The Effectiveness of Retrofitting RC Frames with a Combination of Different Techniques

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Abstract-During the last two decades, the attention of researchers has been focused on repairing and retrofitting concrete frames to make them more earthquake-resistant. Two methods have been developed to increase the seismic resistance of previously undamaged structures before they are subjected to an earthquake. The first is through the addition of new structural members, such as steel braces and the second is by selectively strengthening structural elements, for instance through steel caging. Seismic response analysis results have been utilized in multi-story RC frames that were designed without seismic design criteria. This study aims to determine whether the retrofitting technique is effective based on comparisons between steel braces, steel cages, and their combinations. The seismic performance is defined by the seismic code for Algeria RPA 2003 according to the latest recommendations. Static nonlinear analysis was used to compare seismic responses of existing non-ductile reinforced concrete RC frames under a variety of retrofit schemes. The results show that retrofitting with steel caging gives excellent performance in terms of ductility and low shear capacity. The retrofitting with steel bracing increased the shear capacity but led to a severe ductility deficiency. The retrofitting structure combined with steel bracing and steel caging shows good performance in shear capacity and ductility. Using the Zipper system (steel bracing) and V system in combination with steel caging gives similar results to the RPA model.

Keywords-RC frame; retrofit; steel bracing; steel-cage technique

I. INTRODUCTION

Most structures before the '70s were designed to be able to resist gravity loads, and while these structures performed well under such loads, their performance under seismic loads was questionable. Several recent earthquakes, such as those in Taiwan (1999) and Algeria (2003), have caused significant damages to buildings and many reinforced concrete structures collapsed because they did not comply with the current seismic codes and had deficiencies such as poor detailing, discontinuous load paths, and a lack of capacity design provisions.

Two main retrofitting approaches have been identified to improve the seismic performance of existing undamaged structures before they are exposed to an earthquake. One is the insertion of new structural elements such as structural walls or steel braces and the other is selective strengthening of deficient structural elements, for example by using concrete or steel caging and fiber reinforced polymers. For the first approach, steel bracing is typically used in the retrofitting of RC frames. This type of structure is efficient and economical for resisting lateral loads. Among the first studies on retrofitting using this technique were [1, 2]. Model tests have also been reported in [3]. Their study indicated the effectiveness of this method in increasing the shear resistance capacity of the structure. Two of the flaws of this method are architectural details and difficulties making connections between the steel bracing and the RC frames. Authors in [4] performed experimental studies on the pushover response of scaled RC frames braced with both diagonal and knee bracing systems. Authors in [5] investigated the seismic behavior of RC frames reinforced with various steel bracing systems, including X, inverted V, ZX, and Zipper systems. By adding bracing, they were able to improve deformation, strength, and ductility. It was found that X and Zipper bracing systems perform better than others. Authors in [6] examined the use of hysteretic dampers and column strengthening to develop the desired behavior of buildings with an open first floor. Authors in [7] studied the impact of retrofitting RC frames with steel X-bracing on the global behavior of the frame, including its global displacement, performance level, and inter-story drifts. Similarly, the authors in [8] analyzed the seismic response of steel X-bracing numerically and concluded that it greatly reduces the shear loads on the beam–column joint. The maximum lateral displacement in RC frames is also reduced by retrofitting them with X-braces. In the tests conducted in [9], the joint displayed excellent self-centering properties without deteriorating in strength. The application of friction dampers to a self-centering PC frame was also studied for seismic retrofitting of reinforced concrete structures. A recent study [10] found that disk springs could provide self-centering capabilities without the drawbacks associated with post-tensioned tendons.

The steel caging method is generally favored because of its high retrofitting effectiveness and economic efficiency [11-12]. Authors in [13-16] first applied the steel-cage retrofitting method for bridge columns in California. Authors in [17] studied the efficiency of rectangular solid steel caging and

partial steel caging. Authors in [18-19] described the effect of a partially stiffened steel caging and composite prefabricated jacket on improving the strength and ductility of RC columns. Recently, authors in [20] suggested an extension of the previous works, introducing a new genetic algorithm that minimizes the cost of seismic upgrading.

In the current study, a structure that was designed without seismic design criteria was retrofitted with three techniques: steel caging technique, steel bracing system, and their combination were studied and examined. The seismic performance of these frames was determined by nonlinear static pushover analysis.

II. DESCRIPTION OF DIFFERENT RETROFITTING PROCEDURES

A. Steel Caging Technique

The application of metallic jackets in RC columns aims to increase shear strength and strengthen the lap-splicing region and the ductility capacity. The steel caging option involves the total encasement of the column with thin steel plates placed at a small distance from the column surface, with the ensuing gap filled with non-shrink grout. Steel caging is now a common practice in many countries [21]. When the yield stress of the steel is increased, the ultimate load on the strengthened column increases [22, 23].

