a]

[1]*Department of Civil Engineering, Universiti Putra Malaysia, 43000 Serdang, Selangor Malaysia*
[2]*L.C. Smith College of Engineering and Computer Science, 151 Link Hall, Syracuse NY 13244, USA*

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**Abstract.** In order to increase the load carrying capacity and/or increase the service life of existing circular reinforced concrete bridge columns, Carbon Fiber Reinforced Polymer (CFRP) composites could be utilized. Transverse wrapping of circular concrete columns with CFRP sheets increases its axial and shear strengths. In addition, it provides good confinement to the concrete column core, which enhances the bending and compressive strength, as well as, ductility. Several experimental and analytical studies have been conducted on CFRP strengthened concrete cylinders/columns. However, there seem to be lack of thorough investigation of the effect of elevated temperatures on the response of CFRP strengthened circular concrete columns. A concrete confinement model that reflects the effects of elevated temperature on the mechanical properties of CFRP composites, and the efficiency of CFRP in strengthened concrete columns is presented. Tensile strength and modulus of CFRP under hot conditions and their effects on the concrete confinement are the primary parameters that were investigated. A modified concrete confinement model is developed and presented.

**Keywords:** CFRP; circular concrete column; confinement; elevated temperature and humidity

## 1. Introduction

It is widely accepted that the compressive strength and ductility of concrete can be significantly enhanced by fiber-reinforced polymer (FRP) composite wrapping. Easy to manage and install FRP wraps can be utilized to extend the service life of structurally damaged columns, increase load capacity of buildings and bridges, and increase ductility of structures prone to seismic activities.

At present, there are several models available in estimating the strength of CFRP confined circular concrete section. However, for hot-humid regions, it is important to develop an analytical model that incorporates environmental factors, e.g. elevated temperatures. This is by incorporating these factors into an existing concrete confinement model, and column section models.

A widely adopted concrete confinement model for FRP wrapped concrete is given by Eq. (1) (Lam and Teng 2002)

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∗Corresponding author, Ph.D., E-mail: raizal@upm.edu.my
[a]Ph.D., E-mail: rsabouta@syr.edu


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$$\frac{f'_{cc}}{f'_{co}} = 1 + 2\frac{f_l}{f'_{co}} \tag{1}$$

with

$$f_l = \frac{2f_{FRP}\, t}{d} \tag{2}$$

where $f'_{cc}$ is the compressive strengths of the confined concrete, $f'_{co}$ is the compressive strengths of the unconfined concrete and 2 is the confinement effectiveness coefficient for concrete circular column, meanwhile $f_l$ is the lateral confining pressure, $f_{FRP}$ is the CFRP tensile strength, t is total thickness of FRP and d is the diameter of the confined concrete section. This equation was chosen because of its simplification for direct calculation of $f'_{cc}$ and $f'_{co}$ compared to other equations (Karabinis A.I. 1996, Toutanji 1999, Xiao and Wu 2000, Karabinis 2001, Karabinis 2002, Rousakis *et al*. 2012). The detailed explanation regarding this equation can be found in the reference by Lam and Teng (Lam and Teng 2002). In developing Eq. (1), the tensile strength of the CFRP was determined according to ASTM D3039 (ASTM. 1995) or similar method using flat coupon. The axial compression strength models used for steel confined concrete are conservative and unsuitable for FRP confined concrete because of different material properties. Therefore, confinement models incorporating environmental factors used for steel confined concrete are unsuitable for FRP wrapped circular concrete column sections.

In developing Eq. (1), data were collected from three different sets of data to determine the mechanical properties of the FRP with set no. 1 flat coupon test, set no. 2 using ring splitting test, and set no. 3 was obtained from the manufacturers. The data was for various types of FRP which are Carbon Sheets, Carbon Filament, E Glass Sheets, Glass Sheets, Glass and Carbon sheets, Aramid Sheets, S Glass Sheets, E Glass Filament, Glass Strands, E Glass Strands and Glass Filament. However, this paper will only focusing on CFRP sheets, where their properties were measured using flat coupon test according to ASTM D3039 (ASTM. 1995), as it is the most common material and test opted because of its durability and high stiffness.

