Earthquake Engineering and Structural Dynamics

Seismic retrofit schemes for RC structures and local–global consequences

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Summary

A review of repair schemes for reinforced concrete frame buildings is presented in this paper, within the context of global objectives of the intervention process. Local as well as global intervention measures are discussed and their technological application details outlined. The effect of the reviewed repair schemes on the member, sub-assemblage and system performance are qualitatively assessed. The important role of the foundation system in the rehabilitation process is outlined and measures that are consistent with the super-structure intervention methods are given. The paper concludes with a global assessment of the effect of repair methods on stiffness, strength and ductility, the three most important seismic response parameters, to assist researchers and practitioners in decision-making to satisfy their respective intervention objectives. The framework for the paper complies with the requirements of consequence-based Engineering, where the expected damage is addressed only when consequences are higher than acceptable consequences, and a cyclical process of assessment and re-assessment is undertaken until the community objectives are deemed to be satisfied.

Key words: retrofit; repair/strengthening; rehabilitation; structural intervention; seismic upgrading

Prog. Struct. Engng Mater. 2006; **8**:1–15
DOI: 10.1002/pse.208

Introduction

In recent years, devastating earthquakes worldwide confirmed the deficiencies of building structures. The experience gained from field observations and back-analysis led to improvement of the level of knowledge and the evolution of seismic codes.

The interest of the research community is focused on buildings that do not comply with current seismic codes and exhibit deficiencies such as poor detailing, discontinuous load paths and lack of capacity design provisions. Since such buildings comprise the majority of existing building stock, retrofitting is a rather critical issue. Rehabilitation schemes that will provide cost-effective and structurally effective solutions are necessary. Many intervention methods used in the past have been revised and developed in the light of the new seismic code requirements and new methods often based on new materials (e.g. fiber-reinforced polymers FRPs) have been proposed.

In this paper, the term 'rehabilitation' is used as a comprehensive term to include all types of repair, retrofitting and strengthening that lead to reduced earthquake vulnerability. The term 'repair' is defined as reinstatement of the original characteristics of a damaged section or element and is confined to dealing with the as-built system. The term 'strengthening' is defined as intervention that lead to enhancement of one or more seismic response parameters (stiffness, strength, ductility, etc.), depending on the desired performance.

Framework of seismic rehabilitation

Performance objectives are set depending on the structural type, the importance of the building, its role in post-earthquake emergencies, the economic consequences of business interruption, its historical or cultural significance, the construction material and socio-economic factors. They can be specified as limits on one or more response parameter such as stresses, strains, displacements, accelerations, etc. Clearly, different limit states have to be correlated to the level of the seismic action, i.e. to the earthquake demand level.

The selection of the rehabilitation scheme and the level of intervention is a rather complex procedure, because many factors of different nature come into play. A decision has to be taken on the level of intervention. Some common strategies are the restriction or change of use of the building, partial demolition and/or mass reduction, addition of new lateral load resistance system, member replacement, transformation of non-structural into structural components and local or global modification (stiffness, strength and ductility) of elements and system. In addition, methods such as base isolation, provision of supplemental damping and incorporation of passive and active vibration control devices may apply. The alternatives of 'no intervention' or 'demolition' are more likely the outcomes of the evaluation if the seismic retrofit of buildings is quite expensive and disruptive.

Socio-economic issues have to be considered in the decision of the level and type of intervention. Surprisingly, there are documented cases where aesthetic and psychological issues dictate the rehabilitation strategies. For example, in the Mexico City earthquake of 19 September 1985, where external bracing was popular, because it instilled a feeling of confidence in the occupants that significant and visible changes have been made to the structure to make it safer[1]. Cost *vs* importance of the structure is a significant factor, especially in the case that the building is of cultural and/or historical interest. The available workmanship and the level of quality control define the feasibility of the proposed intervention approach. The duration of work/ disruption of use and the disruption to occupants should also be considered. The functionality and aesthetical compatibility of the intervention scheme with the existing building is an additional engagement. Even the reversibility of the scheme in case it is not accepted on a long-term basis should be taken into account.

From a technical point of view the selection of the type and level of intervention have to be based on compatibility with the existing structural system and the repair materials and technology available. Controlled damage to non-structural components and sufficient capacity of the foundation system are essential factors that are often overlooked. Issues such as irregularities of stiffness, strength and ductility have to be considered in detail.

A convenient way to discuss the engineering issues of evaluation and retrofit is to break down the process into steps. The first step involves the collection of information for the as-built structure. The configuration of the structural system, reinforcement detailing, material strengths, foundation system and the level of damage are recorded. In addition, data relevant to the non-structural elements (e.g. infill walls) which play a significant role and influence the seismic response of structures are also compiled. Sources for the above information can become visits to the site, construction drawings, engineering analyses and interviews with the original contractor. The rehabilitation objective is selected from various pairs of performance targets and earthquake hazard levels (i.e. supply and demand, or response and input pairs). The performance target is set according to an acceptable damage level (performance target). Building performance can be described qualitatively in terms of the safety of occupants during and after the event, the cost and feasibility of restoring the building to pre-earthquake condition, the length of time the building is removed from service to effect repairs, and the economic, architectural or historic impacts on the larger community. Variations in actual performance could be associated with unknown geometry and member sizes in existing buildings, deterioration of materials, incomplete site data, and variation of ground motion that can occur within a small area and incomplete knowledge and simplifications related to modeling and analysis. In the next phase, the rehabilitation method is selected starting with the selection of an analysis procedure. The development of a preliminary rehabilitation scheme follows (using one or more rehabilitation strategies) the analysis of the building (including rehabilitation measures), and the evaluation of the analysis results. Further, the performance and verification of the rehabilitation design are conducted. The rehabilitation design is verified to meet the requirements through an analysis of the building, including rehabilitation measures. A separate analytical evaluation is performed for each combination of building performance and seismic hazard specified in the selected rehabilitation objective. If the rehabilitation design fails to comply with the acceptance criteria for the selected objective, the interventions must be redesigned or an alternative strategy considered.