B. Steel Bracing Technique

Steel bracing can be a very effective method for the global strengthening of buildings [24]. Some of its advantages are the ability to accommodate openings, the minimal weight added to the structure, and, in the case of external steel systems, the minimum disruption to the function of the building and its occupants [25]. Alternative configurations of bracing systems may be used in selected bays of a reinforced concrete frame to provide a significant increase in the horizontal capacity of the structure [26]. To improve the seismic performance of an existing reinforced concrete building, authors in [27] used steel bracing. Three methods of seismic evaluation were employed in this study: the nonlinear static pushover as described in FEMA 356 [28] and FEMA 440 [29] and dynamic time history analysis. The retrofitting of an RC frame with the steel X-bracing method can be seen in [30].

III. DESCRIPTION OF THE FRAME MODELS

A five-story RC building has been considered in this study (Figure 1). The slabs were represented in the structural model of the building using their weight in the gravity load case and as concentered masses at all joints, with bay length of 4m and height of 3m. The building was designed without seismic design criteria, while it is located in a high seismicity region with a peak ground acceleration of 0.32g. Table I shows the details of the design sections, where the characteristics of the original frame and the reinforcement of the beams and columns were determined according to the Algerian seismic code (RPA 2003) [31]. To retrofit the structures with the bracing system, it is necessary to have studied the influence of variation in the section of the bracing element and different bracing systems (X, V, and Zipper). Figure 2 shows the RC frames retrofitted with different steel bracing systems.
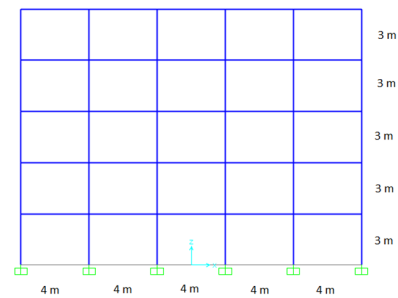

Fig. 1.   Structural model.
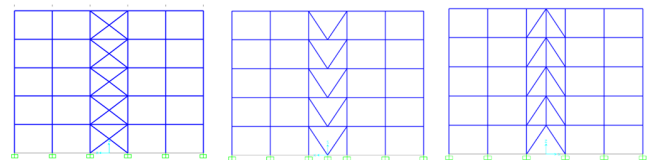
TABLE I.   REINFORCEMENT DETAILS

Fig. 2.   Bracing models.

To retrofit the structures with steel caging, it is important to investigate the impact of retrofitting vertical and horizontal bays with steel caging. Figures 3-4 show the retrofitting details and the models of retrofitting vertical and horizontal bays with steel caging respectively. In order to conclude the comparison between the bracing systems and to properly propose a reinforcement model close to the RPA model, a final comparison was made. A combination of the bracing systems with the steel caging was applied.
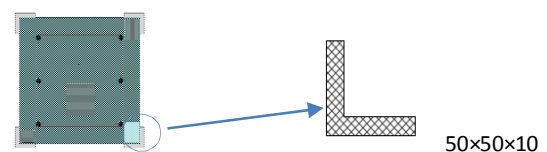

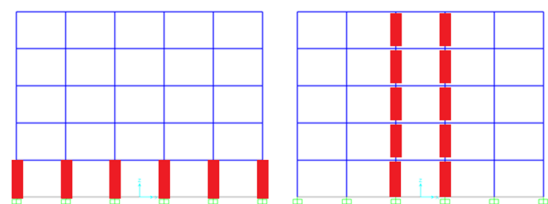Fig. 3.   Retrofitting details with steel caging.

Fig. 4.   Retrofitting with steel caging.

IV. RESULTS AND DISCUSSION

A. Pushover Results of the Original and RPA Frame

The aim of the reinforcement of the structure is to increase the capacity of resistance to shearing, the ductility of the original frame, and to reach the capacity of new structures calculated by the RPA Code. This starts with nonlinear static analysis in order to know the difference between the capacities of the two structures (original and RPA), and then the type of reinforcement is chosen. Figure 5 presents a comparison between the capacity curves of the original frame and the RPA, showing that the base shear of the new structure is larger by 137.5%, and the ductility by 58%.
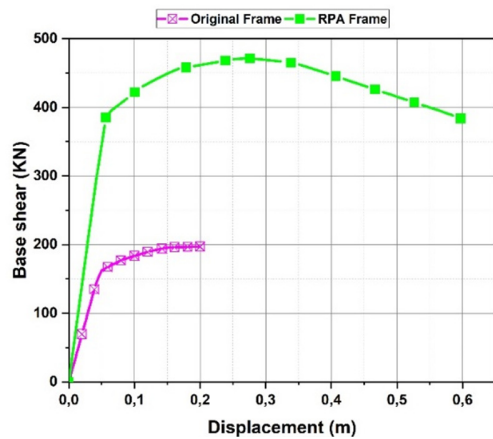

Fig. 5.   Curve of capacity for old and RPA structures.

