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Experimental study on integrated method of NSM and EBR techniques for flexural strengthening of Concrete Beams using CFRP

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Abstract: This paper is based on an experimental analysis carried out to identify the effectiveness of different installation techniques of CFRP (Carbon Fibre Reinforcement) in concrete elements. Two new methods of integration of externally bonded reinforcement (EBR) and near surface mounted (NSM) methods were also experimented with the objective of increasing the flexural capacity of reinforced concrete beams by increasing the effective area of CFRP strips used. The main objective of this research paper is to identify the adaptability of existing guidelines specified for the EBR and NSM methods separately into the new installation method of integrating the two techniques of EBR and NSM.

Keywords: adhesives, externally bonded reinforcement, near surface mounted CFRP, concrete, method of integration

1. Introduction

Concrete is one of the widely used materials in the construction industry. It has a greater compressive strength but proven to be weak in tension. Without inner reinforcement, concrete will become brittle and fail under tension and make it less appropriate for many of the structures. A traditional way of reinforcing concrete is use of steel bars at the time of casting. Since concrete structures have a relatively longer life span, it is quiet common that the loads imposed on it will increase with time. On the other hand due to material deterioration under severe conditions will also affect badly on structures. This will create a necessity to seek approaches on strengthening these structures.

Rehabilitation and reparation of structures have become a very important, yet a critical factor due to above mentioned factors. Instead of designing a building from the very beginning, it has been identified that rehabilitating an existing building is more difficult and complicated as the structural conditions are already set. It can also be more complicating to reach the areas that need to be strengthened and to recognize the amount of strengthening that needs to be done.

This is generally the case for traditional strengthening systems, namely; reinforced overlays, shotcrete or post tension cables placed on the outer surface of the structure. These techniques require much space, machineries or special equipment. In recent years the development of plate bonding repair technique seems to have shown promising results and applicable to many existing structures. This technique can be acknowledged as a method of binding a sheet or a plate with an epoxy on the outer surface of a structure.

CFRP (Carbon Fibre Reinforced Polymer) was introduced by researchers as a more suitable and convenient solution. It has been identified as a material that can be used for remedying reinforced concrete, pre stressed concrete, masonry, timber and also steel. High in strength, lightness in weight, resistance to corrosion and ease in application of CFRP have earned the trust among its users and proved to be more promising in the construction industry. Introduction of CFRP to the construction industry eradicated most of the mentioned issues prevailed in the industry.

CFRP can be installed mainly in two different methods; Near Surface Mounted **(**NSM) and Externally Bonded Reinforcement (EBR) on the element. For both these methods of application, an adhesive needs to be used. This could be either any specified epoxy or cement grout. Out of the two methods of installation, near surface mounted (NSM) CFRP has demonstrated a competitive advantage over externally bonded reinforcement due to many reasons [1]. NSM allows better adhesion compared to EBR, provides a larger specific area for binding with concrete, durable, thermal protection becomes easier, more convenient in installation since there is less preparation of the surface. It has also been recognised as a better method of installation if CFRP bars are expected to be used in pre stressing [2].

Even though the NSM method has been identified as an effective method of installing CFRP in qualitative terms, experimental values have not been provided to verify its effectiveness in terms of flexural strengthening when the same effective area of CFRP is used. This research was designed to bridge the gap existed due to lack of experimental verifications. Therefore in this current study it has been proven that the NSM method provides better flexural strengthening compared to the EBR method and also an integrated method of EBR and NSM can also be effectively used.

Furthermore according to the guidelines of ACI 440-2R.08 [6] [6], the moment capacity of a beam strengthened by NSM and EBR methods can be measured separately. If an integrated method is used a combination of those calculation methods should be adopted along with an additional safety factor. In this paper the additional safety factor has been investigated through experimental data and analysis.