Rehabilitation options

LOCAL INTERVENTION METHODS

The local modification of isolated components of the structural and non-structural system aims to increase the deformation capacity of deficient components so that they will not reach their limit state as the building responds at the required level. Local intervention techniques are applied to a group of members that suffer from structural deficiencies and a combination of these techniques may be used in order to obtain the desired behavior for a seismically designed structure.

Injection of cracks

Crack injection is a versatile and economical method of repairing reinforced concrete (RC) structures. The effectiveness of the repair process depends on the ability of the adhesive material (usually epoxies) to penetrate, under appropriate pressure, into the fine cracks of the damaged concrete. Flexural cracks and shear cracks are mainly continuous and therefore provide unobstructed passages for the epoxy. On the other hand, longitudinal cracks, which develop along reinforcing bars as a result of bond failure, are usually discontinuous and narrow. Difficulties may occur in repairing the steel-to-concrete bond by epoxy injection.

This repair method can be used in minor (<0.1 mm), medium (<3 mm) size cracks, and large crack widths (up to 5–6 mm). In case of larger cracks, up to 20 mm wide, cement grout, as opposed to epoxy compounds, is the appropriate material for injection (Fig. 1). In the first step of the application process, loose material is removed. For the more usual case of epoxy injection, the surface trace of cracks is fully sealed with epoxy paste, leaving only surface-mounted plastic nozzles for injection. The spacing of nozzles along the crack should be dictated by the distance epoxy can travel prior to hardening (this distance depends on crack width and on the viscosity of the epoxy at the application temperature). In members with dimensions larger than hardening distance, ports at both surfaces should be provided along penetrating cracks. Injection is deemed complete for a portion of the crack when epoxy is expelled from the next higher nozzle. Once the repair epoxy has set, the nozzles are bent and tied firmly. They can be cut flush and sealed with an epoxy-patching compound prior to rendering of the affected member.

Flexural tests on RC beams and beam–column joints show that the repair process not only eliminates the unsightly appearance of wide cracks, but also restores the flexural strength and stiffness of the damaged member[2,3]. Push-off tests (both static and dynamic) further indicate that concrete-to-concrete joints can regain their shear strength after being repaired by epoxy resin injection.

Shotcrete (Gunite)

Shotcrete is used as a repair method for RC and masonry structures. There are two distinct types of shotcrete; dry-mix and wet-mix. Shotcrete can be applied to almost any surface; it can also be used in combination with other retrofit schemes (e.g. RC jacket). Because of its generally low water–cement ratio and high-velocity impact, it achieves excellent bond to most competent surfaces. Deficiencies in shotcrete applicability usually fall into one of the following five categories[4]: (i) failure to bond to the receiving surface, (ii) de-lamination at construction joints or interfaces of various application layers, (iii) incomplete filling of the material behind the reinforcing steel, (iv) slough due to excess mixing water (which can generate voids) and (v) weak interface between the concrete and steel. The impact velocity of the material to the application surface is dependent upon both the exit velocity and the distance of the nozzle from the surface. Where bond is important, equipment must be at the proper impact angle of about 90° and reasonably close to the application surface. Further, the surface must be clean, sound and damp. When the shotcrete strikes the application surface (or other hard objects such as reinforcing steel), some of the larger and harder aggregate particles tend to ricochet. These particles are referred to as rebound and are composed primarily of the larger aggregate particles, although some cement and water are included. Because of the nature of its composition, rebound is not capable of obtaining significant strength and should not be allowed in the final work. Many factors affect the amount of rebound such as: (i) orientation of the receiving surface, (ii) shotcrete mix design, (iii) amount of reinforcing steel embedment,

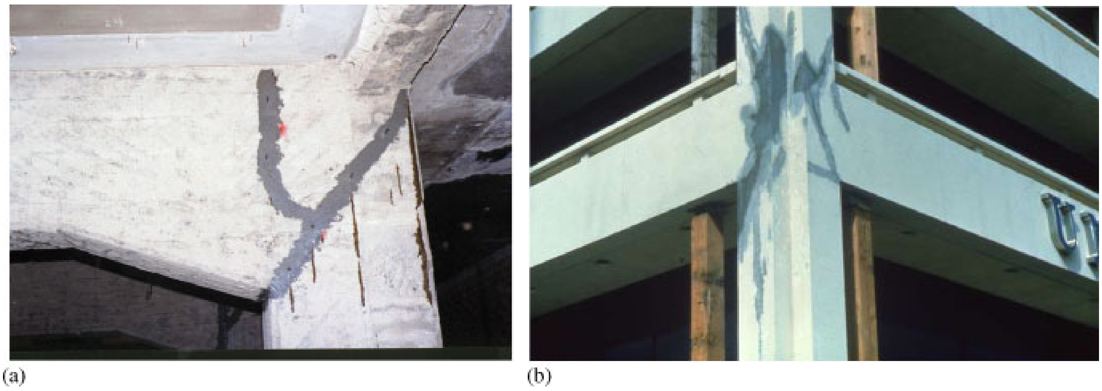
(a) (b)

Fig. 1 Application of the: (a) epoxy resin; (b) cement grout injection in beam–column joints

(iv) thickness of the cross-section, (v) impact velocity, and (vi) spraying technique.

Steel plate adhesion

Steel plate adhesion is mainly used in the case of beams. Both shear and flexural strength enhancement can be achieved. When thick steel plates are needed, it is advisable to use several thin layers instead, to minimize interfacial shear stresses. A sound understanding of both the short- and long-term behavior of the adhesive used is required. In addition, reliable information concerning the adhesion to concrete and steel is required. The execution of the bonding work is also of great importance to achieve a composite action between the adherents. Prevention of premature de-bonding or peeling of externally bonded plates is a most critical aspect of design[5–7].

