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Seismic Retrofit of Sub-Standard RC Columns with Embedded Aramid FRP Reinforcement

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ABSTRACT: Large number of existing reinforced concrete structures, which were constructed with sub-standard characteristics (low quality concrete, plain reinforcing bars, insufficient transverse reinforcement) are in urgent need of seismic retrofitting. Besides financial issues, disturbance to occupants and functions of the structures are among main obstacles for seismic retrofitting. Utilization of fiber reinforced polymer (FRP) composites can reduce disturbance to the occupants and hindrance of the functions of the structures remarkably when compared to traditional retrofitting techniques. In seismic retrofitting, the key issue is the effect of reversed cyclic actions, which impose cycles of compression and tension stresses on the FRP reinforcement. In this study, the applicability and efficiency of flexural seismic retrofitting using aramid FRP (AFRP) pultruded laminates are investigated experimentally. In this study, two major issues are examined i) the anchorage of AFRP pultruded laminates utilized for cyclic flexural strengthening to the low-strength concrete footing, and ii) the efficiency of the presented flexural seismic retrofitting technique for low-strength concrete members subjected to excessive displacement reversals.According to the test results, a remarkable enhancement in flexural strength was obtained for the retrofitted specimens. More importantly, the enhanced strength could be sustained until 3% drift ratio.

1 INTRODUCTION

A significant portion of existing reinforced concrete (RC) structures in seismic areas, which were not designed or constructed properly, need urgent seismic retrofitting. While financial constraints are also important, disturbance to the occupants and functions of the structures are other critical obstacles for proper seismic retrofitting of these sub-standard existing structures. In recent years, FRPs have been used widely and preferred due to their lightweight, high tensile strength and non-corrosive character for structural repairing and retrofitting (CEB-FIB 2001; Bakis et al. 2002; Lam and Teng 2003; ACI440-2R-08 2008). While most of the available studies on seismic retrofit are related with external confinement of columns or joints (Seible et al. 1997; Antonopoulos and Triantafillou 2003; Bousias et al. 2004; Tsonos 2007; Ilki et al. 2004, 2009 and 2011), several researchers studied the performance of RC members strengthened in flexure with near surface mounted (NSM) FRP rods or pultruded laminates (Nanni et al. 1999; DeLorenzis et al. 2004; El-Hacha and Rizkalla 2004; Barros et al. 2006; De Lorenzis and Teng 2007; Seracino et al. 2007; El-Maaddawy and El-Dieb 2011). Only very few studies on flexural retrofitting by using FRPs cover cyclic loading conditions (Sena Cruz et al. 2006; Badawi and Soudki 2009; Ceroni 2010), whereas the reversed cyclic loading conditions (which may represent seismic actions) were studied only by Bournas and Triantafillou (2009) and Goksu et al. (2012), according to the authors' best knowledge. In the study of Goksu et al.(2012), which was the precursor of this study, the possibility of using carbon FRP longitudinal (rod, laminate, sheet) and transverse (sheet) reinforcement for the flexural seismic retrofit of low strength reinforced concrete members under reversed cyclic loading conditions was investigated. In that study, enhancement in the flexural capacity was observed until large drift ratios (approximately 6% drift ratio). Moreover, after trying several anchorage types, the most effective anchorage detail was obtained, and was also utilized in the current study. The major difference between the current study and the work reported by Goksu et al. (2012) is the different type of FRP reinforcement utilized in the current study. The reason of utilizing AFRP reinforcement in the current study is the expectation of potentially better performance of AFRP due to its better toughness characteristics. For assessing the potential better performance of longitudinal AFRP reinforcement for seismic flexural retrofitting, in this study, four cantilever RC column specimens were constructed using low-strength concrete and plain bars for representing relatively old sub-standard structures. Then, the specimens were tested under reversed cyclic lateral and constant axial loads before and after retrofitting with embedded AFRP pultruded laminates to obtain enhancement in flexural strength. It should be noted that many existing structures, among other deficiencies, suffer from lack of sufficient flexural strength against seismic actions. While the applied retrofitting technique is similar to near surface mounting (NSM) technique in terms of mechanical contribution of FRP reinforcement to the flexural strength, unlike NSM technique, the external reinforcement was bonded over the core concrete after removal of the concrete cover. After placement of FRP reinforcement, the cover concrete is formed again using high-strength repair mortar. Furthermore, as the final stage of seismic retrofit, the strengthened column is externally jacketed with FRP sheets. It should be noted that the removal process of concrete cover is much easier in case of low-strength concrete and it is generally necessary in practice due to corrosion of internal steel reinforcing bars. While generally, carbon or glass FRPs are used for seismic retrofitting, AFRP laminates are used in this study because of their higher toughness and higher deformation capacity with respect to carbon and glass fibers. The main test variable was the detail of anchorage of longitudinal AFRP laminates to the footing. The efficiency of the proposed retrofitting technique was examined considering the indicators of seismic performance such as strength and drift capacity.

