Analysis of Seismic Retrofitting in Heritage Buildings: Techniques and Conservation Interventions

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Abstract: Earthquakes result in major structural damage or outright collapse of buildings. Recent earthquakes have shown that historic buildings retrofitted to withstand earthquakes survive better than those that have not been upgraded. India is a country with a rich architectural and cultural heritage with a large number of religious and secular buildings dating back to the 2nd century BC. Heritage buildings are especially vulnerable in case of an earthquake. If once they are lost a part of our history is lost forever. Although heritage buildings can be retrofitted to survive earthquakes, many retrofit practices damage or destroy the very features that make such buildings significant. So there is a need to conserve these buildings following the International Venice Charter issued in 1966 to regulate the conservation and restoration of monuments and sites worldwide. This paper studies the various aspects of seismic retrofitting of heritage buildings, new techniques being evolved worldwide, and also discusses preservation issues and scenarios of heritage conservation in India.
***Keywords*:** seismic retrofitting, heritage buildings, techniques, architectural conservation

1. Introduction

The Earthquakes result from sudden movements of the geological plates forming the earth's crust, generally along cracks or fractures known as "faults". If a building has not been designed and constructed to absorb these swaying ground motions, then major structural damage, or outright collapse, can result, with grave risk to human life. Heritage buildings are especially vulnerable in case of an earthquake. India is a country with a rich architectural and cultural heritage with a large number of religious and secular buildings dating back to the 2nd century BC. Earthquakes result in major structural damage or outright collapse of buildings. If once they are lost a part of our history is lost forever. Although heritage buildings can be retrofitted to survive earthquakes, many retrofit practices damage or destroy the very features that make such buildings significant. In modern times, the International Venice Charter issued in 1966 regulates the Conservation and Restoration of Monuments and Sites worldwide. Representatives from 16 countries forming the International Council of Monuments and Sites (ICOMOS) underwrote this. The tolerance of "in-service" masonry buildings to movement, the way they deform in shear and bending and the way cracks develop has been the subject of our research. This paper deals with both the theoretical debate about conservation issues and the technical aspects of the implementation of repair work. This study involves studies of several projects relating to the structural and architectonic conservation of buildings of historic interest and value. (Arnold et al., 1992)

2. Seismic retrofitting and preservation issues in heritage structures in India

In past earthquakes, many of these heritage structures have got damaged thus disintegrating the cultural and architectural heritage of the region. The recent Gujarat earthquake has witnessed the devastation of some of the most enriched architectural buildings in Bhuj, Anjar, Jamnagar, Ahmedabad, and other places. The total loss is estimated at 15500 heritage structures which are in the progressive stage of damage. This calls for attention to major issues regarding other similar heritage structures in earthquake-prone zones.

2.1 Heritage structures in India

Heritage structures in India can be categorized into three major types:

(1) The secular structures such as palaces, darbargarhs, and chatries.

(2) The religious structures of ancient origin still in active use by some sects.

(3) The historic houses and commercial structures like bazaars are character-defining elements of a historic walled city area in areas.

It is these heritage structures, which will continue in the future to be a significant attraction for tourists while at the same time contributing to the local cultural base. The heritage buildings are the most visible and often most important physical manifestation of a rich cultural history of a country like India.

2.2 Balancing seismic retrofitting and architectural conservation

Reinforcing a historic building to meet new construction requirements, as prescribed by many building codes, can destroy much of a historic building's appearance and integrity. This is because the most expedient ways to reinforce a building according to such codes are to impose structural members and to fill irregularities or large openings, regardless of the placement of architectural detail. The results can be quite intrusive. However, structural reinforcement can be introduced sensitively. In such cases, its design, placement, patterning, and detailing respect the historic character of the building, even when the reinforcement itself is visible.

Three important preservation principles should be kept in mind when undertaking seismic retrofit projects:

Historic materials should be preserved and retained to the greatest extent possible and not replaced wholesale in the process of seismic strengthening.

New seismic retrofit systems, whether hidden or exposed, should respect the character and integrity of the historic building and be visually compatible with it in design.

Seismic work should be "reversible" to the greatest extent possible to allow removal for future use of improved systems and traditional repair of remaining historic materials.