Steel jacketing

The steel jacketing option involves the total encasement of the column with thin steel plates placed at a small distance from the column surface, with the ensuing gap filled with non-shrink grout[8,9]. An alternative to a complete jacket (exemplified in Fig. 2b,c) is the steel cage alternative[10,11]. Steel angles are placed at the corners of the existing cross-section and either transversal straps or continuous steel plates are welded on them. In practice, the straps are often laterally stressed either by special wrenches or by preheating to temperatures of about 200–400°C, prior to welding. Any spaces between the steel cage and the existing concrete are usually filled with non-shrink grout. When corrosion or fire protection is required, a grout concrete or shotcrete cover may be provided.

The corrugated steel jacketing technique can be applied for the rehabilitation of columns and beam–column joints[12]. Deficient connections are encased by the steel jacket and the gap between the concrete and the steel jacket is filled with non-shrink grout. A gap is provided between the beam jacket and the column face to minimize flexural strength enhancement of the beam; which may cause excessive forces to develop in the joint and column.

Externally bonded FRPs

The ease of application of FRP composites renders them attractive for use in structural applications; especially in cases where dead weight, space or time restrictions exist. Although FRP composites can have strength levels significantly higher than those of steel and can be formed of constituents such as carbon (CFRP), glass (GFRP), and aramid (AFRP) fibers, it is important to note that its use is often dictated by strain limitations[13] (Fig. 3a). They are very sensitive to transverse actions (i.e. corner or discontinuity effects) and unable to transfer local shear (i.e. interfacial failure). Clearly, they carry no compressive forces. Choosing the type of fibers, their orientation, their thickness and the number of plies, results in a great flexibility in selecting the appropriate retrofit scheme that allows to target the strength hierarchy at both local (i.e. upgrade of single elements) and global (i.e. achievement of a desired global mechanism) levels. In general, FRP composites behave in a linear elastic fashion to failure without any significant yielding or plastic deformation. Additionally, it should be noted that unlike reinforcing steel, some fibers (such as carbon fibers) are anisotropic. This anisotropy is also reflected in the coefficient of

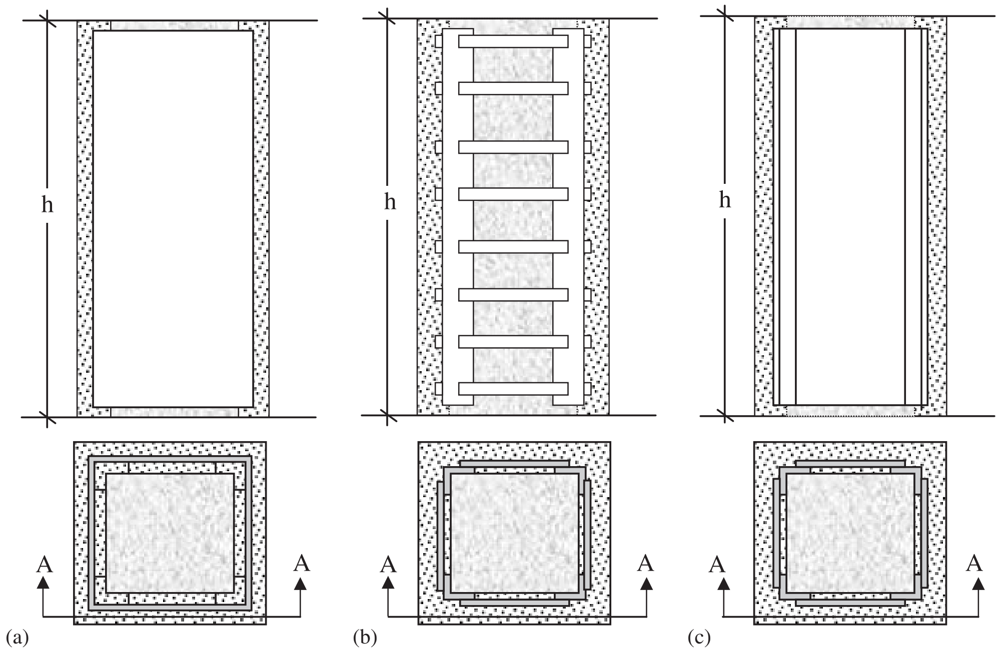

Fig. 2 (a) Steel jacketing; (b) steel cage technique using steel straps or (c) steel plates

(a) (b) (c)

Fig. 3 (a) Material properties[14]; application modes of (b) prefabricated shells; (c) FRP sheets

thermal expansion in the longitudinal and transverse directions. The large differences in strength (transverse strength < longitudinal strength) and coefficients of thermal expansion can result in bond deterioration and splitting of concrete. Moreover, these can cause lateral stresses and low cycle fatigue under repeated thermal cycling[15].

The effectiveness of strengthening depends on the bond conditions, the available anchorage length and/or the type of attachment at the FRP ends, the thickness of the laminates, among other less important factors. According to experimental data, failure of the FRP reinforcement may occur either by peeling off (de-bonding) through the concrete near the concrete–FRP interface or by tensile fracture at a stress which may be lower than the tensile strength of the composite material, because of strength concentrations (e.g. at rounded corners or at de-bonded areas). In many cases, the actual failure mechanism is a combination of FRP de-bonding at certain areas and fracture at others. The choice of constituents and details of the process used to fabricate the composite significantly affect environmental durability. Exposure to a variety of environmental conditions can dramatically change failure modes of the composites, even in cases where performance levels remain unchanged. In other cases, exposures can result in the weakening of the interface between FRP composites and concrete, causing a change in failure mechanism and sometimes a dramatic change in performance.

