Helpdesk Research Report

Seismic retrofit of earthquake damaged masonry housing

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Question

Review and summary/signposting of technical information related to post-earthquake retrofitting of earthquake damaged housing – Masonry structures

Contents

1. Overview

It is widely recognised that seismic repair and retrofitting is a fast and economical solution when compared to large scale reconstruction, in densely populated regions exposed to seismic hazard. Moreover, in post-earthquake situations, it provides a way to address existing damaged structures that may be salvageable but that are unsafe for occupation in their current condition.

The choice of appropriate repair and/or retrofitting techniques for an earthquake damaged building always requires: 1) a preliminary assessment of the current state of the building, to understand its stability and its intrinsic robustness, to determine whether the repair and strengthening is viable in terms of delivering a safe building; 2) a detailed design of the strengthening and definition of the construction sequence to ensure that the end product performs assumed in the assessment phase; 3) an assessment of the materials, skills, logistic and economic resources available to implement a specific repair or retrofitting system.

The present document focuses on strengthening methods for masonry structures. It provides a review of available sources in literature useful to support point 1 and provide a number of different suitable methods to fulfil point 2. To address point 3 the reader should review the specific geographic, socioeconomic and cultural conditions within which the operations are conducted and determine whether the implementation is feasible to a level of quality which will assure the delivery of a safe building. The remainder of the document contains an annotated bibliography, the key advantages and drawbacks associated to the most common strengthening techniques for masonry buildings and a set of conclusions summarising the fundamental steps for a successful strengthening process.

2. Annotated Bibliography

This annotated bibliography contains documents of different type which should support the decision making process and implementation of strengthening techniques suitable for vernacular masonry structures. The bibliography covers: 1) Manuals drafted to support post-earthquake reconstruction effort in countries with building stock similar to the one found in Nepal; 2) Guidelines and standards currently in force in various countries for the purpose of seismic assessment and implementation of strengthening; 3) Training documents for strengthening implementation. A comprehensive consultation of these documents would reveal a degree of repetition and re-interpretation of general concepts and construction details which recur in many of the listed publications and can be traced back to studies made by Arya and his group in the 1980s and 1990s and some experiences developed in Italy and Europe in the last 30 years.

Manuals

The documents and websites included in this section are the results of activities carried out by special commissions of international organizations, NGOs or associations of engineers in the aftermath of major disasters or to prevent the next one from happening. Although these documents do not represent official seismic codes of standards, they are often developed alongside the official documentation. Because they do not require the lengthy process of official approval and ratification required by official seismic codes, they can be more promptly produced and disseminated. However they do not replace the legal framework for design and strengthening of existing buildings represented by the codes in force in a given country or its construction bylaws. The liability for the implementation of the measures contained in such documents remains with the designer and contractor.

Regional

NSET Nepal provides a large number of documents aimed at the reduction of seismic risk in the country. Much of this literature is in Nepali language, so as to be of greater impact and dissemination in Nepali society. A useful document that can be found on NSET website, relevant to this annotated bibliography, is the Geohazards (2005) leaflet on Safe Adobe housing. The construction details outlined can also be used for repair and retrofitting of damaged buildings. The Nepal Housing Recovery and Reconstruction Platform (HRRP, 2016) has recently held a technical Session on retrofitting, at which the Nepal Guidelines for retrofit of Adobe and Masonry Structures were presented. The Masonry Structures document is aimed at engineers in the first part, with methods for assessment of the lateral capacity of bearing walls and a section on strengthening methods in the second part, very similar to the Shrestha et al. (2009). The last section of the document includes examples of assessment calculations and retrofitting. It is largely put together from other sources, reviewed in the following. The document on Adobe Structure is also a compilation of other sources. It has a more construction oriented content and hence might be more appropriate for self-repair and strengthening of single family dwellings.

