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Behavior and Flexural Prediction of Special Cementitious Bonding Material for Fiber Reinforced Strengthening Systems

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Abstract: Strengthening of RC structures with externally bonded FRP (fiber reinforced polymers) has become an important challenge in civil engineering. Epoxy is the main bonding agent used so far, but in the case of a fire, it is subjected to complete loss of his bonding capabilities. Mineral based composites strengthening systems consist of FRPs and a cementitious bonding agent which form a repair or strengthening system that is more compatible with the concrete substrata, and roved its efficiency. The current research introduces the use of a special cementitious material "Grancrete" as a bonding agent. Test results of 32 T-section RC beams strengthened with various FRG (fiber reinforced Grancrete) strengthening systems are presented. The results demonstrated that most of the specimens were likely to fail by debonding of the FRP from the concrete either at the ends or at intermediate flexural cracks. This paper presents an in-depth study aimed at the development of a better understanding of debonding failures in RC beams strengthened with externally bonded FRP systems. Different analytical models, published in the literature for plate end debonding, are reviewed and compared to test results. The results also demonstrated that when using U-wraps, the specimens were likely to fail by FRP sheet rupture.

Key words: RC Beam, concrete, debonding, intermediate crack debonding, FRP, Grancrete, strengthening.

1. Introduction

In recent years, repair and retrofit of existing structures have been among the most important challenges in civil engineering. The need to strengthen and rehabilitate existing concrete and steel structures has increased the use of FRP (fiber reinforced polymers) in structural strengthening applications since the mid 1980s. FRPs are not prone to electrochemical corrosion, they can be formed, fabricated, and bonded easily to concrete substrate. Epoxy has been proven to have excellent bond characteristics which are sufficient to transfer stresses between the fibers and the substrata. Despite the effectiveness of FRP strengthening systems, one of the major limitations on the use of epoxy in structural strengthening applications is the possibility of the complete loss of the strengthening system in case of fire. When FRP strengthening systems are subjected to a combination of high temperatures and sustained loads, the resin polymer matrix could soften and consequently loose its ability to transfer stresses from the concrete to the fibers [1]. Mineral based composites strengthening systems consist of FRPs and a cementitious bonding agent which form a repair or strengthening system that is more compatible with the concrete substrata, can be applied on moist surfaces and preliminary work [2] showed that similar results can be obtained when compared to epoxy-based FRP strengthening systems. The objective of this paper is to investigate the use of Grancrete material as an alternative to epoxy adhesives for FRP strengthening

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applications. Grancrete is a novel patented material co-developed by Jim Paul of Casa Grande in 1996. Grancrete is based on “Ceramicrete”, a material developed by Argonne National Laboratories for the encasement of nuclear waste. Grancrete is environmentally friendly. When mixed with water, this material forms a binding agent that is rapid-setting, develops high early bond strength, and has enhanced durability [3, 4]. The proposed fiber reinforced Grancrete “FRG” strengthening system would have excellent fire and heat resistance in comparison to the current FRP strengthening systems [5].

FRP generally behave linearly elastic to failure. The mechanical properties of FRP vary with the type and orientation of the reinforcing fibers. Therefore, the fibers can be placed in any orientation to maximize the strength in a desired direction. In this paper, only unidirectional FRP sheets are used for developing the analytical models. The current investigation includes testing of thirty-two reinforced concrete beams strengthened in flexure using various externally bonded FRP-Grancrete systems. Different failure modes have been observed in the experimental program. These modes can be divided into two general categories: “flexural” and “local” failures. “Flexural failure” is defined as yielding of the longitudinal steel or rupture of the FRP sheets in tension. “Local failure” is defined as the peeling of the FRP sheets at the location of high interfacial stresses and shear failure of the concrete layer between the strengthening material and the longitudinal reinforcement. Since in many cases, the failure of retrofitted beams is governed by the “local” failure, the investigation of the stresses at the concrete/strengthening layer interface is an important issue in analysis and design. An analytical model is presented in this paper to calculate the shear and normal interfacial stresses. The predicted capacities are compared to the measured values [6, 7].

