Bonding Behavior of Interface between CFRP Strand Sheet and Concrete with Various Types of Adhesive

Bahsuan, Rifadli
Department of Urban and Environmental Engineering, Graduate School of Engineering, Kyushu University : Graduate Student

Hino, Shinichi
Department of Civil and Structural Engineering, Faculty of Engineering, Kyushu University : Professor

Yamaguchi, Kohei
Japan Bridge Engineering Center

https://hdl.handle.net/2324/1657739

出版情報：九州大学工学紀要. 75 (1), pp.1-15, 2015-07-31. Faculty of Engineering, Kyushu University

Memoirs of the Faculty of Engineering, Kyushu University, Vol.75, No.1, July 2015

Bonding Behavior of Interface between CFRP Strand Sheet and Concrete with Various Types of Adhesive

by

Rifadli BAHSUAN[*], Shinichi HINO[**] and Kohei YAMAGUCHI[***]

(Received January 26, 2015)

Abstract

This study discusses bonding behavior, as a result of interface between CFRP (Carbon Fiber Reinforced Plastics) strand sheet and concrete with 3 different types of adhesives, namely, Epoxy, MMA (Methyl Methacrylate), PCM (Polymer Cement Mortar). To obtain such behavior, a bonding test based on Japan standard JSCE-E543-2007 was conducted. The test was performed for one layer, two layers and three layers of CFRP strand sheet. Finite element analysis model was made to confirm the experimental result.

The result shows that there were good agreement with experimental and FE analytical results for the maximum load and the effective bond length. Although, it was need a slight change of bond-slip model for strain distribution.

Keywords: Bonding properties, CFRP strand sheet, Epoxy, PCM, MMA

1. Introduction

Many innovations have been carried out for strengthening reinforced concrete structures. Strengthening is required for structural elements in which its strength have been declining due to, such as, age, environmental influences, poor design, lack of maintenance, change of function and damage caused by events such as earthquakes and others.

FRP (Fiber Reinforced Plastics) is proposed as a solution for solving this problem, despite having a fairly expensive price, FRP has many advantages such as corrosion resistance, high tensile strength, durability, good fatigue resistance, lighter specific gravity, easy and fast in application, as well as adjustable processing method of concrete. FRP is a composite material that consists of high strength material fiber embedded in a polymeric resin. The type of fiber that is often used in the fabrication of FRP is carbon, then called Carbon Fiber Reinforced Plastics (CFRP), aramid (Aramid Fiber Reinforced Plastics, ARFP) and glass (Glass Fiber Reinforced Plastics, GFRP). **Figure 1** shows a comparison between CFRP, AFRP and GFRP composites, and reinforcing steel in the stress-strain relationship diagram. It can be seen that CFRP is 7 to 8 times stronger than steel reinforcing.

[*] Graduate Student, Department of Urban and Environmental Engineering
[**] Professor, Department of Civil and Structural Engineering
[***] Engineer, Japan Bridge Engineering Center

It is worth noting that bonding plays an important role in reinforcing design by using FRP materials. Recently, many studies have been carried out to find out the bond behavior between concrete and FRP [1)-7)], but only a few are discuss about bond behavior between CFRP strand sheet and concrete. Numerical prediction of the previous study showed that there was no sufficient assumption regarding the bonding behavior and generally produce erroneous predictions on the ultimate load capacity and stress levels.

CFRP strand sheet, shown in **Photo 1**, is one of CFRP interface bonding system that has been recently developed. CFRP strand sheet has only one direction strengthening and is suitable for structural beam. Some advantages in the use of CFRP strand sheet model compared to conventional sheet model are, CFRP strand sheet can be used without impregnating of adhesive material into the concrete and less possibility of air bubble occurrence in the interface area between CFRP strand sheet and concrete.

This paper discusses the bond behavior of CFRP strand sheet and concrete. To investigate the bond behavior, experimental results and finite element analysis were be used. This study used three types of adhesive namely Epoxy, MMA (Methyl Methacrylate) and PCM (Polymer Cement Mortar) with different variations of layer. To obtain the objective of this research, a doubled faced shear type bond test was conducted [8)]. The bonding test was done by adopting the JSCE - E543 – 2007 [9)], about test method for bonding properties of continuous fiber sheet to concrete.

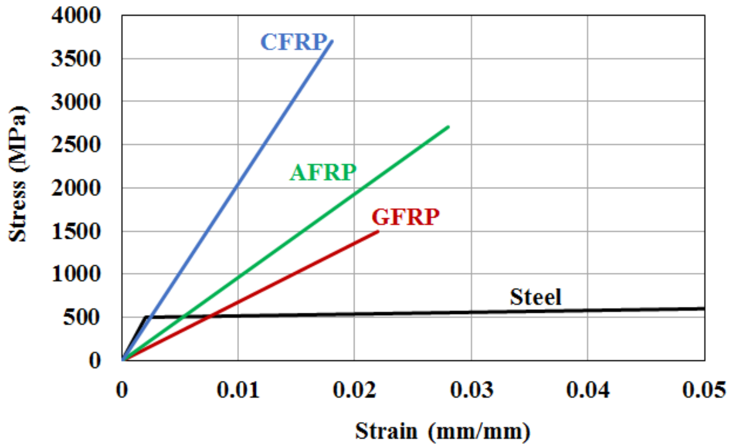


Fig. 1 Stress-strain relationship of reinforcing materials.

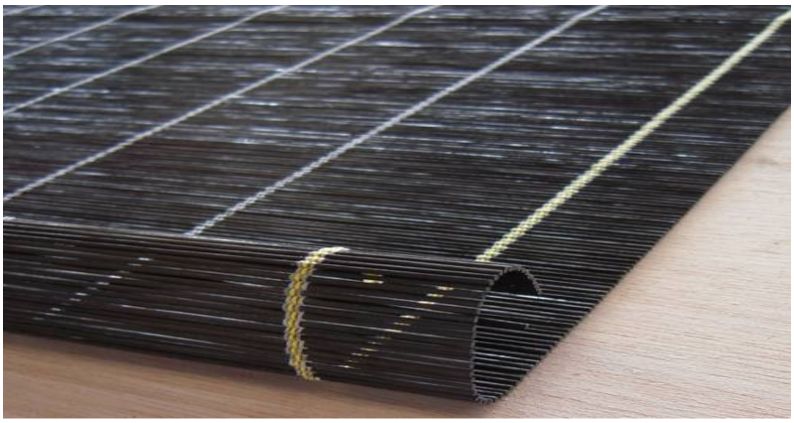


Photo 1 CFRP strand sheet.

