Guide to Upgrade the Seismic Capacity of Existing Reinforced Concrete Buildings

Course No: S02-033
Credit: 2 PDH

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Introduction

Seismic retrofitting is the modification of existing structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. Every structure must have two load resisting systems, a vertical load resisting system for transferring the vertical load to the ground and a horizontal load resisting system for transferring the horizontal load to the vertical load system. The seismic forces must be properly collected by the horizontal framing system and properly transferred into vertical lateral resisting systems. Any discontinuity/ irregularity in this load path or load transfer may cause one of the major contributions to structural damage during strong earthquakes.

Idea & Aims of the Course

This course aims at providing a thorough review of the seismic upgrading techniques, which target reinforced concrete buildings, as the latter constitute the largest portion of the existing building stock. Seismic upgrading techniques can be divided in two major categories, depending on the way they "treat" the structure. At first, there are the ones that operate at the element level (Local Retrofitting Technique) and then those that operate on the structure as a whole (Global Retrofitting Technique).

Fig. 1 shows the goals at which a seismic retrofitting scheme might aim. When only the ductility of a structure needs to be improved, then local measures are typically sufficient and normally do not affect the structure's strength and stiffness, or they affect it marginally. However, if the capacity also needs to be increased, global measures will most likely have to be employed, as achieving a much higher lateral load (seismic)capacity in a structure via local measures alone would be an uneconomical option. Lastly, in cases that both the capacity and ductility of a structure are in need of improvement, then a combination of global and local measures should be employed. It is noted that in the context of this work, the terms "capacity" and "strength" are used interchangeably.

Apart from increasing a building's lateral strength, there is also the alternative of decreasing the earthquake-induced forces, which can be achieved by reducing the mass and/or reducing the lateral stiffness of the structure. Mass reduction can be realized through the use of lighter partition walls, floor removal etc., while stiffness reduction is achieved via the employment of base isolators and energy dissipation systems, while certain energy dissipation systems (e.g. Buckling-restrained braces) may also add stiffness. Fig. 2 outlines the main categories of seismic upgrading techniques targeting RC buildings, whereas Table 1 summarizes the most common measures together with the properties they affect.

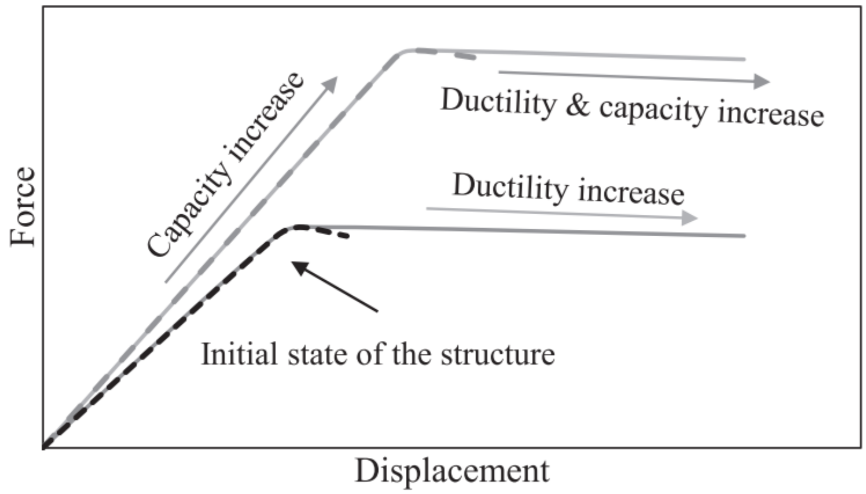

Figure 1. Seismic retrofitting goals.

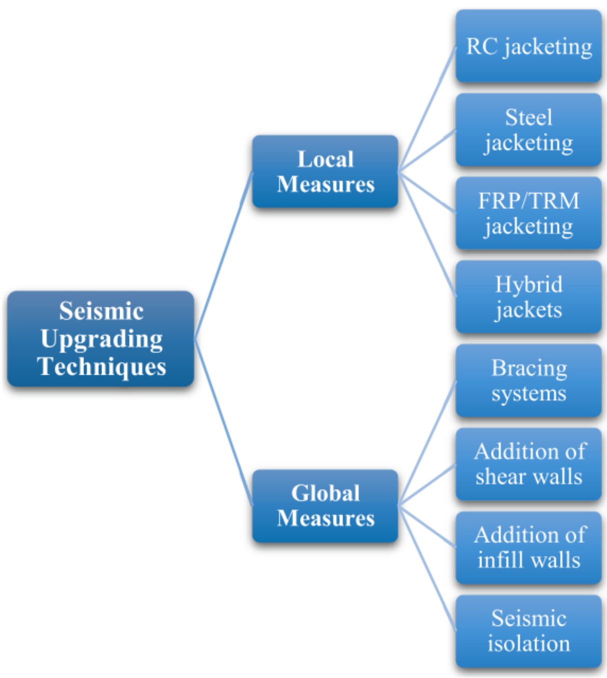

Figure 2. Taxonomy of seismic upgrading techniques

Table 1. Effect of local and global upgrading techniques on building properties

	Technique	Strength	Stiffness	Ductility	Irregularity	Force demand	Deformation demand
Local measures	RC/mortar jacketing	+	+	+		−	+
	Steel jacketing	+		+			
	FRP/TRM jacketing	+		+			
	Hybrid jackets	+		+			
Global measures	Bracing systems	+	+		+	−	+
	Shear walls	+	+		+	−	+
	Infills	+	+		+	−	+
	Mass reduction				+	+	−
	Seismic isolation		−		+	+	+
	Energy dissipation systems		+/-				+

1. Local Upgrading Techniques

The local upgrading techniques comprise measures applied to specific structural elements of a building, in order to enhance their mechanical characteristics. The general idea is to add some sort of external reinforcement to the existing beam/column/joint member and that way increase its flexural and/or shear capacity as well as its ductility.