2. Test program

2.1 Objectives

The main objective of this research is to identify the best method of installing CFRP strips in reinforced concrete beams when the same effective area of CFRP is being used. It has also been investigated and experimented on new methods of installing CFRP strips using the NSM and the EBR method together both in parallel and perpendicular directions. Eventually the moment capacity of the integrated method was calculated according to the guidelines provided in ACI 440-2R.08 [6] and an additional safety factor was introduced by comparing the theoretical values with actual experimental results. The research was carried sequentially as follows;

- A thorough literature review was conducted in order to identify the new trends of CFRP uses and emerging technologies
- The research gap was identified and the experimental programme was planned in order to achieve the objectives
- Experiment was carried out and data was gathered
- A complete analysis was carried out eventually to achieve the pre-defined**.**
- Theoretical results were compared with experimental values to introduce a safety factor when equations specified in design guidelines are used.

2.2 Experimental procedure

Six concrete beams of 150 mm × 150 mm × 750 mm dimensions were cast using G35 concrete. Cubes cast out of the same concrete were tested after 28 days and the average compressive strength was recorded as 39.7 N/mm^2. Two 6mm diameter mild steel bars were used for main bars and 6 mm diameter galvanized iron bars were used as shear links with 75 mm spacing in the concrete beams.

Properties of CFRP strips used for strengthening the reinforced concrete beams are mentioned below in Table 1. Two part epoxy adhesive was used for bonding. The mixing ratio was 4:1 by weight according to manufacturer's technical data sheet.

Table 1: CFRP Manufacturer Specifications [7]

Parameters	Value
Elastic modulus (GPa)	>170
Tensile strength (MPa)	>2800
Elongation at rupture	≥1.6
Fibre volume content	>68
Bond strength (MPa)	≥1.5
Strip thickness (mm)	1.2

Table 2: Epoxy specifications [7]

Parameters	Value
Elastic modulus (N/mm^2)	>7100
Compressive strength (N/mm^2)	>70
Tensile strength (N/mm^2)	≥3
Shear strength (N/mm^2)	>26
Density (g/cm^3)	1.7-1.8

2.2.1 Test matrix

Table 3: Description of test specimens

Description	Beam No
Beams strengthened in EBR method	B1,B2

Beams strengthened in NSM method	B3, B4
NSM and EBR method in parallel direction	B5
NSM and EBR method perpendicular to each other	B6

2.2.2 Specimen preparation

After the beams were cured the surface of the beams were prepared for the installation of CFRP strips. Four different categories of test specimen were needed to be prepared as shown in Table 3.

In the NSM method two grooves of 5 mm width and 15 mm depth were cut with a centre to centre spacing of 30 mm at the bottom surface of the beams. Then an air compressor was used to clean the grooves and there after acetone was used to clean them further. When the groves were prepared an edge distance of 60 mm were allocated in each beam to eliminate the overlapping of tensile stresses induced by the CFRP strips at the point of loading.

In the EBR method, the surface was prepared by grinding and acetone was used to wipe off the dust. In the method of integration of the EBR and NSM methods, the surface was prepared first by grinding and then in one beam two grooves were cut parallel to main reinforcement and in the other beam, six grooves were cut perpendicular to the main reinforcement. (Figure 1 and Figure 2)

Figure 1: Grooves prepared perpendicular to main steel reinforcement

Figure 2: Grooves prepared parallel to main reinforcement

Surface preparation methodologies and groove dimensions were referred to from ACI 440-2R.08 [6]. 10 mm wide CFRP strips were used and the length used was 450 mm. The length was determined according to the effective bond length mentioned in the ACI codes.

In both NSM and integrated systems, the grooves were first half filled with epoxy and then the CFRP strips were installed. The rest of the grooves were filled after inserting CFRP strips. In addition to this, in the two integrated systems, after installing CFRP strips in NSM method, two CFRP strips of the same length as used in EBR method, were pasted on top of the grooves. (Figure 3 and Figure 4).

