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PULL-OUT STRENGTH OF AN EXPANSION STUD ANCHOR IN CARBON FIBER REINFORCED CONCRETE

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ABSTRACT: Carbon Fiber Reinforced Concrete (CFRC) is considered as an innovative structural material because of its better performance characteristics when compared to conventional concrete. Its common applications where expansion stud anchor connection is possible are in slabs on grade, wall panel, curtain walls, and pre-cast elements. The design of this stud anchor in CFRC is of great interest to many structural engineers, however, no model is available as basis for its design. To develop such model, this study investigated the pull-out strength of an expansion stud anchor embedded in CFRC as influenced by fiber volume content (Vf), fiber length (Lf), compressive strength and tensile strength. Three compression, three tension, and five pull-out CFRC specimens each of different Vf (0.10%, 0.15%, 0.20%, 0.25%, 0.30%) and different Lf (19 mm, 30 mm, 38 mm) were prepared, tested, analyzed, and compared to control concrete specimens at design compressive strength of 21 MPa. Tests results show that pull-out strength of an expansion stud anchor in CFRC is maximum at Vf = 0.10% and Lf = 38 mm. Among the parameters considered, tensile strength is the most significant contributing factor that could influence the pull-out strength of stud anchor in CFRC. This is further verified numerically by a FEM model with good agreement to the observed tensile strength. Finally, a Response Surface Methodology (RSM) model is proposed to predict the pull-out strength of an expansion stud anchor embedded in CFRC as influenced by the fiber volume content, fiber length, compressive strength, and tensile strength.

Keywords: Pull-out Strength, Expansion Stud Anchor, Tensile Strength, Fiber Length, Fiber Volume Content

1. INTRODUCTION

Synthetic fibers as replacement of steel reinforcement had recently become the focus of many researchers. According to them, these fibers have the potential to be used as reinforcement in concrete to improve certain physical properties. Among the synthetic fibers, carbon has been concluded in many studies to have excellent physical, mechanical and dynamic properties and can be utilized more effectively as reinforcement in concrete material. It is believed that addition of carbon fibers to concrete effectively increases the strength and toughness of concrete. The inclusion of carbon fiber to concrete is termed as CFRC for carbon fiber reinforced concrete. CFRC is proven to have high resistance to corrosion which makes it more durable. It has been successfully applied to many civil engineering projects such as impact resisting structures, precast elements, panels, bridge deck, slabs-on-grade, pavements and curtain walls. It has been claimed by some researchers that chopped carbon fibers, when included within concrete with the appropriate fiber length and volume fraction, can modify the tensile strength, flexural strength, toughness, impact resistance, and fracture energy of the concrete [1]. They recommended that the chopped carbon fibers regardless of its type, poly-acrylo-nitrile (PAN) or pitch should have an average length of not less than the maximum size of the coarse aggregate, preferably at least twice as long as the maximum size of coarse aggregate at minimum of 0.1% fiber volume content to effectively bind coarse aggregate to achieve a significant result for strengthening a concrete structure.

One possible application of CFRC is in the anchorage connection of structural elements. Assuming that the anchor bolts are designed adequately, the pull-out strength of these anchors in concrete is controlled by the failure mode of the base concrete, which could be concrete breakout, concrete splitting, or frictional pull-out. Hence, the behavior of the base concrete where these anchors will be embedded should be carefully considered in design. It is believed that the base concrete will perform better if it is reinforced with fibers. Fiber-reinforced concrete (FRC) has been observed to perform better compared to plain concrete. One study investigated the performance of adhesive anchor bolts in polypropylene fiber reinforced concrete and in steel fiber reinforced concrete [2]. It has been reported that there was a significant increase in pullout load capacity of adhesive anchors both in polypropylene fiber reinforced concrete and in steel fiber reinforced concrete compared to plain concrete. Another study on pullout performance of a single headed anchor in steel fiber reinforced concrete has been investigated [3]. It was found out that the anchor’s pullout capacity increased with the addition of steel fibers to concrete.