The manual by Desai & Desai (2007) is based on the experience gathered by the National Centre for Peoples'- Action in Disaster Preparedness (NCPDP) team during several months of visiting the earthquake areas of Kashmir following the 2005 earthquake, as well as earlier visits to the earthquake shaken regions of Maharashtra, Uttarakhand, and Gujarat. The main objective is the restoration and retrofitting of structures located in the rural areas of earthquake affected Kashmir, situated in the northernmost area of India and in Pakistan. The authors observe a phenomenon common to many communities hit by large death tolls, losing confidence in their traditional construction techniques and willing to adopt cement- and steel based construction, without appreciating the long-term consequences as well as the viability of such introduced systems in the local context. The manual is the result of the practical application of the Guidelines for Repair, Restoration and Retrofitting of Masonry Buildings in Earthquake Affected Areas of Jammu & Kashmir, issued by National Disaster Management Division, Ministry of Home Affairs, Government of India, to a number of case studies, therein reported. The interesting approach proposed is to explicitly relate the type of strengthening intervention to the level of damage identified. It provides very detailed step by step list of operations to implement a given repair or strengthening solutions, with clear sketches. The only limitation is that this is not accompanied by calculations or checks to prove the level of performance attained and compliance with the standards.

Ali (2009) also addresses the vulnerability and shortcomings of buildings hit by the Kashmir earthquake, on the Pakistani side of the boarder. This manual is intended to provide guidance to designers for repair and strengthening of masonry and concrete structures for seismic resistance. It also provides a Damage Assessment pro forma largely based on the Italian AEDES level 1 and level 2 forms (Protezione Civile Italiana, 2013). As far as masonry structures are concerned this document only considers repair and retrofitting of walls, with no attention to floor structures. However logical and well-structured information is provided for the improvement of connections among walls and different types of interventions are outlined for the repair of cracks depending on their width.

Bothara & Brezv (2011), explains the underlying causes for the poor seismic performance of stone masonry buildings and offers techniques for improving it for both new and existing buildings. The proposed techniques have been proven in field applications, are relatively simple, and can be applied in areas with limited artisan skills and tools. The scope of this tutorial has been limited to discussing stone masonry techniques used primarily in the earthquake-prone countries of Asia, mostly South Asia. For retrofitting it mainly recommends the use of reinforced concrete bands, to transform the unreinforced masonry construction into a confined masonry cage. It also provides specific details of implementation of techniques for floor stiffening, masonry wall integrity and foundation stability. While it acknowledges the issues related with technological challenges and technology transfer, it does not provides indications of the cost and resources associated with the implementation of some of the proposed interventions.

Further afield

The Shrestha et al. (2009) manual is based on experience of vulnerable schools buildings in Indonesia. Importantly it offers an overview of the overall retrofitting process, from assessment of vulnerability to the procurement of materials and skill for strengthening implementation. It emphasises the importance of intensive supervision and quality control. It provides simple guidelines that can be used by lay persons to appreciate the level of vulnerability of a building and the need for strengthening. It has diagrams of various strengthening techniques and two case studies of how a building retrofit is achieved.

A very useful resources is represented by the site http://masonryretrofit.org.nz/ maintained by the University of Auckland. This is a digital repository of resources for assessment and retrofit of masonry structures. For professional structural engineers the 'Seismic Assessment and Retrofit Manuals' will be the documents of most importance. These documents have been prepared in collaboration with NZSEE and SESOC. Although the focus is on constructional methods and details typical of New Zealand structural masonry, it is nonetheless a very useful source of comprehensive guidance on both assessment and retrofitting. Importantly it is also organised chronologically, so that it is easy to identify further useful developments.

Also worth of notice is the digital repository of the European project NIKER NEW INTEGRATED KNOWLEDGE BASED APPROACHES TO THE PROTECTION OF CULTURAL HERITAGE FROM EARTHQUAKE-INDUCED RISK) , especially *Work package 6: Connections and dissipative systems with early warning*, and *Work package 10: Guidelines for end-users. (http://www.niker.eu/downloads/)*. This iare the results of a European project sponsored by The EU FP7 programme in the aftermath of the L'Aquila Italy earthquake and although, the focus is mainly on European historic masonry buildings, many of the guidelines for strengthening are applicable to brick and stone masonry worldwide.

Guidelines and standards

Regional

The Indian seismic Engineering community has been very active over the last 40 years in an effort to produce documents, guidelines and standards that can address the reduction of vulnerability of the existing largely self-built housing stock in prone region of India. The documents reviewed below are the most recent editions of this literature.

