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Research Paper

Cyclic and Monotonic Behavior of Strengthened and Unstrengthened Square Reinforced Concrete Columns

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Abstract. The use of composite materials is an effective technique to enhance the capacity of reinforced concrete columns subjected to the seismic loading due to their high tensile strength. In this paper, numerical models are developed in order to predict the experimental behavior of square reinforced concrete columns strengthened by glass fiber reinforced polymer and steel bars and unstrengthened column under cyclic and monotonic loadings, respectively. Two columns are modeled in the present work. The first one corresponds to the column without strengthening subjected to lateral monotonic loading, and the second one corresponds to the column strengthened by glass fiber reinforced polymer and steel bars subjected to lateral cyclic loading. Comparison of the numerical modeling and the experimental laboratory test results are performed and discussed. A good agreement between the numerical and experimental force-displacement responses is obtained. Moreover, improvements in the strength of the reinforced concrete column subjected to the cyclic loading along with the comparison of the behavior of the strengthened column with the unstrengthened reference column are discussed. The results show a good improvement in the load carrying capacity and ductility of the column. The main objectives of this numerical modeling are to contribute the comprehension of the monotonic and cyclic behavior of the square reinforced concrete columns and to compare the numerical results with the experimental ones.

Keywords: GFRP; RC Columns; Numerical modeling; Experimental tests; Strengthening.

1. Introduction

Composite materials have gained acceptance among civil engineers [1-8]. In particular, fiber-reinforced polymers (FRP) are becoming a viable choice for reinforcing and strengthening reinforced concrete (RC) structures. They offer many functional advantages including lightness, mechanical and chemical resistance, reduced maintenance, and freedom of form. They also enrich the design possibilities for lightening the structures and perform several functions suitable for complex shapes. The columns are critical elements in the reinforced concrete buildings. Partial or total failure of the whole building may happen due to the failure of the columns. The behavior of the structures under cyclic and monotonic loads can be used as a means to evaluate the behavior of structures using different types of strengthening [9, 12]. Among strengthening techniques applied for reinforced concrete structures, the use of fiber reinforced polymer composite [13-15]. This method has been widely used for reinforced concrete structures as a strengthening approach of RC columns [16, 17]. Strengthening the structural elements can increase their compressive [18, 20], shear [21-23], and flexural strength [24-26]. Finite element modelling of concrete material is a challenging task because it requires accurate definition of the concrete material model to represent the behavior of reinforced concrete structures subjected to mechanical and environmental loadings [27-37].

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Many significant researches have been dedicated to the strengthening of reinforced concrete columns using the fiber reinforced polymer and also numerous models were developed. Rahai et al. [38] studied the performance of RC columns strengthened by the carbon fiber reinforced polymer (CFRP). They considered the CFRP thickness, eccentricities, and fiber orientation as influencing parameters, and it was found that an increase in the moment capacity and stiffness along with an improvement in ductility caused a greater level of energy dissipation. Yuan and Wu [39] developed a three dimensional finite element method (FEM) to study the behavior of plastic hinges of RC columns subjected to cyclic and axial loadings. Different parameters were taken into account such as the lengths of plastic hinge zone, rebar yielding zone, and concrete crushing zone. It was found that all the zones are significantly affected by loading types. In a previous study [40], square, rectangular, and circular RC columns strengthened with fiber reinforced polymer composites were investigated using a modified concrete damaged plasticity model (MCDP). The monotonic behavior of RC columns along with the variation of input parameters of the MCDP model were studied. It was shown that the stress-strain response of RC columns strengthened by FRP is predicted by the MCDP model. Realfonzo and Napoli [41] performed experimental studies on rectangular RC columns strengthened by FRP with a high aspect ratio. The columns were subjected to an axial load and lateral cyclic loading. The influence of different parameters such as unconfined concrete strength, longitudinal steel reinforcement, strengthening system, and number of FRP layers was evaluated. Sun et al. [42] performed experimental tests on RC columns strengthened by different reinforcement types including sleet bars, hybrid steel-FRP bars, and steel-FRP composite bars subjected to cyclic loading. The results showed that the strain distributions of the columns reinforced by different bars at the column base prior yielding, the decrease of the loading capacity, and the concentration of the plastic deformation of the ordinary RC column at its base after yielding are similar. Ma et al. [43] investigated the crack process of FRP-strengthened RC column under lateral cyclic loading based on the acoustic emission technique. It was found that the acoustic emission is an effective method that reveals the crack process of both FRP-strengthened and unstrengthened RC columns subjected to cyclic loading.

