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Pull-Out Strength of Rebar Embedded in Fiber-Reinforced High-Strength Concrete Utilizing Dimensional Analysis

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Abstract

Bond strength between reinforcement rebars and concrete has significant importance as this helps determine the structural integrity, durability, ductility, and design of a structural member. Ensuring adequate bond strength between the reinforcement and concrete enhances the safety of the reinforced concrete members when subjected to different loadings. Although fiber-reinforced concrete has been widely investigated, research on fiber-reinforced high-strength concrete remains limited, particularly with respect to rebar pull-out and bond behavior. In addition, various predictive approaches have been applied to evaluate pull-out and bond performance using regression analysis, artificial neural networks, and finite element modeling, limited research has utilized dimensional analysis. This study developed a predictive model for pull-out strength using the method of dimensional analysis. Experimental data from existing literature were utilized, and the model was validated against various datasets, showing predictive values close to actual results.

INTRODUCTION

Bond strength between reinforcement rebars and concrete has significant importance as this will help determine the structural integrity, effective transfer of loads, durability, ductility and design efficiency of a structural member [1]. Good bond strength between rebar and concrete reflects the structural behavior and performance of the structure or building [2]. Investigating bond strength helps in understanding whether both materials effectively complement each other, ensuring the longevity and capacity of the structure to withstand structural failure. Through the use of pull-out tests, particularly for construction purposes, the assessment of strength, stability of the materials, and their corresponding connections helps ensure the load-bearing capacity meets the standard requirement ensuring the performance and overall quality of the project [3].

Predictive models for pull-out strength of rebar have been studied by various researchers. In the study of Khaksefidi et al. [4], bond behavior of high-strength rebar with the ultra-high-performance concrete was investigated. In this study, various parameters were considered, and multiple regression is utilized to formulate a predictive model. To ensure the relevance of the model in each run, insignificant independent variables are removed until the significance level is less than 10%. Bond strength is influenced by various factors, including concrete compressive strength, concrete cover size, and embedded length. Bond strength between concrete and steel increases as concrete compressive strength increases. However, concrete cover restrains as well as changes the pattern of failure from splitting to pull-out failure [5]. Artificial neural networks are utilized by researchers to predict the bond strength of

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rebar embedded in concrete. This technique enables the consideration of factors that were not included in previous study. The combination of ANN and empirical formula improves the accuracy of the predictive model [6]. To gain more insights in the behavior of bond strength, FEM helps visualize the actual performance of the rebar embedded in concrete, showing possible failure during pull-out test if it is pullout, splitting-pullout, and splitting, as well as show the crack propagation of the concrete when load is applied [7].

Based on the previous study, predictive model for determining the bond strength of rebar embedded in concrete utilize regression analysis, artificial neural network, finite element modeling, and machine learning. Dimensional analysis has not been used to formulate a predictive model for bond strength. It has been used in predictive modeling in the study of Phatak and Dhonde [8], which aimed to develop a predictive model for the torsional strength of beams. The main advantage of dimensional analysis is that it is not based on any assumptions or hypothesis but relies on experimental observations and the dimensional homogeneity of the physical phenomenon under consideration [8]. This method is also used in earthquake studies for predicting the frequency-dependent attenuation of blast induced vibration in underground excavation and shows the behavior of the vibration, providing a more accurate prediction compared to existing formula [9]. There is limited use of dimensional analysis in the field of structural engineering, especially in predicting the bond strength of rebar embedded in concrete. This gap led to the goal of this study, which aims to utilize dimensional analysis in formulating predictive model for bond strength.

Bond strength is being studied in various cases and material properties. Sun et al. [10] investigated the bond behavior between bundled bars and concrete using beam-end pullout test since this type of test is essential in ensuring that the design made by structural engineers will safely carry the loads applied on the structure. Parameters such as number of bars of each bundle, bonded length and rebar type such as steel bar, basalt fiber reinforced polymer (BRFP) reinforcing bar and steel fiber-reinforced concrete bars (SFCB) were considered to observe the following failure modes such as rebar pullout without yielding, rebar pullout after yielding, rebar fracture and concrete splitting. Liu et al. [11] investigated the response of reinforced concrete (RC) structures particularly the dynamic bond-slip behavior between steel bar and concrete using Finite Element (FE) model developed in LS-DYNA and verified it through testing results. To obtain the relationship between bond stress and slip, parameters such as concrete specimen shape, concrete cover depth and rebar diameter (c/d ratio), and the concrete strength on the dynamic pull-out test were systematically investigated. The specimen with the highest c/d ratio showed the highest loading sensitivity rate with the largest increment in dynamic loading strength, meaning that as the load is applied more quickly, the bond strength significantly increases. The results show that concrete strength is inversely proportional to dynamic bond strength, meaning that an increase in concrete strength reduces the loading rate sensitivity of the dynamic bond strength.

