

FLEXURAL RETROFIT OF SUPPORT REGIONS OF REINFORCED CONCRETE BEAMS WITH ANCHORED FRP ROPES UNDER REVERSED CYCLIC LOADING

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ABSTRACT

Many studies have been conducted for enhancing the positive moment capacity of the mid-span areas of reinforced concrete (RC) beams strengthened with fiber reinforced polymer (FRP) reinforcement under monotonic increasing loads. However under seismic actions, the support regions of beams may also require retrofitting. In such cases, retrofitting should be effective under reversed cyclic flexural actions. According to the best knowledge of authors, there is no study investigating this important issue in the literature. Therefore, the present study focuses on retrofitting of beam support regions under reversed cyclic flexural moments. As the initial stage of a more comprehensive testing program, three full-scale RC beam-column-slab sub-assemblages were tested. The sub-assemblages also included a part of transverse beams perpendicular to the main beam tested. One specimen was tested as a reference specimen while the remaining two specimens were tested after being retrofitted with near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) ropes with two different details in terms of anchorage of the CFRP ropes into joint region. The anchorage of CFRP ropes was provided by NSM application over the slab next to the column in one of the specimens, while CFRP rope was anchored by epoxy adhesive within the joint core by embedding it through a drilled hole on the column in other specimen. The effectiveness of the proposed anchoring methods was investigated through experimentally. The findings of the study indicated that the specimen retrofitted with NSM anchoring method achieved a remarkable enhancement in flexural capacity, whereas, anchoring through embedment of the CFRP rope within the epoxied drilled hole was not that successful.

KEYWORDS

Anchorage, embedment through section (ETS), flexure, near surface mounted (NSM), reinforced concrete beam, carbon fiber reinforced polymer (CFRP) rope.

INTRODUCTION

Earthquakes have proven that many reinforced concrete (RC) beams are required to be retrofitted. Major studies about the enhancement of flexural behavior of RC beams greatly benefit from the usage of fiber reinforced polymers (FRPs) (Fanning and Kelly 2001; Brena et al. 2003; Shin and Lee 2003; Kotynia et al. 2008). The most recent and promising technique for retrofitting of RC beams with FRPs is known as near surface mounting (NSM). Although, it is a recent method, the strength capacity increase of NSM strengthened beams was validated by many studies (De Lorenzis and Nanni 2001; Hassan and Rizkalla 2003; Teng et al. 2006; Lee and Chang 2013; Wu et al. 2014). Reviewed studies mainly focus on retrofitting the mid-span areas of the beams without taking into account the earthquake effects at the support regions. However, in the case of earthquake actions, support regions of beams can be critical and may require retrofitting.

Limited number of studies have been conducted about the seismic behavior of RC members strengthened with FRP materials by using NSM method (Barros et al. 2008; Bournas and Triantafillou 2009; Goksu et al. 2012; Vrettos et al. 2013). According to the best knowledge of the authors, no studies in published literature have been found on the seismic behavior of retrofitting of RC beam support regions with NSM method.

The present study focuses on the enhancement of the flexural performance of support regions of beams using NSM method under reversed cyclic loadings which resemble the earthquake actions. The specimens realistically represent part of an actual building with columns of two consecutive stories, main beam, slab and transverse

beam. Therefore, it can be asserted that the outcomes of the study are not valid only for laboratory conditions, but they are also valid for real three-dimensional structures.

Providing a sufficient anchorage length for main reinforcing bars is vital for retrofitting of the support regions of beams. Therefore, in the scope of the study, two different techniques were used for anchorage of carbon fiber reinforced polymers (CFRP) ropes within the beam-column joint. For the first anchorage type (Ret1), the CFRP rope was anchored inside the square grooves on the surface of the transverse beam next to the column side surface like the case of typical NSM method. For the second anchorage type (Ret2), a recently developed method, named as embedded through-section (ETS) was used. The results of several studies indicated that ETS technique is very effective for shear retrofitting of RC beams (Valerio et al. 2009; Chaallal et al. 2011, Mofidi et al. 2012). Also, Mofidi et al. (2012)'s study indicated that it is also a very promising method for usage of end anchorage. In the proposed study for the second specimen, the CFRP rope is anchored by embedding inside a pre-drilled epoxied circular hole throughout the bottom section of upper story column.