Part IV-Repair, Restoration and Seismic Retrofitting of Masonry Buildings (Arya, 2003) is part of a larger sets of guidelines produced by the author for the UN/DESA PROJECT INT/98/X70. It covers the topic of restoration of lost strength of cracked masonry walls, cosmetic repair, as well as their seismic retrofitting. The objectives of the document is to produce a set of guidelines and training materials to be applied to existing weak masonry buildings for upgrading their seismic safety in various seismic zones of Afghanistan. The material in this specific Part IV is aimed at the training of the engineers and masons. Many of the later guidelines for the repair and retrofit of traditional masonry construction in the Kush and Himalayan region have used this document as reference.

This document has now essentially been adopted as Indian Standard in the IS.13935.2009 (Indian Standards, 2009).

Further afield

The 'Guidelines for Earthquake Resistant Non-Engineered Construction' was first published by the International Association for Earthquake Engineering (IAEE) in 1986 with the objective of improving the seismic safety of non-engineered housing constructions. Such structures are usually built by common man across many developing countries. It offers basic concepts and construction techniques to improve the earthquake resistance of these commonly built houses. It was based on the experience of Japanese seismic engineers. The edition referred to in the literature list and available on line is a translation in English by NICEE produced in 2004.

In the last decade, following destructive earthquakes in many parts of the world and new development and understanding in seismic engineering a new generation of standards for new and existing construction has been issued. Although they might not be directly applicable to the Nepalese situation, some of them, like the NZS 4229 2013 (https://shop.standards.govt.nz/catalog/4229:2013(NZS)/scope?) have the advantage of setting out the construction requirements for building not requiring specific

engineering design. The document complies with the seismic code and hence buildings constructed or repaired according to the NZS 4229 are also seismically safe and durable. The NZSEE Guidelines 2006 (see http://www.eq-assess.org.nz/) and its new version 2016 to be officially published in 2017 should be used for seismic assessment.
In many of the manuals included in the previous section, reference is made to the series of documents issued by the United States' Federal Emergency Management Agency (FEMA, https://www.fema.gov/earthquake) relating to earthquake assessment and strengthening; specifically FEMA 356 (2000). However more appropriate in this context are FEMA 547 (2006) and FEMA P-774 (2009).

In Europe the seismic design and retrofitting of residential structures is regulated by the Eurocode 8 Part 1(EN 1998–1, 2004) and part 3 (EN 1998–3, 2005) respectively. These documents have general applicability across Europe and different seismic zone. They are also supplemented by national codes, among which the best developed in Europe are the Italians, especially as far as retrofit of masonry structures are concerned. Reference should be made to *NTC2008 - Norme tecniche per le costruzioni - D.M. 14 Gennaio 2008* (NTC08, 2008, in Italian) and to accompanying guidelines documents (Circolare 26/2010, Linee Guida, 2010, in Italian) produced after the L'Aquila, Italy 2009 earthquake to aid the retrofit and reconstruction of masonry buildings in historic city centres damaged by the earthquake. Two documents in English that summarise these standards and can be of beneficial use in the reconstruction in Nepal are CNR – Italian National Research Council (2004) *Technical Guidance Document 200 R1/2004,* providing guidance and technical support for the use of fibro-reinforced polymers in the strengthening and retrofit of masonry structures. A commentary on these documents and their site application following the 2009 L'Aquila earthquake and 2012 Emilia earthquake Italy is offered in D'Ayala (2014), Rossetto et al (2014), D'Ayala and Paganoni (2014).

Training

Regional

NSET-NEPAL has produced a Training Curriculum, accompanying the Seismic Retrofitting Guidelines of Buildings in Nepal (2013). The Training Curriculum is designed to provide the masons with the basic knowledge of retrofitting techniques, tools and quality control of material and works, so as to equip them with the skills necessary to retrofit and deliver seismic resistant buildings. It is conceived in two parts, one for the training of the trainers and one for the trainees. The training material has been prepared with technical assistance from the Centre of Resilient Development (CoRD) with intensive consultation of Ministry of Urban Development (MOUD) and Department of Urban Development and Building Construction (DUDBC) and the support of Comprehensive Disaster Risk Management Programme (CDRMP) of the UNDP. The TC is designed to be delivered to groups of 20-25 masons, with a minimum 1 year experience, over 5 intensive days. An examination is held on the last day and successful trainees are awarded a certificate.

