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Analytical Evaluation of RC Beams Strengthened with Near Surface Mounted CFRP Laminates

by J.-Y. Kang, Y.-H. Park, J.-S. Park, Y.-J. You, and W.-T. Jung

Synopsis: To assess the strengthening efficiency of near-surface mounted (NSM) carbon fiber reinforced polymer (CFRP) laminates according to their groove depth and disposition, 4-point bending tests were performed on 4 specimens strengthened with NSM CFRP. A structural model for the finite element method (FEM) able to simulate accurately the experimental results was determined to analyze the strengthening efficiency of the NSM technique analytically. Applying the model, parametric analysis was performed considering the groove depth and spacing of CFRP laminates. Analytical study on the groove depth revealed the existence of a critical depth beyond which the increase of the ultimate load becomes imperceptible. In other words, this means that there exists a limit of strengthening efficiency where it remains in a definite level even if the groove depth is increased. Analytical results regard to the spacing of the CFRP laminates showed that comparatively smooth fluctuations of the ultimate load were produced by the variation of the spacing and the presence of an optimal spacing range for which relatively better strengthening efficiency can be obtained. Particularly, a spacing preventing the interference between adjacent CFRP laminates and the influence of the concrete cover at the edges as well as allowing the CFRP laminates to behave independently was derived. Using the analytical results, various strengthening schemes could be established with different numbers of CFRP laminates, groove depths and dispositions of the reinforcements for a determinate quantity of reinforcements.

Keywords: carbon fiber reinforced polymer (CFRP); groove depth; near surface mounted (NSM); spacing; strengthening

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INTRODUCTION

Near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) technique becomes attractive for flexural strengthening of slabs and girders, as it has a greater bonding capacity compared to externally bonded CFRP composites (El-Hacha et al. 2004; Hassan and Rizkalla 2003; Lorenzis and Nanni 2002). In the NSM CFRP technique, CFRP composites are embedded into previously epoxy filled grooves pre-cut on the concrete cover. It is a strengthening method utilizing the bonding force developed at the interface between the epoxy and concrete as a stress transferring mechanism (Täljsten et al. 2003; Lorenzis and Nanni 2002). Therefore, the groove depth and disposition of CFRP laminates have a significant effect on the strengthening efficiency of NSM as well as on the workability and the cost (Hassan and Rizkalla 2003). In the case of confined construction areas like concrete beams which present narrow width and restrained concrete cover, one should be able to determine the optimal amount of reinforcement and optimal location of embedment that produce sufficient strengthening efficiency.

This study examines experimentally the flexural behavior of reinforced concrete beams strengthened by NSM CFRP technique regard to the reinforcement groove depth and disposition. An analytical model which simulates accurately such behavior has also been determined. Applying the analytical model, parametric evaluation of the strengthening efficiency is achieved considering the variations of the groove depth and spacing of the CFRP laminates. The range of groove depth and spacing producing the maximum strengthening efficiency has been proposed.

EXPERIMENTS AND ANANLYSIS

Preliminary experiments

To assess the efficiency of NSM technique and to determine the finite element model that can simulate the flexural behavior of strengthened beam, preliminary 4-point bending tests were carried out according to the groove depth and disposition of CFRP laminates. The specimens illustrated in Figure 1 consisted of 1 unstrengthened control specimen, 2 specimens with different groove depths (TYPE 1-1 and TYPE 1-2) and 2 specimens with CFRP strips disposed at different spacing (TYPE 2-1 and TYPE 2-2).

The experimental results, summarized in Table 1, showed that the ultimate loads of the NSM strengthened specimens were increased by 40 % to 95 % compared to the unstrengthened specimen. Especially, the ultimate load of TYPE 1-2 was 1.1 times larger than that of TYPE 1-1 while the sectional area of the reinforcements was 1.65 times larger. Areas of CFRP reinforcements for TYPE 2-1 and TYPE 2-2 were 2 times larger than that of TYPE 1-2; the measured ultimate loads, however, were only 1.27 and 1.24 larger, respectively. In view of the results for TYPE 2-1 and TYPE 2-2, it appears that strengthening efficiency also varies with the disposition of the CFRP reinforcements for the same area of reinforcements. It is seen that, consequently, strengthening efficiency is not directly proportional to the area of CFRP reinforcement and also varies according to the disposition of the reinforcements.