2. Experimental Program

2.1 Phase 1: Water/Grancrete Ratio W/G

The Grancrete paste was selected based on three different water/Grancrete ratio (W/G); 0.25, 0.22, and 0.20. Three Grancrete cubes of dimensions 50 × 50 × 50 mm. were casted from each paste. When tested in compression, the pastes reached an average of 20.8, 41.1, and 60 MPa, respectively [5].

Hence, the concrete compressive strength used in Phase 3 is 35 MPa. The selection of the mix with W/G = 0.22 was made to guaranty a fully mixed paste due to the available facilities in the laboratory.

2.2 Phase 2: Pull-Out Test

Three different Grancrete thicknesses were applied to concrete surfaces as follows: 5 mm plain Grancrete layer thickness, and 10 mm, 15 mm divided into two layers with fiber sheet in the middle applied on a concrete smooth surface. 15 mm Grancrete layer divided into two layers with fiber sheet in the middle without finishing the first Grancrete layer was applied on a concrete rough surface.

The specimens were cored more than 50 mm deep into the substrata using the core drill machine. Steel disks measuring 50 mm diameter and 20 mm thick were bonded to the surface of each individual core specimens using epoxy.

According to the pull-out test results (Fig. 1), the SRP (steel reinforced polymer) sheets were modified from its manufacturing condition by creating voids within the sheets to insure the continuity of Grancrete layer through its thickness, SPR-1 and SRP-2 were selected for Phase 3 [5].

2.3 Phase 3: Externally Bonded FRP Specimens

2.3.1 Material Properties

2.3.1.1 Reinforcing Steel

Based on testing three 13 mm diameter steel bars, the rebars have a yield strength of 420 MPa and an ultimate strength of 690 MPa.

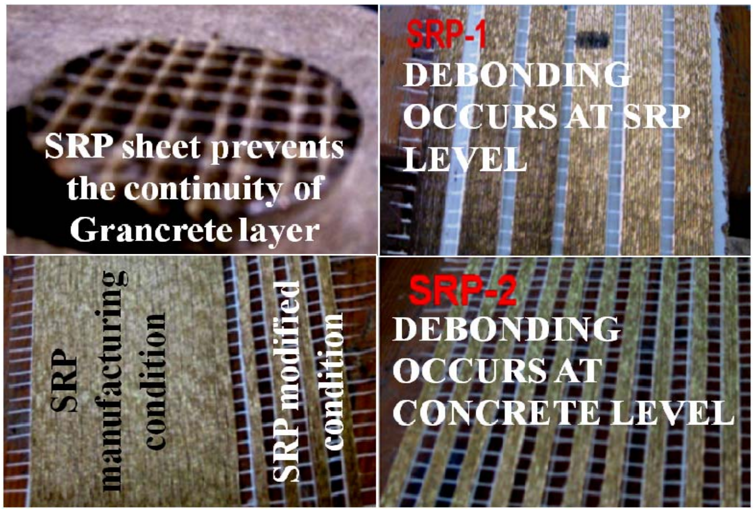

Fig. 1 SRP sheet modification sequence.

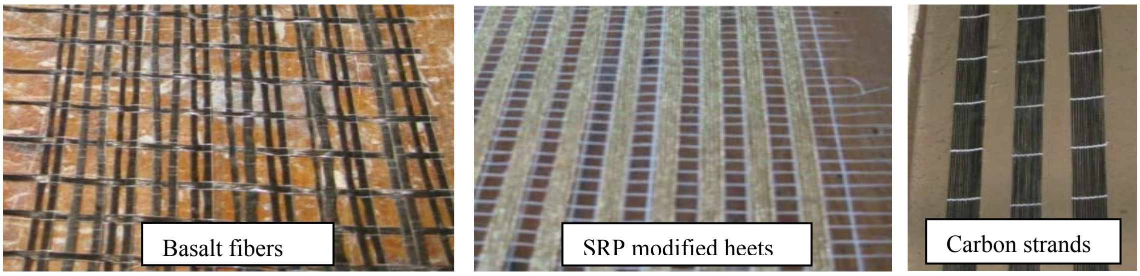

Fig. 2 Different strengthening sheets used in the study.

