INTELLIGENT PREDICTING SYSTEM FOR MODELING OF FLEXURALLY – STRENGTHENED REINFORCED CONCRETE BEAMS WITH CFRP LAMINATES

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In the last years, a great number of experimental tests have been performed to determine the ultimate strength of reinforced concrete (RC) beams retrofitted in flexure by means of externally bonded carbon fiber-reinforced polymers (CFRP). Most of design proposals for flexural strengthening are based on a regression analysis from experimental data corresponding to specific configurations which makes it very difficult to capture the real interrelation among the involved parameters. To avoid this, an intelligent predicting system such as artificial neural network (ANN) has been developed to predict the flexural capacity of concrete beams reinforced with this method. An artificial neural network model was developed using past experimental data on flexural failure of RC beams strengthened by CFRP laminates. Fourteen input parameters cover the CFRP properties, beam geometrical properties and reinforcement properties; the corresponding output is the ultimate load capacity. The proposed ANN model considers the effect of these parameters which are not generally account together in the current existing design codes with the purpose of reaching more reliable designs. This paper presents a short review of the well-known American building code provisions (ACI 440.2R-08) for the flexural strengthening of RC beams using FRP laminates. The accuracy of the code in predicting the flexural capacity of strengthened beams was also examined with comparable way by using same test data. The study shows that the ANN model gives reasonable predictions of the ultimate flexural strength of the strengthened RC beams. Moreover, the study concludes that the ANN model predicts the flexural strength of FRP-strengthened beams better than the design formulas provided by ACI 440.

Keywords: CFRP laminates, RC beam, flexural capacity, neural networks, ACI 440

1. Introduction

The use of fiber reinforced polymer (FRP) sheets as externally bonded reinforcement is nowadays widely recognized as an efficient method for strengthening and upgrading reinforced concrete RC members. In particular, the flexural strength of a reinforced concrete beam can be extensively increased by application of carbon, glass and aramid FRP plates/sheets adhesively bonded to the tension face of the beam (Bank, 2006). In general, external reinforcement by FRP sheets is used for flexural strengthening, improving ductility, and shear strengthening. Over past few years, external strengthening using FRP composites gained popularity over steel

because of several reasons including material cost, lightweight feature, corrosion free and ease of application. At the same time, widespread experimental, numerical and analytical research has been carried out to understand and model the structural behavior of FRP strengthened reinforced concrete beams. Many studies have been done for recognizing and understanding the failure modes that reinforced concrete beams retrofitted with FRP. There are three main categories of failure in concrete structures retrofitted with FRP that have been observed experimentally (Coronado and Lopez, 2006; Ebead and Marzouk, 2005; Lundquist et al., 2005). The first and second type consist of failure modes where the composite action between concrete and FRP is maintained. Typically, in the first failure mode, the steel reinforcement yields, followed by rupture of CFRP as shown in Figure 1 (a). In the second type, there is failure in the concrete. This type occurs either due to crushing of concrete before or after yielding of tensile steel without any damage to the FRP laminate (Fig. 1 (b)), or due to an inclined shear crack at the end of the plate (Fig. 1 (c)). In the third type, the failure modes involving loss of composite action are included. The most recognized failure modes within this group are debonding modes. In such a case, the external reinforcement plates no longer contribute to the beam strength, leading to a brittle failure if no stress redistribution from the laminate to the interior steel reinforcement occurs. Figures 1 (d) – (g) show failure modes of the third type for RC beams retrofitted with FRP. In Figure 1 (d), the failure starts at the end of the plate

