# RECENT ADVANCEMENTS IN RETROFIT OF RC SHEAR WALLS

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**ABSTRACT :**

Reinforced concrete (RC) shear walls are widely used in medium- to high-rise buildings to provide the lateral strength, stiffness and energy dissipation capacity required to resist lateral loads arising from wind or earthquakes. In the past few decades, there has been considerable advancement in the design of RC walls for new construction. The newly adopted performance evaluation methodology and capacity design principles are examples of these important advancements in seismic engineering. Therefore, there is an essential need to upgrade the seismic performance of existing RC shear walls so that they can meet the requirements of the new performance-based seismic design techniques. Several retrofit techniques using different materials are reported in the literature. These ranged from using steel, concrete, fiber-reinforced polymers, and shape memory alloys as retrofitting materials used in different methods of application. This paper presents different retrofit techniques that were used to increase the seismic resistance of existing RC shear walls. The paper discusses the advantages and disadvantages of each retrofit technique and the corresponding characteristic enhancements. The objective of this paper is to provide a state-of-the-art on the recent advancements and challenges in the area of retrofit of RC shear walls.

**KEYWORDS**: Reinforced concrete, shear walls, seismic, retrofit, rehabilitation, strengthening.

## INTRODUCTION

RC walls are classified according to CSA (2004) as bearing walls, non-bearing walls, shear walls, flexural shear walls, and squat shear walls. Shear walls are part of the lateral force resisting system that carry vertical loads, bending moments about the wall strong axis, and shear forces parallel to the wall length. Shear wall system is one of the most common and effective lateral load resisting systems that is widely used in medium- to high-rise buildings. It can provide the adequate strength and stiffness needed for the building to resist wind and earthquake loadings, provided that a proper design is considered, that cares for both wall strength and ductility. Many of the existing RC buildings with shear wall system that are located in seismically active zones are designed according to older design codes, in which the ductility requirements were not enforced. These buildings are seismically deficient according to the new codes due to lack of strength and/or ductility. Therefore, retrofitting of such buildings becomes a necessity and can not be overlooked.

Performance-based (PB) seismic engineering is the modern approach to earthquake resistant design. Figure 1 shows the typical seismic performance of existing structures versus structures designed according to performance-based seismic engineering. Seismic performance (*performance level*) is described by designating the maximum allowable damage state (*damage parameter*) for an identified seismic hazard (*hazard level*). Performance levels describe the state of a structure after being subjected to a certain hazard level as: Fully operational, Operational, Life safe, Near collapse, or Collapse (FEMA 1997; SEAOC 1995). Overall lateral deflection, ductility demand, and inter-storey drift are the most commonly used damage parameters.

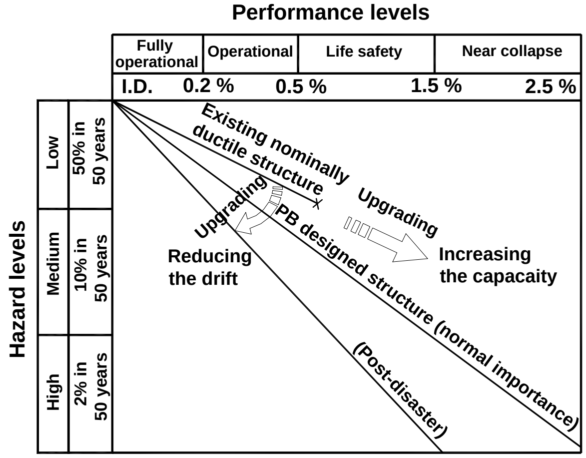



Figure 1 Seismic performance of existing structures and possible ways of upgrading.

The five qualitative performance levels are related to corresponding five quantitative maximum inter-storey drift limits (as a damage parameter) to be: <0.2, <0.5, <1.5, <2.5, and >2.5%, respectively. These limits are functions of the lateral force resisting system and the type of non-structural elements in the building. Therefore, the permissible drift limits should be evaluated using caution and judgment. The hazard level can be represented by the probability of exceedence of 50%, 10% and 2% in 50 years for low, medium and high intensities of ground motions, respectively. From the schematic it can be seen that upgrading the seismic performance of an existing RC building can be achieved by increasing the capacity of its RC shear wall(s) with or without reducing its drift. Increasing the capacity while reducing the lateral interstorey drifts can be achieved by increasing the wall stiffness. Increasing the capacity without reducing the drifts can be achieved by increasing the wall ductility capacity without altering its stiffness.

