Research on the Upgrade of Traditional Seismic Retrofits for Ancient Buddhist Temples in the Region of Spiti and Kinnaur in the Western Himalayas

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Abstract: *The ancient Buddhist temples in the western Himalayas have evolved spontaneously in response to the region's extreme climatic conditions and limited material resources at hand. These structures have been improved through a constant process of trial and error over the years by the local craftsmen/builders to withstand the seismic vibrations and other natural calamities. Unfortunately, these earthen buildings lie in one of the most vulnerable seismic zones, Zone IV (Bureau of Indian Standards 1993), and have experienced some damage in the past. Buildings in the region today are susceptible to damage from the annual precipitation of 7.8–15.6 in. (200–400 mm). One of the main areas of research on the conservation of these historic earthen buildings, conducted as part of a scholarship from the Museum of Archaeology and Anthropology, University of Cambridge, UK, was to design and develop reinforcements for the structural components of the earthen buildings to mitigate the effects of seismic vibration. The research involved detailed documentation and analysis of existing seismic retrofits installed in the buildings, followed by a detailed assessment of the structural risk, through (1) precise documentation of the structural members and their deflection after earthquakes, (2) understanding of the stress on the walls through study models of the historic roofs, and (3) strength analysis of the existing historic adobe bricks. The study also addresses the climatic change the region is experiencing along with an expected increase in moisture levels, which has led to a considerable decrease in the ability of adobe structures to resist any tectonic movements.*

Conservation of this living heritage raises two important conflicting issues. On the one hand, the preservation of the ancient architecture and its features in their original form is of utmost importance as a document of history. On the other hand, this living heritage poses a serious threat to the safety of the inhabitants during an earthquake. Retrofitting could alter and interfere with the historic fabric and poses a serious threat to the resources' authenticity. The practical design and development of seismic retrofits for such ancient existing earthen buildings in the region should consider the potential hazards to life, the present condition of the structures, and materials and their behavior before another earthquake. This paper puts forward the results of the study and describes the condition of historic earthen structures in the region after the earthquake of 1975. It describes the traditional seismic retrofits existing in the structures and explains possible techniques and materials for the development of new seismic retrofits to strengthen the structures and material components before another earthquake.

Introduction

The Spiti and Kinnaur region in the northern Indian state of Himachal Pradesh has some remarkable ancient adobe Buddhist temples. Constructed between the tenth and fifteenth centuries, these temples preserve some of the earliest artistic heritage of Tibetan Buddhism in the form of mural paintings, polychrome clay sculptures, and decorative wooden ceiling members (Luczanits 2004). Over a period of five hundred years, this arid region in the western Himalayas has witnessed the gradual development of Buddhist temple architecture, from simple, single-story buildings constructed on relatively flat land to a complex maze of multi-story fortresses on the mountaintop. Standing on a highly seismic zone and having survived for several centuries, the buildings are undoubtedly living evidence of highly engineered structures.

Study of the materials and the structural configuration of these historic earthen buildings provides information about the evolution and function of each structural module, as well as the traditional seismic retrofit methods that developed gradually and were installed to counter the movements of various components during an earthquake (Sikka 2002b). Constant intervention and experimentation by local craftsmen after each past earthquake furthered understanding of the general behavior of the earthen structures in the region, their inherent construction defects, the effectiveness of locally designed and engineered traditional seismic retrofits, and possible methods and materials for the further reinforcement of these ancient structures.

FIGURE 1 The tapered load-bearing adobe walls at a temple in Spiti provide extra stability to the building during seismic vibration.