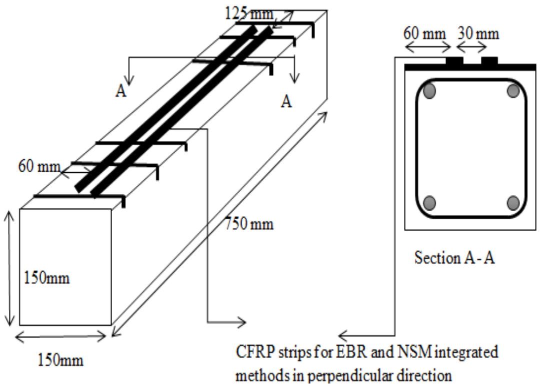

Figure 3: Integrated in perpendicular direction

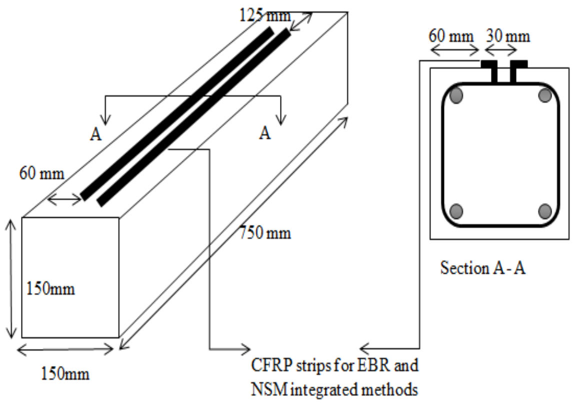

Figure 4: Integrated in parallel direction

2.2.3 Testing methodology

The Amsler machine was used for the four point bending test. Concrete beams were simply supported with a test span of 600 mm. The supports were located at 75 mm away from the CFRP strips to avoid creating end anchorage to CFRP strips from external supports. The experimental set up is shown in Figure 5.

The specimens were gradually loaded and mid span deflection was recorded using dial gauges. The failure load was considered as the load recorded at the point of 0.3 mm crack initiation. The concrete beams were loaded further after reaching its failure loads to clearly observe the failure patterns.

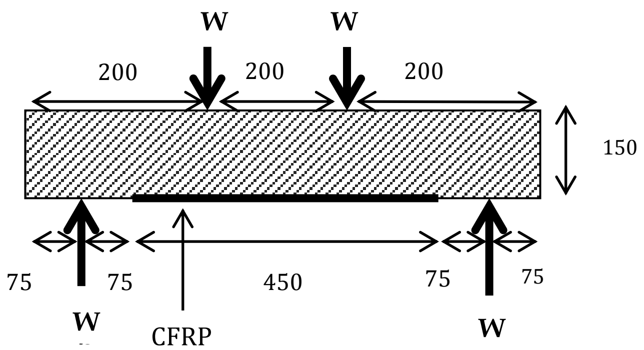

Figure 5 - Experimental set up (in mm)

3. Results and analysis

3.1 Load deflection curve

A ductile system displays sufficient warning before catastrophic failure. It becomes a significant property of a beam which becomes important for seismic design, and since retrofitting is sometimes concerned with upgrading a structure to resist seismic forces, identifying the retrofitting material which gives better ductility is important [5].

From the results obtained from beam testing, the load-deflection curve was drawn. It is shown in Figure 6. According to experimental data the beams strengthened in the NSM method shows the least deformation for a given load. The NSM method showcases the best performance under loading, and it is proven to be more ductile, in return displaying sufficient warning before collapse and being ideal for seismic designing as well.

However with the increase in loading the integrated method in parallel direction also yields better results. Higher the load, greater the ductility is.

