EXTERNAL FLEXURAL STRENGTHENING OF RC BEAMS USING BFRP GRIDS AND PCM

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External strengthening of Reinforcement Concrete (RC) structures using epoxy-bonded Fiber Reinforced Polymer (FRP) sheets has some negative aspects, such as interfacial debonding and poor resistance ability of epoxy resin for fire and ultraviolet (UV), in addition to the working environment restrictions. To overcome some of those negative aspects, FRP grid bonded with Polymer Cement Mortar (PCM) to strengthen RC structures is developed and proposed in this study. The main objective of this paper is to study the efficiency between Basalt FRP grids and PCM in the flexural strengthening of RC beams. A tensile test was first conducted to determine the static longitudinal tensile strength and maximum elongation properties of the different BFRP grids. Then, the well-known double shear test was conducted to determine the bond mechanism between BFRP grids and concrete. Finally, the flexural behavior of the RC beam externally strengthened with BFRP grids was investigated through a four-point bending test. The results showed the efficiency of using BFRP grids as external strengthening method, as well as the stress-strain relationship of RC beams cross-section shows the compatibility with flexural theory.

Key Words: RC beams, BFRP grids, Bond Mechanism, Flexural strengthening

1. INTRODUCTION

In Japan, the issue of strengthening the existing civil engineering infrastructures has received urgent attention after the Kobe Earthquake of 1995. External epoxy-bonded Fiber Reinforced Polymer (FRP) sheets to the concrete surface has proven to be an effective technique since 1980s¹⁻⁴⁾.

However, those strengthening techniques are often unable to attain the full tensile strength of the FRP sheet, because of the undesirable debonding failures⁵⁾. In addition, using epoxy as a bonding agent has some negative aspects, such as the use of organic resins which create a hazardous working environment for the manual worker and have low permeability, diffusion tightness, poor thermal

compatibility with concrete and sensitivity to moisture at application. Also, most of the epoxies are also sensitive to low temperatures at application and after being installed cannot normally withstand temperatures above 70°C ⁶⁾.

Using PCM as a bonding agent is good technique for creating a more environmentally friendly and sustainable strengthening system. PCM is more brittle and may be difficult to penetrate and bond FRP sheets to concrete surfaces, however these mortars are more suitable to bond FRP grid to concrete surface⁷⁾.

Few works have studied the efficiency of using FRP grids as an external strengthening material. Iwashita et al. ⁸⁾ reported that Carbon FRP (CFRP) grids exhibited superior bonding capacity with concrete surface compared to CFRP sheets. Chen et al. ⁹⁾ studied the behavior of RC beams strengthened in shear with FRP grids; the beams strengthened with FRP grids exhibited a higher number of cracks with significantly smaller crack widths compared to beams strengthened with FRP sheets.

External strengthening using BFRP grids bonded with PCM has been proposed in this study to overcome the previously negative aspects of epoxy-bonded FRP sheets.

2. MECHANICAL PROPERTIES OF BFRP GRIDS

A series of tensile tests were conducted to determine the mechanical properties of the BFRP grids used in this study. BFRP grids were manufactured from dry basalt fibers and vinyl ester resin. According to the manufacturer pamphlet, the nominal tensile strength and elastic modulus of the dry basalt fibers were 2200MPa and 85GPa, respectively. The grids used in this study were manufactured in three different thicknesses: 3, 4 and 5mm. the average width of the longitudinal segments was 15mm approximately, and the axial distance between two consecutives longitudinal or transverse segments was 50 mm. The density of the grids was 400kg/m³.

The specimens were prepared and tested according to the described method in ASTM D7205/D7205M. ¹⁰⁾. The tested specimens were cut from the longitudinal segments of the grids with enough projections of the intersection joints to enhance gripping. Glass plates were used as

anchorage devices. The total length of the specimens was 600mm with an anchorage length of 150mm at each end. Epoxy resin was used to bond the specimens to the plates and left to harden for seven days before testing.

