Jurnal Teknologi

Full paper

Structural Performance and Ductility of Fiber Reinforced Polymer Concrete Bonding System Under Tropical Climates

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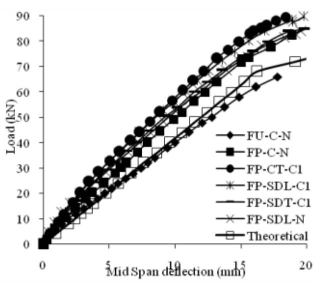
Article history

Received :1 November 2012
Received in revised form :15 January 2013
Accepted :15 March 2013

Graphical abstract



Abstract

Tropical climate combines with saltwater exposure may influence the structural performance and durability of FRP-epoxy-concrete system over long period of time. FRP being non-corrodible material has been proven to be efficient materials in rehabilitation jobs compared to steel. Reinforced concrete structures may be required to be strengthened at a later age of their service life to overcome additional loading capacity and deterioration due to environmental effect. The main objective of the current paper is to study flexural behavior of an externally bonded reinforced concrete beams using carbon FRP plate and fabrics due to exposure to natural tropical climate. The research studies the ability of reinforced concrete beams externally bonded with CFRP plate and fabrics to resist numerous environmental conditions such as tropical weather, normal laboratory environment and saltwater solution. The bonded beams are subjected experimental evaluation by performing four points load test until failure to observe the failure loads, deflection, strain, cracking behavior and the patterns of failure. Strengthening of reinforced concrete beams using CFRP plate and fabrics demonstrated significant improvement in the flexural capacity of the beams by 30% and 16%, respectively compare to control specimen without strengthening.

Keywords: Fiber reinforced polymer; strengthening; durability; concrete; tropical climates

Abstrak

Kombinasi iklim tropika dan pendedahan larutan garam berkemungkinan mempengaruhi keutuhan struktur dan ketahanan Sistem ikatan Konkrit-Polimer Bertetulang Gentian untuk jangka panjang. Polimer Bertetulang Gentian sebagai bahan tidak karat telah dibuktikan bahan efisen dalam kerja pemulihan berbanding besi tetulang. Struktur bertetulang konkrit berkemungkinan perlu dikuatkan dimasa akan datang untuk mengatasi pertambahan kapasiti beban dan kemorosotan disebabkan persekitaran. Objektif utama penyelidikan ini adalah untuk mengkaji prestasi lenturan bagi rasuk bertetulang konkrit yang diperkuat dengan Polimer Bertetulang Gentian Karbon dalam iklim tropika. Penyelidikan ini mengkaji rasuk bertetulang konkrit yang diperkuat dengan Polimer Bertetulang Gentian Karbon didedahkan sepanjang masa di dalam cuaca semulajadi, persekitaran makmal, dan kitaran basah-kering di dalam larutan garam di dalam suhu bilik. Ujian prestasi lenturan dijalankan ke atas rasuk bertetulang konkrit dengan plat dan fabrik karbon sehingga berlaku kegagalan untuk memerhatikan beban maksima, lenturan, pesongan, penarikan, sifat rekahan dan corak kegagalan rasuk. Penguatan rasuk bertetulang konkrit menggunakan CFRP plat dan fabrik menunjukkan peningkatan ketara dalam kapasiti lenturan rasul dalam, masing-masing 30% dan 16% berbanding dengan specimen tidak dikuatkan.

Kata kunci: Polimer bertetulang Gentian; penguatan; ketahanan; konkrit; iklim tropika

1.0 INTRODUCTION

Durability and ductility are essential to the long-term sustainable service life of structural system having FRP-concrete relation [1]. Strengthening of existing reinforced concrete structures may be unavoidable at certain structural age to overcome the increase in loading capacity or the effect of environmental deterioration. Studies have been carried out to utilize FRP effectively and to prolong the service life of selected FRP-concrete structural system in different configurations, techniques and environment [2-10]. This is to ensure the structural reliability and durability of FRP material to resist and capable to avoid material degradation and structural damage. The strengthening of reinforced concrete structures using externally bonded FRP composite system raises two fundamental concerns on the durability of the system. One of the issues is the durability of the FRP material itself. The other issue is the durability of bonding between the FRP material and concrete substrate that concerns with the durability of the interface bond in the FRP-concrete bonding system that can limit the strengthening performance of FRP materials [11-13]. The development of high stress can possibly lead to the debonding of FRP plate from concrete. The long term behavior of the structural bonded joints in civil engineering application need to be guaranteed for a long periods of years for the acceptance of this bonded system in the construction industry [14].

Understanding the effect of tropical climate on FRP and its matrix material in structural element becomes necessary particularly for outdoor exposure, in order to gain acceptance in a country which is experiencing high average annual rainfall of 5080 mm for the East Malaysia (Borneo) compared to 2500 mm of annual rainfall for the Peninsular Malaysia [15]. Even though, the temperature is quite consistent throughout the year, the temperature record in Malaysia for the last fifty years has indicated a warming trend as studied by Tangang *et al.* [16]. Another concern is the annual rainwater pH in Malaysia which is in the range of 4.8 to 5.2 for which the southernmost of Johor and Klang Valley is slightly acidic with average pH of between 4.4 and 4.8 on the average for the three consecutive years between 2006-2009 [17].