Buddhist Temple Architecture: Materials and Method of Construction

Buddhist temple design is characterized by rectangular spaces with carefully designed structural members, the result of years of trial and error under extreme climatic conditions and natural disasters. The walls of these historic structures are made of adobe—large, sun-dried mud brick laid in mud mortar. The foundations of rubble-stone masonry generally rest on stable solid ground.[1] The thickness of the walls varies from 2.5 ft. (0.76 m) to about 5 ft. (1.52 m) in some of the early-period structures. A survey of some twenty-five ancient earthen structures in the region reveals that the ratio of the height (h) of the single story to the thickness of the adobe walls (t) lies within the recommended safe limits of $t > h/8$ of the modern Indian seismic code for earthen structures (Bureau of Indian Standards 1993). Vertical measurements show that sometimes the outer faces of the walls are slanted, so that the wall thickness is wider at the base and gradually tapers to the top, providing extra stability to these tall and flexible structures (fig. 1).

Because of the cold climatic conditions most of the year, the openings in the walls of the temples are kept to a minimum. They contribute to less than 5% of the total wall surface of the rectangular space and are generally located at the center of the wall. The only source of light and ventilation is generally a low and narrow entrance doorway. In addition to the wooden doorframes, punctures in the walls are reinforced with thick vertical and horizontal wooden members connected to one another by flexible joints. There is a series of wooden lintels laid next to one another along the thickness of the walls; they are anchored deep and extend into the masonry on both sides of the openings like additional horizontal tie members.

The roofs of the temples are flat; because of the lack of rainfall in the region, a flat roof with little provision for drain-off is a practical design. Roofs are made of mud laid in various layers and compacted. About 7 in. (0.17 m) of compacted mud rest on 2 in. thick (0.05 m) rectangular wooden panels or a mesh of willow twigs, with a layer of local shrubs or birch bark sandwiched between the two for waterproofing. These are in turn supported by wooden rafters and beams, which are supported directly on load-bearing mud walls and wooden columns.

This historically well-engineered building typology is today susceptible to innumerable natural threats and human interventions. Fluctuation in the climate in the past few years and frequently occurring earthquakes, the two major natural agents of decay, have put these water-soluble and brittle structures under serious threat.

The Western Himalayan Region and Its Tectonic Evolution

The tribal area of the western Himalayan region, which covers most of the area of the Spiti and Kinnaur districts of the state of Himachal Pradesh, stands on the relatively young and highly unstable Himalayan Mountains. Following the collision of the Indian subcontinent with the Eurasia plate about forty-five to fifty million years ago, the uplift caused by the collision resulted in the development of the Himalayan mountain range at the intersection of two tectonic plates (Bagati and Thakur 1993). Further studies on the geology of the western Himalayan region of Lahaul Spiti and Kinnaur in India propose that the tectonic plate of the Indian subcontinent is still moving slowly toward southern Tibet (Bilham et al. 1998; Bilham, Gaur, and Molnar 2001). This results in an increase in the height of the young Himalayan Mountains every year. It is thus understood that the area is geologically active and structurally unstable. This is the reason the region experiences the inevitable and frequent earthquakes and landslides.

Earthquakes in Spiti and Kinnaur

Areas of the Spiti and Kinnaur districts have experienced some significantly strong earthquakes in the last few decades. They lie in the highly seismic Zone IV, identified by the Indian Standard IS 1893:1984 (Bureau of Indian Standards 1993).[2] A major earthquake (Richter magnitude 6.0) struck the region of Lahaul Spiti on the morning of June 17, 1955, causing enormous damage to the villages in the Spiti Valley (www.himvikas.org/jan2004/seis.htm). The most powerful earthquake that struck the region was on the afternoon of January 19, 1975; it killed sixty people in the most sparsely populated region of India. This earthquake registered 6.2 on the Richter scale, with an aftershock of magnitude 5.8. It caused serious damage to several villages in the Lahaul Spiti and Kinnaur districts and even caused some structural damage to the buildings in Ladakh, which is adjacent to the district bordering Himachal Pradesh. Besides such major earthquakes, the region experiences periodic minor tremors. The earthquakes in the past have been fatal for the people of the region and have caused acute damage to the landscape and the cultural heritage. Improving understanding of the earthquake resistance provided by both traditional and modern retrofits, as well as the economic costs of incorporating them in future conservation work, can reduce the seismic risk to people and buildings.