A universal testing machine was used to conduct the tensile tests with a loading rate of 3mm/min. The strain was measured by means of a linear variable differential transducer (LVDT) extensometer with a 5-mm gauge length placed at the mid-span of the tested specimens.

Table 1 summarizes the mechanical properties of the three different BFRP grids used in this study. All test results show a typical elastic behavior until brittle failure occurred. All tested specimens ruptured from tension at the straight portion between the anchorage devices, that proved the efficiency of the anchorage system used, as shown in figure 1. The results show, the maximum applied force increased by increasing the grids thickness, the maximum applied force of BG-H was 30% higher than that of BG-L, as shown in figure 2.

Table 1 Mechanical properties of BFRP grids

ID	Th. mm	Load kN	Strain %	Stress MPa	E GPa
BG-L	3	20.50	2.62	455.6	17.4
BG-M	4	24.60	2.52	410.0	16.3
BG-H	5	28.70	2.49	382.7	15.4

Fig.1 Test setup and failure mode of BFRP grid

Fig.2 Load-strain curve of BFRP grids

3. BOND MECHANISM OF BFRP GRIDS

The bond interfacial between the strengthened materials and the existing structures is a fundamental issue as it significantly influences the mechanical properties of the strengthened structures. So that, a direct bond test was conducted first to estimate the bond interfacial between BFRP grids and concrete surface, and compare with existing strengthening techniques.

(1) Test setup

Nakaba et al ¹¹⁾, showed different bond test types used to determine the bond mechanism between FRP and concrete surface. A double shear test was conducted in this study to obtain the bond characteristics between BFRP grids and concrete surface as shown in figure 3.

A total of eighteen specimens were prepared and tested. Each specimen consisted of two concrete prisms separated by a wood plate and bonded with two segments of BFRP grids on opposite sides. A D20 mm steel rod was embedded in the center of each prism, so that the two prisms were connected only through the bonded BFRP grids. Each prism was 300mm in length with a rectangular cross-section of 150mm in side length. The measured compressive strength of the concrete was 30MPa.

The double shear tests in this study were conducted using a universal testing machine with a loading rate of 1mm/min. Two clip-strain gauges were attached to the opposing free surfaces of the prisms to determine the relative shear displacement. The strain distribution was obtained from six strain gauges set up on the mid longitudinal segment of the grid with intervals of 50mm.

Two parameters were studied; the thickness of the BFRP grids and the type of the bonding agents, three specimens for each test.

Fig.3 Double shear test

Previous studies have demonstrated that the maximum pull-out load initially increased with an increase in bond length until the effective bond length was reached. The maximum load remains constant if the bond length exceeds this value. A debonding of FRP laminates from concrete surface occurs when the bond length is less than the effective bond length, while the failure mode is FRP rupture or concrete prism splitting if the bond length exceeds that value.

A. Yehia et al ¹²⁾, studied the bond mechanism of BFRP grids bonded with epoxy adhesive and recommended a bond length of 250mm. So, the bond length in this study is 300 mm to ensure the full composite action between BFRP grids and concrete surface.

Kamiharako et al ¹³⁾, reported that FRP laminates width has no significant effect on the bond behavior when it is more than 10mm. The BFRP grid total width used in this study is 150mm.

(2) Bonding procedures

Two bonding agents were studied in this study. First bonding agent was a PCM. The mortar was, one component, cement-based polymer reinforced and hydraulic hardening mortar. This mortar also contains a primer that purposed to enhance the bond interface between the concrete surface and the strengthened layer. This primer also prevents moist transportation from the wet mortar to the dry base concrete, leading to lesser crack formations and improved bonding¹⁴⁾. This mortar could be applied by a machine using the dry spraying method, as well as by trowel also. All specimens that bonded with PCM were handled using dry spraying method.

The mechanical properties of the PCM after 28days hardening were, 70MPa for compressive strength, 12MPa for flexural strength, and 23GPa for modulus of elasticity.