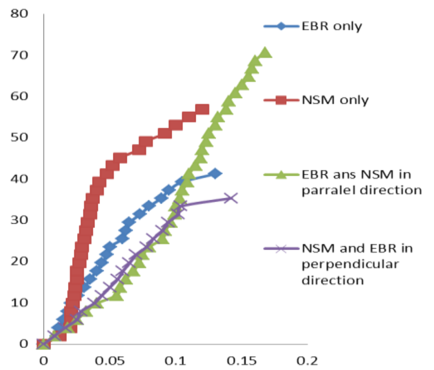

Figure 6: Load

This hints at the anticipatory future of CFRP applications for seismic designs in both existing and emerging building; especially for high rises.

3.2 Flexural strength gain

Of the four methods of installation, the integrated method in parallel direction demonstrated the highest strength gain. In the below Figure 7, increase in percentage with comparison to theoretical load of unstrengthen beam is shown. In the y axis of the graph 1, 2, 3 and 4 indicates the EBR method (B type), NSM method (C type), integrated in parallel (D type) and integrated in perpendicular directions (E type) respectively.

This has been proven in similar experiments carried out in other countries as well. Lack of information about the effective area used inhibits those results from verifying the fact that NSM method performs better in terms of flexural strength. The latest similar experiment that had been carried out by El-Hacha, and Rizkalla in 2004 [2] yields the same conclusion. According to their experiment the NSM method is nearly 54% more effective than the EBR method. In their experiment an anchorage length of 2400 mm had been used and the strips installed by EBR method had further been confined with U- wrap CFRP sheets at the two ends in order to eliminate de-bonding .This is the main reason for not being able to compare the NSM method and EBR method under same effective areas of CFRP strips. The CFRP sheet or the textile too comes into effect in that experiment making the effective areas of CFRP unequal.

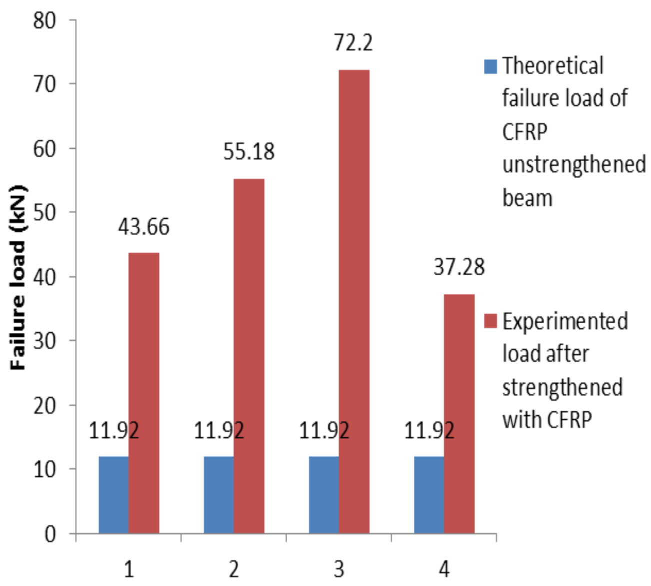

Figure 7: Comparison of loads with unstrengthen CFRP beam

The experimental programme explained in this paper, was planned to make sure that the same effective area of CFRP strips is used through-out without incorporating other CFRP materials to eliminate de-bonding and peeling off. The results obtained exhibits a 26% increment of flexural strength of NSM method Vis a Vis the EBR method (Figure 7).

Another important fact to be identified is that, the external reinforcement is provided as tension reinforcement. For a simply supported beam it is the bottom face of the beam which needs to be reinforced. The beams tested for this research had highly limited surface area due to space allowances provided for edge splitting, cover delamination and generation of excessive tensile stresses at grooves. So the flexural gain cannot be easily enhanced with attempt to mount more CFRP strips on a beam surface. This can be easily and effectively achieved by integrating the NSM and EBR methods together. Not that this method has provided more space for mounting CFRP strips but also has enhanced the flexural capacity by 67% compared to sole EBR method. Compared to the NSM method it is an increment of 31% (Figure 7).