With regards to structural application, carbon, glass and aramid reinforcement are very similar in term of their stress-strain behaviour in which these fibres behave linearly elastic until rupture in the stress-strain diagram. However, the materials do not possess the ductility very similar to steel and the brittleness may limit the ductile behaviour of reinforced concrete system strengthened with FRP composite [18]**.** Results from selected studies reveal that strengthening using FRP as external reinforcement provides a substantial increase in stiffness and ultimate load carrying capacity of the members subjected to flexure [3, 5, 19-23] and shear [24] as well as torsional performance [25, 26].

The interface bond between FRP material and the concrete is a success factor for strengthening method using external bonded FRP plate or sheets. The interface bonding is critical by providing the effective shear stress transfer from the concrete to the externally bonded FRP [11]. Thus, the composite action of structures being externally bonded with FRP material should be preserved during the loading until failure by having a capable and efficient adhesive to transfer stresses between adhesive concrete and adhesive plate bonding [27]. The bonding of adhesive joints between plate and concrete are commonly susceptible to debonding premature failure causes by the interfacial shear stress concentration in the adhesive layers. The debonding failure mechanism has been established by researchers such as Oehlers [28] and Chen and Teng [29]. Understanding the interfacial bond strength using externally plated FRP reinforcement also requires thoughtful consideration of the concrete surface preparation because of the bonding failure could that happen within the concrete layer beneath the adhesive [11].

Many studies have proven the benefit of using FRP as an external reinforcement in concrete structures for flexural strengthening and repairing material. Shahawy *et al.* [19] showed that external reinforcement by bonding one, two and three CFRP laminates to the surface of the reinforced concrete beams increased their ultimate flexural capacity by 13%, 66% and 92%, respectively. Deflections for the laminated beams exhibit a significant reduction with increasing number of CFRP laminates. Li *et al.* [3] in a similar research showed that multilayer and optimum length of externally bonded CFRP can significantly improve the stiffness of strengthened RC beams. The investigation also demonstrated that length and thickness of CFRP can influence crack patterns and ultimate failure load where longer and thicker CFRP can efficiently restrained the crack development and ultimate failure modes of the beams. Doubling the amount of CFRP laminates in the external strengthening of RC beams has also demonstrated an increased by 97% to 162% in load carrying capacity compare to the control beams [4]. The results also showed that bonding the composite material to the full length of the beam provide better bonding between concrete and CFRP and also increase the ductility.

In a different configuration, Alagusundaramoorthy *et al.* [5] added anchored CFRP sheet to his investigation to study the effectiveness of externally bonded CFRP in improving the flexural strength of reinforced concrete beam. Results of the experimental and analytical investigation showed that the flexural strength was increased up to 49%, 58%, and 40% on concrete beams strengthened with CFRP sheets, anchored CFRP sheets, and CFRP fabrics respectively. The strength of beam strengthened with two layers of CFRP fabrics was found to be higher than one layer of fabrics.

Concrete structures bonded with FRP bonded have been subjected to various environmental conditions such as water [6] or salt solution [7], temperature [2, 30], or cold freeze-thaw environment [8, 31-33] in order to study the durability of the FRP as material and as a whole structural system. In general, the results of these studies under the room temperature and various harsh environmental exposures showed that the ultimate flexural load increased in sizeable effect by externally bonding FRP sheets to the tension face of the concrete beam. The specimens strengthened with carbon fibre typically performed better than samples strengthened with glass fibre [8]. Another conclusion and suggestion made were that the best way to enhance the long-term performance of FRP strengthened concrete structures was to increase the water resistance ability and aging resistance capability of polymer matrix [2].

Shimomura and Maruyama [34] studied the long term performance of reinforced concrete beam externally bonded with FRP sheet by investigating the ingression of aggressive solution into concrete and the influence of reinforcement corrosion on the strengthened beam. The results of the test demonstrated that FRP sheets bonded on RC member that has corroded reinforcement can strengthen and increase the mechanical performance of the RC members. An investigation carried out by Wan *et al.* [35] concluded that the presence of water during primer application significantly decreases the bond quality where the greater the amount of water present, the worse the bond. The presence of water also changes the mode of failure, from cohesive failure through concrete to adhesive failure along the concrete/primer interface and also results in deterioration of the bond between FRP and concrete after epoxy has cured. The investigation also concluded that the bond performance degrades with the time of exposure.

In observing tropical climates effect, an experimental research done by Mohd Sam *et al.* [9] demonstrated that reinforced concrete beam strengthened with CFRP plate under load and exposed to tropical climate for a duration of six months had higher stiffness compared to the strengthened and unexposed beam. Better bonding between CFRP plate and concrete subjected to fully cured adhesive upon outdoor exposure is expected to be the reason of such results. In another study from the same region an experiment showed that beams subjected to sustained loading exhibited larger deflection and cracks widths when subjected to longer period of weathering exposure [36]. Meanwhile, beams subjected to outdoor weathering showed 8% larger deflection and 15% larger crack width compared to the specimens kept under ambient laboratory condition. Both the strength and ductility of beams kept under accelerated weathering decreased with longer weathering period.