This mortar could also be used as a concrete repair product for the structural and non-structural repair of concrete structures (plain concrete and reinforced concrete); as a concrete repair product in the case of additional demands on structural support; as well as for establishing/restoring fire resistance. In addition, this mortar is a polymer-modified, cementitious dry spray mortar (SPCC); high resistance to stress from frost/deicing salt; suitable for restoring fire resistance; system test as anode and repair mortar for cathodic protection;

non-combustible, building material class A1; low dust formation; little rebound.

The main steps of external bonding using PCM were, first prepare the concrete substrate surface using high-pressure water jets (>800 bars), to open the pores and shrinkage holes, and remove the outer weak surface to expose a clean new surface, as well as water enhance the moisture condition of the existing concrete surface to minimize the water sucking out from the fresh mortar.

Secondly adjusting the cement – water ratio before spraying to the concrete surface. Then, the BFRP grids were set in the wood frame and the PCM was sprayed with a total thickness of 15 mm, figure 4. Finally, the level and thickness of the strengthening layer were adjusted, and a thin plastic layer was placed over the mortar to avoid early shrinkage. All tested specimens that bonded with PCM were tested 28 days after spraying the PCM.

Second bonding agent in this study was epoxy putty. Specimens bonded with epoxy putty were handled by hand lay-up, the concrete surface was sandblasted to remove contamination and weak surface layers. Secondly a thin layer of a primer, a low viscosity material, was applied to form a chemical connection between the concrete surface and the relatively high viscosity epoxy putty. It was then left for two days to harden. After this, a uniform thin layer of the epoxy layer was applied with a putty knife on the primer layer. The BFRP grid was pressed onto the epoxy putty then the last layer of the epoxy putty was applied over the grid. The total thickness of the external layer in those specimens was 5 mm. all specimens bonded with epoxy putty were tested 7 days after installation.

(3) Failure modes

The average results of the maximum load, relative displacement and failure mode obtained from the double shear test are given in table 2.

As expected, no debonding of BFRP grids from the concrete surfaces occurred in any specimen as the 300mm bonded length exceeded the effective bond length. All specimens that bonded with PCM failed due to mortar failure (M.F) except for BG-H that had a premature failure. That premature failure happened due to the lack in the centricity of the 20D embedded steel rod in the concrete prism of the BG-H-PCM specimens. So that the applied force acting on the concrete prism had an eccentricity led to this premature failure. Other specimens that bonded

with epoxy putty failed due to concrete splitting (C.S) in the upper prism, as shown in figures 5-7.

Table 2 Double shear test results

ID	Max load kN	Max disp. mm	Failure mode
BG-L-PCM	66.98	3.28	M.F.
BG-M-PCM	79.26	3.68	M.F.
BG-H-PCM	53.32	2.37	Pre. Failure
BG-L-PUTTY	65.31	3.44	C.S.
BG-M- PUTTY	80.43	3.65	C.S.
BG-H- PUTTY	81.60	3.31	C.S.

Fig.4 Dry Spray method of PCM

Fig.5 Mortar Failure

Fig.6 Concrete Splitting

Fig.7 Premature Failure

(4) Load-global displacement curve

Figures 8 and 9 present the load-displacement curves for all tested specimens. The total displacement is the average of the data of the two clip-gauge attached to the opposite free surfaces of the prisms. The results clarify that increasing the BFRP grid thickness has a significant influence on increasing the maximum applied load, while has a minimal effect on the relative displacement.

For specimens bonded with PCM, the load-displacement curve consists of two main portions. In the first portion, the trend of the curve is a linear behavior from the start of loading until the first crack in the bonding agent PCM at a load of approximately 20kN.

