Review of retrofitting methods to reduce seismic vulnerability of buildings, with particular reference to hospitals and medical facilities

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SECTION 1

Introduction

Seismic retrofitting consists of one or more structural interventions developed to improve the resistance of existing buildings to seismic loads. The seismic retrofitting of a building is usually the result of a process that, through analysis and evaluation of the current state of its structure, highlights shortcomings which prevent the building from performing as required by the local seismic standards. A structural intervention then needs to be designed and implemented to improve the seismic response of the building, often to the level required by the standard.

Hospitals and health facilities are considered part of the critical infrastructure of a region due to their level of occupancy and their special use. Since these facilities need to remain operational after a destructive earthquake, special assessments are required to ensure that these buildings will be able to deliver the health care needed to the injured casualties.

This implies that more stringent requirements compared to those considered for ordinary buildings should be applied to improve the response of hospital buildings to earthquakes. For a hospital to remain functional after an earthquake, the structure must still be erect, and the mechanical services and the medical equipment hosted by the building should also be undamaged. Most of the services and equipment are vulnerable to interstorey drift (the relative translational displacement between two consecutive floors), while some specific equipment might be vulnerable to lateral acceleration (see D'Ayala et al, 2015c). For this reason it is required to define the seismic performance of hospitals by controlling and measuring their interstorey drift or lateral acceleration under seismic events.

In this respect, Figure 1 shows the relationship between structural performance level and non–structural performance level. The red circle highlights the fact that if equipment and services are required to remain operational, or if the nonstructural performance condition should ensure immediate occupancy, then the structural performance needs to ensure minimal damage or damage control. In Figure 1, 'Operational' signifies that the building is open and can be used immediately after the earthquake, delivering all its functions; Immediate Occupancy means that the building can be used for most of its function but some part or equipment of the building might not be operational (for instance a pipe is burst and the water mains do not work everywhere in the building); Damage Control Range means that the structure and the building should undergo lateral deformations that are smaller than a given threshold so that everything remains in working conditions. This is a very strict requirement for a structure exposed to earthquakes. More details can be found in FEMA 577 (FEMA, 2007).

Figure 1 Combination of structural and nonstructural building performance (adapted from FEMA 577)

Nonstructural Performance Levels	Structural Performance Levels and Ranges					
	S-1 Immediate Occupancy	S-2 Damage Control Range	S-3 Life Safety	S-4 Limited Safety Range	S-5 Collapse Prevention	S-6 Not Considered
N-A Operational	Operational 1-A	2-A	Not recommended	Not recommended	Not recommended	Not recommended
N-B Immediate Occupancy	Immediate Occupancy 1-B	2-B	3-B	Not recommended	Not recommended	Not recommended
N-C Life Safety	1-C	2-C	Life Safety 3-C	4-C	5-C	6-C
N-D Hazards Reduced	Not recommended	2-D	3-D	4-D	5-D	6-D
N-E Not Considered	Not recommended	Not recommended	Not recommended	4-E	Collapse Prevention 5-E	No rehabilitation

Several retrofitting interventions can be realised for a building which needs to be strengthened to withstand seismic events with minimal deformations as required by the condition stated in Figure 1. Besides the performance requirements, the types of intervention are usually chosen according to the deficiencies observed in the building under scrutiny and the economic and technical resources of the region where the building is located.

Typical retrofitting interventions are presented in detail in section 2 in relation to the different building typologies, already identified in D'Ayala et al (2015a). Section 2 covers a number of different retrofitting strategies and technologies. However, some technologies which require both technical and economic resources beyond the current availability in Nepal will not be the object of this report. The input of specialists, with extensive analytical and design expertise in dynamics, is necessary for such interventions to be implemented in an effective manner. Specifically, devices such as isolators and visco-elastic dampers or other types of dissipative devices are not covered in this report. Readers are directed to the technical literature available.

Section 3 discusses the procedures available for design of such interventions, according to international standards. Section 4 uses the framework of FEMA 547 (FEMA, 2006) to provide specific recommendation for the Nepalese health facility stock, starting from the case study examples provided by the Department for International Development (DFID). Section 5 provides an overview of selected retrofitting projects for hospitals and medical facilities similar to the Nepalese cases and available in literature.

Throughout this report the US Federal Emergency Management Agency (FEMA) documents are quoted and referred to since they represent the best, most synthetic and coherent state of the art sets of reports that cover the issue of retrofitting of existing structures at a technical level adequate for implementation in Nepal. In the following sections we provide guidance and direction for the best use of the FEMA guidelines in this context. It is noted that the subject of seismic retrofitting is too vast and too technical to be summarised satisfactorily in a short report.

SECTION 2

Methods for structural seismic retrofitting of hospital buildings

2.1 Introduction

The strengthening of a building as complex as a hospital is a procedure that goes well beyond the choice of a retrofitting method. It needs to evaluate several possibilities in relation to other aspects of the hospital's management and use. This procedure is well described in a series of documents produced by FEMA which are summarised here and to which the reader should refer to be able to put the choice of specific retrofitting strategy in context. A more detailed review of these documents is beyond the remit of this report, but reading of these documents is strongly recommended.

The most recent FEMA Guidelines reference for hospital design and retrofit is the FEMA 577 (FEMA, 2007) document, 'Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds'. The information presented in this publication provides an exhaustive review of mitigation measures and design solutions that can improve the safety of hospitals in natural hazard events. It is presented in a discursive way that is aimed at hospital managers as well as seismic engineering professionals. Chapter 2 of FEMA 577 (FEMA, 2007) specifically examines potential earthquake damage to hospitals, and how these facilities can most efficiently improve their seismic performance. The chapter also provides a review of the best practices in seismic design and seismic retrofitting of hospital facilities. Structural and non-structural performance targets are defined, in relation to the necessity of the hospital to be operational, after an otherwise highly damaging event as already described in Section 1 in relation to Figure 1. Chapter 2 of FEMA 577 (FEMA, 2007):

- Provides an inventory of structural and non-structural components.
- Reports common damage types and failures for each component with reference to case studies.
- Classifies these in terms of damage level and hence performance categories.

Histograms of expected damage distribution for the level of expected spectral acceleration and level of seismic design are provided in chapter 2 and can be used to benchmark hospital buildings in Nepal. This can help to decide whether strengthening might be necessary and, if so, which type.

To supplement this, the FEMA 396 (FEMA, 2003) document on 'Incremental Seismic Rehabilitation of Hospital Buildings' provides guidance on how structural seismic performance improvements can be implemented into a hospital facility. This can be done by integrating them with other maintenance and capital improvement projects which might need to be undertaken for purposes other than seismic strengthening. This approach might substantially reduce costs and make strengthening a more feasible option than demolition and rebuild, especially for large structures.

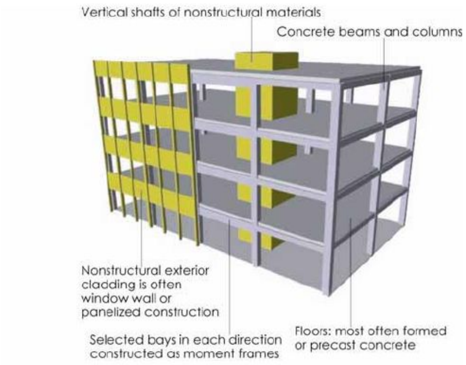
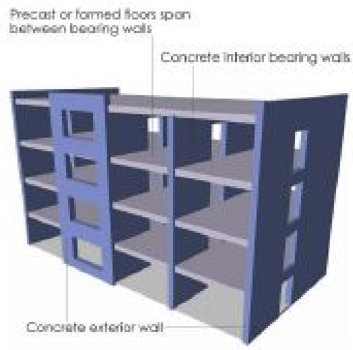
Section C2 of FEMA 396 describes the process of integration in general, with Section C2.10 specifically identifying the various interventions useful for different structural elements, from foundation to vertical and horizontal elements and diaphragms, each with brief descriptions and their purpose. It also shows for which level of seismicity such provision should be considered. This document might be very useful to the facility manager in understanding the relevance and importance of strengthening interventions which might be suggested by the technical team.

However, for detailed technical guidance on seismic retrofitting, reference should be made to FEMA 547 (FEMA, 2006) which applies to all types of buildings and for all types of use and occupancy. The primary purpose of this document is to provide a selected compilation of seismic rehabilitation techniques that are practical and effective. The descriptions of techniques include detailing and constructability tips that might not be otherwise available to engineering offices or individual structural engineers who have limited experience in the seismic rehabilitation of existing buildings.

A secondary purpose of FEMA 547 (FEMA, 2006) is to provide guidance on which techniques are commonly used to mitigate specific seismic deficiencies in various model building types. The document covers bare frames reinforced concrete (RC) buildings (type C1), RC shear walls buildings (C2), infill frame RC buildings (type C3), and unreinforced masonry buildings (URM), all of which are relevant to the Nepalese health facility building stock.

The description of these building typologies relates to examples found in the US building stock, and might differ from actual specific Nepalese buildings, hence the guidance provided should be used as reference and discretion should be used in its application on a case by case basis. Most importantly it should be noted that any recommendation of specific strengthening techniques and their effectiveness should be weighed by the construction and implementation constraints that may arise for the specific project to be undertaken, including technical and economic resources.

