Fracture Mechanics of Concrete and Concrete Structures -
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Strength of RC beams enhanced by CFS with variable bond conditions

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ABSTRACT: In this paper, the damages for strengthened structure with FRP sheet are investigated and the simple analytical prediction is performed. Eight beam specimens are made and retrofitted by FRP sheet corresponding to the experimental objective. Main variables in the design of specimen are the area ratio and pattern of de-bonded part of sheet. One point loading is applied to the centre of specimen which is simply supported. In addition, evaluations are performed for both previous formulas and nonlinear sectional analysis method to find the applicability in predicting the behaviour of RC member strengthened by FRP sheet with partial bond loss. Variation of bond loss of up to 20% didn't significantly affect the strength of RC beams. The flexural behaviour of RC beams retrofitted by CFS with partial bond loss can be suitably simulated by using previous formula or nonlinear sectional analysis if the bond condition is well defined.

1 INTRODUCTION

1.1 *Background*

Strengthening using Carbon Fiber (CF) materials is one of the most useful methods in the retrofit of Reinforced Concrete (RC) members. This is because it makes more easy construction on comparing other techniques in the retrofit of member. Therefore, many RC structures have been rehabilitated by using this method.

However, the deterioration of structural capacity occurs due to the bond loss between RC member and CF materials. The bond loss caused by various factors such as environmental condition, bonding states of those, load states, etc. It leads low strength, premature cracks in concrete and excessive deflection so that the structural capacity may be decreased lower than required.

Kaiser (2002) used a fracture mechanics approach to examine the effect of de-bonded regions on the performance of wet layup FRP systems. He showed that the size of surface voids, in particular, has an adverse effect on the interface bond. Puliyadi (2001), on the other hand, reported that disbond of up to 152 mm in diameter had no significant impact on the performance of FRP systems, except for the localized increase of the interface bond stress. Ahmet, S. K. (2009) studied about the effect of disbond due to the hole and crack through experimental and nonlinear finite element analysis. As a result, he reported that leaving surface disbonds untreated does not have significant impact on the overall structural performance.

Above previous studies focused on the effect of disbonds of FRP to the behavior of RC beam with artificial damages such as hole or slit in order to simulate cracks. Using previous research results, therefore it is harder to find the clear effect of bond loss of CFS since the pre-cracks will affect the behavior.

1.2 *Objective and method*

In this paper, therefore, the behavior of member with only bond loss in attaching the Carbon Fiber Sheet (CFS) to concrete most widely applied to structure is studied. Experimental evaluation is carried out to verify the variation of structural behavior corresponding to the bond loss ratio and type. In addition, the evaluation is performed for both previous formulas and nonlinear sectional analysis method to find the applicability in predicting the behaviour of RC member strengthened by FRP sheet with partial bond loss.

2 STRUCTURAL BEHAVIOR OF RC MEMBER STRENGTHENED BY CFS

As shown in Figure 1, the failure pattern of RC member strengthened by CFS is classified by Teng (2002) from the analysis of previous test results; (a) fracture of CFS, (b) compressive failure of concrete, (c) shear failure of concrete, (d) peeling of cover concrete, (e) peeling of CFS, (f) flexural cracks due to bond failure, (g) shear cracks due to bond failure.

When CFS is perfectly attached to the member, the retrofitted member will show sufficient structural capacity compatible to the design load. The capacity, however, may be less than the required if imperfect attachment exists between CFS and the member as shown in Figure 2.