In the case of columns, shear failure, confinement failure of the flexural plastic hinge region and lap splice de-bonding can be accommodated by the use of FRPs[16–18]. At this juncture it is important to stress that none of these failure modes and associated retrofits should be viewed separately, since retrofitting for one deficiency may only shift the problem to another location and/or failure mode without necessarily improving the overall performance. For example, a shear-critical column, strengthened over the column center region with carbon wraps, is expected to develop flexural plastic hinges at column ends which, in turn, need to be retrofitted for the desired confinement levels. Furthermore, lap splice regions need not only to be checked for the required clamping force to develop the capacity of the longitudinal column reinforcement, but also for confinement and ductility of flexural plastic hinge[17]. Shear and flexural strengthening of beams can be achieved by the application of either epoxy-bonded laminates or fabrics extending in the compression zone or epoxy-bonded FRP fabric wrapped around the beam[19–22]. In the case of beam–column joints, the jacket is designed to replace missing transverse reinforcement in the beam–column joint[23–28]. The FRP technique can be also used for strengthening walls[29].

Selective intervention methods

Where system-optimal performances dictate selectively modifying specific response parameters to pre-defined levels, procedures for affecting single parameters with no effect on others are called for. The initial development of 'selective intervention' techniques, proposed by Elnashai[30] was first applied to structural walls under static loading[31]. Further studies applied the techniques to shaking table-tested walls[32], and culminated with application to a full-scale four story RC building[33]. The fundamental parameters governing structural responses to transverse actions in the inelastic range are: stiffness, strength and ductility. Consequently, selective intervention techniques are referred to as *stiffness-*, *strength-*, and *ductility-only.*

Stiffness-only intervention approaches may be used in order to accommodate problems related to irregular distribution of stiffness or to significant reduction of stiffness due to cracking of concrete members. In the latter case, if concrete crushing and buckling of reinforcement bars do not occur the flexural strength of the members will not necessarily be adversely affected.

Altering the sequence of plastic hinge formation to achieve a predetermined failure mode becomes an essential objective for seismic safety. This requires an increase in strength of strategically located members. Only a selective *strength-only* intervention can be effective in addressing such deficiency.

Problems with lack of ductility supply may be confronted by the application of ductility-only intervention methods. Lot of effort has been put together towards the investigation of alternative ductility-only retrofit schemes. Aboutaha *et al.*[34] investigated the effectiveness of rectangular steel jackets for improving the ductility and strength of columns with inadequate lap splice in the longitudinal reinforcement. Several types of steel jackets were investigated, including rectangular solid steel jackets with and without adhesive anchor bolts. A similar set of experiments was conducted by Aviles *et al.*[35]. The models were deficient in the level of concrete confinement at foundation level and thus retrofitted with steel plate wrapping combined with anchor bolts. Saadatmanesh *et al.*[36] carried out experimental work on the application of high-strength FRP composite straps to retrofit bridge columns. Ghobarah *et al.*[37] investigated the effectiveness of corrugated steel jacketing for the seismic upgrading of RC columns.

GLOBAL INTERVENTION TECHNIQUES

In case of systems with high flexibility or when no uninterrupted transverse load path is available then global intervention techniques are considered. The most well known global retrofit schemes are presented hereafter.

RC jacketing

RC jacketing is one of the most commonly applied methods for the rehabilitation of concrete members. Jacketing is considered to be a global intervention method if the longitudinal reinforcement placed in the jacket passes through holes drilled in the slab and new concrete is placed in the beam–column joint (Fig. 4). However, if the longitudinal reinforcement stops at the floor level then RC jacketing is considered as a member intervention technique. The main advantage of the RC jacketing technique is the fact that the lateral load capacity is uniformly distributed throughout the structure of the building thereby avoiding concentrations of lateral load resistance, which occur when only a few shear walls are added[38]. A disadvantage of the method is the presence of beams which may require most of the new longitudinal bars in the jacket to be bundled into the corners of the jacket. Because of the presence of the existing column, it is difficult to provide cross ties for the new longitudinal bars, which are not at the corners of the jacket.

To date, apart from qualitative guidelines provided in some Codes, no specific design rules exist for dimensioning and detailing of the jackets to reach a predefined performance target. The uncertainty with regard to bond between the jacket and the original member is another disadvantage. Of the many factors influencing jacket performance, slip and shear-stress transfer at the interface between the outside jacket layer and the original member that serves as the core of the upgraded element are overriding considerations[39].

The effectiveness of the method has been studied by many researchers and supported by experimental work[38,40–42]. In cases where building are in close proximity to one another, the method is modified and one-, two- or three-sided jacketing applies[43,44].

Addition of walls

Addition of new RC walls is one of the most common methods used for strengthening of existing structures. This method is efficient in controlling global lateral drift, thus reducing damage in frame members. During the design process, attention must be paid to the distribution of the walls in plan and elevation (to achieve a regular building configuration), transfer of inertial forces to the walls through floor diaphragms, struts and collectors, integration and connection of the

Fig. 4 Reinforced concrete jacketing technique

wall into the existing frame buildings and transfer of loads to the foundations. Added walls are typically designed and detailed as in new structures. To this end, in the plastic hinge zone at the base they are provided with boundary elements, well-confined and detailed for flexural ductility. They are also capacity-designed in shear throughout their height and over-designed in flexure above the plastic hinge region (with respect to the flexural strength in the plastic hinge zone, not the shear strength anywhere), to ensure that inelasticity or pre-emptive failure will not take place elsewhere in the wall before plastic hinging at the base and that the new wall will remain elastic above the plastic hinge zone.

The most convenient way to introduce new shear walls is by partial or full infilling of strategically selected bays of the existing frame[45]. If the wall takes up the full width of a bay, then it incorporates the beams and the two columns, the latter acting as its boundary elements (Fig. 5). In case only the web of the new wall needs to be added, sometimes by shotcreting against a light formwork or a partition wall is performed. In the latter case, shotcrete is normally used for increased adhesion between the existing and the added material. An alternative to the cast-in-place infill wall technique is the addition of pre-cast panels. The pre-case infill wall system should be designed to behave monolithically, and the infill wall should be designed with sufficient shear strength to develop flexural yielding at the base of the wall[46].