In this study, CFRC is investigated as base material of expansion anchor connection. As of now, there is no model that can be used as basis for its design. The pull-out strength of an expansion anchor in CFRC is expected to behave differently from usual ordinary concrete. Specifically, this study investigated the pull-out strength of a single expansion stud anchor in CFRC considering the concrete breakout failure mode as influenced by fiber volume content, fiber length, direct tensile strength and compressive strength. This research will give significant information that is much needed by structural engineers in designing an expansion stud anchor in CFRC which will lead to the solution involving the safety and the economic aspects of its design. Moreover, this study also promotes the application of anchorage in CFRC as well as the utilization of carbon fiber as reinforcement in concrete structures that would result in valuing and increasing awareness of the carbon fiber as innovative construction alternative material. Lastly, the additional benefit of anchorage in CFRC is the ease of drilling for post-installed anchor bolts.

2. METHODS

2.1 Materials

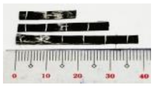
The components of the specimens used in this study were expansion stud anchors and the composite base materials. The composite base material is composed of the carbon fibers (CF) and the concrete matrix. An expansion stud anchor used in this study was a medium-duty anchor with 10 mm diameter with a total length of 90 mm and with yield strength of 640 MPa. The technical data of this anchor such as required torque (T), standard effective embedment depth (h_e), drilling depth (h), drilled hole diameter (D_h), and minimum base thickness (H_{min}) is presented in Table 1.

Table 1 Technical data for expansion stud anchor

Type	T (Nm)	h_e (mm)	h (mm)	D_h (mm)	H_{min} (mm)
	45	60	80	10	120

The fiber type used in this investigation was 0.111 mm thick chopped PAN-based high tensile (HT) strength carbon fibers. According to ACI 544 [4], the length of carbon fibers may vary from 5 mm to 50 mm, but with the predominance of demand for 19 mm or 38 mm fiber length. The selected fiber lengths used in this investigation were 19 mm, 30 mm, and 38 mm. The properties of the PAN-based HT carbon fibers used are presented in Table 2.

Table 2 Properties of PAN-based HT carbon fibers

Lf (mm)	F_t (MPa)	E (MPa)	SG	Width (mm)
	4510	231000	1.80	3.0

Notes: F_t = Tensile Strength of Carbon Fibers
E = Modulus of Elasticity
SG = Specific Gravity

The concrete matrix was composed of cement (C), water (W), fine aggregates (FA), coarse aggregates (CA), and superplasticizer (SP). A high-early strength and with improved workability Portland cement that meets the ASTM standard specification C 595 [5] was used in this study. The water used was clean and of good quality. Crushed coarse aggregates with maximum size of 19 mm having a mass density of 1592 kg/m^3 and 1.01% absorption were used. The mass density and absorption of coarse aggregates were determined according to ASTM C 127-04 [6]. White sand with mass density of 1551 kg/m^3, fineness modulus of 2.4 and having a 3.01% water absorption were used as fine aggregates. The mass density and absorption of fine aggregates were determined according to ASTM C 128-04a [7] and its fineness modulus was determined as per ASTM C 136 [8]. Superplasticizers were added to ensure that all fresh CFRC mixes are workable.

2.2 Specimens

The design mix of the composite base materials were based on the compressive strength of 21 MPa considering the minimum and maximum slump requirement of 25 mm and 100 mm respectively, 2% entrapped air, and water-cement ratio of 0.68. Three compression, three tension, and five pull-out CFRC specimens for each of the different fiber volume contents, Vf (0.10%, 0.15%, 0.20%, 0.25%, 0.30%) and of different fiber lengths, Lf (19 mm, 30 mm, 38 mm) were prepared, tested, and compared to concrete without fiber as the control specimen. The mix proportions of the control and CFRC specimens are given in Table 3.

A variation on the mix proportions of the sand with the fiber volume content is reflected on this table. This is due to the partial replacements of the sand by the carbon fibers.

Table 3 Mix proportions of the specimens

Vf (%)	W (kg/m^3)	C (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	CF (kg/m^3)	SP (gm/kg of C)
0	182.08	301.47	1054.71	841.07	-	-
0.10	182.08	301.47	1054.71	839.52	1.8	3
0.15	182.08	301.47	1054.71	838.71	2.7	3
0.20	182.08	301.47	1054.71	837.93	3.6	3
0.25	182.08	301.47	1054.71	837.16	4.5	3
0.30	182.08	301.47	1054.71	836.38	5.4	3

Before casting all the specimens, the workability of each mix was checked by measuring its slump as per ASTM C 143 [9].