## 2. Effect of high weather temperature on CFRP properties

Most of the investigations on the effect of high temperature on properties of CFRP have focused on exposure of the CFRP confined concrete to fire. The temperature of exposure ranges from 100$^o$C to 700$^o$C (Bisby *et al*. 2011, A. Al-Salloum *et al*. 2011). This extreme heat exposure has several special effects, such as the phase where the CFRP would start to ignite along with combustion of the polymer matrix which is definitely a very complicated scenario to simulate.

To understand this temperature effect, several experimental tests were performed by exposing CFRP strengthened concrete to an accelerated weather condition conducted in laboratory to simulate accelerated degradation process. Based on state of the art review done by (Steward and Douglas 2012), the most common effect of temperature on CFRP was found to be the degradation of the epoxy matrix which is also known as plasticization. This degradation contributes to the loss of shear, tensile and flexural strength and decrease in fracture toughness of the CFRP as presented in Table 1.

As shown in Table 1, conducting accelerated weathering condition experiments, test specimens

Table 1 Summary of property changes and mechanism for epoxy and CFRP system (Steward and Douglas, 2012)

| Material | Exposure condition | Exposure time | Property change | Mechanism |
|---|---|---|---|---|
| CFRP | Water from 40–100C | Up to 20 months | Decrease in Tg*, strength, toughness | Plasticization |
| CFRP | UV at 60C/Condensation at 50C | 50 hours | Decrease in flexural strength | Oxidation |
| CFRP | UV at 60C/Condensation at 50C | 1,000 hours | Decrease in tensile strength | Hydrolysis |
| CFRP | 23 to 80C with and without sea water | Up to 18 months | No significant change in tensile or shear strength | - |
| CFRP | 22–60C in air, water/salt wet/dry cycles, and UV at 60C | Up to 2,000 hours | No significant change in longitudinal properties | - |

*Glass transition temperature of the polymer

Table 2 Typical coefficient of thermal expansion for FRP materials (American concrete Institute committe 440 2002)

| Direction | Coefficient of thermal expansion, x $10^{-6}$/C | | |
|---|---|---|---|
| | GFRP | CFRP | AFRP |
| Longitudinal | 6 to 10 | -1 to 0 | -6 to -2 |
| Transverse | 19 to 23 | 22 to 50 | 60 to 80 |

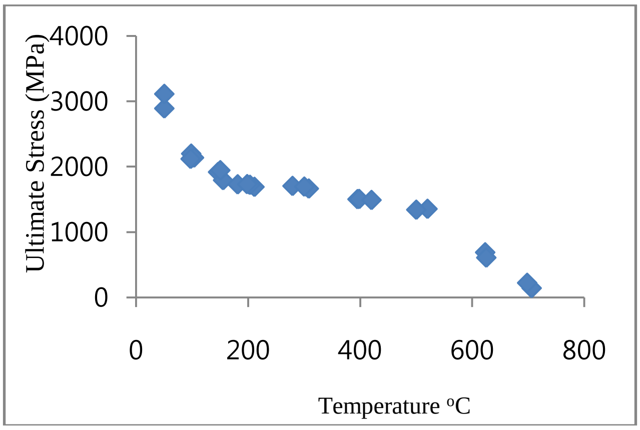


Fig. 1 Relationship between temperature (℃) and ultimate tensile strength of CFRP plate

were not only exposed to elevated temperature but also to Ultra Violet exposure, corrosive solution, wet and dry cycles and other degradation methods. These exposures lead to decrease in

Glass transition temperature of the polymer (Tg), strength toughness, flexural and tensile strength which involved plasticization, oxidation and Hydrolysis mechanism.