2.3.1.2 Concrete

The concrete mix was prepared at the Structural Laboratory to provide a nominal strength of 35 MPa using Type-I-Portland cement. The maximum specified aggregate size was selected to ensure good flow of the concrete around the steel cage and eliminate formation of any honey combing.

2.3.1.3 Grancrete Paste

The Grancrete paste was prepared using water/Grancrete ratio of 0.22. The modulus of the elasticity was determined according to ASTM C469 for the Grancrete paste and was found to be approximately 10,120 MPa [3].

2.3.1.4 Strengthening Sheets

Different strengthening sheets used in the current study are illustrated in Fig. 2 and the mechanical properties are given in Table 1.

2.3.2 Test Specimens

This phase consists of 32 T-section RC beams, 2 control beams (B_{01}, B_{02}) and 30 beams strengthened in flexure using externally bonded FRG systems; after preparing a rough surface of concrete along the bottom of the beam specimens along the loading area (1 m) and a bonded length on each side, a first adhesive layer of Grancrete paste is applied followed by a single fiber sheet, another Grancrete paste layer is applied followed by the second single sheet if present and finally a cover Grancrete paste layer is applied as a protection layer. The specimens were adequately designed to avoid concrete crushing and premature failure due to shear, shear reinforcement consisted Ø10/m'. The top flange was reinforced with 5 Ø10/m'. The top reinforcement consisted of two 10 mm diameter steel bars. All beams were constructed with a depth of 500 mm, 3.00 m span and tested in flexure using a four point bending configuration to develop a constant moment region along the mid-third of the span. Details of FRG systems of the test specimens are given in Table 2.

Table 1 Mechanical properties of materials.

Material	Strength		Modulus of elasticity	Ultimate strain of fibers
	Type	MPa	GPa	
Longitudinal steel	Yield strength	420	200	
	Ultimate strength	690		
Concrete	Compressive strength	36.5	28.5	
Grancrete	Compressive strength	41	10.120	
	Tensile strength	2.34		
Basalt Grid	Tensile strength	926	39.6	0.0233
SRP [5]	Tensile strength	840	75	0.0112
Carbon strands	Tensile strength	2,060	118	0.0175

Table 2 Details of strengthening FRG system of test specimens.