Although a lot of research have been devoted to the behavior of circular columns, fewer investigations have been conducted on square and rectangular RC columns. Moreover, the vast majority of the columns used in building construction are square and rectangular columns. In this paper, numerical modeling of square RC column strengthened by the glass fiber reinforced polymer (GFRP) as well as steel bars, and unstrengthened square RC column subjected to lateral cyclic and monotonic loadings is presented. The numerical models are developed to predict the experimental behavior of the square columns under lateral cyclic and monotonic loadings. It is also described that strengthening by GFRP and steel bars contributes to the improvement of the stiffness and ductility of the RC column subjected to lateral cyclic loading.

2. Experimental Program

According to the experimental tests [44] (Figs. 1 & 2), two columns are studied in the present study. The first column is considered without strengthening subjected to lateral monotonic loading (C1M), and the second is strengthened using glass fiber reinforced polymer and steel bars subjected to lateral cyclic loading (C7C1-BM-GW). The GFRP jackets were applied for an overlap length of 600mm from the base of the column and no anchorage of GFRP jackets to the support of the column was applied in the experimental tests (Fig. 6(c)). The strengthening with the two longitudinal steel bars was applied on left and right sides of the base of the same column and chemically anchored to the support and 2cm deep of vertical silts were cut into the cover concrete. Afterwards, the steel bars were anchored after the holes were drilled in the support of the column. Chemical anchorage was applied to the support using the resin anchor HILTI HIT-RE500 in order to place steel bars into the holes. Following the data of the resin anchor HILTI HIT-RE500 [45], 180mm of anchorage of steel bars was applied. After the anchorage of steel bars was finished, the vertical silts were filled using an epoxy mortar. The steel bars were overlapped with a distance of 700mm. The notation of the column C1M means that the concrete column is subjected to monotonic loading, and the column C7C1-BM-GW means that the concrete column (C7C1) was strengthened by metallic bars (BM) and glass FRP (GW).

Figure 4 shows the geometry and reinforcement details of the RC columns. The columns were subjected to lateral cyclic and monotonic loadings using the compressive force of the hydraulic press. Hydraulic pump was used in the experimental tests to generate the loads (Fig. 5). Figure 6 shows the steps of column strengthening using GFRP materials.

In order to determine the strength properties of the columns, compression tests on concrete and tensile tests on steel bars were performed. Tables 1 and 2 show the mechanical characteristics of concrete and the diameters of steel bars, respectively. The elastic limit of the column was determined by applying an experimental test on a reference column without strengthening. Figure 3 shows the general overview of the reference column (named C1C).

The experimental force-displacement behavior of the reference column is shown in Figure 7. It was found that the column achieves its elastic limit when 25kN of loading and 24mm of displacement are reached.

Table 1. Mechanical characteristics of concrete.

Concrete C16/20		
Compressive strength [MPa]	Elastic modulus E [MPa]	Compressive strength [MPa]
27.5	34500	2.187

Table 2. Mechanical characteristics of steel bars.

Steel bars Ø8, Ø10, Ø12 and Ø16		
Compressive strength [MPa]	Elastic modulus E [MPa]	Compressive strength [MPa]
560	200000	7850

