-Technical Paper-

FLEXURAL STRENGTHENING EFFECT OF CFRP STRAND SHEETS AND PCM ON RC BEAMS

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ABSTRACT
This paper discusses the strengthening effect for RC beams with CFRP strand sheets and PCM as a bonding agent. Three kinds of RC beams—one non-retrofitted beam as a control beam and two retrofitting beams with one and two layers of CFRP strand sheet—have been tested. Both theoretical and numerical analysis model were made to confirm the results. The obtained results showed that the strengthened beams increased the maximum load capacity of RC beams.
Keywords: CFRP strand sheet, PCM, RC beam.

1. INTRODUCTION

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

To solve these problems, in recent years, the use of a carbon fiber reinforced polymer (CFRP) strand sheet for external strengthening has become a solution for strengthening/retrofitting reinforced concrete (RC) members. CFRP strand sheet, shown in Photo.1, has only one direction of strengthening; therefore, it is more compatible in use for beams.

In this strengthening method, the performance of the CFRP strand sheet to concrete interface in providing an effective stress transfer is of crucial importance [1]. This method can be done by attaching the CFRP strand sheet with adhesive to the surface of the concrete. The method of strengthening with a CFRP strand sheet has some advantages such as excellent corrosion resistance, thinness, low weight, easier and faster in workmanship, and adjustable application processing method of concrete. Besides those, it can be used without impregnating adhesive material into the concrete and has low possibility of air bubble occurrence in the interface area between CFRP strand sheet and concrete.

Studies related to CFRP strand sheet has not been widely reported. From similar study, it is known that the behavior of RC beam reinforced beams which are strengthened are influenced by several parameters. The parameters have been studied by Godat et al. [2], who conducted research on the effect of size for the CFRP strip strengthened RC beams in shear capacity. The effect of shear reinforcement models and techniques have been studied by Zhang et al. [3]. In addition, a more complete behavior between the FRP and the concrete has been discussed by the Yuan et al. [1] between the experimental results with a theoretical analysis.

To investigate the behavior and all parameters of the strengthened beams, a finite-element analysis can be used. However, experimental results are required to validate the numerical predictions [2]. Most of the previous studies using numerical prediction showed that having not assumed perfect bonding between FRP and concrete generally produces erroneous predictions on the maximum load capacity and stress levels (Al-Mahaidi et al. [4], Santhakumar et al. [5], Elyasin et al. [6]). Generally, many studies have found that the model for the interfacial behavior between the FRP and the concrete is not able to accurately predict debonding.

Although the strength and stiffness of the CFRP are very good, the bonding behavior of CFRP to concrete is dependent on the behavior of the adhesive that is used as a bonding agent. In this study, polymer cement mortar (PCM) is used as a bonding agent. This investigation presents a complete overview both of experimental program in the laboratory, simple theoretical analysis, and corresponding numerical analysis for the bending effect of strengthened RC beams with CFRP strand sheets and PCM.

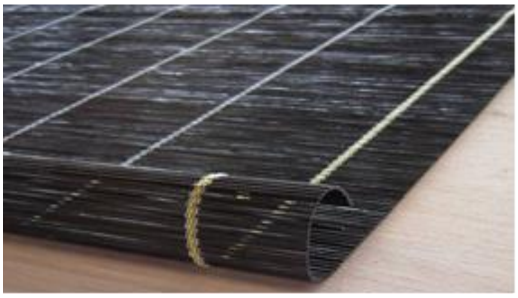

Photo.1 CFRP strand sheet

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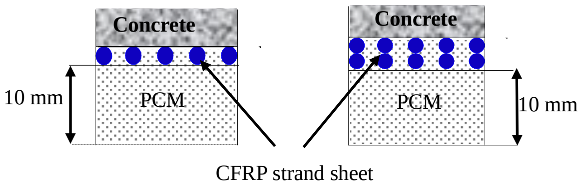


a. One layer (P1) b. Two layers (P2)

Fig.1 Cross section of strengthening RC Beam

Photo.2 Attaching process of CFRP strand sheet and covering by PCM

PCM is used for wet surfaces. It can be applied for waterways or tunnel structures. PCM consists of polymer, cement, and sands. The image of this strengthening method can be viewed in the cross section of the RC beam in Fig.1a for one layer of CFRP strand sheet and Fig.1b for two layers of CFRP strand sheet. Stages of implementation are as follows: a mixture of PCM and water is sprinkled thinly on the surface of the concrete beam. Next, CFRP strand sheet is attached on the paste of PCM. Then impregnation is done in order for PCM to be evenly distributed, followed by the subsequent layer. As a final step, the CFRP strand sheet is covered with PCM paste until designed thickness (10mm). This part of the process can be seen in Photo.2.