Beam ID	Bottom longitudinal reinforcement	Strengthening sheet type	Bonded length (mm)	Number of layers	Grancrete layer thickness (mm)	U-warps for 1 bonded length			
						Type	Width (mm)	No. of U-wraps	Grancrete thickness (mm)
B_{01}-B_{02}	2ϕ12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B1	2ϕ12	B.G.	200	1	20	N/A	N/A	N/A	N/A
B2	2ϕ12	B.G.	400	1	20	N/A	N/A	N/A	N/A
B3	2ϕ12	B.G.	400	2	20	N/A	N/A	N/A	N/A
B4	2ϕ12	B.G.	600	3	30	N/A	N/A	N/A	N/A
B5	2ϕ12	B.G.	600	3	30	N/A	N/A	N/A	N/A
B11	2ϕ12	SRP-1	400	1	20	N/A	N/A	N/A	N/A
B12	2ϕ12	SRP-1	600	1	20	N/A	N/A	N/A	N/A
B13	2ϕ12	SRP-1	800	1	20	N/A	N/A	N/A	N/A
B21	2ϕ12	SRP-2	800	1	20	N/A	N/A	N/A	N/A
B22	2ϕ12	SRP-2	800	1	30	N/A	N/A	N/A	N/A
B23	2ϕ12	SRP-2	800	1	40	N/A	N/A	N/A	N/A
B24	2ϕ12	SRP-2	800	1	50	N/A	N/A	N/A	N/A
B31	2ϕ12	SRP-2	800	1	20	SRP-2	150	2	20
B32	2ϕ12	SRP-2	800	2	30	SRP-2	150	2	20
B33	2ϕ12	SRP-2	800	2	30	SRP-3	150	2	20
B34	2ϕ12	SRP-2	800	2	40	SRP-2	150	2	30
B35	2ϕ12	SRP-2	800	2	40	SRP-2	120	3	20
B41	2 ϕ16	SRP-2	800	1	20	SRP-2	150	2	20
B42	3 ϕ16	SRP-2	800	1	20	SRP-2	150	2	20
C1	2ϕ12	C.S.	800	1	20	N/A	N/A	N/A	N/A
C2	2ϕ12	C.S.	800	1	30	N/A	N/A	N/A	N/A
C3	2ϕ12	C.S.	800	1	40	N/A	N/A	N/A	N/A
C4	2ϕ12	C.S.	800	2	20	N/A	N/A	N/A	N/A
C5	2ϕ12	C.S.	800	2	30	N/A	N/A	N/A	N/A
C6	2ϕ12	C.S.	800	2	20	B.G	150	2	20
C7	2ϕ12	C.S.	800	2	20	CFRP	150	2	20
C8	2ϕ12	C.S.	800	3	30	CFRP	120	3	20
C9	2ϕ12	C.S.	800	1	20	N/A	N/A	N/A	N/A
C10	2ϕ12	C.S.	800	1	20	N/A	N/A	N/A	N/A
C11	2 ϕ16	C.S.	800	1	20	N/A	N/A	N/A	N/A

SRP—steel reinforced polymer, BG—Basalt Grid, CS—carbon strands, CFRP—carbon fiber sheets.

3. Results and Discussions

3.1 Basalt Grid Reinforced Grancrete

The Basalt Grid has a tensile strength of 926 MPa, and its maximum strain is 0.0233. Due to the low elastic modulus of the Basalt sheets, the pre- and post-cracking stiffnesses were identical for all beams regardless of the number of sheet layers and the Grancrete layer thickness (B1-B5). Therefore, its contribution to the overall stiffness of the beams was negligible. Failure of all tested beams was due to rupture of both; Basalt sheets and longitudinal steel reinforcement.

3.2 Steel Reinforced Polymer "SRP" Reinforced Grancrete

The SRP has a tensile strength of 840 MPa, and its maximum strain is 0.0112. The use of SRP sheets with Grancrete paste is a promising strengthening procedure. Four SRP groups were tested, beams B11, B12, and B13 were strengthened using the SRP sheet modified as SRP-1 previously mentioned and showed that due to the low continuity of Grancrete paste, the strengthened beams failed due to sheet delamination at SRP sheet level. As for the beams strengthened with SRP-2, B21 to B24 strengthened using the SRP-2 type, for the same strengthening properties, the beam failed due to sheet delamination at concrete level. It was observed that increasing the Grancrete layer thickness of the strengthening layer slightly led to the increase in the load carrying capacity of the beam. The plate end debonding failure was divided into three debonding modes; the first was due to peeling of the adhesive material, Grancrete; the second was due to internal combined normal and shear forces in the Grancrete level; and the third was due to internal combined shear and normal stresses in concrete level.

The beams B31 to B35 strengthened using SRP-2 type sheets were strengthened using U-wraps outside the loading area consisting of Grancrete and SRP-2 type sheets. For this group of beams, there were no end debonding sheet delamination failure, the types of failure observed for this group were ICD (intermediate crack debonding) failure and sheet rupture failure. The increase in the use of U-wraps units gives better results than using larger U-wraps with larger spacing, it provides better crack propagation, more load carrying capacity and full use of sheet carrying capacity. Beams B41 to B42 were testing the influence of the longitudinal steel reinforcement on the FRG systems.