3. Seismic retrofitting and preservation issues in heritage structures in India

Typical earthquake damage to most older and historic buildings results from poor ductility--or flexibility--of the building and, specifically, poor structural connections between walls, floors, and foundations combined with the very heavy-weight and mass of historic materials that are moved by seismic forces and must be resisted. In buildings that have not been seismically upgraded, particularly unreinforced masonry buildings, parapets, chimneys, and gable ends may dislodge and fall to the ground during a moderate to a severe earthquake. Walls, floors, roofs, skylights, porches, and stairs which rely on tied connections may simply fail. Interior structural supports may partially or collapse. Unreinforced masonry walls between openings often exhibit shear (or diagonal) cracking. Upper stories may collapse onto under-reinforced lower floors with large perimeter openings or atriums. Unbraced infill material between structural or rigid frame supports may dislodge. Adjacent buildings with separate foundations may move differently in an earthquake creating damage between them. Poorly anchored wood frame buildings tend to slide off their foundations (Agarwal and Shrikhande, 2011).

3.1 Factors influencing damage in an earthquake

Six principal factors influence how and why historic buildings are damaged in an earthquake:

(1) Depth of the earthquake and subsequent strength of the waves reaching the surface;

(2) Duration of the earthquake, including after-shock tremors;

(3) The proximity of the building to the earthquake epicenter, although the distance is not necessarily a direct relationship;

(4) Geological and soil conditions;

(5) Building details, including materials, structural systems, and plan configuration

(6) Existing building condition, including maintenance level.

The first three factors i.e. the depth, duration, and proximity to the fault--are beyond human control. Recent earthquakes have shown the fourth factor, geological soil conditions, to be as important as any of the other factors because loose, soft soils tend to amplify ground motion, thereby increasing damage. Further, there is the tendency of soft, unstable soils to "liquefy" as the ground vibrates, causing the building foundations to sink unevenly. This fourth factor, geological and soil conditions, is difficult to address in a retrofit situation, although it can be planned for in new construction. The last two factors -the building's construction type and its existing physical condition--are the two factors over which building owners have control and can ultimately affect how the historic property performs in an earthquake.

Although historic buildings present problems, the way they were constructed often has intrinsic benefits that should not be overlooked. Diagonal sub flooring under tongue-and-groove nailed flooring can provide a diaphragm, or horizontal membrane, that ties the building together. Interior masonry walls employing wire lath with plaster also add strength that binds materials together. The typical construction of older buildings with partition walls that extend from floor to ceiling instead of just to the underside of a dropped ceiling) also provides additional support and load transfer during an earthquake that keeps shifting floors from collapsing. Moreover, buildings constructed of unreinforced masonry with a wall thickness to height ratio that does not exceed code requirements can often survive shaking without serious damage. The stability of unreinforced masonry walls should not be underestimated; while the masonry may crack, it often does not shift out of plumb enough to collapse.

3.2 Building typology and construction system

A historic building's construction and materials determine its behavior during an earthquake. Some buildings, such as wooden frame structures, are quite ductile and, thus, able to absorb substantial movements. Others, such as unreinforced brick or adobe buildings comprised of heavy individual load-bearing units, are more susceptible to damage from shaking. If an earthquake is strong or continues for a long time, building elements that are poorly attached or unreinforced may collapse. The reaction of concrete buildings and concrete frame structures is largely dependent upon the extent and configuration of iron or steel reinforcement. Early buildings constructed of concrete are often inadequately reinforced, inadequately tied, or both, and are thus susceptible to damage during earthquakes.

Recognition of the configuration of the historic structure and inherent areas of weakness are essential to addressing appropriate alternatives for seismic retrofit. For example, the plan and elevation may be as important as building materials and structural systems in determining a historic building's survival in an earthquake. Small round, square, or rectangular buildings generally survive an earthquake because their geometry allows for equal resistance of lateral forces in all directions. The more complex and irregular the plan, however, the more likely the building will be damaged during an earthquake because of its uneven strength and stiffness in different directions. Structures having an "L," "T," "H," "U, or E" shapes have unequal resistance, with the stress concentrated at corners and intersections. This is of particular concern if the buildings have flexible structural systems and/or an irregular layout of shear walls which may cause portions of the building to pull apart (Agarwal and Shrikhande, 2011).