2. EXPERIMENTAL PROGRAM

2.1 Material properties

Table 1 summarizes the mechanical properties of the PCM and concrete. The properties of the PCM and the CFRP strand sheet were obtained from the manufacturer. Table 2 shows the properties of CFRP strand sheet. This research used high tensile strength CFRP strand sheet.

Table 3 presents mechanical properties of rebar. Deformed bars of 19mm in diameter were used as tension reinforcement, 10mm in diameter were used as compression reinforcement, and stirrups as shear reinforcement have a diameter of 13mm.

2.2 RC Beams test specimens

Three RC beams comprising one non retrofitted beam (specimen N) as control beam and two retrofitted beams with one layer (specimen P1) and two layers (specimen P2) of CFRP strand sheet have been tested in this study.

Detail of the experimental program can be seen in Fig.2. Detail A in Fig.2 explains the position of the CFRP strand sheet for the two-layer specimen. To avoid stress concentration at the end, the CFRP strand sheet was shortened by 25mm for the next layer.

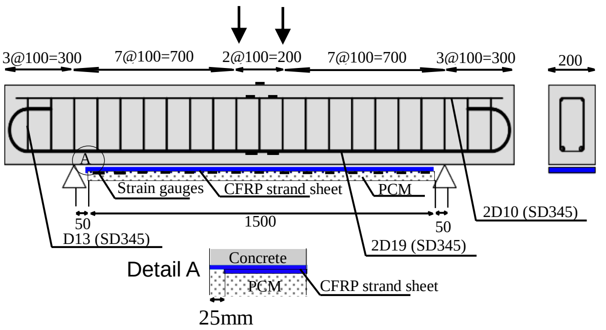


Fig.2 RC Beams specimen detail

All the beams are four-point loading beams that have a span of 2.2m with two small rollers as supports that have a span of 1.6m. The load was applied by a hydraulic jack and measured by a load cell. Deflection control was used in all the tests and deflection measurements were taken at the mid span of the beam. The strain gauges were located 100mm on each CFRP strand sheet, four on the steel reinforcement (two for tension rebar and two for compression rebar), and one on the top of the concrete in the mid span.

3. ANALYTICAL PROGRAM

3.1 Finite element analysis

Numerical analysis in this paper was done by using a two-dimensional FE analysis using DIANA (version 9.4.3) [7]. The CFRP strand sheet was modeled by using truss element L2TRU from DIANA's Element Library [7]. L2TRU is a two-node directly integrated (1-point) truss element which may be used in one-, two-, and three-dimensional modeling with basic variable for displacement, u_x.

CFRP strand sheet was considered as a full elastic material in compression and brittle material in tension. The CFRP strand sheet areas are 66.66mm^2 for one layer and 133.33mm^2 for two layers.

Table 1 Mechanical properties of PCM and concrete (MPa)

Material Properties	PCM	Concrete
Compressive modulus	4,800	33,800
Compressive strength	11.3	49.8
Tensile strength	2.40	4.23
Flexural strength	6.50	-

Table 2 CFRP strand sheet mechanical properties

Tensile modulus (MPa)	245,000
Tensile strength (MPa)	3,400
Unit weight (g/m^2)	600
Design thickness (mm)	0.333

Table 3 Mechanical properties of rebar (MPa)

Material Properties	Rebar		
	Dia.10 mm	Dia.13 mm	Dia.19 mm
Modulus of elasticity		200,000	
Tensile strength	548	551	559
Yield strength	376	395	407

The concrete and the PCM were modeled by applying a four-node quadrilateral linear plane stress element (Q8MEM). Each element has eight degrees of freedom with two displacements (u_x and u_y) at each node [7]. Concrete and PCM were applied to a rotating crack model with a thickness of 200mm.

