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MULTIVARIATE NONLINEAR REGRESSION PREDICTION OF BOND STRENGTH OF FRP BARS IN CONCRETE

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Abstract. *In the reinforced concrete repair and strengthening industry, accurate prediction of fiber reinforcement polymer (FRP) concrete bond behavior is critical. The goal of this study is to conduct a Multivariate Nonlinear Regression (MNR) model for the bond strength of FRP bars in concrete. Nonlinear models may accommodate a wide range of mean functions and can give reasonable estimates of the model's unknown parameters with limited data sets. Several parameters that effect the bonding strength of FRP bars were identified and used to develop the nonlinear model including the compressive strength of concrete, embedment depth, concrete cover, bar diameter, and confinement. The model developed is valid irrespective of FRP type, surface roughness and texture, and failure mechanism namely, splitting and pull-out. A database of 327 test results from the literature is used to develop the model. The suggested nonlinear model estimates the bonding strength of FRP bars in concrete with great accuracy. The predictor factors used were found to be effective at describing bond strength of FRP bars in concrete. The developed equation outperforms the American Concrete Institute (ACI) model, which is frequently used.*

1 INTRODUCTION

Corrosion of reinforcement steel has been a source of concern for engineers for many years. Many research institutes have recently directed their efforts to Fiber Reinforced Polymers (FRP), as a steel reinforcement substitute in concrete construction due to their high tensile strength and non-corrosive composition [1]. FRP is not only more corrosion resistant than steel, but it is also lighter and stronger, while having a lower Young's modulus. To overcome the construction industry's reluctance to accept novel structural materials, study on all elements of their structural behavior is required. Bond development is one of the most fundamental features of structural behavior, as it is the key to reinforcing bar and concrete cooperation. Bond strength is affected by a number of parameters, including bar materials, bar surface texture, bar diameter, concrete compressive and tensile strengths, concrete type, concrete cover, transverse reinforcement, and failure mode [2-5]. Bond strength investigations in concrete reinforced with FRP reinforcing bars have progressed over the last decade as a result of new research methodologies and advancements in the properties of composites. Under direct pullout circumstances, [6] studied the bonding behavior of fiber-reinforced polymer bar. A significant difference was identified between the bond failure modes for FRP bars and deformed steel bars in typical concrete, with damage to the resin surface of the bar occurring during pullout. It is evident from the load slip curves that steel and FRP are fundamentally different materials. They also found that increasing concrete compressive and tensile strength has a positive effect on bond strength and bar development time. Deformed and sand-coated surfaces on FRP bars enhance their ability to adhere to concrete. FRP bars' bond strength has been proven to increase with decreasing bar diameter and increasing concrete strength, resulting in a shorter development length [7, 8]. The load at the concrete-reinforcement interface must be effectively and reliably carried through the bond between the two materials in an ideal RC structure design [9]. Many studies have been done to date to determine the strength of the bar-concrete bond. [10] calculated the bond strength of the GFRP and CFRP bars based on the influences of bar diameter, splice length, concrete cover, and confinement supplied by the transverse reinforcement. The Monte Carlo simulation approach was used by [11] to anticipate the bond strength of GFRP bars, taking into account such variables as the transverse reinforcement, bar surface characteristics, bar diameter, and concrete compressive strength. [12]

came up with an equation to compute the bond strength of the bars with diameters less than 20 mm and embedment lengths less than 20 times the diameter.

Although there are several studies that estimate the bond strength of FRP bars in concrete, studies have revealed that the accuracy of their suggested correlations may be improved. The objective of this study is to develop a generalized bond strength equation for the FRP bars in concrete based on multivariate analysis. Because of variations in fiber composition, surface texturing, and matrix material, FRP reinforcements can have a wide range of physical qualities depending on manufacturer. These characteristics influence the FRP bars' bond strength and development length and thus it will be incorporated in the development of the multivariate equation. The new model will be compared to [13].

2 DATA COLLECTION

The data collected in this paper were taken from references [3] and [14] through [31]. A total of 327 data points were collected. 271 data points were for bars in the bottom position while the rest were positioned at the top. Top bars were not considered in this study. The type of data collected were peak bond strength τ_p in (MPa), concrete compressive strength (f'_c) in MPa, concrete cover (c) in mm, diameter of the bar (d_b) in mm, and embedment length of bar (l_{embd}) in mm. The confinement in this data is represented by eqn (1) as follows:

$$\frac{A_{tr}}{snd_b} \tag{1}$$

Where A_{tr} is the transverse reinforcement, s is the spacing of the transverse reinforcement, n is the number of bars developed. A value of zero indicates no confinement. Figures 1 through 4 show the data scatter of $\tau_p/\sqrt{f'_c}$ versus $\sqrt{f'_c}$, c/d_b, l_{embed}/d_b, and eqn (1) respectively. Other data collected were, the type of fibers, failure mode, and bar surface as summarized in Table 1.