History of Seismic Retrofits in the Region

Historically, earthen buildings in Spiti and Kinnaur were reinforced with additional structural supports to guard against damage from frequently occurring earthquakes. The load-bearing walls of the temples are reinforced with a wooden framework of horizontal wall ties (fig. 2), with a cross section of 6–8 in. by 4–5 in. (approx. 0.15–0.20 m and 0.10–0.12 m), forming a series of ring beams around the building. These are installed externally and flush with the surface of the wall. The ring beams tie the entire structure together, with each beam running at a distance of approximately 3 ft. 3 in. to 6 ft. 6 in. (1.50 to 2.00 m) from the other. These horizontal wall ties are then joined to each other at the corners with wooden vertical ties.[3] This arrangement prevents any outward

FIGURE 2 The external surface of the temple at Nako village in upper Kinnaur (AD 1025) is fitted with horizontal wooden wall ties and supporting rubble stone buttresses at the corners.

movement during seismic vibration, and these wall ties, along with the wooden lintels, disrupt structural cracks that could otherwise extend the full height of the wall, eventually causing total collapse. The strength of the adobe and the mortar joints varies all along the wall; the result is differential loading. The horizontal ties therefore redistribute the load evenly throughout the wall.

In some buildings, in addition to these horizontal members, the load-bearing walls are reinforced at the corners with symmetrically placed buttresses to avoid shear or separation of load-bearing walls at the corners. These buttresses are either made of adobe blocks or rubble stones stacked one over the other against the corners of the building, forming a pyramid (fig. 2). The buttress rests on a solid stone masonry foundation placed or built at the corners as additional support. As buttresses are not integrated into the masonry walls, it is possible they were added later to support the masonry at the corners. There are no vertical tie members.

Aftermath of the Earthquakes

Most of the villages and the vernacular buildings in the region of Spiti and Kinnaur were badly damaged during the last earthquake in 1975, as were the historic Buddhist temples in the region. Structural documentation of the internal and external surfaces of some of the historic structures, conducted by manual measurement of the profiles of the walls in a grid of 1 ft. 7 in. × 1 ft. 7. in. (0.50 x 0.50 m), revealed that there is tremendous outward movement and deformation in the upper portion of the load-bearing walls (Sikka 2002b). The displacement of masonry is not uniform, and neither is the curvature and bulging in the walls. Vertically induced oscillations during the earthquake caused a sudden increase in the roof load, which, when applied against the compressive strength of the adobe walls, resulted in an out-of-plane movement. The upper courses of the adobe wall along the intersection with the roof moved outward as a response to the additional load.

As mentioned above, earthquakes are not the only threat to the historic adobe structures. The historic Buddhist structures, which were originally designed for an arid climate, are now facing problems caused by the increased precipitation and regular rainfall of the last few years. The rain has washed away the clay from the compacted mud on the flat roofs, causing large-scale seepage into the interiors. As an immediate response, the local residents applied additional layers of mud and clay in an attempt to waterproof the roofs. Applications of extra layers of mud have considerably increased the load on the existing structures (Sikka 2002a). This led to further lateral outward horizontal movement in the load-bearing walls, resulting in the separation of joints at the corners of the building which caused vertical cracks in the masonry. Consequently, the lateral movement of masonry resulted in the loss of structural integrity, which further resulted in uneven distribution of concentrated loads on the structural members resting on the load-bearing walls. The structures normally react to additional loads through sagging of the wooden beams and rafters supporting the roof (fig. 3). This makes the structure more vulnerable to future seismic vibrations.

The earthen buildings in the region, although designed very carefully to resist seismic vibrations, have certain inherent construction defects. Ceilings, with their structural wooden beams and rafters, rest directly on the load-bearing mud walls without any wall plates. Point loads exerted by the structural members resting on the walls in the absence of wall plates have created enormous stress on adobe walls, especially during the vertical oscillation of an earthquake. This has resulted in major and minor structural cracks below the ceiling level where the brackets support the wooden beams and rafters on the walls. These points have now become inlet points for the ingress of water into the interiors; they are now a regular feature in many temples in the region of Spiti and Upper Kinnaur.