A non-linear tension softening proposed by Hordijk [8] as shown in Fig.3(a) was applied to the stress–strain relationship of concrete and PCM in tension area. This relationship uses the expression provided by CEB-FIP Model Code 90 [9]. The area under stress and strain curve is given by G_{fc}/h, where G_{fc} is the fracture energy or energy required to spread a tensile crack of unit area and h is the crack bandwidth related to the area of the concrete element. Based on CEB-FIP Model Code 90, the fracture energy was computed to be 0.083N/mm for concrete and 0.029N/mm for PCM. Fig.3(b) shows the behavior of concrete and PCM in the compression area. The behavior was applied by the model proposed by Thorenfeldt, et al. [10].

The idealization of reinforcement used bar elements. All the reinforcement materials were applied in terms of the yield condition of Von Misses as an ideal plasticity material.

For the interface of concrete and PCM, the element was modeled using L8IF. L8IF is a model of interface element that has a four-node based on linear interpolation between two lines in a two-dimensional configuration [7]. The interface layer was assumed to be 0.5 mm in thickness with a total perimeter of 320 mm for one layer and 640 mm for two layers of CFRP strand sheet. The bond stress–slip relationship derived by Popovic's equation, which have done in previous study by Bahsuan, et al [11] (Table 4), was applied for the interface material. The Popovic's equation is given as:

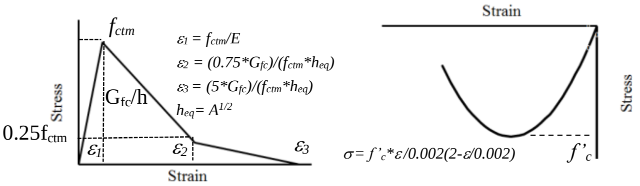
$$\frac{\tau}{\tau_{max}} = \frac{s}{s_{max}} \frac{n}{(n-1)+(s/s_{max})^n} \quad (1)$$

Where,

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

3.2 Theoretical analysis

Theoretical analysis was performed in a simple way by utilizing the principle that the cross-section of the beam remains flat before and after loading. This principle was produced by strain distribution linearly in the cross-section. Then, the strain value can be used to determine the stress that occurs on every material in the cross-section of RC beams.



a. Tension area b. Compression area

Fig.3 Constitutive law of concrete

Table 4 Data from previous study [11]

Specimen	Popovic's equation τ_{max} (MPa)	s_{max} (mm)	n	G_f (N/mm)
N	-		-	-
P1	2.5	0.167	3.00	0.73
P2	2.5	0.100	2.00	0.63

For the strengthened beams (specimens P1 and P2), to obtain a complete picture of the results requires some data that have collected previously. In a previous study [11], an analysis of the bonding properties between concrete and CFRP strand sheet with various types of adhesive have been done. The important result that need to be adopted in this paper is the interfacial fracture energy (Table 4) that will be used in theoretical analysis. The interfacial fracture data is obtained from calculation of CFRP strand sheet stress when the maximum load is achieved. The stress of CFRP strand sheet can be calculated by adopting the equation for a continuous fiber sheet and by generating interfacial fracture energy equation [12], as follows:

$$\sigma_f = \sqrt{\frac{2G_f E_f}{n_f t_f}} \quad (2)$$

Where,

σ_f = Stress of CFRP strand sheet when maximum load is achieved (N/mm^2)
G_f = Interfacial fracture energy of CFRP and concrete (N/mm)
E_f = Tensile modulus of CFRP strand sheet (N/mm^2)
n_f = Number of layer CFRP strand sheet
t_f = Thickness of CFRP strand sheet (mm)

Furthermore, loading phases will be observed and be analyzed only into three stages; the first crack on concrete, the first yield on tension rebar, and the maximum load, respectively.

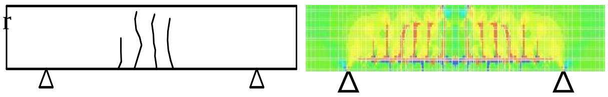
4. RESULTS AND DISCUSSION

4.1 Crack patterns

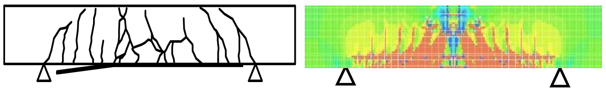
From Fig.4(a), Fig.4(b), Fig.4(c), and Photo.3(a), Photo.3(b), and Photo.3(c), it appears that the failure modes in all the strengthened beams with CFRP strand sheet are the result of debonding at the interface of concrete beams and CFRP strand sheet. This means that the tensile strength of CFRP strand sheet has not been achieved; therefore, behavior between the concrete surface and the CFRP strand sheet are very influential to produce the maximum load.