Bar Location	Failure Mode	Bar Surface	FRP Type	Confinement
Bottom (271)[1]	Splitting (125)	Helical Lugged (120)	Aramid (10)	No Confinement (100)
	Pull-Out (146)	Sand Coated (43)	Carbon (55)	With confinement (171)
		Spiral Wrap (108)	Glass (206)	

1. Number in parentheses is the number of data points.

Table 1 : Data Summary

3 MULTIVARIATE NONLINEAR REGRESSION

It can be observed from figures 1 through 4 that there is a high scatter in the data. The only trend observed is in Figure 3 indicating an inverse relationship between $\tau_p/\sqrt{f'_c}$ and l_{embed}/d_b. The variability of the bond strength was minimized by normalizing it with the square root of the compressive strength of concrete. Both of the embedment length and cover were normalized with respect to the bar diameter to minimize the variability of the bar diameter. In performing nonlinear regression, it is advantageous to know the equation beforehand. The equation was constructed to uphold the following behaviors; an increase in the compressive strength of concrete and cover will cause an increase in the bond peak strength, while an increase in the embedment length will result in a decrease in the bond peak strength.

Thus, the following equation is proposed:

$$\frac{\tau_p}{\sqrt{f_c^{'}}} = (g + b\sqrt{f_c^{'}} + d\frac{c}{d_b})e^{-a\frac{l_{embed}}{d_b}} \tag{2}$$

Where g, b, d, and a are constants to be determined using nonlinear regression. The total number of points where 271, averaging the repeat data points the number of data point remaining are 195. Nonlinear regression was performed using the software [32]. Table 2 shows the parameter estimate. Table 3 Shows the ANOVA results of the nonlinear regression.