3.3 Condition of existing buildings

Much of the damage that occurs during an earthquake is directly related to the building's existing condition and maintenance history. Well-maintained buildings, even without added reinforcement, survive better than buildings weakened by lack of maintenance. The capacity of the structural system to resist earthquakes may be severely reduced if previous alterations or earthquakes have weakened structural connections or if materials have deteriorated from moisture, termite, or other damage. Furthermore, in unreinforced historic masonry buildings, deteriorated mortar joints can weaken entire walls. Maintenance, which reduces moisture penetration and erosion of materials, is therefore essential. Since damage can be cumulative, it is important to analyze the structural capacity of the building.

Over time, structural members can become loose and pose a major liability. Unreinforced historic masonry buildings typically have a friction-fit connection between horizontal and vertical structural members, and the shaking caused by an earthquake pulls them apart. With insufficient bearing surface for beams, joists, and rafters against the load-bearing walls or support columns, they fail. The resulting structural inadequacy may cause a partial or complete building collapse, depending on the severity of the earthquake and the internal wall configuration. Tying the building together by making a positive anchored or braced connection between walls, columns, and framing members is key to the seismic retrofit of historic buildings.

4. Seismic retrofitting and building conservation

Heritage structures can be divided mainly from an earthquake point of view into two main categories (Cox, 2001):

Undamaged or before earthquake heritage structures: The retrofitting needed for these structures is mainly to increase their seismic strength through reinforcement of structural members. This type of approach is known as the conservation approach.

Damaged or after earthquake heritage structures: For earthquake-damaged heritage structure retrofitting techniques are adopted to restore and rehabilitate the damaged structure. This is done by strengthening the walls, columns, and overall fabric of the structure without damaging the character of the building. In case of a partial or full collapse of the portion of the building, it is reconstructed by use of as much historic material as available as possible and after proper documentation of old structure from available records.

4.1 The Venice Charter

The principles guiding the preservation and restoration of ancient buildings must be agreed upon and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions. By defining these basic principles for the first time, the Athens Charter of 1931 contributed towards the development of an extensive international movement which has assumed concrete form in national documents, in the work of ICOM and UNESCO and the establishment by the latter of the International Centre for the Study of the Preservation and the Restoration of Cultural Property (ICOMOS, 2011). Increasing awareness and critical study have been brought to bear on problems that have continually become more complex and varied; now the time has come to examine the Charter afresh to make a thorough study of the principle involved in the seismic retrofitting and conservation of heritage structures.

5. Planning for seismic retrofitting

The level of seismic retrofit generally falls into four classifications, depending on the expected seismic activity and the desired level of performance (David et al., 1998). Realistically, for historic buildings, only the first three categories apply.

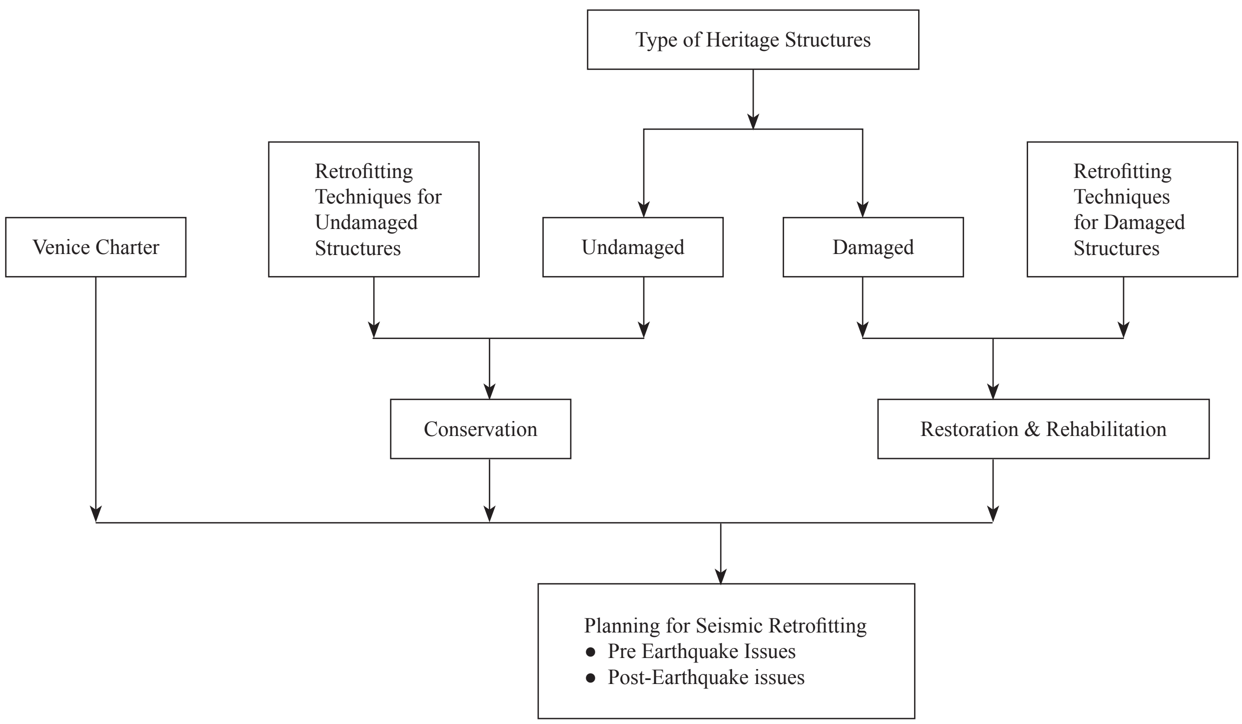
(1) Basic Life Safety. This addresses the most serious life-safety concerns by correcting those deficiencies that could lead to serious human injury or total building collapse. Upgrades may include bracing and tying the most vulnerable elements of the building, such as parapets, chimneys, and projecting ornamentation or reinforcing routes of exit. It is expected that if an earthquake were to occur, the building would not collapse but would be seriously damaged requiring major repairs.