Table 5 Experimental load results

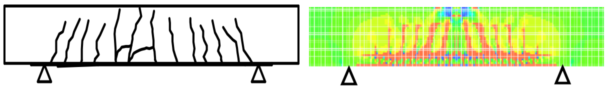
Specimen	P_{Crack} (kN)	P_{Yield} (kN)	$P_{Ultimite}$ (kN)
N	39.8	131	165
P1	40.1	171	223
P2	35.1	191	201



(a) Specimen N



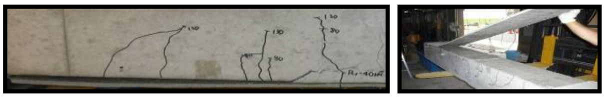
(b) Specimen P1



(c) Specimen P2

Fig.4 Crack pattern of experiment and FE

(a) Specimen N



(b) Specimen P1

(c) Specimen P2

Photo. 3 Crack pattern and failure mode of specimen

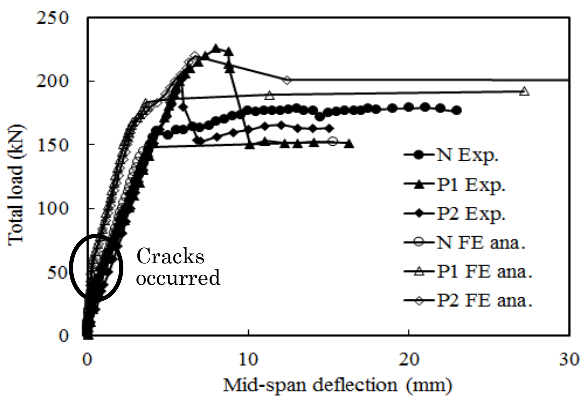


Fig.5 Total load–mid-span deflection of experimental beams and FE analysis

4.2 Experimental load results

The experimental result for each loading stage are given in Table 5. The results show an increase for almost all stages of loading. When in the crack state, the crack load is almost the same; the exception is for P2. It is possible that initial crack has occurred prior to loading on the specimen P2.

At the yield loading stage, strengthened beams with CFRP strand sheet and PCM have an increase in capacity of yield load compared to the normal beam. These show an increase of 30% and 46% in the yield load capacity for specimen P1 and P2, respectively, over the normal beam (specimen N). It means that CFRP strand sheet and PCM, as a bonding agent, could delay the reinforcing steel to experience yield.

For maximum load, an increase in capacity is observed to be 35% and 22% of normal beam for P1 and P2, respectively. It could be noted that although an increase in maximum load but the use of one layer of CFRP strand sheet is more effective than two layers. This is different from assumption that increasing the number of layers will increase the capacity of beam. This is because in the two-layer specimen (specimen P2), the interface layer between CFRP strand sheets are not too effective to resist shear stress and so reduces the capability of existing composite mechanisms.

4.3 Load and displacement

Fig.5 shows the relationship between total load and mid-span deflection of experimental and FE analysis results. For experimental results, in general, it may be noted that a load increase occurs for the specimen given CFRP strand sheet strengthening compared with specimen N. After the maximum load is achieved, load will be closer to the yield load on the specimen N. It means that the specimens show ductile behavior up to failure, so it may be able to absorb the energy well and can avoid the collapse that occurs suddenly.

In FE analysis, specimens P1 and P2 have slightly greater stiffness than experimental ones; however, the FE analysis results for specimen P1 cannot reach the experimental results.

4.4 Load and strain of CFRP strand sheet

Load and strain of CFRP strand sheet is shown in Fig.6. It can be seen that the first crack occurred in the surface of beam at about 45–60kN. An exception in specimen P2 is also confirmed in that the initial crack happened in specimen P2. The ultimate strain that can be reached is around 2000–3500μ, meaning that CFRP strand sheet's ultimate strain (about 13500μ) can never be reached. So, although the PCM, as a bonding agent, can improve the capacity of the RC beam, it is not able to maximize the strength of the CFRP strand sheet.

4.5 Comparison with finite element analysis and theoretical results

Fig.7, Fig.8, and Fig.9 show a comparison of the experimental results and prediction results, which based on FE and theoretical analysis for each stage of loading, respectively.

