Flexural Characteristics of the Overlayed RC Beam Strengthened with Rebars, CFRP, and Steel Plate.

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Abstract

An analytical method based on the nonlinear layered finite element method is used to simulate the load-deflection behavior of strengthened beam. Beams considered in this study are the ones strengthened either with external steel plate or Carbon Fiber Reinforced Plastic (CFRP) sheets bonded to the overlay soffit or with reinforcing rebars in the overlay. The theoretically obtained load-deflections and strains of the strengthened beam are compared to the corresponding experimental values. Comparing the approximate measures on the cumulative slips, efficiencies of the repairing techniques are evaluated. Parametric studies are, then, performed using the developed model to investigate the effects of design variables on the overal flexural behavior of the strengthened beam. Simply supported beams under monotonically increasing symmetrical loads are considered exclusively.

1. Introduction

The strengthening of reinforecd concrete members by externally bonded steel plates or CFRP sheets has also been used exclusively in recent years due to their cost-effetiveness and vesatility. External bonding of CFRP sheets becomes a viable alternative to bonding steel plates for strengthening concrete structures due to its high strength-to-weight ratio, lighweight, resistance to chemicals, good fatigue strength, non-magnetic, and non-conductive properties[1,2].

Both retrofitting methods of bonding steel plates and bonding CFRP externally offer several advantages: (1). inexpensive and rapid applicability in the field with little or no disturbance; (2) keeping the original configuration of the structure; and (3) maintaining the overhead clearance[3].

It is expected that, by combining overlay techniques and external bonding techniques, desirable structural performance may result in increased stiffness and strength of the strengthened beam. Recently, some experimental studies have been made to investigate the structural behavior of the beam overlayed with different repair materials - latex and premix - with different strengthening techniques-reinforcing rebars inside the overlay and external bonding to the soffit to the overlay either by steel plates or CFRP sheets[4].

This paper presents an anaytical model for predicting load-deformation relations, stresses, and strains of such a strengthened set of reinforced concrete beams. The model is used for evaluating the effectivenss of the strengthening methods and parametric study.

2. Previous Studies - Literature Review

In recent years, extensive experimental investigations and theoretical researches have been directed towards finding and understanding the factors that influence the structural performance of steel plated or CFRP laminated concrete beams[1-11]. In experiments, it was found that bonding of thin steel plates to the tension faces of concrete beams can lead to a significant improvement in structural performance, under both service and ultimate load conditions. However, premature failure may occur because of shear and normal stress concentrations at the ends of the steel plates, resulting in debonding or ripping off the concrete cover along the level of conventional internal reinforcement[9]. The structural performance of the externally bonded, steel plated reinforced concrete beams which were initially exposed to the natural elements for periods of 11 to 12 years were experimentally found to be very satisfactory with regard to their stiffness and failure loads[7].

In parallel to the experimental studies, theoretical studies are also performed mainly to (1). determining the moment at which flexural peeling starts and the moment at which the plate separates from the reinforced concrete beam subject to shear and flexure or their interactions [12,13], (2). predicting the shear and normal

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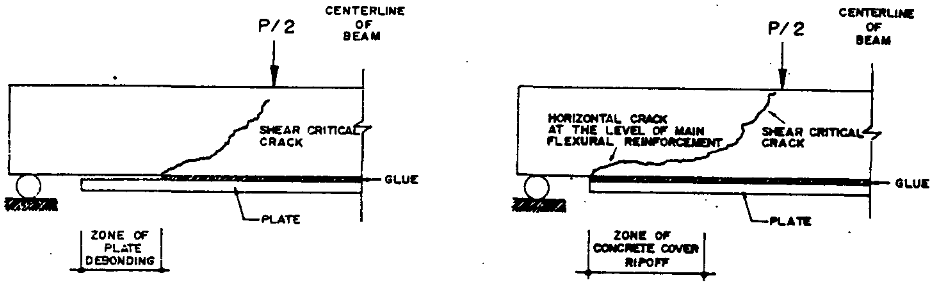
stress concentrations in the adhesive layer of plated reinforced concrete beams[9], (3). estimating the effects of existing and induced cracks and other main parameters like load locations and adhesive thckness based on fracture mechanics and finite element method[2], (4). simulating overall load-deflection behavior of the strengthened beam by compatibility of defomations and equilibrium of forces[4], and (5). suggesting the design guide lines for the externally bonded plates[10]. No study, however, to authors' best knowledge, has been made experimentally and theoretically to study the structural enhancement by the use of external bonding to the overlay.