Analysis scheme

According to the experimental results, the differences in strengthening efficiency with respect to the disposition of the reinforcements for the same groove depth and the non-direct proportionality of increase in load carrying capacity with the variation of the groove depth have been observed. To verify the above results, using the analysis software ABAQUS v.6.4, nonlinear finite element analysis has been performed for RC beams strengthened by NSM technique. Three-dimensional finite element model has been implemented as structural model in order to consider the disposition of the reinforcements within the section of the beams. Prior to the parametric analysis, structural analysis has been carried out on the 5 specimens used in the test and the feasibility of the analysis model has been verified through the comparison of the analytical and experimental results.

The conditions considered in the parametric analysis can be roughly classified into two cases: the arrangement of a single CFRP laminate and the arrangement of two CFRP laminates. In the former case, analysis has been performed with respect to the variation of groove depth from 5 mm to 35 mm by 5 mm. In the latter case, the groove depth and disposition of the reinforcements were simultaneously considered; the embedment depth was fixed to 15 mm or 25 mm and, for each case, the spacing between the two reinforcements was varied from 20 mm to 180 mm.

Description of finite element model

For the finite element analysis of RC beams, 8-node continuum element was used for the concrete and ‘hourglass control’ has been applied to prevent excessive deformation of the elements caused by reduced integration. The reinforcing steel bar was modeled by 2-node 3D truss element and applied as embedded element inside the concrete element. The material properties of concrete and steel rebar have been assumed by the stress-strain relationships plotted in Figures 2 and 3. Similarly to the concrete member, 8-node continuum element was applied for the epoxy block and perfect bonding has been assumed at the concrete-epoxy interface. The CFRP laminates were also modeled by 8-node continuum element assumed as embedded element in the epoxy element. This assumption has been done so as to reflect the failure mode exhibited by the epoxy and CFRP laminate reinforcement, which behaved as a block in the experiments. The stress-strain relationship of CFRP laminate was shown in Figure 4. The boundary conditions of the concrete, epoxy and carbon laminate interface are illustrated in Figure 5.

Three-dimensional nonlinear analysis has been carried out using the modified Riks solver, a nonlinear static equilibrium solver supplied by ABAQUS, in order to consider the instability of the boundary conditions provoked by the failure of the reinforcement element or the concrete element in the RC beam strengthened by NSM technique and to trace exactly the path of the load-displacement curve.

Verification of the analysis model

Comparison of the experimental and analytical results has been performed to verify the feasibility of the analysis model. As shown in Figure 6, the relative errors of the analytical results for CONTROL, were about 2 % for the yield load and 8 % for the ultimate load, which approached fairly the experimental results.

Figure 7 plots the analytical results for TYPE 1-1 and TYPE 1-2, the specimens with groove depth of 15 mm and 25 mm, respectively. An error of 10 % occurred for the maximum displacement. The ultimate load approximated the experimental results by a relative error of less than 8 %.

Figure 8 plots the analytical results for TYPE 2-1 and TYPE 2-2, the specimens with two CFRP laminates disposed at spacing of 60 mm and 120 mm, respectively. As seen in the figure, the load-displacement curve obtained through the analysis approximates the experimental results with an error of less than 10 % for the displacement. Especially, the error for the load being lower than 4 %, the model can be said to simulate the actual behavior with accuracy.

Analysis on groove depth

For NSM technique, the maximum groove depth is limited to about 50 mm corresponding to the thickness of the concrete cover. It can be expected that the strengthening efficiency and load carrying capacity of the strengthened member increase in proportion to the groove depth or the quantity of reinforcements. However, experimental results revealed that the strengthening efficiency is not directly proportional to the groove depth or the quantity of reinforcements. It means that there exists an optimal groove depth which maximizes strengthening efficiency. This study investigated analytically the fluctuations of the increase of load carrying capacity according to the variation of the groove depth for the case of strengthening with a single CFRP laminate;

and a critical value for the groove depth has been derived to produce efficient strengthening.

Table 2 summarizes the results obtained from the parametric analysis on the groove depth varying from 5 mm to 35 mm. It showed that increase in yield load varies from 5 % to 29 % compared to the unstrengthened beam; and increase in ultimate load varies from 5 % to 60 %. Analytical results showed the poor influence of the variation of the groove depth or the variation of the amount of reinforcement on the increase of the yield load; however, it appeared also that these variations have large effect on the increase of the ultimate load after yielding. Table 3 compares the variations of load carrying capacities referring to the area of reinforcement with respect to the groove depth.