Figure 2 Building typologies (adapted from FEMA 547) covered in this report

	
Bare frames RC building (type C1)	Shear walls RC building (C2)

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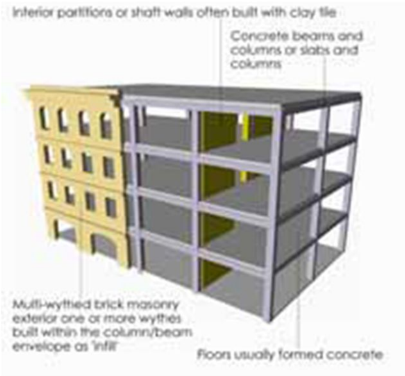
<td>
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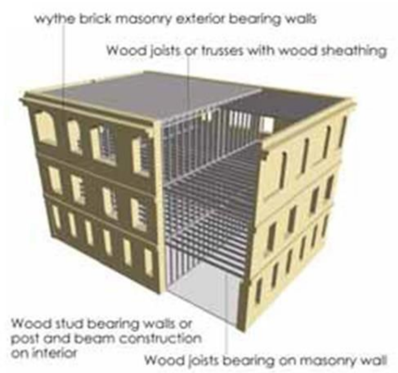
<td>
</td>
</tr>
<tr>
<td>Infill frame RC building (type C3)</td>
<td>Unreinforced masonry building (URM)</td>
</tr>
</table>

In order to select the best possible choice of strengthening given a performance shortcoming emerging from the analysis phase, FEMA 547 (FEMA, 2006) identifies seven categories of seismic deficiencies:

- Global strength
- Global stiffness
- Configuration
- Load path
- Component detailing
- Diaphragms
- Foundations

For each building type and for each deficiency identified, five different classes of rehabilitation measures can be considered. The possible rehabilitation classes are:

- Addition of new elements
- Enhancement of existing elements
- Improvement of connection between elements
- Reduction of demand
- Removal of specific components

The choice of the best rehabilitation measure is usually conditioned by technical considerations, but also by other constraints which might be external to the seismic retrofit project. These constraints can include continued use of the facility, economic resources or other factors, found in detail in FEMA 577 (FEMA, 2007) and FEMA 396 (FEMA, 2003). Very often the response given to a deficiency is a combination of the addition of new elements and strengthening of existing elements. Further details on this are provided in the following sections.

In the following two sub-sections relevant materials included in FEMA 547 (FEMA, 2006) for the three reinforced concrete building types and for unreinforced masonry construction are reviewed. In each section, the deficiencies of each of the four building typologies are described and possible retrofitting to improve the building performance is recommended.

2.2 Retrofitting of Reinforced Concrete Buildings

2.2.1 Bare Frame Buildings (C1)

The typology Reinforced Concrete Bare Frame, C1, is composed of either:

- Reinforced concrete frames of columns and beams distributed in two orthogonal directions.
- Systems of reinforced concrete columns supporting reinforced slabs without gravity beams.

The term bare frame indicates that the exterior cladding of this typology is a non-structural element (see D'Ayala et al, 2015c). This typology is often designed to support only gravity loads.

Bare frames are often characterised by an insufficient number of resistant frames in both principal directions of a building or by the presence of frames with inadequate lateral capacity due to either lack of sufficient reinforcement or lack of sufficient concrete cross section. These types of deficiency impact on the global capacity of C1 types by delivering low stiffness and strength. Common techniques adopted to improve the global capacity consist of inserting in the space enclosed by columns and beams one of:

- Steel bracing
- Additional concrete or steel moment frames
- Additional concrete or reinforced masonry shear walls

The addition of new elements might be precluded by the architectural configuration, such as presence of windows or doors, so that only the enhancement of existing elements may be allowed such as:

- Increasing sizes of beams and columns
- Concrete/steel jacket
- Fibre composite wrap of gravity columns.

Multi-storey buildings with a first storey or more storeys with a portico or large opening, compared to the other floors, are defined as soft or weak storey. Presence of soft or weak storey is a common configuration deficiency for this typology, due to use of the ground storey for commercial purposes or having a large atrium. This deficiency can be minimised with the addition of new elements such as concrete shear walls or masonry shear walls.

Torsion response of bare frames to lateral loads might be caused by deficiencies in relation to:

- Flexible horizontal structures
- Irregularity in the plan and elevation
- Re-entrant corners

This undesired building response can be reduced by adding:

- Chords (reinforced concrete ring beam to stiffen the slab)
- Reinforced concrete topping slab overlay to stiffen the slab

- Concrete/reinforced masonry shear walls to re-equilibrate distribution of stiffness in plan and elevation
- Concrete moment frames, to re-equilibrate the distribution of stiffness in plan and elevation
- Bracing in frames

The interactions and the lack of connections between masonry/concrete non-structural panels and the bare frames and between roof/floors and bare frames are considered a seismic deficiency of the construction details, which can be overcome by adding:

- Concrete/masonry shear walls
- Bracing in frames
- Moment resistant frames
- New concrete/steel chord member at the floor level

The bare frame typology is often characterised by a lack of ductility due to insufficient column splices and shear hoops to prevent shear in columns and beams. These shortcomings require interventions on beam-column joints by concrete/steel jackets or fibre composite wrap.

Specific lack in the foundations due to deficiency of this typology is not expected. However, since the performance of the foundations is affected by the soil type and the interactions between soil and building, specific investigation of the foundations are recommended.

More details about the deficiencies of the present typology and possible retrofit interventions in relation to hospitals and medical facilities in Nepal are reported in Table 4 .

2.2.2 Concrete Shear Wall Buildings (C2)

The typology Concrete Shear Wall Buildings, C2, is composed of either:

- Reinforced concrete walls twinned with RC beam/slab and columns supporting gravity loads.
- Reinforced concrete walls supporting gravity loads and RC beam and column frames.

The RC beam/slabs are designed to behave as a diaphragm to transfer lateral loads from the slab to both RC walls and resistant frames. Reinforced concrete walls act as shear walls, even when they are not designed for this purpose, therefore the lateral stiffness of this typology is significantly higher than the lateral stiffness of the bare frame system, discussed in 0.

The global capacity of this typology can be compromised by the inefficiency or failure of the shear walls. Common techniques adopted to improve the global capacity and consequently to reduce the interstorey drift (defined in Section 2.1) consist of adding new elements:

- Concrete or reinforced masonry shear walls
- Concrete or fibre composite wall overlays
- Chords

Alternative approaches which aim to increase the lateral capacity of this typology by enhancing existing elements focus on:

- Adding of chords to stiffen the slab.

- Increasing cross section of columns and beams.
- Increasing reinforcements.

Deficiencies in relation to the configurations are mainly caused by soft or weak storey. These can be minimised by using concrete or reinforced masonry shear walls.

As for the torsion effect, which is an issue in concrete shear wall buildings with irregular distribution of shear walls, it can be reduced by:

- Concrete walls or moment frames to balance the asymmetry in plan and in elevation.
- Chords to stiffen the slab.

The lack of constructional details in relation to poor connections between floors and bearing walls might cause overturning of the shear walls under lateral loads. In order to prevent this type of failure, the possible retrofit solutions consist of adding:

- Steel or concrete collector to create load path (load direction) from the slabs to both frames and shear walls.
- Concrete and steel corbels (brackets), to create load path from the slabs to both frames and shear walls.
- Concrete/FRP wall overlay to increase the resistance if shear walls to lateral force.
- Chords to stiffen the slab.

Due to the presence of the bearings walls, which behave as cantilevers, rocking at foundation level is a common seismic deficiency for this typology, therefore specific investigation of the foundations are recommended.

More details about the deficiencies of the present typology and possible retrofit interventions in relation to hospitals and medical facilities in Nepal are reported in Table 5 .

2.2.3 Masonry Infilled Frame Buildings (C3)

The typology Masonry Infilled Frame Buildings, C3, is composed of gravity reinforced concrete frame and floor systems of two-way slabs, which behave as diaphragms. The exterior and interior walls are in unreinforced masonry, and fill the space between columns and beams, creating a laterally resisting system where infilled walls, columns and beams interact with each other and resist to seismic actions.

The global capacity of this typology can be compromised by several factors:

- Limited number of bearing walls
- Limited length of bearing walls
- Excessive opening size
- Presence of weak frames

This shortage is usually corrected by:

- Adding interior concrete walls.
- Adding concrete/FRP overlays on the infill walls.
- Infilling selected openings.
- Increasing cross sections or reinforcements of beams and columns.

The most common deficiencies in the infill walls are in relation to the lack of connections between them and the surrounding concrete elements which can cause their failure in overturning under lateral loads. The interventions adopted to overcome this limitation consist of:

- Adding steel and concrete collector.
- Adding concrete/FRP overlays.
- Making cementations or epoxy grouts.
- Creating clean void in the bearing walls, and the filled them up with a better masonry and mortar compared to original ones.

Infill walls might be also failed for shear and this depends on strength of units and mortar and the relative stiffness between infill walls and frame.

To prevent shear failures particular attention should be paid to the structural details by adding column splice plates or strengthening beam-column connections with steel and fibre composite.

Soft or weak storey (defined in Section 2.1) torsional effect and irregularity in plan shape are also common configuration deficiencies for this typology, which can be minimised with addition of balancing concrete or reinforced masonry concrete walls.

In case the slabs do not behave as a diaphragm, it is possible to intervene by adding:

- Concrete or reinforced masonry concrete walls
- RC topping slab overlay
- Steel or concrete chords
- Concrete jacketing or FRP wrapping to beams

Specific lack in the foundations due to deficiency of this typology are not expected, however since the performance of the foundations is affected by the soil type and the interactions between soil and building, specific investigation of the foundations are recommended.

