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Efficient parameters to predict the nonlinear behavior of FRP retrofitted RC columns

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Abstract. While fiber-reinforced plastic (FRP) materials have been largely used in the retrofitting of concrete buildings, its application has been limited because of some problems such as de-bonding of FRP layers from the concrete surface. This paper is the part of a wide experimental and analytical investigation about flexural retrofitting of reinforced concrete (RC) columns using FRP and mechanical fasteners (MF). A new generation of MF is proposed, which is applicable for retrofitting of RC columns. Furthermore, generally, to evaluate a retrofitted structure the nonlinear static and dynamic analyses are the most accurate methods to estimate the performance of a structure. In the nonlinear analysis of a structure, accurate modeling of structural elements is necessary for estimation the reasonable results. So for nonlinear analysis of a structure, modeling parameters for beams, columns, and beam-column joints are essential. According to the concentrated hinge method, which is one of the most popular nonlinear modeling methods, structural members shall be modeled using concentrated or distributed plastic hinge models using modeling parameters. The nonlinear models of members should be capable of representing the inelastic response of the component. On the other hand, in performance based design to make a decision about a structure or design a new one, numerical acceptance should be determined. Modeling parameters and numerical acceptance criteria are different for buildings of different types and for different performance levels. In this paper, a new method was proposed for FRP retrofitted columns to avoid FRP debonding. For this purpose, mechanical fasteners were used to achieve the composite behavior of FRP and concrete columns. The experimental results showed that the use of the new method proposed in this paper increased the flexural strength and lateral load capacity of the columns significantly, and a good composition of FRP and RC column was achieved. Moreover, the modeling parameters and acceptance criteria were presented, which were derived from the experimental study in order to use in nonlinear analysis and performance-based design approach.

Keywords: FRP; performance based design; nonlinear modeling parameters; RC columns; flexural strengthening

1. Introduction

Precast For evaluating the seismic performance of a structure, forces and displacements of the structure should be determined by a suitable analysis method (Ghodrati *et al*. 2009, Ahmadi *et al*. 2019). Generally, in order to evaluate the performance of a structure, nonlinear methods are used (Nicknam *et al*. 2008, Mahdavi *et al*. 2012, Ahmadi and Daneshjoo 2012). The nonlinear analyses help to understand the actual behavior of the structure by specifying the failure mode of the structure and structure collapse (ASCE/SEI 41-13 2014). In general, to perform nonlinear analyses, it is necessary to specify the failure mechanism and non-linear properties of the members (Pakar *et al*. 2014, Bayat *et al*. 2018). Accurate determination of the seismic performance of a structure requires realistic approximation of the seismic characteristics of its elements. The desirable characteristics are the relationships between forces (axial force, bending or shear) and nonlinear displacements (displacement, rotation or drifts) (ASCE/SEI 41-13 2014).

Usually, the behavior of structural components during the earthquake is characterized by modeling parameters and acceptance criteria. The modeling parameters and numerical acceptance criteria for RC columns were studied in many research (Panagiotakos and Fardis 2001, Elwood *et al*. 2007, Elwood and Eberhard 2009, Berry and Eberhard 2007, Nojavan *et al*. 2017) and were discussed by various versions of the seismic rehabilitation standards such as FEMA273(1997), FEMA 356 (2000) and ASCE/SEI 41-06 (2007). Various characteristics of the nonlinear behavior of RC columns, including stiffness, yield and ultimate strength and ductility, could be estimated using the mentioned parameters. However, when a new method is introduced for retrofitting RC columns these parameters would change and should be defined to use in nonlinear analysis.

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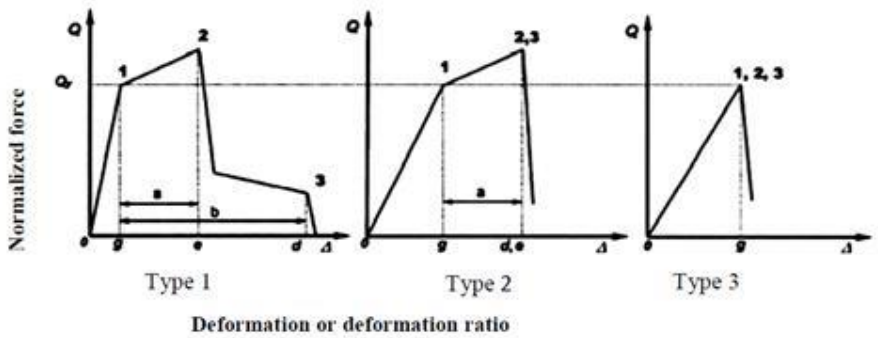