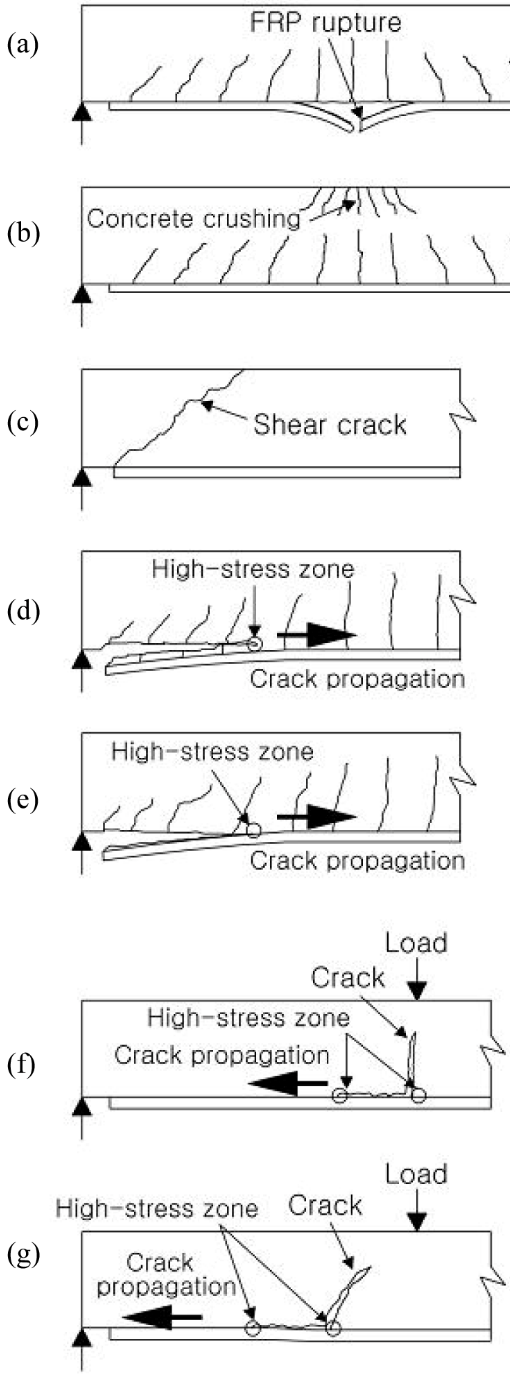


Figure 1. Failure mode of RC beam strengthened by CFS.

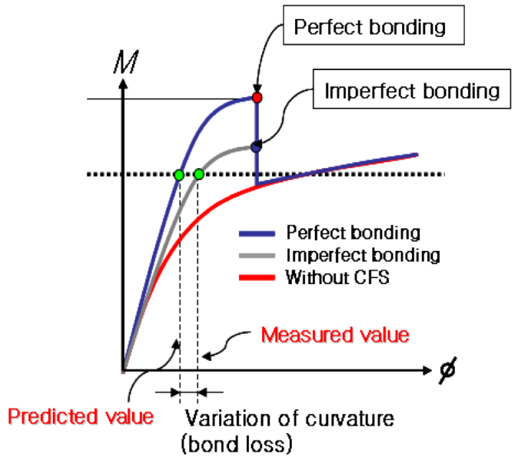


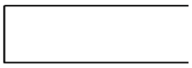
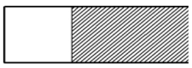
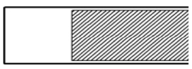
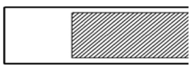
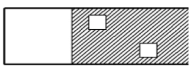
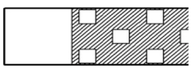
Figure 2. Moment-curvature curves of RC beam imperfectly strengthened by CFS.

The part to which CFS is imperfectly bonded may always exist in site and increase as time goes on after retrofit. Also it may be made just after the retrofit due to construction mistake. In order to keep in safe of the structure about these problems, first, it is needed to find whether there is an imperfect bond between CFS and member and second, how much effective to structural capacity it is.

3 TEST PLAN

As mentioned above, the bond ratio and type of CFS are main test parameter. Table 1 and Figure 3 show the list and layout of specimen, respectively. Total five specimens are planned; specimen CB without retrofit, specimen C100 with perfect bond, specimen C90 and C80 with imperfect bond at edge, specimen R90 and R80 with randomly imperfect bond. All specimens except CB are retrofitted by one lay CFS whose attachment length is 1600mm at center.

Table 1. List of test specimen.