Further afield

The USAID Primer (2014) introduces engineering and development professionals to the basic steps in the process of planning and executing post-disaster seismic retrofit of housing projects funded by the United States Agency for International Development. This Primer addresses various phases of the planning, evaluation, design, and implementation process and the various deliverables and milestones usually included as part of the process. The document also discusses the role and responsibilities of the USAID project manager, including interactions with affected communities, partners, local officials, and other involved organizations. Role and responsibilities of project managers may vary among different aid agencies. The objective is not simply to strengthen buildings, but also to change construction practices and enforcement of codes, while building local capacity.

A similar document was developed by GTZ for UN-ISDR and UNDP's South-South Cooperation (Willison, 2008) recognising the fundamental issue that good design guidelines are not sufficient, unless good construction practice and detailing follow suit. The document is developed on the basis of direct field experience following reconstruction caused by flood and landslides in the period 2005-2008 in the Philippines; however it recognises the importance of determining the effects of multi-hazards associated to specific locations, and particularly earthquakes. The events in Bohol and Cebu of 2013 have proven that such integrated approach to resilience is fundamental (see D'Ayala et al 2016). The Handbook provides both design principles (location foundations, walls and roof connections, bracing and drainage) and construction and materials principles (basic reinforced concrete technology, roofing, connections details, etc) and includes a code for minimum standards and a house building checklist. Fundamental rules are expressed in simple bullet points format and illustrated by photograph of real cases, showing both bad and good practice. The document (in English) is useful for builders or self-builders/owners.

3. Key Lessons

This section contains a summary of key issues related to specific strengthening methods and their implementation which might be in common use for retrofit of buildings in Nepal. Several critical reviews of methods exist in literature, addressing both construction and logistic advantages and disadvantages of specific retrofit solutions (Smith & Redman, 2009; Shresta et al, 2012; Satiparan, 2015). Various forms of mesh and plastering are recommended for in-plane as well as out-of-plane performance enhancement, as well as FRP wrapping. To prevent out-of-plane collapse anchoring to floors and walls is essential, integrated with buttressing or addition of strongback columns for longer spanning walls, while the in–plane performance can be enhanced by introduction of in wall confinement by splint and bandage systems. Key issues for implementation of each of these methods are summarised in the following subsections.

Use of wiremesh/ geopolymer mesh:

Sathiparan (2015) presents a full review of different type of meshing as applied to adobe and stone masonry construction with the purpose of either strengthening or repair. A common issue to wire and polymer meshes is the availability of good quality in Nepal. A second issue also common to both is the very poor environmental durability if they are not properly covered by thick plaster. Alternative to wire and polymer mesh are bamboo meshes. From a structural point of view the weakest link is the connector of the mesh to the adobe or stone units. If properly connected and protected, and if the pace of the mesh and gauge of the wire or strip is properly sized, the mesh can be very effective in containing and redistributing damage, providing distributed confinement and hence enhancing the overall ductility of the system. However implementation of such method is very labour intensive and very sensitive to errors or defect in workmanship. Shresta et al (2012) provide examples of real application of these techniques. They review several detail variations, aimed at minimising costs given the identified deficiency of a number of schools in Nepal. Indicative costs per unit surface of wall retrofitted are provided together with level of protection attained given a level of shaking.

