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A Review of Studies on Lateral Load Reinforcement Systems in RC Structures Frames

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Abstract

Lateral load-bearing systems are part of a structure that has the task of withstanding lateral loads and directing them from a safe path to the foundation. Ancillary forces can include earthquake load, wind load, or other forces. Nowadays, with the increasing use of concrete structures in construction projects, also the basic need to strengthen concrete structures for various reasons such as changing the use of the building, the age of the building and other things, knowing and using new and appropriate methods for Increasing the bearing capacity of concrete building frames against lateral forces is essential and unavoidable. In this article, by reviewing new articles and researches in the field of new types of lateral load reinforcement systems in reinforced concrete frames, the efficiency and productivity of each method have been evaluated and measured.

Keywords: Reinforcement, RC Structures Frames, Braced Concrete Frames, Lateral Load

1. Introduction

As many buildings have been destroyed severely by earthquakes recently, it is proved that the existing reinforced concrete frames are susceptible to strong earthquakes and consequently need to be strengthened. Particularly, there is a great necessity to strengthen high-rise buildings that are more vulnerable to wind force and earthquakes. One of the oldest and the most common methods to increase the strengthening of concrete structures against lateral loads has been using shear walls. In this paper, other methods that have been applied to strengthen lateral reinforced concrete frames more recently have been scrutinized. For instance, one of the new techniques has been the usage of exterior shear walls which are installed in parallel to exterior sides of a building and strengthen RC structures without disturbing their inhabitants as there is no need to vacate the buildings while renovating. Besides, the application of this method significantly improves RC structures' sway stiffness and capacity (Kaplan, Yilmaz, Cetinkaya, & Atimtay, 2011; Zhang, Zhang, Deng, Zhou, Yi, He, & Li, 2020). Another suitable method for the retrofit of RC frames is buckling-restrained braces which use braces without steel frames. BRBs show the ideal integration of yielding dampers and structural members that act as structural fuses. The main feature of BRBs is their capability to prevent the energy from dissipation without any strength reduction. Also, they fill the limitation of brace forces by the highly stressed anchorage and are cost-effective in comparison with other kinds of braced frames (Mahrenholtz, Lin, Wu, Tsai, Hwang, Lin & Bhayusukma, 2014). The next practical method is FRP-bracing-based infilled walls which were used by Choi, Park, and Park (2017). The mentioned method decreases the number of FRP bracings for the strengthening, increases the dissipated energy, and satisfies constraints that are related to inter-story drift and structural collapse. It is used to reinforce 5- and 10-story RC frames and optimal retrofit schemes suggesting the number of FRP bracings and locations are gained. In another study by Unal and Kaltakci (2016), the behavior of concentrically steel braced frames was evaluated and their application in the strengthening of RC frames by external usage was investigated. Another new method for seismic retrofit of concrete structures is precast prestressed concrete braces which have the following advantages: (1) no wet concrete work in the site of the construction; (2) no bolt and anchorage to existing frames; (3) the Short period of the construction; and (4) the low cost of the construction. Stazi, Serpilli, and Pavone (2019) also applied Cross Laminated Timber (CLT) panels as infill shear walls for strengthening RC buildings. In fact, CLT has been increasingly used as a sustainable construction system for both mid-and high-rise buildings. However, the need for constructing higher buildings (higher than the ones built with CLT) made researchers develop hybrid techniques such as CLT infill shear walls as the base of an integrated seismic and energy retrofit. RC structures have also been strengthened using different steel braces due to the rapid system implementation and a dramatic rise in the strength and stiffness of the structure. By applying different types of steel braces to retrofit RC frames, the seismic features of the structure such as its stiffness, strength, strength reduction factor, and ductility undergo some changes (TahamouliRoudsari, Entezari, & Hadidi, 2017). The last popular method mentioned in this review paper is fiber-reinforced-polymer (FRP) carbon composite laminates used by Mosallam and Nasr (2016) and Hadad, Metwally, and El-Betar (2014) to strengthen RC shear walls with different opening geometries. Indeed, FRP composite laminates increase both the ductility and strength of retrofitted shear walls.

2. Fundamentals of Study and Research Background

In the first study by Kaplan, Yilmaz, Cetinkaya, and Atimtay (2011), an experimental investigation on the seismic strengthening of the RC buildings by exterior shear walls has been carried out. Structures of the two-story framed model were tested under the imposed reversed cyclic lateral sway to simulate seismic loadings. The cracking pattern of both experimental and numerical models is shown in Fig 1.