3. Objective

The nonlinear layered fininte element has been developed in this study in order to investigate the effects of design variables on the flexural strength and ductility of the strengthened beam either with plate externally bonded to the overlay soffit or with reinforcing rebars embedded inside overlay. Using the developed model, efficiencies of the repairing techniques are evaluated based on the approximate measures on the cumulative slips. Some parametric studies are made as well to investigate effects of main design parameters.

4. Applicability of the Developed Model

Depending on the strengthening, externally plated beam may fail by extensive and progressive flexural concrete cracking or by sudden, brittle premature manner. The latter type of failure may result from thick plating, use of weak adhesive, and improper gluing[6](Fig.1).



(a) Failure by plate debonding (b) Failure by ripping off of the concrete cover

Fig. 1. Sudden Shear Faiures of Plated Beams[6]

For the externally bonded CFRP laminates, either debonding of the CFRP laminates or peeling of the CFRP sheet through shearing of the concrete layer between CFRP sheet and the steel reinforcement may occur. The former type of faiure can be avoided by reasonbly good quality control and the use of high-quality epoxy adhesives, while the latter type of failure by properly confining the two ends of the CFRP sheets through clamping through wrapping the beam's cross sections at the CFRP sheet ends with unidirectional composite elements, in the form of external rectangular ties[1].

The developed model in this study is applicable to the strengthened beam which has the sufficiently small area of the steel plate to ensure ductile flexural failure without brittle mode of shear failure. No separation of concrete layer between the plate and longitudinal steel rebars, and no debonding or peeling of the CFRP sheets through shearing of the concrete layer between the CFRP and the steel reinforcement are considered in the model. In previous experiments, the beams which were strengthened with CFRP sheets had their two ends confined by CFRP sheets to avoid aforementioned failure.

Based on the above discussion, the following assumptions are made in the analysis:

(1) the effect of area of the steel plate or CFRP sheet are negligible and, therefore, the ultimate force in the plate or sheets are sufficiently small so that shear failure of concrete layer bewteen the plate or sheets and longitudinal rebars will not occur ; and

(2) in consequence, plane section remains plane after deformation and strain compatibility is preserved.

5. Description of Nonlinear Layered Finite Element Method

5.1 Non-linear Layered Finite Element Method

In the layered finite element methods, strain compatiblitiy is assumed and each cross section of a member is divided in to N_l layers, some of which may represent the reinforcing bars or externally reinforced bonded plates or CFRP sheets. The column matrices of forces($\boldsymbol{F}$) and element displacements($\boldsymbol{d}$) are: $\boldsymbol{F} = (Ni,\ Vi,\ Mi,\ Nj,\ Vj,\ Mj)^T$and $\boldsymbol{d} = (ui, vi, \theta i, uj, vj, \theta j)^T$, where T denotes transpose of a corresponding vector, and subscripts i and j represent the adjacent cross sections at the ends of element, respectively. The meanings of nodal values in the componets of $\boldsymbol{F}$ and $\boldsymbol{d}$ are shown in Fig.

2. The internal forces as well as nodal displacements are based on the local member axes x and y.

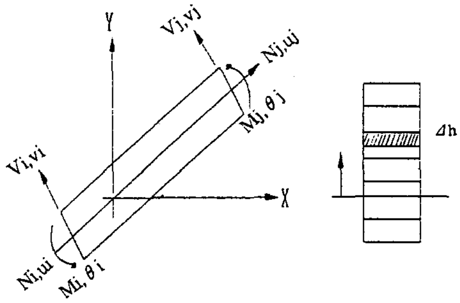


Fig. 2. Notations in the Layered Finite Element

The displacements in the axial direction are assumed to be linear while in the vertical direction with a cubic variation:

$$u(x,0) = (1-a)\cdot u_i + u_j$$

$$v(x,0) = (1-3a^2 + 2a^3)\cdot v_i + (3a^2 - 2a^3)\cdot v_j + L(a - 2a^2 + a^3)\cdot \theta_i + L(a^3 + a^2)\cdot \theta_j$$