The compressive strength specimens were tested using 100 mm x 200 mm cylinders as per ASTM C 39-05 [10] after 28 days of curing period. The direct tensile strength specimens using a dumbbell shape with a critical section of 75 mm x 50 mm, and a gauge length of 300 mm were tested after 28 days of curing period. A 50 mm thickness was selected to consider a 3D orientation of the fiber in concrete matrix.

The test set-up for direct tensile strength and its failure mode at the critical section are shown in Fig. 1. It is noticeable that the failure on this dumbbell specimen occurred at the critical section within its gauge length as expected.

The base material specimens in rectangular solid shape measuring 360 mm x 360 mm x 150 mm were made and cured for 28 days.

The stud anchors were set in the base material specimens following the setting instruction recommended by the manufacturer and tested them for pull-out strength in accordance to ASTM E 488-96 [11]. The set-up of pull-out strength test for expansion stud anchors and its concrete cone breakout failure mode are presented in Fig. 2.

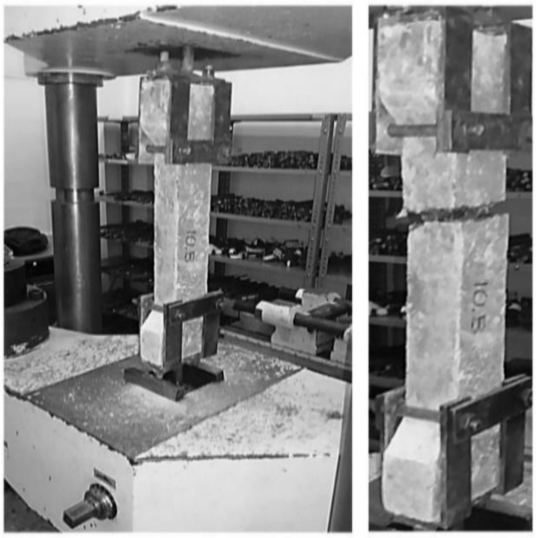


Fig. 1 Tension test set up and failure mode

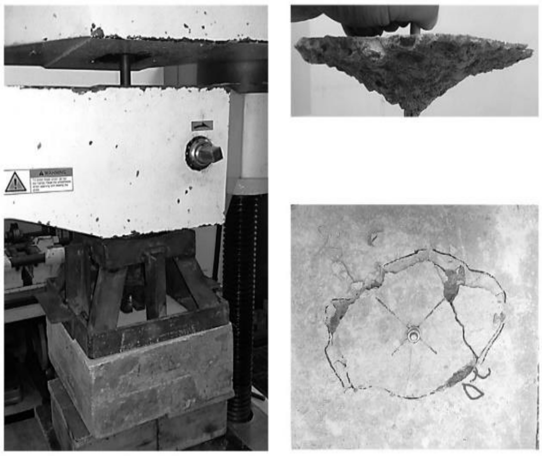


Fig. 2 Pull-out test set up and failure mode

The observed pull-out strength of the stud anchor in concrete base material without fiber was compared to ETAG 001 (Guideline for European Approval of Metal Anchors) [12], and ACI 355.2 [13] and NSCP 2010 (National Structural Code of the Philippines) [14] equations for verification. ETAG 001 equation for concrete breakout of a single anchor in plain concrete is given by

$$N_{Rk,c}^{0} = k_1 \sqrt{f_{ck,cube}}\, h_{ef}^{\;1.5} \quad (1)$$

where, k_1 is 10.1 for applications in non-cracked concrete. The compressive strength using cube specimen was computed using the equation of Kumavat HR and Patel VJ [15],

$$f_{ck,cube} = f'_c / 0.95 \quad (2)$$

While, the NSCP 2010 and ACI 355.2 equation for concrete breakout of a single post-installed anchor in plain concrete is given by

$$N_b = \psi_{c,N} k_c \sqrt{f'_c} h_{ef}^{1.5} \quad (3)$$

where, $\psi_{c,N}$ is 1.4 and k_c is 7 for applications in non-cracked concrete.