2. Experiment on bonding test

2.1 Test set up

The specimens of this research are shown in **Fig. 2** and **Photo 2**. They were made three for each of sample. The sample are one, two, three layers for Epoxy and MMA adhesive and one, two layers for PCM adhesive. The bond test specimen was a double-face type consisting of a concrete prism (100mm x 100mm x 620mm) with two CFRP strand sheets with 50mm width which were bonded at two opposite sides of the specimen. One side of the specimen was given a confinement sheet. There were two notches at the center of the prism which made at the time of casting, the two steel bars also had no connection. This means that the two prisms were connected only with the CFRP strand sheet and debonding failure occurred only on the opposite side of confined area, where strain gauges were set. The strain gauge had a distance of 30mm, the bond length total of CFRP strand sheet was 280mm. To avoid stress concentration, at each end of the specimen had two or three layers, the upper layer was made shorter than the previous layer by 25mm (**Fig. 2** Detail J). Monotonic static loading test method was carried out in this investigation. A universal testing machine with a capacity of 1000kN was used, as shown in **Photo 3**. The increase rate of the load was approximately 5kN per minute and the strain gauge was recorded at 1kN of load increment.

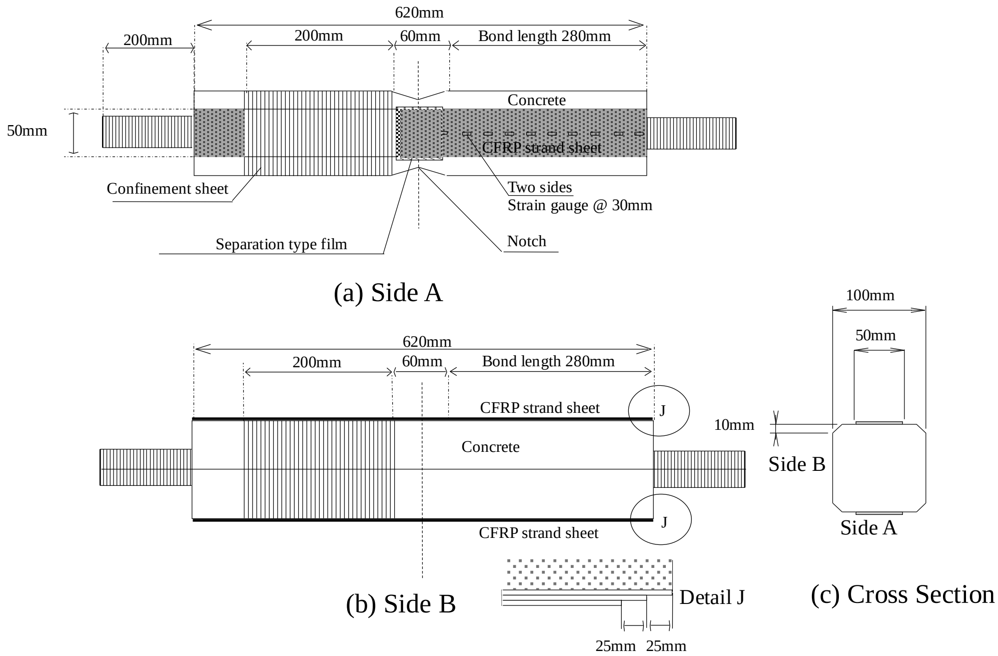


Fig. 2 Geometry for bonding test specimen.

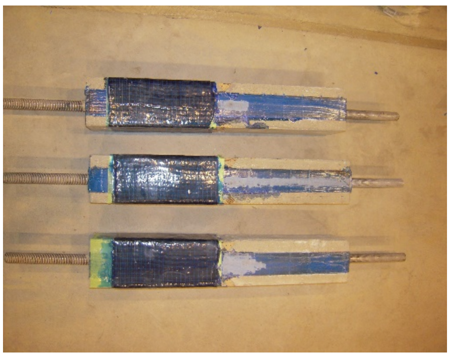


Photo 2 Specimen for bonding test.

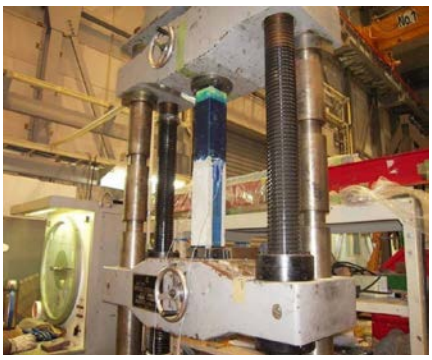


Photo 3 Testing of specimen.

The properties of adhesive and CFRP strand sheet were obtained from the manufacturer. **Table 1** shows the mechanical properties of adhesive. Epoxy is commonly used as standard adhesive in the use of FRP. MMA is a quick-drying adhesive can also be used in low temperature conditions. The MMA can be used after two hours of installation. PCM is used for wet surfaces. In this study, the use of Epoxy and MMA adhesive was about 2.5 kg/m^2. PCM, for surface protection, had a thickness of 10 mm from CFRP strand sheet layer.

High tensile strength of CFRP strand sheet was used in this study. For more details of the CFRP strand sheet mechanical properties capture in **Table 2**. Furthermore, the quality of concrete was used in this study can be seen in **Table 3**.

2.2 Adhesives used in specimens

(a) Epoxy material

Figures 3a, **3b** and **3c** are the cross-section of CFRP strand sheet reinforcing element using Epoxy resin as a bonding agent with 1 ~ 3 layers. The process of implementation was begun after Epoxy resin prepared coated on the concrete, then followed by attaching process of CFRP strand sheet. CFRP strand sheet was placed while pressed in order that adhesive was evenly distributed. After it was done, the next layer was coated in the same way.

Table 1 Mechanical properties of adhesive (MPa).

Type	Epoxy	MMA	PCM
Compressive Strength	78.3	79.0	11.3
Compressive Modulus	3,970	2,500	4,800
Tensile Strength	35.8	43.0	2.4
Flexural Strength	58.8	71.0	6.5
Lap-share Strength	25.8	22.0	-

Table 2 Mechanical properties of CFRP strand sheet.

Type	High-Strength Type
Tensile Strength (MPa)	3,400
Tensile Modulus (MPa)	245,000
Design thickness (mm)	0.333
Unit Weight (g/m^2)	600

Table 3 Mechanical properties of concrete (MPa).