Teng *et al.* [37] associated concrete cover separation and plate end interfacial debonding to plate end debonding failure and interfacial cracked-induced debonding as intermediate crack-induced interfacial debonding failures. Nonetheless, the important parameters for failure modes to a given fibre reinforced beams depends on the internal reinforcement, geometric and material properties materials used in the FRP system [37]. Ritchie *et al.* [22] as one of the earliest researcher on the knowledge of understanding of failure modes in flexural strengthening showed bonded plate were viable method of improving the stiffness and strength of strengthened reinforced concrete beam. The results showed an increase in the range of 17% to beyond 90% compared to the control beam.

Examination on the flexural behaviour of reinforced concrete beams strengthened with externally bonded unidirectional FRP plate and showed that beams failed by fibre rupture after the yielding of tension steel reinforcement [38, 39]. The plate thickness and method of anchorage also affected the failure mechanism in which thinner FRP plate reinforcement results in lower shear and normal stress at the end of the FRP plate. As such, an under-reinforced repaired beam would fail by rupturing the plate. On the other side, increasing plate thickness has demonstrated that shear and normal stress developed at the end of the plate and caused plate debonding. Eventually, concrete rip-off occurred as the plate separated and followed by local shear failure along the steel reinforcement in the concrete.

The pressing problem associated with the proven sound and efficient characteristics of FRP-concrete bonding system in repairing works has been found to be susceptible to premature failure due to separation of the FRP plate from the original reinforced concrete structures. The most common flexural failures modes for FRP strengthened beam is plate end debonding by means of separation of the concrete cover and plate end interfacial debonding. The debonding failure occurred at the zone of high stress concentration which is often related to the region having discontinuities and presence of cracks. The debonding failure due to this high interfacial stress often causes significant loss in structural capacity due to the initiation or propagation of debonding along bonded joint [40].

■2.0 EXPERIMENTAL

2.1 Materials

The effect tropical climate exposure as well as salt solution on the durability and performance of externally bonded FRP plate on concrete structures is the main subject of this report. The specimens used in the investigation are reinforced concrete beam having dimension of 140 × 180 ×2400 mm strengthened with CFRP plate. The beams were provided with two 16 mm diameter high tensile steel reinforcement and 6 mm diameter steel for stirrups. The beams were not designed for compression reinforcement and designed to fail in flexure. The designed compressive strength of concrete at 28 day test was 50 MPa using a maximum coarse aggregates size of 10 mm. 2000mm length pultruded CFRP plate with 1.5 mm for thickness, 50 mm for the width bonded to the concrete for external strengthening purposes. Unidirectional CFRP fabric was also cut into similar dimension as FRP plate as a basis of comparison.

Table **1** shows the mechanical properties of the CFRP plate and CFRP fabrics which were obtained from the manufacturer's catalog. Structural and saturated epoxy from the same brand with CFRP plate and fabric were used as the adhesive to FRP to concrete. Both of these epoxy was mixed accordingly based on the manufacturer recommendation for the bonding application. A mix ratio of 3:1 (epoxy-hardener) was used for the structural epoxy and mix ratio of 4:1 was used for the saturating epoxy. All prepared beams were tested for flexural performance under four point load test.

Table 1 Properties of CFRP plate and fabrics used in the study

FRP Materials	Carboplate E170	Sikawrap 201C
Width (mm)	50	50 (cut)
Tensile Strength (MPa)	3100	4900
Tensile Modulus (GPa)	170	230
Thickness (mm)	1.4	0.11
Elongation At break (%)	2.0	2.1
Fibre Volume (%)	68	NA

2.2 Method

Air tool hammer was used and operated attentively to expose and roughen the surface of concrete beam to bond FRP and concrete to ensure a perfect bonding between the two materials. The exposed surface was cleaned of any dirt, dust or any small concrete particles. The surface of CFRP plate to be bonded was also given similar attention. Epoxy was applied to both surface of concrete and CFRP plate for bonding purposes. Homogenous hand pressure was manually applied throughout the bonded length to provide a firm bond between the plate and concrete. CFRP fabric, on the other hand was bonded to the concrete surface by applying the fabric onto a layer of saturating epoxy. Another layer of saturating epoxy was applied on top of the bonded fabrics to ensure fully and firm bond of CFRP fabrics without air trapped. n a two-component gel, it is easy to modify the molecular structure of either of the two components.

The main focuses of testing the specimens are the determination and observation of the ultimate load, load deflection behavior, interfacial stress, ductility and mode of failure of the beams. Linear Variable Displacement Transducers (LVDT), Electrical strain gauges and demec disc were installed on the beams specimens for deflection and strains during loading. Some of the reinforced concrete beams were prepared and tested under pre-cracked condition. The beams were subjected to various environmental conditions as shown in Table 2 for six months duration. Three (3) types control reinforced concrete beams were prepared for this investigation that comprise of beam without strengthening, and beam strengthened with CFRP plate and a beam strengthened with one layer of CFRP fabric. Figure 2 shows the bonded beams being conditioned under combination of tropical climate and salt water.