Figure 1. Failure modes in beam retrofitted with FRP sheets in flexure [4]

due to the stress concentration and ends up with de-bonding propagation inwards. Stresses at this location are essentially shear stress but due to small but non-zero bending stiffness of the laminate, normal stress can arise. In Figure 1 (e), the entire concrete cover is separated. This failure mode usually results from the formation of a crack at or near the end of the plate, due to the interfacial shear and normal stress concentrations. Once a crack occurs in the concrete near the plate end, the crack will propagate to the level of tensile reinforcement and extend horizontally along the bottom of the tension steel reinforcement. With increasing external load, the horizontal crack may propagate to cause the concrete cover to separate with the FRP plate. In Figure 1 (f) and (g), the failure is caused by crack propagation in the concrete parallel to the bonded plate and adjacent to the adhesive to concrete interface, starting from the critically stressed portions towards one of the ends of the plate. It is believed to be the result of high interfacial shear and normal stresses concentrated at a crack along the beam. Also mid span de-bonding may take concrete cover with it.

This paper proposes a new approach to the problem, using an empirical model developed from observations of the actual performance of laboratory beams. Specifically, a neural network approach is proposed due to its proven ability to solve problems of this type. That is, problems requiring the rapid generation of solutions, the accurate modeling of functions that are non-linear, and comprise many poorly defined independent variables. The objective was to determine the viability of using this approach to obtain accurate predictions of the maximum strength of externally CFRP-strengthened RC beams. As an added advantage, the neural network approach was expected to make predictions of beam performance within a fraction of a second. This, in turn, would make it possible to evaluate a very large number of alternative external reinforcement configurations, and thus determine a more optimal design solution. The success of experimental studies produced growing demand for analytical investigations since predicting the ultimate flexural strength of the strengthened RC structures is crucial. Therefore, several proposed analytical formulations have been developed to guide the design, detailing and installation of FRP based systems (ACCI Committee 440, 2008; Fib Bulletin 14, 2001; Canadian Standards Association, 2002; CNR, 2005; CIDAR, 2006). The developed analytical equations estimated the contribution of FRP reinforcements within certain limits but not accurately in some cases. The assumptions that were made while designating the behavior of the strengthened specimen did not resemble to actual behavior due to some special situations and that cause the calculated results to be different from the obtained flexural capacity. There are several parameters that cause differences between the calculated and the obtained flexural capacity. For example, some design guidelines and codes ignore the influence of the length of FRP sheet, concrete compressive strength, and concrete cover in tension zone on prediction of ultimate flexural capacity. These are the major assumptions that cause divergence towards the experimental results, Since the ultimate flexural behavior of strengthened RC beam is affected by many factors and parameters, artificial neural network (ANN) method can be used as an effective tool to predict the ultimate flexural behavior of strengthened RC beams (Guang and Zong, 2000; Sanad and Saka, 2001; Jamal et al., 2007; Ghaboussi et al., 1991; Hajela and Berke, 1991). The proposed ANN model considers the effect of various parameters (Table 1) which is not generally account together in existing design codes. ANN model contains data for both application schemes. Eighty three (83) experimental data of CFRP-strengthened RC beams were collected from literature. As it is aimed to suggest a practical ANN model, the mechanical properties of strengthening material and mechanical and dimensional properties of beams are selected as inputs (Table 1). The predicted ANN results are primarily compared

with experimental CFRP contributions of strengthened beams and then with the predicted results of theoretical guideline equation by American guidelines ACI 440 [1]. It was chosen among all current design codes, because it attained the best prediction of flexural capacity of FRP-strengthened RC beams as reported by Al-Zaid et al. (2012). Performed analysis showed that the neural network model is more accurate than the ACI 440 guideline equation with respect to the experimental results and it can be applied satisfactorily within the range of parameters covered in this study.