3.3 Carbon Strands Reinforced Grancrete

The carbon strands have a tensile strength of 2,060 MPa, and its maximum strain is 0.0175. Carbon strands sheet is a promising material to be used with Grancrete in the fiber reinforced Grancrete FRG systems. Working similarly as the SRP sheets; the need of U-wraps with an appropriate spacing, it gives good results. The use of carbon strands sheets led to an increase in the load carrying capacity of the beam and a decrease in the beam deflection.

As for the crack pattern distribution, beams with carbon strands sheet could be classified as brittle beams as they do not allow clear distribution of cracks along the failure pattern unless the strengthening layers along with the concrete beam are working in a full composite action, which could only be guaranteed with the presence of an appropriate distribution of U-wraps.

4. Analytical Modeling

In this section, analytical models are developed to predict the flexural ultimate load carrying capacity for the strengthen beams based on their different modes of failure [5].

4.1 Flexural Prediction—Cracked Section Analysis

This analysis is based on the standard strain compatibility, equilibrium, and material constitutive relations for concrete, reinforcing steel and FRP.

$$C + T_s^c = T_s^t + T_{frp} \tag{1}$$

$$\alpha_1 \times \beta_1 \times h_n \times B \times f_c' + A_s^c \times E_s \times \varepsilon_s^c = A_s^T \times E_s \times \varepsilon_s^T + A_{frp} \times E_{frp} \times \varepsilon_{frp} \quad (2)$$

$$\alpha_1 = \frac{\frac{\varepsilon_c}{\varepsilon_o} - \frac{1}{3} x \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2}{\beta_1} \quad (3)$$

$$\beta_1 = \frac{4 - \frac{\varepsilon_c}{\varepsilon_o}}{6 - 2\frac{\varepsilon_c}{\varepsilon_o}} \quad (4)$$

$$E_G = 1580(f_G)^{1/2} \quad (5)$$

$$\varepsilon_c = \varepsilon_{frp} x \frac{h_n}{D - h_n} \quad (6)$$

$$\varepsilon_s^t = \varepsilon_{frp} x \frac{d - h_n}{D - h_n} \quad (7)$$

$$\varepsilon_s^c = \varepsilon_{frp} x \frac{d' - h_n}{D - h_n} \quad (8)$$

where, "C" compression force in concrete is assumed to follow the widely accepted stress-strain behavior taking the initial strain in the concrete at the time of strengthening "ε_o" = 0.002 and "ε_c" is the axial strain at the interface of concrete and strengthening layer, "B" is the breadth of the flange, "f_c'" is the compressive strength of concrete, and using the equivalent stress block parameters (α_1 and β_1) coefficients used in cracked section analysis [8] as expressed in E qs. (3) and (4). "T_s^c" is the compression force in upper steel, "T_s^t, T_{frp}" are the tension force in bottom steel and FRP, respectively, "A_s^c, A_s^T, A_{frp}" are the area of longitudinal compression steel, tension steel, and FRP, respectively, "E_s, E_{frp}" are the elastic modulus of longitudinal steel and FRP, respectively. "ε_s^c, ε_s^T" are the axial strain in longitudinal compression steel and tension steel, respectively. The modulus of elasticity of the Grancrete paste "E_G" was obtained in Eq. (5), where "f_G" is the normal stress in the Grancrete layer [3].