A major drawback of the addition of walls is the need for strengthening the foundations to resist the increased overturning moment and the need for integrating the wall with the rest of the structure. Foundation intervention is usually costly and quite disruptive, thus rendering the application of this technique unsuitable for buildings without an existing adequate foundation system.

External buttresses

To reduce or eliminate the disruption to the use of a building, external buttresses may be constructed to increase the lateral resistance of the structure as a whole. Such an intervention scheme, in common with the construction of RC walls, requires a new foundation system. The foundation scheme would possibly be eccentric footings (eccentric with respect to the axis of the buttress to avoid excavation under the building). The two most intricate problems in strengthening by building a set of external buttresses are: (i) the buttress stability may be critical since it is not actually loaded vertically downwards in the same way that the structure is. The vertical action on the buttress is only its own weight. This increases the possibility of uplifting of the foundations and may even cause over-turning, (ii) the connections between the buttresses on the one hand and the building on the other is far from straightforward. To insure full interaction and load sharing when the structure is subjected to lateral actions, the buttress should be connected to the floors and columns at all levels. The connection area will be subjected to unusual levels of stresses that require special attention.

Steel bracing

Steel bracing can be a very effective method for global strengthening of buildings. Some of the advantages are the ability to accommodate openings, the minimal added weight to the structure and in the case of external steel systems minimum disruption to the function of the building and its occupants.

Alternative configurations of bracing systems may be used in selected bays of a RC frame to provide a significant increase in horizontal capacity of the structure. Concentric steel bracing systems have been investigated for the rehabilitation of non-ductile buildings by many researchers[47–50]. Using the eccentric steel bracing in the rehabilitation of RC

Fig. 5 Cast-in-place infill walls

structures has lagged behind concentric steel bracing applications due to the lack of sufficient research and information about the design, modeling and behavior of the combined concrete and steel system. Further research is needed in several areas such as testing of the RC beam–steel link connection details and design as well as the development and implementation of link elements models in analysis software[51]. Post-tensioned steel bracing can be used for the seismic upgrading of infilled non-ductile buildings limited to low-rise and squat medium-rise buildings[52]. The method was successfully used by Miranda & Bertero[53] to effectively upgrade the response of low-rise school buildings in Mexico.

Base isolation

Seismic isolation is mostly adopted for rehabilitation of critical or essential facilities, buildings with expensive and valuable contents and structures where performance well above performance levels is required. Seismic isolation system significantly reduces the seismic impact on the building structure and assemblies. Generally, the isolation devices are inserted at the bottom or at the top of the first floor columns. Retrofitting mostly requires traditional intervention; in the first case the addition of a floor in order to connect all the columns above the isolators while in the second case the strengthening of the first floor columns (enlarging of the cross-sections, addition of reinforcing bars or construction of new resistant elements). Nevertheless, inserting an isolator within an existing column is not so simple because of the necessity of cutting the element, temporarily supporting the weight of the above structure, putting in place the isolators and then giving back the load to the column, without causing damages to persons and to structural and non-structural elements.

Recently, efforts have been made to extend this valuable earthquake resistant strategy to inexpensive housing and public buildings[54]. The results of a joint research program conducted by the International Rubber Research and the Development Board (IRRDB) of United Kingdom show that the method can be both cost effective and functional for the protection of small buildings in high seismicity regions. A comparative study conducted by Bruno & Valente[55] on conventional and innovative seismic protection strategies concluded that base isolation provides higher degrees of safety than energy dissipation does, regardless of the type of devices employed. Moreover the comparison between conventional and innovative devices showed that shape memory alloys-based devices are far more effective than rubber isolators in reducing seismic vibrations.

Effect of retrofit on global response

Development of a complete strategy guiding the retrofit solution through established objectives or criteria is an ongoing effort of the earthquake engineering research community. In general, seismic rehabilitation may aim to either recover or upgrade the original performance or reduce the seismic response[56]. In the first case, the retrofit schemes that will be chosen have to reinstate the structural characteristics at member level and have negligible impact on the global response. The crack injection (epoxy resin injection or grout injection) technique and the member replacement (substitute part of the damaged member) may apply.

When the seismic demand is to be reduced, this can be achieved by adopting base isolation techniques or by providing the structure with supplemental dissipation devices. Reducing the masses at each story level accommodating irregularities in the mass distribution along the height of the building is an effective way of reducing seismic demand. In many cases (in areas of rapid economic and industrial development) the functionality of residential buildings is changed and they are used for either storage or installation of heavy industrial equipment. Due to the discontinuity in mass distribution the particular floors are susceptible to failure. Moreover, the total or partial demolition of the top stories of structures can result in the reduction of the period so as to comply with the seismic demand.

In the case of the seismic upgrading, the aim of the retrofit strategy as an operational framework is to balance supply and demand. The supply refers to the capacity of the structural system, which has to be assessed in detail before selecting the intervention scheme. The demand is expressed by either a code design spectrum or a site-specific set of records as a function of period and shape of vibration characteristics of the upgraded system. By modifying strength, stiffness or ductility of the system alternative retrofit options are obtained, as shown in Fig. 6. Ductility enhancement applies to systems with poor detailing (sparse shear reinforcement, insufficient lap splicing), stiffness and strength enhancement to systems with inherently low deformation capacity (so as to reduce displacement demand), whereas stiffness, strength and ductility enhancement apply to systems with low capacity or where seismic demand is high[57].