A new kind of CFRP reinforcement defined as CFRP rope was used for retrofitting. Since it is a new material, very few studies were conducted with CFRP ropes for concrete confinement and enhancement of shear capacity of beams (Rousakis 2013; El-Saikaly et al. 2014). In the published literature, no study was found on enhancement of flexural capacity of beams with CFRP ropes except the work done by (Kaya 2014, Kaya et al.).

The findings of the study indicated that specimens retrofitted with FRP ropes using NSM anchoring method achieved a remarkable enhancement in flexural capacity, whereas, anchoring of the CFRP rope through embedment within the epoxied drilled hole was not that successful.

EXPERIMENTAL PROGRAM

Design and Construction of Specimens

The features and designations of specimens used in this paper are shown in Table 1. In this table, f'_c is the characteristic compressive strength of concrete. The compressive strengths in Table 1 were calculated according to the average compressive strength are the average of compressive strengths of 83×83 mm core samples tested in accordance with ASTM C39/C39M-05 (ASTM 2005) standard. The day of compressive strength tests of cores are also presented in Table 1.

The nomenclature of specimens represents the condition of specimen whether it is reference specimen (without retrofitting), *Ref*, retrofitted specimen with NSM anchorage detail, *Ret1*, and ETS anchorage detail, *Ret2*. Ret1 stands for the retrofitting technique of NSM method for both outside and inside (anchorage) the joint region. Ret2 stands for the retrofitting technique of NSM and ETS method for outside and inside the joint region, respectively. Therefore, Ret1 and Ret 2 retrofitting techniques are designated with of NSM+NSM and NSM+ETS, respectively.

Table 1 Specimen details.

Designation of specimen	f'_c (MPa)	Age		Dimensions of ^c		Retrofitting	
		Days ^a	Days ^b	Columns	Beams	Total area of FRP ropes (mm ²)	Application ^d
Ref	35	268	282	250×400	250×400	-	-
Ret1	31	281	282	250×400	250×400	56	NSM+NSM
Ret2	35	275	282	250×400	250×400	56	NSM+ ETS

^a The day of the experiment, ^b The day of compressive strength tests of drilled core samples, ^c Width* Depth, ^d See Figure 2.

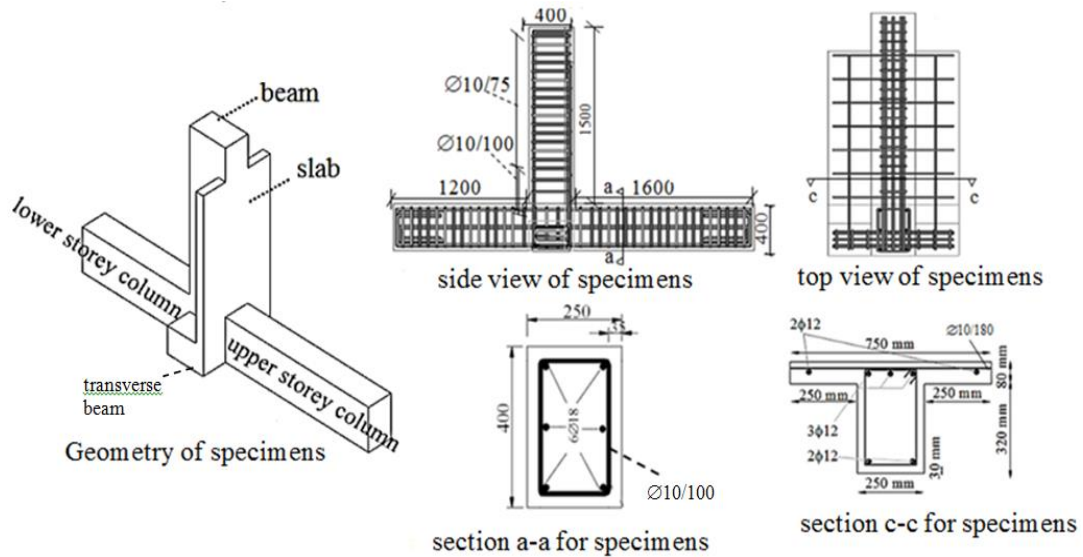


Figure 1 Geometry and reinforcement details of specimens (units in mm).