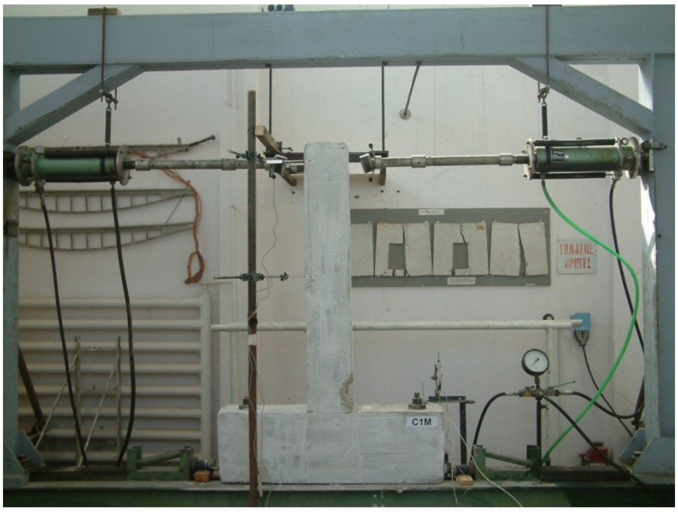

Fig. 1. General view of the experimental stand element C1M [44]

Fig. 2. General view of the experimental stand element C7C1-BM-GW [44]

Fig. 3. General view of the experimental stand element C1C [44]

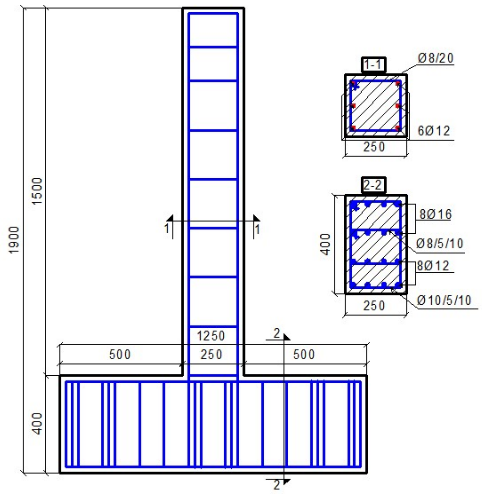

Fig. 4. Reinforcement of the columns

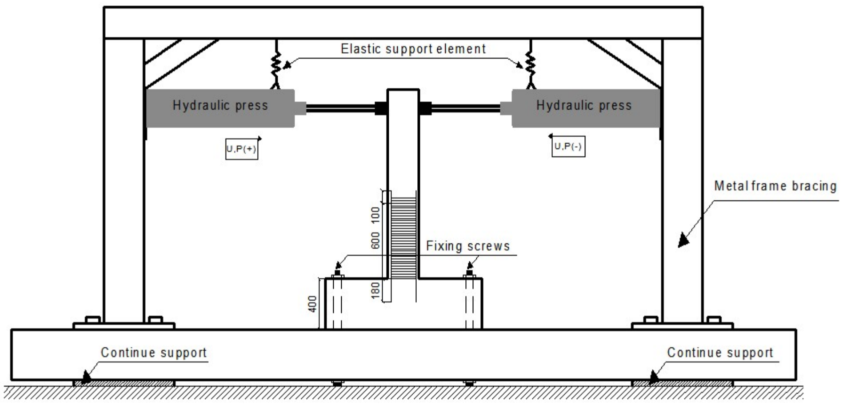

Fig. 5. Elements of the test instrumentation [44]

Fig. 6. Column preparation: a) cleaning the surface, b) application of the epoxy resin, and c) application of the wrapping tissue of GFRP [44]

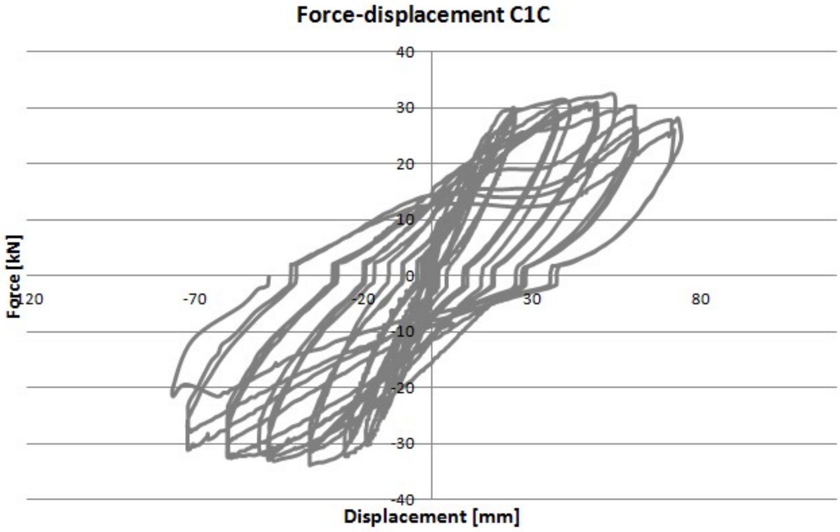

Fig. 7. Experimental force-displacement behavior of the reference column C1C [44]