Biscaia and Carmo [12] investigated the bond assessment between embedded rebars, such as ribbed steel rebars or fiber reinforced polymer (FRP) rebars, embedded into a parent material such as concrete or timber. The aim of this research is to propose a novel, continuous, nonlinear and single-function bond slip model which can be calibrated and used to model the pull-out test, detailing the detachment process of an embedded rebar from a parent material. To describe the behavior between an embedded rebar and the parent material, three (3) stages - namely Elastic (E), Softening (S) and Friction (F) were studied, wherein the stages can be identified when bond stress reaches its maximum, zero and constant value.

This study aims to identify which of the following factor such as concrete strength, steel yield strength, bar diameter, and embedment length greatly affects the pull-out strength of the rebars embedded in concrete. This study will incorporate dimensional analysis to develop a mathematical model in predicting the influence of several factors on the pull-out strength of rebar embedded in concrete with the aid of multiple linear regression. By utilizing this method, it helps reduce complex relationships into simpler equations, develop non-dimensional parameters, create predictive models, identify significant variables, and predict the possible interaction behavior between rebar and concrete. This approach is fundamental to ensure the safety, performance, and efficiency of structural design. Furthermore, it can contribute to the future development of empirical formulas and design codes by identifying the optimum parameters and factor values for determining the pull-out capacity of rebar embedded in concrete.

METHODS

Data

The data used in this research paper are existing data collected by a previous researcher who also aimed to understand the characteristics of pull-out strength with various parameters. The data that are utilized are from the study of Kareem et al. [13] on reinforcement bars development length determination for ultra high-performance concrete. The UHPC used in this study was mixed with steel fiber to enhance its strength. The dependent variable is the pull-out strength of the rebar (P), and the independent variables are concrete strength ($f'c$), steel yield strength (fy), rebar diameter (d), and embedment length (l). The data comprises 48 specimens tested using a pull-out machine. Each specimen had dimensions of 150 x 150 x 150 mm, with 4 variations of concrete strength: 80, 100, 120, and 140 MPa. However, during the 28th day of the actual testing of the concrete, the recorded compressive strengths were 83.98, 101.77, 117.52, and 145.48 MPa. The rebars embedded in concrete have three (3) variations in diameter - 10, 12, and 16 mm - with yield strengths of 580, 540, and 585 MPa, respectively. The embedment length of the rebar is measured in terms of its diameter (2d, 3d, 4d, and 5d).

Table 1. Descriptive Statistics of the Parameters

	Concrete strength (*f'c*)	Steel yield strength (*fy*)	Rebar diameter (*d*)	Embedment length (*l*)	Pull-out strength (*P*)
mean	112.19	568.33	12.67	44.33	68.16
std dev	22.83	20.35	2.52	17.05	25.76
minimum	83.98	540.00	10.00	20.00	34.00
maximum	145.48	585.00	16.00	80.00	151.96
skewness	0.30	-0.70	0.39	0.52	1.30
kurtosis	-1.20	-1.53	-1.53	-0.43	1.72
n	48	48	48	48	48

Table 1 displays the summary of the variables used in the study. The concrete compressive strength (*f'c*) has an average value of 112.19 MPa, which is slightly higher than the nominal design strengths. The distribution for *f'c* is slightly skewed to the right (skewness = 0.30) and lower than normal kurtosis (-1.20), suggesting a symmetric but less peaked distribution. Meanwhile, the steel yield strength (*fy*) has a mean value of 568.33 MPa with variability of 20.35 and slightly negatively skewed distribution (skewness = -0.70). The rebar diameter (*d*) has a mean 12.67 mm and a slightly positively skewed distribution (skewness = 0.39). Embedment length (*l*), measured as a multiple of rebar diameter, had an average value of 44.33 and a slightly positive skew (skewness = 0.52). The dependent variable (*P*) provides an average of 68.16 kN with a positively skewed distribution (skewness = 1.30) and a kurtosis of 1.72.

Dimensional Analysis

The model to be developed is based on a Rayleigh method of dimensional analysis, considering the various parameters. To derive the formula, mathematical manipulation will be used using the basic units of length (L), time (T), and mass (M). The dimensional analysis is of the form (Equations (1) to (3)):

$$P = k(f'c)^a(fy)^b(d)^c(l)^d \tag{1}$$

where

$$P = MLT^{-2};$$
$$f'c = ML^{-1}T^{-2};$$
$$fy = ML^{-1}T^{-2};$$
$$d = L;$$
$$l = L.$$

Substituting the variables into its basic dimensions,

$$MLT^{-2} = (ML^{-1}T^{-2})^a(ML^{-1}T^{-2})^b(L)^c(L)^d \tag{2}$$

which can be simplified as,

$$MLT^{-2} = M^{a+b}L^{-a-b+c+d}T^{-2a-2b} \tag{3}$$

$M: a + b = 1$, $L: -a - b + c + d = 1$, and $T: a + b = 1$.