B. Pushover Results of Different Retrofitting Systems

Figure 6 shows the results of the nonlinear analysis of the structure frame strengthened with different bracing systems (X, V, and Zipper) and the variation in the cross-section of the bracing element. The results show that when the bracing section is increased, ductility is decreased and strength is increased, in accordance with the findings in [5]. The behavior of the different systems is much stiffer. The results show that the section of D76.1×3.2 for all the bracing systems except the X system gives a behavior close to the RPA frame with reference to the lateral load. Compared to the original frame, for the retrofitting with the 76.1 Tube section, the capacity of Zipper, X, and V systems is increased by 2.3, 3.4, and 2.02 respectively. The highest ductility reduction factor is given by the Zipper system with the 76.1 Tube section which equals to almost 4.08. For the X and V systems, the ductility reduction factor is equal to 2.7 and 3.1 respectively.

C. Pushover Results for Steel Caging Technique

Figure 7 shows the lateral response of the structure frame with retrofitting with steel caging of the horizontal and vertical bays. The results show that whatever the reinforcement of the structures, whether horizontal or vertical, the ductility is almost identical to the RPA frame, but the lateral capacity is increased by 27.3% in comparison with the original frame. Meanwhile, the results indicate that the lateral capacity with vertical reinforcement gives a smaller increase than the horizontal reinforcement.
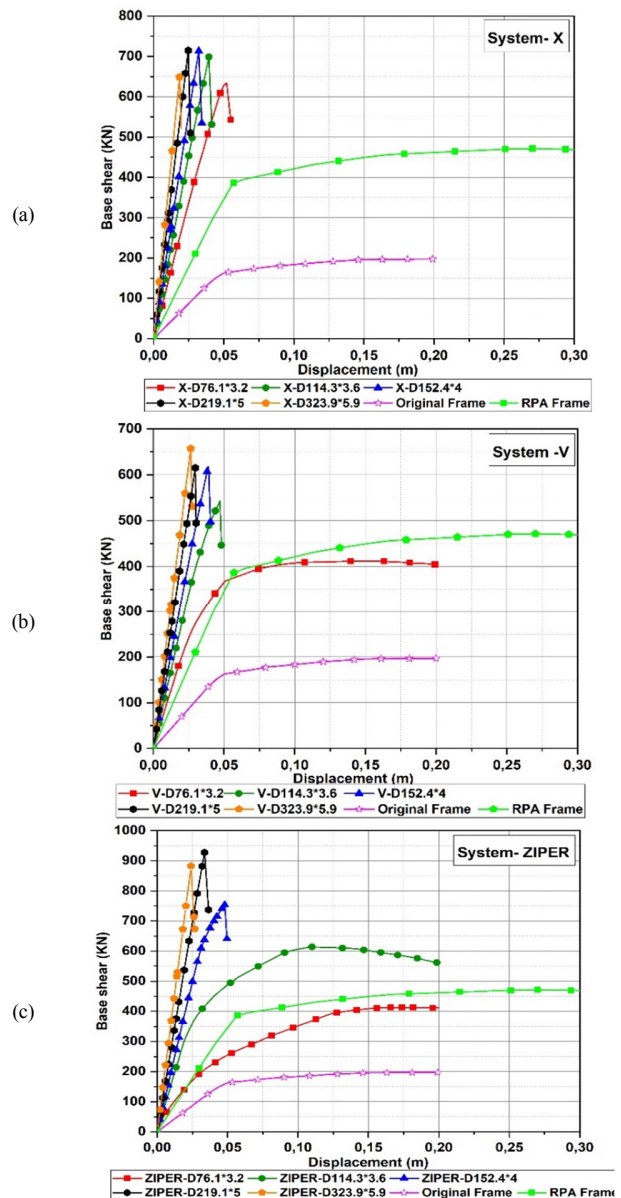

Fig. 6.   Lateral load–displacement response retrofitting with different steel bracing systems.
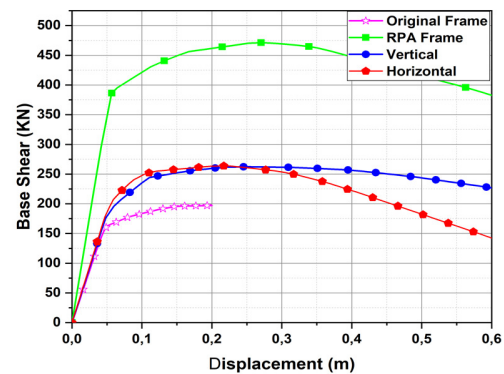

Fig. 7.   Lateral load–displacement response retrofitting with steel caging technique.