3. Numerical Modeling

The aim of the numerical modeling is to describe the experimental behavior of the RC column strengthened with GFRP under lateral cyclic loading and the unstrengthened RC column under monotonic loading (Fig. 8). Two numerical models were developed using the finite element method. The software of concrete and reinforced concrete structures analysis ATENA [46] was used in this work in which the 2D finite element model was created. The 4-node solid element (SBETA) was used to define the concrete material of RC columns according to the software material library. Each node has two degrees of freedom, namely translations on x and y directions. The definition of steel bars and the GFRP was based on 2-node structural bar elements.

The loads were applied on the columns in a similar way as the experimental tests [44] in which the columns were fixed in their supports and subjected to lateral loading on their tops. For the column that is strengthened with GFRP, the loads were divided into two stages. In the first stage, the imposed force (value of 1kN) in several load steps was applied until the elastic limit was reached. In the second stage, the imposed displacement (value of 1mm) in several load steps was applied until failure. One monitoring point was defined to control the displacement of the column (D1 in Fig. 9(a)), and four monitoring points were defined to control the force at the loading application points on the right and left side of the column (*U, P* (-) and *U, P* (+) in Fig. 9(a)). It should be noted that *U* and *P* represent the imposed displacement and force in the right (+) and left (-) directions, respectively.

In case of the unstrengthened column subjected to lateral monotonic loading, the support of the column was fixed, and 1mm of displacement was applied on its top until failure. The force was controlled at the load application point, and also the displacement was controlled at the point D1 (Fig. 9(b)). It should be noted that the loading and boundary conditions of the columns were applied in the numerical modeling in a similar way as the experimental tests [44]. Table 3 shows the mechanical characteristics of GFRP and steel bars used in the numerical modeling.

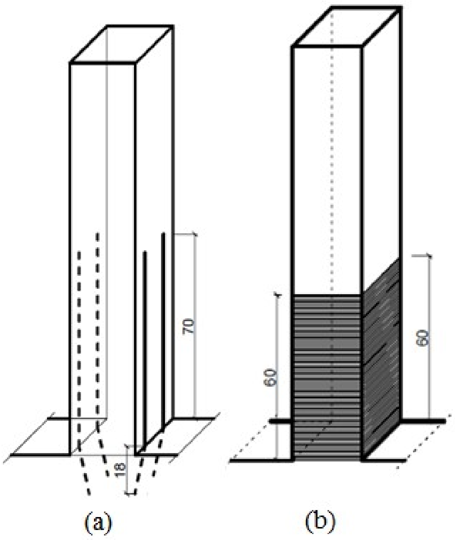

Fig. 8. Details of steel bars (a) and GFRP sheets of the column C7C1-BM-GW [44]

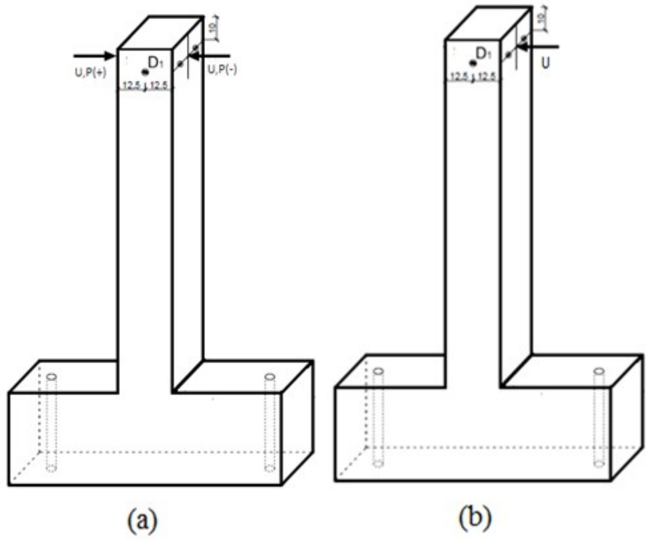

Fig. 9. Displacement and force application points of the columns C7C1-BM-GW (a) and C1M (b) [44]

Table 3. Mechanic characteristics of GFRP and steel bars.