Regression Analysis

The derived formula for the pull-out strength of rebar requires a constant of proportionality, k, which can only be estimated through experiments and using regression analysis. The formula of the regression analysis is given by Equation (4).

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n, + \quad (4)$$

where n is the number of variables. Before using the regression analysis, the list of assumptions must be satisfied. Table 2 confirms that the key assumptions are satisfied, ensuring the reliability and validity of the constructed model.

Table 2. Assumptions of Linear Regression

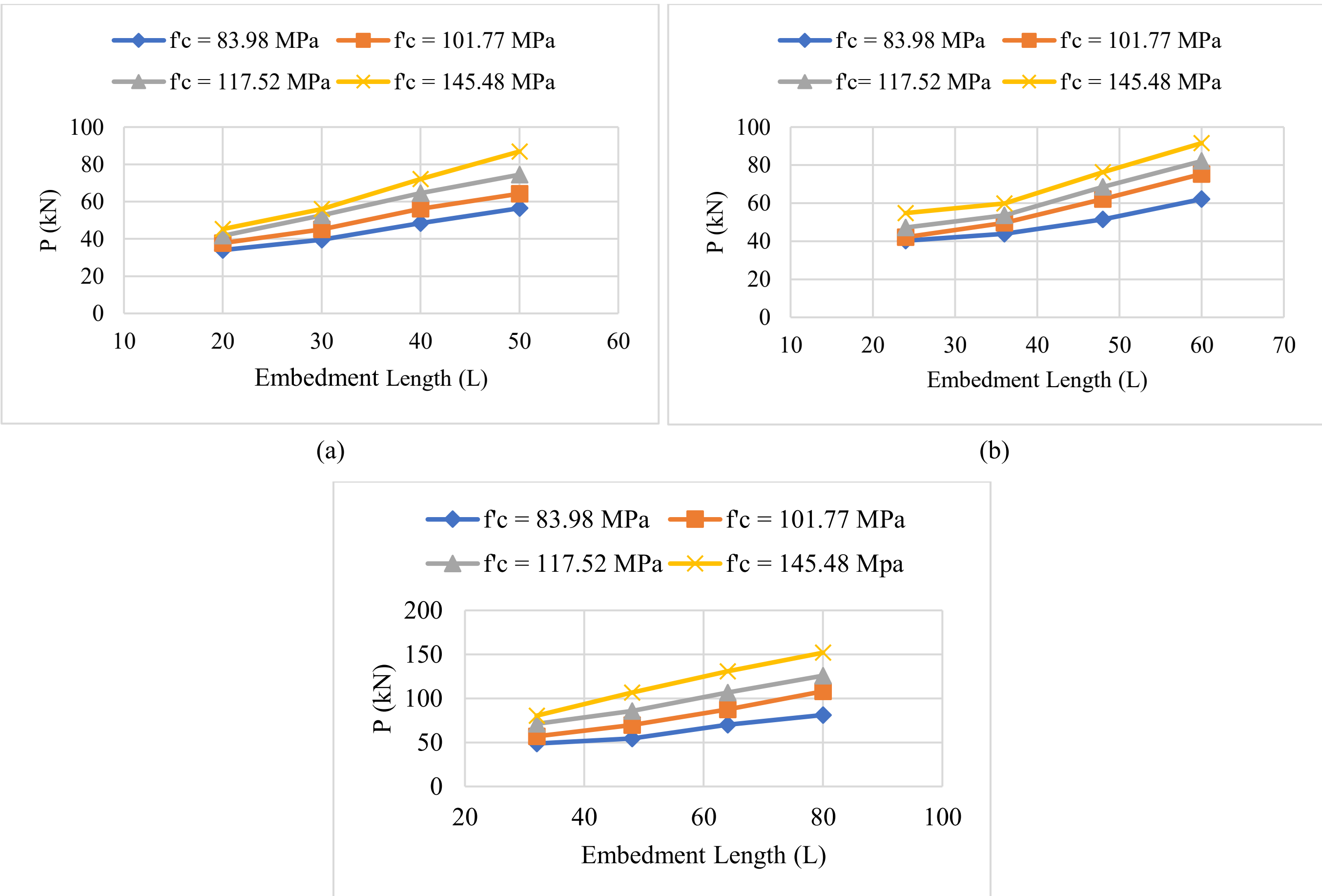
	p-value	Conclusion
Normality Test	0.420	Normal distribution
Homogeneity of Variance	0.085	Equal Variance
Independent Observation		
Multicollinearity		

RESULTS AND DISCUSSION

Factors Affecting Pull-Out Strength of Rebar

The maximum pull-out strength of rebar embedded in concrete is influenced by various factors, such as concrete strength, steel yield strength, bar diameter, and embedment length. Due to these factors, there are various failures that will occur like splitting failure because of the lack of concrete cover, concrete cone failure due to short embedment length, and rebar yielding when the bond strength is greater than the yielding strength of steel [14]. The bond stress between the interfacial of concrete and rebar decreases as the embedment length and diameter increases, which agrees with the studies of Kareem et al. [13] and Chandra et al. [15]. To verify the validity of the model derived through dimensional analysis, the proposed formulation was applied to existing experimental data, and the predicted pull-out capacities were compared with the corresponding experimental results.