Use of columns – strongbacks

The use of columns strongbacks to brace walls and reduce out of plane deformation follows from temporary bracing in the aftermath of an earthquake. The role of these columns is not to take gravity loads but only to transfer lateral loads from the walls to the ground. Strongbacks are recommended by both the New Zealand and U.S. strengthening guidelines. In this case the critical issue is the connections between the frame and the masonry. Although strongbacks made of steel are recommended, in case of vernacular structures might be more appropriate to use timber or bamboo columns, with a stiffness better correlated to the stiffness of the walls, and uing materials that might be more readily available on site and at lower costs. It should be noted that the use of timber columns and frames to laterally brace brickwork, is characteristic of Newari construction, and hence well known to builders in the Kathmandu Valley (see D'Ayala 2006 and D'Ayala 2011). Arya (2003) also recommends construction of stone buttresses to laterally support walls. Importantly the stone work of the buttresses and of the walls should be keyed in by sufficient overlapping.

Use of seismic belts - ring beams

Arya (2003) recommends the use of horizontal seismic belts at eave level and above lintel' levels to tie together walls and ensure box behaviour. Seismic belts are also recommended to frame gable walls, to prevent overturning. Importantly it also provides geometric and construction conditions for which the distribution and extent of these belts can be minimised. These seismic belts should have a minimum height of 250 mm and reinforced with wire-mesh of increasing gauge depending on free length of wall. The thickness of the micro-concrete is not specified and where the belt is provided both internally and externally, connectors should be distributed at no more than 300m distance. The belts are constructed by imbedding the mesh in 30 mm of plaster, so that the additional mass of the belt is kept to a minimum, while its stiffness is comparable to the masonry substratum. Such measures are all contained in the IS.13935.2009 (Indian Standards 2009). IS.13935.2009 also includes reference to the use of ring beams to connect concrete slab roof or floor structure to masonry walls. This method should be implemented very carefully and only on solid walls of good fabric. The adverse effect of ring beams on masonry three leaf rubble walls with poor internal connection is amply documented as post-earthquake evidence in several events in both Europe and Asia. The Italian Linee Guida (2010) advice against the use of ring beams on historic masonry walls. It is also unadvisable to adopt them with timber roof structure, as the embedment of the head of the timber rafters in the concrete beam, often causes rotting of the timber, due to diverse hygrothermal behaviour and condensation.

Connections of timber floors and roof to walls

The Linee Guida (Circolare n. 26/2010) recommends the use of ties and anchors to connect vaults and timber floors to walls, and walls to walls. A thorough review of traditional and modern solutions, their effectiveness, shortcomings and possible improvement by use of simple dissipative devices is included in D'Ayala and Paganoni (2014). Strengthening of floor to improve diaphragm action is recommended by the Linee Guida (Circolare n. 26/2010). This can be achieved by either nailing superimposed sets of floorboards at right angles or by adding a lightweight reinforced lime-based concrete screed above the existing set of floorboards. The reinforcement should be anchored in the perimeter masonry walls. Extensive tests campaign have been carried out at several institution in Italy in past years to devise the best technical details and performance improvement that can be obtained with such interventions (Riggio et al. 2012). The joists and beams forming the floor structures should also be anchored to the walls by means of ties. This type of intervention was traditionally extensively applied in the past and it can be observed that in cases where the ties have been well maintained and are regularly distributed on the wall, the damage is usually well contained even for earthquakes greater than Ms 6.

In Nepalese traditional construction floor joists are anchored to walls by means of two sets of vertical pegs (on each side of the wall or between wythes in multi-layer walls, which prevent joists form sliding out and walls from bending out of plane (D'Ayala, 2006; D'Ayala, 2011) . Recent experimental work carried out by Kunming University of Science and Technology in collaboration with Beijing Normal University and NSET-Nepal by shaking table tests on ½ scale buildings, show the effectiveness of this arrangement. (http://iccr-drr.bnu.edu.cn/en/) . Effective details of bracing of timber floor and roof structures are contained in Desai & Desai (2007)

Use of fibre reinforced polymers

The Italian guidelines CNR-DT 200 R1/13, (CNR-DT 200 R1/13, 2013 in Italian, CNR-DT 200/04 in English) provide advice for use of FRP for the "Design, installation and control of strengthening intervention with Fibre Reinforced composites", to either strengthen or reconstruct structural elements, or to connect structural elements with different roles to improve the behaviour of the whole structure. The document covers all structural materials, including masonry. Some global pre- conditions need to be ensured to achieve a good performance of any localised strengthening:

- The masonry structural substratum should be adequately consolidated to withstand the design actions or replaced;
- Orthogonal walls should be appropriately connected;
- Inadequate connections between the walls and the horizontal floors and roof should be improved;
- Thrust from roofs, arches and vaults should be adequately contrasted
- Floor should be sufficiently stiff in their plane to redistribute the horizontal action while at the same time act as constraint for out-of-plane motion of walls.