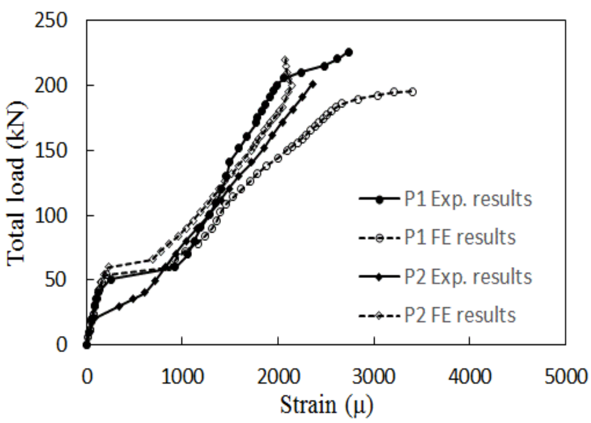


Fig.6 Total load vs strain of CFRP strand sheet

When cracking first occurred, the load ratio of experimental/theoretical (P_{ex}/P_{the}) range from 0.95 to 1.25, while the ratio of experimental/FE (P_{ex}/P_{FE}) range from 1.04 to 1.53. Meanwhile, when the yield occurred, the load ratio of P_{ex}/P_{the} are from 1.04 to 1.11 and from 1.02 to 1.09 for the P_{ex}/P_{FE} ratio. For maximum load, the load ratio of P_{ex}/P_{the} are 0.92 to 1.09 and 0.87 to 1.09 for P_{ex}/P_{FE} ratio. At the maximum load state, the deviation from experimental results ranged from $\pm$10% given the fact that the predictions are reasonably accurate with results for P2 smaller than predictions.