In the scope of the study, three full-scale exterior beam-column-slab sub-assemblages were constructed and tested, as shown in Figure 1. All sections of specimens were heavily reinforced against shear forces to ensure that they would be flexure-critical. The specimens were detailed based on the seismic design philosophy of weak beam-strong column both for reference and retrofitted specimens.

Table 2 presents the mechanical properties of three types of reinforcing bars used. In this table, f_y and ϵ_y are the yield stress and strain; ϵ_{sh} is the strain at the beginning of strain hardening; $f_{s\ max}$ and $\epsilon_{s\ max}$ are the maximum stress and strain, and f_{su} and ϵ_{su} are the rupture stress and strain.

Table 2 Mechanical properties of reinforcing bars.

Reinforcement	Diameter (mm)	f_y (MPa)	ϵ_y	ϵ_{sh}	$f_{s\ max}$ (MPa)	$\epsilon_{s\ max}$	f_{su} (MPa)	ϵ_{su}
Ø18	18	474	0.0022	0.025	612	0.14	482	0.21
Ø12	12	470	0.0023	0.026	605	0.13	472	0.19
Ø10	10	471	0.0022	0.027	611	0.13	533	0.20

Retrofit Design and Application

For retrofitting applications, a new type of material; CFRP ropes were utilized in longitudinal direction. This material was intentionally chosen due to its high flexibility and potential for better anchorage. It consists of a bundle of flexible CFRP fibers, which are held together by a thin net (El-Saikaly et al. 2014). According to the manufacturer's product data sheet, the nominal cross section area, ultimate rupture strain and tensile modulus of CFRP rope are 28 mm², 1.6% and 240 GPa. For bonding and impregnation, commercial epoxy adhesive with a tensile strength of 30 MPa, elastic modulus of 4500 MPa and ultimate elongation of 0.90% was used.

Two different techniques in terms of anchorage of CFRP ropes at the support region were utilized in the scope of the study. For the first anchoring type (Ret1), the FRP material was anchored inside the square grooves on the surface of the transverse beam next to the column side surface through typical NSM method. For the second anchoring type (Ret2), a recently developed method, named as embedded through-section (ETS) was utilized. For this, the CFRP rope was anchored by embedding inside pre-drilled circular holes throughout the bottom section of the upper story column. The retrofitting method between the tip of the beam and interface of joint region was identical for both retrofitted specimens. Typical NSM retrofitting technique was used in this region. Therefore, the retrofitting methods Ret1 and Ret2 were designated as NSM+NSM and NSM+ETS, respectively.

The details of grooves and retrofitting methods are presented in Table 3. In this table D is the diameter of circular holes drilled inside the joint region for ETS method, d_g is the square groove size, l_b is the bonded/development length, k is the groove size factor, d is the diameter of CFRP rope (6 mm). The holes in

ETS method were in the shape of circular since they were opened with a rotary hammer drill and they were bonded to whole perimeter unlike the three surface bonded square grooves opened for NSM method.