Fig. 1 General force-displacement curves of structural members (ASCE/SEI 41-13 2014)

Moreover, FRP as a new material for rehabilitation has many challenges in practical using. One of the important challenges is the brittle behavior of RC members strengthened with FRP due to rupture or debonding of FRP (Bonacci and Maalej 2001, Buyukozturk *et al*. 2004, Kim *et al*. 2011, Xu *et al*. 2011,Deng *et al*. 2016, Khatibinia and Mohammadizade 2017, Mohseni and Ng 2017, Jiao *et al*. 2017,Hoque and Jumaat 2018). Although in recent research, the use of MFs is emerging as a solution to improve the structural behavior of FRP-strengthened members (Lamanna 2004, Ekenel *et al*. 2006, Bank and Arora 2007, Martin and Lamanna 2008, Jumaat and Alam 2010). In general, the primary role of FRP anchorage is to prevent or delay the process of debonding. However, in some cases, they are used to prevent sudden brittle failure and provide the load transfer mechanism at the critical sections and ductile failure mode for the structural members (Rizzo *et al*. 2005, Gamino*et al*. 2009, Napoli *et al*. 2010, Hosen *et al*. 2015, Saribiyik and Caglar 2016).

In this paper, a new method was proposed for retrofitting RC columns using FRP and MF. Consequently, to use this new method of retrofitting, modeling parameters and numerical acceptance criteria were proposed to define non-linear properties of these members to use in nonlinear analysis approach in Practicing engineering.

2. Theoretical basis

2.1 Performance based design

In recent years, the design of seismic-resistance structures has been changed widely and the emphasis shifting from “strength” to “performance”. Different studies show that increasing strength may not improve safety, nor essentially reduce damage (ATC-40 1996). Structural designers use inelastic analysis methods for the evaluation and retrofitting of existing buildings and other structures, as well as the design of new constructions. The practical purpose of nonlinear seismic analysis is to estimate the probable behavior of the structure in future earthquakes. This has become ever more essential with the appearance of performance-based engineering (PBE) as a procedure for seismic assessment and design. PBE uses the prediction of structural performance to decide about the safety of structures. For this purpose, PBE describes performance, principally in terms of expected damage to structural and nonstructural elements (ATC-40 1996, BSSC 2001).

In general, most of the codes are based on similar procedures that rely on nonlinear analysis methods to estimate structural demands. However, the most important procedure in the prediction of a force-deformation curve of the structure is the estimation of nonlinear characteristics of the structural elements includes post-elastic strength and deformation properties beside the elastic behavior (ASCE/SEI 41-13 2014). The nonlinear properties of the structural elements are normally based on approximations obtained from theoretical analyses or experimental results.

2.2 Modeling of seismic behavior of structural components

According to ASCE/SEI 41-13 (2014), the general forms of the lateral force-displacement behavior of displacement-controlled structural elements could be represented in three types. As it is shown in Figure 1 the type 1 curve represents ductile behavior, which is displaying an elastic range from the point 0 to 1 on the curve and a plastic range from the point 1 to 3. The loss of seismic -resisting capacity and gravity load-resisting capacity happens at point 4.

The type 2 curve represents of ductile behavior where there is an elastic part and also a plastic part. In this type extensive loss of seismic- resisting capacity happens at point 3 and the Loss of gravity-load resisting capacity occurs at the point 4.

Finally, The type 3 curve shows a brittle or nonductile behavior covering an elastic range and the loss of seismic-resisting capacity at point 3 and loss of gravity-load resisting capacity at the point 4 (ASCE/SEI 41-13 2014)

So it is obvious from Figure 1 the main parameters that identify the seismic behavior of these elements are values of the parameters “a” and “b” that will be called the modeling parameters hereafter.