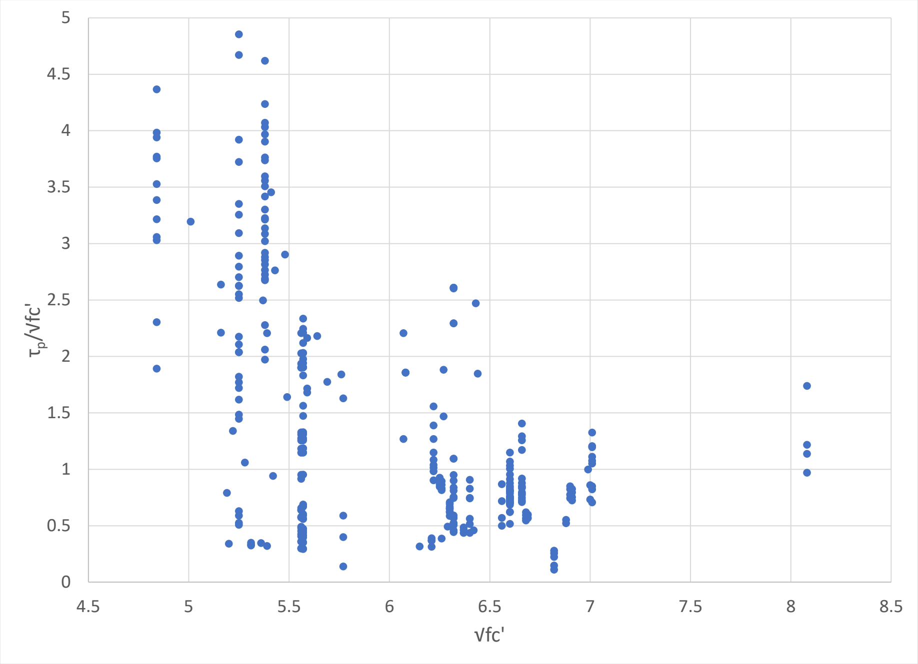

Figure 1. $\tau_p/\sqrt{f'c}$ versus $\sqrt{f'c}$

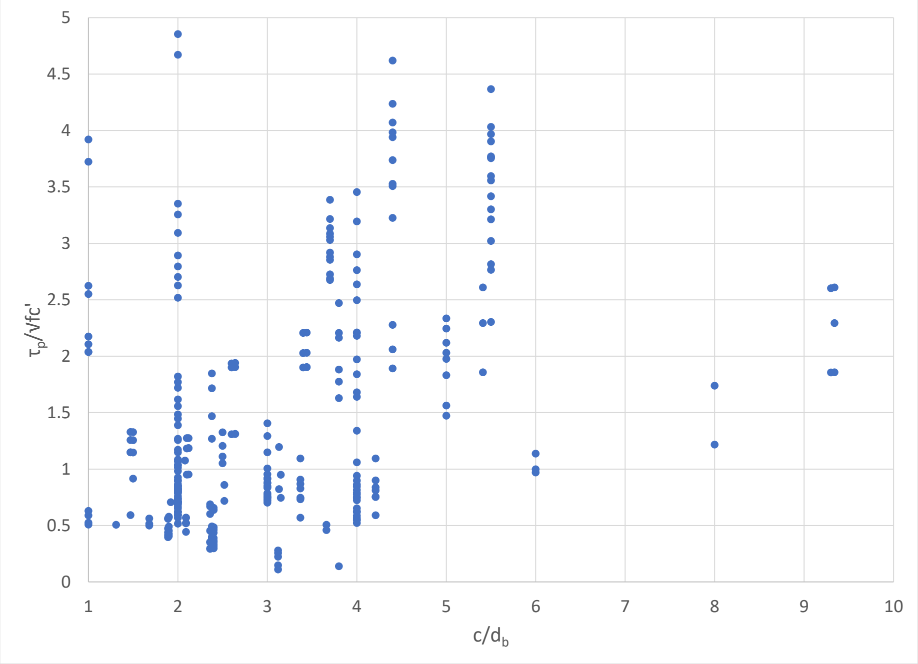

Figure 2. $\tau_p/\sqrt{f'c}$ versus c/d_b

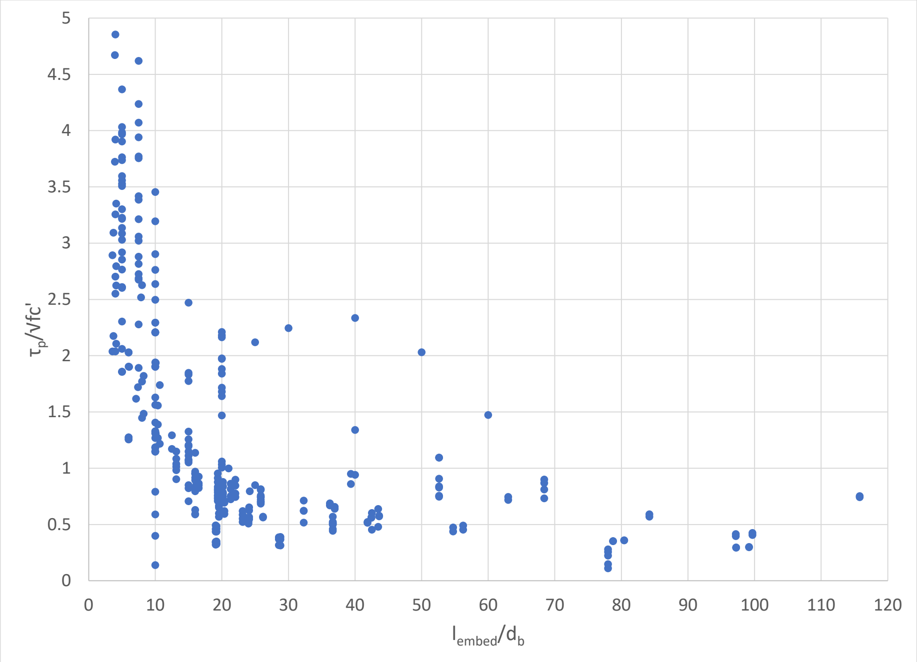

Figure 3. $\tau_p/\sqrt{f'c}$ versus l_{embed}/d_b

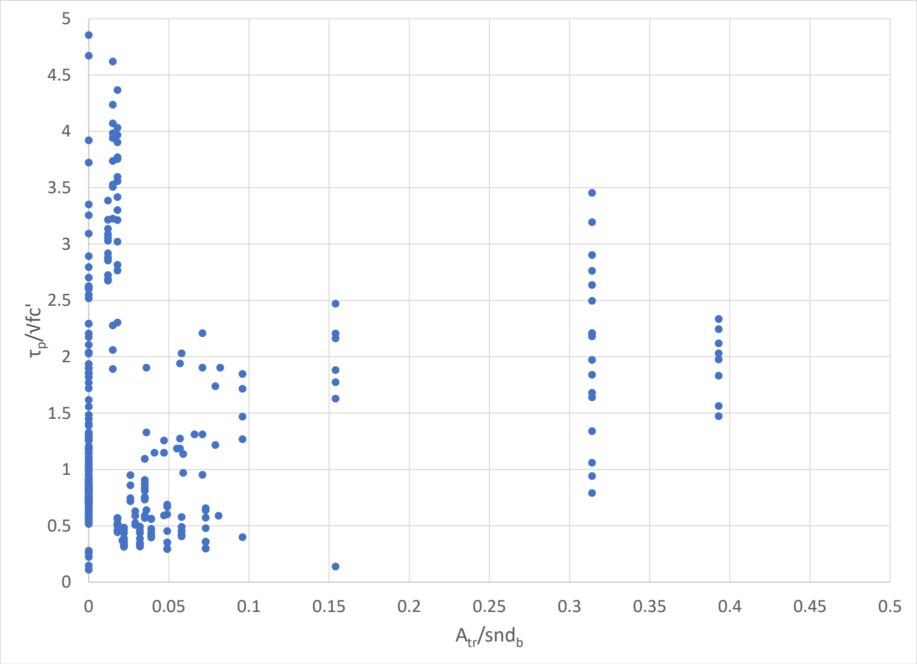

Figure 4. $\tau_p/\sqrt{f'c}$ versus eqn (1)

	Estimate	Standard Error	t-Static	P-Value
g	6.92581	0.52682	13.1464	0
b	-0.984184	0.0897127	-10.9704	0
d	0.284907	0.0298838	9.53386	0
a	0.0206222	0.00264903	7.78484	0

Table 2: Parameter estimates

	Degree of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)
Model	4	472.837	118.209
Error	191	50.4514	0.264144
Uncorrected Total	195	523.288	
Corrected Total	194	160.016	

Table 3: ANOVA

The adjusted R^2 is equal to 0.902. The ACI 440.1R-06 uses the following equation to calculate the peak bond strength,

$$\frac{\tau_p}{\sqrt{f_c^{'}}} = 0.33 + 0.025\frac{c}{d_b} + 8.3\frac{d_b}{l_{embed}} \tag{3}$$

Figure 5 shows the residual plot for both the developed equation and the ACI 440.1R-06. It is observed that the residual values for eqn (2) outperform that of the ACI 440.1R-06. Both equations underpredict the peak bond strength at higher values. The model developed is valid irrespective of FRP type, surface roughness and texture, and failure mechanism namely, splitting and pull-out. Regarding the confinement it was found that it has minimal influence on the developed equation (R^2=0.902, the parameter estimate coefficient of confinement has a P-Value of 0.128>0.05 thus it can be dropped out of the equation).