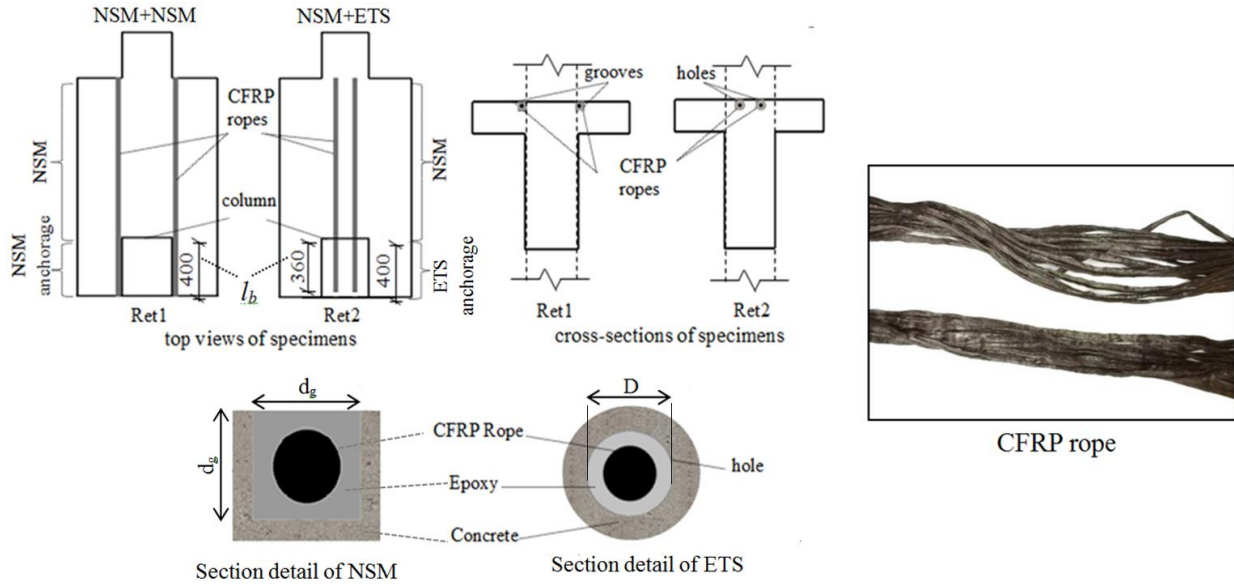


Figure 2. Schematic illustrations of retrofitting methods and and illustration of CFRP rope.

In this study, the theoretical bond strengths for these two different methods are determined according to the recommendations of De Lorenzis et al. (2002) Eqs. (1-3). According to these equations the debonding is foreseen to occur at the interface of the groove surface and epoxy.

$$\tau_{avlu} = P_{max} / (3 d_g l_b) \quad (1)$$

$$P_{max} = E_{frp} \varepsilon_{frpu} A_{frp} \quad (2)$$

$$d_g = k d \quad (3)$$

$$\tau_{avlu} = P_{max} / (11 D l_b) \quad (4)$$

$$D = k d \quad (5)$$

In Eq. (1-3), P_{max} is the ultimate load, d_g is the square groove size, l_b is the bonded/development length, k is the groove-size-to-actual-rope-diameter-ratio, d is the diameter of CFRP rope (6 mm), D is the diameter of hole and τ_{avlu} is the average bond strength. E_{frp} , ε_{frpu} and A_{frp} are the elastic modulus (240 GPa), ultimate strain (rupture strain) (0.016) and cross-section area of FRP (28 mm²), respectively. The FRP characteristics are provided by the manufacturer.

P_{max} is the ultimate load that corresponds to the rupture strength of CFRP rope [Eq. (2) and (4)]. For all retrofitted specimens P_{max} is constant and calculated as 107520 kN. The average bond strength for both retrofitted specimens (τ_{avlu}) is assumed as 5 MPa in order to allow a fair comparison between them [Eq. (1)]. ACI 440.2R-08 (2008) recommends to take the bond strength for NSM retrofitted members as 6.9 Mpa. Godat et al. (2012)'s study indicated that the bond strength of ETS retrofitted specimens varied between 8.4 and 15.1 MPa. Also, De Lorenzis et al. (2002)'s study revealed that the bond strength of specimens retrofitted with similiar surface preparation and reinforcement material with the proposed study were between 8.19 and 9.54 MPa. It can be concluded that the recommendation of the design code and findings of other studies point to an average bond strength over 5 MPa for NSM and ETS techniques. Therefore, it can be asserted that the assumption of the bond strength as 5 MPa enables to remain in conservative side according to the higher bond strength of literature studies and design code (ACI 440.2R-08 (2008)). For Ret1 and Ret2 specimens, the development lengths were equal to 400 and 360 mm. The difference between two development lengths stemmed from the presence of internal steel reinforcement for type2 retrofitted specimen. For the holes to be drilled inside the joint region at

the bottom of the column, Eq. (1) was modified to Eq. (4) consider the whole perimeter of the hole around FRP ropes bonded. The square groove sizes (d_g) and diameter of holes (D) were calculated according to the Eqs. (1) and (4), respectively (Table 3).