Relationship of Embedment Length, Concrete Strength, and Bar Diameter



(a) (b) (c)

Figure 1. Relationship of Embedment Length and Pullout Strength: (a) 10 mm, (b) 12 mm, and (c) 16 mm

The pull-out strength of the rebar with different bar diameters has the same trend that it increases as the embedment length increases, as shown in Figure 1. The embedment length is in terms of 2d, 3d, 4d, and 5d. It is noticeable that this pull-out strength is dependent on the length of embedment. Moreover, variations in concrete strength, as illustrated in the figure, also influence the pull-out capacity. A similar trend is observed wherein, for a constant embedment length, an increase in concrete strength results in higher pull-out strength. These findings are consistent with the results reported in the study [16–18], demonstrating that concrete strength, embedment length, and bond strength has positive relationship.

Relationship of Bar Diameter, Concrete Strength, and Embedment Length

It is shown in Figure 2 that in all cases of the embedment length in 2d, 3d, 4d, and 5d, the pull-out strength increases as the bar diameter increases. This is because, as the bar diameter increases, the contact surface area also increases, resulting in a higher pull-out strength. In the figure, the relationship between the pull-out strength and concrete strength is directly proportional, meaning that as the concrete strength increases, the pull-out strength also increases.

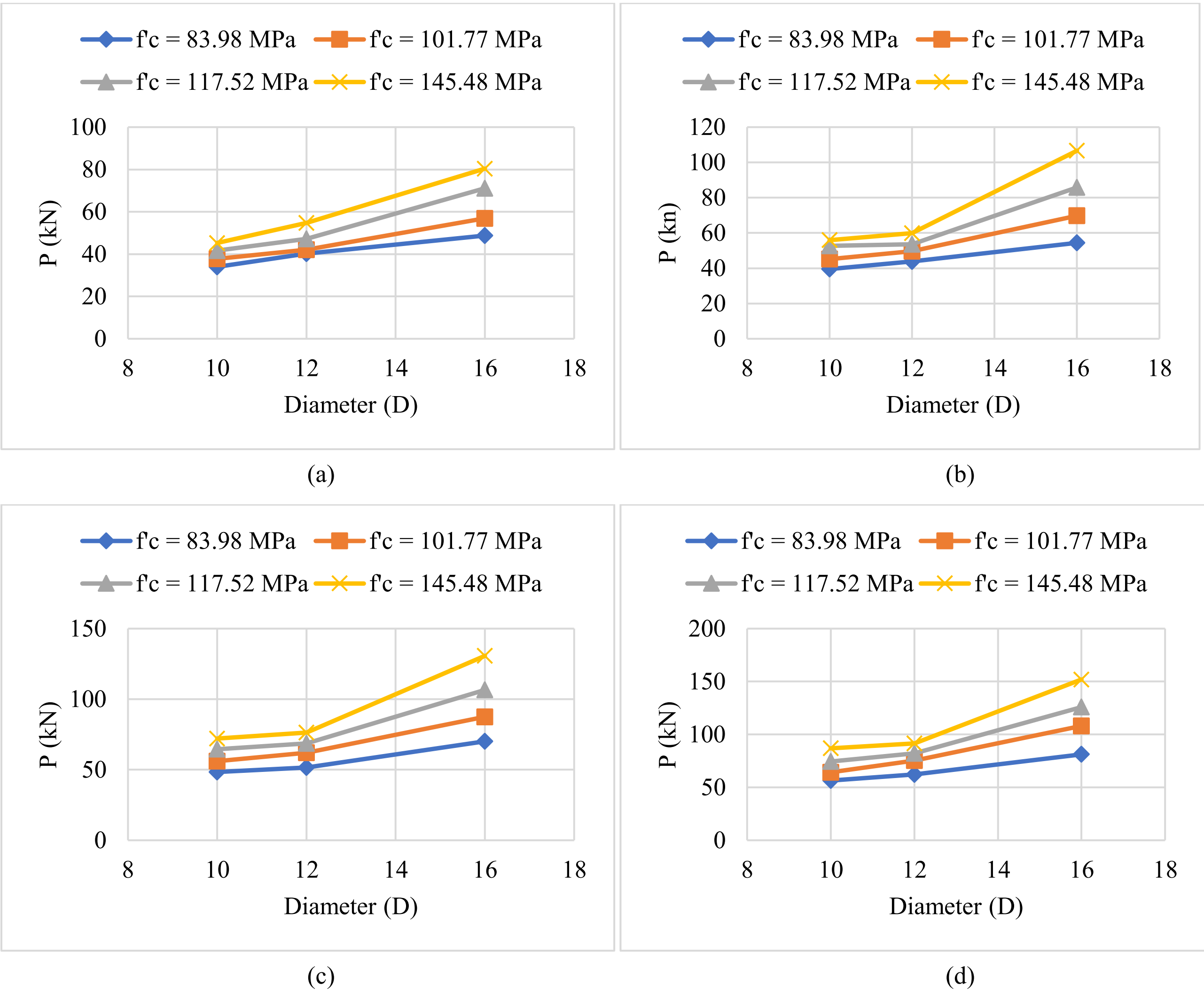


Figure 2. Relationship of Bar Diameter and Pullout Strength: (a) 2d, (b) 3d, (c) 4d, and (d) 5d