2 TESTING PROGRAM

2.1 ***Specimens***

Four sub-standard symmetrically reinforced cantilever RC columns were tested under reversed cyclic lateral and constant axial loads. Axial load was kept constant at approximately 20% of the axial load capacity (without consideration of the reinforcement) of the specimens. The geometry and the reinforcement details of the specimens are presented in Fig. 1. As seen in this figure, the longitudinal bars were (4ϕ14) continuous from the bottom of the footing to the top of the specimen. All internal reinforcing bars were plain round bars, which have been used commonly until 1990s in Turkey. The concrete was intentionally designed to be of poor quality to represent relatively old buildings.

All specimens were identical (before retrofitting) and flexure-critical. The aim of the proposed retrofitting technique is the enhancement of flexural capacity under cyclic lateral loading in the presence of constant axial loading. On the other hand, like many existing sub-standard RC frame members, the transverse reinforcement of the specimens was also insufficient causing deficiencies in terms of ductility and shear strength. Therefore, after retrofitting through longitudinal reinforcement, the columns were also confined externally with CFRP sheets in transverse direction.

All the specimens except the reference one (REF) were retrofitted with aramid pultruded laminates in longitudinal direction (LAM, LAM-LAM, LAM-PB). Additional aramid pultruded laminate anchor was used for the specimen LAM-LAM with respect to the specimen LAM, while the first 10 mm of the longitudinal aramid laminate reinforcement at the interface of the column-foundation was partially bonded by using insulating tape with the specimen LAM-PB. Details on each retrofitting scheme are presented in "Retrofit Application".