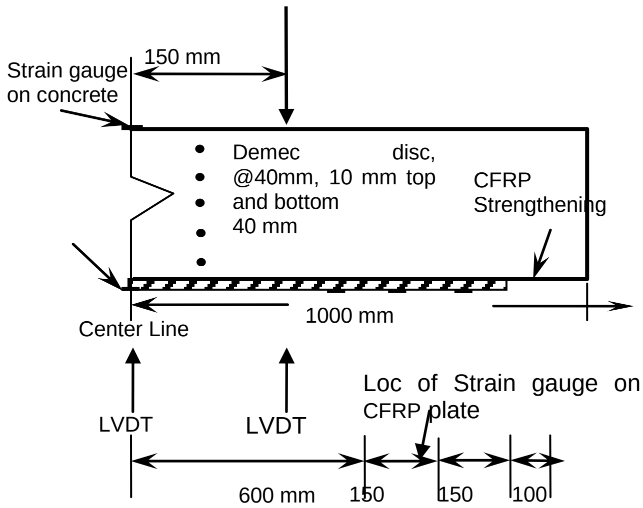


Figure 1 Instrumentation set-up for flexural test on beam shown on half side

Table 2: Exposure programme for bonded reinforced concrete beam

Exposure Condition	Duration 28 days	6 months
Control (without strengthening) (FU-C-N)	Continuous	
Control strengthening, lab (FP-C-N, FF-C-N, FF-CL2-N)	Continuous	
Tropical Climate (FP-CT-N, FP-CT-C1, FF-CT-C1)	-	Continuous
Wet Dry cycle saltwater (FP-SDL-C1, FP-SDL-C1,FP-SDL-C1, FF-SDL-C1)		3 days wet – 4 days dry
Dual Exposure Wet-Dry saltwater – Tropical Climate) (FP-SDT-C1)	-	3 days wet – 4 days dry - 7 days tropical (2 weeks/cycle) 12 cycles

Notes:
FU- Flexural without strengthening
FP - Flexural plate
FF - Flexural fabric
C – control, CT – continuous natural weather
SDT – dual, immersion in saltwater, wet- dry in laboratory combined with tropical weather
N – no crack
C1 – pre-cracked

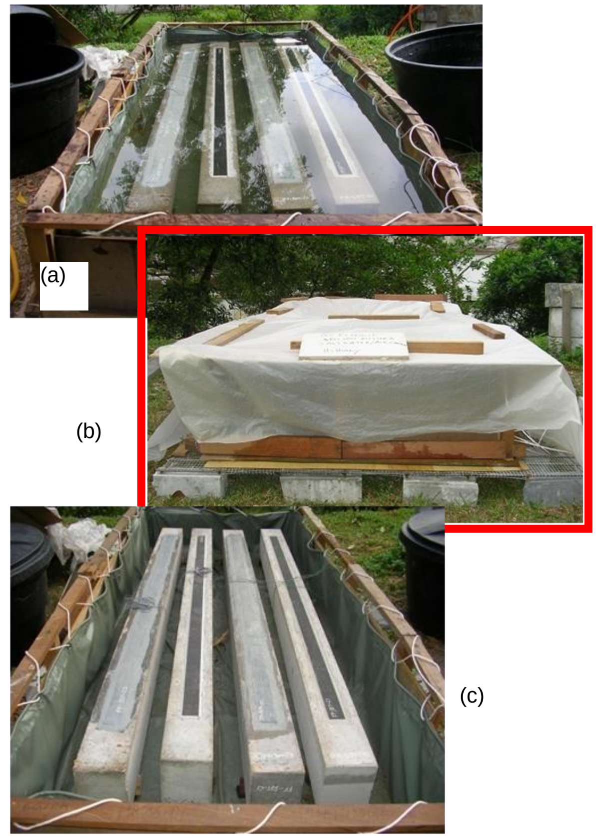


Figure 2 Strengthened beams subjected to dual exposure of salt water and tropical weather (a) full immersion in saltwater for dual saltwater and tropical exposure (b) wet-dry in saltwater (with cover) and (e) 1 week tropical exposure