Specimen	Bonding type	Width of CFS (mm)	Bonding ratio (%)	Bonding area (m^2)
CB		-	-	-
C100		200	100	0.320
C90		180	100	0.288
C80		160	100	0.256
R90		200	90	0.288
R80		200	80	0.256

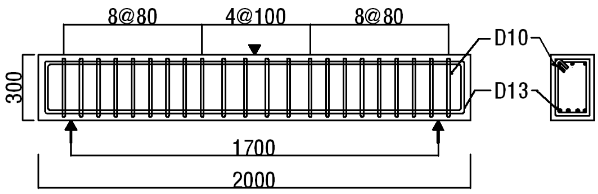


Figure 3. Detail of test specimen.

Each beam has a cross section of 200mm×300mm and a length of 2000mm. D13 and D10 are used as main reinforcement and stirrup, respectively. The amount of compression reinforcement in the section is decided to prevent the compressive failure even when the bottom, tension stress region is strengthened by CFS. More stirrups than require is intentionally arranged to protect the shear failure in the end side of the beam. The average 28-day compressive strength of concrete was 37MPa.

Table 2 shows the mechanical properties of reinforcing bars, concrete and CFS used in this study. The tensile and bond strength of epoxy used for adhesion of CFS are 41.6MPa, 17.5MPa, respectively.

Table 2. Mechanical properties of materials.

Reinforcement			Concrete	CFS
Bar Size	Yield strength (MPa)	Tensile strength (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
HD13	516	625	37	4103
HD10	345	423		

Monotonically increasing load is applied to the center of the specimen simply supported as shown in Figure 4. To obtain an accurate deflection value, five Linear Variable Differential Transducers (LVDTs) are mounted on the bottom surface of the beam. Strain gauges are placed on the bottom and top surface of beam and on the tension bar.

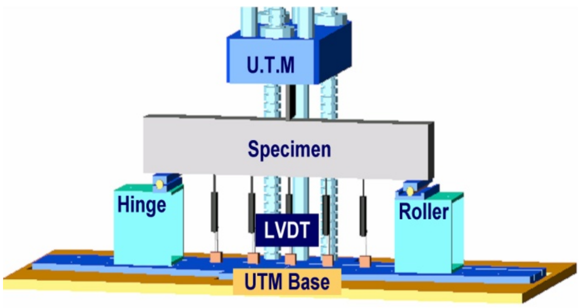


Figure 4. Test set up.

4 TEST RESULT

4.1 *Crack pattern*

The final crack patterns developed in the specimens are shown in Figure 5. In the member retrofitted by CFS, generally, the stress acting on reinforcements is distributed to CFS which is attached to the member for retrofit so that the flexural strength as well as initial stiffness is increased. After reaching the maximum load, CFS or cover concrete is separated from the member. At that time, the failure pattern will be similar to that of the member not retrofitted.

The specimens in this paper showed typical flexural failure pattern; as load increase, flexural cracks occurred at the bottom of mid-span showing elastic behavior up to yield point and reached to maximum strength after yielding of bottom reinforcement. Beyond the peak point, load suddenly dropped at the same time when CFS came apart from the bottom. Finally specimens failed showing rupture of bottom reinforcements.