Compressive Strength	Modulus of Elasticity
37.1	26900

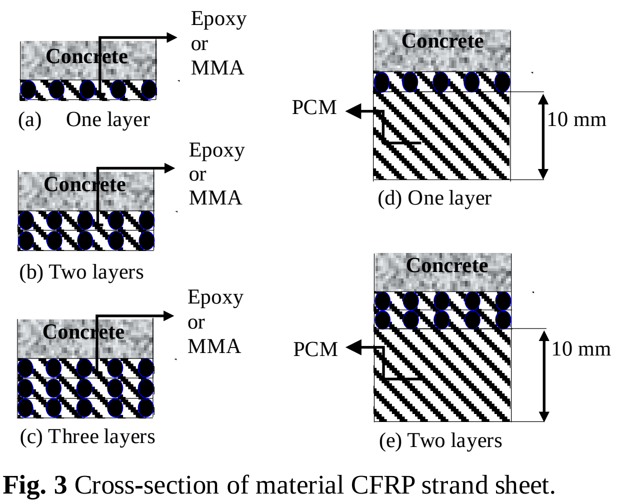


Fig. 3 Cross-section of material CFRP strand sheet.

(b) MMA (Methyl Methacrylate) material

Figures 3a, **3b** and **3c** illustrate in brief retrofitting types that were used MMA as an adhesive for 1 to 3 layers. Stages of implementation are as follows; prepared the primer material, then given evenly on the CFRP strand sheet and the surface of the concrete beam. Next, sprinkled MMA material on the concrete surface. Then the CFRP strand sheets were attached to the concrete surface while pressed in order to be spread evenly, after it was done, did overcoat for the next layer.

(c) PCM (Polymer Cement Mortar) material

The use of PCM as an adhesive in retrofitting methods can be seen in the cross-section at **Fig. 3d** and **Fig. 3e**. Stages of implementation are as follows; after prepared PCM mixed with the water, spread thinly on the surface of concrete beams. Subsequently, CFRP strand sheet was attached with on the whole surface and was pressed such that the impregnation could be evenly distributed. After that, followed by the next layer. Finally, CFRP strand sheet was covered with the PCM until designed thickness (10mm).

3. Test results and discussion

3.1 Maximum load, bond strength and interfacial fracture energy

Table 4 presents the results of maximum load. For all types of adhesive shows that the more layer increase the maximum load. When comparing to a single layer of the specimen, it became clear that the largest maximum load on the adhesive type Epoxy followed MMA and PCM, respectively.

Table 4 also capture the bond strength and the interfacial fracture energy results. The interfacial fracture energy, G_f, is area enclosed the interfacial bond stress (τ) and slip (s) curve relationship that is a significant parameter for the bonding properties. In the analysis, τ_u and G_f were calculated by equation 1) and 2), based on JSCE - E543 – 2007.

$$\tau_u = \frac{P_{max}}{2bl} \tag{1}$$

$$G_f = \frac{P_{max}^{\ 2}}{8nb^2E_ft} \tag{2}$$

Where,

G_f = interfacial fracture energy (N/mm)

τ_u = bond strength (MPa)

P_{max} = maximum load (N)

b = average width of CFRP strand sheet (mm)

E_f = tensile modulus of CFRP strand sheet (MPa)

t = thickness of CFRP strand sheet (mm)

l = length of bond (mm)

n = number of layer of CFRP strand sheet

Table 4 shows that the bond strength of Epoxy is greater than those of MMA and PCM in the same layer. For one layer, the bond strength of Epoxy are 17% and 23% higher than those of MMA and PCM, respectively. For two layers, the Epoxy results are 22% and 14% greater than those of MMA and PCM, respectively, and it has 20% higher than that of MMA for three layers. In general it can be seen that adding the number of layers will increase the of bond strength.

For results of interfacial fracture energy G_f can be seen that the value of G_f is related to number of the layer, increasing the number of layers the results of G_f will be decrease. Epoxy has the greatest for the interfacial fracture energy, and this confirms that Epoxy is the best of the three types of adhesive followed by MMA and PCM.

3.2 Failure detail

JSCE – E543 – 2007 confirms that there are two categories for test specimen failure; (a) the interfacial failure, which is a debonding failure between surface CFRP strand sheet and concrete, and (b) base material failure, which is the CFRP strand sheet reaches its ultimate strength.

Typical failure of bonding test is shown in **Photo 4**. It can be seen that the typical failures of the specimen were the interfacial failure which occurred only one side of the prism. It was caused by eccentricity of the load in the loading machine. Besides that, these facts were related to the interface between CFRP strand sheet and concrete. In this case, the bonding strength did not depend on the concrete strength or the strength of the CFRP strand sheet. For this reason, in this study, the interface behavior will be a focus to describe for the overall of bonding test result.

Table 4 Results of bond test.

Type of Adhesive	Numb. of layers	No. of spec.	Max. Load, P_{max} (kN)		Bond Strength, τ_u (MPa)		Interfacial Fracture Energy, G_f (N/mm)	
			Result	Ave	Result	Ave	Result	Ave
Epoxy	1	1EB1	43.3	42.1	1.55	1.51	1.15	1.09
		1EB2	41.9		1.50		1.08	
		1EB3	41.2		1.47		1.04	
	2	2EB1	51.2	51.7	1.83	1.84	0.80	0.82
		2EB2	46.6		1.66		0.67	
		2EB3	57.2		2.04		1.00	
	3	3EB1	56.4	56.7	2.01	2.02	0.65	0.66
		3EB2	54.7		1.95		0.61	
		3EB3	59.0		2.11		0.71	
MMA	1	1MB1	40.6	36.0	1.45	1.29	1.01	0.80
		1MB2	32.2		1.15		0.64	
		1MB3	35.2		1.26		0.76	
	2	2MB1	42.2	42.3	1.51	1.51	0.55	0.55
		2MB2	41.4		1.48		0.53	
		2MB3	43.3		1.55		0.57	
	3	3MB1	43.7	47.1	1.56	1.68	0.39	0.46
		3MB2	50.7		1.81		0.53	
		3MB3	47.0		1.68		0.45	
PCM	1	1PB1	35.8	34.5	1.28	1.23	0.79	0.73
		1PB2	32.6		1.17		0.65	
		1PB3	35.0		1.25		0.75	
	2	2PB1	44.1	45.1	1.58	1.61	0.60	0.63
		2PB2	42.3		1.51		0.55	
		2PB3	49.0		1.75		0.74	