2.3 The modeling parameters and acceptance criteria

Practical estimation of the seismic performance of a structure requires nonlinear analyses. In nonlinear procedures, the load-deformation response of the structural elements should be determined by nonlinear load-deformation relations. The nonlinear load-deformation relations are estimated based upon experimental results or taken from quantities specified in codes. Figure 2 shows the

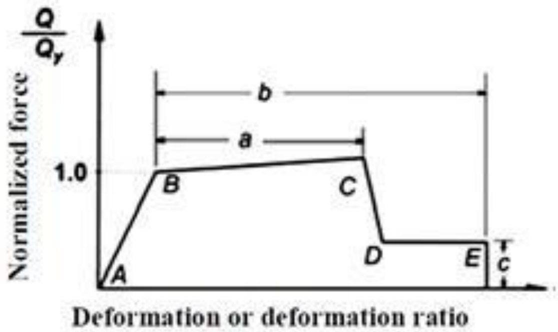

Fig. 2 Generalized component force-deformation relations for depicting modeling and acceptance criteria (ASCE/SEI 41-13 2014)

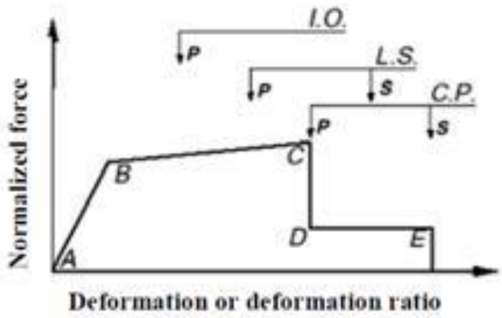

Fig. 3 Acceptance criteria illustration (ASCE/SEI 41-13 2014)

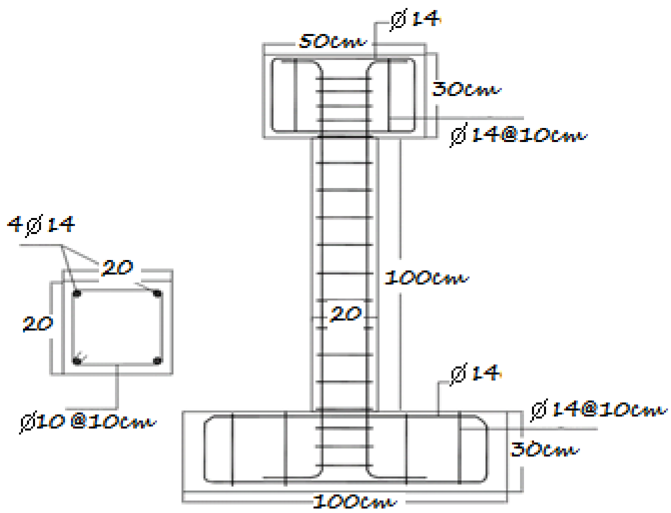

Fig. 4 Geometry of the RC columns

generalized force-deformation curve used throughout ASCE/SEI 41-13 (2014) to specify concrete element modeling and acceptance criteria for deformation-controlled actions in concrete members.

Different structural performance necessities might be preferred for a structure according to the type of building and time periods of concern. Three types of Structural Performance Levels are defined in ASCE/SEI 41-13 (2014): Immediate Occupancy, Life Safety, and Collapse Prevention. "Immediate Occupancy", is defined as the post-earthquake damage state in which a structure remains safe to occupy and essentially retains its pre-earthquake strength and stiffness.

"Life Safety", is defined as the post-earthquake damage state in which a structure has damaged components, but retains a margin against the beginning of partial or total collapse. "Collapse Prevention", is defined as the post-earthquake damage state in which a structure has damaged components and continues to support gravity loads but retains no margin against collapse (ASCE/SEI41-13 2014).

The acceptance criteria for deformation-controlled members used in nonlinear procedures shall be the deformations corresponding with the following points on the load-deformation curves of the members (Fig. 3). Immediate Occupancy is the deformation at which permanent, visible damage occurred and refers to point 2. Immediate Occupancy is limited to 67% of the deformation limit for Life Safety specified in Figure 3 Life Safety is 0.75 times the deformation at point E and Collapse Prevention is 1.0 times the deformation at point E on the curve (ASCE/SEI 41-13 2014).

3. Experimental program

3.1 Specimens

Five column specimens of an approximately 1/3 scale were tested in International Institute of Earthquake Engineering and Seismology laboratory. This is a summary of the basic content of the experiments. The column height of all specimens was 1000mm, and the cross-section was 200mm in width and depth. The columns were reinforced with four bars of 14mm diameter, and the volumetric ratio of the longitudinal steel was 1.53%. Transverse reinforcement was steel stirrups with 10mm diameter spaced 100mm centers. The geometry of the model is depicted in Figure 4.