Table 1. Range of input parameters and output variables

Input no.	Parameter	Symbol	Minimum	Maximum
	Inputs			
1	Concrete cylinder comp. strength, MPa	f'_c	18	55.2
2	Width of beam, mm	b	100	500
3	Effective depth, mm	d	50.8	419
4	Effective span, mm	l	1400	5000
5	Area of tension reinforcement, mm ²	A_s	71	2413
6	Area of comp. reinforcement, mm ²	A'_s	28	1609
7	Yield strength of steel rfts, MPa	f_y	335	590
8	Modulus of elasticity of of steel rfts, GPa	E_s	165	201
9	Concrete cover in tension side, mm	cov	15	55
10	No. of CFRP layers	n_f	1	4
11	Modulus of elasticity of CFRP sheet, GPa	E_f	11	240
12	Width of CFRP sheet, mm	b_f	25	480
13	Thickness of CFRP sheets, mm	t_f	0.11	6
14	Length of CFRP sheet, mm	l_f	1200	4800
Output no.	Output			
1	Ultimate flexural load, kN	P_u	16.1	669.3

2. Experimental technique and data

An extensive literature review has been carried out and eighty three (83) RC beams strengthened in flexure with CFRP laminates were collected from the published literature. These test results are used to provide the experimental data for ANN. All tested beams are simply supported and subjected to two point loads acting symmetrically with respect to the centerline of the span as shown in Figure 2. This case provides a larger amount of data, which is

essential for better training of a network. During the collection of the data, specimens that do not have flexural failures have been excluded from the training set. The selected specimens covered all modes of failure of flexurally - strengthened RC beams with CFRP laminates as mentioned above. The basic parameters that control the ultimate load of beams, based on previous research works are listed in Table 1. The experimental data include 83 beam results, which are taken from the tests carried out by references [2 – 5, 7, 9, 10, 13, 14, 18, 19, 21, 24, 28, 30, 32 – 36 and 38] as shown in Appendix A. The data are rearranged in such a way that 14 basic parameters are listed as input values, and the ultimate load is included as the corresponding output targets (Table 1). There is no single design code that considers all these parameters.

Figure 2. Typical FRP-strengthened RC beam

3. Analytical study

3.1 Neural Network Model of CFRP- Strengthened Beams

An artificial neural network (ANN) is a simplified mathematical model or computational model that tries to simulate the structure and/or functional aspects of biological neural networks for engineering problems. It contains an interconnected group of artificial neurons and processes information using a connectionist approach to computation. In most cases, the ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase and can be used as a prediction tool for cases where the output solution is not available. Modern neural networks are non-linear statistical data modeling tools. ANN contains three main sections which are classified as, input layer, hidden (inner) layer, and the output layer. Input parameters are presented in the input layer and the solution of the problem is evaluated with the output layer. In between these layers, hidden layer is placed and provides help to the network in the learning process. The number of neurons of the input and output layers are determined in order to represent the characteristic of the existing problem accurately. Hidden layers can be formed with one or more layers and the number of neurons in the hidden layer is determined by the users. The number of the neurons in the input layer is equal to the number of the independent variables in the experiment as shown in Table 1. The number of the hidden layers and the number of

the neurons in each layer is chosen to provide a minimum value for the error between the measured output and the network's output while maintaining the ability of the network to generalize. In the current research, Feed-forward back-propagation neural networks (FBNNs) were applied for prediction the capacity of strengthened beams with one input layer (it contains 14 independent variables (Table 1) that may affect the flexural capacity), one hidden layer have 20 neurons, and one output layer was designed to predict the flexural load capacity. The TRAINLM training function available in MATLAB Neural Toolbox [31] was used to train the network using the LERNGDM adaption learning function. The input data was divided into three sets. The first set consists of 70 % of the data is used to train the network. The second and third sets, each consists of 15 % of the data are used to validate and test the generalization ability of the network, respectively. Several architectures were tried and the one that gave the least error was chosen (Fig. 3). The selection of optimal configuration of ANN is the key point to achieve successful results from the suggested ANN model. Therefore, the mechanical properties of strengthening material and mechanical and dimensional properties of experimental beams are selected as inputs. In the literature, the strengthened specimens have concrete strength is generally above 20 MPa. In addition, some guidelines (Chajes et al., 1994) do not propose to use FRP strengthening technique (due to the bond problems) to the structures with compressive strength below 17 MPa. However, the concrete strength of buildings that require retrofitting is generally lower than the pre mentioned value. In this study, the structures that have low concrete compressive strength are also accounted in the proposed ANN model in order to achieve the aspects of strengthening philosophy. Therefore, experimental data that will direct ANN model to evaluate such structures was especially collected from literature. The neural network model is built by considering these approaches and it contains fourteen input nodes (Table 1). The optimum network is selected based on minimum error and maximum correlation coefficient between data. The properties of the selected network are shown in Table 2.