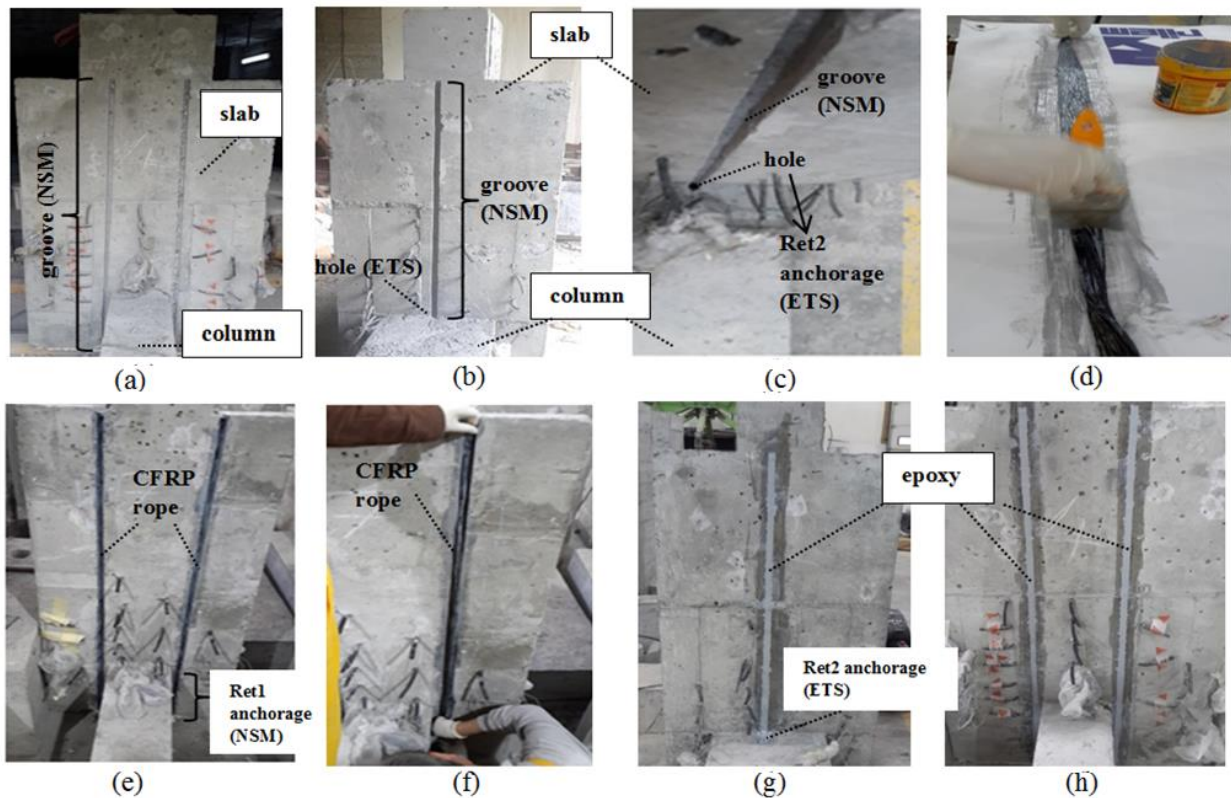


Figure 3. Retrofit application stages; (a) drilling the grooves of Ret1; (b) drilling the holes of Ret2; (c) top view of Ret2; (d) impregnation of CFRP ropes with epoxy paste; (e) insertion of CFRP ropes into drilled holes for Ret1; (f) insertion of CFRP ropes for Ret2; (g) final view of specimens retrofitted with Ret2; (h) final view of specimens retrofitted with Ret1.

Table 3 Details of retrofitted specimens.

Designation of specimen	Retrofitting Method	Anchorage Type	Amount of FRP (mm ²)	l_b (mm)	k	Groove (square) /Hole (circle) shapes & dimensions	
						Outside the joint region (mm)	Inside the joint region (mm)
Ret1	Type1 (NSM+NSM)	NSM	56	400 (67d)	3	Square $d_g = 18$	Square $d_g = 18$
Ret2	Type2 (NSM+ ETS)	ETS	56	360 (60d)	2.5	Square $d_g = 18$	Circle $D = 19$

Test Setup

The specimens were tested with the beams in vertical position and columns in horizontal position. One half of the column represents the lower half of the upper-storey column and the other half of the column represents the upper half of the lower-storey column (Figure 4).

The specimens were supported by rollers at both ends of the columns which restrain vertical translation and release the rotation. The reversed cyclic lateral displacement/load was applied at the tip of the beam. During application of reversed cyclic lateral displacement/load, a constant axial load of 375 kN, which corresponds to the level of $0.1 f'_c bh$ was applied to columns by a hydraulic jack, where b and h are the width and depth of the column, respectively and f'_c is the compressive strength of core samples.