■3.0 RESULTS AND DISCUSSION

3.1 Flexural Performance

Table 3 shows the flexural load carrying capacity using CFRP plate as an external strengthening material for reinforced concrete beams for various conditions of exposures. Figure 3 shows the load deflection behavior at mid-span of the beam for beam strengthened with CFRP plate and Figure 4 for CFRP fabrics. Strengthening using CFRP plate improves the flexural capacity by about 30% and strengthening using one layer of CFRP fabric increased by 16%. The failure load capacity for the control strengthened beams with CFRP plate (FP-C-N) is higher compared to control beam without strengthening (FU-C-N). The failure load for beam strengthened with one layer of fabric is also higher than control beam, FU-C-N. These results demonstrated the capability of FRP as an external strengthening material of reinforced concrete beam to increase the flexural performance of the beams. The investigation also demonstrated that bonding of one layer of CFRP fabric to reinforced concrete beam resulted in lower improvement in flexural performance compared to CFRP plate by 11%. The characteristics of CFRP fabrics being flexible compared to the rigidity of the CFRP plate may have contributed to both materials' ability to resist bending load. In general, the results of four-point load test showed that applying external CFRP reinforcement to reinforced concrete beams and subjected to various exposure conditions can improve the flexural load capacity of the bonded beam compared to original beam without strengthening (FU-C-N). There was an improvement in the range of 10% to 37% at various specific conditions comparing to the control beam of 66 kN. The study also shows that bonding CFRP plate to reinforced concrete beams resulted in better flexural capacity about twice of CFRP fabrics in term of failure load ratio. The results of load and mid-span deflection showed that the increase in strengthening capacity was also associated with an improvement in deflection capacity. This indicates an increase in stiffness of the strengthened and exposed beam using CFRP plated compared to the control beam without strengthening. The stiffness of beam strengthened with one layer of CFRP fabric was also initially about the same as control beam without strengthening. Conclusion can also be made that conditioning the strengthened beams for six months is not sufficient to demonstrate degradation of bonding. However, certain type of exposure environment affected the flexural behavior of the strengthened beams more than the other. The pre-cracking condition also did not significantly affect the flexural behavior of the strengthened and exposed beams

Generally, it can be observed that the penetration of moisture, rain water, or saltwater during the exposure period did not caused much expected deterioration to the flexural behavior of the exposed strengthened beams. It can be seen that beam subjected to continuous tropical climate exposure (FP-CT-C1) recorded better load-deflection behavior at approximately the same failure load. So, beam FP-CT-C1 showed better stiffness behavior compared to beam conditioned in wet-dry saltwater (FP-SDL-C1, FP-SDL-N) and dual exposure wet-dry saltwater (FP-SDT-C1). Strengthened beam subjected to dual exposure, FP-SDT-C1 were found to have lower stiffness than beam FP-CT-C1 probably due to penetration of saltwater into concrete voids inside the beam. The voids may be filled up with salt crystal during drying stage that at later time can give outward pressure to the concrete to cause micro-cracking. This eventually may cause deterioration to the load carrying capacity and deflection behavior of the exposed beam.

Table 3 Load carrying capacity of strengthened beams

Specimen	Load at ultimate failure P_{fail} (kN)	Ratio of Strengthened/ Un-strengthened (P_{fail} Load FU-C-N)
FU-C-N	66	-
FP-C-N	85.9	1.30
FF-C-N	76.6	1.16
FP-CT-N	90.6	1.37
FP-CT-C1	89.6	1.36
FP-SDL-C1	89.7	1.36
FP-SDL-N	86.8	1.32
FP-SDT-C1	87.6	1.33
FF-CT-C1	73.1	1.11
FF-SDL-C1	73.8	1.12
FF-SDT-C1	72.8	1.10
FF-CL2-N	69.6	1.05
Comparison between plate and fabric		
FP-C-N	85.9	-
FF-C-N	76.6	0.89

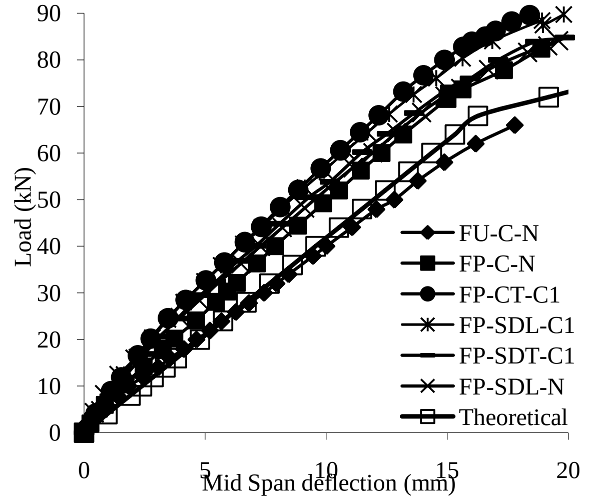


Figure 3 Load deflection behavior of beam strengthened with FRP plate

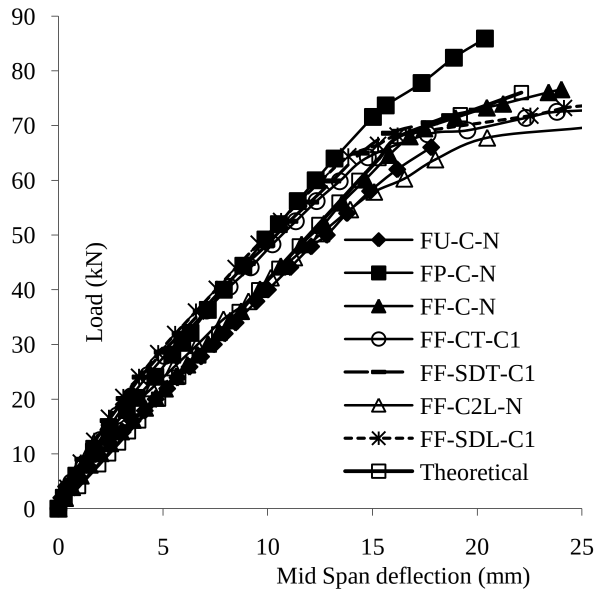


Figure 4 Load deflection behavior of beam strengthened with FRP fabrics

The experimental and calculated mid-span deflection behaviour at ultimate failure load is presented in Table 4. The calculated deflection is measured using theoretical mid-span deflection expression as shown in Equation 1,