For flexural strengthening of the RC columns, the conventional method was used beside the new proposed MF-FRP method. Two of the specimens were retrofitted using the conventional method and FRP layers which were bonded to the concrete surface using epoxy resin. For the

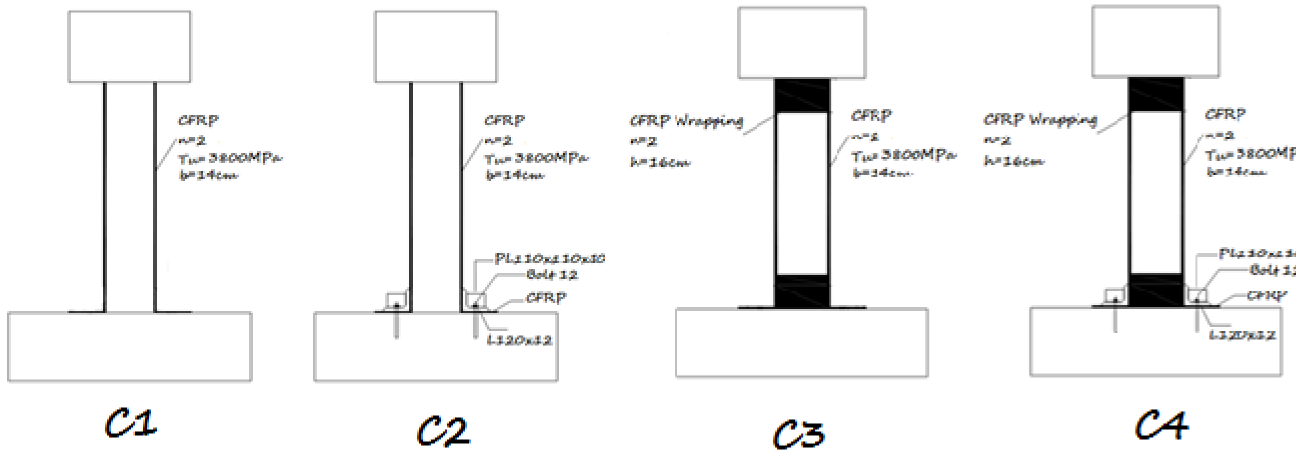

Fig. 5 FRP strengthening layouts

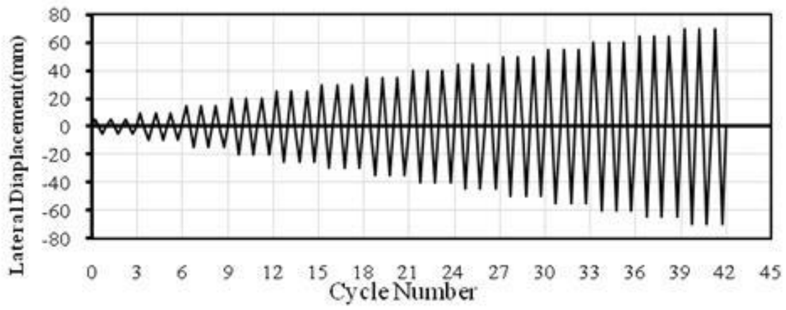

Fig. 6 Loading protocol

two other RC columns, mechanical fasteners (MFs) were used to fix the FRP layers to the RC column and especially the column-to-foundation connection. After FRP layers were bonded to the concrete surface using epoxy resin the anchorage system was assembled to avoid FRP debonding.

The characteristics of the five specimens were defined as:

- C0 was left unstrengthened to serve as the reference specimen.
- C1 was strengthened using the longitudinal FRP layers.
- C2 is similar to C1 but using FRP jackets in both top and bottom of the column to confine the concrete in plastic hinge zones.
- C3 was strengthened using the longitudinal FRP layers and mechanical fasteners.
- C4 was strengthened using the longitudinal FRP layers and mechanical fasteners and FRP jackets used in plastic hinge zones.

Fig. 5 shows the detail of the retrofitted columns and Table 1 shows the material properties.