2.3 Finite Element Modeling (FEM)

In this study, FEM was applied to simulate, and verify the tensile stress response of the CFRC base material specimens subjected to tensile loading applied into a single expansion stud anchor. Since numerical analysis using FEM may lead to a very large equations and complex solutions, the use of FEM software is important. In this study, ABAQUS software was used to verify and compare the direct tensile stress response of CFRC base material specimens subjected to tensile loading applied to a single expansion anchor against the actual tensile stress of the specimens. The base material is modeled as an isotropic 2D elastic material under tensile load induced by an expansion stud anchor as shown in Fig. 3 with assumed Poisson ratio of 0.20.

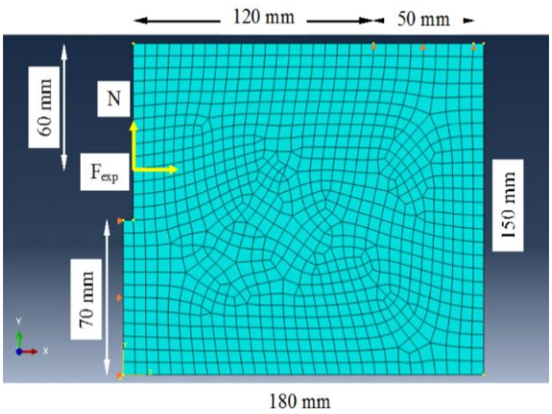


Fig. 3 FEM model

The experimental parameters used in the simulation of tensile stress (FEM_{ft}) are compressive strength (f_c), mass density of base material (w_c), and pull-out strength (N), while normal force through the anchor's sleeve expansion (F_{exp}) was derived using the equation,

$$N = uF_{exp} \quad (4)$$

where, u is the coefficient of friction and was assumed 0.372. This coefficient is nearly equal to the value cited in CEB (Comite Euro-International du Beton) [16], where u of expansion anchor varies from 0.4 to 0.6. The modulus of elasticity, E_c of the specimens were computed using the equation given by NSCP 2010,

$$E_c = w_c^{1.5} 0.043 \sqrt{f'_c} \quad (5)$$

2.4 Response Surface Methodology

Response Surface Methodology (RSM) can model linear and non-linear dynamics, and stochastic phenomenon. The data requirement for a given output is low and the errors are assumed to be random. Supposed that Y is the response of interest and x_1, x_2, x_3, x_4 are the predictor variables. The response of interest in this study can be expressed as $Y = f(x_1, x_2, x_3, x_4)$. The function $f(x_1, x_2, x_3, x_4)$ denotes the response surface. The first step in this process is to find an appropriate approximation for the true relationships between the response and the predictor variables [17]. In this study, the response of interest is the pull-out strength of an expansion stud anchor in CFRC, while the predictor variables are the fiber volume content, fiber length, direct tensile strength and compressive strength at standard effective embedment length, h_{ef} = 60 mm. First-order and second-order RSM models were considered in developing the proposed model in this study. RSM modeling always starts at first-order model because it is often suitable, but if the curvature is evident on the curve fitting, the second-order model will be used. The fitted model of the first-order and second-order are generally defined as

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i \quad (6)$$

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i<j}\sum \hat{\beta}_{ij} x_i x_j \quad (7)$$

respectively, where, $\hat{\beta}$ is the least squares estimate of model coefficients. The next step is the evaluation of the adequacy of the fitted model. This is to ensure that the recommended model will give a satisfactory estimate of the true system. The adjusted coefficient of multiple determination or R^2_{adj} was used in this study instead of R^2 because in most cases, it doesn't always increase as the terms are added to the model with k regressors [18]. It is a measure that estimates Pearson's correlation ratio with value from 0 to 1 and is defined as:

$$R^2_{adj} = 1 - \frac{n-1}{n-p}\left(\frac{SS_E}{SS_T}\right) \quad (8)$$

where, SS_E is the sum of squares of the residuals, SS_T is the total sum of squares and p = k+1 degrees of freedom. Moreover, the fitted model was also subjected to test of significance by F-test at level of significance, α = 0.05. The best model is the one that is adequate by F-test, with highest R^2_{adj} and with least error. Error metric was defined to each model and compared. The metric of comparison used aside from R^2_{adj}, is the mean square of error or MSE. The error metric is given as

$$MSE = \frac{\sum\left(y - \hat{y}\right)^2}{n\sigma_y^2} \quad (9)$$

where, y is the observed value, $\hat{y}$ is the predicted value, and σ_y^2 is the variance of the observed value.