Traditional techniques make use of conventional materials like concrete and structural steel, whilst novel ones employ more innovative materials like Fiber Reinforced Polymers (FRP), Textile Reinforced Mortars (TRM) etc. In the following sections, both conventional and novel techniques will be described, putting more emphasis on the latter.

1.1. RC Jacketing

The first and probably most traditional technique of seismic upgrading of RC members, is that of constructing an RC jacket around the initial element (Fig. 3), thus enlarging its sectional area and increasing both its longitudinal and transversal reinforcement. This technique can greatly increase the member's flexural and shear capacity, as well as its ductility.

Moreover, due to the increase in the dimensions and the addition of extra flexural reinforcement, the element's bending stiffness also increases, a side-effect that might not be desirable in some cases. RC jackets of various types have been widely used in practice in the recent past successfully.

Figure 3. Seismic upgrading with RC jacketing

Recently, there is a tendency to replace the concrete in such jackets with high-performance materials, due to their higher durability and better mechanical properties. Within this field, a number of concrete alternatives have been proposed and are listed below. High-performance, fiber-reinforced cementitious composite mortars (HPFRCC) may be used for the strengthening of the critical region of RC columns, even when they are corrosion-damaged. Such schemes can result in a significant reduction in shear and bending cracks, an overall enhancement of the force–displacement behavior, better energy dissipation and less stiffness degradation . The use of self-compacting ultra-high-performance fiber-reinforced concrete (UHPFRC) in RC columns with insufficient lap slices, has also been found to eliminate bond failure and damage in the plastic hinge regions . Other studies employed jackets made of ferro-cement [20], engineered cementitious composites (ECC) and high-strength micro-concrete.

The seismic upgrading of RC members with RC or other high-performance cementitious mortar jacket has proved itself over the years both in the lab and in practice. The most important benefits and drawbacks of this family of strengthening techniques are summarized below:

- Significant increase in strength and ductility.
- Adaptable to any shape of section.
- Makes use of materials that both engineers and workers are familiar with.
- Expensive, labor intensive and time-consuming method.
- Significant occupancy disruption.

- Loss in floor area due to the increase of the cross section sizes.
- Modification of the stiffness of the member.
- Use of large quantities of materials (i.e. concrete and steel) with high environmental burden (higher embodied CO_2 emissions, more energy in manufacturing).

1.2.Steel Jacketing

Instead of RC or other cementitious materials, structural steel can be used as external reinforcement to enhance the behavior of existing RC elements (Fig. 4). A combination of steel angles and plates can be used to form a cage around an RC element, thus increasing its flexural and shear strength, but also its ductility and stiffness. Alternatively, tubed steel elements or sheets can be wrapped around elements to provide extra confinement to the inner concrete and that way increase its ductility and shear capacity. In the latter case, the volume between the added steel and the existing concrete may be filled with grout.

Figure 4. Seismic upgrading with steel jacketing

Upgrading RC elements with steel jacketing techniques is a less popular method in engineering practice, but it can still provide excellent solutions in specific cases. The most important strengths and weaknesses of steel jacketing related methods are summarized below:

- Significant increase in strength and ductility.

- Makes use of materials that both engineers and workers are familiar with.
  Relatively expensive, labor intensive and time-consuming method *.
- Occupancy disruption *.
- Need for corrosion protection.
- Modification of the stiffness of the member and addition of significant extra weight *.

(* These drawbacks are less significant in comparison to RC jacketing)

1.3.FRP Jacketing

Probably the most popular technique for the seismic retrofitting of individual RC elements involves the use of fiber-reinforced polymers (FRP). When compared to traditional retrofitting methods, FRP are a very competitive alternative, as they offer ease and speed of installation, less labor work, minimum geometric changes, very high strength to weight ratio and minimum occupancy disruption. On the other side, they exhibit very poor behavior when exposed to high temperatures, in which case they need protection, and demand high quality work to be performed by experienced personnel. Yet, in the (not so common) case of open jackets (e.g. U-shaped jackets in T-beams), the effective utilization of the high strength of FRP may be low (e.g. in the order of 35%), due to the fact that debonding failures precede the material failures. The use of spike anchors increases the utilization of FRP tensile strength.

1.3.1.Fiber Types

Fibers in FRP materials can be of various types. The most usual fiber type used in seismic retrofitting applications is carbon (CFRP), due to its high elastic modulus and excellent durability; however, it is the most expensive material as well. A lower cost choice is to use glass fibers (GFRP), however as glass has roughly 1/3 of carbon fibers' elasticity modulus, larger material quantities need to be applied. Other fiber types that can be used (but are not common) are aramid, basalt, polyester, polyparaphenylene benzobisoxazole (PBO) and polyethylene terephthalate (PET). Lastly, it is also possible to form hybrid FRP by combining two or more materials together. Typical stress–strain curves for various types of fibers are given in Fig. 5.