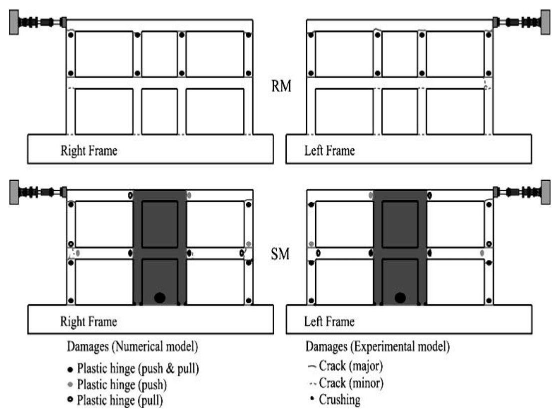

Fig. 1. Cracking pattern of the reference model (RM) and the strengthened model (SM) [3]

It was observed that the implementation of shear walls to the structural system has improved the capacity of the bare frame as expected. The main conclusions of the study were as follows:

(a) It was observed and measured that the newly added external shear wall and the connected end columns and beams behave like a monolithic member. Minor cracks between new and existing elements have been formed after 1% drift. Even after these minor cracks, the shear walls did not lose their load-bearing capacity.

(b) The first cracking occurred at the bottom of the exterior shear walls due to bending in the initial stages of the experiment. During the subsequent cycles, the sliding shear capacity of the shear walls drooped due to the rupturing of the longitudinal bars and in addition, shear sliding behavior was observed at the bottom of the walls. This had an adverse effect on the ductility and energy absorption capacity of the system. To prevent such damage, additional shear reinforcement is required at the web of the wall.

(c) In order to test the behavior without any overstrength of dowel capacity, no material factor was considered in the design process and experimental yield strength values were used instead of characteristic yield strength. For designing the dowels, ACI318 (ACI 2005) shear friction formulae were used. Although the dowels possessed no overstrength, they adequately transferred the loads between existing and new elements safely. Therefore, the shear friction formula can be used for designing the connection of exterior shear walls with existing structural elements.

(d) In the experimental study, the strengthened model reached yield strength at about 4–5 mm roof displacement, where the base shear capacity started to fall after 23 mm of roof displacement.

(e) Results obtained from the experimental models were close to numerical results. In this regard, it has been proven again that with the correct structural model, it is possible to create a successful design for strengthening the existing structures. However, further studies are needed to develop sliding shear models for nonlinear analyses of shear walled structures. In the present work, sliding shear capacity was calculated based on the code formulations, which produced a smaller capacity than the actual base shear capacity. Besides, it is found out that composite cross-sections of the dowel-bonded exterior shear walls and the existing column elements can be modeled as a single frame element using wide column analogy. This behavior has been observed experimentally and numerical solutions yielded reasonable results.

(f) The strengthened model is asymmetric structure and therefore, uniform strengthening walls were used. Application of the proposed technique to asymmetric buildings requires a carefully performed design to minimize the effects of torsional loads by minimizing the eccentricity, which can be compensated by an appropriate arrangement of the new shear walls. Since the model used in this study was loaded uniaxially, it was strengthened with respect to that direction only. However, existing seismically deficient buildings are vulnerable to seismic forces from any direction. Therefore, buildings must be strengthened at right angles in real-life applications of exterior shear walls.

(g) The technique has been tested on an undamaged model. However, the existing literature presents many techniques for the reparation of damaged buildings and similarly, this method can also be used for strengthening damaged buildings. In this case, the designer should keep in mind the possibility of a significant decrease in stiffness and the capacities of previously damaged elements, and consider that the level of the damage may significantly affect the cost of strengthening works. Consequently, the strengthening of damaged buildings by exterior shear walls is an important topic for future researches.