The linear elastic behavior could be associated with the linear elastic behavior of the mortar before the first crack. After a load of about 20kN, the trend of the curve became nonlinear, which is called the second portion. In this portion, the interface between BFRP grid and PCM or between PCM and

Fig. 8 Load-displacement curve for PCM specimens

Fig.9 Load-displacement curve for Epoxy Putty specimens

concrete surface could experience some micro-damages from increasing cracks width and numbers. The value of applied load increases until the total failure of the mortar. The specimens that bonded with epoxy putty failed due to concrete splitting in the upper prism. While the maximum applied load and relative displacement of the two bonding agents were similar, the PCM shows more efficiency with increasing the grid width.

(5) Strain distribution

The strain distribution versus the bond length of the specimen was obtained from the six strain gauges on the mid longitudinal segment of the grid. Figures 10-15 show the strain distribution of the different tested specimens at the max load before failure. The results show, the effective bond length for specimens bonded with PCM was 150mm, and for the specimens bonded with epoxy putty was 200mm. It's clear that the effective bond length decreased when PCM is used, showing its efficiency compared with putty as a bonding agent.

Fig.10 Strain distribution for BG-L-PCM

Fig.11 Strain distribution for BG-L-PUTTY

Fig.15 Strain distribution for BG-H-PUTTY

Fig.12 Strain distribution for BG-M-PCM

Fig.13 Strain distribution for BG-M-PUTTY

Fig.14 Strain distribution for BG-H-PCM

(6) The interfacial fracture energy G_f

Wu and Yin ¹⁵⁾ defined the interfacial fracture energy (G_f) as a key parameter to describe the shear strength of the bond interface of the FRP laminates and the concrete surface.

Täljsten ¹⁶⁾ derived a simple equation to express the maximum pull-out load by the interfacial fracture energy and mechanical properties of FRP laminates as shown in the following equation (1).

$$G_f = \frac{P_{\max}^2}{2b_f^2 E_f t_f} \quad (1)$$

where,

$P_{\max}$ the maximum pull-out load,
 E_f the strengthened layer's elasticity modulus,
 t_f the strengthened layer's thickness, and;
 b_f the strengthened layer's total width.

Table 3 summarized the calculated values of the interfacial fracture energy compared with previous studies done by Nakaba et al. ¹¹⁾ The interfacial fracture energy of BG-L, BG-M and BG-H bonded with PCM were 4.51, 5.35 and 2.14N/mm, respectively. However, the maximum stiffness and relative interfacial fracture energy of FRP sheets tested by Nakaba et al. were 87.19kN/mm and 1.50N/mm, respectively with almost double concrete compressive strength of the prisms. From the results, BFRP grids have a high interfacial fracture energy compared with FRP sheets, this is an indicator of the bond efficiency of this technique as an external strengthening method.

Table 3 The interfacial fracture energy G_f

I.D.	Concrete Compressive strength	FRP material	FRP type	Bonding Agent	Max Pull-out load	Fiber width b_f	Stiffness $E_f \cdot t_f$	G_f
BG-L-PCM	30	Basalt	Grid	PCM	66.98	150	22.11	4.51
BG-M-PCM	30	Basalt	Grid	PCM	79.29	150	26.10	5.35
BG-H-PCM	30	Basalt	Grid	PCM	53.32	150	29.56	2.14
BG-L-PUTTY	30	Basalt	Grid	PUTTY	65.31	150	23.77	3.99
BG-M-PUTTY	30	Basalt	Grid	PUTTY	80.43	150	27.35	5.26
BG-H-PUTTY	30	Basalt	Grid	PUTTY	81.60	150	30.35	4.88
C5-ARF	57.6	Aramid	sheets	Epoxy	11.79	50	24.04	1.16
C5-HCF	57.6	Carbon	sheets	Epoxy	21.60	50	70.14	1.33
C5-SCF	57.6	Carbon	sheets	Epoxy	16.35	50	43.60	1.23
C5-SCFH	57.6	Carbon	sheets	Epoxy	25.63	50	87.19	1.51
C5-SCFL	57.6	Carbon	sheets	Epoxy	11.48	50	21.80	1.21
M5-ARF	50.9	Aramid	sheets	Epoxy	12.43	50	24.04	1.29
M5-HCF	50.9	Carbon	sheets	Epoxy	16.37	50	70.14	0.76
M5-SCF	50.9	Carbon	sheets	Epoxy	15.70	50	43.60	1.13
M5-SCFH	50.9	Carbon	sheets	Epoxy	22.29	50	87.19	1.14
M5-SCFL	50.9	Carbon	sheets	Epoxy	9.35	50	21.80	0.80
C2-SCF	23.8	Carbon	sheets	Epoxy	15.71	50	43.60	1.13