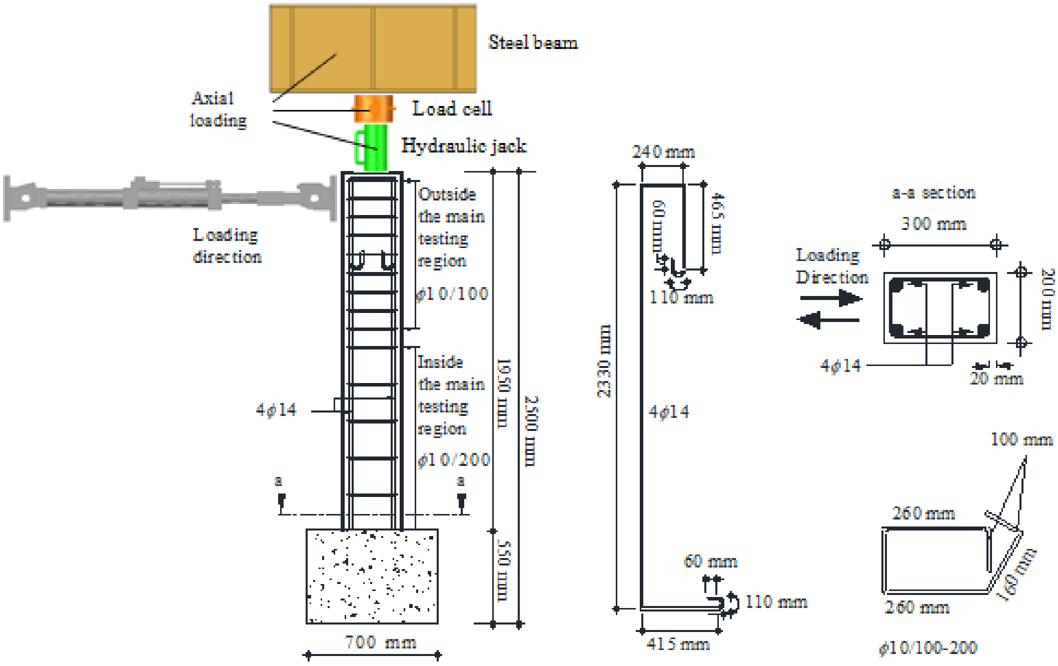


Figure 1. The geometry and reinforcement details of the tested columns.

2.2 *Material Characteristics*

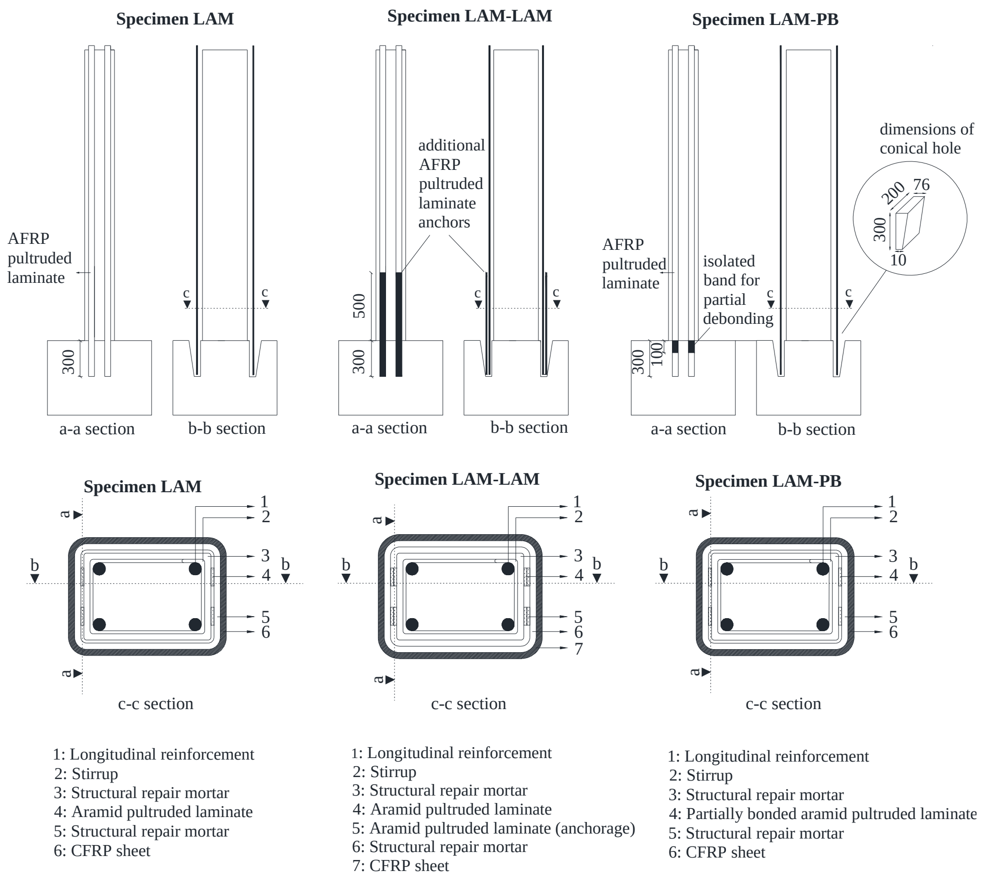
The average compressive strength of concrete at the time of testing was 10 MPa (obtained from compression tests of 150 mm×300 mm cylinder specimens). The average mechanical characteristics of 14 mm diameter longitudinal and 10 mm diameter transverse bars are given in Table 1. In this table; f_y, f_{max}, f_u are yield, maximum and ultimate tensile stresses, and ε_y, ε_{max} and ε_u are the tensile strains corresponding to f_y, f_{max} and f_u, respectively. As shown in Fig.2a, two different types of FRP reinforcement were used in retrofitting; AFRP pultruded laminates in longitudinal and CFRP sheets in transverse direction. The geometrical and mechanical characteristics of the pultruded aramid laminates and carbon sheets are presented in Table 2. In this table, t_f, w_f and E_f are the effective thickness, the effective width and the tensile elastic modulus of FRP reinforcement. The appearances of the laminates and sheets used in the study are presented in Fig. 2b. The compressive strengths of the cement based structural repair mortar used for forming the new concrete cover, the epoxy adhesive used for bonding the pultruded laminates to the member surface (after flattening of the core concrete using a thin layer of the cement based structural repair mortar), the epoxy adhesive used for bonding CFRP sheets in transverse direction to the member surface (after application of the cement based structural repair mortar over the AFRP laminates to form the cover concrete), and the epoxy grout used for anchoring aramid laminates in the footing were 50, 75, 60 and 80 MPa (after 7 days of age), respectively.