The main objective of the present study is to enhance the negative bending moment capacity of RC beam support regions which are to be subjected to both negative and flexural moments under reversed cyclic seismic actions. Before application of reversed cyclic displacement reversals, the support region of the beam was subjected to negative moment for representing the effects of vertical dead and live loads. Then additional displacement reversals were applied to the specimen such that the negative moment capacity of the beam is exceeded leading to non-linear inelastic deformations, where as the displacements were in the range of linear behaviour for positive moment for replicating most of the actual situations during seismic actions. Therefore, loads in pushing direction which lead to tension at beam webs were restricted to 60% of positive bending capacity. Each cyclic test was started with the initial drift ratio (Δ_{G+Q}) corresponding to beam displacements caused by the sum of dead and live loads. After reaching the initial displacement, a symmetrical pulling and pushing displacement controlled loading pattern which resembles seismic actions was applied to all specimens until reaching the pushing load which corresponded to 60% of the positive bending moment capacity of the beam. After this stage, the pulling displacements were increased according to predetermined target drift ratios, whereas the ultimate pushing drift ratios (Δ_{up}) which corresponds to 60% of the positive moment capacity were kept constant.

The applied loading pattern is illustrated in Figure 4.

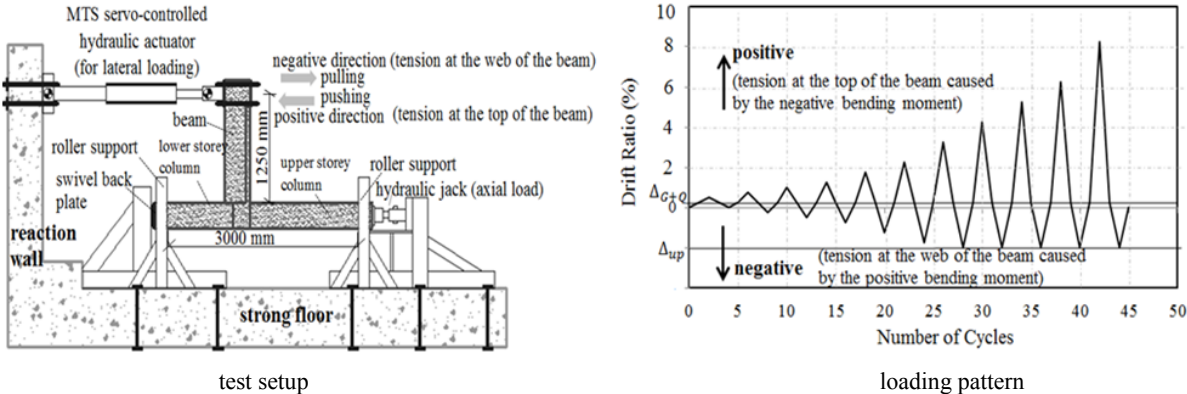


Figure 4 Test setup and loading pattern.

TEST RESULTS AND DISCUSSIONS

The failure of the reference specimen occurred due to concrete crushing in compression at large drifts after yielding of reinforcing bars in tension in pulling direction. Retrofitted specimens experienced failure due to the combination of CFRP rope debonding and partial rupture of some fibers (Figure 5). For both retrofitted specimens the debonding occurred at the interface of groove surface and epoxy. This findings coincided with the assumptions that the equations of De Lorenzis et. al (2002)’s study are based on [Eqs (1)-(5)]. Although these two different failure mode generally do not occur together (Sena Cruz and Barros 2004; De Lorenzis and Teng 2007; Bilotta et al. 2011), it is believed that this combination of failure stemmed from the characteristics of CFRP rope and approximately equal strengths of retrofitted specimens for debonding and rupture of CFRP ropes.

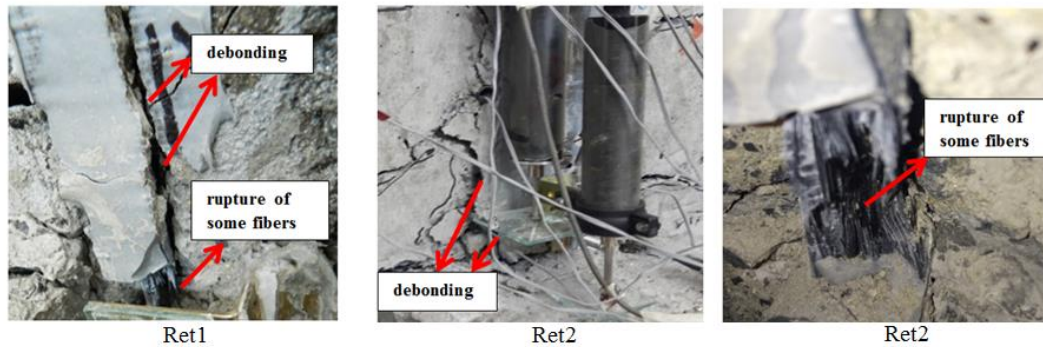


Figure 5 Failure of CFRP rope for retrofitted specimens.