In the second study by Mahrenholtz, Lin, Wu, Tsai, Hwang, Lin, and Bhayusukma (2014), Large-scale tests were conducted at a laboratory in the Taiwan National Center for Research on Earthquake Engineering (NCREE) on buckling-restrained brace (BRB) connected to reinforced concrete frames by post-installed concrete anchors over three phases that are illustrated in Figures below:

Fig. 2. Specimen after Phase 1 test [4]

(a) (b)

Fig. 3. Cracking of concrete close to (a) lower and (b) upper anchor brackets during opening corner moments [4]

(a) (b)

Fig. 4. Buckled BRB joint zone of (a) upper connection and (b) lower connection after Phase 3 test [4]

The specimens were loaded by increasing the drift amplitudes stepwise to failure. These were the first tests of this kind for which the anchorage of post-installed BRBs was directly connected to the RC structure without unfavorable steel frames. The detailing of the post-installed anchors was designed and carried out under realistic conditions and delivered valuable data for improving earthquake retrofitting solutions. The following conclusions are the primary findings of the experimental studies reported in this paper:

(a) The tests proved that the concept is feasible and suggest that the bonded expansion anchors are effective for the proposed connection. The peak-to-peak stiffness decreased only corresponding to the plasticization and the dissipated energy was about five times higher if compared to the concrete frame alone.

(b) Both all-steel bolted-end BRBs and the connection performed well without any damage, at least for drifts less than 0.03 rad. The test results indicate that the design of gusset plates with anchor brackets considering the combined effects of the BRB axial force and frame action leads to a conservative and safe design.

(c) The confining effects in the anchorage region because of closing corner moments simultaneous to the BRB tension loading and concrete anchors potentially increase the anchorage capacity. The accumulated displacement of the concrete anchors and the lack of counter bolting, however, allow anchor brackets to displace, causing misalignment of the gusset plate. The resulting imperfections may trigger the buckling of the connected BRB's joint zone.

In the third study, Zhang, Zhang, Deng, Zhou, Yi, He, and Li (2020) conducted a study on the seismic behavior of two types of buckling-restrained braced concrete frames. The working mechanism of double-level yielding buckling restrained brace was introduced firstly. The single-level yielding buckling-restrained braced concrete frame (SYBRBCF) and the double-level yielding buckling restrained braced concrete frame (DYBRBCF) were designed and subjected to cyclic loading. The layout of these models is represented in Fig. 5 and Fig. 6 below:

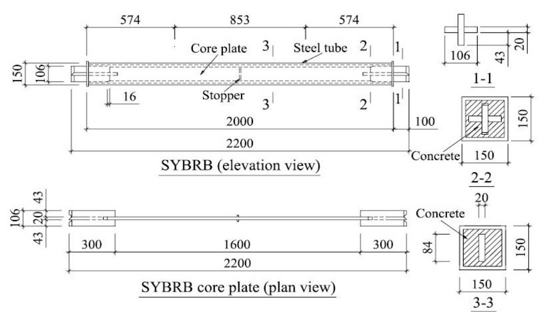

Fig. 5. Layout of SYBRB [9]

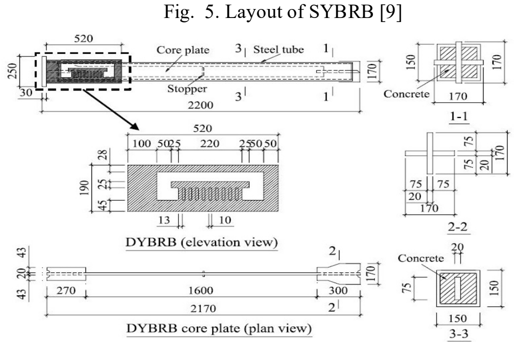

Fig. 6. Layout of DYBRB [9]

The seismic performance of SYBRBCF and DYBRBCF was evaluated and compared in detail. The main conclusions can be summarized as follows:

(a) The loading–displacement hysteretic curves of SYBRBCF and DYBRBCF were plump, indicating a favorable seismic behavior. No evident degradation of the load-bearing capacity occurred during the loading program, and the degradation of the stiffness was stable. The strength degradation was slight, indicating the stable load-bearing capacity of the specimens.

(b) The failure modes of the two specimens were similar and satisfied the strong-column–weak-beam design concept. However, the DYBRB can better reduce the seismic damage of the concrete frame than the SYBRBCF.

(c) The DYBRBCF achieves a higher load-bearing capacity and stiffness. The maximum values of the lateral load and initial stiffness were enhanced by 39.3% and 109.8%, respectively. The test results imply that the design concept of the DYBRB is reasonable.

(d) The loading–displacement hysteretic curves of the DYBRBCF were fuller than those of the SYBRBCF. The DYBRBCF also exhibited a better ductility and energy dissipation capacity than those of the SYBRBCF. The ductility coefficient and total energy dissipation were enhanced by 72.2% and 23.4%, respectively. Therefore, DYBRBs can further improve the seismic performance of the concrete frame.