For both C2 and C4 column's transverse layers of FRP were used to confine the concrete of plastic-hinge zones. Finally, for C3 and C4, MFs were used to fix the FRP layers to the RC column substrate and foundation. Foundation connection obtained using an angle bolted to the foundation and RC column.

Table 1 The material properties

Row	Material	Properties
1	Concrete	f'_c=22.51 (MPa),E=22.81 (GPa), ε_o=0.002
2	Steel bars- Φ14	f_y= 411.6 (MPa),E=182 (GPa)
3	Steel stirrups- Φ10	f_y= 322.4 (MPa),E=142 (GPa)
4	FRP Sheet	F_{au}=3800 (MPa), E=240 (GPa), ε_{au}=0.0155
5	Epoxy Resin	F_{au}=54 (MPa) , E=3 (GPa), ε_{au}=0.025

Table 2 Modeling parameters for C0 specimen

Specimen	Modeling parameters (ASCE/SEI 41-13 2014)		Modeling parameters (experimental data)		Force-Deformation curve points		
	a	b	a	b	Point 1	Point 2	Point 3
C0	0.0248	0.047	0.023	0.0495	0.012	0.035	0.0615

3.2 Specimens

The test setup consisted of reaction frame supporting lateral and vertical hydraulic actuator so retrofitted columns tested under combined axial and lateral loads. Before the application of the lateral load, RC columns first were loaded with constant axial load using a hydraulic jack at the top. The 200kN axial load applied primarily is approximately 25% of ultimate axial load capacity. After initial axial

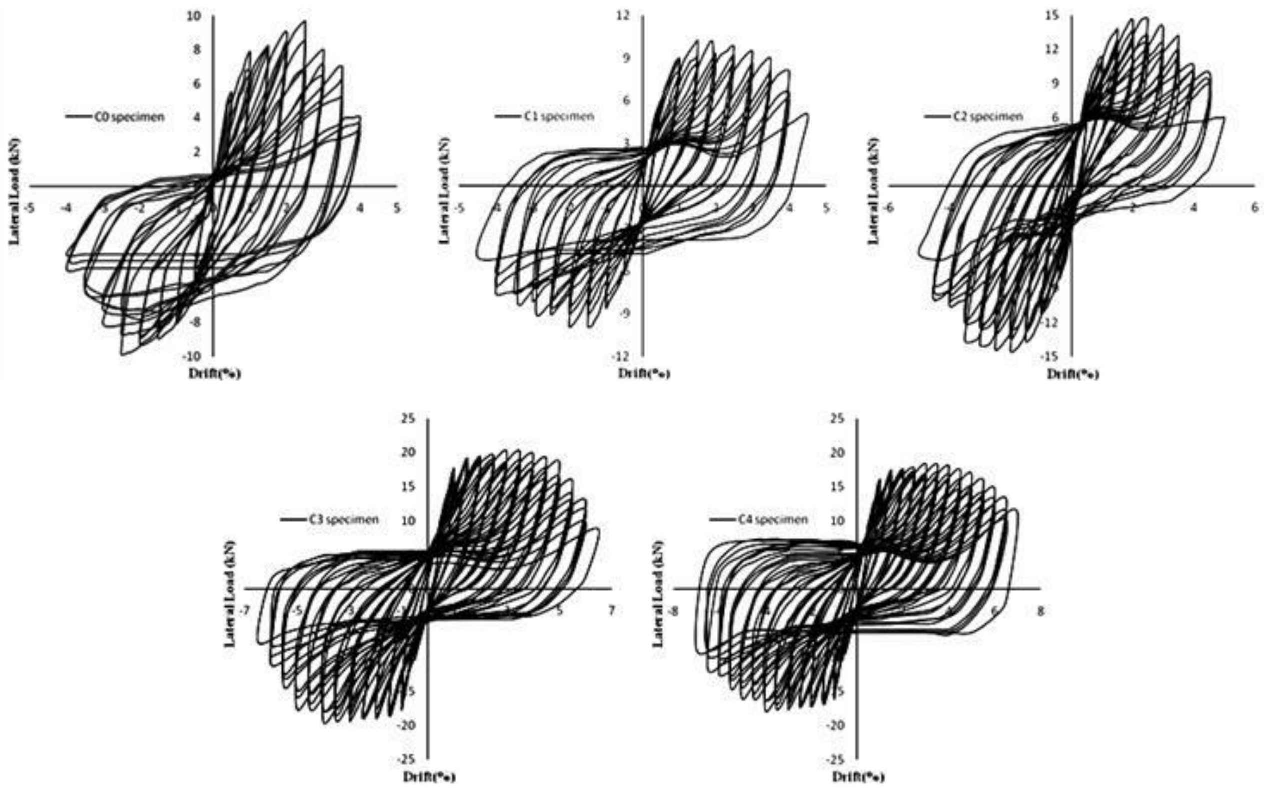

Fig. 7 Hysteresis curves for all of the specimens

loading, the lateral load was applied in a displacement control mode. Figure 6 shows the details of the loading protocol applied similarly to all the specimens.