An effective retrofit scheme for dealing with ductility deficiencies of the structural system is FRP jacketing. Assuming that the as-built system has been designed according to the strong-column weak-beam mechanism approach, FRP jacketing of the vertical elements provides additional confinement of the existing columns. The effectiveness of the method depends on reassuring that slip of longitudinal bars of the existing column will not occur and to the bond conditions between the existing member and the new material. The behavior of the retrofitted structure is represented herein, for demonstration purposes, by the behavior of the retrofitted 2-story, 2-bay RC frame shown in Fig. 7a. The span length of the frame is 5 m, while the story height is 2.7 m. The columns have dimensions 0.40 × 0.40 m, longitudinal reinforcement ratio $\rho_l = 0.77\%$ and confinement reinforcement volumetric ratio $\rho_{sw} = 0.22\%$ (#6/0.15 m). The material strengths of the existing structure are C16 and S300. Using FRP jacketing in order to increase the confinement factor to a value of, $K = 2$, and by performing pushover analysis by ZEUS-NL[58] the top displacement at ultimate is increased by 122%. If the seismic upgrading targets the modification of stiffness, strength and ductility levels, RC jacketing can be chosen as a retrofit solution. The response of the retrofitted structure depends on the characteristics of the jacket such as longitudinal reinforcement, confinement reinforcement and material strengths. In this case the effectiveness of the solution scheme depends on the continuity between the existing and the new material and the effectiveness of anchorage of the additional reinforcement of the jacket. The response of the retrofitted frame is shown in Fig. 7b for two alternative jacket configurations J_1 and J_2, respectively. In both cases the jacket dimensions are 0.50 × 0.50 m, the material strength characteristics C20 and S400, but in the first case (J_1) the total longitudinal reinforcement ratio of the jacketed cross-section is $\rho_{lj} = 0.85\%$ and confinement reinforcement volumetric ratio $\rho_{swj} = 0.93\%$ (#10/0.075 m), while in the second (J_2) the total longitudinal reinforcement ratio of the jacketed cross-section is $\rho_{lj} = 1.31\%$ and confinement reinforcement volumetric ratio $\rho_{swj} = 1.40\%$ (#10/0.050 m). The first jacket configuration (J_1) increases the strength level (maximum base shear) by 55%, while the second (J_2) by 89% (Fig. 7b). In both cases the ductility level is increased dramatically.

The response modification of the existing structural system may be achieved by adopting a combination of the pre-described local and global intervention techniques. The strategic use of the retrofit schemes can accommodate all deficiencies observed at local and/or global level and result in a cost- and time-effective solution.

SYSTEM-LEVEL DEFICIENCIES

System-level deficiencies such as eccentricities of stiffness (or strength) and mass in both plan and elevation are common in existing structures. This class of deficiency is a consequence of old construction practices (poor level of confinement details, negligible material-property control). Due to lack of specific guidelines most retrofit strategies adopted in practice are based mainly on experience and in few cases on simple analysis (with the exception of major structures in high seismicity regions, such as California and parts of Japan). Recent earthquakes have demonstrated that the rehabilitation measures taken in the past failed to meet the retrofit performance objectives. In many cases, misuse of the retrofit solution schemes was observed. A major issue seems to be the difficulty in understanding the interaction between the retrofit scheme and the existing structural system. A sound understanding of the response of the existing structural system and a clear definition of the performance objectives of the

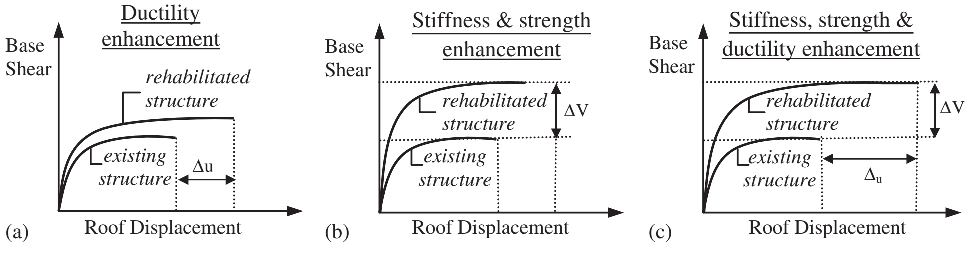

Fig. 6 Alternative retrofit strategies for seismic upgrading[57]

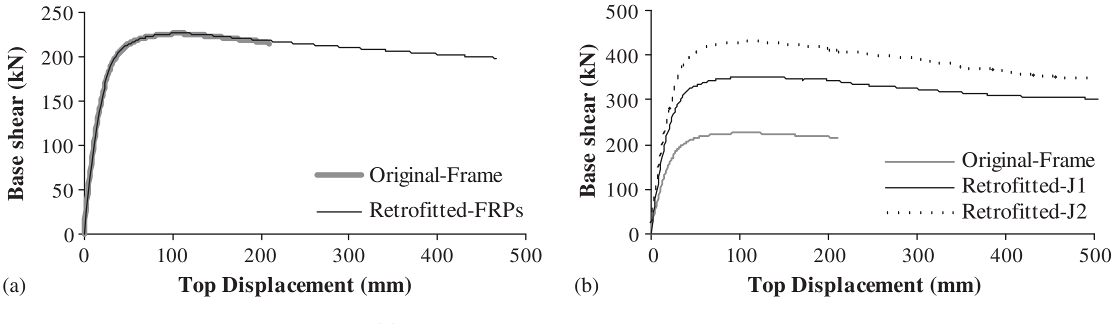

Fig. 7 (a) Ductility enhancement—FRP jackets; (b) stiffness, strength and ductility enhancement—RC jackets

retrofit strategy are necessary before embarking on the design of the retrofit solution.

Vertical irregularities (irregularities along the vertical axis) are due to either irregular distribution of mass or stiffness along the height of the building. As mentioned above, buildings may be used for a different purpose from their original intended function. The concentration of mass at a particular story attracts higher seismic forces and results in the creation of a soft story.

Vertical irregularities may also be due to irregular stiffness distribution. A special case is the soft-story mechanism. A common structural configuration (typical of the construction practice in Southern Europe) susceptible to a soft-story failure mechanism is the *pilotis* frame. The ground story used for commercial facilities is an open frame (bare frame), while the stories above are infilled. Under lateral loading, the ground-story columns have to resist the large base shear which leads to large story drift concentrated in the first story. The large demand increases progressively due to second-order effects, often leading to the collapse of the structure in a soft-story mechanism.