Table 1. The mechanical characteristics of reinforcing bars

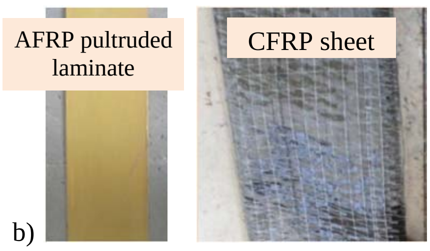
Reinforcing bars	f_y (MPa)	ε_y	f_{max} (MPa)	ε_{max}	f_u (MPa)	ε_u
ϕ14	296	0.0015	398	0.2092	250	0.3066
ϕ10	315	0.0014	400	0.2170	270	0.3164

Table 2. Characteristics of FRP reinforcement

FRP reinforcement	E_f (N/mm^2)	t_f (mm)	w_f (mm)	Ultimate strain
Pultruded Laminate (Aramid)	70000	1.4	42	0.023
Sheet (Carbon)	230000	0.166	500	0.015



a)



b)

Figure 2. a) The retrofit schemes of the specimens (Note: Dimension units in mm), b) The surface appearance of the FRP reinforcement.

2.3 Retrofit Application

Three specimens were retrofitted with AFRP reinforcement for enhanced flexural capacity through additional longitudinal FRP reinforcement, embedded within the cover concrete (after removal of weak cover) and anchored to the existing footing. The retrofitting details and the application stages are presented in Figures 2-3, respectively. As seen in these figures, firstly the weak concrete cover was removed for more effective utilization of AFRP reinforcement in longitudinal direction by avoiding premature cover spalling off and providing a better bond to existing concrete. Furthermore, such an application allows better representation of basic corrosion repair procedure, which is generally observed on the columns of existing structures built with low-quality concrete. In the proposed retrofit method, the AFRP reinforcement was bonded on a thin layer (10 to 20 mm) of high strength cement based structural repair mortar placed over the core concrete, and concrete cover was formed over the AFRP reinforcement using another layer of high strength repair mortar. Furthermore, placing the AFRP reinforcement between the core concrete and newly formed high quality concrete cover, as done in this study and in Goksu et al. (2012), is more advantageous due to prevention of buckling of FRP reinforcement under compression and also leads to better bond between FRP reinforcement and concrete. Buckling of NSM FRP bars have been observed during the reversed cyclic tests carried out by Bournas and Triantafillou (2009). Therefore, after installation of FRP reinforcement and formation of concrete cover with high strength repair mortar, CFRP sheets were wrapped around the columns in transverse direction to improve column performance by avoiding buckling of AFRP laminates under compression as well as for enhancing the deformability through confinement action and to avoid potential shear damages failure due to increased flexural strength. Other function of the CFRP sheets wrapped around the members in transverse direction was to contribute to the bond between the AFRP reinforcement and surrounding repair mortar. Additionally, FRP confinement is believed to enhance the bond between the core concrete and repair mortar placed beneath and over the FRP reinforcement. In Fig. 3, each step of retrofitting scheme is presented. As the first step, the concrete cover was removed until the longitudinal bars were exposed (Fig. 3a). Then, a thin layer of cement based structural repair mortar was applied to obtain a flat surface over the steel reinforcement (Fig. 3b). After the preparation of pultruded aramid laminates, epoxy based primer was applied over the repair mortar in order to increase the adhesion (Fig. 3c). For all specimens, two pultruded AFRP laminates of 1.4 mm thickness and 42 mm width were placed symmetrically on each side, with an anchorage length of 300 mm and bonded to the substrate by using a high strength epoxy adhesive. For the connection of the AFRP longitudinal reinforcement to the footing, conical holes were opened in the footing (Fig. 2a). Additional AFRP laminates of 800 mm length were used at the column-footing interface for enhanced anchorage of the longitudinal AFRP reinforcement of the specimen LAM-LAM (Fig. 3d). The 300 mm long part of the AFRP anchor laminates was inserted into the opened conical hole. While epoxy paste was used for bonding AFRP anchorage laminates near the longitudinal AFRP reinforcement in the footing, they were anchored to the footing (in the pre-opened conical hole) together with the longitudinal AFRP reinforcement by using epoxy grout. In case of specimen LAM-PB, the top 100 mm long part of the longitudinal AFRP reinforcement in the conical hole was wrapped with a plastic isolating band in order to create a partially bonded anchor (Figs. 2a and 3e). Therefore, total bonded lengths of the AFRP reinforcement were 200 mm (rather than 300 mm) for specimen LAM-PB. Partial debonding of AFRP reinforcement in the anchorage zone was for examining; i) whether 200 mm long anchorage is sufficient for transferring stresses, ii) whether the local damage of the AFRP reinforcement at the interface of column and footing can be avoided through prevention of localization of stresses at this critical zone. After all, a layer of cement based repair mortar was applied to bring the column cross-section to its original dimensions

(200×300 mm) (Fig. 3f). As a final step, two plies of CFRP sheets were wrapped around all retrofitted specimens, externally in transverse direction with 200 mm overlap at the end of the wrap (Fig. 3g).