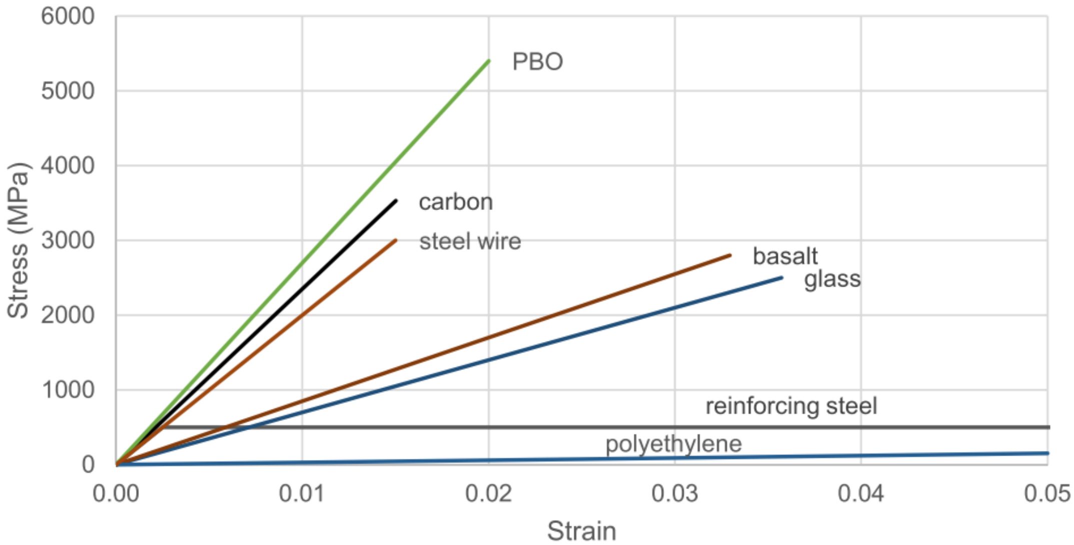

Figure 5. Typical σ-ε curves for various types of fibers.

1.3.2.Strengthening Methods

General. FRP are normally used in the field of RC member strengthening as externally bonded reinforcement (EBR) and can be applied (typically) in two distinct ways. The first and most frequent is to use FRP in the form of fabrics (Fig. 6) and attach them to the concrete substrate using epoxy resins. This way, they can be used as shear reinforcement in beams and columns with insufficient stirrups in order to ensure a ductile flexural response. Moreover, when wrapped around columns they provide confinement to the inner concrete and that way significantly increase the section’s ductility. The application of fabrics is possible on simple cross section shapes (circular or rectangular with low aspect ratio) as well as on more complicated shapes (e.g. T, L, rectangular with high aspect ratio) through the use of anchors. Alternatively, and rather rarely in seismic retrofitting, FRPs can be used in the form of prefabricated laminates, strips or bars (Fig. 7) to act as external longitudinal or transverse reinforcement in existing elements and thus increase their flexural or shear capacity. Their application can be either external, on the faces of an RC member, or inside grooves, in which case we have the near surface mounted (NSM) method. It should be emphasized though, that when used as external flexural reinforcement, strengthened members do achieve higher flexural strengths, but lower deformation capacities as fibers fail (or de-bond) at significantly lower strains than reinforcing steel (e.g. see Fig. 5). Strengthening and seismic retrofitting solutions with FRP are summarized in Fig. 8.

(a) (b) (c)

Figure 6. Wrapping of RC (a) columns and (b) beams with CFRP; (c) wrapping of RC shear wall with GFRP

(a) (b)

Figure 7. (a) Flexural and shear strengthening with FRP laminates; (b) flexural strengthening with NSM reinforcement [Source: Lecture notes, T. Triantafillou].

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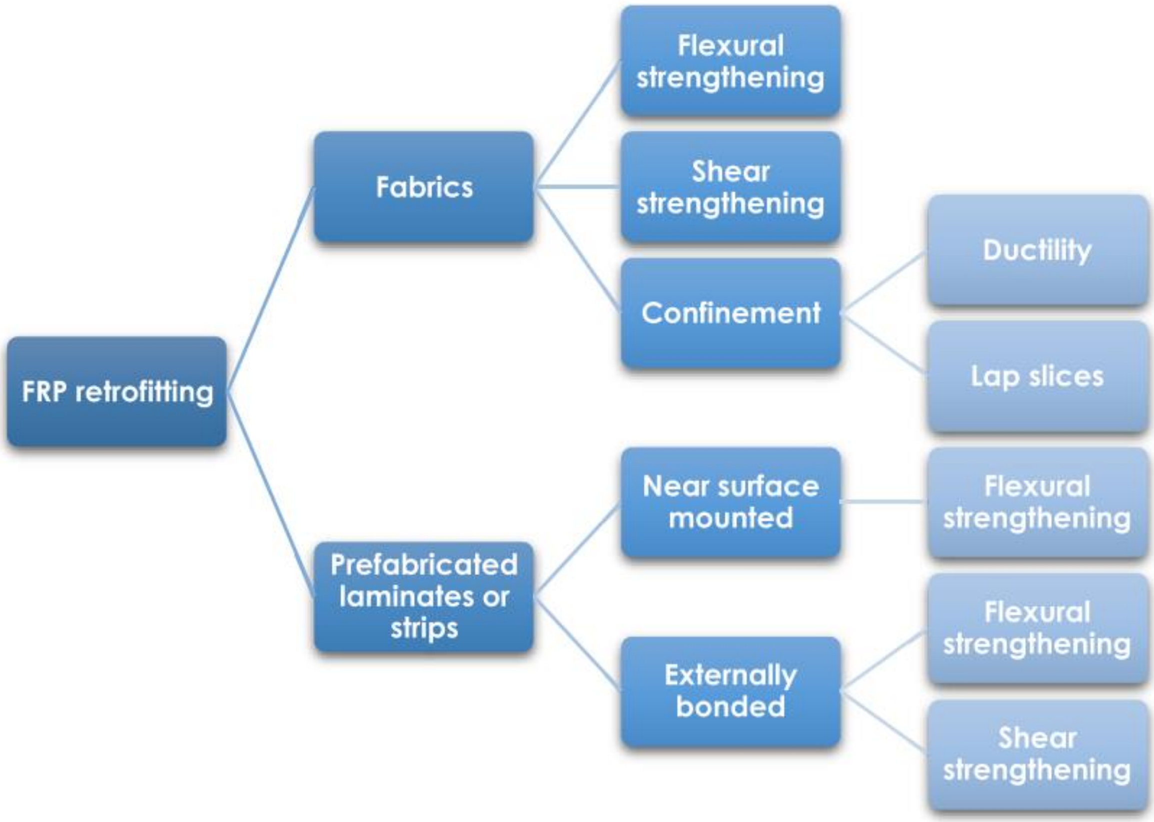