Ret1 and Ret2 specimens were retrofitted with same amount of CFRP rope but, the results indicate that anchoring with ETS method (*Ret2*) is not as efficient as anchoring with NSM method (*Ret1*) in terms ductility and load carrying capacity.

For Ret1 specimen, the maximum load carrying capacity (103kN) was observed at drift ratio of 2%. At this drift ratio, the reference and Ret2 specimens corresponding capacities are 85 and 83 kN, respectively. Therefore, it can be asserted that the load carrying increase for Ret1 is equal to 21% when compared with the reference specimen. For Ret2 specimen, the maximum load carrying capacity (89 kN) was observed at drift ratio of 1.2 %. At this drift ratio the reference and Ret1 specimens corresponding capacities are 80 and 91 kN, respectively. Therefore, it can be asserted that the load carrying increase for Ret1 is equal to 11% when compared with the reference specimen. The enhanced strengths could not be sustained after these drift ratios. However, Ret1 and Ret2 experienced higher load carrying capacities until the failure of CFRP rope anchorages at the drift ratios of 2.6 and 1.3%, respectively (Table 4).

Table 4 Development of damage.

Specimen	First flexural crack		First yielding of longitudinal bar		Maximum strength			Failure of CFRP rope		Crushing of Concrete	
	Load (kN)	Drift Ratio (%)	Load (kN)	Drift Ratio (%)	Load (kN)	Drift Ratio (%)	Load Increase (%)	Load (kN)	Drift Ratio (%)	Load (kN)	Drift Ratio (%)
Ref	31	0.13	72	0.4	90	9	-	-	-	81	3.3
Ret1	30	0.09	61	0.5	103	2	21	81	2.6	103	3.4
Ret2	47	0.3	57	0.5	89	1.2	11	80	1.3	-78	3

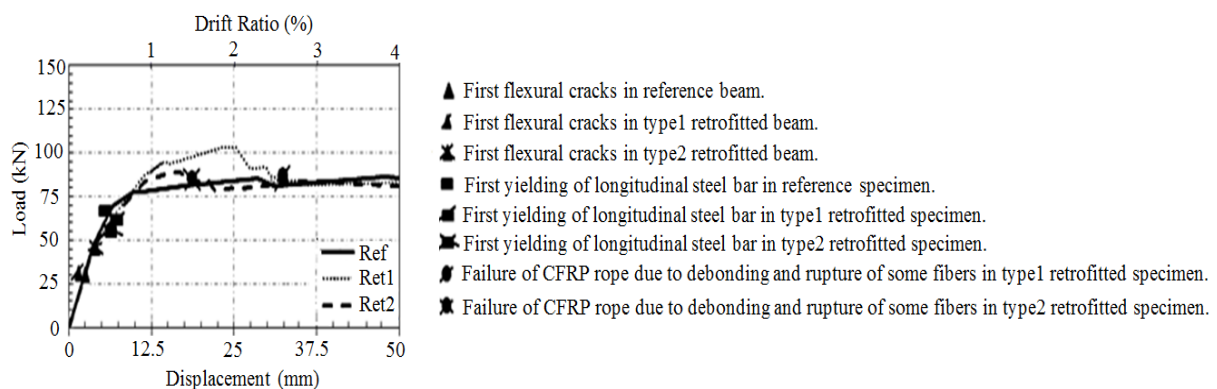


Figure 6 Envelopes of lateral load-drift ratios and development of damage.