D. Pushover Results for Retrofitting with Steel Bracing and Steel Caging

Figure 8 represents the lateral response of the structure frame with retrofitting of the vertical bays with steel caging and the different bracing systems (X, V, and Zipper) at the same time.
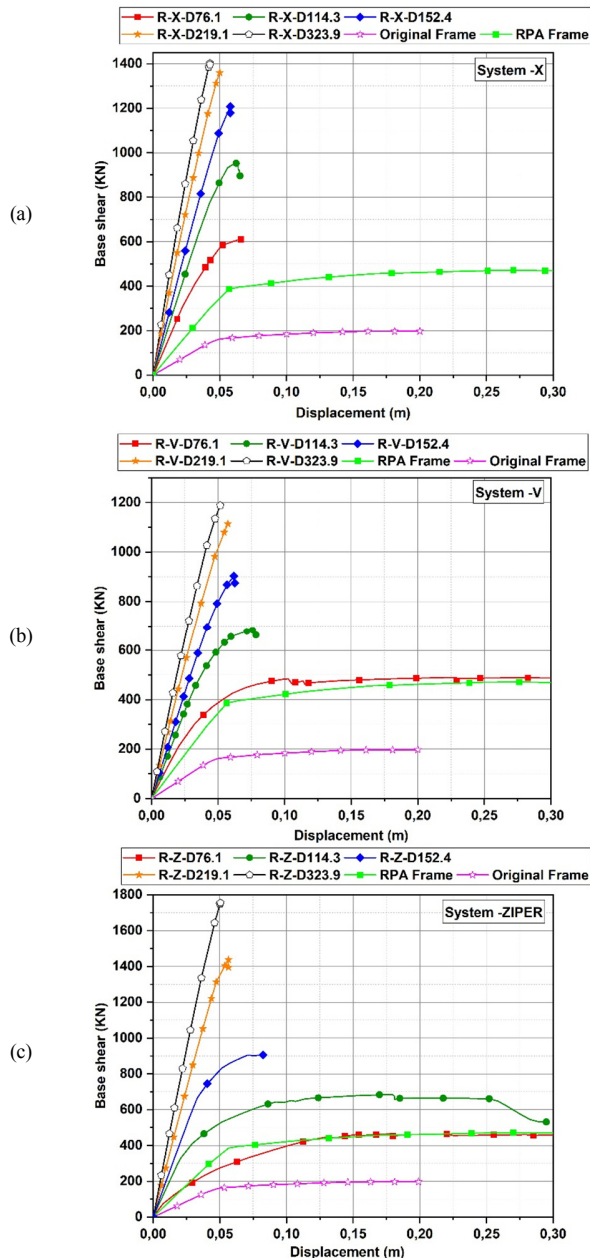
(a)

(b)

(c)

Fig. 8. Lateral load–displacement response retrofitting with steel bracing system and steel caging.

It is clear from Figure 8 that the base shear was increased by 100% compared to the reinforcement with the steel bracing system only. The V and Zipper system with the steel caging technique give almost the same curves as the RPA frame. The results show that the section of D76.1×3.2 for all the bracing

systems gives a behavior close to the RPA frame with reference to the lateral load. Compared to the original frame, for the retrofitting with the 76.1 Tube section, the capacity of Zipper, X, and V systems is increased by a factor 2.5, 3.02, and 2.4 respectively. The highest ductility reduction factor is given by the V system with the 76.1 Tube section which equals almost to 8.25. For the Zipper and the X systems, the ductility reduction factor is equal to 6.03 and 4.1 respectively.

V. CONCLUSION

The main purpose of this research is the retrofitting of an RC frame that has been designed without seismic design criteria, and is located in a region of high seismicity. In the present work, the retrofitting of this structure was done by three techniques, namely the steel bracing system, the steel caging technique, and the combination of these two methods. The main results of the present work can be summarized as follows:

- The results show that all systems have a given ductility for a small section and when there is an increase in the section of the bracing the ductility is decreased and the strength is increased. The behavior of different systems is much stiffer.

- Whatever the reinforcement of the structures, whether horizontal or vertical, the ductility is almost identical to the RPA frame.

- Retrofitting with Zipper and V systems in combination with steel caging gives similar results to the RPA model.

- The models with steel bracing and steel caging are good for predicting damage in the nonlinear analysis of RC structures.

Therefore, retrofitting for RC frames with a combination technique should take into account the two demand measures, MIDR and MID, particularly under NFD-HR and NFFS earthquakes.

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