More details about the deficiencies of the present typology and possible retrofit interventions in relation to hospitals and medical facilities in Nepal are reported in Table 6 .

2.3 Retrofitting of Masonry Buildings

2.3.1 Unreinforced Masonry Buildings (URM)

Unreinforced Masonry Buildings, URM, is a typology composed of unreinforced masonry bearing walls in bricks and/or stones with horizontal structures in wood joists, bricks/stones vaults and steel beams, or concrete slabs. Differences in masonry units, masonry fabric, type of walls (e.g. solid, 2 leaves with void, multi-leaf), and the floor constructions in different types of unreinforced masonry buildings may result in substantially different structural systems. This means that different types of unreinforced masonry buildings can demonstrate varying responses to similar seismic events.

Diaphragms in timber or jack arches are usually more flexible and have smaller in plane stiffness than concrete slabs, therefore the rigid diaphragm assumption is not applicable. However they are also usually lighter than concrete slabs and hence contribute less to lateral forces, reducing the shear demand on walls.

The global strength of this typology depends on the in plane shear capacity (defined in Task 1) of the bearing walls, which require strengthening if they are not able to prevent severe damage. At interior locations, the standard approach is to add new elements such as reinforced masonry/concrete shear walls or steel braced frames or moment frames.

For the exterior location, if the architectural configuration allows, the most common interventions consist of adding steel braced frames or moment frames, or adding concrete/fibre composite overlays.

The global stiffness is not usually an issue, since the bearing walls are very stiff. However walls with very slender piers might suffer lack of strength, therefore local interventions might be necessary. These involve ground injections or concrete/FRP overlays.

The flexibility of the horizontal structures coupled with absence of connections between bearing walls and between bearing walls and roof/floors generates an overturning of the bearing walls. In order to prevent out-of plane failures (defined in D'Ayala et al, 2015a) it is possible to intervene in this typology, providing stiffness to horizontal structures through:

- Reinforced cores
- Bond beams
- Connecting plates
- Anchors or cross-ties to connect vaults and timber roof/floors to walls, and walls to walls

In URM with good connections, which behave as a 'box' under lateral forces, bending and shear can cause in plane failures. The occurrence of in plane or out of plane failures depends on several parameters:

- Geometry of the piers
- Mechanical and geometric properties of the masonry units
- Load path

Rehabilitation techniques to prevent in plane failures include the use of concrete frames and masonry shear walls for increasing the strength and grout injections in the bearing walls for improving the mechanical properties of deteriorated construction materials.

Specific lack in the foundations due to deficiency of this typology are not expected, however since the performance of the foundations is affected by the soil type and the interactions between soil and building, specific investigation of the foundations are recommended.

More details about the deficiencies of the present typology and possible retrofit interventions in relation to hospitals and medical facilities in Nepal are reported in Table 7 .

2.4 Cost of retrofitting

There are very modest sources available in literature on the costing of retrofit. As shown in FEMA 577 (FEMA, 2007) the costs are dependent not just on the specific intervention type, but also on its extension and on the disruption that might be caused to the normal running of the operational facilities. For this reason, in general interventions that can be implemented on the external façades are only preferable to interventions that require opening up of floor structures. A document produced by the Pan American Health Organization (PAHO, 2000) includes reference to retrofitting using bracing and additional frames in high rise concrete bare frames in Costa Rica. Some evidence of costing is also presented in this document, highlighting that the cost of rehabilitation and retrofitting could range between 4% and 8% of the hospital value. In general terms, it is very difficult to quantify costs without considering the details of the current conditions of the hospital and the specific retrofitting strategy chosen.

A more recent cost analysis is reported in Chartrand (2008) for the seismic retrofit of the St. Justine Hospital in Montreal, Canada. The retrofitted building is a seven storey high rectangular shaped concrete frame from the 1950s where shear walls have been in façade as a means of stiffening and reducing maximum drift. The concrete walls have been implemented by shotcreting, a more expensive solution than cast in situ. The overall cost of the intervention was $1.5 million, of which only 40% represents the implementation of the structural retrofit.

A detailed review of application of cost benefit analysis and multi-criteria analysis to the retrofit of hospitals is included in D’Ayala et al (2015b).

SECTION 3

Overview of Guidelines and Building Codes for design of Seismic Retrofitting

In Section 2 of this document it has been shown how FEMA 547 (FEMA, 2006) can be used to identify seismic structural deficiencies pertaining to different aspects of the seismic response for each specific structural typology. FEMA 547 (FEMA, 2006) also indicates the typical mitigation measures and strengthening techniques that can be used to remedy the deficiencies identified, also providing some of the technical details necessary for correct implementation. These will be reviewed in detail in section 4 of this report.

However, before implementing a strengthening technique, appropriate design and checks need to be carried out to ensure compliance with a specific reference code. This step is not included in FEMA 547 (FEMA, 2006) and for this reason other standards and guidelines have been highlighted that can be used for this purpose. These are the Eurocode 8 part 3, chapter 6 and Annexes A and C (section 3.1), and Guidelines for the Use of Fibre Reinforced Plastic Materials for Retrofit of Concrete Structures (section 3.2).

3.1 Eurocode 8

The purpose of this section is to highlight how the method used for the assessment of the structure influences the judgement on the safety level attained and subsequently the need for strengthening and the type of strengthening. This step is critical and cannot be ignored, even though the deficiency in the structure might have been identified in a qualitative way on the basis of the approach explained in Section 2.

According to EC8 Chapter 6 Design of Structural Intervention, the design procedure should include conceptual design, analysis and verifications.

The conceptual design should cover:

1. Selection of techniques and/or materials, as well as selection of the type and configuration of the intervention.
2. Preliminary estimation of dimensions of additional structural parts.
3. Preliminary estimation of the modified stiffness of the retrofitted element.

The output of the conceptual design will determine an initial model of the new retrofitted structure. This can be analysed according to the same methods recommended for the Assessment outlined in D'Ayala et al (2015a) or as recommended by the Nepalese seismic code for equivalent new structures. The output of the analysis conducted with these new models should be used for the verification of the single structural elements, both strengthened and un-strengthened. These verifications should be carried out using the set of provisions described in the following.

These compliance criteria consist essentially of checking for each limit state (LS) that the demands, calculated by using the allowed methods of analysis, do not exceed their corresponding capacities.

In the verification procedure, it is important to distinguish between 'ductile' and 'brittle' structural elements. The difference between ductile and brittle elements applies both to the type of action for which they are verified, and for the way in which the demands are computed. Specifically:

a. Ductile elements are checked in terms of deformation.
b. Brittle elements are checked in terms of forces.

For the different procedures to be adopted for evaluating demands and capacities for the cases of linear or non-linear types of analysis for concrete elements, reference can be made to Bisch et al (2012). The essential steps of the procedures are summarised in Table 1 .

One of the major issues is that, in the assessment phase, the requirements for the compliance with a limit state are formulated in qualitative terms and refer to given states of damage involving the structural system as a whole. For instance: “excessive lateral deformation” or “appearance of cracks”. These statements do not relate directly to the performance of any specific structural element.

On the other hand in the verification phase, the requirements are expressed in quantitative terms, for instance “lateral deformation not greater than 2%” and should be satisfied by all structural elements. This will lead to a building being considered seismically deficient even if only a single element is found not to verify the condition requested.

To obviate this point in practice, national standards usually allow for the existing structures to comply with a level of lateral demand somewhat lower than the one requested for new structures. In Italy, for instance, following the L’Aquila earthquake 2009, a range of 60-80% of the design acceleration for new builds was accepted for the repair and retrofitting of structures.

However when considering the verification step, according to EC8 part 3, the capacity is computed by considering what is called a Confidence Factor (CF) (see Table 1), by which the mean capacity is reduced. The lower the level of knowledge associated with the structure, the higher the confidence factor and hence the lower the value of the capacity used in the verification. The level of knowledge depends on the possibility of conducting tests and surveys to ascertain both the geometry and material characteristic of the structure.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Linear Model (LM)</th><th colspan="2">Non-linear Model</th></tr>
<tr><th>Demand</th><th>Capacity</th><th>Demand</th><th>Capacity</th></tr>
<tr><td rowspan="7">Type of element or mechanism (e/m)</td><td rowspan="4">Ductile</td><td colspan="2">Acceptability of Linear Model (for checking of $\rho_i = D_i/C_i$ values)</td><td rowspan="7">From analysis. Use mean values of properties in model.</td><td rowspan="4">In terms of deformation. Use mean values of properties divided by CF.</td></tr>
<tr><td>From analysis. Use mean values of properties in model.</td><td>In terms of strength. Use mean values of properties</td></tr>
<tr><td colspan="2">Verifications (if LM accepted)</td></tr>
<tr><td>From analysis.</td><td>In terms of deformation. Use mean values of properties divided by CF.</td></tr>
<tr><td rowspan="3">Brittle</td><td colspan="2">Verifications (if LM accepted)</td><td rowspan="3">In terms of strength. Use mean values of properties divided by CF and by partial factor.</td></tr>
<tr><td>If $\rho_i \leq 1$: from analysis.</td><td rowspan="2">In terms of strength. Use mean values of properties divided by CF and by partial factor.</td></tr>
<tr><td>If $\rho_i > 1$: from equilibrium with strength of ductile e/m. Use mean values of properties multiplied by CF.</td></tr>
</table>

Table 1 Verification procedure for ductile and brittle element/failure mode for RC structures (adapted from Bisch et al 2012)

3.1.1 Specific provision for concrete structures

Annex A of EC8 part 3 contains specific information for the assessment of reinforced concrete buildings in their present state, and for their upgrading, when necessary. Equations to verify the maximum chord rotation capacity for ductile elements are provided, applicable to beams, columns and walls. Several specific conditions and corresponding modification factors are included. The same approach is also used for brittle failure modes, i.e. shear failures. Section A.4 of the document relates to "capacity models for strengthening". The interventions considered are:

- Concrete jacketing
- Steel jacketing
- FRP overlay and wrapping

Hence these provisions can be used directly to design and dimension the interventions recommended in Section 2.1.