3.3 Failure modes

Not many different types of failure modes were observed. Even though the methods of installation varied significantly from each other, the failure modes did not differ much from each other. B1, B2 (EBR method) beams failed due to strip end de-bonding (Figure8). This type occurs with a loss in the composite action between the bonded CFRP and the RC member. De-bonding in CFRP strengthened RC members occurs in regions of high stress concentrations, which are often associated with material discontinuities and with the presence of cracks. If de-bonding from end plate was avoided by transverse clamping with CFRP U-wraps or steel plates with anchor bolts at the end, the failure load could have been increased. The transverse clamping could have prevented de-bonding at the end and delay the failure.

Figure 8: De-bonding at plate end

C1, C2 beams that were strengthened in NSM method failed due to the splitting of epoxy (Figure 9). This is the usual method of crack initiation in an NSM mounted method according to Zsombor K. Szabo`[3].

Figure 9: Surface splitting in NSM method

In the experiment carried out, the surface splitting of the adhesive occurred closer to the supports. So the splitting of epoxy that is known as a secondary failure can be the result of shear failure around the reinforcement. The flexural strength of the beam had been enhanced by this arrangement and now that the failure occurs due to lack of shear strength.

Splitting in the epoxy cover is a result of high tensile stresses at the CFRP and epoxy interface. Increasing the thickness of the epoxy cover can reduce the tensile stresses induced. [4] In order to increase the thickness of the epoxy cover, the groove has to be cut deeper into the beam. However this is impossible unless the cover is greater in the beam. The cover in the beams used was 25 mm. And the depth of the groove was nearly 15 mm. This could have been extended a bit further, but will be restricted at the depth of 25 mm. Instead of this solution an epoxy with higher tensile stress can be used. These remedies can increase the failure load of the strengthened beams under NSM method.

Figure 10: Crack initiation in the epoxy cover in the integrated method

D1 beam which was strengthened in the integrated method in parallel direction failed in a similar way to C2 beams and E1 beams that was strengthened by the integrated method (perpendicular to the main reinforcement direction) failed at a very low ultimate load due to de-bonding of the CFRP strips.

This emphasises the fact that in beam D1, even though it is an integration of both NSM and EBR methods, the same failure pattern seen in the NSM method could be seen here as well. It depicts that the NSM method is more predominant in the integration method. And the externally bonded CFRP strips in D1 beam behaved as if they had been clamped, (Figure 10) which means that the CFRP strips installed in NSM method have reduced the stress concentration induced at plate ends. Instead it had increased the shear stress at the supports and made the beam fail in shear failure. This indicates that this method has improved the flexural strength, and now it had been the shear strength which had weakened the beam's capacity. If proper shear reinforcement was provided through CFRP the failure load could have been increased.

3.4 Moment capacity

According to ACI 440-2R.08 [6] design recommendations CFRP strengthening systems should be designed to resist tensile forces while maintaining strain compatibility between the CFRP and the concrete substrate. In section 9 of ACI 440.2R-08 the design philosophy of calculating the moment capacity of a CFRP strengthened beam is discussed. According to the researches carried out it has been recommended to use an environmental reduction factor of 0.9 for CFRP strengthening systems with the assumption that the exposure condition is interior. Additional safety factors need to be applied when CFRP reinforcement is used to reflect uncertainties inherent in CFRP systems compared with steel reinforced and pre-stressed concrete.