In the fourth study, Choi, Park, and Park (2017) proposed an optimal seismic retrofit method for an existing infilled reinforced concrete moment frame with FRP bracings (shown in Fig.7), based on nondominated sorting genetic algorithm II

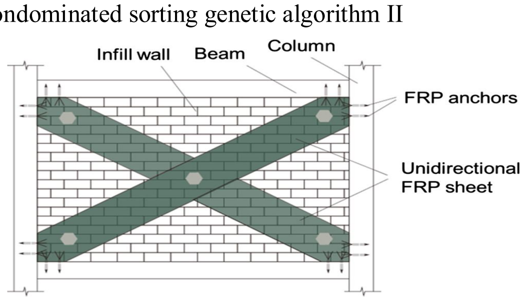

Fig. 7. Retrofit of infilled reinforced concrete frames with FRP bracings [1]

The proposed method is formulated to minimize the retrofit amount and maximize the dissipated energy while satisfying the constraint conditions for the inter-story drift ratio and structural collapse. The application of the proposed method to examples of a 5-story and a 10-story building provided 13 solutions and 25 solutions, respectively. These solutions can benefit building owners and engineers by expanding the range of choice to determine a final retrofit plan. However, these solutions could appear as clusters because of the limits of NSGAII. Therefore, this study selected four representative solutions from the acquired Pareto solutions and investigated them. At smaller retrofit amounts, the reinforcement is concentrated on the lower levels with little resistance to lateral deformation. For increasing retrofit amounts, however, reinforcement also occurs on the higher levels that are not vulnerable to lateral deformation. The seismic performance is improved by reinforcing higher levels, but its efficiency is decreased. The results of the example performance evaluation reveal that the energy dissipation ratio of the retrofit structure for the existing buildings, i.e., the 5-story and 10-story examples, appeared to be in the range of 1.76–2.88 and 2.49–5.00, respectively. The rate of increase of the initial stiffness is 1.26 and 1.22, respectively, and the ductility ratio is in the range of 1.18–1.65 and 1.23–1.85, respectively.

In the fifth study, Unal and Kaltakci (2016) evaluated behaviors of “Concentrically Steel Braced Frames” types defined in TEC-2007 under lateral loads, dimensional analysis of Concentrically Steel Braced Frames designed with different scales and dimensions was conducted, the results were controlled according to TEC-2007, and after conducting static pushover analysis, behavior and load capacity of the Concentrically Steel Braced Frames and hinges sequence of the elements constituting the Concentrically Steel Braced Frames were tested. Concentrically Steel Braced Frames that were tested analytically consist of 2 storey and one bay, and are formed as two groups with the scales 1/2 and 1/3. In the study, Concentrically Steel Braced Frames described in TEC-2007 were designed, which are 7 types in total being non-braced, X-braced, V-braced, Λ- braced, \- braced, /- braced and K- braced (shown in Fig. 8).

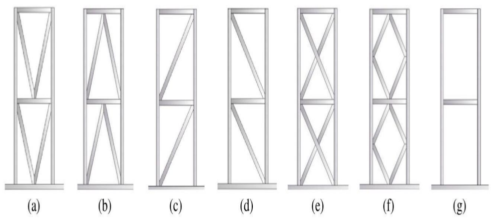

Fig. 8. (a) V braced; (b) Inverted V braced; (c) Diagonal braced; (d)Inverse diagonal braced; (e) X braced; (f) K braced; (g) Non-braced [8]

Furthermore, in order to verify the accuracy of the analytic studies performed, the 1/2 scaled concentrically steel X-braced frame test element made up of box profiles and 1/3 scaled reinforced concrete frame with insufficient earthquake resistance were tested individually under lateral loads, and test results were compared with the results derived from analytic studies and interpreted. Similar results were obtained from both experimental studies and pushover analyses. Experimental studies and pushover analyses revealed similar results for the analyzed systems throughout this study. The load-carrying capacity of RC frames with inadequate earthquake resistance was increased significantly by adding CSBFs. Specimens designed in accordance with TEC-2007 have more load-carrying capacities compared to those that are not designed conveniently with TEC-2007 (2007). The specimens having different scales (1/2 and 1/3) revealed similar behavior. One of the most significant findings of the study is that structures can be strengthened by the suggested method, without complete evacuation and/or partial closure. For buildings to be strengthened via this technique, it is primarily suggested to add foundations outside of buildings and connect them rigidly between each other and also with the main structure. Additionally, strengthening RC buildings with Λ- braced and X braced gives better results in terms of ductility, energy consumption capacity, and load-carrying capacity. Therefore, using Λ- brace and X brace is recommended for strengthening with CSBF.