And by substituting "ε_{frp}" with the ultimate strain of the fibers, the location of the neutral axis "h_n" is calculated, "D" is the distance between the top of the concrete beam and the centroid of the strengthening sheet, "d" is the distance between the top of the concrete beam and the centroid of the bottom longitudinal steel, "d'" is the distance between the top of the concrete beam and the centroid of the compression longitudinal steel, hence, the ultimate moment "M" can be calculated from Eq. (9):

$$M = C\,(d - (\beta_1 \times h_n / 2)) + T_s^c \times (d - d') + T_{frp}\,(D - d) \quad (9)$$

Results of the analysis show that the ultimate flexural capacity of FRP systems can be predicted with sufficient accuracy using the traditional flexural analysis procedures as given in Table 3.

Table 3 Results of cracked section analysis.

Beam	ε_c	ε_s^c	ε_s^t	$M_{predicted}$ (kN·m)	$M_{measured}$ (kN·m)	$M_{predicted}/M_{measured}$
B_{O1}	0.001299	0.01134	0.12	69	77.5	0.9
B_{O2}	0.001299	0.01134	0.12	69	77.5	0.9
B31	0.000843	0.00034	0.010488	108	95	1.14
B35	0.000954	0.00021	0.010194	143	155	0.92
B41	0.001055	0.00014	0.010397	163	155	1.05
B42	0.001279	6.45E-05	0.010382	226	220	1.03
B1	0.00125	0.00115	0.021752	97	82.5	1.17
B2	0.001249	0.00114	0.02173	97	85	1.14
C2	0.000974	0.00082	0.016212	85	90	0.94
C6	0.001031	0.00078	0.016334	95	100	0.95
C9	0.000978	0.00082	0.016313	85	102.5	0.83
C11	0.001273	0.00057	0.016415	141	160	0.88

Table 4 Results of end-plated debonding analysis.

Beam	M_p (kN·m)	M_c (kN·m)	M_G (kN·m)	M_M (kN·M)	M/M_M (ratio)	Beam	M_p (kN·m)	M_c (kN·m)	M_G (kN·m)	M_M (kN·M)	M/M_M (ratio)
B11	112.4	90	70.5	71.25	0.99	C1	157.5	151.5	118.5	87.5	1.35
B12	111.5	97	76	80	0.95	C3	90.5	106.5	83.5	85	0.98
B13	162.5	132	103.5	100	1.04	C4	176	146	114	105	1.09
B21	144.4	137.5	107.5	90	1.19	C5	131	127	99	105	0.94
B22	126.9	122	95.5	97.5	0.98	C10	183.7	151.5	118.5	85	1.39
B23	130.6	108.5	85	100	0.85						
B24	105.1	90.5	71	85	0.84						

4.2 Sheet End Debonding

The critical combination of normal "$\sigma_{n\ max}$" and shear "τ_{max}" stresses at cutoff points between externally bonded steel plate and concrete was established by Brosens and Van Gemert (2001) [6]. This relationship was modified to better serve the FRG systems, where "f_G^T" is the tensile stress in the Grancrete layer as follows:

$$\tau_{\max}^{x} = \left(\frac{f_G f_{Gt}}{f_G + f_{Gt}}\right)^2 - \frac{f_G f_{Gt}}{\left(f_G + f_{Gt}\right)^2}\left(f_G - f_{Gt}\right)\sigma_{n\ \max} - \frac{f_G f_{Gt}}{\left(f_G + f_{Gt}\right)^2}\sigma_{n\ \max}^2 \quad (10)$$

Malek et al. 1998 developed an approach for the classical plate-end debonding [7], based on their work, the following equations have been applied for the FRG systems:

$$\text{Shear stress: } \tau_{\max} = t_p \cdot b_3 \cdot (A)^{1/2} + b_3 \quad (11)$$

$$A = G_a/(t_a \cdot t_p \cdot E_p) \quad (12)$$

$$M_{xo} = a_1 x_o^2 + a_2 x_o + a_3 \quad (13)$$

$$b_1 = (y' a_1 E_p)/(I_{tr} \cdot E_c) \quad (14)$$

$$b_2 = (y' E_p / I_{tr} E_c)(2a_1 L_o + a_2) \quad (15)$$

$$b_3 = E_p \cdot [(y'/I_{tr} E_c)(a_1 L_o^2 + a_2 \mathrm{L_o} + \mathrm{a_3}) + 2b_1 (t_a t_p / G_a)] \quad (16)$$