3.3 Results of experimental approach

The failure modes of all the tested specimens were controlled by flexure due to their high ratio of transverse reinforcement and low ratio of longitudinal reinforcement. Figure 7 shows the hysteresis curves of the lateral load and lateral drift for all specimens.

4. Determination of modeling parameters and acceptance criteria of benchmark specimen

In general, modeling parameters and acceptance criteria for structural members could be derived from information contained in standards for various components. However, for new-method retrofitting members, these parameters should be derived from experimental results as they were not specifically addressed by the current standards. Since the FRP-MF retrofitted columns strengthened with a new method modeling parameters and acceptance criteria should be defined to use in practical engineering.

Therefore, to define these parameters for the FRP-MF retrofitted RC columns the standard steps in ASCE/SEI 41-13 (2014)were followed. According to this standard, the below procedure was followed to develop the modeling parameters and acceptance criteria for structural elements based upon experimental data.

1. Force–deformation curves which were developed from the experimental data, idealized using the standard methods.

2. An average of the multilinear curves derived based on the comparison of curves.

3. The estimated final curve was categorized as type 1, type 2, or type 3 as described in section 3.

4. The acceptance criteria were defined as the deformations related to the mentioned points on the force–deformation curves as discussed in section 4.

So according to ASCE/SEI 41-13 (2014) the backbone curves which were obtained from the experimental results were approximated by a series of linear segments (Figure 8). The estimated curves were categorized according to the types which were discussed in Figure 1, and the parameters “a” and “b” were derived from these curves.

In ASCE/SEI 41-13 (2014) the column behavior is classified into four major modes of flexural (condition i), shear-flexural (condition ii), shear (condition iii) and slippage of lap-splice (condition iv). This classification is performed based on the ratio of V_p/V_n, in which V_p and V_n are the shear demand due to the formation of the plastic hinges and the nominal shear strength respectively. The values of the parameters “a” and “b” for each condition has been assumed to be dependent on three parameters, including, $\frac{P}{A_g f'_c}$, $\frac{V}{b_w d \sqrt{f'_c}}$ and, $\rho = \frac{A_v}{b_w s}$, in which P: axial force, V: shear force, b_w: width of the section, f'_c: Compressive strength of concrete, d: depth of neutral axis, A_g: Area of tension steel reinforcement, A_v and s are the area and spacing between transverse reinforcements, respectively.

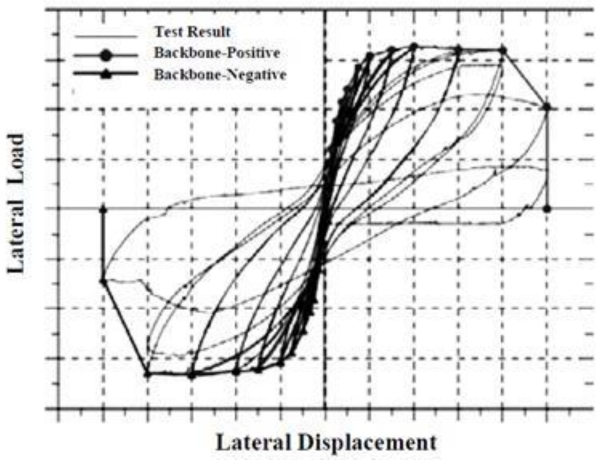

Fig. 8 Backbone curve for experimental data (ASCE/SEI 41-13 2014)

Results of the lateral tests on the first RC column as the benchmark specimen were used to determine the values of the parameters “a” and “b”. These values are summarized in Table 2 and were compared with the values which are given in ASCE/SEI 41-13 (2014).