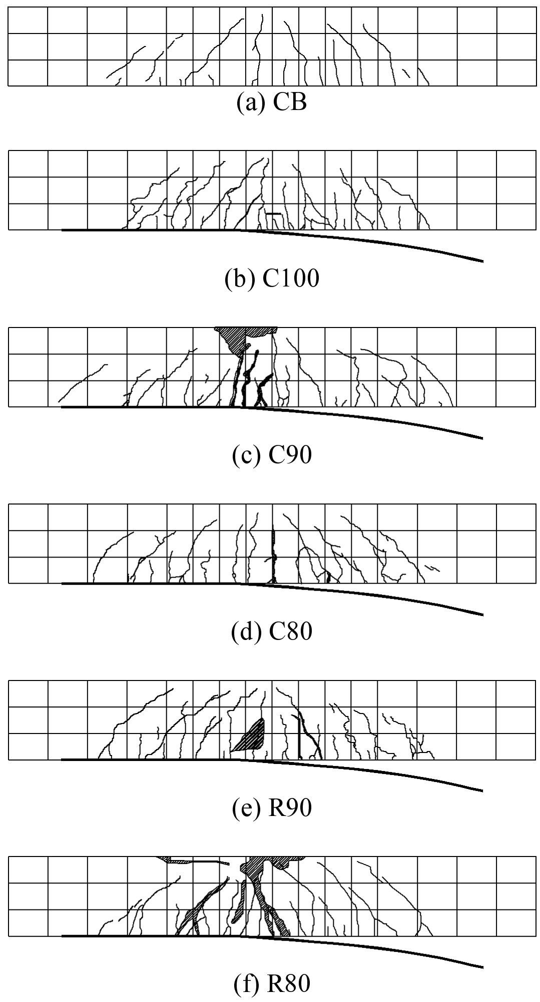


Figure 5. Final crack patterns.

4.2 *Load-displacement curve*

The load-displacement relation of specimens is presented in Figure 6. In the figure, rectangular mark means the point that initial crack occurs while circle mark means the point that bottom reinforcement yields. Until initial point, all specimen's load-displacement relation is similar each other. However, beyond initial crack point, the specimens enhanced by CFS showed higher stiffness than specimen CB without retrofit.

In Table 2, the result is summarized. The comparison between specimens with different bond ratio presents that there is few difference of strength but slight difference of displacement at maximum load. The specimen with low bond ratio has less value of displacement at maximum load. Similar pattern was found in the specimens with partially de-bonded CFS .

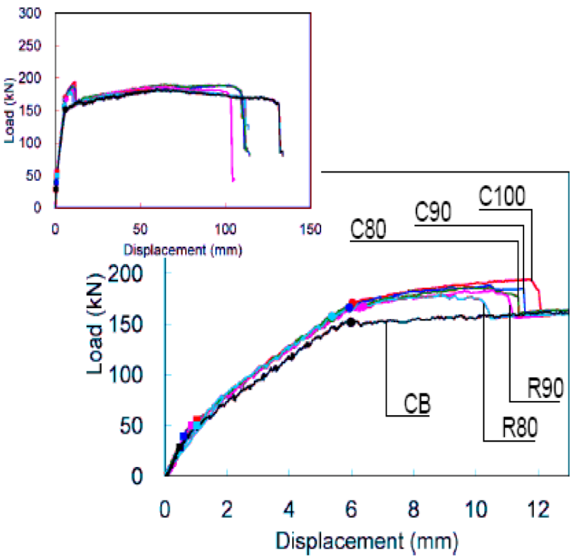


Figure 6. Load-displacement curve.

At the ultimate point, the variation of strength ratio of the specimens with de-bonded CFS for the specimen without de-bonding (C100) is ranged from 0.97 to 0.92. Also, the displacement ratio at that time is ranged from 0.97 to 0.86.

4.3 *Load-strain curve*

The strain of bottom tensile reinforcements, CFS and upper concrete was measured during the test and is presented in Figure 7 as a graph. From the figure, it can be seen that the strain of CFS exceeds that of the bottom reinforcements even though the debonded ratio of CFS reaches to 20%. Similar result was found in the specimens randomly de-bonded. This means that the retrofit capacity can be acquired even if the CFS is not perfectly attached to RC member when the de-bonded ratio of CFS is less than 20%.