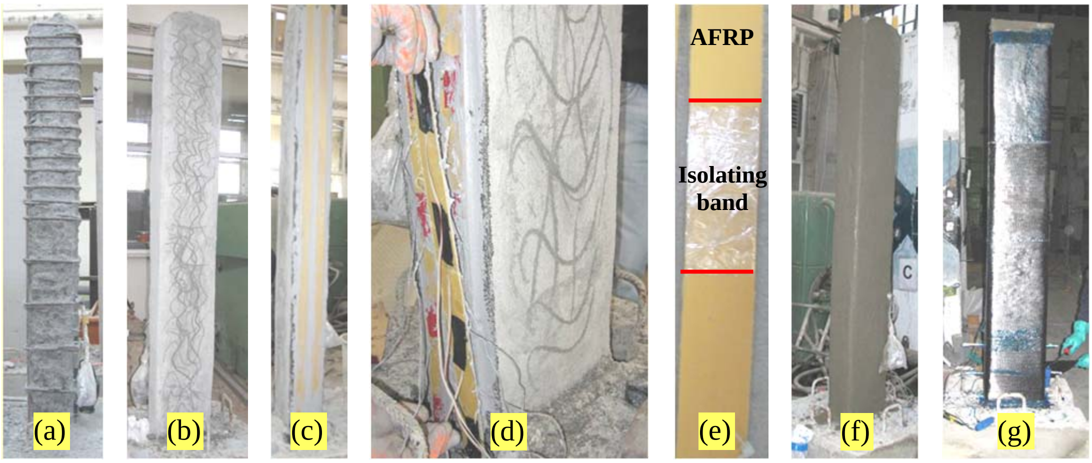


Figure 3. a) Removal of cover concrete, b) Application of a thin layer of cement based structural repair mortar to obtain a flat surface, c) Installation of the AFRP pultruded laminates (the specimen LAM), d) Application of additional AFRP laminate anchorages (only for the specimen LAM-LAM), e) Wrapping with a plastic isolating band (only for the specimen LAM-PB), f) Application of last layer of structural repair mortar, g) Wrapping with CFRP sheets in transverse direction.

2.4 Test Setup

The specimens were tested under reversed cyclic lateral loads in a quasi-static displacement-controlled manner. Target lateral drift ratios calculated as the ratio of the lateral displacement of the tip of the specimen (at the axis of actuator) to the specimen height (from bottom of the column to the height of column at the axis of actuator) were ±0.1, ±0.25, ±0.5, ±1, ±2, ±3, ±4, ±6 and ±8% in pushing and pulling directions. During application of lateral displacement reversals, the columns were also subjected to a constant axial load (120 kN). The axial load corresponded to approximately 20% of the axial load capacity of the column without consideration of the reinforcement. Other than large number of displacement transducers, a number of straingages were also used on steel bars and AFRP pultruded laminates in longitudinal direction and on stirrups in transverse direction.

3 RESULTS AND DISCUSSION

The test results are outlined through hysteretic load-displacement curves and envelopes of these relationships. The hysteretic lateral load-displacement relationships and their envelopes are presented in Fig. 4 and Fig. 5, respectively. As seen in Figs. 4 and 5, the reference specimen exhibited a ductile behavior. The specimen LAM, retrofitted with AFRP pultruded laminates, experienced an enhancement in strength up to the drift ratio of 3%. At this drift the enhancement in strength was around 38% with respect to the reference specimen. The sudden remarkable loss of strength upon exceeding the drift ratio of 3% was due to the fracture of AFRP reinforcement at the interface of the member and the footing. Therefore, it is clear that the full capacity of the AFRP reinforcement was utilized. The behavior of this specimen was quite similar to the reference specimens after failure of the AFRP reinforcement.

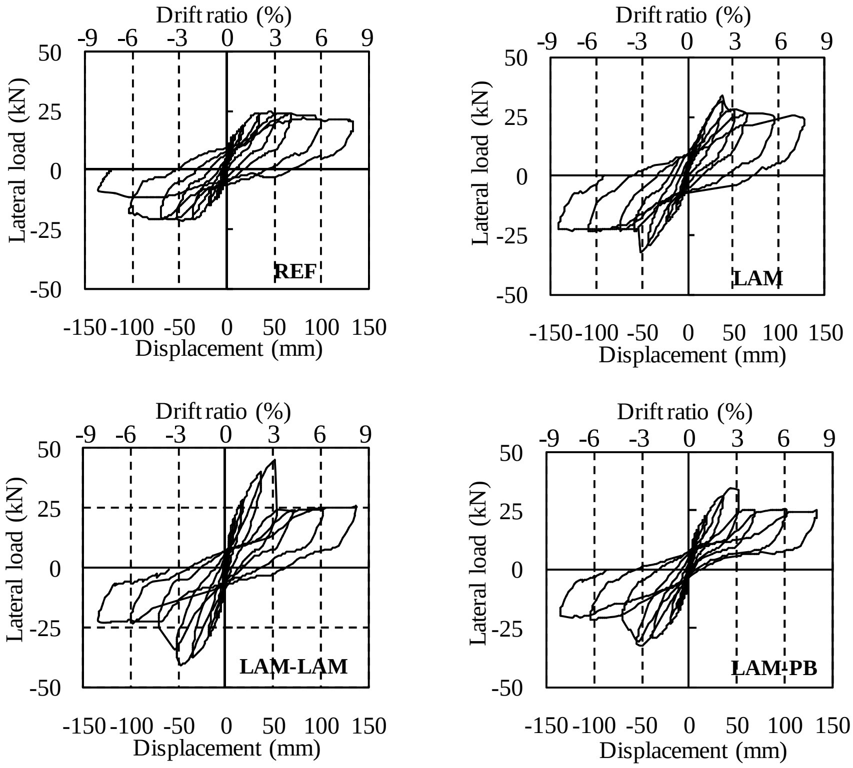


Figure 4. Lateral load-displacement curves for all specimens.