where L = element length; and

$$a = \frac{x}{L};$$

Then based on the beam theory, at any point in a beam element,

$$u(x,y) = u(x,0) - y\cdot \frac{\partial v(x,0)}{\partial x} \text{ and}$$

$$\varepsilon(\mathrm{x},\mathrm{y}) = \frac{\partial \mathrm{u}(\mathrm{x},\mathrm{y})}{\partial \mathrm{x}}$$

$$= [\mathrm{B}]\ \mathbf{d}.$$

Application of these to the virtual work principle yields:

$$\delta d\cdot F = \int_V \delta\varepsilon^T \cdot \sigma\, dV$$

$$= \delta d^T \cdot \int_V [B]^T \cdot \sigma\, dV$$

Since the above relation must hold for arbitrary $\delta \mathbf{d}^{\mathrm{T}}$, we obtain:

$$F = \int_V [B]^T \cdot \sigma\, dV$$

$$= \int_V [B]^T \cdot E_s \cdot [B] \cdot dV \cdot d$$

$$= [K_e]_{6\times6} \cdot d_{6\times1}$$

where V, Es, and $[K_e]$ are element volume, secant modulus of elasticity, and element stiffness matix, respcectively.

In the layered finite element method, $[\mathrm{K_e}]$ are constructed by integrating analytically and summing its results over all layers.

$$[K_e] = \int_V [B]^T \cdot E_s \cdot [B]\ dV$$

$$= \sum_{i=1}^{ne} [B]^T \cdot E_s \cdot [B] \cdot b_i \cdot \Delta h_i \cdot L$$

where ne, b_i, and Δh_i stand for number of elements in an element, width of an i-th layer, and depth of the i-th layer, respectively.

In order to find solution, the direct interation method is used. The algorithm can be summarized as follows:

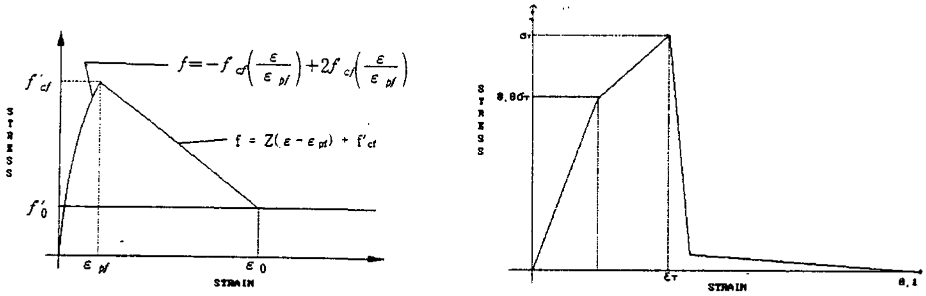
(1). Initiallize. Input necessary data on structural geoemtry and material properties.
(2). Given small prescribed displacement increments Δw of conrolled displacement w;
  (2.1) calculate new nodal displacements and corresponding strains at midpoints of all layers in all nodal cross sections;
  (2.2) update the secant modulus of elasticities in each layer;
  (2.3) find new nodal displacements and strains; and
  (2.4) repeat the above process until $\sum_{i=1}^{N} |u_{i,old} - u_{i,new}| <$ tolerance, where

  $u_{i,old}$, $u_{i,new}$, and N represent previous and new ith displacement components and number of total degrees of freedom of the model, respectively.
(3). Calculate load P as the reaction at the point of prescribed displacement, w.
(4). Calculate internal forces for each finite element and the strains and stresses of all layers.
(5). Return to step (2) and start for the next step, unless the last step has been reached.

Since the displacements are prescribed, the model can trace the descending portion of the load-deflection curve of the beam under loads.

5.2 Constitutive Models

Empirical constitutive models for the concrete and steel rebar and steel plate are given in Fig.3 and 4, respectively. Based on the experimental observations, the linear elastic behavior up to failure is assumed for CFRP under tension. Since overlay materials are subjected only to tensile stresses throughout the loading process, stress-strain curves identical in shape to the plain concrete in tension are used.