It is not openly stated whether strengthening with FRP is suitable to meet this performance criteria or whether these are prerequisites to the use of FRP in masonry structures, however some disclaimers are included:

- Intervention with FRP cannot as a rule improve or amend situations characterised by strong irregularities in terms of strength and stiffness, even though, if applied to a reduced number of elements, they can provide a more even distribution of strength
- Interventions with FRP aimed at improving local ductility such as columns or pillars confinements are always appropriate, although it should be verified that as a result of the intervention the adjacent parts of the structure do not become vulnerable.
- Local intervention with FRP should not reduce the overall ductility of the structure.

Important research on the topic of affordable repair and strengthening methods for rural stone masonry houses in Nepal is being carried out within a project funded by the International Centre for Collaborative Research in Disaster Risk Reduction (ICCR-DRR, http://iccr-drr.bnu.edu.cn/en/, funded by UK DfID). The project is coordinated by Beijing Normal University and delivered by NSET-Nepal and Kunming University of Science and Technology. They have reviewed and tested several arrangements, based on combination of timber posts and band, gabion mesh and tarpaulin strips, all low cost material easily found in rural Nepal. (for more details contact Dr R. Guragain at NSET-Nepal).

4. Conclusions

The above reviews of document points out the critical importance of strictly linking any activity of repair strengthening and retrofitting to the essential understanding, on one hand, of the current state of the building and its intrinsic vulnerability, on the other on the logistic constraints affecting the implementation of any of the provisions listed above. These needs are well summarised by the flowchart of Figure 1, briefly commented herein:

1. *State and condition of structure*: level of damage and reparability: structure should show an inherent level of integrity and verticality, so that the stability of any and all part of the building are not compromised. If this is not the case it is best to dismantle and rebuild, using as much of the original material as possible to reduce costs.
2. *Vulnerability Assessment*: A visual inspection maybe sufficient to identify fundamental vulnerabilities, such as lack of connections between walls or between walls and floor/roof; or excessive free length of inflection of walls, or lack of lintels above windows and doors; or poor fabric of the walls (lack of good binding mortar, lack of through stones, voids among rubble stones).
3. *Technical assessment:* if the structure shows specific vulnerabilities, before intervening might be necessary to ascertain and quantify the capacity of both weak and resilient elements. The limitation is that for vernacular structures it might be necessary to conduct some in situ tests to obtain such quantification.
4. *Check of code requirements:* One limitation often encountered for vernacular structures is that they are not included in codes and hence required performances and methods for achieving them are not clear, or calculation might be difficult. The rule of thumbs and guidance offered in the manuals discussed in section 2 of this document, offer answers to this problem.
5. *Retrofitting design:* this should be carried out to ensure the global integrity and stability of the structure, and to reduce the specific vulnerabilities identified. Check should be carried out to ensure that parts of the structures are not over-strengthened to the detriment of other portions or elements. The choice of appropriate strengthening techniques is discussed in the Guidelines documents listed in section 2, with the advice notes summarised in section 3 of this document. Detailed design should be tailored to each individual situation, with the objective of compliance to seismic standards.
6. *Economic resources and equipment:* these will have a critical influence on the feasibility and implementation of the design and should be investigated at an early stage, considering alternative low cost solutions, which ensure the use of locally available materials and techniques with whom the local workmanship is familiar. Advice is offered in several sources referenced in section 3 and in the documents reviewed under “Training” in section 2 of this document.
7. *Logistic planning*: two levels of planning are necessary. The first relates to the economic resources. These might not be sufficient to carry out all required strengthening works at once. In this case measures need to be prioritised and scheduled in relation to available funds. A second more detailed level of planning is required for the building site, so that materials and workmanship is available when needed, properly stored and kept to prevent deterioration.