$$\beta = (K_n b_p / 4E_p I_p)^{0.25} \quad (17)$$

$$K_n = E_a / t_a \quad (18)$$

$$V_c = V_o - b_p y_c' t_p \cdot [b_3 (A)^{0.5} + b_2] \quad (19)$$

$$V_p = -0.5 \cdot b_p t_p^2 \cdot [b_3 (A)^{0.5} + \mathrm{b_2}] \quad (20)$$

$$\text{Normal stress (peeling): } f_{n.\max} = (K_n / 2\beta^3)[(V_p / E_p I_p) - (V_c + \beta M_o)/E_c I_c] + (q E_p I_p / b_p E_c I_c) \quad (21)$$

$$t_p = t_G - t_a + t_{frp} \quad (22)$$

$$E_p A_p = E_{frp} A_{frp} + E_G b (t_G - t_a) \quad (23)$$

where, "t_a, t_p, t_G, t_{frp}" are the thickness of Grancrete adhesive layer, strengthening plate, total Grancrete layer, and FRP, respectively. "b_p" is the width of FRP plate, "G_a" is the shear modulus of Grangrete, "E_a, E_p, E_c" are the elastic modulus of adhesive (Grancrete), strengthening plate, and concrete, respectively. "y', y_c'" are the distance of the center of FRP plate to the centroid of the strengthened beam, and the centroid and the bottom of concrete beam, respectively. "I_{tr}, I_p" are the inertia of transformed section, and strengthened plate element, respectively. "x_o" is the longitudinal distance in the definition of bending moment, "L_o" is the distance between origin of x_o and cutoff point, "a_1, a_2, a_3" are the coefficients of bending moment polynomial, , "A, β" are coefficients used in the shear/normal stress equation, "K_n" is the normal stiffness per unit area of adhesive, "V_c, V_o, V_p" are the shear force in the concrete beam, the concrete beam at the cutoff point due to external load, and in the plate beam, respectively, "q" is external distributed load applied on concrete beam.

The predicted moment, M_M, due to debonding is the least of the three different failure scenarios: when the normal stress equates the tensile strength of Grancrete "peeling of Grancrete layer"; M_p, debonding occurs at concrete-Grancrete interface, M_c, and debonding occurs at Grancrete-FRP interface, M_G.

The results of the analysis are given in Table 4.

5. Conclusions

Fiber reinforced Grancrete FRG could exist in the engineering dictionary for strengthening reinforced concrete beams.

Shear anchorages; U-wraps are an essential parameter for FRG systems. A good distribution provides full usage of cross section capacity. Its presence prevents the plate end debonding and delays the intermediate crack debonding failure and increases the load carrying capacity of the beams. The Basalt Grid sheets showed better results than the Carbon sheets when used in the U-wraps.

SRP sheets and carbon strands are ideal to be used with Grancrete, a good Grancrete paste continuity should be guaranteed in order to provide a complete composite action, good distribution of U-wraps is necessary for the full usage of material properties. The Basalt Grid sheet showed no significant increase in load carrying capacity of the beam which eliminates its usage as externally bonded sheet in flexure.

Flexural capacity of FRP-Grancrete systems can be predicted with sufficient accuracy using traditional cracked section analyses for reinforced concrete and ignoring the tensile strength of Grancrete. Due to the relatively low tensile and compressive properties of Grancrete compared to epoxy, new failure modes; peeling of Grancrete and delamination at the Grancrete-FRP interface were observed in the experimental program.

The predicted capacities at the onset of debonding closely matched the measured values with an average of 5% deviation from the experimental results. It should be highlighted that the thickness of the Grancrete adhesive layer strongly influences the bond results.

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