For each intervention, the specific behaviour enhancement or mitigation of deficiency is identified and the corresponding verification parameters and equations are provided. This allows sizing of the strengthening intervention and verifying compliance with the local limit states criteria. In particular, the assumptions that are made in designing a specific intervention are as follows.

For **concrete jacketing**, the objective is to increase:

- Bearing capacity
- Flexural and/or shear strength
- Deformation capacity

It is assumed that the jacket acts monolithically with the original column, delivering full composite action. The concrete characteristic of the jacket are assumed to apply to the whole cross section.

For **steel jacketing** the objective is mainly to increase shear strength by passive confinement. The shear capacity delivered by the confinement is assumed additional to the existing capacity.

For **fibre reinforced plastic (FRP)** strips or plates the objectives can vary substantially depending on the specific application. The main use of externally bonded FRP is for the enhancement of shear capacity when used in wrapping. Enhancement of the available ductility at members' ends through concrete confinement is also obtained by wrapping. FRP plates are also laid longitudinally to beams and columns to improve their flexural behaviour. FRP can also be used to mitigate the poor shear capacity from a lack of lap slices in beam column joints or slab column joints. It is assumed that the FRP is perfectly bonded to the concrete and that its brittle strain limit is not exceeded. Design is conducted assuming a yielding of the internal reinforcement. Checks should be made to ensure that the strengthened cross section is not over reinforced to prevent brittle failure.

Some of the common provisions for strengthening of column beam joints are illustrated in the Appendix.

3.1.2 Specific provision for masonry structures

Annex C of EC8 part 3 covers strengthening provisions for masonry buildings. Emphasis is put on identifying the structural details, such as:

- The type of masonry walls (unreinforced, reinforced or confined).
- The type and size of units and mortar, whether solid masonry or multi-leaves, and in the latter case presence and distribution of ties.
- The quality of connections among orthogonal walls, and between floors and walls.

Once the deficiencies have been identified, before moving to the phase of strengthening design, it is recommended to use specific non-destructive testing techniques to determine the quality of the masonry fabric. These techniques include:

- Ultrasonic or mechanical pulse velocity, to determine variation of density and presence of crack.
- Impact echo to confirm grouting in concrete block reinforced masonry.
- Radiography and cover meters to localise metallic elements.

This information can be used to improve the knowledge level, as indicated in Table 1 above, and hence to reduce the confidence factor. This can be further reduced if semi-destructive tests are carried out, such as:

- Flat jack test to determine the mechanical characteristic of masonry.
- Diagonal compression test to determine its shear capacity.

These tests should be carried out by qualified companies with substantial in-situ tests experience. To the authors knowledge neither the equipment nor the expertise might be available in Nepal. Given the importance of this phase, it might be necessary to invest in training.

A number of repair and strengthening techniques are recommended, which correspond to the ones already identified in Section 2.3 of this document. Some indications of the suitability of such interventions to mitigate specific damages or identified vulnerabilities are provided. No specific indication is provided as to how to design such interventions, in terms of sizing of the new elements and verifying their effectiveness and overall improved performance.

It should be noted that when implementing any of these interventions, the interaction between new and existing materials should be carefully evaluated, the redistribution of local and global stiffness re-assessed and the medium to long terms side effects including environmentally caused decay addressed.

Graphics and detailed descriptions of how to implement such strengthening interventions on simple one storey buildings are included in Bothara & Brzev (2011) and in Shrestha et al (2010). See Appendix for graphic representation of common strengthening provisions.

3.2 Guidelines for strengthening with Fibre Reinforced Plastic (FRP) strips or sheets

The use of FRP fabric to confine concrete columns or to enhance the bending and shear capacity of concrete frame elements is currently recommended in several documents. The ones most commonly used are included in Table 2 .

Issuing body	Title	Geographical remit	Year
ACI	440 F - Seismic Strengthening of Concrete Buildings Using FRP Composites	U.S.A	2009
CNR	DT 200.R1/2003 - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures -	ITALY	2012
CEN	Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings - ANNEX A.4	EUROPE	2013

Table 2 Summary of guidelines for design of FRP reinforcement

An evaluation of these guidelines carried out by Pohoryles & Rossetto (2014) shows that the approach of Eurocode 8 and CNR DT-200 are the most accurate with the lowest variance in their predictions, when applied to different concrete frame lay-outs and different designs of FRP strengthening. The equations used in these two guidelines are more complex because they explicitly include the variability mentioned above.

SECTION 4

Recommendations for the Nepalese Building Stock

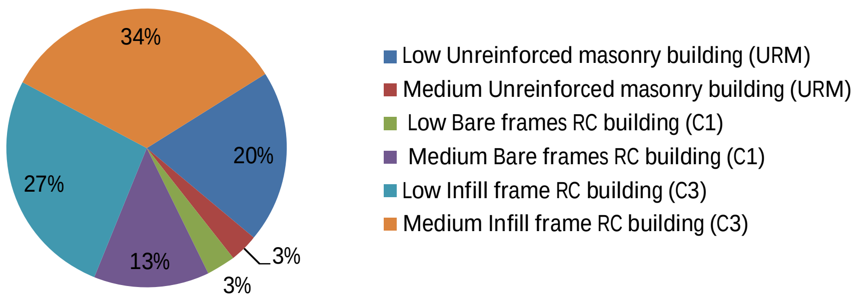
4.1 Overview of Existing Nepalese Portfolio of Hospitals and Medical Facilities

Guragain et al (2004) includes, in Annex IV of the Guideline on Seismic Vulnerability Assessment of Hospitals in Nepal, a structural assessment checklist for the main building typologies for hospitals and medical facilities identified in the same study and used here as reference for the health facility building stock of Nepal. Such checklists can be usefully employed to determine deficiencies of structural behaviour as categorised with FEMA 547 (FEMA, 2006) and appropriate strengthening interventions. As already stated, although a building can be categorised in a typology, its vulnerability and hence the most appropriate choice of strengthening might be influenced by specific details that need to be investigated on a case by case basis.

To illustrate how to use FEMA 547 (FEMA, 2006) for determining appropriate strengthening measures, the authors have used the four case studies provided by DFID within the framework of the Seismic Safety of Priority Hospitals in Nepal Programme (2012). For each of the hospitals we have classified the buildings by typology, identified their main lateral loadbearing system and horizontal structures, the number of storeys, the presence of element improving seismic behaviour and the deficiencies identified with a rapid visual screening assessment based on FEMA 154 form and the GNDT CNR masonry form.

Six classes have been identified (Figure 3), subdividing the three main typologies in two subclasses in relation to the number of storeys. This will substantially influence the building response in terms of drift and hence, the specific strengthening needed to control relative displacement or interstorey drift to minimise non-structural damage and ensure functionality. According to this classification, the most common structural type is masonry infilled reinforced concrete frames of medium height followed by the low height of the same type. This classification, together with the level of occupancy and specific use of the building, can be useful in determining the costs of the structural intervention and balance them with the benefit achieved.

Figure 3 Classification of buildings by structural type and number of storeys.



From Table 3 it can be seen that irregularity in plan is the most common problem, meaning that structural joints should be included in buildings to simplify their plans, ensure a more balanced behaviour and reduce possible torsion effect.

For masonry buildings, the connection of the roof with the wall is often deficient, and the quality of material is a concern.

For reinforced concrete frame buildings, short columns are common, as they are soft storey as defined in Section 2.1.

The surveys conducted in 2012 have shown in general a lack of maintenance and a deterioration of the original material which might considerably affect the performance of these buildings. Some buildings are very slender, implying that they could undergo severe sway deflections in the event of an earthquake, possibly compromising their functionality in the post-event emergency phase.

Foundations were not investigated, but before undertaking any decision on strengthening, it is appropriate to have them open up and inspected.

To mitigate the deficiencies summarised in Table 3 , in the following subsections provide a table of recommended strengthening for each main typology. Sketches on specific solutions can be found in FEMA 547 (FEMA, 2006), Bothara & Brzev (2011) and in Shrestha et al (2010).