(a). Compressive Stress-Strain Model (b). Tensile Stress-Strain Model

Fig. 3. Constitutive Models for Concrete

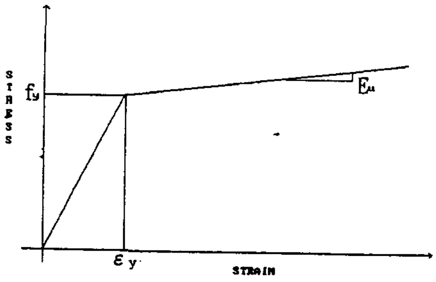


Fig. 4. Constitutive Models for Rebar and Steel Plate

6. Comparisons between Test Results and Theretical Predictions

6.1. Experimental Program

14 beams were tested. The reinforcement details and loading scheme are given in Fig. 5 and table 1 summarizes the values of different materials used in the experiments.

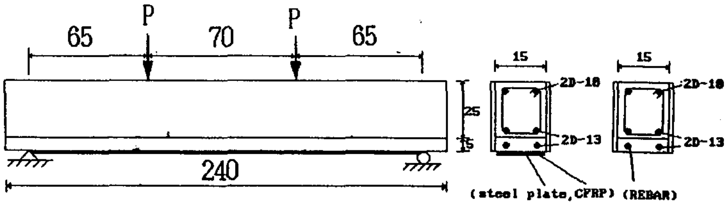


Fig. 5. Strengthening Details and Loading Scheme (unit : cm)

Table 1. Characteristic Values of Different Materials in the Test

materials	strength (kg/cm^2)		strain at peak (%)		Elastic Modulus(x10^5)
	compression	tension	compression	tension	
concrete	220	22	0.0021	0.0002	2.3
latex	286	29	0.011	0.0011	1.52
premix	383	33	0.0035	0.00035	2.01
rebar	-	2800 (yield)	-	0.0014	20.4
		3200(ultimate)		0.0016	
plate	-	2400 (yield)	-	0.0013	18.0
		2800(ultimate)		0.0014	
CFRP sheet	-	34000	-	0.015	23.5

Table 2 summarizes the details of the test beams. The detailed preparation of the test beams and test results describing load-deflection curves, crack patterns, failure modes and strains measured at rebars as well as strengthening materials can be found elsewhere[4].

Table 2. Details of the Test Beams

Strengthening Methods	Specimen Name	Depth of Overlay(cm)	Comments
Control	CON - S	-	-
Reinforcing Rebar inside Overlay	RE-L_CS	15X5X240	CF:CFRP RE:Rebar SP:Steel Plate L:Latex P:Premix CS:CFRP Wing CU:CFRP U-Jacket SS:Steel Strip SU:Steel Wing
	RE-P-CS		
	RE-L-CU		
	RE-P-CU		
	RE-L-SS		
	RE-P-SS		
Plate or CFRP sheet Bonded to Overlay Soffit	CF2-L-CS		
	CF2-P-CS		
	CF2-L-CU		
	CF2-P-CU		
	SP-L-SS		
	SP-P-SS		
Steel Plate Wing	RE-L-SU		
Total Number	14		

6.2 Comparisons between Experimental Results and Model Predictions

Figs.6 through 8 show the comparisons between the test results and the theoretical results predicted by the model based on nonlinear layered finite element method. Reasonably good aggrements are obtained. *In general, the model* predictions show higher stiffness in the prepeak region in the load-deflection curve, which seems to be deviated mainly from the approximate nature of the model in assuming the strain compatiblity between the different layers in a beam.

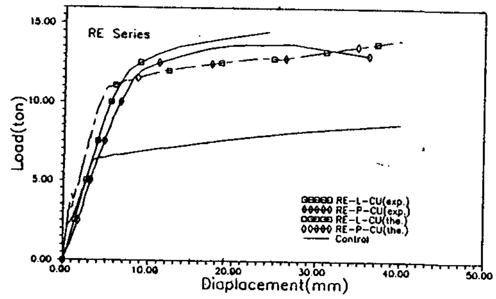


Fig. 6. Comparisons with Test Results and Theoretical Predictions (RE series)

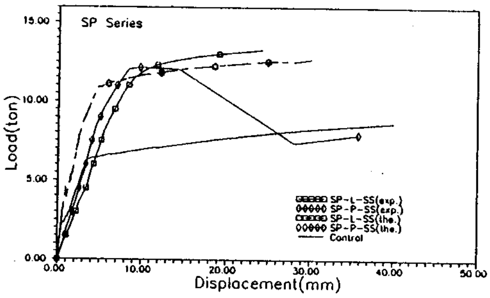


Fig. 7. Comparisons with Test Results and Theoretical Predictions (SP series)