Figure 9 plots the increase rate of the ultimate load according to the variation of groove depth. The increase rate of the ultimate load is shown to converge toward a determinate value beyond a certain groove depth; hence, the ultimate load-groove depth relationship can be represented as a second-order function shown in Figure 9. For the dimension of the beam adopted in this study, the ultimate load tended to increase until the critical groove depth of 35 mm, and beyond that depth, no additional strengthening effect was observed; although this tendency and critical groove depth can be altered for different dimensions of beams.

Analysis on disposition of CFRP reinforcements

In cases where insufficient load carrying capacity is expected for a beam to be strengthened with a single CFRP laminate, two or more CFRP laminates disposed at regular spacing should be installed. In such cases, attention should be paid on securing a certain spacing between the CFRP laminates so as to prevent mutual interference which causes reduction of strengthening efficiency. On the other hand, if this spacing becomes excessive, adverse effects may drop off the strengthening efficiency because the CFRP laminate near the concrete edge can not acquire bonding capacity; furthermore, it causes surface spalling of the edge of concrete cover. Consequently, deciding an optimal spacing that is able to maximize the strengthening efficiency, is necessary; in other words, by deciding an optimal disposition, each of the CFRP laminates behaves independently and, at the same time, the influence of the distance to the concrete edge can be avoided.

Table 4 summarizes the analytical results on spacing of the CFRP laminates when two rows of laminate are disposed. The increase rate of the ultimate load is seen to range between 65 % and 98 % according to the spacing for the groove depth of 25 mm; and between 52 % and 75 % for the groove depth of 15 mm. The spacing exhibiting the maximum strengthening efficiency was 80 mm around which the strengthening efficiency was seen to decline.

Figure 10 plots two cases of analytical results together to derive the optimal spacing range that enables the maximum strengthening efficiency. It can be seen that the highest strengthening efficiency is developed for spacing between the reinforcements ranging between 80 mm and 120 mm. The increase rate of ultimate load reaches up to 65 % for the groove depth of 15 mm; and runs up to 95 % for the groove depth of 25 mm. In addition, parametric analysis showed that the strengthening efficiency appears to decline relatively if either the disposed spacing or the distance to concrete edge is less than 40 mm. Consequently, the following preconditions should be satisfied for NSM technique; (1) to ensure a minimal spacing of 40 mm between adjacent CFRP laminates for independent behavior; (2) to dispose CFRP laminate at a distance of more than 40 mm from concrete edge.

DISCUSSION

This paper deals with the strengthening efficiency of NSM for particular RC beams used in experiments and parametric analysis. Since the behavior of RC beams with arbitrary dimensions may be different from the results of this study, it is highly recommended to derive the general relationships between the increase of load carrying capacity and the amount of reinforcements. To that goal, wider range of experimental and analytical data considering the following should be secured: (1) the behavior considering the spacing of reinforcements with respect to the groove depth; (2) the behavior according to varying number of reinforcements; (3) the behavior for different dimensions and steel reinforcement ratios; and (4) the behavior regard to the strength of material. Once generalized relationships of reinforcement ratio versus increase rate of load carrying capacity will be prepared through future tests or parametric studies, it will be possible to establish easily the strengthening scheme for NSM, as shown in Figure 12.

CONCLUSIONS

Analytical investigation on the ultimate load versus groove depth relationship revealed the existence of a critical groove depth beyond which the increase of the ultimate load of strengthened member becomes very slight. In other words, the existence of a critical load carrying capacity, beyond which additional strengthening effect could not be obtained even if the groove depth was continuously increased, could be presumed. In terms of the dimensions of the specimens applied in this parametric study, the maximum groove depth being 35 mm, the critical load carrying capacity that could be secured by NSM technique reached 1.6 times that of the unstrengthened beam.