It is important to identify Tg, as the degradation may involve plasticizing mechanism the exposure temperature exceeds Tg. Meanwhile, degradation by oxidation and hydrolysis mechanism involves changes in chemical component that lead to reduction of flexural and toughness strength of CFRP. These clearly indicate that elevated temperature does contribute to the degradation of modulus and strength properties of CFRP.

Wang *et al*. (2011) conducted an experimental investigation to measure the residual ultimate strength of CFRP pultruded plates exposed to elevated temperatures between 20$^{o}$C to 700$^{o}$C. The results are plotted in Fig. 1. The results clearly show that the ultimate strength of CFRP plates decreases as the temperature increases. Fig. 1 also shows three degradation zones, as follows: Zone 1; where the temperature ranges between 22$^{o}$C to 150$^{o}$C, Zone 2, where the temperature ranges between 150$^{o}$C to 450$^{o}$C, and Zone 3; where the temperature is higher than 450$^{o}$C. The first strength reduction, Zone 1, was caused by the softening and gasification of the epoxy resin followed by fibre rupture, meanwhile the second strength reduction, Zone 2, was caused by the epoxy having self-ignited and completely burned with oxidization of more than half of the carbon fibers.

In addition, another characteristic that needs to be mentioned is the thermal expansion for both CFRP and concrete. Table 2 (American Concrete Institute Committe 440 2002) clearly shows that there are significant differences in the longitudinal and transverse thermal coefficients, which also depending on the type of fiber. Meanwhile coefficient of thermal expansion for concrete ranges between $7 \times 10^{-6}$ to $11 \times 10^{-6}$/C. Based on this thermal coefficient data, it is most likely that the CFRP may contract in the longitudinal direction as the temperatures increases, while it may expand in the transverse direction. This explains why at a certain point of temperature increment, CFRP may contract providing higher confinement toward the concrete column and furthermore at some point both concrete and CFRP will eventually expand and fail.

In this paper, CFRP confined circular concrete column exposed to seasonal temperature ranging from room temperature (25$^{o}$C ± 2) to 100$^{o}$C are considered in developing a modified analytical model based on Equation 1. Within this temperature range, the properties of the CFRP change, which results in change in the CFRP confining effect.

## 3. Test data

In order to develop a modified model for CFRP confined circular concrete columns, an extensive data-base was established, as presented in Table 3, (Harmon and Slattery 1992, Demers and Neale 1994, Picher *et al*. 1996, Watanable *et al*. 1997, Miyauchi *et al*. 1997, Harries *et al*. 1998, Toutanji and Balaguru 1998, Toutanji 1999, Matthys *et al*. 1999, Xiao and Wu 2000 and Zhang *et al*. 2000). Most of this data was compiled and presented by Lam and Teng (Lam and Teng 2002). For the first 60 data sets, the specimens were wrapped and tested at room temperature of 25oC ± 2. Meanwhile the remaining 23 data sets were at different temperatures (Micelli *et al*. 2002, El-Hacha *et al*. 2010, Bae and Belarbi 2010; A. Al-Salloum *et al*. 2011, Bisby *et al*. 2011, Hadi and Louk Fanggi 2012). In total, 83 data sets were considered in this investigation. For this set of data, all the circular concrete specimens were without any steel reinforcement, having length to depth ratio L/d not exceeding 4, and concrete compressive strength not exceeding 60.2 MPa. In Table 3, the $f'_{cc}$ values for the first four data sets were calculated from stress-strain curves, while the others were obtained from experimental compression tests.

Table 3 Experimental data of CFRP strengthened circular column section (CFRP sheets)