In the sixth study, Stazi, Serpilli, and Pavone (2019) investigated a novel strengthening method for RC framed structures in which CLT panels are used as infill shear walls. This research group developed a new integrated retrofit solution based on the use of CLT shear walls encased as infill in existing RC framed structures (Fig. 9a). This retrofit intervention has the main purpose of increasing the overall lateral stiffness of the structure and, consequently, reducing the lateral drift values, as demanded by different structural seismic codes. An energy efficiency upgrading can be also obtained by adding an external insulation layer directly connected to the CLT panels or leaving a vented air gap (Fig. 9b).

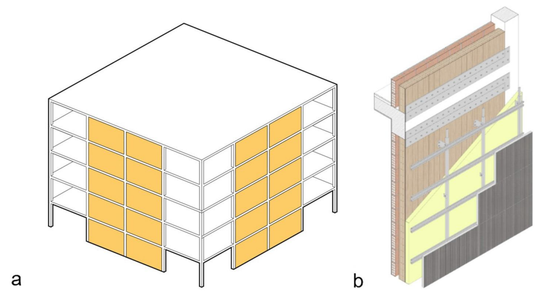

Fig. 9. (a) An example of a building layout with CLT infill shear walls; (b) An example of CLT infill panel with a hooked external skin (ventilated façade) for the integrated seismic and energy retrofit [6]

Several monotonic diagonal compression tests have been carried out and post-elastic behavior has been surveyed. The use of metal shoes has been also considered in order to reproduce a direct load transmission on the lateral sides of the panel. In addition, numerical simulations have been performed in order to study the stress state acting in the panel during diagonal compression tests and to investigate the change in the lateral response of a one-story one-bay RC frame due to the insertion of a CLT infill (shown in Fig.10).

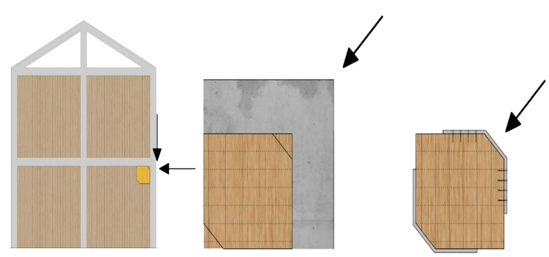

Fig. 10. Interaction between the CLT infill wall and the RC frame under seismic actions [6]

From the diagonal tests, a brittle linear behavior has been found for all the tested panels. As expected, the highest maximum load and stiffness values have been obtained for the confined panels and where a residual strength of about 70% of the maximum load has been recorded. Concerning the damage pattern, the presence of the metal shoes has mitigated but not avoid the damages caused by the sliding of the boards. A comparison in terms of shear strength with strengthened masonry infill panels has been also carried out, showing that CLT infills have the highest Smax, highlighting the potentiality of the CLT to strengthen an RC frame. Numerical results on an RC frame have been then carried out to confirm this result.

In the seventh study, Tahamouli Roudsari, Entezari, and Hadidi (2017) experimentally investigated the effect of adding different types of steel braces on the behavioral properties of RC moment-resisting frames. Eight RC moment resisting frames with identical steel bar configuration and concrete strength were built and seven of which were retrofitted with different braces such as the X, the knee, the chevron, the eccentric brace, and the chevron brace with a vertical link (illustrated in Fig.11).

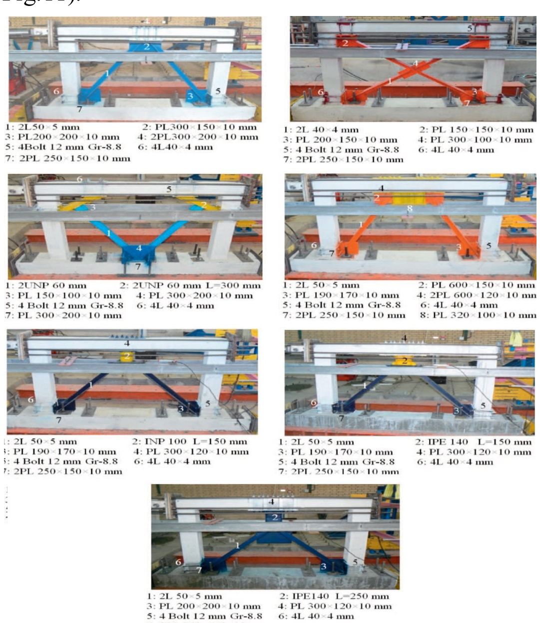

Fig. 11. Details of specimens [7]