Table 2. The Network Properties

No.	Parameter	Property	R
1	Network function	Feed-forward back-propagation	
2	Network architecture	14-20-1	
3	The number of training data	59	0.99
4	The number of verifying data	12	0.99
5	The number of testing data	12	0.96
6	No. of all data	83	0.99

In this section, an experimental database (consists of 83 RC beams strengthened with CFRP sheets in flexure) is used to investigate the accuracy of ACI 440, and train and test the ANN model in the prediction of the flexural load of RC beams. The results of the ANN model are compared with ACI 440 empirical code, based on calculating the mean (M), standard deviation (STD), coefficient of variation (COV), and variation (VAR). Also, the R^2 of the linear regression line for the predicted values by both ANN model and ACI 440 code are determined.

Figure 3. Artificial Neural Network Structure

Figure 4. Regression analysis for training, validation, testing, and whole data

Figure 4 shows the relationship between the experimental data and the training, validation and testing sets. It can be shown that the relationship between the complete set of the experimental data and the data predicted by the neural network is excellent.

To show the efficiency of the proposed ANN model, the experimental database are used and the flexural load of CFRP-strengthened RC beams is calculated using ACI 440 formula and ANN model. Also, to evaluate the performance and accuracy of the ACI 440 and ANN, values of the flexural capacity from ACI 440 design code and ANN are compared with measured experimental data. Comparisons between observed (experimental) and predicted flexural load are shown in Figure 5. It can be seen that the predicted loads by ACI 440 are more scattered from the experimental ones compared to ANN predictions.

a) ACI 440 Formula

b) ANN Model

Figure 5. Comparison between experimental and predicted flexural capacities

To show the superiority of proposed ANN model, the mean (M), standard deviation (STD), coefficient of variation (COV), variation (VAR), and R^2 values for ANN model and ACI 440 code are presented in Appendix A and Figure 5. Comparison of the results indicates that the ANN model has satisfactory values of R-square and M (close to one) and a lower value of STD, COV and VAR, so that its performance is more accurate. Also, the ANN model performs a much better prediction, compared with ACI 440 empirical code.

Figure 5 shows a linear regression between the experimental and the neural loads. The agreement is excellent as attested to by the R^2 -value (0.98) of the regression analysis and descriptive statistics (Mean = 1.01, STD = 0.15, COV = 15.12, VAR = 0.02) it means that the prediction by neural networks have a smallest coefficient of variation, smallest scatter and better confidence intervals compared with ACI 440 (Mean = 1.09, STD = 0.25, COV = 22.68, VAR = 0.06) as reported in Appendix A. ACI 440 produced nearly close predictions to the experimental results. However, at almost every step they underestimated the experimental results and this shows that their predictions are always on the safe side because of the safety factors that were used while calculation.

3.2 Influencing of Input Parameters

Because the weight of input parameters in the network cannot be easily understood in the form of a numeric matrix, they may be transformed into coding values in the form of a percentage by dividing the weights by the sum for all the input parameters, which gives the relative importance for each input parameter to output parameter. The relative importance for various input parameters are shown in Figure 6. As the figure indicates, the major important and influencing parameters are the beam depth (18.8 %) and length of CFRP sheet (16.1) while the most of other input parameters has insignificant importance on the predicting of ultimate load

Figure 6. Relative importance of input parameter for ANN model

Figure 7. Experimental to predicted ultimate flexural loads of CFRP-strengthened beams versus d , l_f , A_s , cov , f_c , b , f_y , and E_s respectively.