Different retrofit techniques were used to upgrade the seismic performance of RC shear walls. The expected mode of failure for a specific existing wall determines the appropriate retrofitting technique that should be used for that wall. These retrofitting techniques aim to improve the wall's strength, stiffness, ductility, or a combination of these. Increasing the wall energy dissipation capacity is a main aspect for a proper retrofitting due to the nature of dynamic load excitation. Control of the wall permanent deformations is another important target, which can be achieved by using re-centering materials such as shape memory alloys (SMA). Most of the tests conducted on RC shear walls identify their existing and retrofitted performance using roof displacement-base shear, moment-rotation, energy dissipated, and displacement time history relationships. Figure 2 shows different wall characteristics to be improved by retrofit. Different materials could be used for retrofit such as steel, concrete, fiber-reinforced polymers (FRP) composites, and SMA. The aim of this paper is to provide a state-of-the-art on different retrofitting techniques that were used for upgrading the seismic performance of RC shear walls, as well as the recent advancements and challenges in the area of retrofit of RC walls. This will be presented through some of the previous experimental work done by the researchers on the retrofit of RC walls.

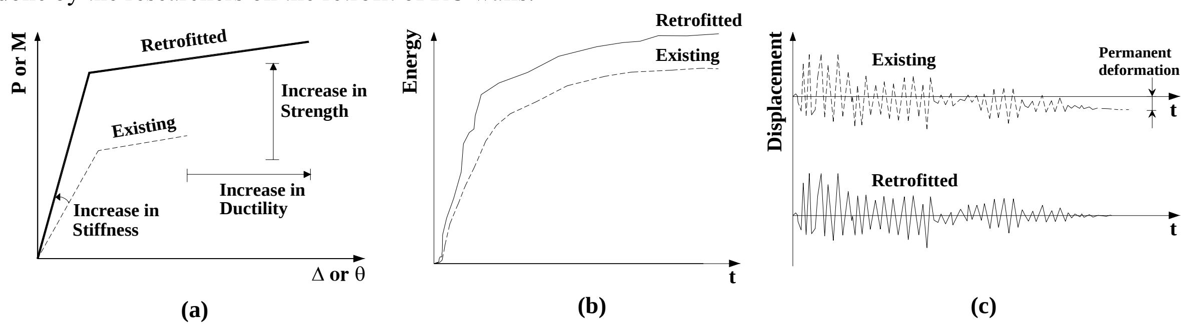



Figure 2 Different characteristics to be improved by retrofit (a) Stiffness, Strength, and/or ductility (b) Energy dissipation capacity (c) Permanent deformation control.

## 1. MODES OF FAILURE OF RC SHEAR WALLS

There are several modes of damage/failure of RC shear walls that were observed from post-earthquake events' reconnaissance or reported from controlled experimental research work. It is important to be able to predict and evaluate the expected response of an existing RC wall in order to be able to choose the most suitable and effective retrofitting technique that meets a target performance. The following subsections identify the most common failure modes of RC shear walls.

### 1.1. Flexural failure

In this mode of failure, considerable flexure cracks appear near the bottom part of the tensile zone of the wall, yielding of tensile steel or compression steel may occur, crushing of concrete in the compression zone could happen at the ultimate stages. The compression steel also might buckle if the concrete cover in the compression zone spalled off. This type of failure occurs when the flexural capacity of the RC wall is lower than its shear capacity, which is usually the case for high-rise walls. Figure 3 shows the crack pattern for a wall failed in a flexure manner (Greifenhagen and Lestuzzi 2005).

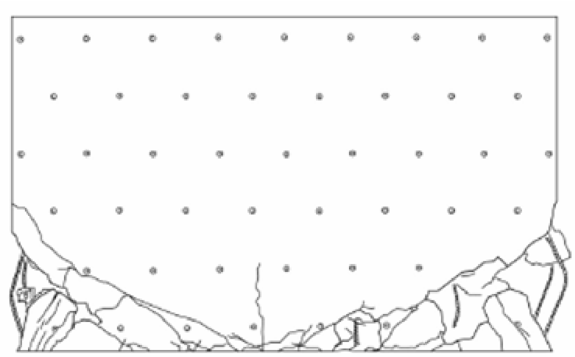


Figure 3 Flexural failure of RC walls. (Greifenhagen and Lestuzzi 2005)

This mode of failure was reported in the experimental work conducted by Lefas and Kotsovos (1990), Zhang and Wang (2000) and Adebar et al. (2007). Tremblay et al. (2001) indicated the importance of higher mode effects for high-rise walls that result in higher shear forces and bending moments in upper region of the wall. This would lead to the formation of a plastic hinge in that region. Similar conclusions were reported by Bachmann and Linde (1995), Priestley and Amaris (2002), and Panneton et al. (2006). Therefore, for existing low-rise shear walls, it might be needed to rehabilitate the lower part of the wall only (in the expected location of the plastic hinge region), while for the high-rise walls, it might be needed to rehabilitate other region that might experience plastic hinge formation at higher level (due to higher mode effects that might not have been considered in the original design of the wall). Predicting such behaviour is important in the design of the rehabilitated wall to avoid the wall failure at higher levels.