Analytic results on spacing of the CFRP laminates showed that, for a definite amount of reinforcement, the yield load increased uniformly indifferently from the variation of spacing; and it showed relatively smooth fluctuations of the ultimate load regard to the variation of spacing. The presence of an optimal range of spacing for which relatively high strengthening efficiency was obtained has also been found. Especially, by the parametric study, the particular conclusions were also ascertained as follows: (1) there exists a minimum spacing between adjacent CFRP laminates to be secured to prevent mutual interference; and (2) there exists a minimum distance to the concrete edge that avoids the influence of the concrete cover in the vicinity of the edges of the beam. It has been verified that this minimum spacing and minimum distance to edge should exceed 40 mm to ensure that each of CFRP laminates behaves independently. As these features are supposed to occur regardless of the dimensions of the beam to be strengthened, these requisites should be preceded when deciding the disposition of more than 2 rows of

CFRP laminates.

Results of this parametric analysis made it possible to know that the strengthening efficiency depends on the groove depth, the amount of reinforcements according to the groove depth, and the disposition of the reinforcements. The possibility to derive several alternatives of strengthening scheme with respect to the required increase of load carrying capacity of a member to be strengthened by NSM technique has also been highlighted. It has been seen that, for a prescribed amount of reinforcement, larger strengthening efficiency could be realized by disposing several reinforcements at regular spacing near the surface instead of a single reinforcement. However, because it is rational to reduce the processes such as the cutting of the grooves or the epoxy filling, it is advisable to decide the disposition of the reinforcements after consideration of the workability and economical efficiency.

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Table 1 – Summary of test results

Specimen	P_y (kN)	d_y (mm)	P_u (kN)	d_u (mm)	% increase in P_y	% increase in P_u
CONTROL	46.7	12.78	56.2	71.68	–	–
TYPE 1-1	57.5	15.5	78.4	58.9	23.1	39.5
TYPE 1-2	62.0	16.1	86.2	54.0	32.8	53.4
TYPE 2-1	72.0	16.5	109.7	46.9	54.2	95.2
TYPE 2-2	70.5	14.2	107.0	44.4	51.0	90.4

P_y : yield load
d_y : midspan deflection at yielding
P_u : ultimate failure load
d_u : midspan deflection at failure

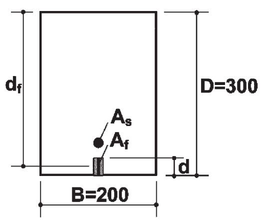
Table 2 – Comparison of the increase of P_u according to groove depth

d (mm)	P_y (kN)	P_u (kN)	$P_y/P_{y(control)}$	$P_u/P_{u(control)}$	Specimen
CONTROL	46.69	56.19	1.00	1.00	CONTROL
5	48.87	59.04	1.05	1.05	–
10	51.53	69.49	1.10	1.24	–
15	53.98	76.33	1.16	1.36	TYPE 1-1
17.5	54.76	78.27	1.17	1.39	–
20	55.34	80.58	1.19	1.43	–
25	56.84	84.37	1.22	1.50	TYPE 1-2
27.5	58.15	86.62	1.25	1.54	–
30	59.05	84.7	1.26	1.51	–
35	60.37	89.76	1.29	1.60	–

d : groove depth
P_y : yield load
d_y : midspan deflection at yielding
P_u : ultimate failure load
d_u : midspan deflection at failure

Table 3 – Comparison of the increase rate of P_u according to amount of reinforcements

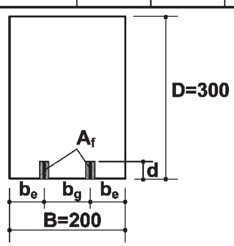
d (mm)	Dimension of CFRP laminate	A_f (mm^2)	d_f (mm)	ρ_f ($\times 10^{-3}$)	ρ_f/ρ_s	P_y / $P_{y(control)}$	Pu/ $P_{u(control)}$
5	1.2 × 5	6	297.5	0.101	0.0245	1.047	1.051
10	1.2 × 10	12	295.0	0.203	0.0494	1.104	1.237
15	1.2 × 15	18	292.5	0.308	0.0748	1.156	1.358
17.5	1.2 × 17.5	21	291.3	0.361	0.0876	1.173	1.393
20	1.2 × 20	24	290.0	0.414	0.1006	1.185	1.434
25	1.2 × 25	30	287.5	0.522	0.1268	1.217	1.501
27.5	1.2 × 27.5	33	286.3	0.576	0.1401	1.245	1.541
30	1.2 × 30	36	285.0	0.632	0.1535	1.265	1.507
35	1.2 × 35	42	282.5	0.743	0.1806	1.293	1.597



d : groove depth
A_f (=1.2d) : section area of CFRP laminate
ρ_f (=A_f/Bd_f) : ratio of CFRP laminate
ρ_s (=A_s/BD) : ratio of reinforcing steel bar
P_y : yield load
P_u : ultimate load