(10.6 % – 0.7 %). Beside the beam depth and length of CFRP sheet, six parameters were select from the residual twelve parameters, (which have importance more than 5 % which is considered as the min limit as reported by Yousif and Al-Jurmaa (2010)), these are (A_s , cov , f_c , b , f_y , and E_s).

Figure 7 also present the experimental-to-calculated flexural load versus d , l_f , A_s , cov , f_c , b , f_y , and E_s , from this figure, it is evident that the level of accuracy of the ultimate flexural load predicted by the ANN model seems to be consistent with the varying the various parameters. The proposed model has been compared to the current design guidelines provided by ACI 440. More accurate and consistent predictions have been obtained using the model produced by ANN.

CONCLUSIONS

The following conclusions can be drawn based on the performed analyses and comparisons reported in this paper:

1. In this study, a **Feed-forward back-propagation neural network** with fourteen input neuron, twenty hidden neurons and one output neuron was developed to introduce a reliable flexural design of CFRP-strengthened RC beams with high accuracy. Results show that the ANN model provided a better prediction of flexural load than the ACI 440 model and is more accurate. In addition, the predictions of ANN model were distributed around experimental results, while ACI 440 was more scattered from experimental results, indicating that they predominately under-estimate the flexural capacities.
2. The proposed ANN model provides the most accurate results in calculating the ultimate flexural load. It considers the effect of various 14 parameters which is not generally account together in the current existing design codes.
3. The effective beam depth and length of CFRP sheet are the major important and influencing parameters that affecting the prediction of the ultimate load capacity of RC beams strengthened with CFRP sheet.
4. Some guidelines do not recommend the use of FRP strengthening technique (due to the bond problems) to the structures with compressive strength below 17 MPa. However, the concrete strength of buildings that require retrofitting is generally lower than the pre mentioned value. Therefore, an ANN model is developed that is addressing the need for retrofitting structures with low concrete compressive strength in this study. Accordingly, obtained results showed that ANN model can successfully predict the FRP contribution for structures with low concrete compressive strength within acceptable limits.