### 1.2. Shear failure

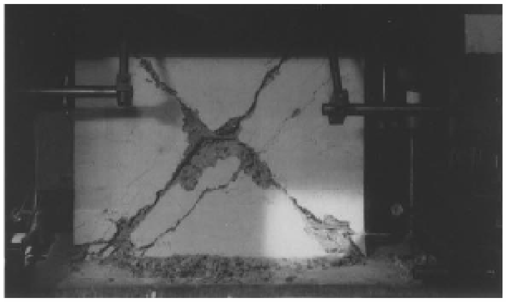
This mode of failure occurs usually for shear walls with low aspect ratio or with inadequate shear capacity. Shear failure is brittle in nature which would reduce the energy dissipation capacity of the wall/structure when subjected to a severe ground motion. For this reason, the main aim for all seismic design codes is to avoid such a mode of failure by ensuring that the shear capacity of the wall exceeds its flexural capacity. According to Paulay et al. (1982), shear failure of squat RC walls could occur in 3 modes; diagonal tension, diagonal compression, and sliding shear failure.

#### *1.2.1 Diagonal tension and diagonal compression*

Due to principal tensile stresses, inclined shear cracks starts to appear, and hence the shear force acting on the wall is resisted by the compression struts formed between the cracks and the tension in the web reinforcement steel. Diagonal tension failure occurs when insufficient horizontal or diagonal reinforcement is used (yielding of shear reinforcement). If the shear reinforcement was sufficient to transfer high shear forces through the shear cracks, diagonal compression failure could occur due to high compression forces in the diagonal compression struts. For that mode of failure and in case of cyclic loading, the web starts to have X-shaped cracks, and then followed by a brittle failure of the concrete web. The concrete compressive strength is the main factor that affects the capacity of the wall that will experience this mode of failure. Figure 4(a) shows the shear failure of a RC wall tested by Lopes (2001).

#### *1.2.2 Sliding shear failure*

Sliding shear failure occurs when the wall has sufficient horizontal reinforcement and relatively small amount of vertical reinforcement in the wall web. In this mode of failure, a continuous horizontal crack originating from flexure will be formed at the base of the wall or at the construction joint (i.e. the weak plane). In this case, the wall section will resist the acting shear forces by the dowel action of the vertical reinforcement and by the friction between the concrete surfaces. For walls with low axial load value, the friction between the concrete layers will not be high, and hence this mode of failure could be critical. To increase the capacity of RC walls against sliding, the amount of vertical web reinforcement could be increased, or the concrete surface could be intentionally roughened at locations of construction joints to a full amplitude of at least 5 mm as recommended by the CSA (2004). Figure 4(b) shows the sliding shear failure of the RC wall tested by Riva et al. (2003).


(a)


(b)

Figure 4 Shear failure of RC walls, (a) Diagonal compression (Lopes 2001), (b) Sliding shear (Riva et al. 2003)

### 1.3. Local buckling of web (Instability of thin wall section)

This mode of failure occurs for slender walls with rectangular sections. To avoid such mode of failure, the design codes require a minimum thickness for the wall as a ratio of the unsupported height of the wall $\ell_u$ (e.g. $\ell_u$ /10 in the

CSA standard for rectangular walls). The local buckling of web can be also avoided by having boundary elements for the wall, such as columns or flanges at the wall ends.

### 1.4. In-plane splitting failure

In-plane splitting failure was noticed in lightweight RC walls under high compression forces that can result from lateral loads or higher gravity loads (Mosalam et al. 2003). This type of failure occurs suddenly and without any indication. This failure can be prevented by proper confinement of the wall.

### 1.5. Rocking failure

This type of failure occurs when the overturning moment acting on the wall due to lateral loads is greater than the stabilizing moment of the axial load acting on the wall about the foundation corner. This behaviour is common for masonry walls, where the bond between the masonry blocks is lost at one plane, and then the wall starts to rock about this plane. This could occur also in case of RC precast walls, when the connection between the wall and the foundation is lost. Taghdi et al. (2000) found that RC walls might experience rocking behaviour at a late stage of their testing. They stated that although the rocking behaviour would dissipate the earthquake energy, but still the lateral load resistance of the wall could be insufficient to resist the lateral loads, and hence retrofit would be necessary.