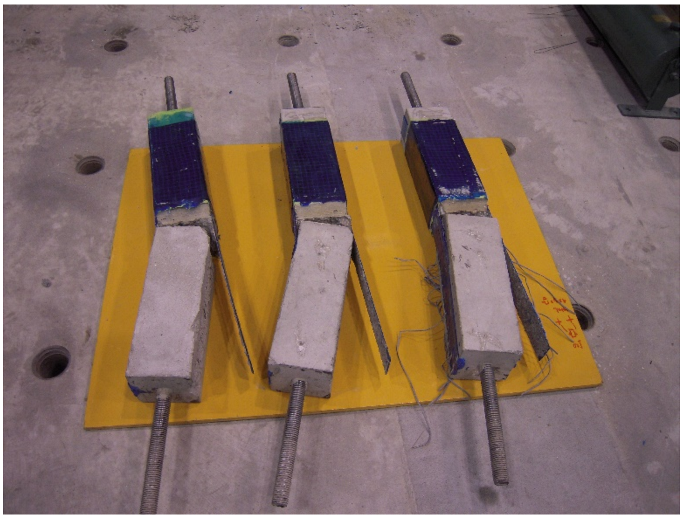


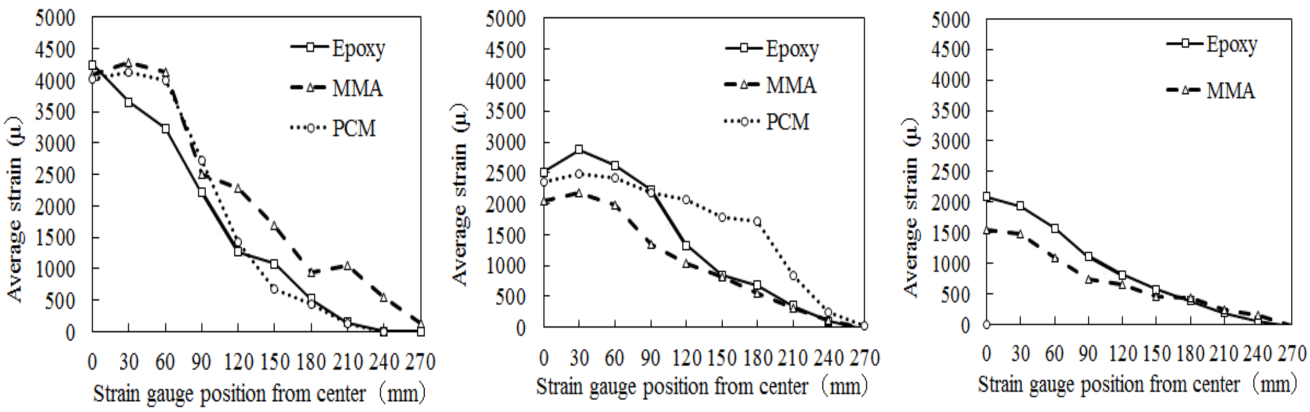
Photo 4 Typical failure model of bonding test (Epoxy 2 layers).

3.3 Strain distribution of CFRP strand sheet at the maximum load

Figures 4(a), 4(b) and **4(c)** show the strain distribution generated from each strain gauge to the specimen. Strain distribution, that presented, was the average strain of the entire specimen when the maximum load was achieved. From the strain distribution at the maximum load, it can be seen that fewer layers produce larger strain. This means that thickness affect the amount of strain that occur. The differences of strain are not too large on the same layers specimen, it confirms that the types of adhesive do not provide a significant influence on the strain that produced.

3.4 Effective bond length

Currently, many methods were used to evaluate the effective bond length. Effective bond length can be defined as a length over which majority of bond stress maintained. The effective bond length takes the entire load to a certain level at which localized debonding occurs, causing the effective bond length to shift to another active bonding zone. This phenomenon continued until the CFRP strand sheet was completely debonding from the concrete [10].



(a) One layer (b) Two layers (c) Three layers

Fig. 4 Strain distribution at the maximum load.

In this study, effective bond length was obtained by determining the maximum stress that occurred in the CFRP strand sheet. An calculation was done on the strain distribution diagram of the maximum load by assuming that a constant maximum stress occurred to the longitudinal direction of the specimen that be computed by using equation (3) and the effective bond length could be determined by using equations (4). **Figure 5** shows how to specify the points that be used to determine the effective bond length in this study.

$$\tau_{max} = \frac{\Delta\varepsilon_f \ E_f A_f}{s_g b} \tag{3}$$

$$l_e = \frac{P_{\max}}{2\tau_{\max} b} \tag{4}$$

Where,

τ_{max} = the maximum bond strength (N/mm^2)
l_e = the effective bond length (mm)
$\Delta\varepsilon_f$ = difference strain at a steepest area
E_f = tensile modulus of CFRP strand sheet (MPa)
A_f = area of CFRP strand sheet (mm^2)
s_g = interval of strain at steepest area (mm)
b = average width of CFRP strand sheet (mm)

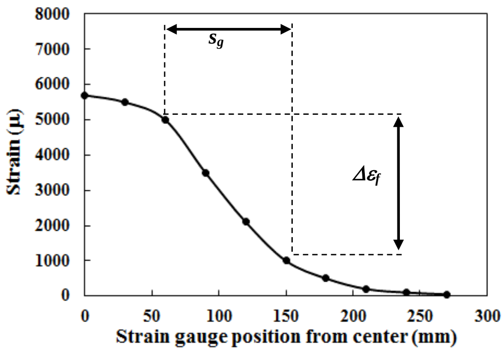


Fig. 5 Determine point in the strain distribution for effective bond length analysis.

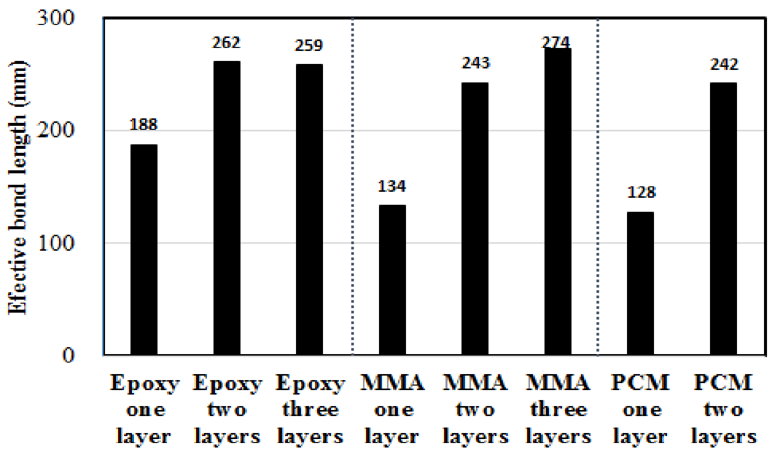


Fig. 6 Effective bond length (mm).

The average results of effective bond length are shown in **Fig. 6**. It can be seen that effective bond length increases significantly on the two layers specimen (from 40% up to 90%) compared with one layer specimen. Whereas, for three-layers specimen does not have a significant increase or a decrease compared with two layers specimen.