Table 4 – Analytic results according to groove depth and spacing of reinforcements

d (mm)	A_f (mm^2)	b_g (mm)	b_e (mm)	b_g/B	P_y (kN)	P_u (kN)	$P_y/P_{y(control)}$	$P_u/P_{u(control)}$
0 (CONTROL)	0	0	0	0	46.69	56.19	-	-
25	30	20	90	0.1	72.25	97.89	1.55	1.74
		40	80	0.2	73.24	98.06	1.57	1.75
		50	75	0.25	73.91	103.31	1.58	1.84
		60	70	0.3	72.61	108.43	1.56	1.93
		80	60	0.4	72.93	111.19	1.56	1.98
		100	50	0.5	71.62	106.51	1.53	1.90
		120	40	0.6	72.64	107.89	1.56	1.92
		140	30	0.7	71.27	103.77	1.53	1.85
		160	20	0.8	71.63	105.05	1.53	1.87
		180	10	0.9	72.61	92.44	1.56	1.65
15	18	20	90	0.1	59.12	88.59	1.27	1.58
		40	80	0.2	59.02	86.17	1.26	1.53
		60	70	0.3	59.43	87.51	1.27	1.56
		80	60	0.4	58.14	98.41	1.25	1.75
		100	50	0.5	58.14	89.06	1.25	1.58
		120	40	0.6	57.12	95.25	1.22	1.70
		140	30	0.7	56.8	89.79	1.22	1.60
		160	20	0.8	57.47	90.01	1.23	1.60
		180	10	0.9	57.47	85.56	1.23	1.52



d : groove depth
A_f (=1.2d) : section area of CFRP laminate
b_g : spacing of CFRP laminates
b_e : distance to concrete edge
P_y : yield load
P_u : ultimate load

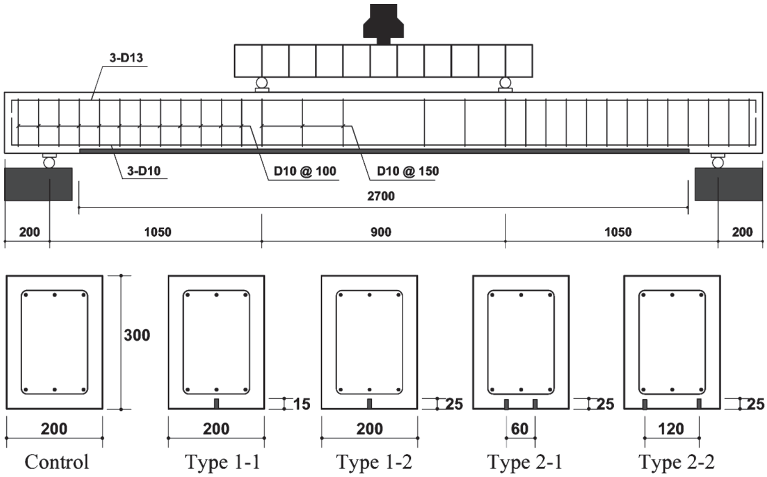
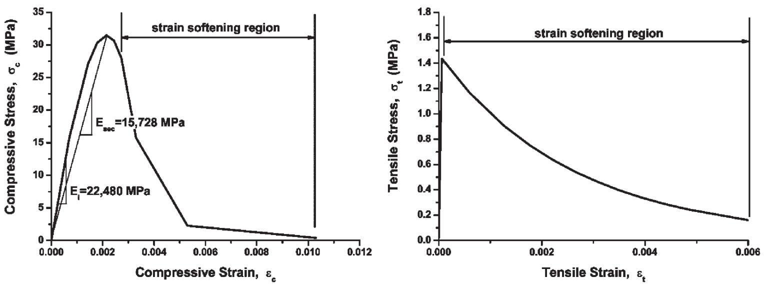