3. RESULTS AND DISCUSSIONS

3.1 Slumps of CFRC Fresh Concrete

The workability of fresh CFRC mixes and plain concrete resulted from the slump tests are presented in Fig. 4. The slump of CFRC mixes range from 75 mm down to 47 mm, while the control specimen has a slump of 80 mm. It reveals that all the mixes have passed the slump requirement from 25 mm to 100 mm. The addition of superplasticizer to CFRC mixes would have caused this satisfaction in slump. Moreover, the result indicates that regardless of the fiber length used, the slump tends to decrease consistently with increasing fiber volume content from 0.10% to 0.30% with an increment of 0.05%. This only implies that the slumps of the CFRC mixes are significantly affected by their fiber volume contents.

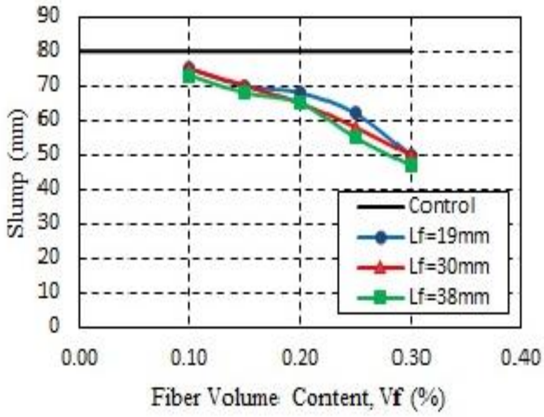


Fig. 4 Effect of fiber volume content to slump of CFRC mix

3.2 Pull-out Strength of an Expansion Stud Anchor

Test data on pull-out strength of the expansion stud anchor considering the concrete breakout failure mode of different base material specimens are shown in Fig. 5. The control specimen's pull-out strength was measured 21.53 KN. This result is similar to 21.63 KN computed from Eq. (1). It is also close to 20.46 KN calculated from Eq. (3). Moreover, Fig. 5 shows that in 19 mm fiber length case, pull-out strength tends to increase when fiber volume content increases. The pull-out strength measures 21.52 KN initially at 0.1% fiber volume content and increased to 24.33 KN at 0.30% fiber volume by 13.03%. In the case of 30 mm and 38 mm fiber lengths, a negative trend between the pull-out strength and fiber volume content is noticed. Despite this, it was observed that there was a significant increased of pull-out strength with the addtion of 38 mm fiber length at 0.10% fiber volume content and at 0.15% fiber volume content by 24.61% and 11.83% respectively. At 30 mm fiber length, however, no significant increased was observed. Among the cases, it has found out that the maximum pull-out strength occurred with the addition of 38 mm fiber length at 0.1% fiber volume content by 24.61% increase compared to control specimen.