Advice is provided in the documents reviewed in the subsections Manuals and Training of section 2 of this document.

8. *Supervision and on-site training*: Training and site supervision by skilled professionals is essential to ensure that quality is upheld and delivered from site to site, so that as a result the entire building stock vulnerability is reduced and the overall risk to population is reduced. Training and site supervision should be seen as a fundamental measure to improve the resilience fo the local population and society. Advice is offered in the documents listed in section 2, Training.

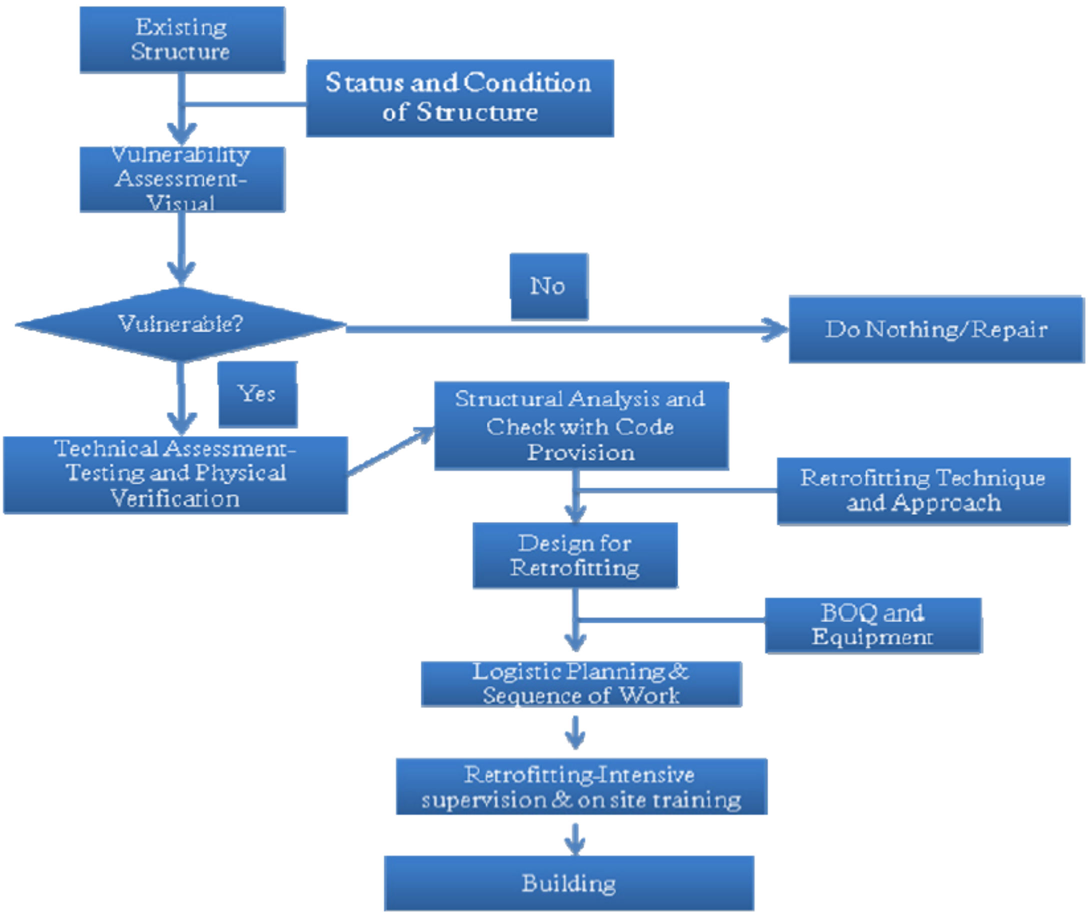

Figure 1: Integrated process of retrofitting (from Shrestha et al., 2009)

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Key websites

- University of Auckland portal on resources on masonry assessment and retrofit: http://masonryretrofit.org.nz/
- NIKER - NEW INTEGRATED KNOWLEDGE BASED APPROACHES TO THE PROTECTION OF CULTURAL HERITAGE FROM EARTHQUAKE-INDUCED RISK: http://www.niker.eu/downloads/

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