Nr	Material	Elastic modulus E [MPa]	Tensile strength [MPa]	Density [Kg/m3]	Thickness [mm]
1	GFRP	70000	2250	2530	0.17
2	BM	200000	560	7850	Ø=12mm

4. Material Models

The concrete behavior is defined to have nonlinear properties. The strain softening law defined by means of the softening modulus and based on the strain was used for the strain softening model of the concrete material in compression. The exponential crack opening law was used to simulate the model of tensile softening based on the crack band theory [47]. In order to take the rotation of cracks directions into account, the rotating crack model [48] was used. The behavior of steel bars was defined by the nonlinear stress-strain relationship and cyclic rules as presented by Menegotto and pinto (Fig. 10) [49]. According to experimental tests, the perfect bond between GFRP, steel, and the concrete material was considered in the numerical model.

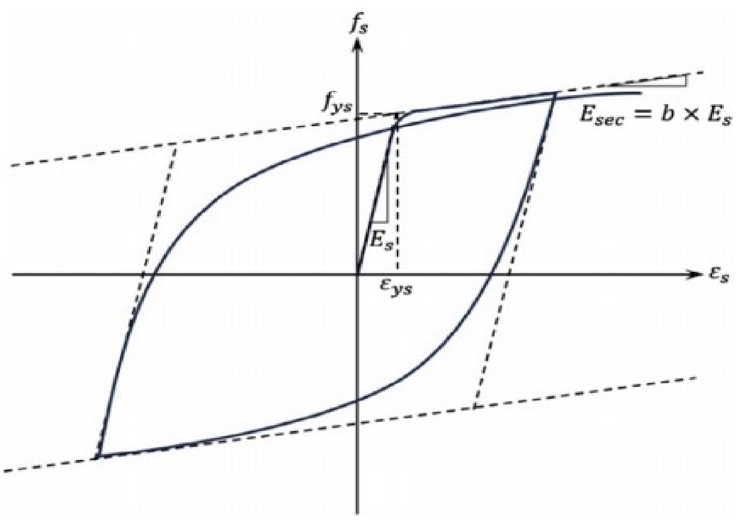

Fig. 10. Menegotto-Pinto stress-strain model [49]

5. Results and comparison

5.1 Unstrengthened Column

Figure 11 shows the experimental and numerical force-displacement responses of the unstrengthened column subjected to lateral monotonic loading. It is observed that the maximum displacements in the numerical analysis and the experimental test are 91.22mm and 85.69 mm, respectively, and the maximum forces supported by the column in the numerical analysis and the experimental test are 36.00kN and 35.20kN, respectively.

The results show that the numerical model follow the experimental behavior of the column very closely in terms of the force and displacement in addition to the estimation of the maximal displacement to its corresponding lateral load. It is also observed that the numerical model overestimated the force in the elastic path of the column. This overestimation of the force is observed because of some micro-cracks stated in the concrete material before the application of the experimental test. These micro-cracks might be the results of the non-hydration of some particles of cement. Figure 11 shows a good agreement between the numerical model and the experimental test.