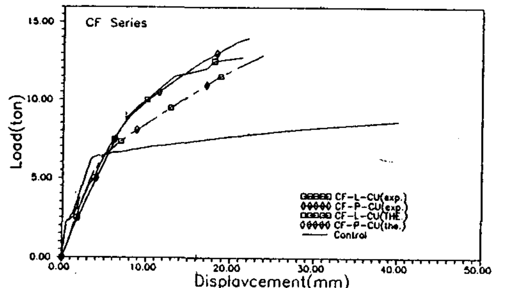


Fig. 8. Comparisons with Test Results and Theoretical Predictions (CF series)

7. Relative Effectiveness of the Strengthening Scheme

Two different overlay matrices (latex and premix) and three different strengthening methods (rebars inside overlay, and steel plates or CFRP sheets bonded to the overlay soffit) are used in the experiments. In order to examine their relative effectiveness of composite action in strengthening, experimentally obtained tensile strains of rebars, steel plates, and CFRP sheets at the midspan are compared with the corresponding theoretical ones for the same deflection. Since the model assumes the strain compatibility, the gaps in strain values between the theoretical ones and the measured ones at the same deflection can be regarded as differences resulted from cumulative slips that exist in the interface between strengthening materials and its surrounding materials. More effective method would, therefore, result in a better composite action, yielding caculated measured strain values closer to the theretically obtained ones(Fig.9). Fig.10 shows the measured and theoretically obtained strains of the reinforcing rebars in latex overlay

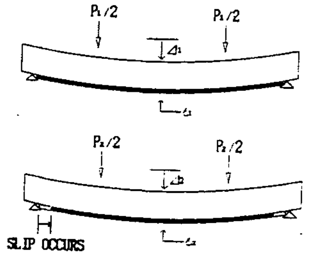


Fig.9. Less Strains from Experiments than Theoretical Ones due to Less Composite Action.

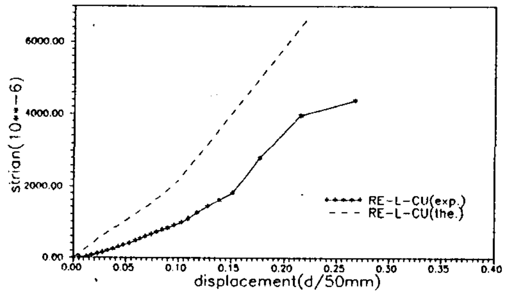
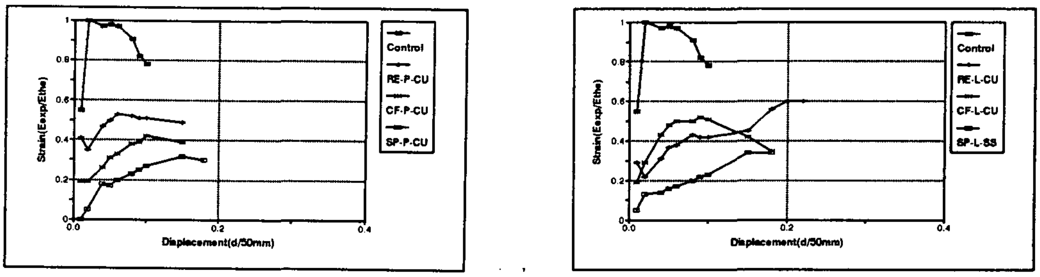


Fig.10. Differences in Measured and Theoretical Strains of Strengthening Material at the Same Deflection.

Measured strains normalized with the theoretical ones at the identical deflections are shown in Fig.11. The value in y-axis equal to 1.0 means the perfect bond (or no slip) and thus perfect composite action. The closer the strain values to 1.0, the more effective the composite action. From Fig.11, it can be shown that although all the strengthening techniques experience the certain amount of slippage, RE and CF series are more effective than the SP series in achieving the composite action. In premix overaly, RE series clearly demonstrates its effectiveness in composite action than the other two (i.e., CF and SP series) although no clear difference between RE and CF series can be seen in the oerlay with latex. For each series, no clear difference in bonding effect is observed between the different overlay materials of latex and premix.