Response Surface Methodology

To examine the response surface of the various parameters, such as concrete strength (*f'c*), steel yield strength (*fy*), bar diameter (*d*), and embedment length (*l*), the data were plotted using MATLAB. Since it is not possible to visualize all independent variables simultaneously in a single plot, the dependent variable was combined with two independent variables at a time. As shown in Figure 3, concrete strength, bar diameter, and embedment length exhibit a positive relationship with the pull-out strength of rebar embedded in concrete, indicating that increases in these parameters enhance bond performance. However, steel yield strength (*fy*) was found to have a comparatively smaller influence on pull-out strength than the other three variables.

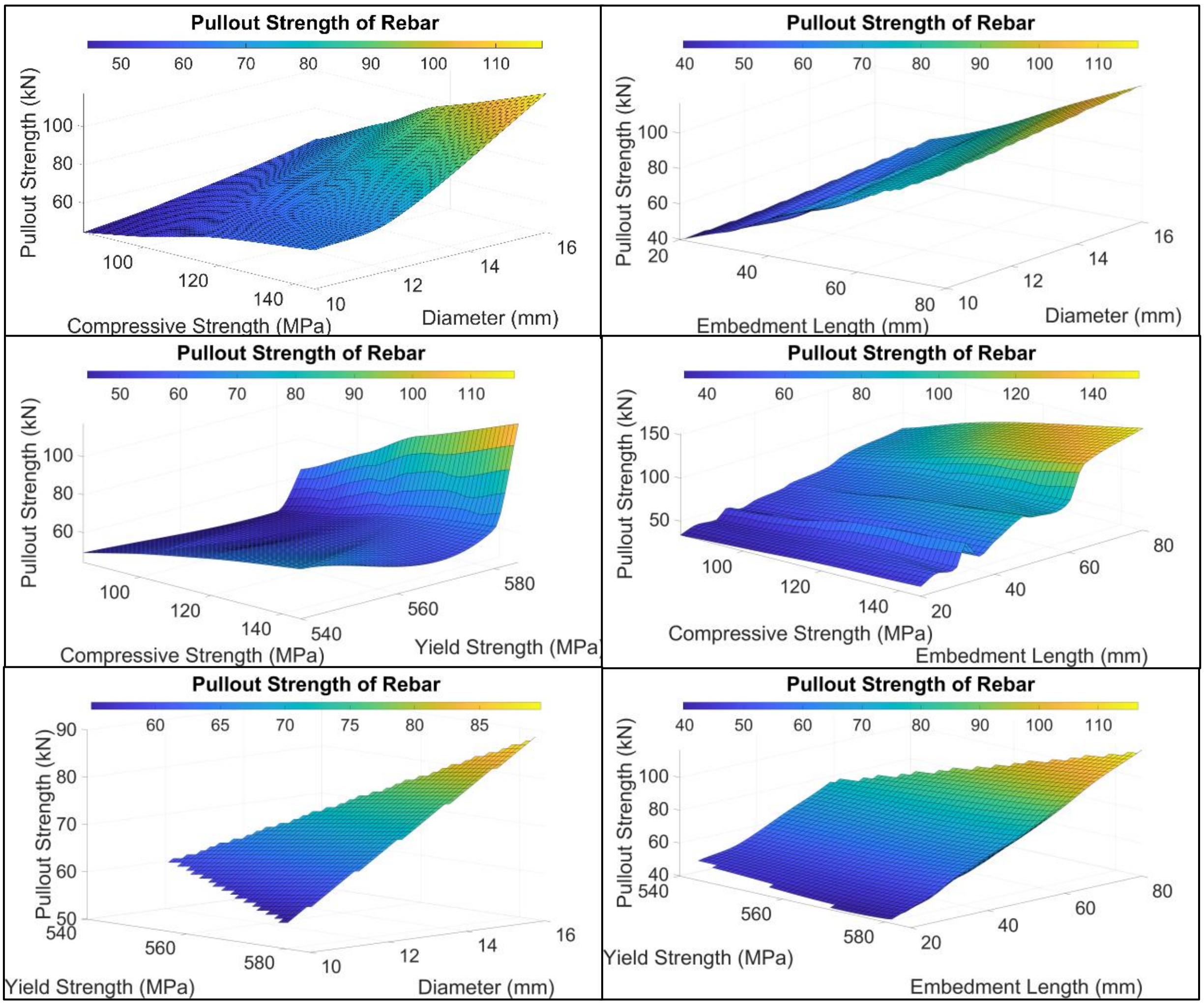


Figure 3. Surface Plot

Dimensional Analysis

The results in Table 3 represent the dimensional analysis that derive a predictive formula for the parameter P as a function of various key parameters with their respective exponents a, b, c, and d. The results indicate that the length (l) has the greatest impact, with an exponent of 1.15. This implies that changing the embedment length of the rebar will strongly influence the outcome (P). This emphasizes the importance of rebar dimensions and embedment in enhancing bond performance.

Table 3. Dimensional Analysis Result

Value	Model
$\boldsymbol{a = 0.62}$	$P = k(f'c)^{0.62}(fy)^{0.38}(d)^{0.85}(l)^{1.15}$
$\boldsymbol{b = 0.38}$	
$\boldsymbol{c = 0.85}$	
$\boldsymbol{d = 1.15}$	

Table 4. Correlation Result

	fc'	**fy**	**dia.**	**l**	**P(kN)**
fc'	1				
fy	0	1			
dia.	1.05086E-17	0.287543	1		
l	2.48629E-17	0.14882	0.517556	1	
P (kN)	**0.460321336**	**0.280524**	**0.593586**	**0.808271**	1

Based on the limitations of the Rayleigh method, no similar dimensions should be present during the derivation. Upon examining the derivation, both $f'c$ and fy have similar dimensions, as well as the d and l, which makes the solution impossible to solve for the exact values. Consequently, the equations derived produced multiple solutions, necessitating an alternative approach. To establish a reasonable assumption, the correlation values among the independent variables and pullout strength were examined, as presented in Table 4. The exponents were subsequently determined based on the weighted contribution of each variable's correlation with the dependent variable (P), as shown in the same table.

Regression Analysis