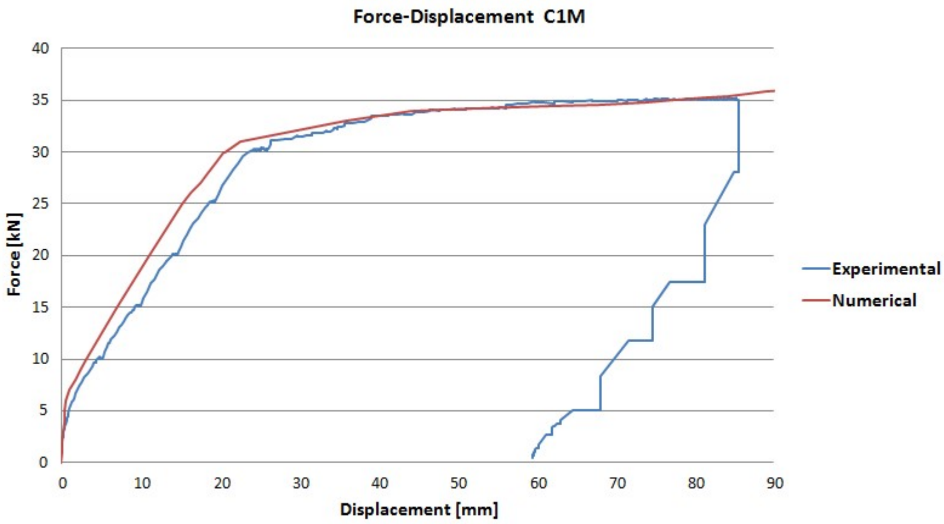

Fig. 11. Comparison of the experimental and numerical force-displacement responses of the column C1M

5.2 Column strengthened with GFRP and steel bars

Figure 12 shows the behavior of the column strengthened using GFRP and steel bars in the numerical analysis and experimental test. It is observed that the maximum displacements in the numerical analysis and the experimental test are 99.70 mm and 105.74 mm, respectively, and the maximum forces supported by the column in the numerical analysis and the experimental test are 24.52kN and 48.20kN, respectively. These results show a small difference in the displacement (6.06%) and the force (96.57%) in the experimental test compared to the numerical modeling. It is observed that the experimental behavior presents a higher peak load capacity. This difference may be due to the perfect bond in the interfaces concrete/GFRP and concrete/steel-bars, and the neglecting of the GFRP creep for the short term cyclic loading in the numerical analysis. GFRP creeps under the supported loads, and this includes fiber straightening and resin creep. When a creep model is used, different parameters are considered in the numerical analysis such as stress redistribution and history, damage degree, creep failure of the column, etc. However, one can see that the numerical ductility of the column is closely predicted to the ductility achieved in the experimental test. Moreover, the ultimate displacement is also closely predicted in the numerical model compared to the experimental test. Even though the cyclic behavior of the columns was calibrated to describe the experimental behavior, it is important to note that the numerical simulation of RC columns strengthened with different methods is sensitive to some material properties at the microscale level which may have an influence on the structural behavior of the structural elements (interface concrete/FRP, aggregate size, cement hydration, etc).

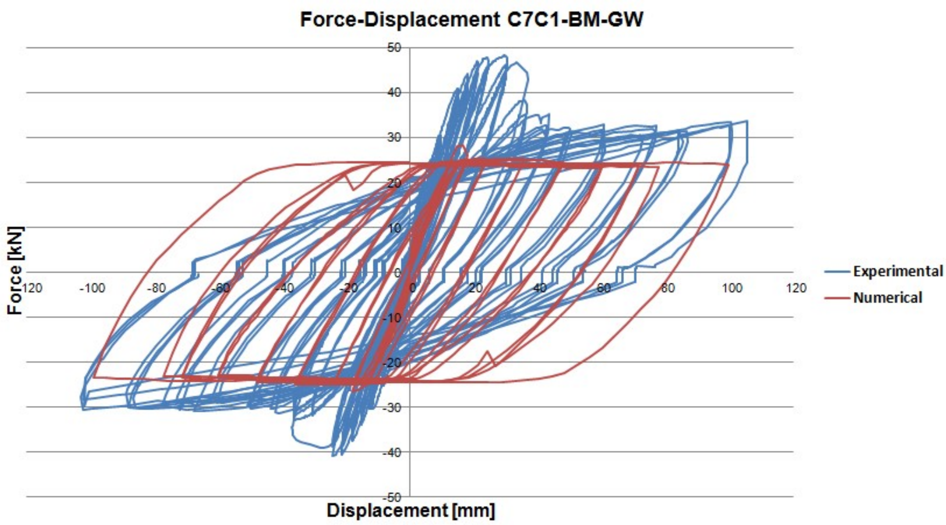

Fig. 12. Comparison of the experimental and numerical force-displacement responses of the column C7C1-BM-GW