$$\delta = Pa\,(3L^2 - 4a^2/24E_cI_g \qquad \text{Equation 1}$$

where δ = deflection at mid-span, P = applied load, L = the span of the beam, a = shear span, E_c = concrete modulus of elasticity, and I_g = gross transformed section of moment of inertia including the FRP plate. The gross transformed section of moment of inertia, I_g, at each stages of moment-curvature relationship i.e precracking, cracking and post cracking is derived from Faruqi's *et al*. [41] for its simplicity.

Table 4 Deflection behavior of all beams at ultimate load

Specimen	Exp. load at ultimate failure P_{fail} (kN)	Exp. Deflect. @ ultimate load Δ_{fail} (mm)	Calc. δ	Exp. δ / Calc. δ
FU-C-N	66	17.8	15.8	1.13
FP-C-N	85.9	20.4	20.6	0.99
FF-C-N	76.6	24.0	18.3	1.31
FP-CT-N	90.6	***	21.7	***
FP-CT-C1	89.6	18.4	21.4	0.86
FP-SDL-C1	89.7	19.8	21.5	0.92
FP-SDL-N	86.8	21.5	20.8	1.03
FP-SDT-C1	87.6	20.4	21.0	0.98
FF-CT-C1	73.1	27.9	17.5	1.60
FF-SDL-C1	73.8	25.6	17.7	1.45
FF-SDT-C1	72.8	20.0	17.4	1.15
FF-CL2-N	69.6	25.1	16.7	1.50

The ratio of comparison of the exposed beams was calculated based on the control beam without strengthening. The results show that the deflection of the exposed beams at the ultimate load level differs with the control beam without strengthening (FU-C-N) in the range as low as 3% to a high of 57%. Beams externally bonded with CFRP plate showed lower range of different in deflection between 3% and 21%. On the other hand, beams bonded with CFRP fabrics showed a higher range of different in deflection between 12% and 57%. The calculated deflection at the ultimate load varied between 15.8 mm and 24.8 mm for control and exposed beams. The ratio of experimental deflection and calculated deflection was also presented in

The results show that the ratio varied from 0.86 to 1.60. It is good to note that the results also provide significant understanding on better ductility behavior of CFRP fabrics bonded beam compared to CFRP plated beam.

Typical flexural crack pattern developed during loading along the constant moment region and shear regions for all tested beams. Only flexural cracks were observed in all of the tested beams. Cracks in the flexural span were mostly vertical cracks perpendicular to the principal stress by the action of pure moment. However, as the applied load increased, the cracks started to incline as shear played more roles. As a result, the cracks started to develop in the shear span as load increases. The mode of failure observed in control beam without strengthening (FU-C-N) and beams strengthened with CFRP plate (FP-C-N) and fabrics (FF-C-N) started with steel reinforcement yielding followed by crushing of concrete in the compression zone. However, all beams strengthened with CFRP plate failed by means of plate end debonding with a thin layer of concrete remained attached to the plate along the debonded length. This may well indicates the reduction in bonding strength between FRP and concrete when the cracks propagated into the shear region that eventually debonded the plate from the concrete which also suggested a failure occurred in the concrete adjacent to the adhesive-concrete interface. On the other hand, assumption can be made that strong enough bonding exist between concrete and the adhesive and adhesive-plate interface to cause failure within the concrete. In all of the cases, the debonding of the CFRP was accompanied by a sudden loud sound which could be due to large interfacial energy developed in the bonded joints. The debonded zone extended from either one end of the plate to location beyond the centre of the beam but not to the other end. The behaviour could be explained as the cracks propagated into the shear region the bonding strength between FRP and the concrete started to decrease and eventually debonded the plate from the concrete. Beam strengthened with CFRP fabrics (FF-C-N) failed with concrete crushing with no major debonding or failure of CFRP fabrics. There was a sign of detachment of CFRP fabric bonded at the centre of the beam from the concrete due to crack. A thin layer of concrete was also attached to the debonded fabrics similar to debonded plate, which shows the existence of perfect bonding between epoxy and fabrics.

On the average the results show that the crack spacing for beam strengthened with CFRP plate and fabrics (Table **4**5) was less than the beam without external strengthening (FP-U-N). This behavior indicates that externally bonded CFRP plate and fabrics to the tension side of reinforced concrete beam can contribute to reduction of cracks spacing in flexural strengthening method. This could imply that the stiffness of the reinforcement can affect the cracking behavior of strengthened beams. The combination of natural weather and salts solution is able to improve the cracking performance of concrete beam with spacing reduction in the range of 23% to 32%. The number of cracks was also in the same pattern with average spacing. An increased in the number of cracks caused the reduction in cracks spacing. Thus, better stiffness of the strengthened beams may have caused the lower cracks spacing characteristics. The results also showed that wet-dry conditioning in salt water affected the cracking behaviour a previously cracked (FP-SDL-C1) reinforced concrete beam in which the pre-cracked beam had lower increase in numbers of cracks and average crack spacing compared to un-cracked beam (FP-SDL-N) at approximately 4% and 24%, respectively. However, the difference was very minimal to beams continuously exposed to natural weather (FP-CT-N, C1) and dual environment (FP-SDT-C1).