4.4 *Strength evaluation by previous formulas*

The strength of specimens is calculated by using previous formulas as shown in Equation 1 and Equation 2, which are presented by Shin (1998) and ACI (2002), respectively. The former Equation showed reliable relation with test data in previous study done by Seo (2008) and Yi (2001).

$$M_n = T_s(d-k) + T_{cfs}(h-k) \tag{1}$$

$$\varepsilon_c = \frac{c}{h-c}\varepsilon_{cfs}$$

$$\varepsilon_s{}' = \frac{c-d'}{h-c}\varepsilon_{cfs}$$

$$\varepsilon_s = \frac{d-c}{h-c}\varepsilon_{cfs}$$

$\varepsilon_s < 0.002$

$$C_c = \frac{c^2\varepsilon_{cfs}}{(h-c)0.002}0.85f_c{}'\frac{b}{2}$$

$\varepsilon_s > 0.002$

$$C_c = 0.85f_c'b\left(1+\frac{0.001}{\varepsilon_{cfs}}\right)c - 0.85f_c'001\frac{b}{\varepsilon_{cfs}}h$$

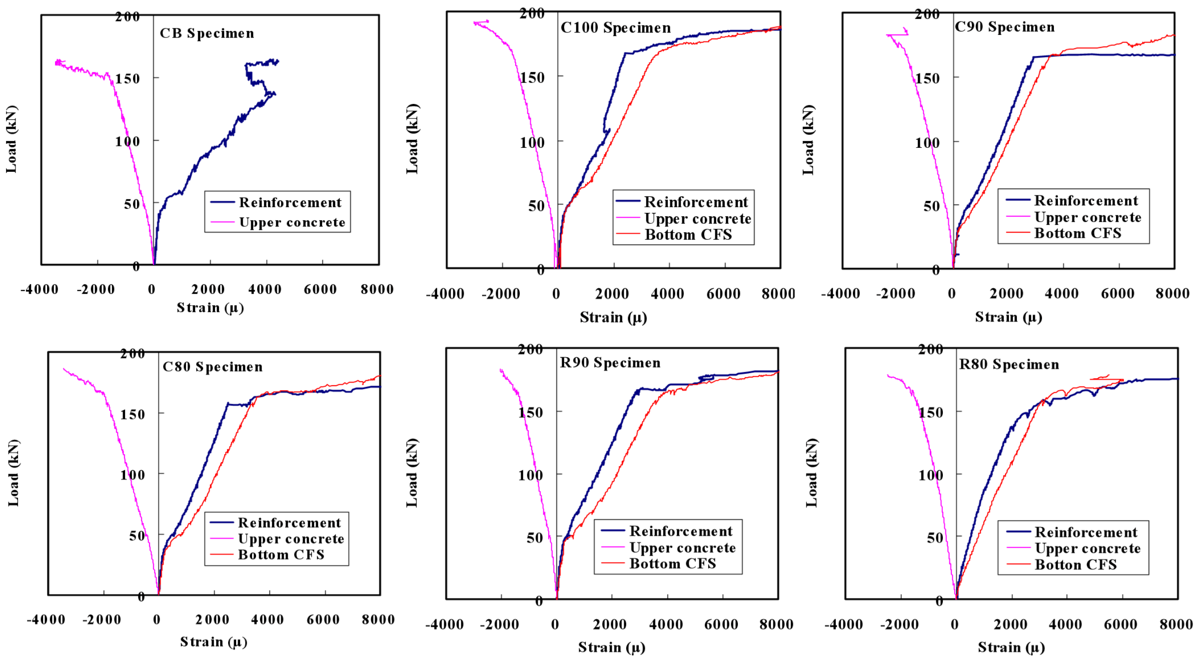


Figure 7. Load-strain curves.

$$C_s = \frac{c-d'}{h-c}\varepsilon_{cfs}E_sA_s' \quad (2)$$
$$T_s = \varepsilon_s E_s A_s$$
$$T_{cfs} = \varepsilon_{cfs}E_{cfs}A_{cfs}$$
$$M_n = A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + \varphi A_{cfs} f_{cfs}(h - \frac{\beta_1}{2})$$

where, k is distance between Cc and Cs, ε_{cfs} is fracture strain of CFS, d is effective depth, d' is distance from compressive extreme fiber to top reinforcement, h is height of member, c is distance from compressive extreme fiber to center, A_{cfs} and f_{cfs} are area and tensile strength of CFS, respectively, A_s and f_s are area and yield strength of tension reinforcement, respectively.