(2) Enhanced Life Safety. In this approach, the building is upgraded using a flexible approach to the building codes for moderate earthquakes. Inherent deficiencies found in older buildings, such as poor floor-to-wall framing connections and unbraced masonry walls would be corrected. After a design-level earthquake, some structural damage is anticipated, such as masonry cracking, and the building would be temporarily unusable.

(3) Enhanced Damage Control. Historic buildings are substantially rehabilitated to meet, to the extent possible, the proscribed building code provision. Some minor repairable damage would be expected after a major earthquake.

(4) Immediate Occupancy. This approach is intended for designated hospitals and emergency preparedness centers remaining open and operational after a major earthquake. Even most modern buildings do not meet this level of construction, and so for a historic building to meet this requirement, it would have to be almost totally reconstructed of new materials which, philosophically, do not reflect preservation criteria.

The most appropriate approach for a particular historic building will depend on a variety of factors, including the building's use, whether it remains occupied during construction, applicable codes, budgetary constraints, and projected risk of damage. From a design perspective, the vast majority of historic buildings can tolerate a well-planned hidden system of reinforcement. The figure below presents a Schematic Plan showing the conservation approach to retrofitting heritage buildings



6. Reasons for destruction of heritage structures in Gujarat earthquake

The general construction technique adopted in most of these structures was random rubble stone masonry. The binding power of lime has deteriorated with age has caused havoc for the structures. The walls are sometimes extended up to over 15 feet in un-braced height to support the ridge of the roof. Some of the constructions were open colonnade types with heavy roofs without any jointing and inadequate bearing. A heavy structure on comparatively slender and un-buttressed columns has resulted in the collapse of the structure fully or partly (Figure 1). The damage patterns seen in the various heritage buildings of Gujarat were exactly the opposite. There were numerous examples of buildings (Figure 2), which were heavily damaged at the roof and upper levels, but suffered very much less severely on the ground floor (Langenbac, 2001). Four possible reasons for the higher damage at the top of masonry buildings are as follows.

6.1 Weathering

This applies particularly to brick-mortar construction, where the joints tend to be exposed to wind and rain at the top and so it deteriorates more. This weakens their seismic resistance.

6.2 More open structures

Both for reasons of aesthetics and because of the reduced gravity loads, masonry buildings often become much more open toward the top than is the case for modern buildings. This weakens their lateral resistance and may make them more prone to damage.