The outcomes of the study which are presented in Table 4 and Figure 6 indicated that specimens retrofitted with NSM anchoring method (*Ret1*) achieved a remarkable enhancement in flexural capacity (21%) at drift ratio of 2%, whereas, specimens retrofitted with ETS technique (*Ret2*) achieved lower carrying capacity increase (11%) at lower drift ratio of 1.2% than Ret1. Therefore, it can be asserted that specimen retrofitted with NSM anchorage detail (*Ret1*) achieved higher load carrying capacity increase and maintained the increase until higher drift ratios (up to 2%) compared to the specimen retrofitted with ETS anchorage detail (*Ret2*).

The reason of the different performance results for Ret1 and Ret2 specimens is believed to be stemming from the challenging task of anchoring the CFRP rope within a length of 360 mm in a drilled holes for Ret2. Therefore, in order to examine the cross section of ETS anchorage method in detail, core samples within the area of the application of anchorage were extracted in horizontal direction. The samples indicated that specimen retrofitted with Ret2 have some deficiencies in terms of unimpregnated fibers and voids (Figure 7) which was not the case for Ret1. Therefore, it can be asserted that embedment CFRP rope material within a long length such as 360 mm, may lead to application faults and inadequate results.

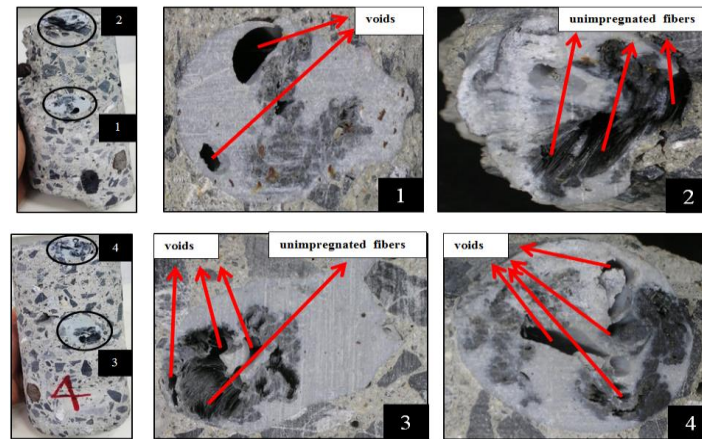


Figure 7. Core samples and images for specimen Ret2 and view of interfaces of concrete, CFRP rope and epoxy.

CONCLUSIONS

The present experimental study is conducted to investigate the effectiveness of two different anchoring techniques used during FRP retrofitting of beam support sections for enhancement of the flexural strength with CFRP ropes under reversed cyclic loading conditions. Proposed techniques in this paper consist of two different methods in terms of anchoring the CFRP ropes to the support regions. For both retrofitting types, NSM method was utilized outside the joint region. For the first retrofitting type, Ret1 (*NSM+NSM*), NSM method with square grooves was used for the anchorage of CFRP rope material on the slab next to the column side surface inside the joint region. For the second retrofitting type, Ret2 (*NSM+ETS*), embedment of CFRP rope material within the pre-drilled circular holes opened with rotary hammer drill throughout the bottom section of the upper storey column was used for anchorage of CFRP ropes inside the joint region.

Specimen retrofitted with NSM anchorage detail exhibited superior behaviour than the specimen retrofitted with ETS anchorage detail. It experienced the ultimate load carrying capacity increase (21%) at drift ratio of 2% and the failure of CFRP rope anchorage occurred at relatively higher drift ratio (2.6%). On the other hand, specimen retrofitted with ETS method experienced its ultimate load carrying capacity increase (11%) at drift ratio of 1.2% and the failure of CFRP rope anchorage occurred at quite lower drift ratio (1.3%) due to the failure of CFRP rope anchorage.

After physical investigation it was figured out that specimen retrofitted with ETS anchorage method had some deficiencies in terms of impregnation of fibers and proper filling of the anchorage hole. These deficiencies are attributed to the application problems due to the difficulty of embedding FRP ropes within an anchorage hole of 360 mm length.

Further studies should be carried out in order to better understand the behavior of CFRP ropes anchored in the joint either with NSM or ETS type details. Since this study is one of the first studies using this new form of FRP reinforcement, further studies should be carried out in order to support and improve the findings of this study.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the Scientific and Technological Research Council of Turkey (TUBITAK) Grant No. 113M112 and ITU-BAP (Scientific Research Projects Unit of Istanbul Technical University). The authors also thank to Boler Celik for modifying the test setup and SIKA, in particular to Mr. Berset for his advices and support for providing the CFRP ropes and retrofit application.

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