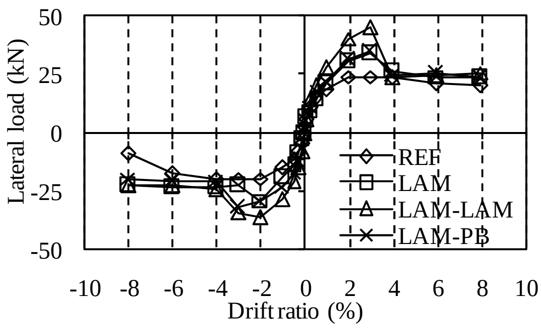


Figure 5. The envelopes of load-displacement relationships.

The specimen LAM-PB exhibited a similar behavior with the specimen LAM in terms of maximum lateral load and the failure of AFRP reinforcement. While the enhancement in strength was around 41% with respect to the reference specimen at 3% drift ratio. The sudden remarkable loss of strength upon exceeding the drift ratio of 3% was due to the fracture of AFRP reinforcement at the isolated section. As seen in Figs. 4 and 5, and as expected, the specimen LAM-LAM exhibited a remarkably superior performance with respect to the reference and other retrofitted specimens. The specimen LAM-LAM resisted lateral loads, approximately 1.8 and 1.3 times that of the reference and other retrofitted specimens, respectively. As seen in Figs. 4 and 5, the specimen LAM-LAM sustained its lateral load capacity at drift ratio of 3%, around which the AFRP reinforcement and AFRP anchors fractured. The higher strength of the specimen LAM-LAM is due to the contribution of AFRP anchor laminates, which have sufficient development length in the column section. It is important to note that, since the specimens were wrapped with CFRP sheets in transverse direction through the height of the column; all damage was accumulated at the base of the column. Consequently, the crack width reached several centimeters at the intersection of the column and the footing. This type of damage may be quite disadvantageous in case of seismic events due to prevention of the distribution of plastic deformations through the potential plastic hinge length resulting from presence of a rigid transverse CFRP jacket. The accumulation of a remarkable portion of plastic deformations only at the interface of the column and the footing may significantly reduce the drift capacity of the structural member. The strengths of the retrofitted specimens were lost right after exceeding the drift ratio of approximately 3%, both in pushing and pulling directions.

As it is seen in Figs. 4-5, and as expected, the reference specimen behaved in a remarkably ductile manner since it was under-reinforced and was designed to fail in flexure. However, the retrofitted specimens experienced a quite sudden loss in strength due to the failure of longitudinal AFRP reinforcement. It should be noted that the linear elastic AFRP reinforcement could be utilized perfectly in case of all retrofitted specimens, since the longitudinal AFRP reinforcement ruptured in all cases.

4 CONCLUSIONS

In this paper, the performance of using embedded AFRP reinforcement for the flexural seismic retrofit of low-strength RC columns under constant axial and reversed cyclic lateral loading was investigated. Using the proposed retrofitting technique, a remarkable enhancement was obtained in flexural strength. In addition, potential buckling and debonding of AFRP reinforcement and shear damages could be avoided until large cyclic drifts. All retrofitted specimens experienced the rupture of the longitudinal AFRP reinforcement at the drift ratio of approximately 3%. The additional anchors used in the specimen LAM-LAM, behaved as an additional flexural reinforcement due to its sufficient development length in the column section (500 mm) resulting with a higher lateral load capacity.

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