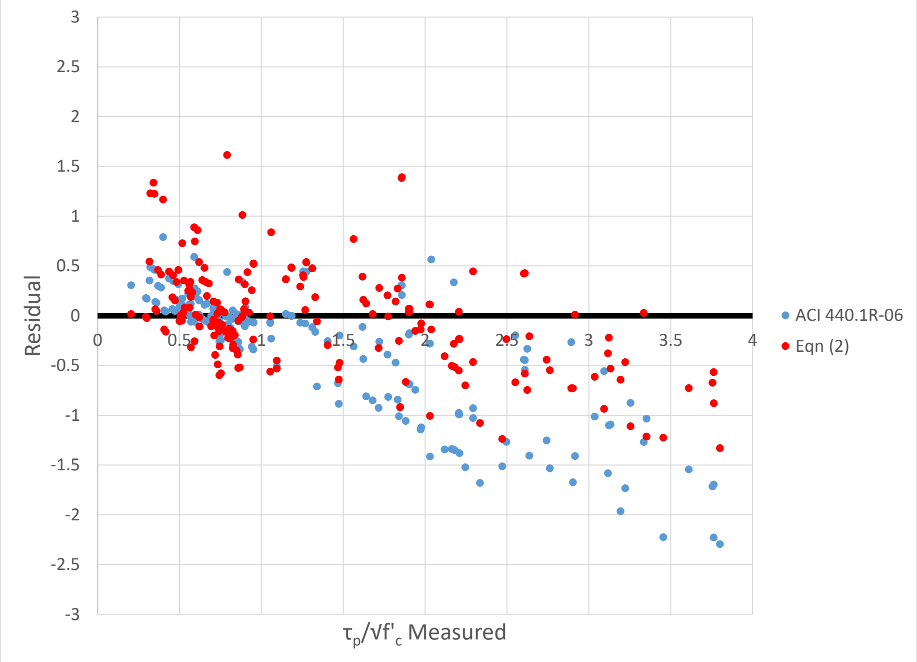

Figure 5. Residual values for eqn (2) and ACI 440.1R-06

4 CONCLUSIONS

A new equation is developed to predicted the peak bond strength for FRP bars in concrete with great accuracy as compared to the ACI 440.1R-06 equation. The developed equation upheld the behavior of the variables used to predict the peak bond strength, namely increasing the concrete compressive strength and cover increases the peak bond strength, while an inverse relationship exists between the embedment length and the peak bond strength. The developed equation is insensitive of FRP type, surface roughness and texture, and failure mechanism namely, splitting and pull-out. Confinement had minimal influence on the developed equation.

REFERENCES

[1] Masuelli, M. A. (2013). Introduction of Fibre-Reinforced Polymers − Polymers and Composites: Concepts, Properties and Processes, Fiber Reinforced Polymers - The Technology Applied for Concrete Repair, Martin Alberto Masuelli, IntechOpen.

[2] Tepfers, R., Hedlund, G., andRosinski, B. (1998), “Pull-out and tensile reinforcement splice tests with GFRP bars” Proceedings of the Second International Conference on Composites in Infrastructure, ICCI´98, Tucson, Arizona, January 3-4, , Vol. II, 37-51.

[3] Tighiouart, B., Benmokrane, B., and Gao, D. (1998). “Investigation of bond in concrete member with fibre reinforced polymer (FRP) bars.” Construction and Building Materials, Vol. 12, pp. 453-462.