Figure 1. The extensively damaged old palace of Dabargadh

Figure 2. Eastern corner turret of Ranjit Vilas, Wankaner

6.3 Consequences of increased accelerations with height

The swaying in an earthquake causes accelerations to increase towards the top. This especially affects decorative elements, such as parapets and external ornamentation, which were observed to be heavily damaged (Figure 3). However, it also affects main load-carrying walls, because the 'out of plane' seismic forces (ie the earthquake pushing the wall out at right angles to itself, which is its weak direction) depend directly on the acceleration at that level. By contrast, the 'in plane' seismic forces (acting along the length of the wall in its strong direction) increase towards the bottom of the building, because they are accumulated from the floors above.

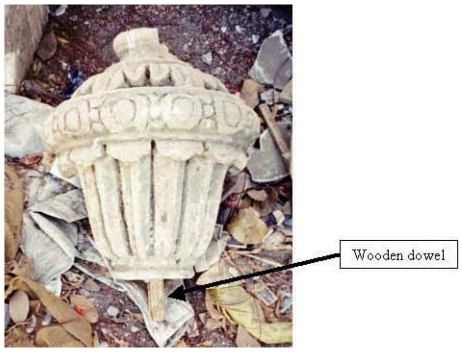


Figure 3. Ornamentation fell from roof level of Amah Vilas, Jamnagar

6.4 Shear strength of dressed stone masonry depends primarily on friction

The horizontal strength of dressed, good quality stone depends mainly on the vertical load from above, tending to clamp the stone blocks together. This vertical clamping force is less at the top of the building because there is less of the building weighing down from above. Therefore, the seismic resistance is also less towards the top of the building. An example of the strong beam and weak column mechanism can be seen in Tomb of Sayed Usman at Usmanpura, Ahmadabad, and also in chatries at Bhuj (Figure 4 & 5). For retrofitting of Heritage buildings there were examples of the use of reinforced concrete elements added to historic buildings at Jamnagar, Dhranghedra, and Halvad, which undoubtedly reduced the local damage suffered in the earthquake (Figure 6), although the longer-term consequences of this type of intervention may be more questionable. It is essential that the use of modern materials and technology is integrated with traditional techniques in a harmonious and compatible manner to inject new life into the building (Figure 7).

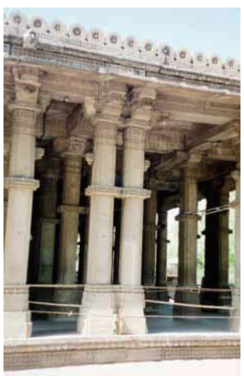



Figure 4. Overview and details of cracks at the tomb of Syed Usman at Usmanpura, Ahmedabad


Figure 5. Chatris, before and after an earthquake at Bhuj, Gujrat

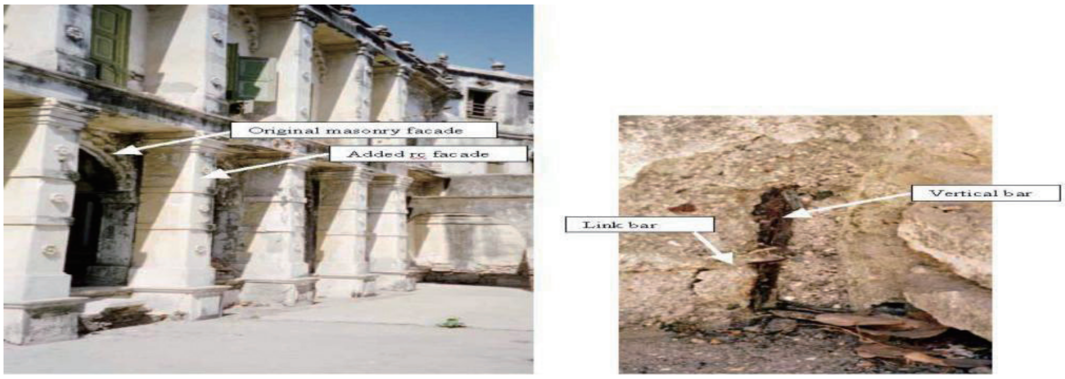


Figure 6. Reinforced concrete strengthening facade and detail of corroded reinforcement

Figure 7. Stainless steel ropes introduced into the courses of cylindrical masonry structures to secure them against lateral failure in Bashir's Minars, Ahmadabad

7. Techniques for seismic retrofitting

Techniques of retrofitting to be adopted are divided into five broad categories depending on the type and condition of structure:

Seismic Strengthening Approaches
Maintenance/Preparedness
Basic/Traditional Measures
Rehabilitation
Specialized Technologies

7.1 Seismic strengthening approaches

Seismic strength within buildings is achieved through the reinforcement of structural elements. Such reinforcement can include anchored ties, reinforced mortar joints, braced frames, bond beams, moment-resisting frames, shear walls, and horizontal diaphragms (Figure 8). Most historic buildings can use these standards, traditional methods of strengthening successfully if properly designed to conform to the historic character of the building. Also, there are new technologies and better designs for traditional connection devices as well as a greater acceptance of alternative approaches to meeting seismic requirements. While some technologies may still be new for retrofit, the key preservation principles explained above should be applied, to ensure that they would not damage historic buildings.

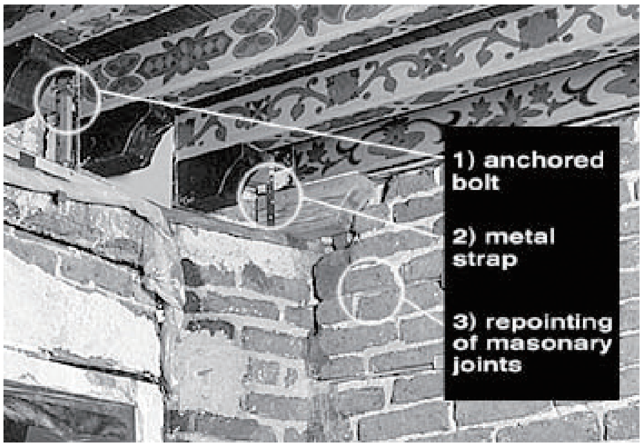


Figure 8. Limited intervention should correct obvious structural deficiencies, such as tying vulnerable elements together and repointing masonry. Upon replastering and painting, these reinforcements will not be visible

7.2 Building maintenance or preparedness

Adequate maintenance ensures that existing historic materials remain in good condition and are not weakened by rot, rust, decay, or other moisture problems. Without exception, historic buildings should be well maintained and an evacuation plan developed. The expectation that an earthquake will occur sometime in the future should prepare the owner to have emergency information and supplies on hand.

The roofs, gutters, and foundations for moisture problems, and corrosion of metal ties for parapets and chimneys should be checked. Repairs should be periodically done and the metalwork should be painted and kept in good condition.

Inspection should be done to keep termite and wood-boring insects away from wooden structural members. Check exit steps and porches to ensure that they are tightly connected and will not collapse during an emergency exit.

The deteriorating mortar of the masonry should be checked, and never defer repairs. repoint, matching the historic mortar in composition and detailing.

Contact utility companies for information on flexible connectors for gas and water lines and earthquake-activated gas shut-off valves. Strap oil tanks down and anchor water heaters to wall framing.

Collect local emergency material for reference and implement simple household or office mitigation measures, such as installing latches to keep cabinets from flying open or braces to attach tall bookcases to walls. Keep drinking water, tarpaulins, and other emergency supplies on hand.

7.3 Basic or traditional measures

Bolt sill plates to foundations and add plywood stiffeners to cripple wall framing around wood frame buildings. Keep reinforcement behind decorative crawlspace lattice or other historic features.

Reinforce floor and roof framing connections to walls using joist hangers, metal straps, threaded bolts, or other means of mechanical fasteners. Tie columns to beams; reinforce porch and stair connections as well.

Repair weakened wooden structural systems by adding, pairing, or bracing existing members. Consider adding non-ferrous metal straps in alternating mortar joints if extensive repointing is done in masonry walls.

Reinforce projecting parapets and tie parapets, chimneys, balconies, and unsecured decorative elements to structural framing. Make the connections as unobtrusive as possible. In some cases, concrete bond beams can be added to reinforce the top of unreinforced masonry or adobe walls.

Properly install and anchor new diaphragms, such as roof sheathing or subflooring, to the walls of a structure before installing finish materials.

Avoid awkwardly placed exposed metal plates when using threaded bolts through masonry walls. When exposed plates will interfere with the decorative elements of the facade, use less visible grouted bolts or plates that can be set underneath exposed finished materials. Use sensitively designed metal bracing along building exteriors to tie the unsupported face of long exterior walls to the floor framing. This is often seen alongside or party walls in commercial or industrial buildings.