Observation of practical application has shown that there is lack of clarity with regard to the way soft-story mechanism is treated. Increasing the stiffness of the ground level only to reach the stiffness of the infilled floor above is not the correct approach, since the stiffness of the floor above depends on the strength of the masonry infills. In a future earthquake, as soon as the masonry infills start cracking, or even shed out-of-plane, the localization of damage is transferred to the story above. The retrofit strategy should aim to develop a uniform distribution of stiffness along the height of the building. RC jacketing and the addition of RC walls can be effective retrofit solutions provided they are applied to achieve a target displaced shape.

Horizontal irregularities (irregularities in the plan of the structure) are due to the eccentricity between the centers of mass and stiffness. The uneven distribution of stiffness may be the result of architectural (e.g. L-shaped buildings) or functional (e.g. facade of commercial buildings) features. The position of the elevator shaft walls plays an important role in the distribution of stiffness in plan. Walls and columns have to be placed in strategic positions in order to accommodate irregularities. The retrofit strategy should aim to balance the stiffness or mass irregularities in plan. The addition of new elements (e.g. RC walls, external buttresses) may be used to advantage in addressing plan irregularities.

The effect of the various intervention schemes at local and global level and some useful comments with regard to the effectiveness of the method and parameters that should be taken into account in the design phase are presented in the appendix (Table A1).

ROLE OF FOUNDATION SYSTEM

Seismic upgrading of the super-structure has a direct effect on the demand imposed on the existing foundation system. Structural requirements may dictate considerable strength enhancement in locations that are connected directly to the foundations. Capacity design principles immediately dictate that foundation strengthening is needed. Moreover, parameters such as soil conditions and soil–structure interaction play an important role in foundation-strengthening projects.

Old buildings mainly supported by isolated footings and in fewer cases by combined footings are weak or flexible compared to the current seismic design philosophy. In the majority of cases, the foundation system along with the rest of the structure are representative of construction practices adopted in the past and may be susceptible to a number of different modes of brittle failure.

Retrofit strategies may aim at either strengthening the existing foundation system and/or adding supplemental foundation elements (footings or piles). Larger spread footings can distribute the load and additional reinforcement can increase their shear and bending resistance. The incorporation of existing footings into grade beams or mats, which can spread load over a larger soil area and activate the gravity loads in other columns in the resistance of the overturning moments and uplift forces, is another option. Projects involving the addition of grade beams or increased size of spread footings usually require excavation under difficult circumstances and there are difficulties in pinning or attaching the existing footings to the new elements[59]. Moreover, piles may be added to improve the overturning resistance. Adding piles along the perimeter of the building can be an easier task from an economical and constructional point of view compared to the case where piles are added under the interior of the buildings.

The selection of the RC jacketing as the retrofit solution for the super-structure results in a uniform distribution of stiffness. The retrofit of the foundation system can be relatively easily accommodated by extending the jacketing to the foundation level (Fig. 8). On the other hand, the addition of new elements (e.g. RC walls, external bracings) may add strength and stiffness to the building at critical locations. In these cases, greater demands on the foundation system are placed. The shear transmitted between the soil and the strengthened structure may be higher because of the increased strength and stiffness of the structure[59]. Stiff structural components generate large bending moments at the base. Large overturning movements may cause large dynamic axial forces to develop in the columns of braced frames or at the boundary elements of shear walls.

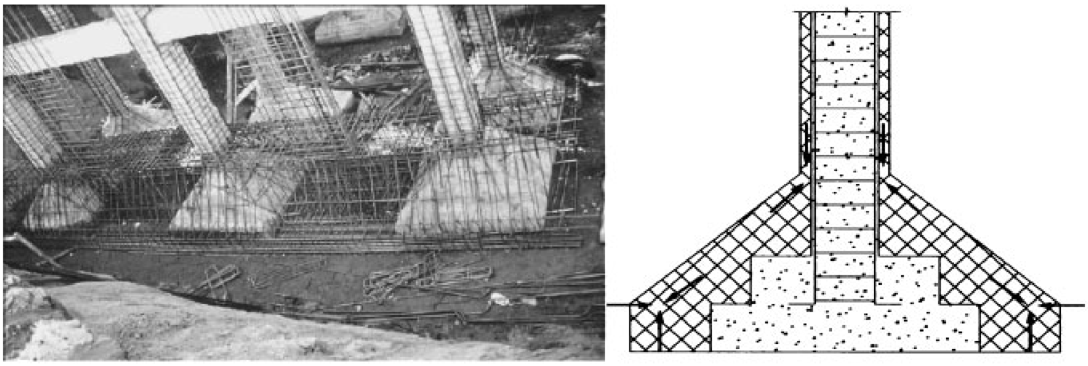

Fig. 8 Strengthening of footings—RC jacketing

A foundation system that allows the development of hinges in the super-structure is vital for the stability of structural and non-structural components. Seismic upgrading of foundations is usually a disruptive process. The cost varies depending on the type and the level of intervention. In cases where piles have to be installed in the existing system the cost may dominate the total seismic retrofit project.

Conclusions

Numerous retrofit schemes adopted in practice for the seismic upgrading of old and substandard reinforced concrete buildings are presented. A multiplicity of factors influence the selection of the retrofit solution and therefore no general rules apply. To aid in the selection, the effectiveness of the retrofit schemes and their interaction at local and global level is explored. The main system-level deficiencies (vertical and horizontal irregularities) are presented and related modeling issues are clarified. The impact of strengthening of the super-structure on the foundation system and the alternative retrofit options for the foundation system are discussed. The paper concludes with a table summary of the retrofit options, motivation for use, local and global effects, technological and design requirements, intended to provide a quicklook guide to potential users.

Appendix A

The summary of the effect of retrofit on local and global response is shown in Table A1.