3.5 Local bond stress– slip relationship

Based on the failure model of bonding test defined previously, it confirms that the role of the bond stress-slip relationship is very important. The previous study [7] stated that during bonding process adhesive infiltrated into the rough surface of the concrete. The interface shear strength was mainly provided by the interlocking between the adhesive and the concrete surface irregularities. As a result, local bond stress occurs at the interface area and local slip. The increase of bond stress with slip until it reaches the peak stress τ_{max}, which the value of the slip s_{max}. Then, the debonding failure starts with reducing the shear stress and increasing interfacial slip, the bond stress reduces to zero when the slip exceeds and signifying failure of a local element.

To plot the bond-slip curve, the average bond stress τ of section between two strain gauges was calculated by dividing the difference of tensile by surface of bond area as shown in equation (5). The average slip s_i was calculated as the incremental sum of the CFRP extension in equation (6). In equation (6), the concrete elongation was ignored since the concrete block was much stiffer than the CFRP strand sheet.

$$\tau = \frac{E_f\left(\varepsilon_{f,i+1} - \varepsilon_{f,i}\right)t_f}{\Delta L} \tag{5}$$

$$s_i = \frac{\left(\varepsilon_{f,i+1} + \varepsilon_{f,i}\right)}{2}\Delta L + s_{i-1} \tag{6}$$

Where,

τ = average bond strength (MPa)
s_i = slip of section *i*
$\varepsilon_{f,i}$ = average of CFRP strand sheet strains in section *i*
E_f = tensile modulus of CFRP strand sheet (MPa)
t_f = thickness of CFRP strand sheet
Δl = distance between strain gauges (30mm)

After calculating all data, local bond stress versus slip was plotted in a graph for each interval of strain gauge on each specimen. Popovich's equation [1), 5), 7), 11)] was utilized to represent the local bond stress and slip relationship, shown as follows.

$$\frac{\tau}{\tau_{\max}} = \frac{s}{s_{\max}} \frac{n}{(n-1)+\left(s/s_{\max}\right)^n} \tag{7}$$

Where,

τ_{max} = maximum local bond stress (MPa)
s_{max} = slip at τ_{max}
n = constant

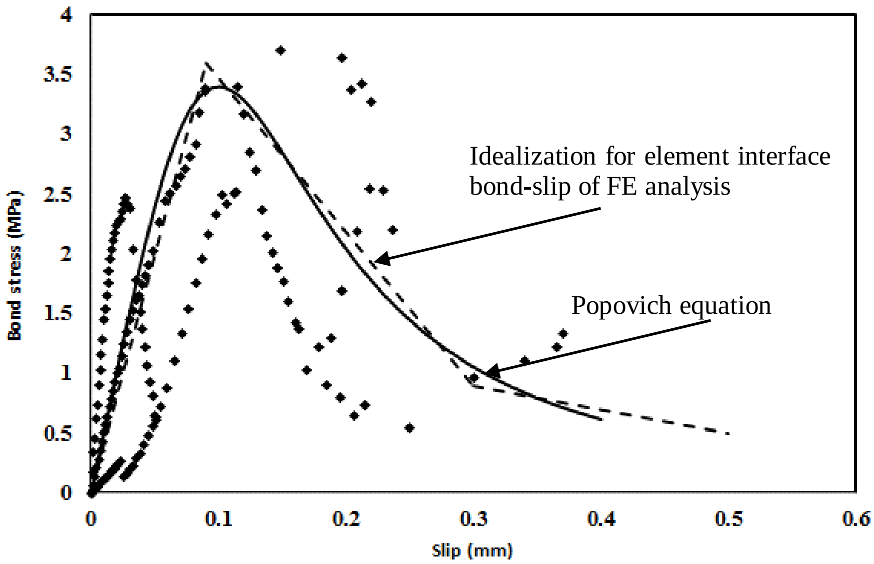


Fig. 7 Fitted bond stress-slip relationship by Popovics equation for specimen Epoxy two layers of CFRP strand sheet.

Table 5 Fitting results by Popovich equation.

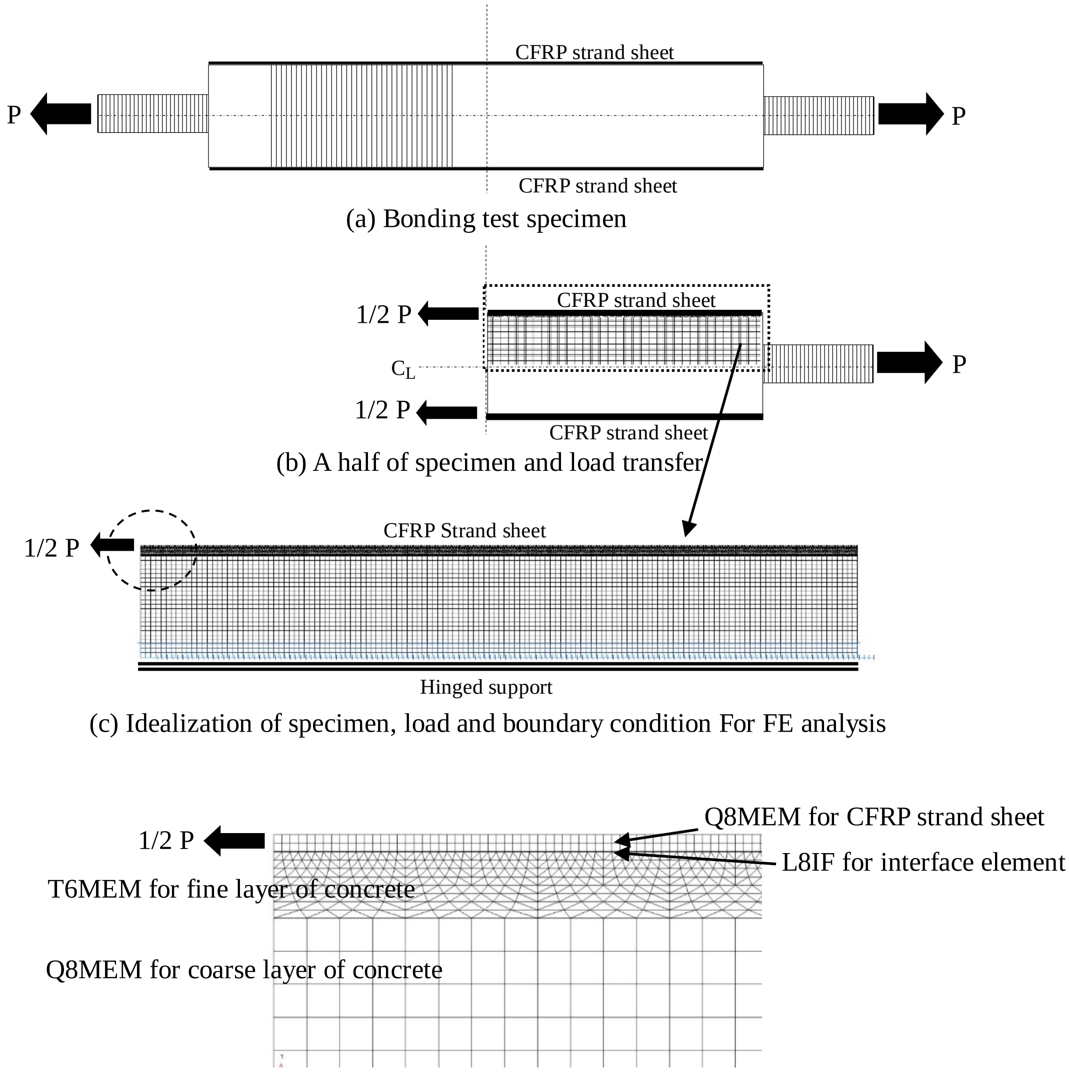
Numb. of layers	Adhe Sive	Max. bond stress approx. τ_{max} (MPa)	Slip at max bond stress approx. s_{max} (mm)	Value of n
1	Epoxy	3.00	0.050	2.0
2		3.40	0.100	3.0
3		3.50	0.100	4.5
1	MMA	1.80	0.350	4.0
2		2.50	0.100	4.0
3		3.00	0.070	3.0
1	PCM	2.50	0.100	3.0
2		2.50	0.100	2.0