Figure 13 shows the comparison of the experimental behavior of the column strengthened by GFRP and steel bars (C7C1-BM-GW) with the reference column without strengthening (C1C). It is observed that the maximum displacements for the columns C7C1-BM-GW and C1C are 105.74 mm and 76.76mm, respectively, and the maximum forces are 47.20kN and 33.05kN, respectively. It is clearly shown that the load carrying capacity and the ductility of the column strengthened with glass fiber reinforced polymer and steel bars are larger than the load carrying capacity and the ductility of the reference column without strengthening. This confirms that adding GFRP and steel bars to the column improves the strength and stiffness of the RC column subjected to lateral cyclic loading.

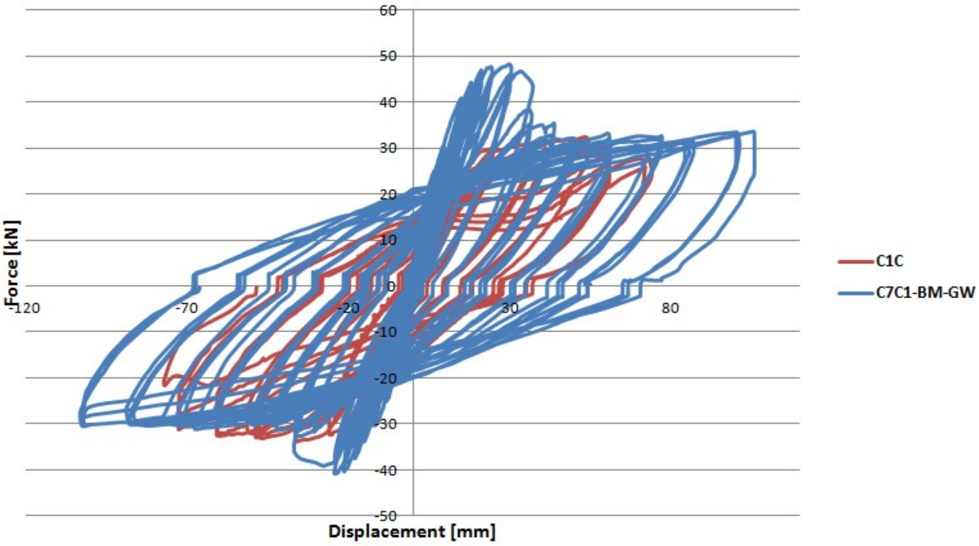

Fig. 13. Comparison of the experimental behavior of the columns C7C1-BM-GW and C1C

6. Conclusion

In the present study, numerical modeling of two square RC columns was performed. The first column was strengthened by glass fiber reinforced polymer and steel bars subjected to lateral cyclic loading, and the second was unstrengthened and subjected to lateral monotonic loading. The experimental behavior of RC columns was predicted numerically by means of the finite element method. It was found that the numerical models applied on the unstrengthened and strengthened columns reflect the behavior of the experimentally tested ones in terms of the load capacity and the maximal displacement. On the other hand, the numerical model of the column strengthened with GFRP underestimate the load capacity compared to the experimental test which might be due to the assumption of perfect bond in the interfaces concrete/GFRP and concrete-steel-bars, and the neglecting of the FRP creep for the short term cyclic loading. The comparison of the behavior of the column strengthened with glass fiber reinforced polymer and steel bars with the unstrengthened reference column under lateral cyclic loading was also performed. It was found that the load carrying capacity and the ductility of the strengthened column are larger than the load carrying capacity and the ductility of the unstrengthened reference column, which confirms the contribution of the strengthening method to the improvement of the strength and stiffness of the column. Future work might address the influence of the interface FRP/sleet-concrete and the consideration of FRP creep analysis on the structural behavior of RC columns.

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Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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