Hospital	building number	typology	rise	floor type	restraining elements	deficiency
BAJHANG DISTRICT HOSPITAL	3	URM	low	1timber + 1timber truss and C.G.I. sheet + 1 RC	Ridge beam	irregularity in plan, no lintels, no connection between bearing walls and internal panels, deterioration, humidity, water tanks on the roof, possibility of pounding with adjacent buildings
GULMI DISTRICT HOSPITAL	2	URM	low	1) RC 2)timber truss and C.G.I. sheet		irregularity in plan, presence of inadequate seismic joints, no connection between roof and bearing walls, humidity, water tanks on the roof possibility of pounding with adjacent buildings
	1	C3	low	RC		humidity, possibility of pounding with adjacent buildings
NATIONAL ACADEMY OF MEDICAL SCIENCE (BIR HOSPITAL)	1	URM	low	2 floors cement concrete slab + 1 floor CGI sheet roofing	pilasters	irregularity in plan, designed for two floors, irregularity in plan, low quality material, poor connections between roof and walls
	1	URM	medium	RC apart from the two way pitch roof over timber rafters		irregularity in plan, large openings, roof disconnected from the bearing walls possibility of pounding with adjacent buildings
	4	C1	medium	4) RC 1)cement concrete precast slab		irregularity in plan, short columns, non-structural panels are not connected, passages between building are very slender, deterioration of reinforcements, leaking
TRIBHUVAN UNIVERSITY TEACHING HOSPITAL	1	C1	low	RC		Soft storey; irregularity in plan; passages between building are very slender and not connected
	7	C3	low	RC		irregularity in plan, passages between building are very slender and not connected, presence of inadequate seismic joints, leaking, lack of maintenance; possible sliding and overturning of the water tanks on the roof
	10	C3	medium	RC	long spans are provided with hunches at their ends	irregularity in plan, short columns, passages between building are very slender and not connected, presence of inadequate seismic joints, deterioration of reinforcements, leaking, possible sliding and overturning of the water tanks on the roof

Table 3 Classification of the buildings forming the 4 Nepalese hospital complexes used as case study

4.2 Recommendations for Reinforced Concrete Buildings

4.2.1 Bare Frame RC Buildings

bare frames								
types of retrofitting	**Structural function**	**types of retrofitting options**	**suitable for addressing these typical deficiencies**	**technical complexity**	**maintenance requirements**	**material**	**disruption of the building and its use**	**further details**
Add new elements	Increase Global Strength	shear walls	Insufficient number of frames or weak frames	medium	low	Concrete or reinforced masonry	high	
		moment frames		medium	low	Concrete	high	
	Increase Global Stiffness	shear walls	Insufficient number of frames or weak frames	medium	low	Concrete or reinforced masonry	high	
		moment frames		medium	low	Concrete	high	
	Improve Configurations	shear walls	Soft or weak story	medium	low	Concrete or reinforced masonry	high	
		shear walls	torsion layout	medium	low	Concrete or reinforced masonry	high	
		moment frames				Concrete	high	
	Improve Load Path	collector	Inadequate collector	medium/high	low	steel	medium	
	Create Diaphragm Action	shear walls	Inadequate in plane shear capacity for one-way slab	medium	low	Concrete or reinforced masonry	medium	
		moment frames		medium	low	Concrete	medium	
		chords	Inadequate chord capacity	medium/high	low	concrete or steel	medium	
			Excessive stresses at openings and irregularities	medium/high	low	concrete or steel	medium	
Enhance Existing Elements	Increase Global Strength	Increase size of columns and/or beams	Insufficient number of frames or weak frames	low	low	concrete	high	
	Increase Global Stiffness	Increase size of columns and/or beams	Insufficient number of frames or weak frames	low	low	concrete	high	
		jacketing of gravity columns		low	low	concrete or steel	high	
		wrapping columns		high	low	FRP	high	avoid sun light
	Create Diaphragm Action	topping slab overlay	Inadequate in plane shear capacity for one-way slab	low	low	RC	medium	
		increase cross section of existing beams by jacketing		low	low	concrete	low	
		wrapping of columns	Inadequate chord capacity	high	low	FRP	low	avoid sun light
Improve Connections between elements	Improve Configurations	chords	torsion layout	medium/high	low	concrete or steel	medium	
	Improve Component detailing	jacketing of columns or beams	Lack of ductility for inadequate shear strength in column or beam or joints	low	low	concrete or steel	low	
		wrapping columns or beams		high	low	FRP	low	avoid sun light
		jacketing of columns or beams	splices	low	low	concrete or steel	low	
		wrapping columns or beams		high	low	FRP	low	avoid sun light
Reduced demand	Increase Global Strength	remove upper stories	Insufficient number of frames or weak frames	low	NA	NA	high	
Remove selected components	Increase Global Stiffness	remove elements creating short columns	Insufficient number of frames or weak frames	low	NA	NA	high	
	Improve Configurations	remove incidental walls	torsion layout	NA	NA	NA	medium	
	Create Diaphragm Action	Infill openings	Excessive stresses at openings and irregularities	low	low	Concrete or masonry	medium	

Table 4 Deficiencies and retrofit interventions for hospitals and medical facilities in Nepal classified as bare frame RC buildings (C1)

4.2.2 Concrete Shear Walls Buildings

concrete shear walls								
types of retrofitting	**Structural function**	**types of retrofitting options**	**suitable for addressing these typical deficiencies**	**technical complexity**	**maintenance requirements**	**material**	**disruption of the building and its use**	**further details**
Add new elements	Increase Global Strength	shear walls	Insufficient in plane wall shear strength	medium	low	Concrete or reinforced masonry	high	
			Insufficient flexural capacity					
			Inadequate capacity of coupling beams					
	Increase Global Stiffness	shear walls	Excess drift	medium	low	Concrete or reinforced masonry	high	
	Improve Configurations	shear walls	Discontinuous walls	medium	low	Concrete or reinforced masonry	high	
		columns beneath		medium	low	Concrete	high	
		shear walls	Soft or weak story	medium	low	Concrete or reinforced masonry	high	
		shear walls	Soft or weak story	medium	low	Concrete or reinforced masonry	high	
		moment frames	torsion layout	medium	low	Concrete	high	
	Improve Load Path	Collector	Inadequate collector	medium/high	low	steel or concrete	medium	
	Improve Component detailing	add strong-backs	wall inadequate for out-of plane bending	medium/high	low	steel	medium	
	Create Diaphragm Action	shear walls	Inadequate in plane shear capacity	medium	low	Concrete or reinforced masonry	medium	
		moment frames		medium	low	Concrete	medium	
		chords	Inadequate chord capacity	medium/high	low	concrete or steel	medium	
			Excessive stresses at openings and irregularities					
Enhance Existing Elements	Increase Global Strength	wall overlay	Insufficient in plane wall shear strength	low	low	Concrete	high	
		chords	Insufficient flexural capacity	medium/high	low	concrete or steel	high	
		increase cross of beams	Inadequate capacity of coupling beams	low	low	concrete	high	
		increase reinforcement in beams		medium	low	steel	high	
		improve anchorage between beams and wall		medium/high	low	steel or concrete	high	
	Increase Global Stiffness	wall overlay	Excess drift	low	low	Concrete	high	
	Improve Configurations	jacketing of columns	Discontinuous walls	low	low	Concrete/steel	high	
		wrapping of columns		high	low	FRP	high	avoid sun light
	Improve Component detailing	wall overlay	wall inadequate for out-of plane bending	low	low	Concrete	low	
		wall overlay	wall inadequate for shear strength	high	low	FRP	low	avoid sun light
	Create Diaphragm Action	topping slab overlay	Inadequate in plane shear capacity	low	low	RC	medium	
		jacketing of beams	Inadequate chord capacity	low	low	concrete	low	
		wrapping of beams	Inadequate chord capacity	high	low	FRP	low	avoid sun light
Improve Connections between elements	Improve Configurations	Improve Connections Diaphragm	Discontinuous walls	medium/high	low	steel or concrete	low	
		chords	torsion layout	medium/high	low	concrete or steel	medium	
	Improve Load Path	add dowels	Inadequate slab bearing on walls	medium/high	low	concrete or steel	medium	
		add ledger		medium/high	low	steel	medium	
	Create Diaphragm	add dowels	Inadequate shear transfer to walls	medium/high	low	concrete or steel	medium	
		add ledger		medium/high	low	steel	medium	
Reduce demand	Increase Global Strength	Remove upper stories	Insufficient in plane wall shear strength	low	low	NA	low	
Remove selected components	Increase Global Strength	Remove beams	Inadequate capacity of coupling beams	low	low	NA	low	
	Improve Configurations	Remove Wall	Discontinuous walls	low	low	NA	low	
		Remove incidental walls	torsion layout	low	low	NA	low	
	Create Diaphragm Action	Infill openings	Excessive stresses at openings and irregularities	low	low	concrete and masonry	low	

Table 5 Deficiencies and retrofit interventions for hospitals and medical facilities in Nepal classified as shear walls RC buildings (C2)