## 2. DIFFERENT RETROFIT TECHNIQUES FOR RC SHEAR WALLS

Retrofit of an existing RC wall includes either the repair, rehabilitation or strengthening terms. The "*rehabilitation*" and "*strengthening*" terms are used when the performance of the existing wall does not satisfy the existing requirements of the design code and needs to be enhanced. However, the term "*strengthening*" is used when the wall was not subjected to any damage, while the term "*rehabilitation*" is used when the wall has already been damaged and its resistance needs to be restored and improved as well. If the damaged wall's performance was satisfying before the damage occurred, and it is needed to restore its capacity without any additional resistance, then the term "*repair*" will be representative. There are several factors that control the choice of the retrofitting technique for RC shear walls, some of these factors are:

- The deficiency in the existing wall and its expected mode of failure.
- The goal of intervention (e.g. increased stiffness, strength, ductility, etc).
- Consequences of wall rehabilitation (e.g. increased demand on foundation, etc).
- The allocated budget for retrofit.
- Physical constraints (e.g. architectural requirements, accessibility of the building during the retrofitting process, etc).

Table 1 shows different retrofit techniques for RC walls and examples of experimental work conducted by pervious researchers and available in the literature to the authors.

Table 1 Different techniques used in retrofit of RC walls

| Retrofit technique | | Examples of the previous experimental work |
|---|---|---|
| Using traditional materials | Concrete replacement | Fiorato et al. (1983), Lefas and Kotsovos (1990), Vecchio et al. (2002), and others. |
| | Concrete Jacketing | Fiorato et al. (1983), and others. |
| | Using steel sections | Elnashai and Pinho (1997), Cho et al. (2004), and others. |
| | Using steel bracings | Taghdi et al. (2000), and others. |
| | Through-thickness rods | Mosalam et al. (2003), and others. |
| Using new materials | FRP laminates | Lombard et al. (2000), Kanakubo et al. (2000), Paterson and Mitchell (2003), Antoniades et al. (2003), Khalil and Ghobarah (2005), and others. |
| | Shape Memory Alloys | Effendy et al. (2006), and others. |

### 2.1. Concrete replacement

Concrete replacement is the simplest and cheapest technique that can be used to restore strength and ductility of RC walls (Fiorato et al. 1983). In this technique, the damaged concrete is removed, the aggregate of the old concrete is exposed and the surface of the old concrete should be cleaned to remove any loose material and to ensure a strong bond between the old concrete and the new one. If the reinforcing steel bars in the compression zone were slightly buckled after concrete crushing, they should be straightened (Lefas and Kotsovos 1990). The formwork of the web is prepared, the new concrete is mixed and poured from one side of the wall. The top part can be completed using a high-strength epoxy grout to ensure a proper bond with the old concrete (Vecchio et al. 2002). After the removal of formwork, the new concrete should be cured. Therefore, repairing the shear wall by concrete replacement is causing disturbance to the building function, and hence it is not suitable if the building has to be accessible during repair.

In some cases, in order to improve the strength and ductility of the RC wall, the major flexural cracks could be sealed using low-viscosity epoxy resins (Lefas and Kotsovos 1990). For this technique, a viscous epoxy adhesive is used to seal the crack along its length on the two sides of the wall, then staggered nozzles are located at reasonable spacing (e.g. 50 mm), then a very low-viscosity resin is injected under pressure through the nozzles until the crack is completely full of resin, then the nozzles are sealed off. For the previously mentioned procedures, no additional strength or deformation capacity will be gained as long as there is no increase of the web thickness or reinforcement. Even strength, stiffness and ductility capacities will not be completely restored, especially for the stiffness and ductility which are reduced significantly due to damage. However, if the wall is to be rehabilitated, other techniques like concrete or steel jacketing can be used.

### 2.2. Concrete jacketing

In this technique, the wall dimensions are increased by adding new concrete to the original web. Additional reinforcement could be used to increase the strength and ductility of the wall. The new reinforcement can be vertical and horizontal bars that form the reinforcement mesh or it can be diagonal bars. The new reinforcement should be anchored to the wall foundation. One way of anchoring is by placing the reinforcement in holes that are drilled in the foundation, and then it is grouted with epoxy. The new concrete is casted with the new dimensions and cured after solidification. Fiorato et al. (1983) tested two RC walls, one rehabilitated using diagonal bars after removal of the damaged web concrete in the plastic hinge region and the other one is rehabilitated by increasing the web thickness (jacketing). The tests showed that the strength and deformation capacities of the rehabilitated walls had increased, while their initial stiffness was almost half that of the original walls. It should be noted that, in some cases when the wall foundation is not over-designed, it will be needed to strengthen the foundation as well in order to be able to carry the additional weight of the wall and the increased lateral load expected to be carried by the wall.