4. FLEXURAL STRENGTHENING OF RC BEAM

A total of seven simply supported rectangular RC beams were constructed and tested to study the flexural strengthening efficiency of using BFRP grids. One beam was a control beam, while the other six beams were strengthened with BFRP grids. Three beams bonded with PCM, while the remaining three beams bonded with epoxy putty. The bond procedures were same as in double-shear test. All beams were tested in a four-point bending test under a static load.

(1) Test setup

The basic beam geometry has a height of 300mm, a width of 150mm, and a span of 1800mm with a clear span 1600mm. The tensile reinforcement bars consisted of two D13 bars, and compression bars are two D6 bars. Shear reinforcement consisted of double-legged rectangular steel stirrups with a nominal diameter of 10mm, as shown in figure 16. The yield stress of the longitudinal reinforcement was 440MPa, and modulus of elasticity 200GPa. Ready-mixed concrete was used with a specified compressive strength of 30MPa. All beams were tested until failure using a 500kN capacity servo-controlled hydraulic actuator.

Fig.16 Details of the strengthened beam

Three LVDTs were used to measure the deflection at mid-span and at both ends of the bottom surface of the beam. The data was automatically collected using a data logger device (TDS-102). The location of cracks and their propagation was marked on the concrete surface at load increments of 10kN until the tensile reinforced bars yielding. Six strain gauges were installed on the side of the beam to measure the strain distribution of the cross-section of the beam. A strain gauge on the mid span of each steel bar and the longitudinal ribs of the grids was installed to measure the strain during the loading. The results of all tested beams are summarized in table 4.

(2) Failure mode

The control beam exhibited the ideal plastic behavior after steel yielding and the failure mode was concrete compressive crushing by exceeding the ultimate compressive strain in the concrete

compressive zone. Intermediate crack induced interfacial debonding (IC debonding) failure mode was observed in all strengthened beams.

IC debonding initiated at the flexural crack at the mid-span and then propagated towards the end of the external strengthening layer. Debonding failure involves a loss of the composite action between the beam and the strengthening layer.

The number of cracks increased while its width decreased by increasing the thickness of the BFRP grids, this behavior proves that using BFRP grids enhances the stress distribution along the beam length. Figures 17-23 show the failure mode of the seven tested beams.

Fig.17 Failure mode of beam B0

Fig.18 Failure mode of beam BG-L-PCM

Fig.19 Failure mode of beam BG-L-PUTTY

Fig.20 Failure mode of beam BG-M-PCM

Table 4 Flexural test results

Beam ID	Crack Load kN	Yield Load kN	Ult. Load kN	Max Defl. mm
B0	32.12	120.3	139.6	39.15
BG-L-PCM	45.70	159.2	223.9	22.00
BG-L-PUTTY	37.85	148.5	221.7	20.71
BG-M-PCM	45.72	160.2	228.4	18.48
BG-M-PUTTY	37.96	150.2	229.5	20.86
BG-H-PCM	46.36	163.9	219.5	13.85
BG-H-PUTTY	39.17	154.2	206.0	15.01