4.2.3 Infill Frame RC Buildings

infilled frames								
types of retrofitting	**Structural function**	**types of retrofitting options**	**suitable for addressing these typical deficiencies**	**technical complexity**	**maintenance requirements**	**material**	**disruption of the building and its use**	**further details**
Add new elements	Increase Global Strength and Stiffness	Interior shear walls	Inadequate length of exterior wall	medium	low	Concrete and Reinforced Masonry	high	
			Excessive sized openings in infill panels					
			weak or deteriorated masonry					
	Improve Configurations	Interior shear walls	Soft or weak story	medium	low	Concrete and Reinforced Masonry	high	
		balancing shear walls	torsion layout	medium	low	Concrete and Reinforced Masonry	high	
		balancing shear walls	Irregular plan shape	medium	low	Concrete and Reinforced Masonry	high	
	Improve Load Path	collector	Inadequate collectors	medium/high	low	Steel and Concrete	medium	
	Create Diaphragm Action	shear walls	Inadequate in plane shear capacity	medium	low	Concrete and Reinforced Masonry	medium	
		moment frames		medium	low	Concrete	medium	
		chords	Inadequate chord capacity	medium/high	low	Concrete and steel	medium	
		chords	Excessive stresses at openings and irregularities	medium/high	low	Concrete and steel	medium	
Enhance Existing Elements	Increase Global Strength and Stiffness	wall overlay	Inadequate length of exterior wall	low	low	Concrete	high	
				high	low	FRP	high	avoid sun light
		Infill openings	Excessive sized openings in infill panels	low	low	Concrete and masonry	high	
		Longitudinal wrapping of columns	Inadequate columns for overturning forces	high	low	FRP	high	avoid sun light
		increase reinforcements in columns		medium	low	Steel	high	
		increase cross section of columns with jacketing		low	low	Concrete	high	
		grout injections	weak or deteriorated masonry	low	low	Concrete or mortar	high	
	Improve Configurations	shear walls	Soft or weak story	medium	low	Concrete and reinforced masonry	high	
	Improve Load Path	walls supports	Out-of-plane of infill wall	medium/high	low	Steel and Concrete	medium	
		shortcrete		medium/high	low	Concrete	medium	
		wall overlay		low	low	Concrete	medium	
				high	low	FRP	medium	avoid sun light
	Create Diaphragm Action	topping slab overlay	Inadequate in plane shear capacity	low	low	RC	medium	
		increase cross section of beams with jacketing	Inadequate chord capacity	low	low	Concrete	medium	
		wrapping of beams		high	low	FRP	medium	avoid sun light
Improve Connections between elements	Improve Component detailing	create void and repack them using materials which are better from the original ones	weaker incompletely filled joint between masonry and surrounding components	low	low	masonry and mortar	low	
		grout injections		low	low	Concrete or mortar	low	
	Create Diaphragm Action	add dowels and ledger	Inadequate shear transfer to walls	medium/high	low	Steel	medium	
remove selected components	Improve Configurations	Remove selected infill panels or solid walls	torsion layout	low	NA	NA	high	
	Create Diaphragm Action	Infill openings	Excessive stresses at openings and irregularities	low	low	Concrete and masonry	low	

Table 6 Deficiencies and retrofit interventions for hospitals and medical facilities in Nepal classified as infill frame RC buildings (C3)

4.3 Recommendations for Masonry Buildings

4.3.1 Unreinforced Masonry Buildings

Unreinforced masonry buildings								
types of retrofitting	**Structural function**	**types of retrofitting options**	**suitable for addressing these typical deficiencies**	**technical complexity**	**maintenance requirements**	**material**	**disruption of the building and its use**	**further details**
Add new elements	Increase Global Strength and	Shear walls	Insufficient in plane wall strength	medium	low	Concrete/reinforced masonry	high	
	Improve Configurations	shear walls	Soft or weak story	medium	low	Concrete/reinforced masonry	high	
	Improve Load Path	collector	missing collector	medium/high	low	Steel and Concrete	medium	
	Improve Component Detailing	strong backs	wall inadequate for out-of-plane bending	medium/high	low	Steel	low	
	Create Diaphragm Action	shear walls	Inadequate in plane strength and/or stiffness	medium	low	Concrete/reinforced masonry	medium	
		strap/angle	inadequate chord capacity	medium	low	Steel	medium	
Enhance Existing Elements	Increase Global Strength and Stiffness	wall overlay	Insufficient in plane wall strength	high	low	Concrete / FRP	high	avoid sun light
		Grouting injections		low	low	Concrete or mortar	high	
		Infill openings		low	low	Concrete or mortar	high	
	Improve Component Detailing	Increase reinforcements in concrete cores	wall inadequate for out-of-plane bending	medium	low	steel	low	
		wall overlay		high	low	FRP	low	avoid sun light
		brace parapet	unbraced parapet	low	low	steel	low	
		brace chimney	unbraced chimney	low	low	steel	low	
	Create Diaphragm Action	add retrofit for wood diaphragms	Inadequate in plane strength and/or stiffness	medium/high	low	steel	medium	
Improve Connections between elements	Improve Load Path	Tension/shear anchors	Inadequate or missing wall-diaphragm tie	medium/high	low	steel/timber	medium	
		cross ties, diagonal bracing, supplemental vertical support for beams		medium/high	low	steel	medium	
	Improve Component Detailing	bracing from floor structure and strong backs	wall inadequate for out-of-plane bending	medium/high	low	Steel and Concrete	low	
Reduce demand	Improve Component Detailing	reduce chimney height	unbraced chimney	low	NA	NA	low	
Remove selected components	Improve Component Detailing	remove chimney	unbraced chimney	low	NA	NA	low	

Table 7 Deficiencies and retrofit interventions for hospitals and medical facilities in Nepal classified as unreinforced masonry buildings (URM)

SECTION 5

Examples of Implementation

5.1 The Carlos Alberto Seguín Escobedo National Hospital, Arequipa, Peru

The Carlos Alberto Seguín Escobedo National Hospital in Arequipa, Peru, is composed of several buildings which vary in their constructional period, typologies, materials and heights.

The most catastrophic events for this hospital are the earthquake of 1979 with Ms=6.7, which has mainly caused damage to non-structural panels, and the earthquake of 2001 with Ms=8.4, which has extensively damaged both structural and non-structural elements of some of the buildings in the hospital complex.

Since the hospital buildings were designed with different construction techniques, different structural interventions were applied with the aim of increasing the lateral load resistance and reducing the lateral drift (Muñoz et al, 2004).

In the tallest building of the hospital block, severe damage was observed, and seven storeys of this building, except the first one, were evacuated.

This building, classified as medium rise bare frame RC building (C1 type, see Section 2.1), has a configuration and a damage state which are very similar the ones observed in the Emergency Block, Out-patient blocks I-III and the Surgical Ward Block of the National Academy of Medical Science (Bir Hospital), Nepal, as reported in Table 3 .

The building was used for hospitalisation and consulting rooms and has a gross constructed area of 14 000 m^2. The building was designed only for vertical loads, with reinforced concrete frames disposed perpendicular to the main facades and concrete walls only located in the elevator and staircase boxes. The building was originally divided into two blocks by a 0.05 m central joint (passage) which was enlarged after the 2001 earthquake to reduce the effect of pounding with its adjacent buildings. The architectural configuration of the building allowed intervention on its longitudinal direction with concrete jackets to improve the connections between columns and beams and to overcome the lack of ductile frames, as also recommended in Table 4 for the medical facilities in Nepal.

In the hospital complex, several damage types were also observed in the following two buildings:

- The three-story administrative building, belonging to the class C1 (bare frame RC buildings of medium rise) comparable to several buildings of the National Academy of Medical Science mentioned above (see Table 3).
- The one-story building, belonging to the class URM (unreinforced masonry of low rise) comparable to three buildings of the Bajhang District Hospital and the LPD and OPD Block of the Gulmi District Hospital (see Table 3).

The first building was retrofitted with shear walls to reduce its torsional effects and with column jackets to increase its global stiffness under lateral loads, as also recommended in

Table 4 for the Nepalese medical facilities in class C1. As for the second building, this was strengthened by adding reinforced concrete columns and beams. This type of intervention is not included in Table 7 for the URM medical facilities in Nepal, since most of the interventions proposed for the unreinforced masonry constructions are realised with non-invasive techniques.

The repair interventions for Carlos Alberto Seguín Escobedo National Hospital were performed with very limited information of the hospital complex, reduced economic resources, and a shortage of time. This has allowed the development of a retrofitting project with standards lower than the ones indicated in FEMA 356 or ATC-40 or SEAOC, which are used only as a reference in Peru.

5.2 The Agio Andreas Hospital aggregate, Greece

The Agios Andreas Hospital is a four storey building aggregate, designed in the 1960's as a reinforced concrete load-bearing system, which belongs to class C1 with medium rise. As this hospital is representative of several buildings in the Academy of Medical Science (Bir Hospital, see Table 3) the approach used to select the best retrofit intervention for the Agios Andreas Hospital can be also adopted in the Nepalese context.

This hospital has been damaged by several earthquakes, causing detachment of its infill walls from the bearing systems, and several cracks on the load bearing members. Moreover, humidity has also accelerated the deterioration of the entire constructions, as several corroded reinforcements in columns and beams were found.

The retrofit strategy proposed for the Agios Andreas Hospital aims at minimising the horizontal displacement of the whole complex, reducing damage on both structural elements and electromechanical equipment and ensuring its functionality in emergency conditions.

Two retrofit solutions are proposed in the work developed by Syrmakezis (2006):

- A traditional technique consisting of increasing beam and column cross sections with concrete jackets.
- A more innovative and expensive technique consisting of adding damper braces.

The first solution has also been included as a possible intervention to enhance existing elements in the medical facilities in Nepal, as reported in Table 4 , while the second intervention is not considered feasible for the Nepalese constructions, as this technique requires extensive analytical expertise in dynamics in order to be designed as discussed in Chapter 1. However, both solutions are discussed, in order to provide guidance for the reader to select the best retrofit technique in the Nepalese context.

In order to identify the most adequate retrofit solution between the ones proposed for the Agios Andreas Hospital, in the work by Syrmakezis (2006) finite element models were developed to:

- Simulate the structural behaviour of the hospital before the retrofitting.
- Estimate the benefits of the proposed retrofit interventions.
- Compare the results and choice the adequate intervention.

The results obtained from the numerical analysis have highlighted that both interventions improve the overall strength of the hospital. In particular, the concrete jackets reduce the horizontal displacement by 40% and rotation by 30%, and damper braces reduce the horizontal displacement by 60% and rotation by 80%.

The damper braces, due to their higher capability to dissipate energy, better satisfy the retrofit criteria of minimising the displacements, compared to the concrete jackets. Therefore, in the work by Syrmakezis (2006), damper braces are recommended for improving the seismic response of the Agios Andreas Hospital, although their installation requires not only specific expertise, as mentioned earlier, but also considerable economic resources. In the study of Syrmakezis (2006), it is not stated if the retrofit project has been implemented.