| Number | Data | d (mm) | L (mm) | $f'_{co}$ (MPa) | t (mm) | $f_{frp}$ (MPa) | $E_{frp}$ (MPa) | $f_l$ | $f_l / f'_{co}$ | $f'_{cc}$ (MPa) | $f'_{cc}/f'_{co}$ | Temp. $^oC$ | Relative Humidity (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Harmon and Slattery 1992* | 51 | 102 | 41.0 | 0.09 | 3500 | 235000 | 12.35 | 0.30 | 86.0 | 2.10 | 25 | 74 |
| 2 | Harmon and Slattery 1992* | 51 | 102 | 41.0 | 0.18 | 3500 | 235000 | 24.71 | 0.60 | 117.0 | 2.85 | 25 | 74 |
| 3 | Harmon and Slattery 1992* | 51 | 102 | 41.0 | 0.34 | 3500 | 235000 | 46.67 | 1.14 | 158.0 | 3.85 | 25 | 74 |
| 4 | Demers and Neale 1994 | 152 | 305 | 32.2 | 0.30 | 380 | 25000 | 1.50 | 0.05 | 41.1 | 1.28 | 25 | 74 |
| 5 | Demers and Neale 1994 | 152 | 305 | 43.7 | 0.30 | 380 | 25000 | 1.50 | 0.03 | 48.4 | 1.11 | 25 | 74 |
| 6 | Demers and Neale 1994 | 152 | 305 | 43.7 | 0.90 | 380 | 25000 | 4.50 | 0.10 | 75.2 | 1.72 | 25 | 74 |
| 7 | Demers and Neale 1994 | 152 | 305 | 43.7 | 0.90 | 380 | 25000 | 4.50 | 0.10 | 73.4 | 1.68 | 25 | 74 |
| 8 | Picher *et al* 1994 | 152 | 304 | 39.7 | 0.90 | 1266 | 83000 | 14.99 | 0.38 | 56.0 | 1.41 | 25 | 74 |
| 9 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.17 | 2716 | 224600 | 9.23 | 0.31 | 46.6 | 1.54 | 25 | 74 |
| 10 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.50 | 2873 | 224600 | 28.73 | 0.95 | 87.2 | 2.89 | 25 | 74 |
| 11 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.67 | 2658 | 224600 | 35.62 | 1.18 | 104.6 | 3.46 | 25 | 74 |
| 12 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.14 | 1579 | 628600 | 4.42 | 0.15 | 41.7 | 1.38 | 25 | 74 |
| 13 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.28 | 1824 | 628600 | 10.21 | 0.34 | 56.0 | 1.85 | 25 | 74 |
| 14 | Watanabe *et al* 1994 | 100 | 200 | 30.2 | 0.42 | 1285 | 576600 | 10.79 | 0.36 | 63.3 | 2.10 | 25 | 74 |
| 15 | Miyauchi *et al* 1997 | 150 | 300 | 45.2 | 0.11 | 3481 | 230500 | 5.11 | 0.11 | 59.4 | 1.31 | 25 | 74 |