7.4 Rehabilitation

When buildings are being rehabilitated, it is generally the most cost-effective time to make major upgrades that affect the structural performance of the building. New elements, such as concrete shear walls or fiber reinforcing systems can be added while the structure is exposed for other rehabilitation or code compliance work.

Inspect and improve all lateral tie connections and diaphragms.

Reinforce walls and large openings to improve shear strength in locations of doors, windows, and storefront openings. Carefully locate "X" and "K" bracing to avoid visual intrusion, or use moment frames, which are a hidden perimeter bracing in large openings from a preservation perspective, the use of a more hidden system in finished spaces is generally preferable (Figure 9).

Figure 9. An interior diagonal frame that will dampen and transfer seismic loads in a designed path from foundation to roof

Strengthen masonry walls or columns with new concrete reinforcement or fiber wrap systems. Avoid the use of heavy spray concrete or projecting reinforced walls that seriously alter the historic relationship of the wall to windows, trim, and other architectural moldings or details.

Selectively locate new shear walls constructed to assist the continuous transfer of loads from the foundation to the roof. If these walls cannot be set behind historic finishes, they should be located in secondary spaces in conjunction with other types of reinforcement of the primary spaces or features.

Consider the internal grouting of rubble masonry walls using an injected grout mixture that is compatible in composition with existing mortar. Ensure that exposed areas are repaired and that the mortar matches all visual qualities of the historic mortar joints in tooling, width, color, and texture.

Evaluate odd-shaped buildings and consider the reinforcement of corners and connections instead of infilling openings with new construction. Altering the basic configuration and appearance of primary facades of buildings is damaging to those qualities that make the building architecturally significant.

Restore failed arches immediately and take precautionary measures to safeguard the same. At the springing level, insert a tie rod at the two ends of the wall. Place the tie rod in the holes along the span of the arch and grout the holes with cement concrete.

The collapse of Chatries is the result of, uneven settlement and failure of foundation due to earthquake, the slenderness of columns and beams, twisting of floors, and stiffness irregularity. For strengthening of foundation, it is essentials to carry out the operation of underpinning. Adequate drainage must be provided to drain off water from the foundation. The addition of chemicals to stabilize the soil around the foundation for strength and stability can be done.

A major reason for the collapse of Chatries is the strong beam and weak column mechanism. The column can be protected from failure by jacketing.

7.5 Specialized technologies

New technologies, being developed all the time, may have applicability to historic preservation projects. These specialized technologies include vertical and center core drilling systems for unreinforced masonry buildings, base isolation at the foundations, superstructure damping systems, bonded resin coatings and reproducing lost elements in lighter materials (Figure 10).

Figure 10. The new base isolator allows the structural support member at the foundation to move horizontally as it absorbs the earthquake forces

However, many new technologies may also be non-reversible treatments resulting in difficulties of repair after an earthquake. The reinforcement of historic materials with special resins or the use of core drilling to provide a reinforced vertical connection from foundation to roof may not be as repairable after an earthquake as would more traditional means of wall reinforcement. New technologies should be carefully evaluated by the design team for both their benefits as well as their shortcomings.

Using computer modeling of how historic buildings may act in an earthquake suggests options for a seismic upgrade using a combination of traditional methods and new technologies. Each building will need its survey and evaluation to determine the most appropriate seismic reinforcement. While most projects involving base isolation and other complex damping systems constitute only a small percentage of the projects nationwide that are seismically reinforced, they may be appropriate for buildings with significant interior spaces that should not be disturbed or removed during the retrofit

Italian SME FIP Industrial SpA is developing a revolutionary technique for improving the stability of historic monuments in earthquake zones, using 'shape memory' alloys originally employed in the aerospace industry. The ISTECH project (1) has developed a technique, which retains the natural flexibility of walls and columns, while greatly extending their resilience.