5.3 Existing hospital in Sudan

A specific study by Hassaballa et al (2014) was undertaken to estimate the seismic performance of an existing hospital in Sudan designed according to the Regulations of the Egyptian Society for Earthquake Engineering (ESEE). The name of the hospital is not stated so it is not possible to refer to a specific building. However, since its configuration is representative of several medical facilities identified in Nepal, this example is discussed to illustrate retrofit techniques which can be adopted to improve the performance of hospitals under seismic events.

The building considered in the study of Hassaballa et al (2014) is a reinforced concrete frame structure with infill masonry walls, belonging to class C3 with medium rise. In Table 3 , nine buildings in the Tribhuvan University Teaching Hospital located in Nepal are infill frame RC buildings. The hospital in Sudan can therefore provide interesting retrofit solutions which might be adopted in the Nepalese context.

The hospital is three storeys high and has an overall plan dimension of 21.5 m x 13 m with 9.6 m in total height. Finite element methods are used to simulate the performance of the building, which has been modelled with a flat slab system, and beam and column cross sections faithful to the original design of the hospital, as specified by Hassaballa et al (2014). The infill walls have been modelled by using shell elements and their out-of plane stiffness has also been taken into account.

The 3D frame model of the hospital is checked for two load cases:

- Dead, live and wind loads
- Dead, live and seismic loads

The results obtained from the numerical models have highlighted that the column cross sections and reinforcements for the first load case are under-designed to withstand the additional load from the earthquake.

In order to improve the global strength and stiffness of the building, Hassaballa et al (2014) propose to add new elements in the shortest direction of the hospital, which is assumed to be affected by the seismic loads. As it is reported in Table 6 , the solutions proposed for the hospital in Sudan are also recommended for the medical facilities in Nepal for improving their global capacity.

In particular, Hassaballa et al (2014) propose to improve the global capacity of the hospital in Sudan by using two different dispositions of shear walls:

- Two sets of shear walls of length 2.5 m with varying wall thicknesses (15 cm, 20 cm, 25 cm and 30 cm)
- Two sets of shear walls of length 4.5 m and 15 cm width

Specific finite element models are developed to verify the beneficial effects of both solutions. These demonstrated that the first solution is not sufficient to prevent the failure of all columns of the hospital, and requires an increase of the cross sections and reinforcements of the columns to improve their resistance to lateral loads.

The second solution, which is recommended by Hassaballa et al (2014) for the present case study, is able to improve the global capacity of the hospital by preserving the original quantity of reinforcements and cross sections of the columns.

In the study of Hassaballa et al (2014), it is not stated if the retrofit project has been implemented.

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Glossary

BRACED FRAME: An essentially vertical truss, or its equivalent, of the concentric or eccentric type that is provided in a building frame or dual system to resist lateral forces.

BRACING: Chevron bracing that intersects a beam from above. Inverted V-bracing is that form of chevron bracing that intersects a beam from below.

CHORD: See DIAPHRAGM CHORD.

COLLECTOR: A member or element provided to transfer lateral forces from a portion of a structure to vertical elements of the lateral-force-resisting system (also called a drag strut).

DEMAND: The prescribed design forces required to be resisted by a structural element, subsystem, or system.

DIAPHRAGM: A horizontal, or nearly horizontal, system designed to transmit lateral forces to the vertical elements of the lateral-force-resisting system. The term "diaphragm" includes horizontal bracing systems.

DIAPHRAGM CHORD: The boundary element of a diaphragm or shear wall that is assumed to take axial tension or compression.

DIAPHRAGM STRUT: The element of a diaphragm parallel to the applied load that collects and transfers diaphragm shear to vertical-resisting elements or distributes loads within the diaphragm. Such members may take axial tension or compression. Also refers to drag strut, tie, or collector.

DRIFT: See STOREY DRIFT.

DUCTILITY: The ability of a structure or element to dissipate energy inelastically when displaced beyond its elastic limit without a significant loss in load-carrying capacity.

MOMENT RESISTING FRAME: A structural system with an essentially complete space frame
providing support for vertical loads.

PLATES: Steel column stiffeners at the top and bottom of the panel zone. They are also known as transverse stiffeners.

SHEAR WALL: A wall, bearing or nonbearing, designed to resist lateral forces acting in the plane of the wall.

SHOTCRETE: Concrete that is pneumatically placed on vertical or near vertical surfaces typically with a minimum use of forms.

SOFT STOREY: A story in which the lateral stiffness is less than 70 percent of the stiffness of the story above.

STOREY DRIFT: The displacement of one level relative to the level above or below.

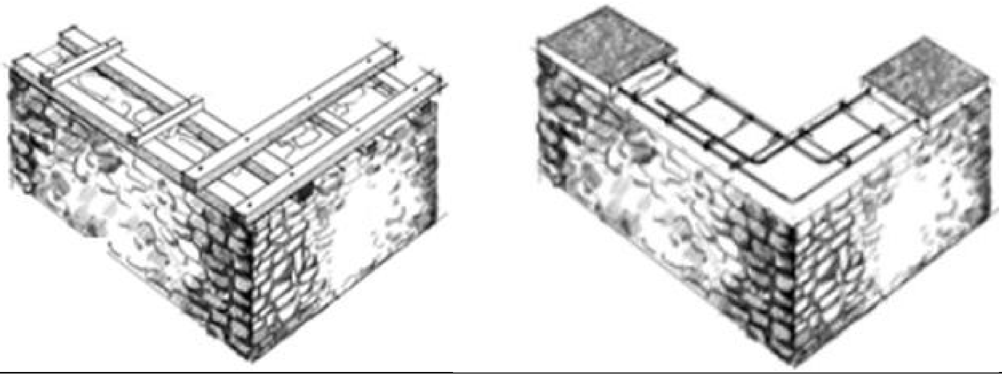
STRUCTURE: An assemblage of framing members designed to support gravity loads and resist lateral forces. Structures may be categorised as building structures or nonbuilding structures.

TIES: Structural members and connections that provide a load path between diaphragms chords to distribute out-of-plane wall loads.

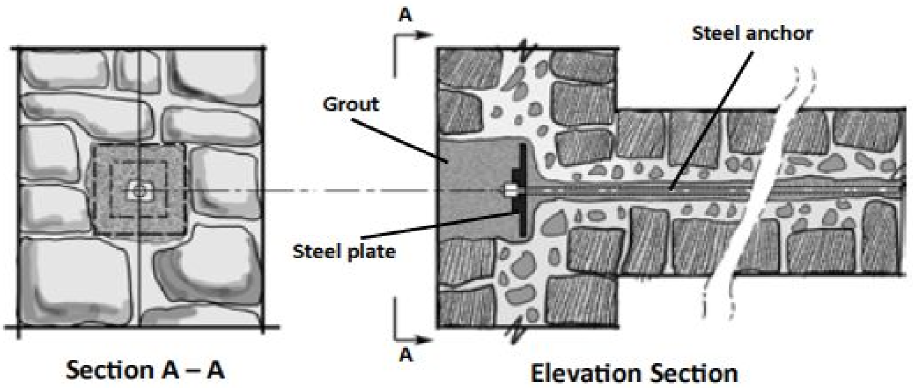
VERTICAL-RESISTING ELEMENTS: That part of the structural system located in a vertical or near vertical plane that resists lateral loads (typically a moment frame, shear wall, or braced frame).

WEAK STOREY: A storey in which the lateral strength is less than 80 percent of that in the storey above.

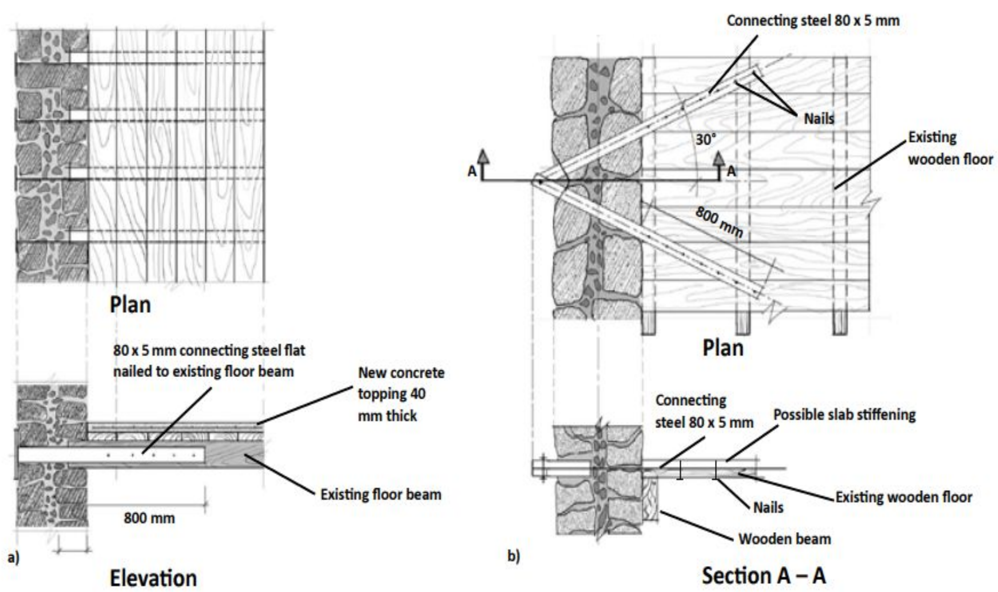
Appendix 1 Common Strengthening Positions