Figure 8. FRP strengthening roadmap.

Seismic Retrofitting with FRP. When it comes to seismic retrofitting, FRP have been proved to be most effective when used in the form of sheets as shear reinforcement or as a means to provide extra confinement. A review on seismic retrofitting of RC with FRP. A few of the numerous other studies are summarized below.

- When shear-deficient RC columns are wrapped with CFRP, they exhibit stable flexural behavior, as is they can sustain numerous loading/unloading cycles with no or little strength loss. The external reinforcement acted similarly to classical steel hoops, preventing shear-type failures and confining the inner concrete section, thus greatly increasing the section’s available ductility.

- It was also found that ductility was increased, column failure was delayed and that buckling of longitudinal bars could be avoided through the use of stiffer CFRP jackets

- GFRP wrapping improves the ductility, energy dissipation and capacity of RC columns, as well as the seismic performance of RC columns with insufficient lap slices.

- Efficiency of CFRP versus GFRP jacketing on RC columns with or without corroded reinforcement. It was found that, for the same circumferential stiffness (FRP elasticity modulus times the jacket thickness), the effectiveness was the same.

- Concerning the cross-sectional geometry of the RC elements, it was found that confinement was most effective in circular sections, followed by square and then rectangular. This effectiveness was reduced in case the elements had already sustained some damage.

- Regarding the behavior of CFRP reinforced RC columns with lap slices. The experiments observed that the jackets improved significantly the bond strength of the spliced bars. This in turn resulted in higher capacity and ductility, but also lower pinching effect and bond deterioration.

- It was also observed that the rotation capacity and energy dissipation of CFRP retrofitted columns was increased. At the same time, the stiffness degradation was significantly reduced

- CFRP jacketing is an effective rehabilitation measure for improving the seismic performance of existing beam-column joints with inadequate seismic details in terms of increased joint shear strength and inelastic rotation capacity.

- Regarding the effectiveness of full CFRP versus strap CFRP wrapping as external reinforcement in shear-controlled RC columns. The retrofitted columns showed increased shear capacity and ductility, which dropped with higher axial loads. The authors concluded that, for the same volumetric ratio, CFRP straps were more efficient than full wrapping.

- Regarding using of polyester FRP sheets for strengthening RC columns with insufficient reinforcement. It was found that the retrofitted specimens showed ductile behavior, along with significantly increased energy dissipation.

- Regarding using of basalt FRP (BFRP) and compared them to CFRP, applied on RC columns. It is found that the BFRP retrofitted columns exhibited the same or even better performance than those retrofitted with CFRP. Taking also into account that BFRP sheets cost about one-fifth the price of CFRP sheets.

1.4.TRM Jacketing

Fiber Reinforced Polymers have been used widely over the last years as a means to achieve better seismic behavior in deficient RC elements, mainly columns. However, apart from their advantages related to their application in retrofitting schemes, ***FRP entail a number of problems, which are listed below:***

• Resins behave poorly in high temperatures (above their glass transition temperature T_g), therefore the FRP reinforcement needs to be protected if it has to stay active during a fire.

• Epoxy resins are expensive.

• Application of resins has to be made on clean, dry surfaces, within regular temperatures and by experienced workers, as they are hazardous materials.

• In case of wrapped elements, the final product is vapor impermeable, due to the zero porosity of the resins, something that may cause damage to the concrete below.

• It is difficult to conduct a post-earthquake assessment of a strengthened element, as the FRP jacket will “hide” any damage suffered by the inner concrete.

A possible solution to address the above-mentioned issues is to use the same fibrous materials (carbon, glass, basalt etc.) in the form of textiles embedded in cementitious mortars, instead of fabrics impregnated in epoxy resins. These textiles are essentially fabric meshes made of long woven, knitted, or even unwoven fiber rovings in at least two (typically orthogonal) directions. The density (quantity and spacing) of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh. The end material is called Textile Reinforced Mortar (TRM), but it can also be found in the literature by other names, such as Textile Reinforced Concrete (TRC) or Fiber Reinforced Cementitious Matrix (FRCM). TRM have demonstrated superior performance than FRP as strengthening materials at high temperatures, whereas the TRM mechanical behaviour has also been found satisfactory after exposure to fire. Fig. 9 shows the application of TRM in RC columns and beams, respectively.