Fig.21 Failure mode of beam BG-M-PUTTY

Fig.22 Failure mode of beam BG-H-PCM

Fig.23 Failure mode of beam BG-H-PUTTY

(3) Load-deflection relationship

Figure 24 shows the load deflection curve of all tested strengthened beams bonded with PCM. The flexural behavior of all tested beams had three main stages. First stage is a non-cracked stage, from initial loading until the initiation of the first crack. The first crack and relative cracking load was determined by visual inspection of the beam during loading. The behavior of the beams in this stage was characteristic of linear-elastic behavior. The cracking load of the strengthened beams bonded with PCM and putty was about 43.0%, and 19.3%

higher than the cracking load of the control beam, respectively. The increases in cracking load of strengthened beams bonded with PCM was almost double of the beams bonded that with putty. The increases in the cracking load was a result of the new geometry of the beam, the thickness and the mechanical properties of the external bonding layer.

After the concrete cracked, the beam reached the second stage, which is called the in-service stage. This stage is characterized by the geometry of the beam and the axial stiffness of the tensile reinforcement bars and external strengthening layer. From load-deflection curves, strengthened beams had a higher flexural stiffness compared to the control beam. Since the yield strain of the tensile reinforcement bars is about 10% of the ultimate failure strain of the grids, there was no FRP rupture in this stage.

The yield loads of the strengthened beams BG-L-PCM, BG-M-PCM, and BG-H-PCM were 159.2, 160.2, and 163.9kN, respectively. While, the yield loads of the beams bonded with epoxy putty were 148.5, 150.2 and 154.2kN, respectively.

After tensile bars yielded, the control beam B0 exhibited typical plastic behavior until the compressive concrete crushing, while the strengthened beams exhibited a hardening behavior due to existing of BFRP grids. The flexural stiffness of the strengthened beams decreased after steel yielding as the tensile stresses on reinforcement bars remained essentially constant.

On the other hand, the hardening stiffness of the strengthened beams increased by increasing the thickness of the BFRP grids. The hardening behavior improved the flexural capacity of the beams, while reducing the deflection of the beams.

The load-deflection behavior in the hardening stage was almost linear up to final failure.

The ultimate load of the strengthened beams BG-L-PCM, BG-M-PCM, and BG-H-PCM was 223.9, 228.4, and 219.5kN, respectively. While, the ultimate load of the beams bonded with epoxy putty was 221.7, 229.5 and 206.0kN, respectively.

From figures 25-27, the load-deflection curves show that using epoxy putty as a bonding agent has some limitations in the bond mechanism with increasing the fiber content comparing to PCM.

Fig.24 Load-deflection curve for strengthened beam with BFRP grids and PCM

Fig.25 Load-deflection curve for strengthened beam BG-L

Fig.26 Load-deflection curve for strengthened beam BG-M

Fig.27 Load-deflection curve for strengthened beam BG-H

(4) Design of the strengthened beams

Figures 28-30 show the strain distribution along the cross-section at the mid-span of the beam. The distribution of that measured strains was nearly linear during the loading until failure. The visual inspection of the strengthened beams during loading shows that there is a good compatibility between RC beams and PCM, even after steel bar yielding. The strain distributions along the cross-section of the tested strengthened beams were proportional to the distance from the neutral axis of the beam, so that flexural theory could be apply to a strengthening design by this technique.

5. CONCLUSIONS

This study presented a series of experimental studies on the bond mechanism of BFRP grids to concrete surface and the flexural strengthening of RC beams.

- The double shear tests showed the bond efficiency of using BFRP grid and PCM as an external strengthening material.
- The interfacial fracture energy G_f of the BFRP grids is higher than FRP sheets reported in the literature.
- The ultimate load of strengthened beams with BFRP grids was enhanced by 47.60 – 63.65% in comparison to the reference beam.
- The flexural capacity of strengthened RC beams with BFRP grids bonded with PCM could be estimated based on the flexural theory.
- Epoxy putty showed some limitations in the bond mechanism with increasing the fiber content comparison to using PCM as a bonding agent.

Fig.28 Strain distribution of BG-L-PCM

Fig.29 Strain distribution of BG-M-PCM

Fig.30 Strain distribution of BG-H-PCM

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