Table 3 in which the calculated result is summarized with test one, shows that the results by Equation 1 have a good correlation with test one while the results by Equation 2 are a little bit higher than test one.

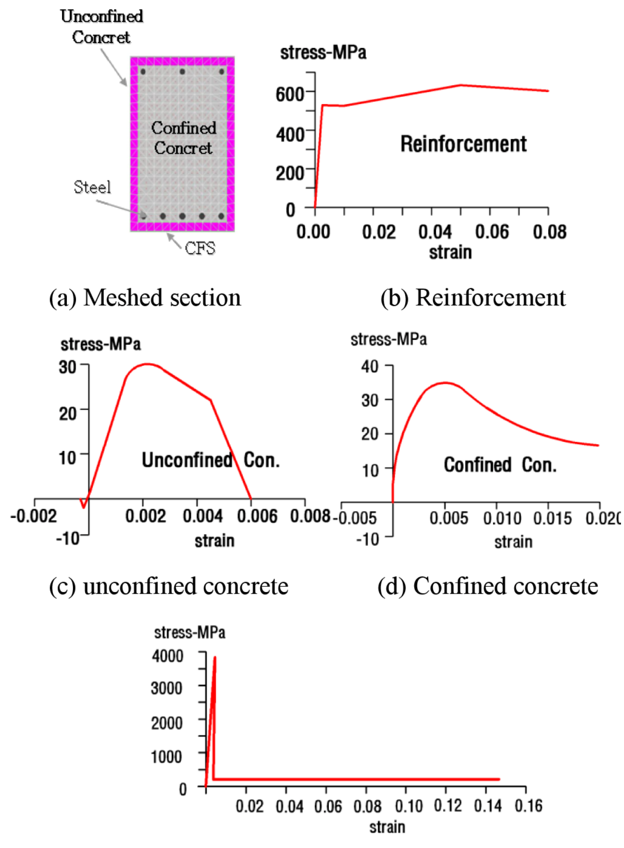
In Equation 2, the strain value of CFS at bond failure should be based on material properties such as epoxy and CFS. In previous study, Equation 2 tended to underestimate the strength of RC flexural member strengthened by CFS. However, in the case that CFS is partially de-bonded such as this study, Equation 2 overestimates the strength of the member. This phenomenon was observed in Equation 1 also. This overestimation may be because of that the material property was somewhat overestimated in the calculation; the value of the material property used in the calculation was given not from a test result but by manufacture.

Therefore, in doing an evaluation of structural capacity of already retrofitted members by CFS, it is necessary to consider the reduction factor of property of bonding material unless suitable test result is prepared.

5 NONLINEAR SECTIONAL ANALYSIS

5.1 *Analysis process*

Nonlinear sectional analysis by using XTRACT program (2004) is performed to simulate the behavior of retrofitted beams with bond loss of CFS. In the program, the section can be divided into finite elements possessing their own material property. Figure 8 presents material models. CFS attached to concrete surface is idealized to have linear elastic stiffness up to maximum strength and drastic drop beyond that as shown in Figure 8(e).



(a) Meshed section (b) Reinforcement

(c) unconfined concrete (d) Confined concrete

(e) CFS with epoxy

Figure 8. Mashed section and material models.

Table 3. Predicted and observed ultimate strength.

Specimen		Test result: Yield strength (kN)	Ultimate strength (kN)	Displacement at ultimate strength (mm)	Ratio of test result: Ratio of ultimate strength ③④⑤⑥/②	Ratio of ultimate strength ⑤/③ ⑥/④	Ratio of displacement ③④⑤⑥/②	Ratio of displacement ⑤/③ ⑥/④	Calculation result: Shin's equation Result (kN)	Shin's equation Test/Cal.	ACI code Result (kN)	ACI code Test/Cal.	Analysis result: Yield strength (kN) Result (kN)	Yield strength Test/Anal.	Ultimate strength (kN) Result (kN)	Ultimate strength Test/Anal.
①	CB	150	184	15.32	-	-	-	-	170	1.08	177	1.04	132	1.14	179	1.03
②	C100	170	194	11.84	-	-	-	-	184	1.05	197	0.98	156	1.09	194	1.00
③	C90	166	188	11.54	0.97	-	0.97	-	184	1.02	195	0.96	153	1.08	190	0.99
④	C80	156	186	11.36	0.96	-	0.96	-	183	1.01	193	0.96	150	1.04	186	1.00
⑤	R90	167	183	11.03	0.94	0.97	0.93	0.96	184	0.99	195	0.94	-	-	-	-
⑥	R80	157	179	10.20	0.92	0.96	0.86	0.90	183	0.98	193	0.93	-	-	-	-