Figure 1 – Test set-up and specimen details



(a) Compressive stress-strain relationship (b) Tensile stress-strain relationship

Figure 2 – Property of concrete

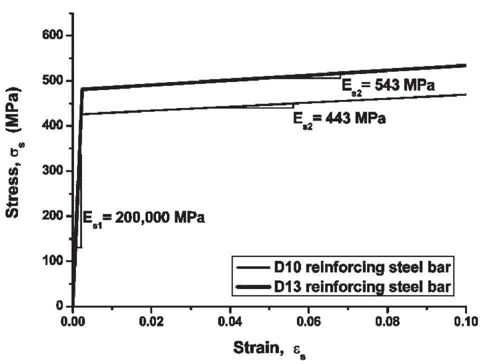


Figure 3 – Property of reinforcing bar

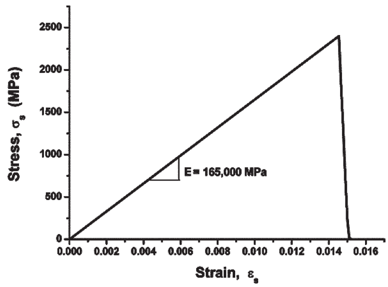


Figure 4 – Property of CFRP laminate

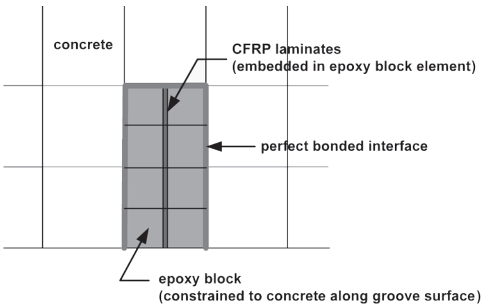


Figure 5 – Boundary conditions at interface

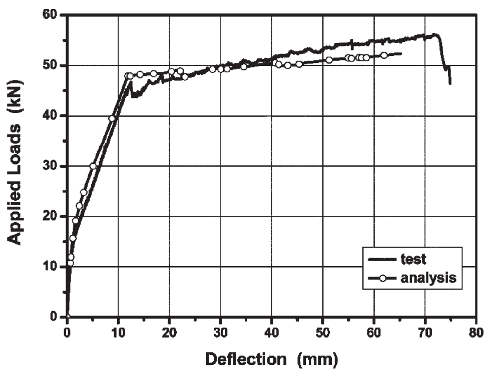
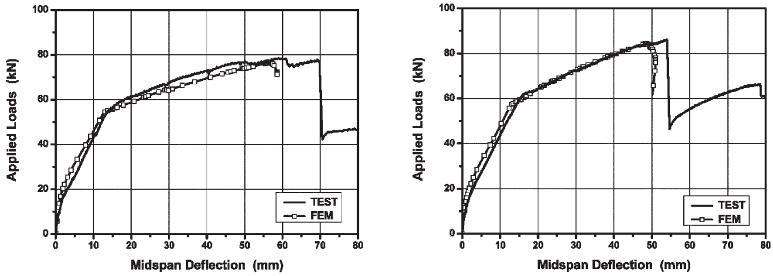
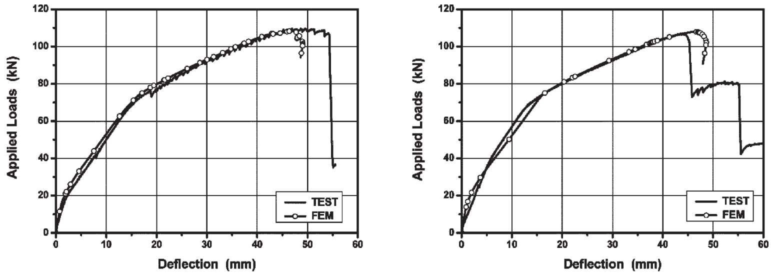


Figure 6 – Comparison of analytic and experimental results for CONTROL



(a) TYPE 1-1 (b) TYPE 1-2

Figure 7 – Comparison of analytical and experimental results according to groove depth



(a) TYPE 2-1 (b) TYPE 2-2

Figure 8 – Comparison of analytical and experimental results according to spacing