Using the data gathered from literature, a regression analysis was conducted to compute for the value of coefficient (k), where the pull-out strength P(kN) is the dependent variable and $fc'^{0.62} fy^{0.38} d^{0.85} l^{1.15}$ is the equation composed of independent variables. It shows that the R-squared is 0.885 shown in table 5, and the final equation is derived using the coefficient given by the regression analysis.

Table 5. Result of Linear Regression Analysis

	Coefficient	t statistics	p-value
Intercept	26.7076	10.4923	0.000
$f'c^{0.62} f_y^{0.38} d^{0.85} l^{1.15}$	0.0002817	18.81	0.000
R square		0.885	

Therefore, using the regression results, the final model can be expressed as (Equation (5),

$$P = 0.0002817 f'c^{0.62} f_y^{0.38} d^{0.85} l^{1.15} + 26.7076 \quad (5)$$

Model Validity

The model derived using dimensional analysis will be validated using existing data to check its validity and reliability. As shown in Figure 4, the actual and predicted values of the original data are graphed to assess the predictive capability of the model. The data gathered from existing studies are also used to calculate predicted values using the model. It is noticeable in the graph that the actual versus predicted values of the other data follow the same trend as the original data. However, the other data used have different parameters. The original data are from the study of Kareem et al. [13], which focuses on the development length of rebar under ultra-high-performance concrete. Comparing the actual and predicted values from various experiments, the results follow a similar to that of the data used in the regression analysis utilizing dimensional analysis. FRP-recycled data are from the study of Gao et al. [17], which explores bond strength predictions of bars embedded in concrete where the concrete is steel-polypropylene hybrid fiber reinforced recycled aggregate concrete (HFRAC). Another dataset is an engineered cementitious composite from the study of Ding, Jiepeng, and Weihao [19], where they use steel-polyethylene hybrid fiber engineered cementitious composite to observe the bond strength of the rebar embedded in it. The last dataset used is from the study of Khaksefidi et al. [4], in which high-strength rebar, as well as ultra high-performance concrete are used to determine the bond strength of the embedded rebar. As shown in the figure below, the trend the used existing data follows the same trend as original data used in the regression analysis. Considering the differences in material properties, the formulated model provides commendable predicted values, which is a good indication of a reliable model.