### 2.3. Retrofitting using steel material

Steel is the most common material that was used for retrofitting of RC structures. Steel sections were used to retrofit RC shear walls with different schemes to enhance different response parameters. The lower added weight to the structure (compared to concrete jacketing) and the minimum disruption to the building occupants are advantages of using steel retrofitting systems (Ghobarah and Abou Elfath 2001). On the other hand, steel vulnerability to corrosion, the need for scaffolding, the difficulty of handling the heavy steel plates at the site are problems that arise when retrofitting using steel (Bakis et al. 2002). The following sections discuss the main techniques that were used for retrofit of RC shear walls using steel and the corresponding experimental tests.

#### *2.3.1 Using steel sections*

In this technique, steel plates are attached to the wall to increase the wall strength, stiffness, ductility or a combination of them. The steel plates can be attached vertically or horizontally according to the enhanced property. Elnashai and Pinho (1997) studied the effect of rehabilitation scheme used for retrofitting shear walls using steel plates on the enhancement of a certain property (e.g. wall stiffness, strength or ductility) without altering the other properties. Figure 5 shows different rehabilitation schemes of the walls studied by Elnashai and Pinho (1997). They concluded that enhancing the wall stiffness without altering the strength can be achieved by using external steel plates bonded along the wall length near the edges as shown in Figure 5(a), the plates can be bonded along the whole height or along the expected plastic hinge height, and a gap should exist between the plates and the foundation or the top slab in order not to affect the wall strength as the critical section will remain as before.

Increasing the wall strength without altering the stiffness can be achieved by using external unbonded steel plates or bars connected with an Interaction Delay Mechanism (IDM) as shown in Figure 5(b). The IDM allows the added plates or bars to work only after a certain displacement is exceeded. The plates or bars can be attached to the slabs between the wall height, and then enclosed by a ductile material that provide corrosion and fire resistance to the steel. This retrofitting scheme can be used provided that the concrete will be able to carry the additional shear and compression forces applied on it due to strengthening without crushing.

Increasing the wall ductility with a minor increase of the stiffness and strength can be achieved by using U-shaped external confining steel plates that are bonded to the wall using epoxy, and bolted using prestressed bolts as shown in Figure 5(c). Increasing the wall ductility will increase the energy dissipation capacity of the wall which will enhance the seismic behaviour of the retrofitted wall.

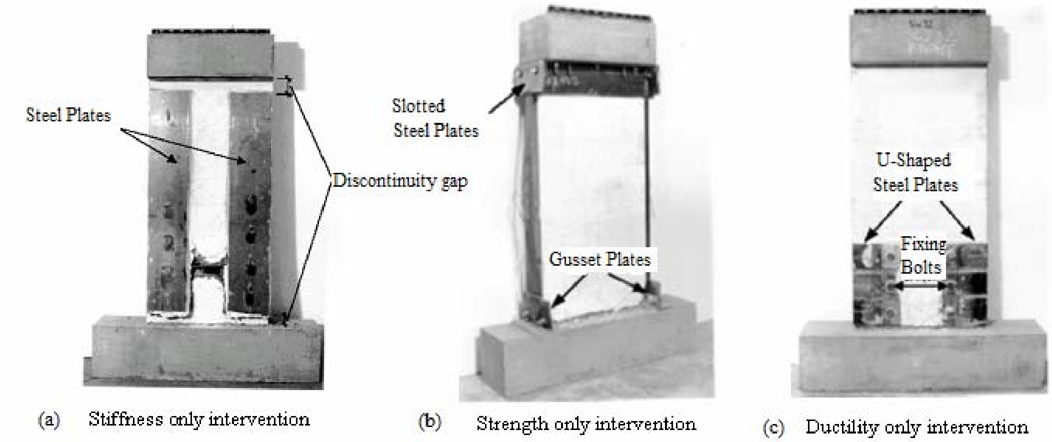



Figure 5 Different rehabilitation schemes studied by Elnashai and Pinho (1997)

To increase the shear strength of RC walls, Elnashai and Pinho (1997) used staggered horizontal steel plates that are epoxy-bonded to the wall and bent at both wall extremities. The increase of the wall shear strength would lead to ensure ductile flexural behaviour of the wall under dynamic loading. This would increase the wall deformation capacity (ductility) and hence increasing the energy that could be dissipated by the wall during an earthquake. Cho et al. (2004) studied RC wall strengthened with channel steel sections as boundary elements, the channels were connected with the concrete wall using headed studs. The tests showed that the boundary elements improved the performance of the wall significantly, and lead to a higher energy dissipation capacity and ductility. The tests showed also that local buckling of the added steel sections is an important issue that should be considered.