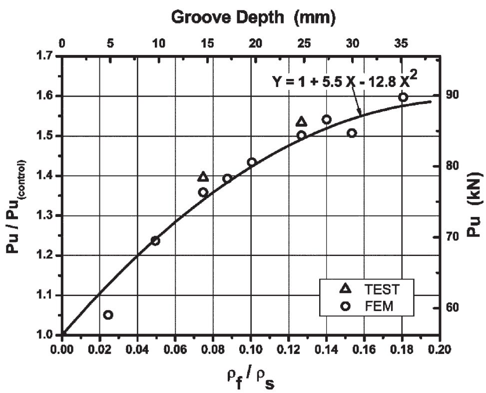


Figure 9 – Increase rate of ultimate load vs. reinforcement area ratio

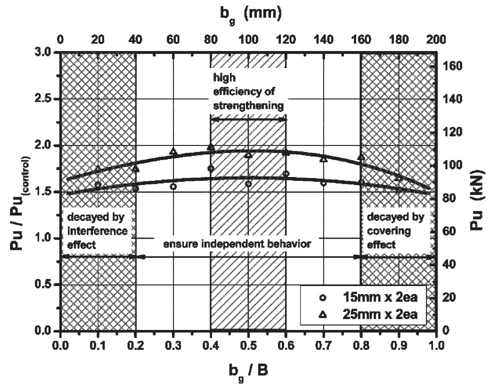


Figure 10 – Comparison of ultimate load by groove depth relative to spacing ratio

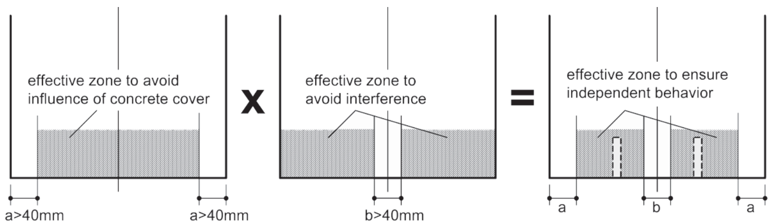


Figure 11 – Disposition to ensure independent behavior of the CFRP reinforcements

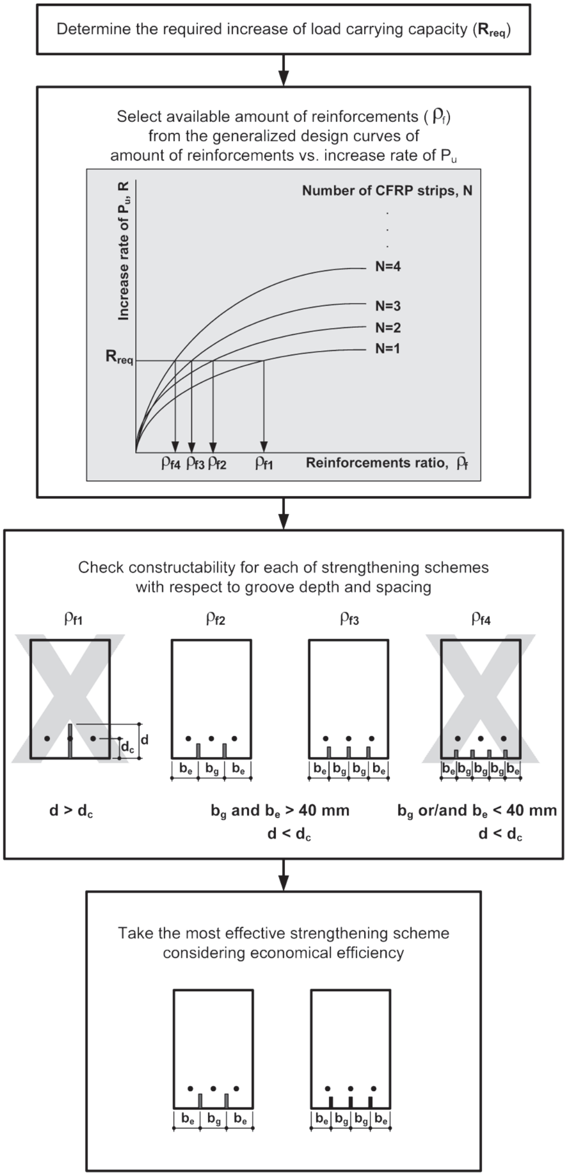


Figure 12 – Conceptual design flow of NSM reinforcement