Table 4 Cracks and failure modes pattern

Beams	Nos. Of Cracks			Range Crack spacing (Avg) mm	Failure Modes
	S	C	Tot		
FU-C-N	17	4	21	40-150 (82)	CR
FP-C-N	17	5	22	40-180 (79)	PED
FF-C-N	20	4	24	40-125 (63)	CR
FP-CT-N	22	6	28	30-100 (60)	PED
FP-CT-C1	23	6	29	30-105 (63)	PED
FP-SDL-C1	19	5	24	40-110 (79)	PED
FP-SDL-N	22	5	27	30-140 (62)	PED
FP-SDT-C1	23	6	29	30-100 (55)	PED
FF-CT-C1	19	6	25	30-190 (64)	PED
FF-SDL-C1	16	4	20	55-120 (81)	CR
FF-SDT-C1	17	6	23	25-140 (72)	PED
FF-C2L-N	16	5	21	50-110 (78)	

Note: S – Shear C = Constant Moment Region

3.1 Structural Ductility

Ductility is one of the important properties of structural system which can be characterized as the structural element capacity to resist large deformation prior to total failure. Such property is important for structural members to be able to sustain load beyond their maximum strength. Ductility of any reinforced concrete structures can be measured by parameters such as deflections, strains or curvatures. Ductility can be expressed as factor or index at certain critical stage of structural member's performance. In the case of reinforced concrete structures, the yield point of the steel reinforcement is used as the basis to identify ductility. This is related to zone on the stress strain curve of steel reinforcement indicated by the structural member ability to sustain large deformation. However, FRP materials do not possess the same yield behavior as steel reinforcement. As such, the ductility of CFRP materials being used in this investigation cannot be based on internal steel reinforcement deformation behavior. Hence, in this this research, the deflection, curvature and energy based on steel yielding were used as a criterion of ductility for assessing the structural performance of reinforced concrete beam bonded with CFRP material, exposed to tropical climate and saltwater solution. The following equations defined the structural ductility adopted:

Deflection ductility factor:

$$\mu_{\Delta} = \Delta_u / \Delta_y \qquad \text{Equation 1}$$

where Δ_u is the ultimate deflection at mid span, and Δ_y is the mid-span deflection at steel reinforcement yield point.

Curvature Ductility Factor:

$$\mu_{\varphi} = \varphi_u / \varphi_y \qquad \text{Equation 2}$$

where φ_u is the ultimate curvature at mid span, and φ_y is the curvature at steel reinforcement yield point.

Energy Ductility Factor:

$$\mu_E = E_u / E_y \qquad \text{Equation 3}$$

where E_u is total area under the load deflection curve, and E_y is area under load deflection curve at yielding of tension steel.

Table 6 and Table 7 summarize the calculated ductility factor for all beams tested in this study and also the ratios of ductility for all beams compared to the control beam without strengthening. The values of calculated ductility may well provide information on the behavior the reinforced concrete beams upon being strengthened with CFRP plate and fabrics and also after being subjected to environmental effect. The deflection ductility was calculated using Equation 1. It can be seen that that the deflection ductility of all strengthened beams was higher than the control beam without strengthening. The values of ductility for conditioned beams strengthened with CFRP plate ranged from 1.17 to 2.08 compared to the control beam without strengthening. The results demonstrated that, the ductility of beam strengthened with CFRP fabrics resulted in higher ductility compared to beam strengthened with CFRP plate. The ductility of control beam strengthened two layers of CFRP fabrics was higher than one layer of CFRP fabrics. However, the higher ductility of conditioned beam strengthened with CFRP fabrics possessed lower flexural load and lower stiffness compared to conditioned beams strengthened with CFRP plate. It seems that the lower flexural capacity of beams strengthened with CFRP fabric could sustain large deformation before the occurrence of failure to the strengthened beams.

Table 6 Ductility indices

Specimen	Load at failure P_{fail} (kN)	Deflection ductility Δ_u/Δ_y	Curvature Ductility φ_u/φ_y	Energy Ductility E_u/E_y
1	2	3	4	5
FU-C-N	66.0	1.10	0.98	1.20
FP-C-N	85.9	1.36	1.55	2.16
FF-C-N	76.6	1.37	1.14	1.82
FP-CT-N	90.6	****	1.08	****
FP-CT-C1	89.6	1.17	1.30	1.92
FP-SDL-C1	89.7	1.17	2.31	1.85
FP-SDL-N	86.8	1.28	2.82	2.00
FP-SDT-C1	87.6	1.28	1.54	2.05
FF-CL2-N	69.6	1.66	1.19	2.48