3.4.1 EBR method

When the moment capacity of the reinforced concrete beam strengthened by the EBR method was calculated it could be seen that the effective strain in CFRP reinforcement is limited by the de bonding strain of the CFRP strip. Hence the flexural moment provided by the CFRP strengthening system is dictated by the stress induced at the point at which the CFRP de bonds from the substrate.

$$\varepsilon_{fd} = 0.41\sqrt{(fc'/nE_f t_f)} \leq 0.9\varepsilon fu \text{ in SI units} \quad (1)$$

ε_{fd} is the strain level at which de bonding occurs and fc', n, E_f, εfu and t_f represent the design compressive strength of concrete, number of CFRP strips used, elastic modulus of CFRP strips, design rupture strain of CFRP strips and thickness of the strips respectively.

fc' = 35 N/mm^2, n = 2, E_f = 170000 N/mm^2 , εfu = 0.0152 ($\varepsilon fu = C_E\, \varepsilon fu^*$ *in which* C_E =0.9 *and* εfu^* =0.016) *and* t_f = 1.2 mm

In the EBR method when the strain level at de bonding was calculated it was found that the value is 0.0038 and it was less than the given limit.

$$\varepsilon_{fe} = 0.003\left(\frac{d_f - c}{c}\right) - \varepsilon_{bi} \leq \varepsilon_{fd} \quad (2)$$

Equation 2 calculates the effective strain in the CFRP strip (ε_{fe}) when the concrete is at its crushing point. It is calculated using the strian at the substrate which is indicated by ε_{bi} and d_f and c representing the effecticve depth to CFRP strips and depth to the neutral axis respectively. d_f is observed to be 150 mm as the CFRP strips are pasted at the bottom surface for the EBR method. This could be taken as 142.5 mm for the NSM method as CFRP strips are inserted inside the beam by cutting a groove in the bottom surface of the beam. c is found through an iteration process and the last iteration value was taken as 24.98 mm. Equations used to arrive at c value is clearly shown in ACI 440-2R.08 [6] under section 9.

The strain at the substrate can be found using separate equations specified in ACI 440-2R.08 [6] under section 9. When determining the strain at the substrate only the dead loads are taken into account. When data was insereted to eqaution 2 it was seen that the maximum effective strain at the CFRP strips at failure was greater than its de bonding strain which was stated as 0.0038 in the earlier paragraph. So the effective strain at the CFRP strips at failure was restriced to its de bonding failure strain. So it was concluded that the failure occurs due to de bonding of the strips and the moment capacity was found accordingly.

$$f_{fe} = E_f \varepsilon_{fe} \quad (3)$$

$$M_{nf} = A_f f_{fe}\left(d_f - \frac{\beta_1 c}{2}\right) \quad (4)$$

The stress of the CFRP strips can be calculated using equation 3 and this stress (f_{fe}) is used to determine the moment capacity of CFRP strengthened beams as shown in equation 4. M_{nf} represents the moment achieved only due to CFRP strengthening and A_f represents the CFRP area while β1 gives the ratio of depth of equivalent rectangular stress block to depth of the neutral axis. The total flexural strength comes as a combination of M_{nf} and moment due to steel reinforcement.

According to design philosophy in section 9 of ACI 440.2R-08 the theoretical increment of moment capacity in the EBR strengthened method due to CFRP strengthening using all the equations given, is 78% and the total flexural strength obtained is 4.19 kNm.

3.4.2 NSM method

If the same procedure was applied for the NSM strengthening method, the de bonding strain will once again govern the maximum strain level that can be achieved in the CFRP reinforcement. But the de bonding strain limit can be applied only for externally bonded method as the NSM model hardly fails under de bonding failure. So in this case the maximum strain is decided by the crushing of concrete.

Thus the maximum strain obtained will be determined from equation 2 and the de bonding strain will be ignored. This strain is then applied to equation 3 and 4 sequentially. Hence the theoretical increment of moment capacity due to NSM strengthening would be nearly 250% and the total flexural strength obtained was 8.82 kNm.

3.4.3 Integrated method

When these two methods were integrated in the parallel direction the experimental value obtained for the failure load was 72.2 kN. The calculated moment capacity at the mid span was 9.06 kNm via equation 5

$$M = \frac{wl^2}{8} + \frac{Wl_1}{2} \tag{5}$$

In equation 5, w (0.54 kN/m) is the self-weight of the beam and W (72.2 kN) is the point load imposed at the point of failure (This load was imposed on the beam as two point loads at the four point bending test). l (750 mm) is the length of the beam. l_1 (250 mm) is the distance between the support and the point load.