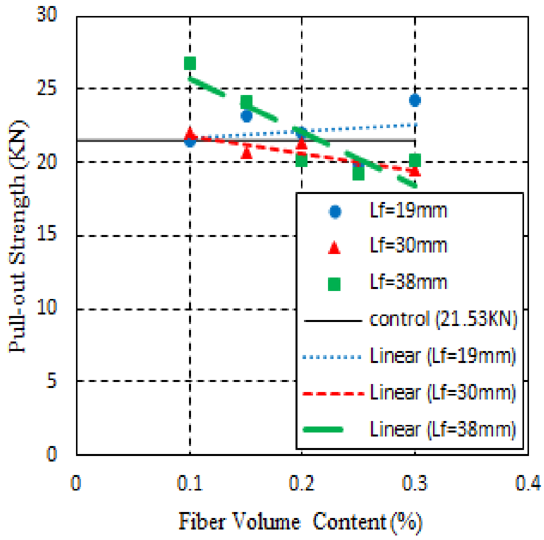


Fig. 5 Influence of fiber volume content to pull-out strength of CFRC

On the other hand, Fig. 6 and Fig. 7 show the influence of compressive stress and direct tensile stress to the pull-out strength of an expansion stud anchor in CFRC base material respectively. The graphs consistently show a positive linear trend with the addition of 19 mm fiber length and 38 mm fiber length. With the addition of 19 mm fiber length, it is evident that pull-out strength is maximum at f_c = 19.84 MPa and at f_t = 1.903 MPa. This pull-out strength measures 24.33 KN and is 13.03% more than the pull-out strength of the control specimen at f_c = 20.17 MPa and at f_t = 1.683 MPa. On the other hand, with the addition of 38 mm fiber length, the pull-out strength is highest at f_c = 21.85 MPa and at f_t = 2.047 MPa. This pull-out strength measures 26.82 KN and is 24.61% more than the pull-out strength of the control specimen at f_c = 20.17 MPa and at f_t = 1.683 MPa. It is also evident that compressive stress of CFRC at fiber lengths 19 mm and 38 mm slightly affect the pull-out strength, but significantly affect by the direct tensile stress. While, no trend is consistently observed to pull-out strength with the addition of 30 mm fiber length both for compressive stress and direct tensile stress.

3.3 FEM of CFRC Tensile Strength

The comparison between the observed tensile strengths and the FEM tensile strengths resulted from the simulation of the tensile strength response of the CFRC base material specimens subjected to tensile loading applied into a single expansion stud anchor using the FEM software, ABAQUS is presented in Fig. 8.

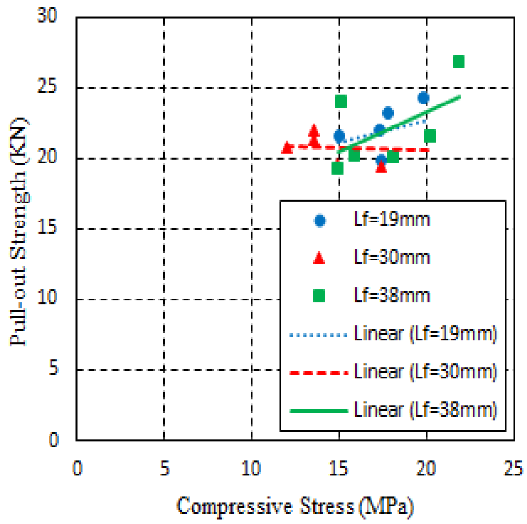


Fig. 6 Influence of compressive stress to pull-out strength of CFRC

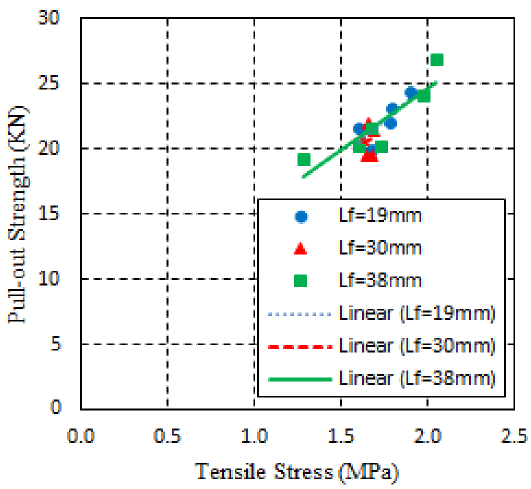


Fig. 7 Influence of tensile stress to pull-out strength of CFRC

The graph resulted from the FEM simulation shows a perfect linear relationship between the direct tensile strength and pull-out strength of an expansion stud anchor in CFRC base materials. The graph also shows that there is a good agreement between the observed tensile stress values and simulated tensile stress values subjected to a tensile loading applied into a single expansion stud anchor embedded in both control and CFRC specimens with adjusted regression coefficient, R_{adj} of 0.818 and 1.0 respectively. This result implies only that the tensile strength is the most important influencing factor to predict the pull-out strength of an expansion stud anchor embedded in CFRC. This is similar from finding of a previous study where the pullout load capacity of a headed anchor was dominated by the tensile strength of its composite base material, Engineered Cementitious Composites (ECC) [19].