Figure 9. Applications of TRM jacketing on RC (a) column and (b) beam

As far as confinement is concerned, in recent paper published in the literature, some set of axial compression experiments using concrete cylinders and short rectangular columns, confined with TRM. It is found that the, TRM jackets can provide a substantial gain in the compressive strength as well as deformation capacity of concrete cylinders, with that gain being higher as the number of the confining layers increases. Comparing the efficiency of TRM jackets versus resin-impregnated (i.e. FRP) textile jackets and found that the former were only slightly inferior to the latter with respect to strength and ultimate deformation. Similar results were drawn from the tests on short rectangular columns, in which the performance of TRM was found to be very close to that of equivalent FRP jackets. Lastly, it was observed that the failure of TRM jackets was less abrupt than that of resin-impregnated textile jackets, a phenomenon that was attributed to the slowly progressing fracture of individual fiber bundles.

As far as shear strengthening is concerned, the tested shear-dominated RC members, strengthened with closed TRM jackets. The jackets were effective in transforming the failure mechanism from shear to flexural and that way prevent a brittle response. Compared to FRP jackets, the authors stated that the TRM strengthening system was about 55% as effective.

Regarding the shear strengthening of RC beams with TRM jackets, investigating the TRM vs FRP jacketing in side-bonding, U-wrapping and full-wrapping, different number of the strengthening layers and the effect of the shear span-to-depth ratio in beams strengthened in shear with U-shaped TRM jackets. It is concluded that the TRM is generally less effective than FRP in increasing the shear capacity of concrete; however the effectiveness depends on both the strengthening configuration and the number of layers. Wrapping strengthening configuration is much more effective than side bonding in case of TRM jackets and the effectiveness of TRM jackets increases considerably with increasing the number of layers. It was also concluded that the shear span-to-depth ratio has no effect on neither the failure mode nor the contribution of the TRM jacket to the total shear resistance of the beams.

Regarding cyclic loading tests, many papers recently published show a large set of cyclic loading tests experiments on RC T-beams strengthened in shear using U-shaped TRM jackets. Mechanical anchors through the RC slab were also used to provide end anchorage to the jacket. In this study, it was concluded that the jacket effectiveness increases substantially when steel anchors are employed and that high strains can be achieved in the TRM. Moreover, it was stated that TRM U-jackets are nearly as effective as FRP U-jackets in increasing the shear capacity of RC T-beams.

In recently published papers, a tested 10 full-scale RC T-beams strengthened in shear with TRM jackets and textile-based anchors. It is concluded that: (1) the use of textile-based anchors increases dramatically the effectiveness of TRM U-jackets; (2) increasing the number of layers in non-anchored jackets results in an almost proportional increase of the shear capacity; and (c) TRM jackets can be as effective as FRP jackets in increasing the shear capacity of full-scale RC T-beams.

1.5.Hybrid jacketing systems

Via the concurrent employment of different strengthening techniques, a more efficient retrofitting scheme can be designed and achieved. The next sections present the main developments on this subject during the last years.

1.5.1.FRP/TRM jackets with NSM reinforcement

The most common hybrid method found in the literature is the combination of FRP/TRM jackets with NSM strips. These systems result in flexural and shear strengthening, as well as in confinement, without affecting the member's dimensions.

Strengthened RC columns using different types of NSM materials (FRP and stainless steel) combined with TRM jackets (Fig. 10). It is reported that NSM FRP or steel are effective in increasing a member's flexural strength, by a factor of up to two, without diversely affecting its deformation capacity. Moreover, it was observed that the TRM jacket was very effective in controlling the buckling of the NSM bars, thus allowing them to reach high strains until failure.

(a) (b)

Figure 10. (a) NSM strips combined with (b) TRM jacketing

Using of NSM FRP in combination with CFRP jackets and reported a significant increase of up to 86% in the flexural capacity of RC columns, as well as an overall improvement in the members' seismic performance.

FRP jackets have also been combined with NSM FRP other than glass or carbon. Some researchers used aramid FRP and were able to achieve up to 90% higher flexural strength, as well as satisfactory drifts of 3%. Similarly, using of basalt FRP obtained very good results in terms of both flexural capacity and ductility.

Recently, some works were studied experimentally the seismic behavior of non-ductile building frames retrofitted with the NSM-FRP hybrid system. The full-scale dynamic testing was performed on the retrofitted test frame to realistically measure dynamic responses and quantify the retrofit effects. The hybrid retrofit system reduced the peak inter-story drift of the first-story columns by about 25% and their hinge rotation by approximately 76%. Additionally, the retrofit system uniformly distributed the damage or drift over the entire structure.

Steel/FRP and high-performance materials

Repair/strengthening and/or seismic retrofitting of damaged RC elements has been achieved by combining composites with high performance cementitious mortars. Recently published papers show repaired damaged RC columns using fast curing early-strength cement mortar along with basalt FRP and reported a significant improvement in both energy dissipation (by around 50%) and ductility (by two times). The flexural strength of moderately damaged elements was fully restored; when the damage was more severe though, a full capacity restoration could not be achieved.

Using of high-performance fiber-reinforced cementitious composite (HPFRCC) sprayed mortar together with steel bars in order to enhance the seismic behavior of under-reinforced RC columns, typical of old constructions. Under cyclic lateral loading tests, which showed that the retrofitting technique was effective in increasing the columns' lateral strength by 20% and achieving a many times higher deformation capacity, by altering the failure mode from shear to flexure. Cracking was also reduced, and higher energy dissipation was observed. Recently, some works presents repaired corrosion-damaged RC columns with HPFRC in combination with GFRP jackets. It is reported that the performance of the retrofitted columns was adequate in terms of restoring the member's load capacity, but it could not satisfy the ductility demands, posed by modern regulations.