(a) Premix Overlay (b) Latex Overlay

Fig.11. Relative Effectiveness in Bonding

8. Parametric Study

Using the developed model, parametric studies are conducted to investigate the effects of main design parameters. The load-deflection curves are generated for both control beam and strengthened beams. The control beam of cross sectional dimension 30cm x 60cm with 8m span is reinforced with tensile reinforcement ratio of 0.01. All beams are subjected to a third point loading. Table 3 summarizes the design parameters and their selected values for parametric studies..

Table 3. Selected Values for Parametric Study

Observed Effects.	No.	Beam		Overlay			Steel Plate			CFRP Sheet			
		f_c' (kg/cm^2)	ρ	material	d_a (cm)	ρ_a	f_{py}	$E(\times 10^6)$ (kg/cm^2)	ρ_p	fct	$E(\times 10^6)$ (kg/cm^2)	ε_y	$t_{cf}(cm)$
f_c'	1	240	0.01	latex	5	0.01	-	-	-	-	-	-	-
	2	400	″	″	″	″	-	-	-	-	-	-	-
	3	240	″	″	″	-	2400	3.4	0.006	-	-	-	-
	4	400	″	″	″	-	″	″	″	-	-	-	-
	5	240	″	″	″	-	-	-	-	35500	2.35	0.015	0.11×2
	6	400	″	″	″	-	-	-	-	″	″	″	″
ρ_a	7	240	″	″	″	0.005	-	-	-	-	-	-	-
	8	″	″	″	″	0.01	-	-	-	-	-	-	-
ρ_p	9	″	″	″	″	-	2400	3.4	0.002	-	-	-	-
	10	″	″	″	″	-	2400	″	0.012	-	-	-	-
	11	″	″	″	″	-	4800	6.8	0.002	-	-	-	-
	12	″	″	″	″	-	″	″	0.012	-	-	-	-
d_p	13	″	″	″	10	0.01	-	-	-	-	-	-	-
	14	″	″	″	5	″	-	-	-	-	-	-	-
	15	″	″	″	10	-	2400	3.4	0.006	-	-	-	-
	16	″	″	″	5	-	4800	″	0.006	-	-	-	-
	17	″	″	″	10	-	-	-	-	35500	2.35	0.015	0.11×2
	18	″	″	″	5	-	-	-	-	″	″	″	″
CFRP	19	″	″	″	5	-	-	-	-	″	″	″	″
	20	″	″	″	″	-	-	-	-	30000	3.8	0.8	0.165×1.6
Overlay Material	21	″	″	premix	″	0.01	-	-	-	-	-	-	-
	22	″	″	latex	″	″	-	-	-	-	-	-	-

where, d_a= overlay depth, ρ_a=reinforcing rebar ratio(As/bh), ρ_p=steel plating ratio(Ap/bh),

f_{cf}=ultimate strength of CFRP sheet, ε_{cf}=CFRP strain at peak, t_{cf}=thickness of CFRP sheet

8.1 Effects of Concrete Compressive Strength

The beams overlayed to the soffit with the 50mm depth of latex is considered throughout. To find the effects of compressive strength, two different compressive strengths - 240 or 400 kg/cm^2 - are considered. Fig.12 shows that all strengthened beams with different methods have only marginal increases in flexrual strength and in stiffness with the increased compressive strength.

8.2 Effects of Reinforcement Ratio of Rebars in Overlay

Fig.13 shows that as the reinforcement ratio of rebars in overlay increases, the flexural strength and its stiffness increase. These increases seem to be proportional to the sum of total reinforcement ratio of rebars and steel plates. The ductility, however, decreases since the increased tensile reinforcement ratio.

8.3 Effects of Reinforcement Ratio of Bonded Steel Plate

It is shown in Fig.14 that the more plating effect in increasing the flexural strength is observed for higher *reinforcement ratio (* $\rho_p = 0.012$*) for different yield strengths of the plate.* As both the reinforcement ratio and yield strength of the plate increase, ductiltiy is significantly reduced. When steel plating is applied, the area of steel plate needs be carefully chosen to avoid brittle failure mode.

8.4 Effects of Overlay Depth

Fig.15 shows that the increased depth of overlay leads to the increased flexural stiffness and strength in beams with steel plating and CFRP reinforcements due to the increased length of internal lever arms. Little change is in the beam with rebar reinforcement in increased overlay

8.5 Effects of CFRP Sheets

Two different CFRP sheets are used in paremetric study. The one has lower ultimate tensile strength but *almost 1.6 times htgher stiffness than the other.* Fig. 16 shows that flexural strength as well as stiffness of the beam strengthened with the former CFRP is superior to the latter for both reinforcement ratios(i.e., 0.01 and 0.005). Both beams with different CFRP sheets fail in brittle manner.