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Appendix-A

No.	Ref.	Beam ID	f_c MPa	b mm	d mm	l mm	A_s mm ²	A'_s mm ²	f_y MPa	E_s GPa	cov mm	n_r	E_r GPa	b_r mm	T_r mm	l_t mm	$P_{u,exp.}$ kN	Failure Mode*	$P_{u,exp}/P_{u,pred}$	
																			ACI-440	ANN
1	16	B-II-1	30	500	214	5000	804	452	568	200	36	1	165	480	1.4	4800	244.4	2	1.25	1.00
2	17	B-II-2	30	500	214	5000	804	452	568	200	36	1	165	240	1.4	4800	164.8	2	1.16	1.00
3	17	B-II-3	30	500	214	5000	804	452	568	200	36	2	165	240	1.4	4800	222.42	2	1.40	1.21
4	17	B-II-5	30	500	214	5000	804	452	568	200	36	3	240	240	0.293	4800	157.88	2	1.12	1.00
5	18	1B	54.8	200	154.8	2742	142	142	410	200	45.2	1	138	203	0.445	2740	80.1	2	0.99	1.09
6	18	2B	54.8	200	152.2	2742	253	142	410	200	47.8	1	138	203	0.445	2740	79.9	2	0.85	0.98
7	18	3B	54.8	200	159.6	2742	397	142	410	200	40.4	1	138	203	0.445	2740	109.03	2	0.97	1.06
8	19	A3	35.1	203	318	3000	402	142	440	200	38	2	230	50	0.165	2542	138.3	2	1.15	1.02
9	19	A4	37.2	203	318	3000	402	142	440	200	38	1	230	100	0.165	2161	129.0	2	0.99	0.95
10	19	B1	37.2	203	318	3000	402	142	440	200	38	2	230	75	0.165	2669	132.6	2	1.01	0.97
11	19	C2	35.1	203	368	3000	402	142	440	200	38	2	62	50	1.040	2872	125.9	2	0.99	1.11
12	19	D2	37.2	203	368	3000	402	142	440	200	38	1	155	50	1.190	2872	133.9	2	1.01	1.00
13	20	B3	39.2	250	120	2000	151	151	485	200	30	1	214	50	1.2	1200	62.8	2	1.23	0.98
14	20	B4	39.2	250	120	2000	151	151	485	200	30	1	155	50	1.2	1200	58.4	2	1.21	0.99
15	21	BF2	36.5	200	419	3800	804	101	590	200	31	1	159	100	1.2	3140	370.0	2	1.04	1.03
16	21	BF3	34.9	200	419	3800	804	101	590	200	31	1	159	100	1.2	3140	372.0	2	1.06	1.01
17	21	BF4-Prc	30.8	200	419	3800	804	101	590	200	31	1	159	100	1.2	3140	368.4	2	1.07	0.96
18	21	BF5-Sus	37.4	200	419	3800	402	101	590	200	31	1	159	100	1.2	3140	354.0	2	0.98	1.22
19	21	BF8	39.4	200	419	3800	402	101	590	200	31	1	159	100	1.2	3140	222.6	2	1.00	0.79
20	21	BF9	39.4	200	419	3800	402	101	590	200	31	2	233	100	0.111	3140	191.6	2	1.01	1.00
21	22	B2	29.3	270	341	3650	896	142	485	201	40	2	230	250	0.167	3448	296.0	2	1.03	0.93
22	22	B3-Sus	29.3	270	341	3650	896	142	485	201	40	2	230	250	0.167	3448	280.0	2	0.97	0.88
23	23	B-04/0.5S	36.6	150	269	3000	157	157	421	199	31	1	172	40	1.2	2700	98.0	2	1.34	1.30
24	23	B-08/S1	33.8	150	268	4200	339	157	490	195	32	1	172	80	1.2	4200	180.0	2	1.14	1.27
25	23	BF-04/0.5S	33.0	150	269	3000	157	157	421	199	31	1	172	40	1.2	2700	48.0	2	1.26	0.79
26	23	BF-06/S	32.5	150	268	3000	226	157	490	195	32	1	172	80	1.2	2700	86.0	2	1.28	0.92