The effect of bond loss is considered in the analysis by reducing the area of CFS with respect to the bond loss.

5.2 *Analysis result*

Moment-curvature relation of analysis results is presented in Figure 9. The strength variation due to the bond loss of CFS was suitably expressed in the analysis. The moment-curvature relation was converted to load-displacement one for the comparison of test results and described in Figure 10. The yield and ultimate strength value from both test and analysis are presented in Table 3. As shown in Table, there is a good relation between those.

From this, the strength of flexural member retrofitted by CFS with partially bond loss can be predicted through simple sectional analysis if correct information about the bond condition of CFS is given.

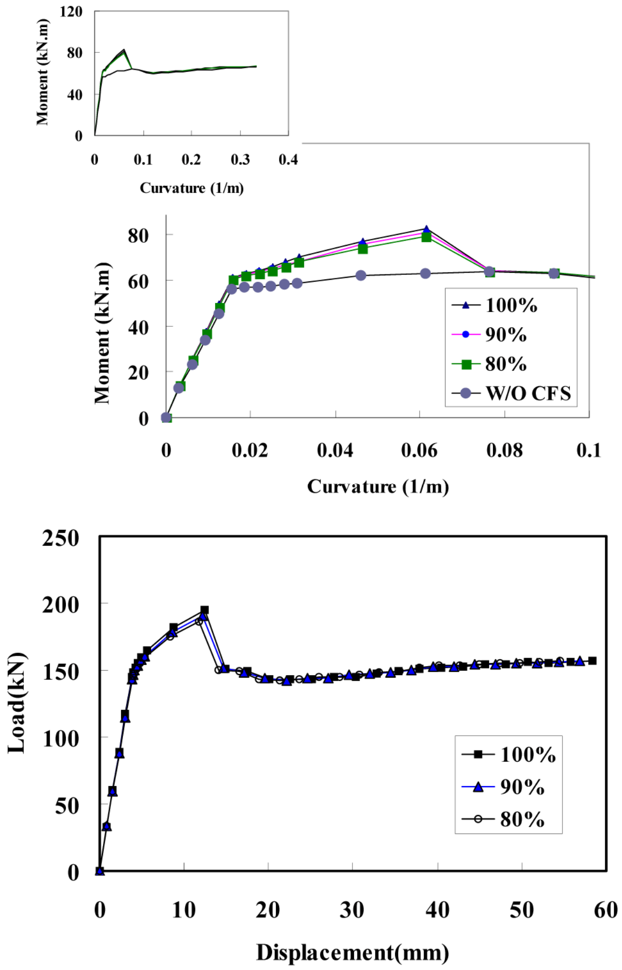


Figure 9. Load-displacement curve from analysis.

6 CONCLUSION

1) Variation of bond loss of up to 20% didn't significantly affect the strength of RC beams.
2) However slight decrement of displacement at peak load was found at low bonding ratio. This means that premature failure may be developed when the bond is weakened.
3) Strength and displacement at peak load vary with respect to the de-bonding type even if the bonding ratio is same.
4) The calculated strength by previous formula for beam with imperfect bond of CFS was found to be compatible with test one. From this, it may be concluded that the strength of beam can be suitably predicted by considering the bond loss.
5) Simple nonlinear sectional analysis method also is acceptable to be used in predicting the behavior of beam strengthened by CFS if the bond condition is well defined

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