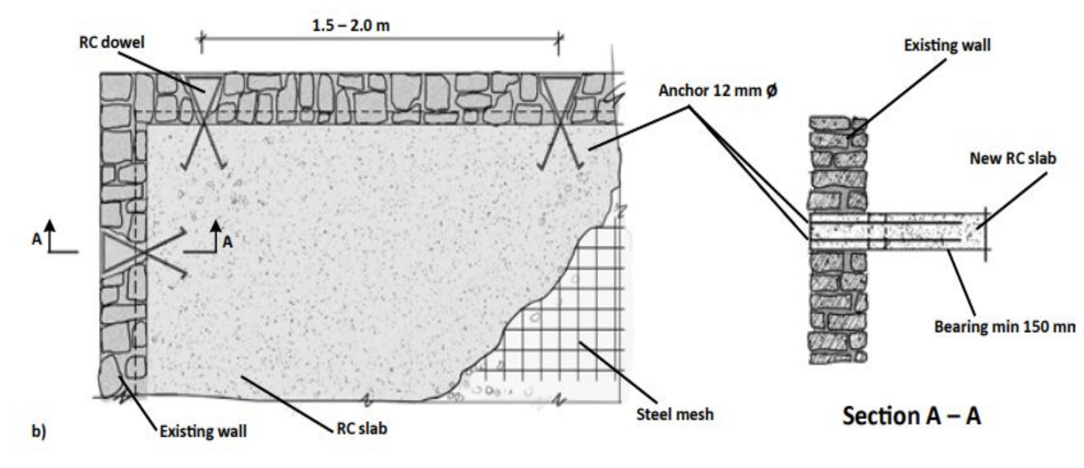
Timber collectors and RC collectors (adapted from: T. Schacher and C.V.R. Murty)



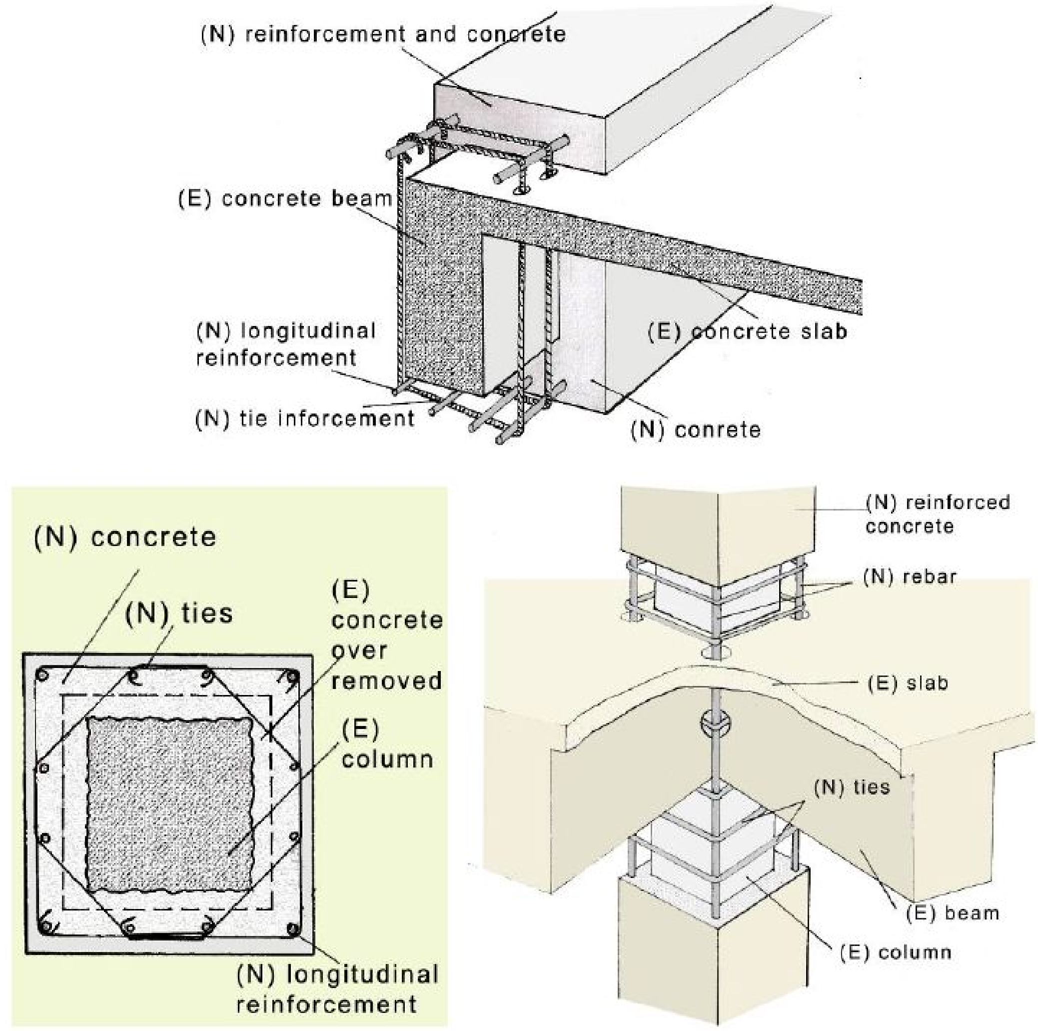
Installation of post-tensioned steel anchors to enhance connections between the intersecting walls (source: Maffei et al. 2006)



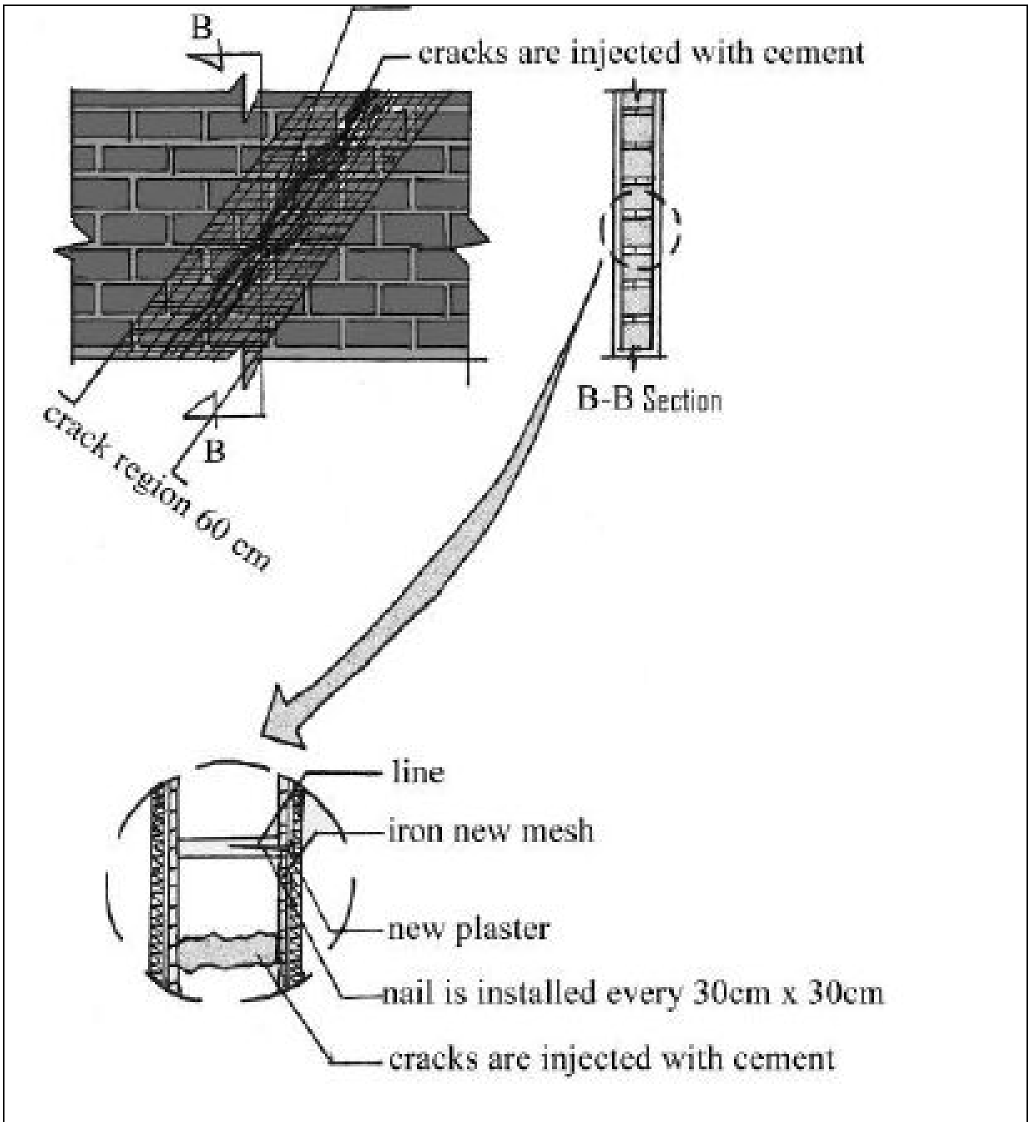
Steel straps for wall-to-floor anchorage: a) floor beams perpendicular to the wall, and b) floor beams parallel to the wall (source: UNIDO 1983)



Retrofitting the floor and roof structures: a new RC slab (adapted from: Tomazevic 1999)



Concrete Jacketing (source: Shrestha et al 2011)



Cracks Injection (source: Shrestha et al 2011