No.	Ref.	Beam ID	f_c MPa	b mm	d mm	l mm	A_s mm ²	A'_s mm ²	f_y MPa	E_s GPa	cov	n_k	E_t GPa	b_h mm	T_t mm	h mm	$P_{exp.}$ kN	Failure Mode*	P_{exp}/P_{uped}	
																			ACI-440	ANN
27	23	B-08M	37.3	150	268	4200	339	157	490	195	32	1	172	120	1.2	4200	140.0	2	1.25	0.89
28	23	B-08S2	32.3	150	268	4050	339	157	490	195	32	1	172	50	1.2	4050	94.0	2	1.21	0.89
29	24	H1	36.6	152	229	4537	380	142	429	200	25	1	155	25	1.4	4517	37.68	2	1.05	1.04
30	24	H2	36.6	152	229	4537	380	142	429	200	25	1	155	51	1.4	4517	43.55	2	1.05	0.95
31	24	H2x1	36.6	152	229	4537	380	142	429	200	25	1	155	51	1.4	4517	45.15	2	1.08	0.99
32	24	H4	36.6	152	229	4537	380	142	429	200	25	1	155	102	1.4	4517	49.24	2	0.93	0.85
33	25	H-75-2	55.2	152	212	2440	402	142	415	200	34	1	22	152	1.5	2236	130.8	2	1.06	1.73
34	26	B3	38.2	152.4	265	2896	402	157	410	200	25.4	1	235	90	1	2744	183.79	2	1.30	1.00
35	27	A3	42.8	115	120	1500	236	157	547	180	26	1	235	107.8	0.165	1450	77.50	2	1.00	1.15
36	27	A5	42.8	115	120	1500	236	157	547	180	26	2	235	107.8	0.165	1450	87.40	2	0.96	1.02
37	27	B3	42.8	230	240	3000	943	628	544	183	52	2	235	215.6	0.165	2900	263.50	2	0.90	1.00
38	27	B5	42.8	230	240	3000	943	628	544	183	52	4	235	215.6	0.165	2900	294.70	2	0.91	1.00
39	27	C4	42.8	368	384	4800	2413	1609	552	181	52	3	235	368	0.165	4840	669.30	2	0.93	1.00
40	28	A2	33.6	100	150	2000	157	101	452	165	15	1	230	100	0.167	1400	37.40	2	0.98	1.01
41	29	B	35	205	400	4575	982	266	456	200	55	1	37	152	6	4265	250	2	1.08	1.00
42	30	A1	42.1	127	50.8	2000	71	28	413	200	25	1	11	127	1.04	1400	16.27	2	1.06	0.92
43	31	B2O	18	150	218.7	2400	253	142	435	200	31.3	2	235	130	0.11	2200	78.75	2	0.98	0.89
44	31	R2L	18	150	218.7	2400	253	142	435	200	31.3	2	235	130	0.11	2200	81.75	2	1.02	0.93
45	31	R2H	18	150	218.7	2400	253	142	435	200	31.3	2	235	130	0.11	2200	99.75	2	1.24	1.13
46	31	R3O	18	150	218.7	2400	380	142	435	200	31.3	2	235	130	0.11	2200	115.00	2	1.11	1.02
47	31	R3L	18	150	218.7	2400	380	142	435	200	31.3	2	235	130	0.11	2200	117.00	2	1.13	1.03
48	31	R3H	18	150	218.7	2400	380	142	435	200	31.3	2	235	130	0.11	2200	109.25	2	1.05	0.96
49	32	B2-12D-1K15	25.2	150	166	1600	226	157	400	200	25	1	237	150	0.176	1400	61.45	1	0.88	0.99
50	32	B3-12D-2L15	25.2	150	166	1600	226	157	400	200	25	2	237	150	0.176	1400	70.94	4	1.02	1.03
51	32	B4-12D-3L15	25.2	150	166	1600	226	157	400	200	25	3	237	150	0.176	1400	74.44	4	1.07	0.98