All the frames were subject to cyclic loading and their hysteresis load-displacement diagrams were plotted. Strength, stiffness, crack expansion, ductility, energy dissipation, and the strength reduction factor of all the frames were assessed. From the ductility and strength reduction factor viewpoints, the results indicate that the eccentric brace has a better performance compared to the other specimens. However, from the stiffness, strength, and cracking control standpoints, the behavior of the X brace is more desirable. More specifically, the following results were observed:

(a) Retrofitting the RC moment-resisting frame with eccentric braces resulted in a reasonably good performance, and increased the stiffness, strength, and energy dissipation of the structure by 7.9 times, 6.3 times, and 8.7 times, respectively. The important point is that the ductility and the strength reduction factor of the structure have increased also. Therefore, the structure's performance has improved from every aspect. However, this sample underwent a more severe failure at the end of loading and therefore its connections and link beams must be retrofitted carefully. The retrofitting convention in Iran is such that not enough attention is paid to the connections of RC structures and therefore this retrofitting convention is not recommended to be used in Iran.

(b) The chevron brace increased the stiffness, strength, and energy dissipation of the structure by 9.2, 5.8, and 1.4 times, respectively. It, however, decreased the strength reduction factor by a small amount. So, the performance of this brace can be considered acceptable.

(c) The X brace increased the stiffness and the strength of the structure by 7.7 and 6.4 times, respectively. Although the X brace reduced the energy dissipation, ductility, and strength reduction factor of the structure, its cracks, and failure type were much better than the other samples. So, it has the potential to perform suitably against average earthquakes. Since this bracing system has a lower strength reduction factor, if this hybrid system is designed to withstand a higher force, it would certainly have a good performance.

(d)The knee brace augmented the stiffness, strength, and energy dissipation of the structure by 5.7, 4.3, and 2.5 times, respectively. It did, however, caused a slight decrease in the strength reduction factor and therefore it can be said that it had acceptable performance.

(e) Using the chevron brace with a vertical link, depending upon the length and the strength of the link yields different results. If the link is small in length and goes through shear yielding before the braces buckle, the performance would be very good. This way, the pinching effect is very small in the hysteresis diagram. But, it is better to prevent shear failure by installing shear stiffeners in the web of the link. If the link is strong, the performance would be very similar to that of the chevron brace. Based on the three carried out tests, the stiffness, strength, and energy dissipation of the structure was increased between 4 and 8, 4 to 7, and 3 to 7 times, respectively. Also, the strength reduction factor experienced a small decrease or increase compared to the RC moment-resisting frame.

(f) By comparing crack commencement and expansion, and the conditions of the frames at the end of loading some results can be achieved. It is clear that the final state of the MRF-X sample is better compared to the other samples. Thus, considering the increased stiffness of the structure, a good performance is expected from the frame during average earthquakes.

(g) Based on the results of this study, the strength reduction factor of the RC moment resisting frames retrofitted with eccentric, chevron, knee, X, and chevron with vertical link braces are recommended to be 7, 5, 5, 3, and 5, respectively.

In the eighth study, Mosallam and Nasr (2016) aimed at evaluating the structural performance of reinforced concrete (RC) shear walls, with different opening geometries (shown in Fig. 12) strengthened with fiber-reinforced-polymer (FRP) carbon/epoxy composites laminates.