Table 3 Continued

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | Miyauchi *et al* 1997 | 150 | 300 | 45.2 | 0.22 | 3481 | 230500 | 10.21 | 0.23 | 79.4 | 1.76 | 25 | 74 |
| 17 | Miyauchi *et al* 1997 | 150 | 300 | 31.2 | 0.11 | 3481 | 230500 | 5.11 | 0.16 | 52.4 | 1.68 | 25 | 74 |
| 18 | Miyauchi *et al* 1997 | 150 | 300 | 31.2 | 0.22 | 3481 | 230500 | 10.21 | 0.33 | 67.4 | 2.16 | 25 | 74 |
| 19 | Miyauchi *et al* 1997 | 150 | 300 | 31.2 | 0.33 | 3481 | 230500 | 15.32 | 0.49 | 81.7 | 2.62 | 25 | 74 |
| 20 | Miyauchi *et al* 1997 | 150 | 300 | 51.9 | 0.11 | 3481 | 230500 | 7.66 | 0.15 | 75.2 | 1.45 | 25 | 74 |
| 21 | Miyauchi *et al* 1997 | 150 | 300 | 51.9 | 0.22 | 3481 | 230500 | 15.32 | 0.30 | 104.6 | 2.02 | 25 | 74 |
| 22 | Miyauchi *et al* 1997 | 150 | 300 | 33.7 | 0.11 | 3481 | 230500 | 7.66 | 0.23 | 69.6 | 2.07 | 25 | 74 |
| 23 | Miyauchi *et al* 1997 | 150 | 300 | 33.7 | 0.22 | 3481 | 230500 | 15.32 | 0.45 | 88.0 | 2.61 | 25 | 74 |
| 24 | Miyauchi *et al* 1997 | 150 | 300 | 33.7 | 0.33 | 3481 | 230500 | 22.97 | 0.68 | 109.9 | 3.26 | 25 | 74 |
| 25 | Harries *et al* 1998 | 152 | 610 | 26.2 | 1.00 | 580 | 38100 | 7.63 | 0.29 | 50.6 | 1.93 | 25 | 74 |
| 26 | Harries *et al* 1998 | 152 | 610 | 26.2 | 2.00 | 580 | 38100 | 15.26 | 0.58 | 64.0 | 2.44 | 25 | 74 |
| 27 | Toutanji and Balaguru 1998 | 76 | 305 | 31.8 | 0.22 | 1518 | 228000 | 20.18 | 0.63 | 98.7 | 3.10 | 25 | 74 |
| 28 | Toutanji and Balaguru 1998 | 76 | 305 | 31.8 | 0.33 | 3485 | 373000 | 25.53 | 0.80 | 96.0 | 3.02 | 25 | 74 |
| 29 | Toutanji 1999 | 76 | 305 | 31.0 | 0.24 | 2940 | 372800 | 18.57 | 0.60 | 60.8 | 1.96 | 25 | 74 |
| 30 | Matthys *et al*. 1999 | 150 | 300 | 34.9 | 0.12 | 2600 | 200000 | 4.16 | 0.12 | 44.3 | 1.27 | 25 | 74 |
| 31 | Matthys *et al*. 1999 | 150 | 300 | 34.9 | 0.24 | 1100 | 420000 | 3.52 | 0.10 | 41.3 | 1.18 | 25 | 74 |

Table 3 Continued

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.38 | 1577 | 105000 | 7.89 | 0.23 | 47.9 | 1.42 | 25 | 74 |
| 33 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.38 | 1577 | 105000 | 7.89 | 0.23 | 49.7 | 1.47 | 25 | 74 |
| 34 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.38 | 1577 | 105000 | 7.89 | 0.23 | 49.4 | 1.47 | 25 | 74 |
| 35 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.76 | 1577 | 105000 | 15.77 | 0.47 | 64.6 | 1.92 | 25 | 74 |
| 36 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.76 | 1577 | 105000 | 15.77 | 0.47 | 75.2 | 2.23 | 25 | 74 |
| 37 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 0.76 | 1577 | 105000 | 15.77 | 0.47 | 71.8 | 2.13 | 25 | 74 |
| 38 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 1.14 | 1577 | 105000 | 23.66 | 0.70 | 82.9 | 2.46 | 25 | 74 |
| 39 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 1.14 | 1577 | 105000 | 23.66 | 0.70 | 86.2 | 2.56 | 25 | 74 |
| 40 | Xiao and Wu 2000 | 152 | 305 | 33.7 | 1.14 | 1577 | 105000 | 23.66 | 0.70 | 95.4 | 2.83 | 25 | 74 |
| 41 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.38 | 1577 | 105000 | 7.89 | 0.18 | 54.7 | 1.25 | 25 | 74 |
| 42 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.38 | 1577 | 105000 | 7.89 | 0.18 | 52.1 | 1.19 | 25 | 74 |
| 43 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.38 | 1577 | 105000 | 7.89 | 0.18 | 48.7 | 1.11 | 25 | 74 |
| 44 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.76 | 1577 | 105000 | 15.77 | 0.36 | 84.0 | 1.92 | 25 | 74 |
| 45 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.76 | 1577 | 105000 | 15.77 | 0.36 | 79.2 | 1.81 | 25 | 74 |
| 46 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 0.76 | 1577 | 105000 | 15.77 | 0.36 | 85.0 | 1.94 | 25 | 74 |
| 47 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 1.14 | 1577 | 105000 | 23.66 | 0.54 | 96.5 | 2.20 | 25 | 74 |
| 48 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 1.14 | 1577 | 105000 | 23.66 | 0.54 | 92.6 | 2.11 | 25 | 74 |
| 49 | Xiao and Wu 2000 | 152 | 305 | 43.8 | 1.14 | 1577 | 105000 | 23.66 | 0.54 | 94.0 | 2.15 | 25 | 74 |
| 50 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.38 | 1577 | 105000 | 7.89 | 0.14 | 57.9 | 1.05 | 25 | 74 |
| 51 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.38 | 1577 | 105000 | 7.89 | 0.14 | 62.9 | 1.14 | 25 | 74 |
| 52 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.38 | 1577 | 105000 | 7.89 | 0.14 | 58.1 | 1.05 | 25 | 74 |
| 53 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.76 | 1577 | 105000 | 15.77 | 0.29 | 74.6 | 1.35 | 25 | 74 |
| 54 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.76 | 1577 | 105000 | 15.77 | 0.29 | 77.6 | 1.41 | 25 | 74 |
| 55 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 0.76 | 1577 | 105000 | 15.77 | 0.29 | 77.0 | 1.39 | 25 | 74 |