*2.3.2 Using steel bracing*

Steel bracings are mostly used for rehabilitation of nominally-ductile moment resisting frame structures. They can provide the adequate strength, stiffness and ductility required for the structure, provided that a special attention should be directed to their connections with the existing structure. Steel bracings can be also used to enhance the seismic performance of RC shear walls. In that case, the steel bracing can be anchored to the RC wall at small intervals to minimize the buckling length, which will increase the capacity of the bracing member compared to the case of retrofitting the moment resisting frames that is governed mainly by buckling of the compressed bracing member.

It is usually recommended to add vertical steel strips at the wall edges when using diagonal bracings, due to the fact that the diagonal forces in bracing members will have a vertical (compression/tension) components that will add higher forces on the wall, in that case it is better to provide vertical strips at the wall ends to resist a part of these forces with the concrete. Taghdi et al. (2000) tested a RC wall that is retrofitted using this technique. Figure 6 shows the retrofitted wall at 1.0 % drift. The tests showed that the retrofitted wall reached an ultimate lateral load capacity up to 2.8 times its original capacity, and an energy dissipation capacity up to 4 times the original one, which indicates the efficiency of this technique in retrofitting RC walls.

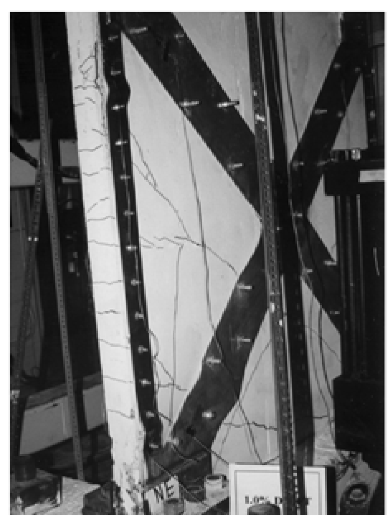


Figure 6 Retrofitted RC wall using steel bracings at 1.0 % drift (Taghdi et al. 2000)

## 2.4. Retrofitting using composite materials

Fibre-reinforced polymer (FRP) composite materials have received an increasing attention in the past few decades as a potential material for retrofitting of existing structures due to their high strength, light weight, ease of application, and their high resistance to corrosion. FRP laminates, sheets or rods can be used, and the fibres might be prestressed to increase the efficiency of retrofit. The use of FRP composites offers also a faster and easier retrofit alternative, especially when the evacuation of the entire building during the retrofit is not possible, in that case FRP will provide the required strength without interrupting the use of the building. Yet, some of the characteristics of FRP composites such as long-term performance, performance under dynamic excitations, etc., are still under investigation.

*2.4.1 Increasing the wall shear capacity*

Additional shear strength contribution can be obtained by orienting the fibres normal to the axis of the member or to cross potential shear cracks. The wrapping pattern and the number of FRP layers used in the retrofit determine the additional strength and ductility of the wall, and hence the ductility of the structure and its overall response when subjected to a specified seismic hazard level. In that case, FRP wrapping will have a slight effect on the wall flexure strength and stiffness, and hence minimal additional forces will be expected due to retrofit. Also due to the light weight of FRP, negligible weight will be added to the wall foundation.

Paterson and Mitchell (2003) retrofitted RC shear wall using CFRP wraps and through-thickness headed reinforcement. The retrofit scheme aimed to increase the wall shear strength and confinement. The retrofitted wall was able to reach displacement ductility 57% higher than the control wall, and it was able to dissipate three times the energy absorbed by the original wall. Khalil and Ghobarah (2005) tested two RC walls rehabilitated using FRP composites. The rehabilitation aims to increase the shear capacity and ductility of the walls. The first wall was rehabilitated by wrapping two layers of bi-directional diagonal fibres around the wall, and by applying uni-directional horizontal U-wraps around the end columns. FRP anchors were used to anchor the horizontal U-wraps as shown in Figure 7(a). The second wall was rehabilitated using the same pattern but four steel through-thickness bolts were fixed at the higher and lower region of the diagonal FRP sheets, and the U-wraps were anchored using nine bolts on each face along the column height as shown in Figure 7(b). It was found that the lateral load capacity has increased by about 40 and 57 % for the first and second wall, respectively. The two rehabilitated walls were able to reach displacement ductilities of 3 and 4 at their maximum strength compared to displacement ductility of less than 1 for the control wall. The study concluded also that the use of steel anchors allows almost full utilization of the material, and hence the wall performance was significantly improved compared to the case of FRP anchors.