Figure 7 shows example of fitting result of Epoxy specimen with two layers of CFRP strand sheet by Popovich equation for 0-30mm, 30-60mm and 60-90mm interval of strain gauge. This ignore other results of strain gauge interval because of data consistency. τ_{max} and s_{max} are approximate value from experimental after bond-slip relationship was plotted. **Table 5** captures a fitting results from each types of adhesive and layer. The largest maximum local bond stress τ_{max} is 3.50 MPa for Epoxy adhesive with three layers and the constant value for all specimen n is approximately 3.

4. Comparison of test and analytical results

4.1 Finite element idealization

A typical finite mesh and boundary were successfully used to model the bond between CFRP and concrete in previous research. For numerical analysis, this paper will adopted a typical finite element used in previous research [7)]. This simulation was done by using two-dimensional FE analysis DIANA (version 9.4.3). The process of idealization of specimen, load, boundary conditions and typical finite element mesh are shown in **Fig. 8**.



(a) Bonding test specimen

(b) A half of specimen and load transfer

(c) Idealization of specimen, load and boundary condition For FE analysis

(d) Meshing element

Fig. 8 Idealization and typical finite element mesh.

The concrete prism was idealized half of the laboratory specimen with the assumption that the load of FE analysis is half of the actual load in the laboratory. The concrete block was modeled using two models of mesh. A fine layer and a coarse layer with element size were approximately 4mm and 46mm, respectively. The element size of CFRP strand sheet layer were 0.333mm for one layer, 0.666mm for two layers and 0.999mm for three layers. The concrete and the CFRP strand sheet were assumed to be isotropic with thicknesses of two-dimensional material are 100 mm and 50mm, respectively.

The CFRP strand sheet was connected to the top of the concrete via an interface element replaced adhesive behavior. The interface was assumed with a thick of 0.05mm. For overall interfaces, including PCM as surface at specimen with PCM as adhesive, used bond–slip relationship that obtained from the experiment after fitted by Popovics equation and simplified to be multi-linear for each adhesives (**Fig. 7)**. This treatment differs from previous research [7)] that considers the connection between CFRP-concrete is a linear elastic.

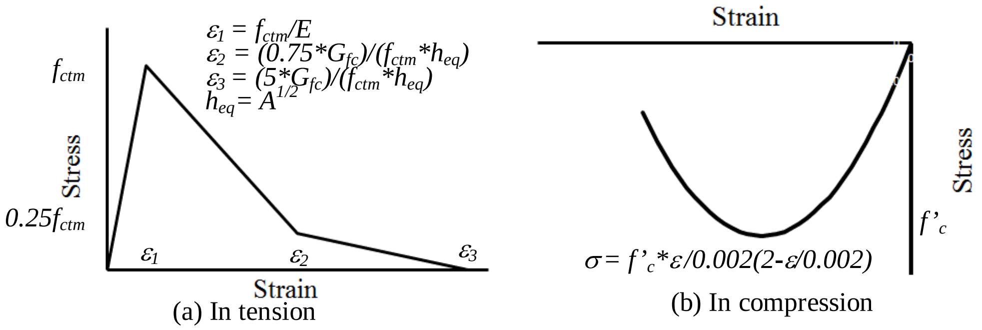


Fig. 9 Constituve law of concrete.

The CFRP strand sheet and the concrete in the coarse layer were modelled using Q8MEM four-nodes quadrilateral linear plane stress element with each element has eight degrees of freedom with two displacement u_x and u_y at each node [12]. The concrete in the fine layer has been modelled using T6MEM three-nodes quadrilateral linear plane stress element, each elements has six degrees of freedom with two displacement u_x and u_y at each node [12]. For the interface was using L8IF. The L8IF is a four nodes line interface element between two lines in a two-dimensional configuration, the local *xy* axes for the displacements are evaluated in the first node with *x* from node1 to node 2 [12].

Concrete was idealized using total strain rotating crack model. In tension, this model used a non-linier tension softening stress-strain relationship proposed by Hordijk [13] as shown in **Fig. 9(a)**. This relationship is using expression provided by CEB-FIP Model Code [14], where G_{fc} is the fracture energy or energy required to spread a tensile crack of unit area and *h* is the crack bandwith that related to area of element. The G_{fc} was computed to be 0.0833N/m. The tensile strength of concrete has been determined to be 4.23MPa. In compression, the concrete model applied model which was described by the function proposed by Thorenfeldt, et. all [15] as shown in **Fig. 9(b)**. Moreover, CFRP strand sheet was modelled with linear elastic properties.