Table 3 Continued

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 56 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 1.14 | 1577 | 105000 | 23.66 | 0.43 | 106.5 | 1.93 | 25 | 74 |
| 57 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 1.14 | 1577 | 105000 | 23.66 | 0.43 | 108.0 | 1.96 | 25 | 74 |
| 58 | Xiao and Wu 2000 | 152 | 305 | 55.2 | 1.14 | 1577 | 105000 | 23.66 | 0.43 | 103.3 | 1.87 | 25 | 74 |
| 59 | Zhang *et al* 2000 | 150 | 300 | 34.3 | 1.00 | 423 | 37000 | 5.64 | 0.16 | 44.2 | 1.29 | 25 | 74 |
| 60 | Zhang *et al* 2000 | 150 | 300 | 34.3 | 1.00 | 753 | 91000 | 10.04 | 0.29 | 59.4 | 1.73 | 25 | 74 |
| 61 | F. Micelli *et al* 2002 | 102 | 204 | 37.0 | 0.16 | 3793 | 227000 | 11.90 | 0.32 | 60.0 | 1.62 | 22 | 76 |
| 62 | El-Hacha *et al* 2010 | 150 | 300 | 52.7 | 0.16 | 3400 | 230000 | 7.25 | 0.14 | 66.1 | 1.25 | 20 | 77 |
| 63 | El-Hacha *et al* 2010 | 150 | 300 | 52.7 | 0.16 | 3400 | 230000 | 7.25 | 0.14 | 75.4 | 1.43 | 45 | 63 |
| 64 | Bae and Belarbi 2010 | 203 | 914 | 28.3 | 0.16 | 3790 | 227000 | 5.97 | 0.21 | 30.2 | 1.07 | 25 | 74 |
| 65 | Bae and Belarbi 2010 | 203 | 914 | 28.3 | 0.16 | 3790 | 227000 | 5.97 | 0.21 | 29.9 | 1.06 | 25 | 74 |
| 66 | Al-Salloum *et al* 2011 | 100 | 200 | 38.8 | 1.00 | 846 | 77280 | 16.92 | 0.44 | 95.4 | 2.46 | 25 | 74 |
| 67 | Al-Salloum *et al* 2011 | 100 | 200 | 38.8 | 1.00 | 846 | 77280 | 16.92 | 0.44 | 95.4 | 2.46 | 25 | 74 |
| 68 | Al-Salloum *et al* 2011 | 100 | 200 | 38.8 | 1.00 | 846 | 77280 | 16.92 | 0.44 | 95.4 | 2.46 | 25 | 74 |
| 69 | Al-Salloum *et al* 2011 | 100 | 200 | 38.2 | 1.00 | 846 | 77280 | 16.92 | 0.44 | 94.7 | 2.48 | 100 | 33 |
| 70 | Al-Salloum *et al* 2011 | 100 | 200 | 38.1 | 1.00 | 846 | 77280 | 16.92 | 0.44 | 94.5 | 2.48 | 100 | 33 |
| 71 | Al-Salloum *et al* 2011 | 100 | 200 | 37.0 | 1.00 | 846 | 77280 | 16.92 | 0.46 | 90.5 | 2.45 | 100 | 33 |
| 72 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 32.0 | 1.07 | 22 | 76 |
| 73 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 63.0 | 2.10 | 22 | 76 |
| 74 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 61.0 | 2.03 | 22 | 76 |
| 75 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 53.0 | 1.77 | 22 | 76 |
| 76 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 55.0 | 1.83 | 22 | 76 |
| 77 | Bisby *et al* 2011 | 100 | 200 | 30.0 | 0.16 | 4100 | 231000 | 13.12 | 0.44 | 59.0 | 1.97 | 22 | 76 |
| 78 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.00 | 621.67 | 628076 | 12.43 | 0.21 | 107.7 | 1.79 | 20 | 77 |