Table A1 Summary of the effect of retrofit on local and global response

Method	Deficiency type	Local effect	Global effect	Technology considerations	Design considerations
Injection of cracks	Shear or shear-flexural cracks	Flexural strength and stiffness restoration. Shear strength is regained in concrete-to-concrete joints	Repair method—no modification of the response of the original structure	The quality and the environmental durability of the materials used play an important role. The adhesive material should penetrate into the fine cracks of the damaged concrete and infill all the voids	Reduction factors for concrete strength may be used to take into account any uncertainty regarding the effectiveness of the method and quality of materials
Shotcrete (Gunite)	Extensive crack patterns at concrete members or masonry; converting non-structural to structural walls	Reinstatement of the original characteristics of the element for repair; increase in force demand if applied as a retrofitting option	Minimum effect when applied as a repair method if layer is very think and with wire mesh only. Complete change of response when applied otherwise	Judicious attention to surface cleanliness. Mix design is critical. Experienced personnel are necessary	The applied layer of concrete provides adequate strength. It is used often in combination with other retrofit schemes (e.g. RC jacketing). Amount of reinforcement and thickness of layer dictates local and global effects
Steel jacketing—plate adhesion	Insufficient shear strength and ductility due to old type of detailing (sparse confinement reinforcement, insufficient lap splicing)	Jacketing: Deformation capacity is increased Plate adhesion: Shear and flexural strength enhancement	Deformation capacity is enhanced. Strength capacity may be increased or remain the same depending on the effect of the retrofit scheme at local level	The effectiveness of the method is related to the type of grouts used for infilling the gap between the steel jacket and the existing member. The bonding work is of great importance to achieve a composite action between the adherents	Before deciding for steel jacketing premature failure due to other mechanisms (e.g. pull-out of the longitudinal reinforcement of the existing member) should be prevailed. Steel jacket should be considered as additional confinement reinforcement, while steel plates adhered at the bottom flange of beams as additional bottom reinforcement
FRP jacketing	Insufficient shear strength and ductility due to old type of detailing (sparse confinement reinforcement, insufficient lap splicing)	Columns: Deformation capacity is enhanced Beams: Shear and flexural strengthening Beam–column joints: Shear failure is eliminated in connections	Ductility and shear strength at structural level are improved	Exposure to a variety of environmental conditions can dramatically change failure modes of the composites, even in cases where performance levels remain unchanged. High quality control is required. The bonding work is very important	The effectiveness depends on the anchorage conditions of the longitudinal reinforcement of the existing member. Limitations due to stress concentrations should be considered in the design phase. FRP layers are equivalent to additional confinement
Selective intervention methods	The damage pattern varies depending on the deficient parameter	Increase of stiffness, strength or ductility	Structural response can be tuned to meet the performance objectives	Experienced personnel are required in the execution phase	Refined modeling is required in order to take into account the increase of the specific parameter. Specialized design expressions necessary
RC jacketing	Insufficient lateral strength, insufficient deformation	If the jacket is applied at floor level, both axial and shear	If the jacket continues between successive floors,	The uncertainty with regard to bond between the jacket	The response is modified to strong-column weak-beam

	capacity and stiffness discontinuity between successive floors	strength of the column are improved, while flexural strength and strength of the beam–column joints remain the same	stiffness, strength and ductility are enhanced	and the original member is accommodated by the use of monolithic factors for the estimation of the deformation and strength capacity of the composite member	mechanism with distinct plastic hinge regions. The seismic demand is increased due to shift of the period. Uniform distribution of strength and deformation capacity is attained. Extension of jacketing to foundation level may be necessary
Addition of walls or external buttresses	Insufficient lateral stiffness and strength, torsionally unbalanced structures	Deformation demand at member level is decreased, while strength demand may be increased. High demand at connection between existing structure and walls or buttresses is generated	Global lateral drifts are controlled. Considerable strength and stiffness are added to the existing structural system. Resulting system is totally different from the original structure requiring full reassessment	In the case of infill walls, the interface between the existing and the new element should be checked. A new foundation system is necessary if walls (usually Γ-shaped in the perimeter of the building) or buttresses are added. In any case, the existing foundation system needs to be strengthened to resist the increased overturning moment and the larger weight of the structure	A critical aspect in the design phase is to insure full interaction and load sharing between the existing structural system and the new one (infill, external walls or buttresses). Connectors should be placed at floor level and behave elastically for the design earthquake. Strengthening of existing horizontal members may be required. Response modification of the system from shear to cantilever type is attained with a shift in period. Strategic distribution of walls may accommodate any system-level deficiencies
Steel bracing	Insufficient lateral stiffness and strength	High levels of force may be introduced at brace ends and connections between brace members and existing structure	Lateral stiffness and strength of the existing structure are increased. Additional energy dissipation is provided	Installation of post-tensioned bars can significantly modify the distribution of internal forces of existing RC members. Bracing members should be designed to behave in a ductile manner	The lateral strength of the existing members may be adversely affected by the level of axial forces induced by the steel braces. Strengthening of columns, beams and beam–column joints of braced bays needed for the adequate performance of the bracing system. Foundation system should withstand the increased strength and stiffness effects
Base isolation	Rehabilitation of critical or essential facilities	The seismic impact on structural and non-structural components is reduced	The seismic energy is absorbed by isolation devices inserted at the bottom or at the top of the first floor columns	Specialized engineering expertise is necessary	There is no need for retrofitting the upper part of the structure. The equipment should be provided with capabilities to withstand the expected large horizontal displacement between the foundation and the superstructure

Acknowledgements

The first author was funded by the European Research Project SPEAR (Seismic Performance Assessment and Rehabilitation, Contract Number G6RD-CT-2001-00525) through Imperial College of Science, Technology and Medicine, London. The contribution of the second author was partially funded by the US National Science Foundation through the Mid-America Earthquake Center, Award Number EEC 97-01785.

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