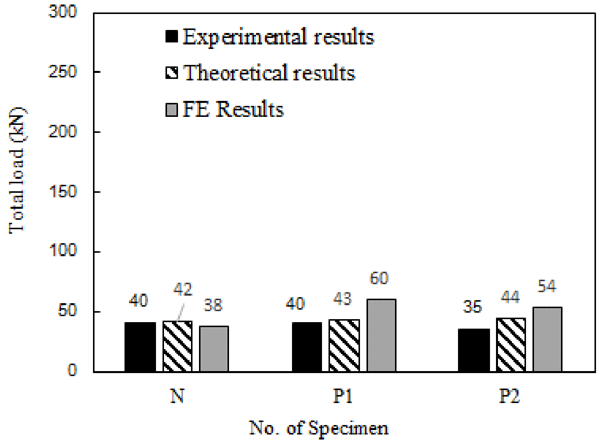


Fig.7 Comparison of load at first crack state

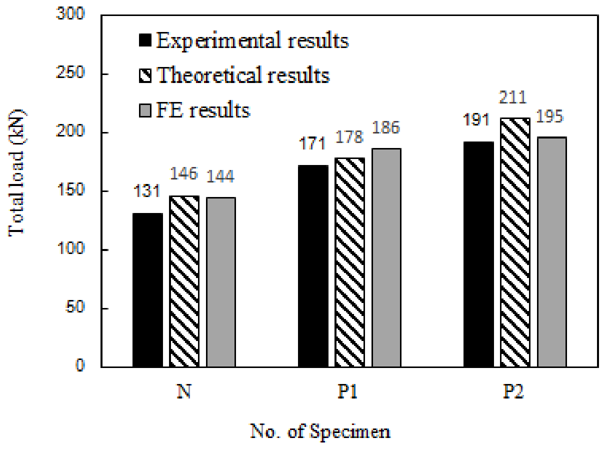


Fig.8 Comparison of load at yield state

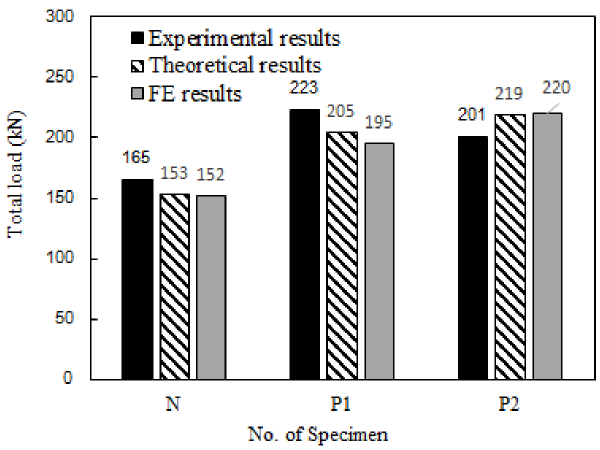


Fig.9 Comparison of load at maximum load state

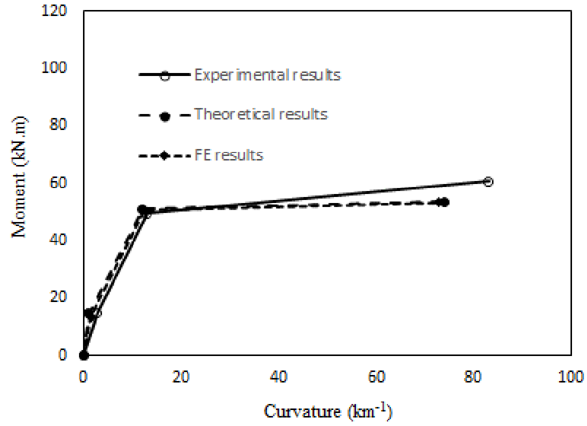


Fig.10 External moment vs curvature for specimen N

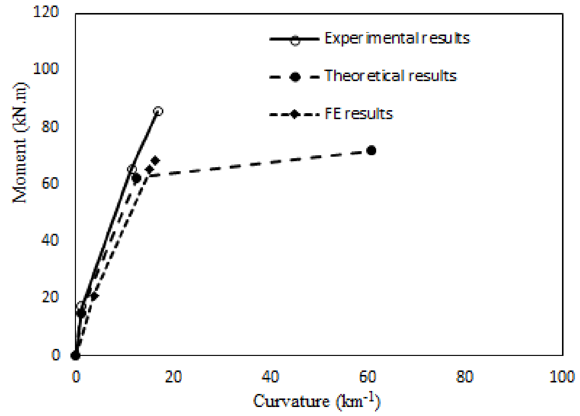


Fig.11 External moment vs curvature for specimen P1

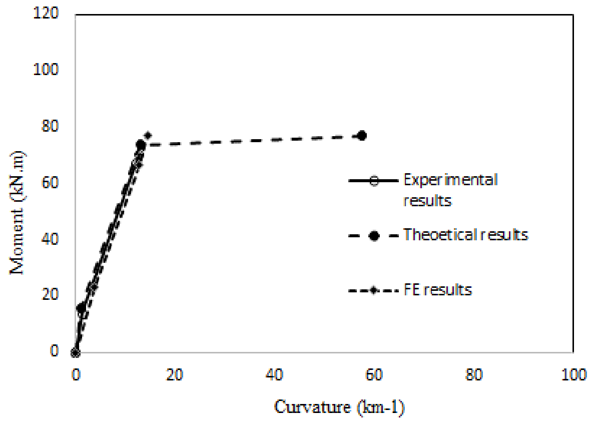


Fig.12 External moment vs curvature for specimen P2

4.6 Beam curvature

Results of strain gauge from experimental results, strain data from finite-element results and strain at each of the stage loads in theoretical method will be used to determine the beam curvature. The data that are used are a strain gauge at mid-span that is located on the top of beam and tensile reinforcement. To determine compression depth, *c*, linear interpolation from existing strain is done. For more detail, a relation between external moment and beam curvature can be seen in Fig.10, Fig.11, and Fig.12.

In Fig.10, specimen N shows a good relationship between external moment and curvature. On the other hand, specimens P1 and P2 (Fig.11 and Fig.12) indicate that the relationships have a good agreement up to the yield load. The results show that on the strengthened beams, application of the principle that the cross-section of the beam still remains flat before and after loading is not appropriate for maximum load of strengthened beams. The principle also does not consider the model of bond slip between CFRP and concrete.

5. CONCLUSION

The following conclusion are summarized from this study:

(1) Strengthening with CFRP strand sheet and PCM can improve the capacity of RC beam
(2) After maximum load is achieved, the load of strengthened RC beams (specimens P1 and P2) will be closer to yield point on the beam normal.
(3) The deviation of prediction results (theoretical and FE results) are $\pm$ 10% from experimental, at the maximum load.
(4) For strengthened RC beams, the relationship between external moment and curvature has a good agreement until yield point is achieved.
(5) The ultimate strain of CFRP strand sheet that can be reach is around 2000–3500μ.
(6) For strengthened RC beams, the failure mode that occurs is debonding at the interface of concrete beams and CFRP strand sheet.

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