As can be seen, the values predicted by the experimental data give acceptable estimations of the parameters “a” and “b” for predicting values of the displacement capacity of RC column. As the results shown in Table 1, the maximum error ratios of the experimentally obtained values of the parameters “a” and “b”, in comparison with those predicted by the ASCE/SEI 41-13 (2014) are 5.3% and 7% that shows the procedures to predict the values of these parameters could be accepted.

5. Determination of modeling parameters and acceptance criteria of retrofitted columns

The proposed procedures in ASCE/SEI 41-13 (2014) were used for predicting the values of the displacement capacity of RC columns. These proposed values are summarized in Table 3. Comparing the results was shown in Table 2 and 3, it is clear that the values of the parameters “a” and “b” changed due to the FRP-MF retrofitting method. Therefore, the experimental results of the abovementioned specimens were used to estimate the values for the parameters “a” and “b” based on the proposed method in ASCE/SEI 41-13 (2014).

It is important to note that the levels of axial load and shear reinforcement were the same in all columns. The values of $\frac{P}{A_g f'_c}$ was 0.21 and $\frac{A_v}{b_w s}$ was 0.0078 for all specimens.

It is obvious from the results which were represented in Table 3 that the values of modeling parameters had changed due to the retrofitting methods and the old values of codes for retrofitted concrete RC columns could not estimate satisfied values for these parameters.

Moreover, in performance-based design, the adequacy of structural components must be evaluated using the acceptance criteria provided in codes for different structural elements. Therefore, it is necessary to determine the acceptance criteria for FRP-MF retrofitted method as a new method of retrofitting RC columns for using in the performance-based design. The acceptance criteria of experimental specimens were estimated using the proposed method in ASCE/SEI 41-13 (2014) which was discussed in previous sections and were shown in Table 4.

Table 3 Modeling parameters of retrofitted columns

Row	Specimens	Modeling parameters		Force-Deformation curve points		
		a	b	Point 1	Point 2	Point 3
1	C1	0.023	0.048	0.012	0.035	0.06
2	C2	0.023	0.048	0.012	0.035	0.06
3	C3	0.031	0.066	0.014	0.045	0.08
4	C4	0.032	0.067	0.013	0.045	0.08

Table 4 Acceptance criteria of retrofitted columns

Row	Specimens	Acceptance Criteria		
		IO	LS	CP
1	C1	0.015	0.022	0.03
2	C2	0.015	0.022	0.03
3	C3	0.022	0.034	0.045
4	C4	0.023	0.033	0.045

6. Conclusions

In FRP-retrofitted members, the bond properties are essential for the successful application, since in some cases de-bonding of FRP layers from the concrete surface could change the seismic behavior of these members. In this paper to avoid FRP debonding and in order to get a better composite behavior between concrete and the FRP layers in retrofitted RC columns, a newly designed connection was introduced and tested.

Moreover, for Seismic evaluation and retrofitting of existing buildings, force-displacement behavior of the structure should be defined to estimate the capacity and demand of the structure during the earthquakes. So, nonlinear analysis of the structure should be used to estimate the force-displacement behavior of the structure. Different methods proposed to analyze a structure nonlinearly such as concentrated hinge model which most of the standards confirmed the efficiency of this method. For nonlinear analysis of a structure, the load-deformation response of the structural elements should be characterized by modeling parameters. These parameters might be defined based on quantities specified in codes. However, the standards provide and suggest these parameters for common details and behavior observed in past earthquakes that are found in common building types. Since every structure is unique and may contain features and details that are not covered by these standards, when a new method is introduced by literature, the useful parameters should be defined to use in nonlinear analysis and performance-based design in practical engineering.

In this study, five column specimens were tested under axial and lateral loads. The first specimen was the benchmark, two of the specimens were retrofitted conventionally using FRP and two of them were retrofitted using MFs and FRP. The nonlinear force-displacement behavior of RC column specimens was estimated from the experimental results and the two parameters which were named “a” and “b” in the seismic rehabilitation standards were derived for the RC retrofitted columns. So to model the nonlinear behavior of the RC columns retrofitted using these methods these parameters might be used in nonlinear modeling procedures.

Moreover, the acceptance criteria which were introduced as the Limiting values of properties in standards, such as inelastic deformation and used to determine the acceptability of the RC retrofitted column at a given Performance Level, were estimated and proposed for FRP-retrofitted RC columns with new and conventional methods to use in performance-based design.

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