*2.4.2 Increasing the wall flexural capacity*

The flexural strength of a RC shear wall can be enhanced by orienting the fibres parallel to the wall axis at its extremities. FRP sheets are bonded to the wall surface using epoxy and anchored to the wall foundation and to the top slab using steel or FRP anchors. Lombard et al. (2000), Kanakubo et al. (2000) and Antoniades et al. (2005) discussed several ways of anchorage of FRP sheets that can be used for flexural strengthening. Local buckling failure of compressed FRP sheets is also an important issue in case of cyclic loading, and it should be avoided. Increasing the wall flexural capacity will be useful if the original wall would experience flexural mode of failure and hence additional flexural capacity is required. In that case, the target flexural capacity of the retrofitted wall should not exceed the wall shear capacity, otherwise both flexural and shear capacities should be increased.

*2.4.3 Increasing the wall flexural and shear capacity*

Both flexural and shear capacities can be enhanced together at the same time using horizontal and vertical FRP strips. Lombard et al. (2000) studied retrofitting three RC shear walls using FRP composites when subjected to cyclic lateral excitations. The first wall was repaired to restore the wall original flexural capacity and stiffness. One vertical layer of carbon FRP (CFRP) sheets was applied on each wall face and anchored to the foundation using steel angles. The second wall was strengthened using the same technique to have higher stiffness and flexural capacity. The third wall was strengthened to increase the wall stiffness, flexural capacity, and shear capacity by applying one horizontal layer of CFRP sheet that is sandwiched between two vertical layers of CFRP on the two long sides of the wall. The walls were designed to have a ductile flexural failure after retrofit. It was found that FRP-retrofitted walls have better performance provided that a proper anchorage system for the sheets is used. It should be noted that, premature debonding of FRP sheets due to the compressive stresses in FRP vertical laminates is a critical issue that should be taken into account especially for the case of cyclic loading.

**2.5. Reduction of flexural strength**

This can be a solution to change the wall mode of failure from the brittle shear failure to the ductile flexural failure (ASCE 2006). This can be done by saw-cutting some of the wall vertical rebars near the wall ends. However, the wall still should possess the adequate flexural capacity needed for lateral load resistance.

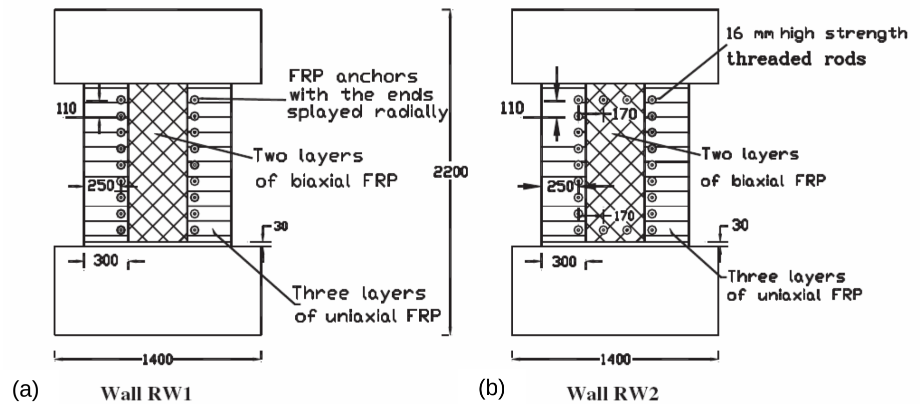



Figure 7 The two rehabilitation schemes tested by Khalil and Ghobarah (2005)

## 2.6. Use of through-thickness rods for lightweight RC walls

As mentioned before, Lightweight RC walls could experience in-plane splitting failure under high axial load especially if embedded steel elements were used in constructing the wall. In that case, confining the wall is the solution to prevent such a brittle failure mode.

Mosalam et al. (2003) used steel rods that can be anchored through the whole wall thickness to confine the wall. The rods can be bonded or unbonded to concrete (Figure 8). They concluded that this technique was effective in enhancing the performance of the wall and preventing such mode of failure.