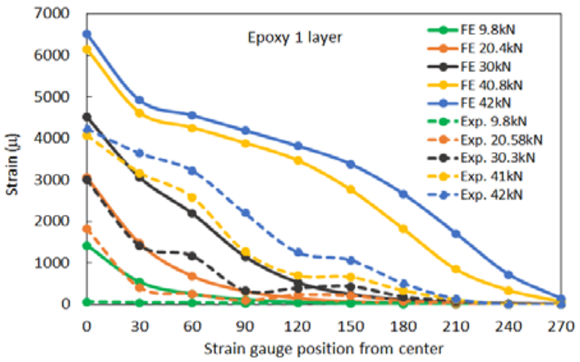
4.2 Verification of FE model with experimental test

(a) Strain distribution

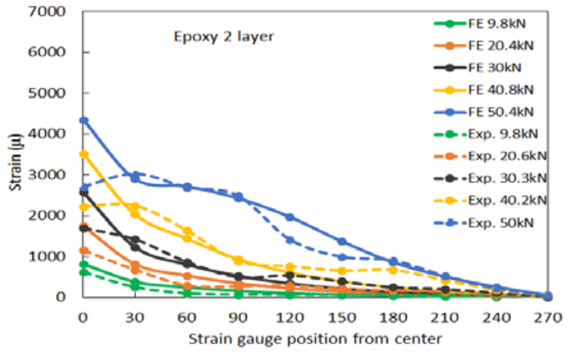
Figure 10 describes strain distribution of FE analysis and experiment results for all types adhesive and number of layer. The data of strain distribution were taken for several load condition of about 10kN, 20kN, 30kN, 40kN and 50kN or any maximum load. It can be seen that at the same load level the strain of FE is generally larger than experiment result, although there are some parts that show the experiment are greater. There are some specimens have a good agreement between FE and experiment results. However, some of them do not show a good correspondent as shown at Epoxy 1 layer and MMA 1 layer. In addition, at early stage of loading, the strain distribution of experiment does not appear so sensitive, differs with the results of FE analysis. It seems bond slip model must be corrected to get a good agreement.

(b) Maximum load

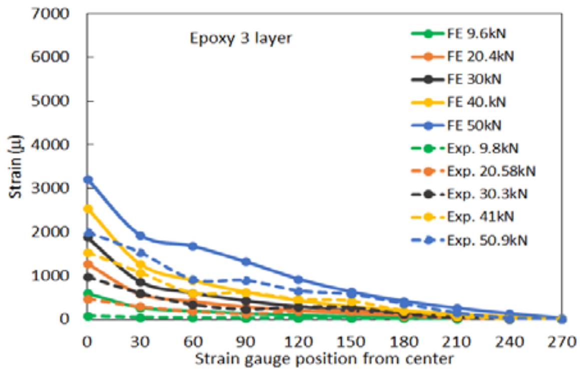
The maximum load which was calculated by the finite element analysis and experimental results for all specimens are compared in **Fig. 11**. Load results which were obtained from the FE analysis were multiplied by two and compared with experimental results. It can be seen that the maximum load trends can be captured well by the FE models. The differences from the experimental results range from 0,4% to 16,2%. **Fig. 11** also shows that the maximum load related with area of the CFRP strand sheet, it applies the results of FE analysis as well as experiment.



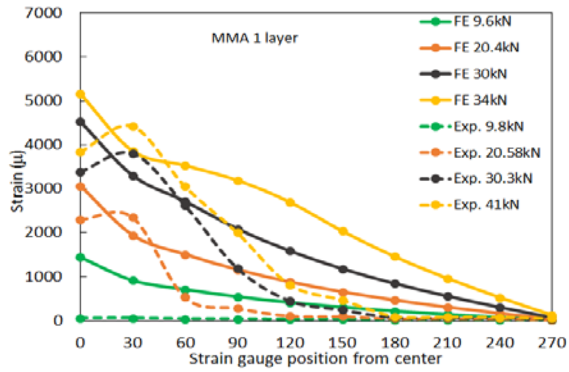
(a) Epoxy 1 layer



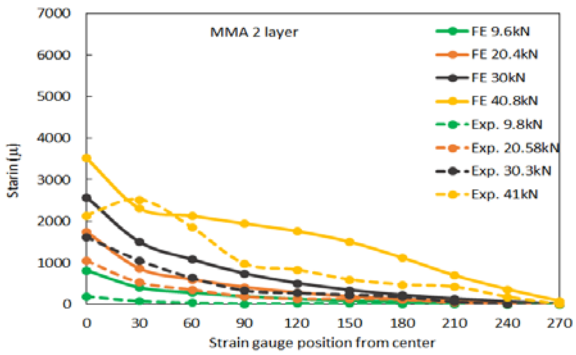
(b) Epoxy 2 layers



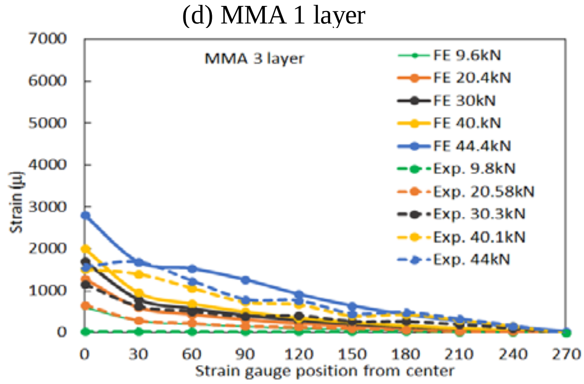
(c) Epoxy 3 layers



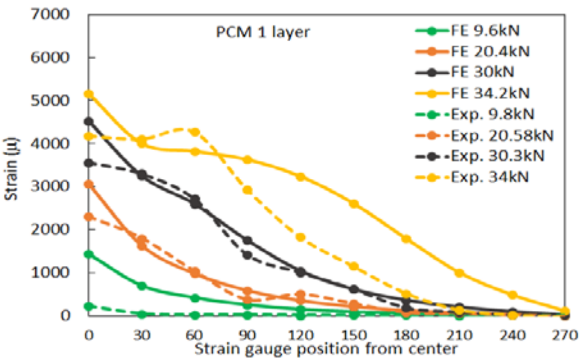
(d) MMA 1 layer



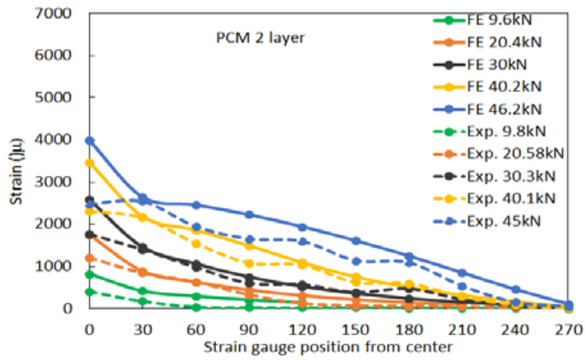
(e) MMA 2 layers



(f) MMA 3 layers



(g) PCM 1 layer



(h) PCM 2 layer

Fig. 10 CFRP strand sheet strain distribution of FE analysis and experimental results.