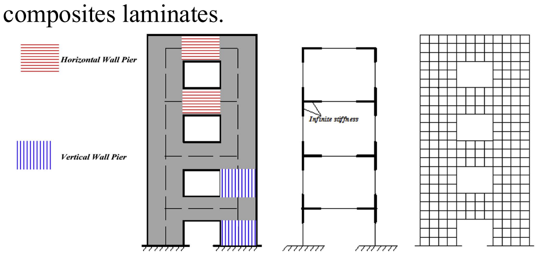

Fig. 12. Analysis of RC Shear Walls with Openings: (a) Real Structure, (b) Equivalent Frame Idealization (EFI), and c) Shell Elements Idealization (SEI) [5]

Results of this study indicated that the FRP laminates are successful not only in restoring the original capacity but also in enhancing the overall performance of reinforced concrete (RC) shear walls as compared to unstrengthened walls with post-construction openings. As expected, the structural capacity of RC walls with openings was lower than those without openings. The peak loads of both the unstrengthened shear wall with central window opening and eccentric door opening were about 13% less than that of the control solid wall (C-S). The external composite system designed for this study was successful in achieving a significant strength increase of the retrofitted walls, as compared to the unstrengthened control walls with post-construction openings. The average peak load of the CFRP-strengthened wall specimen with window opening (RWO) was 1.32 times the average peak load of the unstrengthened wall with central window opening (C-WO). Similarly, in the CFRP strengthened wall specimen with eccentric door opening (R-DO), the average peak load was 1.25 times the average peak load of the unstrengthened wall with door opening (C-DO). This study confirmed the impact of the opening geometry, size, and location on ductility and strength characteristics of the retrofitted walls. For example, results obtained from the large-scale experimental program conducted in this study indicated that the ductility index of the RC shear wall with post-construction central window opening (R-WO) that was strengthened with carbon/epoxy laminates has increased was higher than the ductility of the original "as-built" solid wall (6.00 vs. 5.00) as well as the unstrengthened wall specimen with post-construction central window opening (6.00 vs.4.00). The results of this study also highlighted the major effect of size, location, and retrofitting scheme on the effectiveness and the overall performance of the strengthened walls. For instant, the ductility of the retrofitted wall with eccentric door opening (R-DO) was 3.33 compared to 5.00 for the unstrengthened wall specimen with post-construction eccentric door opening (C-DO). This can be attributed to the existence of severe localized interfacial shear stresses at the CFRP laminate/concrete interface that led to local debonding of the composite laminates and the loss of connection between the top spandrel and the narrow wall pier. The proposed metallic wall/footing mechanical anchorage system adopted in this study was capable of transferring the forces generated at the vertical CFRP laminates located at the wall base. As evidence to this conclusion, no sign of debonding or visual local damages between the steel angle or the CFRP laminates or the steel high-strength threaded rods up to ultimate failure load. It should be noted that no mechanical anchors were utilized to support the edges of the CFRP laminates at termination edges where the highest interfacial shear stresses exist. It is believed that had composite or metallic anchors were used at the CFRP termination edges, better performance may be achieved. The results of this study clearly indicated that there is an urgent need to mandate that any approval for any FRP composite retrofitting system is evaluated for this application and that evaluating such systems for solid shear wall application is insufficient and compromised the safety and underestimate both strength and ductility based on slid wall performance. Furthermore, both the American Concrete Institute (ACI) 440 design guide document (2008) and the International Code Council Evaluation Service Acceptance Criteria (ICC-ES AC125) must highlight these issues and requirements to avoid any safety concerns in using FRP composites in these applications. It is also recommended that more rigorous experimental and analytical research be conducted to measure the different variables and retrofitting schemes for shear walls.

In the last study, Hadad, Metwally, and El-Betar (2014) studied the effect of the different types of bracing on the lateral load capacity of the frame. Also, the research contained a comparison between the braced and infilled frames to decide the best system. The research scheme consisted of four frames; the bare frame, two frames one was braced with concrete, the second was braced with steel bracing and the fourth frame was infilled with solid cement bricks. The mentioned frames are illustrated in Fig. 13.

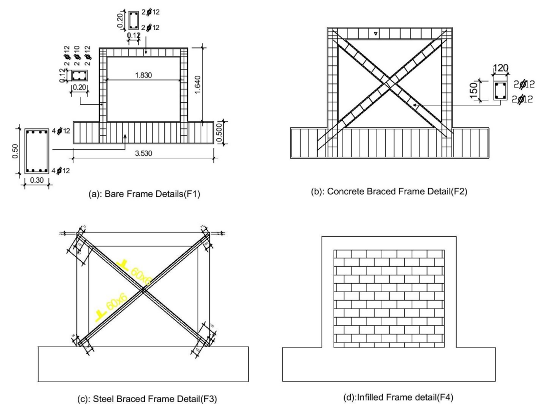

Fig. 13. The specimen reinforcement and details (F1, F2, F3, and F4) [2]

All the specimens were tested under cyclic loading. Also, numerical modeling was carried out with the nonlinear software platform (IDARC). The numerical results obtained with the calibrated nonlinear model are presented and compared with the experimental results. Good agreement was achieved between the numerical simulation and the test results. The results gave some important conclusions:

(a) Using any type of bracing increases the lateral strength of the bare frame depending on the type of bracing. The increases in lateral strength of concrete and steel bracing were 200%, 142%, respectively.