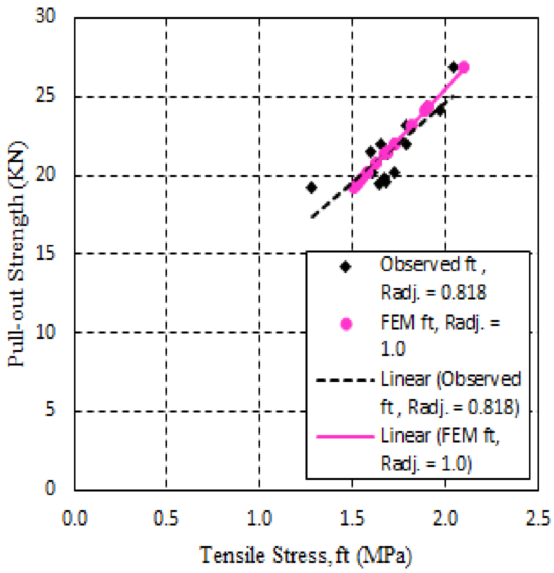


Fig. 8 Comparison of observed f_t and FEM f_t

3.4 RSM Model

Table 4 shows the performance of each RSM model to predict the pull-out strength of an expansion stud anchor in CFRC as influence by combination of different predictor variables such as the fiber length, fiber volume content, compressive strength and direct tensile strength.

Table 4 Performance of RSM models

Model	Or	R_{adj}	MSE	Adequacy
N= f(f_c)	1	0.43	0.71	No
N=f(f_t)	1	0.82	0.29	Yes
N=f(f_c,f_t)	1	0.81	0.28	Yes
N=f(Lf,Vf)	1	0.35	0.70	No
N=f(Lf,Vf,f_c)	1	0.60	0.48	Yes
N=f(Lf,Vf,f_t)	1	0.85	0.21	Yes
N=f(Lf,Vf,f_c,f_t)	1	0.85	0.19	Yes
N=f(Lf,Vf)	2	0.76	0.26	Yes

Note: Or = Order of RSM model

Each combination was tested for the adequacy of the first-order and second-order RSM models using F-test at level of significance, α = 0.05. Moreover, the R_{adj} and MSE for each RSM model were determined. It is noticeable that direct tensile strength is the most significant lone predictor with R_{adj} of 0.82 and MSE of 0.29 at first order. It is also evident that pull-out strength of an expansion stud anchor in CFRC using the predictor variables, fiber length and fiber volume content is adequate to estimate at second order with R_{adj} of 0.76 and MSE of 0.26. However, when all the four predictor variables were considered, the R_{adj} is at the highest and the MSE is at the least. This implies that the pull-out strength of an expansion stud anchor in CFRC base material is best predicted by RSM model with fiber length, fiber volume content, compressive strength, and direct tensile strength as its predictor variables at R_{adj} of 0.85 and MSE of 0.19. The proposed RSM model is then given by

$$N = 0.038Lf - 8.785Vf + 0.146 f_c + 8.237 f_t + 5.7 \quad (10)$$

4. CONCLUSIONS

In general, it is concluded that CFRC increased the pull-out strength of the expansion stud anchor. Test results show that pull-out strength is highest with the addition of 38 mm fiber length at 0.10% fiber volume content. Moreover, among the predictors considered, direct tensile strength turned out as the most significant variable to influence the pull-out strength of an expansion stud anchor in CFRC. This finding is further verified by numerical analysis using the FEM Software, ABAQUS. It is also concluded that pull-out strength of an expansion stud anchor in CFRC is best predicted by Response Surface Methodology model with fiber length, fiber volume content, compressive strength, and direct tensile strength as its predictor variables.

5. ACKNOWLEDGEMENTS

The carbon fiber used in this study was UT70-20 TORAYCA, and the expansion stud anchor used in this study was HST M10X90/10 from Hilti Philippines. The authors would like to thank De La Salle University, Department of Science and Technology – Engineering Research and Development for Technology, Mapua Institute of Technology, and Alphatec Chemical Corporation for their valuable supports in this study.

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