Table 3Continued

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.00 | 621.67 | 628076 | 12.43 | 0.21 | 105.2 | 1.75 | 70 | 50 |
| 80 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.00 | 621.67 | 628076 | 12.43 | 0.21 | 108.1 | 1.80 | 70 | 50 |
| 81 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 168.7 | 2.80 | 20 | 70 |
| 82 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 172.4 | 2.86 | 70 | 50 |
| 83 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 176.5 | 2.93 | 70 | 50 |
| 79 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.00 | 621.67 | 628076 | 12.43 | 0.21 | 105.2 | 1.75 | 70 | 50 |
| 80 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.00 | 621.67 | 628076 | 12.43 | 0.21 | 108.1 | 1.80 | 70 | 50 |
| 81 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 168.7 | 2.80 | 20 | 70 |
| 82 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 172.4 | 2.86 | 70 | 50 |
| 83 | Hadi and Fanggi 2012 | 100 | 200 | 60.2 | 1.32 | 952.11 | 628076 | 25.14 | 0.42 | 176.5 | 2.93 | 70 | 50 |

* = $f'_{cc}$ calculated from stress-strain curves

## 4. Confinement ratio and strengthening ratio

Fig. 2 shows the relationship between confinements and strengthening ratio for the CFRP confined concrete for 75 data sets tested at room temperature, based on Eq. 1 and 2. The chart in Fig. 2 suggests that without considering high weather temperature, an increase in confining pressure results in an increase in compressive strength.

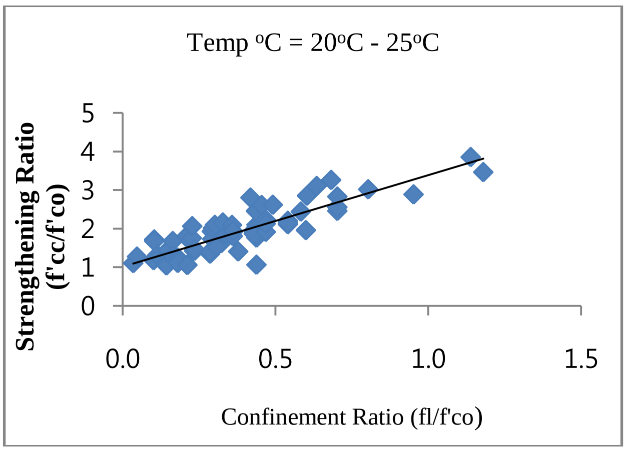


Fig. 2 Relationship between confinement ratio and strengthening ratio

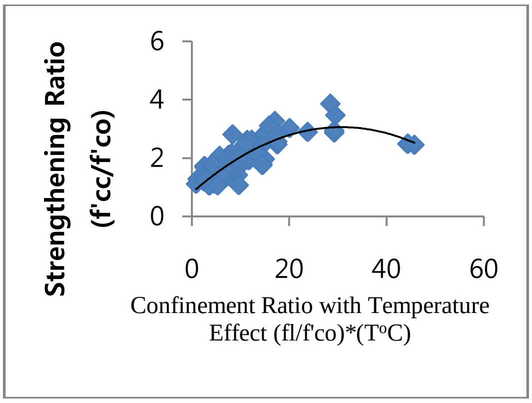


Fig. 3 Effect of confinement ratio with temperature (T °C) effects on strengthening ratio