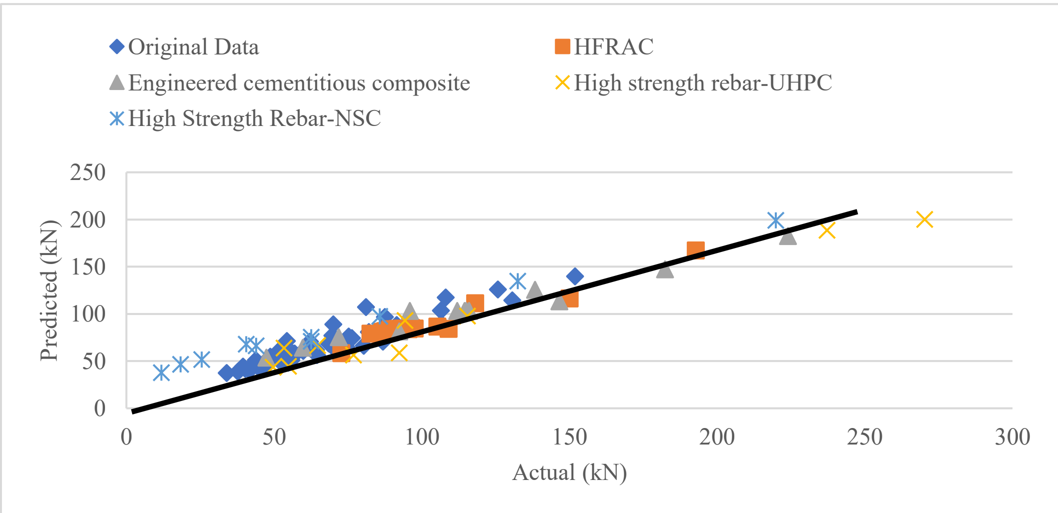


Figure 4. Actual vs. Predicted

Table 6. Summary of Data and Results

Specimen ID	fc' (MPa)	fy (MPa)	d (mm)	l (mm)	P (kN)	Predicted (kN)	Predicted/Actual
				HFRAC			
R50S00P00	52.64	450	16	80	87.15	82.96	1.07
R0S10P10	61.13	450	16	80	105.28	87.48	1.22
R30S10P10	58.88	450	16	80	96.46	86.32	1.13
R50S10P10	57.83	450	16	80	93.63	85.76	1.11
R70S10P10	56.33	450	16	80	91.74	84.97	1.10
R100S10P10	54.6	450	16	80	89.59	84.03	1.09
R50S00P10	51.42	450	16	80	87.15	82.28	1.08
R50S05P10	54.62	450	16	80	90.11	84.04	1.09
R50S15P10	58	450	16	80	97.57	85.85	1.15
R100S00P10	49.68	450	16	80	82.63	81.29	1.04
R100S05P10	52.24	450	16	80	86.93	82.73	1.07
R100S15P10	56.91	450	16	80	95.56	85.28	1.14
R50S10P00	56.77	450	16	80	89.43	85.20	1.07
R50S10P05	57.3	450	16	80	91.88	85.48	1.09
R50S10P15	56.26	450	16	80	91.36	84.93	1.09
R100S10P00	52.12	450	16	80	86.53	82.67	1.07
R100S10P05	52.7	450	16	80	88.22	82.99	1.08
R100S10P15	53.52	450	16	80	87.66	83.44	1.07
R50S10P10D16L48	57.3	450	16	48	72.82	61.15	1.24
R50S10P10D16L80	57.3	450	16	80	109.16	85.48	1.30
R50S10P10D16L112	57.3	450	16	112	118.16	109.82	1.06
R50S10P10D20L100	57.3	450	20	100	150.1	119.71	1.29
R50S10P10D25L125	57.3	450	25	125	192.81	173.18	1.15
				Engineered Cementitious Composite			
14-3d-5d	70	425	14	42	47.3807313	53.77	0.88
14-4d-5d	70	425	14	56	59.75082736	64.39	0.93
14-5d-5d	70	425	14	70	71.8869445	75.41	0.95
20-4d-5d	70	420	20	60	92.435496	81.69	1.13
20-4d-5d	70	420	20	80	115.054296	103.26	1.11
20-4d-5d	70	420	20	100	138.35166	125.65	1.10
20-4d-1.5d	70	420	20	80	96.00424	103.26	0.93
20-4d-2.5d	70	420	20	80	112.038456	103.26	1.09
20-4d-4d	70	420	20	80	114.551656	103.26	1.11
20-4d-6d	70	420	20	80	116.059576	103.26	1.12
25-3d-5d	70	430	25	75	146.6687813	113.40	1.29
25-4d-5d	70	430	25	100	182.4426125	147.39	1.24
25-5d-5d	70	430	25	125	224.0282188	182.69	1.23
				High Strength Rebar-UHPC			
U4-12-2d	102.62	600.3	12	24	54.87	44.74	1.23
U4-12-4d	102.62	600.3	12	48	64.78	66.72	0.97
U4-16-2d	102.62	600.3	16	32	92.45	58.76	1.57
U4-16-4d	102.62	600.3	16	64	115.52	97.84	1.18
U3-25-4d	102.62	600.3	25	100	270.35	200.37	1.35
U3-12-2d	102.62	499.8	12	24	49.72	43.53	1.14
U3-12-4d	102.62	499.8	12	48	53.35	64.03	0.83
U3-16-2d	102.62	499.8	16	32	76.91	56.61	1.36
U3-16-4d	102.62	499.8	16	64	94.41	93.06	1.01
U3-25-4d	102.62	499.8	25	100	237.28	188.69	1.26
				High Strength Rebar-NSC			
C4-12-2d	47.87	600.3	12	24	11.92	37.95	0.31
C4-12-4d	47.87	600.3	12	48	25.52	51.65	0.49
C4-12-6d	47.87	600.3	12	72	44	66.46	0.66
C4-16-2d	47.87	600.3	16	32	18.43	46.69	0.39
C4-16-4d	47.87	600.3	16	64	62.58	71.04	0.88
C4-16-6d	47.87	600.3	16	96	85.81	97.38	0.88
C4-25-2d	47.87	600.3	25	50	62.58	75.48	0.83
C4-25-4d	47.87	600.3	25	100	132.52	134.94	0.98
C4-25-6d	47.87	600.3	25	150	219.92	199.24	1.10
C3-16-4d	47.87	499.8	16	64	40.6	68.06	0.60