[4] Islam, S., Afefy, H.M., Sennah, K., and Azimi, H. (2015), "Bond characteristics of straight- and headed-end, ribbed-surface, GFRP bars embedded in high-strength concrete" Construction and Building Material, Vol. 83, pp. 283-298.
[5] Yan, F., and Lin, Z. (2017), "Bond durability assessment and longterm degradation prediction for GFRP bars to fiber-reinforced concrete under saline solutions" Composite Structures, Vol. 161, pp. 393-406.
[6] Achillides, Z, and Pilakoutas, K. (2004). "Bond behavior of fiber reinforced polymer bars under direct pullout conditions" Journal of Composites for Construction, Vol. 8, No. 2, pp. 173-181.
[7] Wambeke, B. W., and Shield, C. K. (2006). "Development Length of Glass Fiber-Reinforced Polymer Bars in Concrete", ACI structural Journal, Vol. 103(1), pp. 11–17.
[8] Yan, F., Lin, Z., and Yang, M. (2016). "Bond mechanism and bond strength of GFRP bars to concrete: A review", Composites Part B: Engineering, Vol. 98, pp. 56–69.
[9] Golafshani, E.M., Rahai, A. and Hosseini Kebria, S.S. (2014), "Prediction of the bond strength of ribbed steel bars in concrete based on genetic programming", Comput. Concrete, Vol. 14(3), pp. 327-345.
[10] Aly, R. (2005), "Experimental and analytical studies on bond behavior of tensile lap spliced FRP reinforcing bars in concrete", Ph.D. Dissertation, Department of Civil Engineering, University of Sherbrook, Sherbrook.
[11] Esfahani, M.R., Rakhshanimehr, M. and Mousavi, S.R. (2013), "Bond strength of lap-spliced GFRP bars in concrete beams", J. Compos. Constr., Vol. 17(3), pp. 314-323.
[12] Xue, W., Zheng, Q., Yang, Y. and Fang, Z. (2014), "Bond behavior of sand-coated deformed glass fiber reinforced polymer rebars", Journal of Reinforced Plastics and Composites, Vol. 33(10), pp. 895-910.
[13] ACI Committee 440 (2006). "Guide for the design and construction of structural concrete reinforced with FRP bars (ACI 440.1R-06)." American Concrete Institute, Farmington Hills, MI, 44 pp.
[14] Aly, R. (2007). "Stress along tensile lap-spliced fibre reinforced polymer reinforcing bars in concrete." Canadian Journal of Civil Engineering, Vol. 34, pp. 1149-1158
[15] Aly, R., and Benmokrane, B. (2005). "Bond splitting strength of lap splicing of GFRP bars in concrete." Proc., 33rd Annual General Conference of the Canadian Society for Civil Engineering, Toronto, ON, Canada, 1-10. (CD-ROM)
[16] Aly, R., Benmokrane, B., and Ebead, U. (2006). "Tensile lap splicing of bundled CFRP reinforcing bars in concrete." Journal of Composites for Construction, Vol. 10, No. 4, pp. 287- 294.
[17] Aly, R., Benmokrane, B., and Ebead, U. (2006). "Tensile lap splicing of fibre-reinforced polymer reinforcing bars in concrete." ACI Structural Journal, VOL. 103, No. 6, pp. 857-864.
[18] Benmokrane, B., Tighiouart, B., and Chaallal, O. (1996). "Bond strength and load distribution of composite GFRP reinforcing bars in concrete." ACI Materials Journal, Vol. 93, No. 3, pp. 246- 253.
[19] Benmokrane, B., and Masmoudi, R. (1996). "FRP C-bar as reinforcing rod for concrete structures." Proc., 2nd Int. Conf. on Advanced Compos. Mat. in Bridge Struct., M. El-Badry, ed.
[20] DeFreese, J. M., and Roberts-Wollmann, C. L. (2002). "Glass fibre reinforced polymer bars as top mat reinforcement for bridge decks." Contract Report for Virginia Transportation Research Council.
[21] Ehsani, M. R., Saadatmanesh, H., and Tao, S. (1996). "Design recommendations for bond of GFRP rebars to concrete." Journal of Structural Engineering-ASCE, Vol. 122, No. 3, pp. 247-254.
[22] Faza, S. S., and GangaRao, H. V. S. (1990). "Bending and bond behaviour of concrete beams reinforced with plastic rebars." Transportation Research Record No. 1290, Vol. 2, pp. 185-193.
[23] Kanakubo, T., Yonemaru, K., Fukuyama, H., Fujisawa, M., and Sonobe, Y. (1993). "Bond performance of concrete members reinforced with FRP bars." Fibre-Reinforced-Plastic Reinforcement for Concrete Structures-Int. Symp., ACI SP138-46, pp. 767-788.

[24] Maji, A., and Orozco, A. L. (2005). "Prediction of bond failure and deflection of carbon fibre reinforced plastic reinforced concrete beams." Experimental Mechanics, Vol. 45, No. 1, pp. 35- 41.
[25] Makitani, E., Irisawa, I., and Nishiura, N. (1993). "Investigation of bond in concrete member with fibre reinforced plastic bars." Fibre-Reinforced-Plastic Reinforcement for Concrete Structures-Int. Symp., ACI SP138-20, pp. 315-331.
[26] Mosley, C. P., Tureyen, A. K., and Frosch, R. J. (2008). "Bond strength of nonmetallic reinforcing bars." ACI Structural Journal, Vol. 105, No. 5, pp. 634-642.
[27] Mosley, C. P. (2000). "Bond performance of fibre reinforced plastic (FRP) reinforcement in concrete." MS Thesis, Purdue University, West Lafayette, IN.
[28] Okelo, R. (2007). "Realistic bond strength of FRP rebars in NSC from beam specimens." Journal of Aerospace Engineering, Vol. 20, No. 3, pp. 133-140.
[29] Pecce, M., Manfredi, G., Realfonzo, R., and Cosenza, E. (2001). "Experimental and analytical evaluation of bond properties of GFRP bars." Journal of Materials in Civil Engineering, Vol. 13, No. 4, pp. 282-290.
[30] Shield, C. K., French, C. W., and Hanus, J. P. (1999). "Bond of glass fibre reinforced plastic reinforcing bar for consideration in bridge decks." ACI SP Int. Symp. on FRP in Reinforced Concrete, SP188-36, pp. 393-406.
[31] Tighiouart, B., Benmokrane, B., and Mukhopadhyaya, P. (1999). "Bond strength of glass FRP rebar splices in beams under static loading." Construction and Building Materials, Vol. 13, pp. 383-392.
[32] Wolfram Research, Inc., Mathematica, Version 9.0, Champaign, IL (2021).