52	32	B6-16D- II10	23.8	150	164	1600	402	157	406	200	25	1	237	100	0.176	1600	84.93	1	0.75	0.96
53	32	B7-16D- II15	23.8	150	164	1600	402	157	406	200	25	1	237	150	0.176	1600	94.92	1	0.84	1.14
54	32	B8-16D- 2L15	23.8	150	164	1600	402	157	406	200	25	2	237	150	0.176	1600	105.91	1	0.94	1.17
55	32	B10-20D- II10	24.1	150	162	1600	628	157	350	200	25	1	237	100	0.176	1600	106.32	1	0.76	1.04
56	32	B11-20D- II15	24.1	150	162	1600	628	157	350	200	25	1	237	150	0.176	1600	108.91	2	0.78	1.05
57	32	B12-20D- 2L15	24.1	150	162	1600	628	157	350	200	25	2	237	150	0.176	1600	113.41	3	0.81	0.98
58	33	SP-C1	35	200	165	1800	265	142	360	200	28	1	236	200	0.167	1700	78.3	1	1.14	0.84
59	33	SP-C1s	35	200	165	1800	265	142	360	200	28	1	236	200	0.167	1700	101	1	1.47	1.09
60	33	SP-C2	35	200	165	1800	265	142	360	200	28	2	236	200	0.167	1700	109	1	1.60	1.04
61	33	SP-C2s	35	200	165	1800	265	142	360	200	28	2	236	200	0.167	1700	148	4	2.18	1.41
62	33	SP-C3	35	200	165	1800	265	142	360	200	28	3	236	200	0.167	1700	108	4	1.59	1.00
63	33	SP-C3s	35	200	165	1800	265	142	360	200	28	3	236	200	0.167	1700	116.6	4	1.72	1.08
64	34	CB3-2S	31	230	342	4576	982	127	414	200	16.5	2	138	76	1.4	4270	263	1	1.20	1.01
65	34	CB5-1S	31	230	342	4576	982	127	414	200	16.5	3	138	76	1.4	4270	287	5	1.31	1.01
66	34	CB7-1S	31	230	342	4576	982	127	414	200	16.5	1	138	102	4.78	4270	256	1	1.15	1.00
67	35	A10	18.4	120	211	2000	226	157	335	200	25	1	235	120	0.111	1800	62.7	2	1.07	0.99
68	35	A20	18.4	120	211	2000	226	157	335	200	25	2	235	120	0.111	1800	75.8	2	1.30	1.01
69	35	B10	18.4	120	209	2000	402	157	335	200	25	1	235	120	0.111	1800	82.4	2	0.88	1.08
70	35	B20	18.4	120	209	2000	402	157	335	200	25	2	235	120	0.111	1800	85.1	5	0.91	1.02
71	36	B-01	35	200	357	4000	226	226	440	200	25	1	158	50	1.4	3200	110.8	2	1.57	0.97
72	36	B-02	35	200	357	4000	226	226	440	200	25	2	158	100	1.4	3200	122.4	4	1.72	1.01
73	37	A2	29	150	85	1800	85	85	530	200	15	1	230	110	0.165	1700	18.5	1	1.14	0.96
74	37	A3	29	150	85	1800	85	85	530	200	15	2	230	110	0.165	1700	19.2	1	1.19	0.77
75	37	A4	29	150	85	1800	85	85	530	200	15	1	230	100	0.165	1700	19.6	6	1.21	1.04
76	37	B2	29	150	85	1800	134	134	530	200	15	1	230	110	0.165	1700	25.8	6	1.06	1.20
77	37	B3	29	150	85	1800	134	134	530	200	15	1	230	110	0.165	1700	25.8	6	1.06	1.20
78	37	B4	29	150	85	1800	134	134	530	200	15	2	230	110	0.165	1700	24.5	1	1.02	0.81

No.	Ref.	Beam ID	f_c MPa	b mm	d mm	l mm	A_c mm ²	A_s' mm ²	f_y MPa	E_s GPa	cov mm	n	E_t GPa	b_t mm	T_f mm	k mm	$P_u,exp.$ kN	Failure Mode*	$P_u,exp/P_{u,pred}$		
																			ACI-440	ANN	
79	37	C3	29	100	135	1800	90	90	530	200	15	1	230	80	0.165	1700	17.9	1	0.66	0.58	
80	37	C4	29	100	135	1800	90	90	530	200	15	1	230	80	0.165	1700	16.1	1	0.59	0.52	
81	37	D2	29	100	135	1400	142	142	530	200	15	1	230	80	0.165	1300	40.1	1	0.77	0.93	
82	37	D3	29	100	135	1400	142	142	530	200	15	1	230	80	0.165	1300	42.1	1	0.81	0.98	
83	37	E2	29	150	85	1800	268	134	530	200	15	1	230	100	0.165	1700	35	6	0.84	1.15	
Statistical Operations																			Mean	1.09	1.01
																			STD**	0.25	0.15
																			COV**	22.68	15.12
																			Variance	0.06	0.02

STD**: Standard Deviation

COV**: Coefficient of Variation

Failure mode*

1 – Rupture of the FRP laminate after yielding of the steel in tension

2 – Interfacial de-bonding induced by flexural crack

3 – Interfacial de-bonding induced by flexural-shear crack

4 – Cover delamination at the end of FRP

5 – Separation of CFRP sheets and crushing of concrete after yielding of the steel in tension

6 – Concrete crushing (compression failure)