Presented in table 6 is the summary of the data being evaluated using the model developed using dimensional analysis. It shows all the factors concrete strength, steel yield strength, embedment length, actual pullout strength, and predicted values. To determine the reliability of the model the ratio of actual to predicted is determined such that this value indicates the relative closeness between the experimental and predicted pull-out strengths, where values approaching 1.0 signify higher prediction accuracy. For the high-strength fiber-reinforced concrete (HFRAC) dataset, the ratios range from 1.07 (closest) to 1.30 (farthest). In the case of engineered cementitious composites (ECC), the closest ratio is 0.95, while the farthest is 1.29. These results indicate that the proposed model provides satisfactory prediction accuracy for both HFRAC and ECC. However, for high-strength rebar embedded in ultra-high-performance concrete (UHPC), the predicted values exhibit greater variability, ranging from 1.01 to 1.57, suggesting that the model's performance is sensitive to the extreme mechanical properties and bond characteristics of UHPC. It is important to note that the UHPC data used to derive the model were obtained from steel-fiber-reinforced UHPC, whereas the UHPC used in the third validation datasets was non-fibered. Similarly, the normal-strength concrete dataset used for validation was also non-fibered. The absence of fibers in these mixes likely reduced interfacial confinement, crack-bridging capability, and post-cracking toughness, leading to lower and more scattered bond strength values. Furthermore, the addition of fiber more likely increases the bond strength of the rebar because of the increase of mechanical properties which fiber reduces structural deformations of concrete based on the study of Nurhuda et al. [20]. Consequently, when the model was applied to normal-strength concrete, it produced poor prediction accuracy, with a significant deviation (ratio = 0.31) from the actual values. This discrepancy arises because the model was developed primarily from high-strength and fiber-reinforced concrete data, whose governing bond mechanisms differ substantially from those of non-fibered and normal-strength concretes. The model demonstrates strong predictive capability for high-strength and fiber-reinforced concretes but limited applicability to non-fibered and normal-strength concretes due to differences in bond behavior, interfacial mechanics, and failure mechanisms. And in Table 7 the descriptive statistics of the predicted values were shown.

Table 7. Descriptive Statistics of the Predicted Values

	HFRAC	**Engineered Cementitious Composite**	**High Strength Rebar-UHPC**	**High Strength Rebar-NSC**
Mean	89.87	104.67	91.43	84.89
Standard Deviation	20.97	34.20	57.24	48.77
Coefficient of Variation	23.33	32.67	62.61	57.45
Sample Variance	439.68	1169.68	3276.30	2378.88
Kurtosis	11.94	1.21	0.62	2.82
Skewness	3.16	0.81	1.40	1.69
Minimum	61.15	53.77	43.53	37.95
Maximum	173.18	182.69	200.37	199.24
n	23	13	10	10

CONCLUSIONS

Pull-out strength of rebar embedded in concrete is a very crucial factor in the design of concrete structures. Inadequate bond strength can result in catastrophic incidents and lead to structural failure. The formulated model is a good tool for estimating and predicting the pull-out strength of rebar with various parameters, such as compressive strength (f'c), steel yield strength (fy), diameter of rebar (d), and embedment length (l). Based on the results, the model demonstrates good predictive capability, especially when applied to data from different studies, where the predicted values are very close to the experimental results. However, it produces inaccurate and scattered results for normal-strength concrete, particularly non-fiber-reinforced mixes. Considering the overall results, the model provides good predictions for HFRAC, ECC, and UHPC. Therefore, the researchers recommended further validation through actual testing to ensure accuracy and reliability in predicting the pull-out strength of rebar embedded in concrete. This predictive model may be inconsistent when applied to conditions beyond the range of the current data sets. Therefore, it is important to consider factors beyond those included in the current dataset, such as rebar diameter, concrete compressive strength, and steel yield strength. Lastly, further exploration of this model using various materials relevant to pull-out strength, including FRP concrete, self-compacting concrete, and other concrete types, is recommended.

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