One of the most significant observations at the experimental program of the integrated beam was that the CFRP strip end de bonding did not occur even though they had been pasted at the bottom surface of the beam in EBR method. Instead the beam failed due to concrete crushing as in NSM method. So the strain of the CFRP strips at failure should be determined via equation 2. The ultimate moment capacity obtained from the above mentioned set of equations as specified in ACI 440-2R.08 [6] is 14.5 kNm. This value is obtained when four strips of CFRP strips were used; two strips inserted in NSM method and another two pasted in EBR method. An issue encountered in this theoretical calculation is that the guidelines tend to consider both CFRP strips installed in NSM and EBR methods to have been installed in NSM method only. This is mainly due to the similar failure patterns of the integrated method and the NSM method.

A modification factor can be proposed as a ratio between the theoretical value calculated according to the guidelines in ACI 440-2R.08 and the experimental value obtained from this test series. This additional safety factor can be calculated as 0.6 but needs to be verified further by using a numerical analysis method as well.

4. Recommendations

If transverse clamping had been used in beams B1 and B2, the failure load could have been increased. If an adhesive with better tensile strength was used, beams C1 and C2 could have failed under heavier loads. The deepening of the groove in C1 and C2 also could have enhanced the failure load. However the space allocations required in installation of CFRP strips in accordance with ACI 440-2R.08 [6] and the minimum cover of a beam hinder such procedures.

When the moment capacity of the integrated method was found it could have been summarised as follow;

The ultimate moment capacity of a CFRP strengthened beam is given by the equation 6 below

$$\Phi M_n = \phi\left[M_{ns} + \Psi_f M_{nf}\right] \tag{6}$$

M_n, M_{ns} and M_{nf} represent the flexural strength gain due to the addition of steel and CFRP reinforcements, strength gain due to steel reinforcement only and strength gain due to CFRP reinforcement only respectively.

The rest of the symbols represent various modification factors specified in the guidelines. This equation is used in both NSM and EBR installations. Hence the new modification factor of 0.6 can be incorporated in equation 6 when it is being used for the integrated method.

ϕ in equation 6 sets the reduction factor at 0.90 for ductile sections and 0.65 for brittle sections where the steel does not yield, and provides a linear transition for the reduction factor between these two extremes. When this model is being used for the integrated method it can be recommended to use ϕ as 0.54 for brittle sections and 0.4 for ductile sections after incorporating the safety factor of 0.6 mentioned above.

5. Conclusions

After examining the failure loads it can be concluded that when the same effective area of CFRP strips are used, the more effective method of installation is the NSM method. In a given area, it is not easy to install as many strips as desired since there are space allowances that need to be allocated. In the method of integration, the effective area of CFRP strips was doubled without causing excessive tensile stresses due to congestion of grooves and CFRP strips. It also improved the flexural capacity nearly by two times compared to the typical EBR method.

Different methods of CFRP installation systems can enhance the flexural capacity of a reinforced concrete beam, so that the beams tend to fail under shear. In order to eliminate this, the beams should be adequately strengthened in shear as well.

When the two methods are integrated in parallel direction, the NSM method dominates and this method of integration also acts as transverse clamping to the CFRP strips bonded in EBR method on the surface. If the integration of the two methods were done in perpendicular direction to each other, the EBR method dominates the failure pattern of the beam.

A modification factor of 0.6 can be introduced for the determination of flexural strength of the integrated method in parallel direction. This additional safety factor should be incorporated in the moment equation presented in ACI 440-2R.08 guidelines under section 9. This factor needs to be further investigated through a numerical analysis model.

The NSM method and the integrated system in parallel direction perform better in terms of ductility, which makes them much appropriate in earthquake resistivity.

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