2. Global Upgrading Techniques

When a drastic increase in the lateral load capacity or the stiffness of a structure is needed, it is very likely that local retrofitting measures alone either would not suffice or would demand such extended interventions that the final retrofitting scheme would become uneconomical. In such cases, global measures are employed, aiming at either increasing the structure's lateral strength and stiffness or decreasing the seismic demand. The former is usually achieved by adding new structural elements to the existing building, thus increasing significantly its lateral stiffness and resistance. The alternative of decreasing the earthquake-induced forces to a given structure in the first place, is normally achieved through the employment of base isolation systems or energy dissipating devices (dampers). The following sections provide a state-of-the-art description of such retrofitting schemes, which are applicable to RC buildings.

2.1.Capacity Increase

2.1.1.Addition of Bracing Systems

An effective way to increase a building's stiffness and strength characteristics is by adding a bracing system within selected frames. The new elements can be tailored to take up the lateral loads almost entirely, but since they have to work in conjunction with the existing frame members, great care must be paid to their connections to the frame elements as well as to the increased axial loads, which will be induced to the columns. Furthermore, as the retrofitting works are normally done on the outside frames of the structure, the loss in living space area and the occupancy disruption are minimal. A number of different bracing types exist and can be employed to RC structures. The most usual is that of concentric bracing (Fig. 11a), in which the horizontal seismic forces are resisted by axially loaded members. Alternatively, eccentric braces (Fig. 11b) resist the horizontal forces by a combination of axially loaded members and shear links, which are used as energy dissipating mechanisms.

To address the problem of buckling, which is inherent in braces, buckling-restrained braces have been developed and constitute another viable option. Last, but not least, post-tensioned rods or prestressed cables is a relatively new retrofitting scheme which can also be employed to solve buckling-related problems.

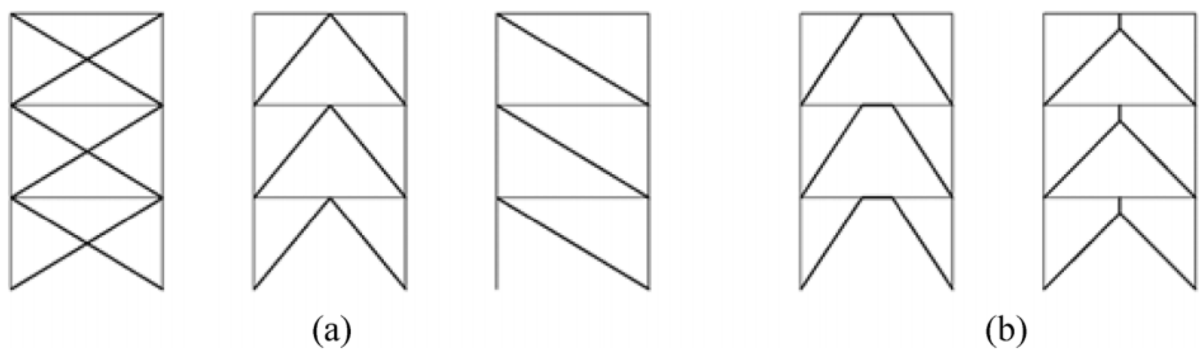

Figure 11. (a) Concentric and (b) eccentric bracing systems

2.1.2.Addition of RC shear walls

The addition of new RC shear walls is an alternative to using steel braces as lateral load resisting mechanisms. The new elements are also designed to resist the majority of seismic loads so that the existing elements only play a secondary role. RC shear walls are very effective in reducing inter-story drifts, mitigating irregularities and preventing soft-story failure mechanisms.

New Shear Walls: New shear walls can be constructed around an existing column, on the external side of a selected frame or externally of the building as buttresses (see Fig. 12). It is very important that the new elements be properly connected to the structure as well as adequately supported to the ground with new, strong foundations. Research has shown that this retrofitting method can significantly increase a building's strength and stiffness.

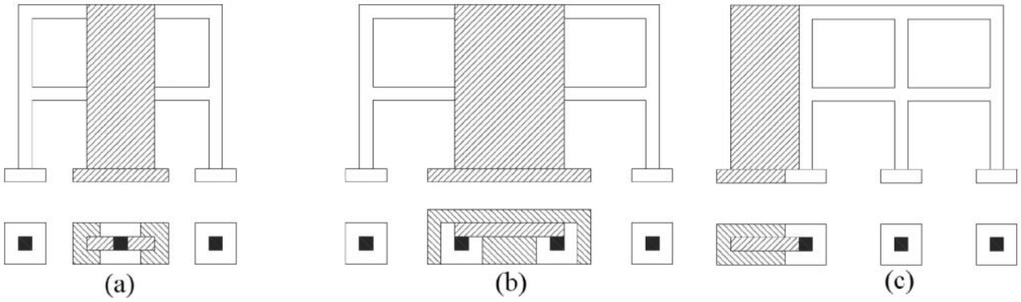

Figure 12. Addition of RC walls (a) placed around a column, (b) external to the frame, (c) as buttress

RC infilling of bays. Shear walls can also be constructed within existing RC frames, thus creating an infill with considerably higher lateral strength and stiffness. Connection of the new element with the surrounding frame has to be provided using shear dowels and its foundation should also be carefully dimensioned, as in the case of new shear walls.