Table 7 Ductility ratio

Specimen	Ratio (Ductility FU-C-N)			Ratio (Ductility FP-C-N or FF-C-N)		
	Δ_u/Δ_y	φ_u/φ_y	E_u/E_y	Δ_u/Δ_y	φ_u/φ_y	E_u/E_y
1	6	7	8	9	10	11
FU-C-N	1.00	1.00	1.00			
FP-C-N	1.23	1.59	1.80	1.00	1.00	1.00
FF-C-N	1.25	1.17	1.52	1.00	1.00	1.00
FP-CT-N	****	1.10	****	****	0.69	****
FP-CT-C1	1.07	1.32	1.61	0.87	0.83	0.89
FP-SDL-C1	1.07	2.36	1.55	0.87	1.49	0.86
FP-SDL-N	1.17	2.88	1.67	0.95	1.81	0.93
FP-SDT-C1	1.17	1.57	1.71	0.95	0.99	0.95
FF-CL2-N	1.51	1.21	2.07	1.21	1.04	1.36

The curvature ductility was calculated using Equation 2. There was an increased in ductility in all specimens based on curvature ductility. The values of ductility varied from the lowest 0.98 for control beam without strengthening to 6.48 for strengthened beams. Similar to deflection ductility, beams strengthened with CFRP plate resulted in lower ductility compared to beams strengthened with CFRP fabrics. The ductility of conditioned beam strengthened with CFRP fabrics were about twice higher than the ductility of conditioned beam bonded with CFRP plate. The curvature ductility of control beam strengthened with two layers of CFRP fabrics was also higher than control beam strengthened with one layer of CFRP fabrics which is also similar to deflection ductility. The ductility ratio of conditioned beam strengthened with one layer of CFRP fabrics were between 5.78 and 6.08 and the ductility ratio of conditioned beams strengthened with CFRP plate were between 1.10 and 2.88. In case of beams strengthened beam with CFRP plate (FP), beams exposed to saltwater has higher ductility compared to tropical environment.

Equation 3 was used to calculate the energy ductility for all beams tested in the investigation. Calculation of area under the load deflection curve is required to measure energy ductility. Integration was applied to each of the load-deflection curves with a limit between zero and to the point of deflection at ultimate load or deflection at yield of internal steel reinforcement. Energy ductility produced a very similar trend with curvature ductility. There was an increased in ductility in all strengthened beams compared to the control beam without strengthening. The ductility of the beams strengthened with fabrics was also higher than beam strengthened with plate. Beams bonded with CFRP fabrics in all exposure conditioned resulted in higher ductility than beam strengthened with CFRP plate. Even the energy ductility of control beam strengthened with two layers of CFRP fabrics was higher than beam strengthened with CFRP plate.

The results also showed that the ductility of beams strengthened with CFRP plate and conditioned under various exposures environment were lower than unexposed control beam strengthened with CFRP plate (FP-C-N). However, the curvature ductility of beam FP-SDL-C1 and FP-SDL-N were higher than the unexposed control beam (FP-C-N). On the other hand, the ductilities of beams strengthened with CFRP fabrics in all exposure condition were higher than the control beam without exposure (FF-C-N). On the overall, it can be seen from the ductility ratio based on the strengthened beam gave better and consistent values compared to the ratio based on ductility of beam without strengthening. This was obvious for ratio of ductility of reinforced concrete beam strengthened with CFRP plate and for deflection and energy ductility. The ductility of beam strengthened with CFRP plate and exposed continuously under tropical weather (FP-CT-C1) and beam subjected to dual exposure (FP-SDT-C1) were consistent in all basis of ductility. The ductility ratio was between 0.83 and 0.89 for FP-CT-C1 and between 0.95 and 0.99 for FP-SDT-C1. The ductility for beam FP-SDL-C1 and FP-SDL-N were close and consistent for deflection and energy ductility only. It can be seen that the ratio was 0.87 and 0.86 for deflection and energy ductility, respectively, for beam FP-SDL-C1 and 0.95 and 0.93 for FP-SDL-N. It seems that deflection and energy ductility can provide reasonable evaluation of ductile behaviour of beam strengthened with CFRP plate. In addition to that, the yield of the tension steel reinforcement was recognized reference point in measuring the ductility on reinforced concrete beam strengthened with FRP plate.

■4.0 CONCLUSION

The use of CFRP as external strengthening material in reinforced concrete structure contribute to the improvement of the flexural performance of this particular type of structures as well as the overall stiffness of FRP bonded system. The higher loading capacity of beam strengthened with CFRP plate lead to higher stiffness. However, beams strengthened with CFRP fabrics which resulted in lower loading capacity, demonstrated more ductile behaviour. The findings might be related to the rigidity of the CFRP plate as material compared to fabrics which were flexible that may have contributed to its ability to resist higher bending load. Thus, the use of FRP as strengthening materials for its structural effectiveness in tropical climate countries for growing development of sustainable infrastructures is expected to be favorable.

Acknowledgement

The authors would like to express gratitude to Universiti Teknologi Malaysia (UTM) and Universiti Teknologi MARA (UiTM) for making this research successful. Special thanks to Mapei (Malaysia) Sdn. Bhd. for supplying the CFRP plate and structural epoxy (adhesive) used in this research works.

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