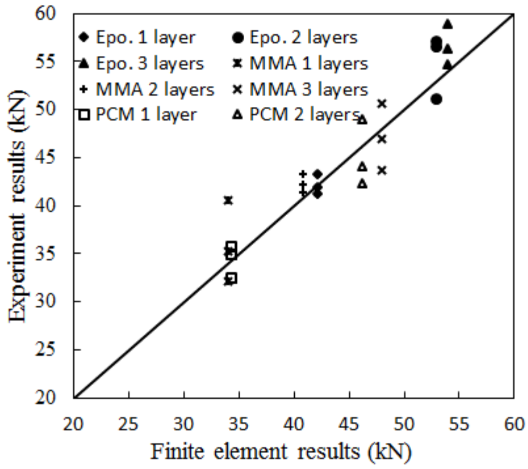


Fig. 11 Comparison of the maximum load by FE model and experimental results

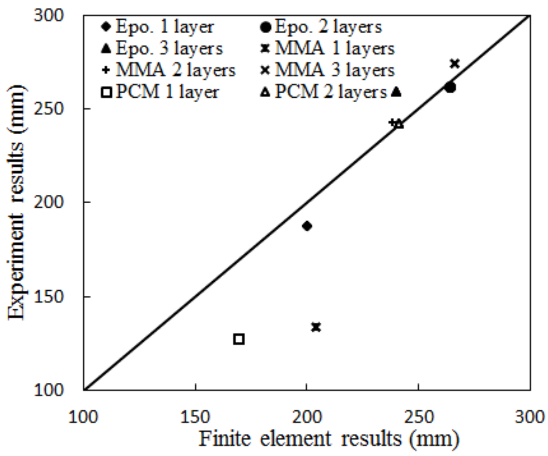


Fig. 12 Comparison of the effective bond length by FE model and experimental results

(c) Effective bond length

With using strain distribution data, determining of the effective bond length results of FE model were done in same manner with experimental test. **Figure 12** captures comparison of FE analysis and experimental results. Generally, they have a good correspondence and have value of comparison below 10% from experimental results. Although, on the specimen MMA 1 and PCM 1 have differences of 52% and 32%, respectively. These differences are due to the strain distribution of FE model and experimental test when the maximum load was reached.

5. Conclusion

This paper provided results from the CFRP strand sheet and concrete bonding properties. Based on the experimental and FE analysis results and discussion, the following conclusions can be drawn up;

1. From the results of bonding test, it can be seen that Epoxy had better performance, for the maximum load (P_{max}), fracture energy (G_f) and bond strength (τ_u), among the types of adhesive that used in this experiment.
2. Typical failure of bonding test was the interfacial failure occurred on only one side of the prism. It can happen due to the specimen were supposed to be under pure tensile force, but it was not possible to avoid the moment caused by eccentricity of load in the loading machine
3. The type of adhesive did not significantly affect the amount of CFRP strand sheet strain that occurred.
4. The local bond-slip curve varied significantly. It was depended on type of adhesive and number of layer and after fitting results by Popovich equation, in which the value of constant *n* was around 3 for all specimen, and the largest of bond stress τ_{max} was 3.50 MPa for Epoxy adhesive with three layers
5. It can be seen the non-linier finite element analysis was able to capture the maximum load and the effective bond length. Although, it is necessary a modification of bond-slip model to get a good agreement with the strain distribution from experimental results.

Acknowledgements

This work was supported by JSPS KAKEN; Grant-in-Aid for Scientific Research (A) Number 24246080 during 2012 to 2014.

References

1) K. Nakaba, T. Kanakubo, et al.; Bond Behavior between Fiber-Reinforced Polymer Laminates and Concrete, ACI Structural Journal, Vol. 98 No3, pp. 1-9 (2001).
2) H. Yuan, J. G. Teng, et. All; Full Range Behavior of FRP to Concrete Bonded Joints, Engineering Structures, 26, pp 553-65 (2004).
3) X. Z. Lu, L. P. Ye, et al; Meso-Scale Finite Element Model for FRP Sheets/Plates Bonded to Concrete, Engineering Structures, 27, pp 564-75 (2005).
4) X. A. Lu, J. G. Teng, et all.; Bond-Slip Models for FRP Sheets/Plates Bonded to concrete, Engineering Structures, 27, pp 920-37 (2005).
5) Z. G. Guo, S. Y. Cao, et. Al; Experimental Study on Bond Stress-Slip Behavior Between FRP Sheets and Concrete, Proc. International Symposium on Bond Behavior of FRP in Structures, Hongkong (December 2005) .
6) C. Pelegrino and C. Modena; Bond-Slip Relationships between FRP Sheets and Concrete, Proc. Fourth International Conference on FRP Composites in Civil Engineering (CICE 2008), Zurich Switzerland (July 2008).
7) H. B. Pham, R. Mahaidi, Modelling of CFRP-Concrete Shear-lap Tests, Construction and Building Material, 21, pp. 727-35 (2007).
8) R. Bahsuan, K. Yamaguchi and S. Hino; Bonding Properties of CFRP Strand Sheet and Concrete with Various Types of Adhesive, Proc. The 6th International Conference of Asian Concrete Federation, Seoul (September 2014).
9) Japan Society of Civil Engineering (JSCE); 'Standard specification for concrete and structure, test method and specification' (May 2007).
10) Mongi. B. O et all; 'Effective bond length pf FRP sheet externally bonded to concrete' International Journal of Concrete Structure and Material Vol.3 No. 2, pp 127 –31 (Dec, 2009).
11) T. Kanakubo, T. Furuta, H. Fukuyama; Bond Strength between Fiber Reinforced Polymer and Concrete. In: FRPRCS-6, Fibre Reinforced Polymer Reinforcement for Concrete Structures, Singapore (2003).
12) TNO DIANA, DIANA User’s Manual Version 9.4.3 1st edition, Delft, The Netherlands (November 2010).
13) D. A. Hordijk DA; Local Approach to Fatique Concrete, Delft University of Technology, (1991).
14) Comite Euro-International du Beton; CEB-FIB Model Code 1990, London, Great Britain, Thomas Telford (1991).
15) E. Thorenfeldt, A. Tomaszewics, and J. J. Jensen; Mechanical Properties of High-Strength Concreteand Application in Design, Porc. Symposium Utilization of High-Strength Concrete , Stavanger, Norway (1987).