More recently published research work, performed pseudo-dynamic tests on a full-scale four-story, three-bay RC building at the European Laboratory for Structural Assessment. The RC infill was constructed within the middle bay, filling its whole length and having the same width (250 mm) as the surrounding columns and beams (Fig. 13). A combination of dowel and starter bars was employed in order to connect the new element to the existing frame. Their distribution was variable along the height of the structure and CFRP U-jackets were constructed at the ground level, at the column bases. It is reported that the strengthened building was able to sustain a 0.25 g earthquake without any significant damage. Moreover, the connection of the wall behaved satisfactorily. This study concluded that the RC infilling technique is a viable method for seismic retrofitting and can be used in cases the strength and ductility of an existing structure is in need of upgrading.

(a) (b)

Figure 13. - (a) RC infill wall dowels and web reinforcement; (b) Prototype testing

2.1.3.Addition/Modification of Infills

Unreinforced masonry (URM) is a material commonly used in RC structures to construct infills within the frames, as well as the internal partitions of a building. URM infills have been thoroughly investigated in the past by the academic community as it has been proved that their contribution to the lateral strength and stiffness of a structure is significant. In most cases, this contribution seems to be beneficial, as they function as a weaker version of shear walls. However, when their height wise or floor-wise positioning is not even or when they are built partially within a bay's height, they can have adverse effects as well. Taking into account the beneficial effects of infills as well as their low construction cost, several researchers have proposed to use them as retrofitting elements. Extra reinforcement, with either traditional or advanced materials, can also be employed to enhance their behavior as well.

2.2.Demand Decrease

Retrofitting techniques which aim at increasing a structure's lateral load capacity and stiffness can be employed in most cases and mitigate successfully the seismic risk. However, their applicability is not always possible, for a number of reasons. First, as they generally cause an increase to the lateral stiffness, higher seismic forces are introduced to the structure's body.

Even if new elements are designed so that they can cope with these increased demands, the soil beneath the structure might fail and lead to a global overturning failure mechanism. Moreover, the capacity-increase-related techniques do not reduce the floor accelerations experienced by the structures during an earthquake. These accelerations can however lead to the failure of various non-structural elements. Last, but not least, in certain cases where sensitive equipment is to be installed inside buildings, the limitation of any possible floor oscillations is of outmost importance. Hence, an alternative route to increasing structural capacity is the reduction of demand; this may be achieved by using base isolation and/or devices for energy dissipation.

2.3. Base Isolation

Base isolation aims at decoupling the superstructure from the underlying foundation soil, so that only minimal vibrations are perceived by it during a strong ground motion (Fig. 14). This can be achieved by using isolation systems (elastomeric bearings, lead-rubber bearings, friction-pendulum bearings etc.) which significantly increase the structure's natural period. The increased period leads to lower spectral accelerations, thus lower base shear demands. At the same time though, the spectral displacements, for large-period structures, are also higher (Fig. 15). This is why, in many cases, the employed isolator systems also have damping-increasing characteristics or are combined with supplementary dampers.

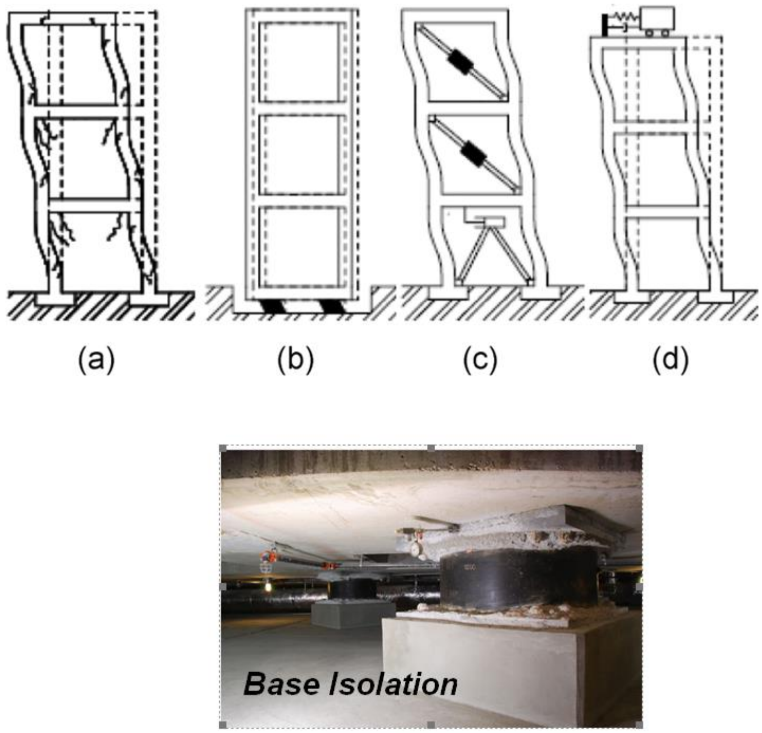

Figure 14. Capacity reduction systems: (a) conventional design of RC frame; (b) base isolation; (c) energy dissipation using dampers; (d) tuned mass damper