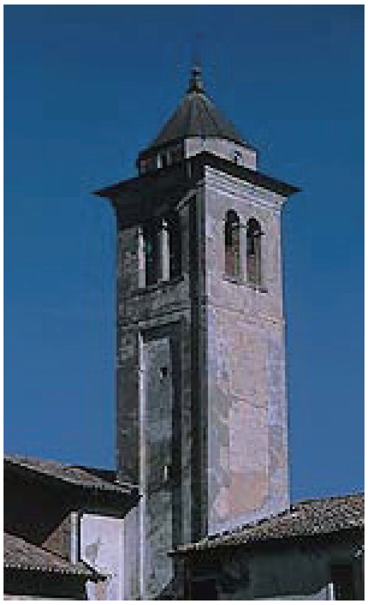


Figure 11. The earthquake-damaged bell-tower of San Giorgio in Trigano, northern Italy, is being restored using a hidden shape-memory alloy device

The technique developed by the ISTECH partners uses wires of the super-elastic alloy to increase the vertical compressive forces which hold a building together. In a quake, the pre-stressed masonry can still shift, dissipating energy, but will not collapse. The devices have been successfully tested using scale models and full-size masonry walls, and are currently being installed in the earthquake-damaged 14th century bell-tower of San Giorgio in Trignano (Figure 11), Northern Italy (Thakkar and Dubey, 2003).

8. Discussion and conclusion

There are varying levels of intervention for seismically retrofitting historic buildings based on the owner's program, the recommendations of the team, applicable codes, and the availability of funds. Recent earthquakes have shown that historic buildings retrofitted to withstand earthquakes survive better than those that have not been upgraded. Even simple efforts, such as bracing parapets, tying buildings to foundations, and anchoring brick walls at the highest, or roof level, have been extremely effective. It has also been proven that well-maintained buildings have fared better than those in poor condition during and after an earthquake. Thus, maintenance and seismic retrofit are two critical components for the protection of historic buildings in areas of seismic activity.

Damage to historic buildings after an earthquake can be as great as the initial damage from the earthquake itself. The ability to act quickly to shore up and stabilize a building and to begin its sensitive rehabilitation is imperative. Communities without earthquake hazard reduction plans in place put their historic buildings--as well as the safety and economic well-being of their residents -- at risk. Having the right team in place is important. Seismic strengthening of existing historic buildings and knowledge of community planning for earthquake response makes the professional opinions of the team members that much more important when obtaining permits to do the work. Local code enforcement officials can only implement the provisions of the model or historic preservation codes if the data and calculations work to ensure public safety. Buildings do not need to be over-retrofitted. A cost-effective balance between protecting the public and the building recognizes that planned for repairable damage can be addressed after an earthquake. Engineers and architects, who specialize in historic buildings and who have a working knowledge of alternative options and expected performance for historic structures, are critical to the process.

Historic and older buildings can be seismically upgraded cost-effectively while retaining or restoring important historic character-defining qualities. Seismic upgrading measures exist that preserve the historic character and materials of buildings. However, it takes a multi-disciplined team to plan and execute sensitive seismic retrofit. It also takes commitment on the part of the city, state, and central leaders to ensure that historic districts are protected from needless demolition after an earthquake so that historic buildings and their communities are preserved for the future.

References

[1] Agarwal, P. and Shrikhande (2011). Earthquake Resistant Design of Structures, PHI Publishers, India

[2] Arnold, C., Eisner R. K. & Elsesser E. (1992). Buildings at Risk: Seismic Design Basics for Practicing Architects. AIA/ACSA Council on Architectural Research, Washington, DC.

[3] Cox, R. S. (2001). Controlling Disaster: Earthquake-Hazard Reduction for Historic Buildings, National Trust for Historic Preservation Washington, DC.

[4] David W. Look, AIA, Terry Wong, PE, & Sylvia Rose Augustus (1998). The Seismic Retrofit of Historic Buildings. Oxford University Press, New York, Oxford.

[5] ICOMOS, (2011). The Athens Charter for the Restoration of Historic Monuments – 1931, https://www.icomos.org/en/167-the-athens-charter-for-the-restoration-of-historic-monuments

[6] Langenbac R. (2001). Unesco Mission to Gujarat, India, for the Conservation of earthquake-damaged Cultural Properties, Heritage And Conservation Division New York. retrieved from https://www.conservationtech.com/india-UNESCO/UNESCO-report.htm on 2 February 2021.

[7] Thakkar, S. K. and Dubey, R. N (7th – 18th July 2003). Short Term Course on Earthquake Resistant Design and Retrofitting of Reinforced Concrete Buildings, I.I.T. Roorkee, Roorkee.