(b) Cracks in infill material and separation from the surrounding concrete frames took place at the early stages of failure and that was clear in specimen F4. The modes of failure can be observed in Fig. 14.

Fig. 14. Modes of failure [2]

(c) The energy dissipation for the braced and infilled frames is always higher than that for the bare frame up to failure. The increased values were 20%, 18%, and 21% that of the bare frame for frames F2, F3, and F4, respectively.

(d) The different types of bracing increased the initial stiffness of the bare frame by reasonable values. The concrete and steel bracing increased the stiffness of the bare frame by 280%, 290%, respectively.

(e) It is preferred to infill some regions in the building frames with reasonably strong bricks to improve the lateral stiffness of these buildings. Using infill from solid cement bricks increases the stiffness of the bare frame 15.34 times.

(f) The force-displacement response of bare and braced frames, was reproduced well using the nonlinear program, IDARC. Reasonably good agreement between experimental measurements and analytical results has been observed for the global behavior of the braced frames.

3. Conclusion

According to the review of the studies above, the following general conclusions were made:

1. The implementation of shear walls to the structural system improves the capacity of the bare frame.
2. Response modification factor (R) is an important parameter for the seismic design of buildings. A response modification factor of 4 to 5 can be used for ESW strengthened buildings to determine the design force demand for the ESWs.
3. The addition of shear walls to a structure will definitely improve its lateral load capacity. This fact has been demonstrated by many experimental studies carried out for infill strengthening walls. However, an infill wall with poorly designed dowels can even improve strength performance considerably by providing a bracing effect. On the other hand, exterior shear walls cannot improve the capacity in case of dowel failure. Exterior shear walls can be successfully applied to existing vulnerable buildings to improve seismic capacity provided that the dowels are well-designed.
4. Directly connected buckling-restrained braces (BRBs) without steel frames, which are post-installed with concrete anchors, are an advanced retrofit solution that is worthy of further development, in particular for weak concrete structures. Investigations are recommended to extend the range of configurations, substantiate the design assumptions made for the design of the concrete anchors, and improve the stability of the anchoring of the anchor bracket with the gusset plate to avoid local buckling.
5. The concrete frame can coordinate with the single-level yielding buckling-restrained braced concrete frame (SYBRBCF) and the double-level yielding buckling restrained braced concrete frame (DYBRBCF) under earthquake. The DYBRB can provide additional damping for structures under frequent earthquake events and an excellent energy dissipation capacity under rare earthquake events as based on the test results.
6. An optimal seismic retrofit method for an existing infilled reinforced concrete moment frame with FRP bracings shows improved results in terms of strength and deformation capacity compared with existing buildings. It is shown that an increase in a retrofit amount generally leads to improvements in the seismic performance, but the retrofit efficiency decreases.
7. The seismically deficient RC frames can be strengthened by adding external concentric steel braced shear walls rapidly, easily, and economically. Another advantage of this method is that the structure can be strengthened without destroying the plasters, paintings, and other finishings.
8. The CLT infill allows the RC frame to reach a lower drift value and a higher peak load with respect to common masonry infills. CLT has thus high potentialities for the strengthening of RC frames.
9. Retrofitting RC frames with different steel braces always increases the stiffness, and the strength of the structure, and from this standpoint, it always has a positive effect on the structure. But, it may cause a(n) increase/decrease in the energy dissipation (EDTM), ductility, or the strength reduction factor of the structure.

10. The fiber-reinforced-polymer (FRP) carbon/epoxy composites laminates are successful not only in restoring the original capacity but also in enhancing the overall performance of reinforced concrete (RC) shear walls.
11. Using any type of bracing increases the lateral strength of the bare frame depending on the type of bracing.
12. The solid brick walls (infill) have a significant effect to resist earthquakes which reduces the large deformation that causes the damage. So, removing the walls in the RC old buildings should be limited especially for weak skeleton structures.

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