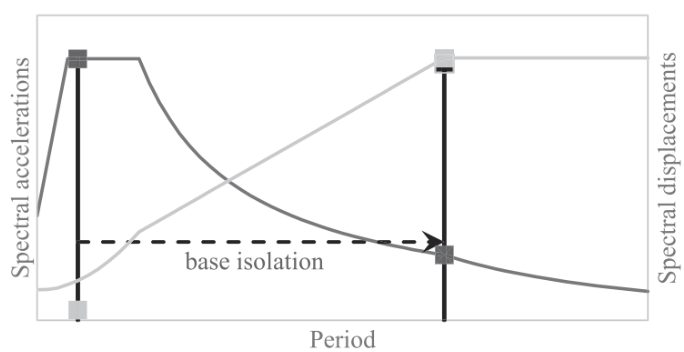

Figure 15. Base isolation principle

Base isolation is very effective in reducing the seismic vulnerability of a given structure, however its implementation in the case of existing structures is not a straightforward task. To address this matter, some resaaecrhers proposed a seismic isolation procedure which consists of creating an isolated platform under the foundations, without touching the building at all. A set of horizontal pipes are inserted below the foundations and the isolation devices are placed at the horizontal diametric plane. A trench is then formed around the building, thus completing its isolation from the surrounding soil. At the end of the intervention, both the structure, as well as the ground directly below it are seismically isolated, without having affected at all any architectural characteristic of the former. It is reported that this isolation scheme is applicable for both historical buildings and industrial plants, in which multiple structures can be isolated at once, thus protecting crucial connecting components; however, it should be noted such a strengthening system is prohibitively expensive for the big majority of the existing buildings.

2.4.Passive Energy Dissipation Systems

An alternative to base isolation, in the broader area of reducing the seismic demands of a given structure, is the installation of passive energy dissipation systems. The role of these devices is to dissipate the largest percentage of the input seismic energy, so that the remaining structural elements remain undamaged. Different options exist and can be applied on both the existing and new RC structures. A brief overview of the available passive energy dissipation systems is given below.

Viscoelastic dampers consist of thin steel plates combined with viscoelastic material laminates. These materials are able to withstand the high shear strains, which develop during strong earthquakes and that way dissipate large amounts of the seismic energy. Such devices are normally installed at the connection points of metallic braces, therefore they can be employed along with a bracing system of a broader seismic retrofitting scheme.

Friction dampers rely on the friction developed between specially treated steel plates, which are clamped in contact using high strength bolts. Relative slip occurs at a predefined load, which is selected so that it is not exceeded under the wind loading cases. The hysteresis loops of these dampers are rectangular, thus resulting in large amounts of energy dissipation and protecting the structural elements. This type of dampers is also installed within bracing systems

Viscous-fluid dampers achieve energy dissipation through the movement of a piston with small slits inside a highly viscous fluid of oily nature. During strong earthquakes, the pistons that are placed as braces within frames start to move, so that the viscous fluid is forced to flow through the tiny cavities. This results in large amounts of dissipated energy and effectively reduces the forces experienced by the structural members.

CONCLUSIONS

This course outlined the seismic upgrading methods that have been developed for application in RC buildings, emphasizing on novel approaches. Both local and global techniques were discussed and assessed in terms of their strengths and weaknesses.

Local retrofitting measures are usually employed when the examined building already has an acceptable level of lateral strength and stiffness. Most common applications include the jacketing of RC beams and columns aiming at increasing their shear strength, available ductility and avoiding lap-slice and buckling failures. Both traditional (concrete and steel) and novel (FRP and TRM) jacketing materials were analyzed, putting more emphasis on the latter. Specifically, FRP have been used successfully in many experimental campaigns as well as real-world applications. They are also corrosion-free and do not affect the elements dimensions and stiffness, as opposed to RC and steel jackets. On the other hand, their poor behavior in high temperatures calls for extra fire-safety measures. TRM offer a promising alternative to FRP, as jacketing materials. They have slightly reduced effectiveness, but are more economic, easy to install and have superior fire resistance.

Global structural retrofitting techniques, both capacity-increasing and demand-decreasing, were also thoroughly discussed. Concerning the former, steel braces, RC shear walls and infills were examined; all these yield a significant increase in a building's lateral strength and stiffness. Steel braces are a very effective means of providing extra strength and stiffness to an existing structure. Eccentric braces offer significant energy dissipation capabilities, while buckling-restrained ones can be employed to avoid buckling failures in the compression members. The addition of RC shear walls, either as new elements or by infilling of existing frames, can also be beneficial for the seismic strengthening of structures. Still, different failure modes need to be considered, depending on the initial deficiencies of the as-built structure. Rocking walls have proved to be very promising, as they suffer minimal damage and can be combined with energy-dissipating devices to further control the structural response. Lastly, masonry infills consist a very economical way of increasing a structure's lateral strength and stiffness. When strengthened using FRP, TRM or reinforced mortar overlays, they form a reliable lateral load resisting mechanism. Precast concrete panels can also be used as frame infills, and result in similar beneficial results. Integrated seismic and energy upgrading can be provided in some of the global seismic retrofitting measures reviewed (e.g. by combining TRM, exoskeleton systems, PCPs, RC/masonry infilling with thermal insulation).

A relatively more advanced approach to the issue of structural retrofitting is through decreasing the seismic demands. Within this area, seismic isolation as well as passive, active and hybrid energy dissipation systems can be employed to effectively reduce the seismically induced vibrations on a given structure. Due to the generally higher cost and complicated nature of such retrofitting schemes, relatively limited applications can be found in the literature and in engineering practice. Nevertheless, in cases of retrofitting important structures or when vibration control is of outmost importance, such methods can yield extremely good results.

Selecting the appropriate retrofitting solution for a given structure is a multi-parametric problem without a one-fits-all solution. The specific details of the examined structure, the desired level of performance upgrade, the availability of materials, specialized personnel etc., and of course, the overall intervention cost need to be accounted for. Moreover, the design of such retrofitting measures usually calls for advanced simulations. Therefore, it is important that engineers have a robust regulatory framework to follow, so that their designs can be reliable.

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