## 5. High temperature effect to confinement ratio

In Fig. 3, a direct comparison between confinement ratio with elevated temperature effect and strength increase ratio is plotted. As the temperature increases to 70°C, the concrete strength increases, however, beyond 70°C, the compressive strength of confined concrete was observed to decrease as the temperature increases. These changes in strength are reflected in Eq. 4, below.

$$\frac{f'cc}{f'co} = 0.807 + 0.147\left(\left(\frac{fl}{f'co}\right) * (T^{o}C)\right) - 0.002\left(\left(\frac{fl}{f'co}\right) * (T^{o}C)\right)^{2} \qquad (4)$$

In addition, Fig. 3 also shows that by including temperature effect to the confinement ratio, it seems the results are much the same scattered distribution compared to Fig. 2. This is probably because only 8 data from Table 3 have temperature higher than the room temperature; 45°C (1 data), 70°C (4 data) and 100°C (3 data).

## 6. Proposed new analytical model

The original confinement model given in Eq. (1) provides a good strength prediction of CFRP wrapped concrete circular section, at room temperature. However with most structures, particularly transportation civil infrastructure, which experience wide range of temperatures. Such lack of practical application highlights the need for a new model that reflects the effects of this critical parameter; which is the temperature.

Based on Eq. (4), a simple statistical analysis was performed by comparing calculated compression strength with experimental results. As shown in Table 4, it was found that Eq. (4) provides a good average prediction with the experimental results.

Without any modifications, the existing Eq. (1) is also being compared to Eq. (4), and from Table 4 it shows that Eq. (4) gives a better average. This scatter distribution of prediction can be overcome by having more data along with an exact temperature and humidity contribution in deriving and perfecting Eq. (4), in the future. Meanwhile in Fig. 4, comparison between these two Equations obviously shows that the proposed Eq. (4), which includes temperature and humidity effects, is in good agreement with the experimental results.

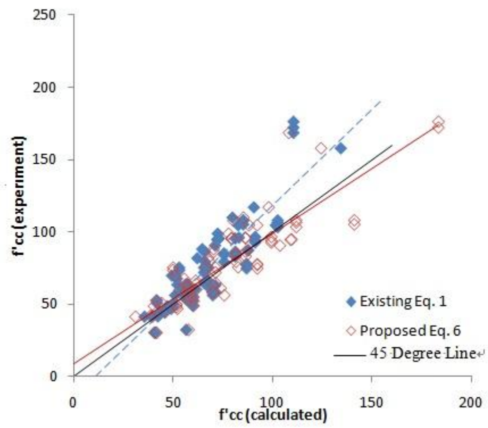


Fig. 4 Prediction of proposed equation compared to existing equation towards experimental results

Table 4 Comparison of the existing and the proposed improved equations

| | $f'_{cc}$ (cal)/$f'_{cc}$ (exp) | | |
|---|---|---|---|
| Equation | Average | Standard deviation | Coefficient of variation (%) |
| 1 | 0.93 | 0.18 | 19 |
| 6 | 1.00 | 0.19 | 19 |

## 7. Conclusions

This paper presented a new modified model for CFRP strengthened circular concrete column section. Unlike the existing model by Lam and Teng, the new model takes into account the effects of various temperatures levels. However, despite the large amount of data collected, and a best fit equation, the model gives relatively large scatter of results. This may be caused by the limited data points at elevated temperatures. More future work is needed to fully understand elevated temperature effects at various humidity levels.

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