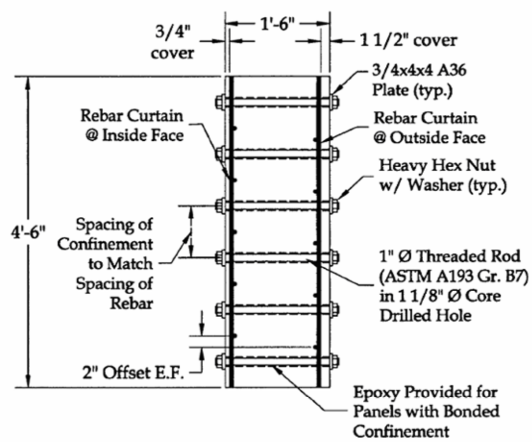



Figure 8 The RC wall strengthened using through-thickness rods (Mosalam et al. 2003)

## 2.7. Addition of wall boundary elements

Addition of boundary elements can be an effective technique for strengthening RC walls that are deficient in flexure (Cho et al. 2004, ASCE 2006). Reinforced concrete elements or steel sections can be added to act as boundary elements. This technique will not be efficient for walls that would experience shear mode of failure. It is worth noting that, a special attention should be considered to the connection between the existing wall and the new boundary elements.

## 2.8. Retrofitting using shape memory alloys (SMA)

Shape memory alloys have recently an increasing attention in civil infrastructure researches and seem to have a brilliant future. However, the reported tests on the use of SMA for seismic retrofit of RC walls have been very limited and still more tests are needed. SMA has the ability to undergo large deformations, then it can restore its original shape when the applied stress is removed (super-elastic effect) or when it is heated (shape memory effect). This will lead to high ductility and energy dissipation capacity without having large permanent deformations in the member (Desroches and Smith 2003). This phenomenon can be very useful in the seismic applications in buildings; such as dampers, bracings, etc. In addition to that, SMA has an excellent resistance against corrosion. Effendy et al. (2006) tested two low-rise RC walls with boundary elements retrofitted using two different types of SMA bracings.

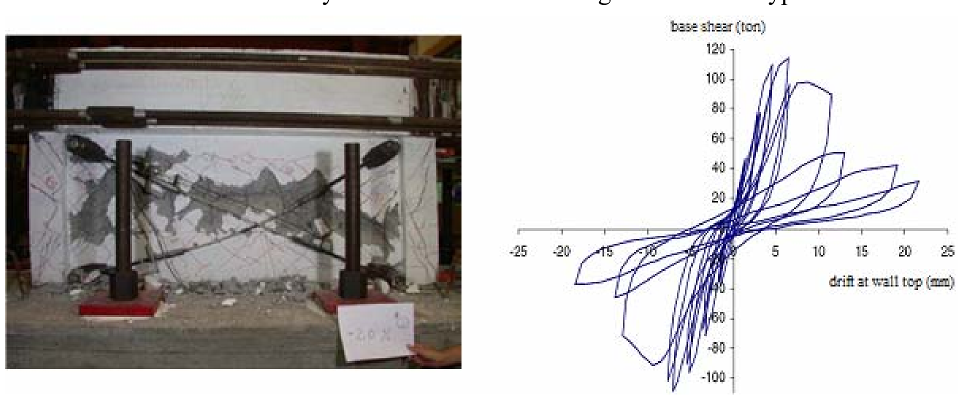



Figure 9 RC wall strengthened using SMA bars at failure and its hysteretic behaviour (Effendy et al. 2006)

One wall was retrofitted using Superelastic SMA rods [superelastic effect] (shown in Figure 9) and the other one using Martensite SMA rods [shape memory effect]. The tests showed that the wall retrofitted with SMA was able to tolerate higher loads with higher deformation capacity. They found that the wall with Superelastic SMA rods had less residual deformations compared to the one with Martensite SMA rods. They concluded also that buckling prevention of SMA bars is an important issue that must be considered.

## SUMMARY

Different retrofit techniques utilizing different materials that were used for repair, strengthening, or rehabilitation of RC walls are discussed. This ranged from using steel, concrete, FRP and shape memory alloys as retrofitting materials used with different methods of application. The retrofit schemes aim to enhance the seismic resistance of RC walls by increasing the stiffness, strength and/or ductility of the retrofitted walls. The paper discussed the advantages and disadvantages of each retrofit technique and the corresponding characteristic enhancements. It is concluded that the choice of the retrofit technique depends on the expected wall mode of failure, consequences of wall retrofit, the physical constraints, and the allocated budget for retrofit. The paper provided a state-of-the-art on the recent advancements and challenges in the area of retrofit of RC shear walls.

## ACKNOWLEDGEMENTS

The financial support of Le fonds Québécois de la recherche sur la nature et les technologies (FQRNT) through the team research project program and the Natural Science and Engineering Research Council (NSERC) of Canada are greatly appreciated.

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