8.6 Effects of Types of Material used in Overlay

Almost identical load-deflection curves are obtained from the beams with *three different overlay* materials(Fig.17). The main role of the overlay material seems to be in the bonding and the strengthening *material to the concrete for the enhancement of the composite action* of the strengthened beam.

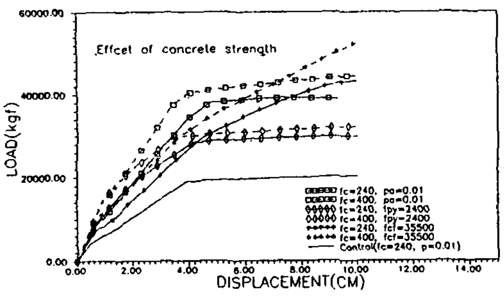


Fig.12 Effects of Concrete Compressive Strength

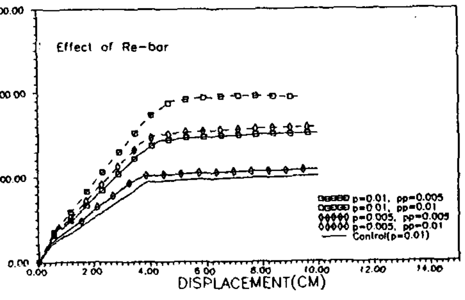


Fig.13 Effects of Reinforcement Ratio of Rebars in Overlay

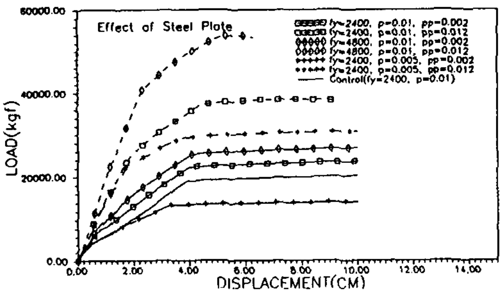


Fig.14 Effects of Reinforcement Ratio of Bonded Steel Plate

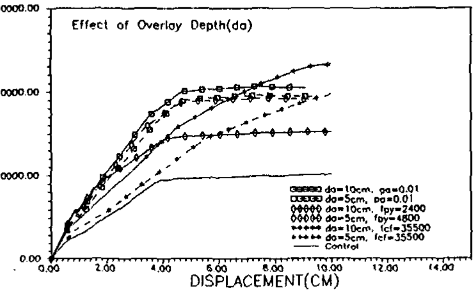


Fig.15 Effects of Overlay Depth

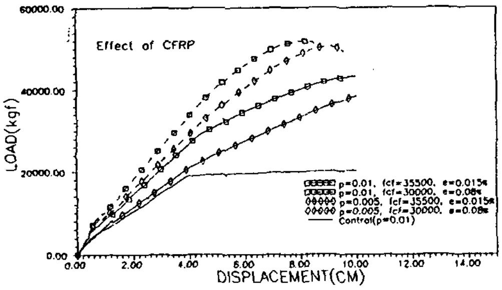


Fig 16 Effects of CFRP Sheets

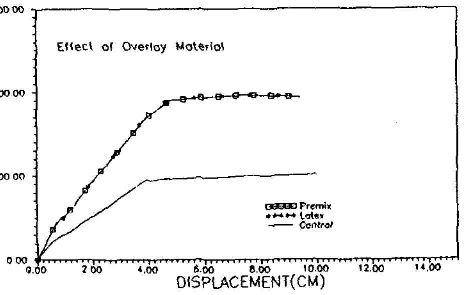


Fig.17 Effects of Types of Material used in Overlay

9. Conclusions

The model based on the nonlinear layered finete element is used to find the effectiveness of the strengthening techniques by approximately measuring the cumulative slips and the effects of design variables on the overal flexural behavior of the overlayed RC beam strengthed with rebars, steel plates and CFRP sheets. From a point of slips, the method of using rebars in overlay has beneficial effect than the other methods. Enhancements in flexural behavior are observed when increased values of design variables are used. No effect, however, is observed for the use of different overlay materials.

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