Not only has water entering the structures caused enormous damage to the murals inside the Buddhist temples, it has also washed away mud from underneath the brackets supporting the beams. Consequently, the brackets have shifted from their original position and have caused further movement in the wooden structural members, leading to loss of structural integrity. The horizontal and vertical wall ties in most of the historic structures are either missing or are discontinuous; therefore, the ties may fail to provide any kind of protection to the structure during an earthquake.

The temples that were built like multi-story forts were affected the most. Earthquake vibrations induced in the integrated structural system of multi-story temples, such as the Dhangker Temple in the Spiti Valley, resulted in serious detachment of the entire building

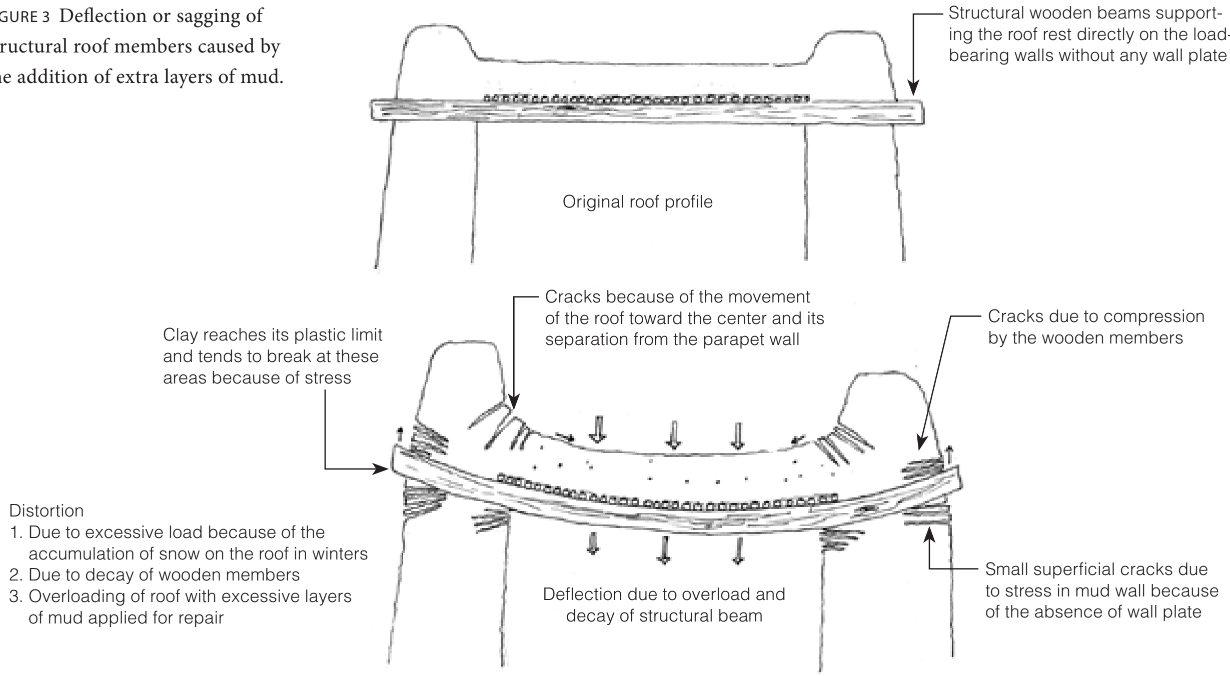

FIGURE 3 Deflection or sagging of structural roof members caused by the addition of extra layers of mud.

from the point of anchorage into the adjacent hill, causing major vertical structural cracks (fig. 4).[4] The process has left the building extremely vulnerable and defenseless to withstand any further seismic vibration.

Last but not least are the environmental humidity and the induced humidity into the structure caused by ingress of water through cracks left by previous earthquakes. This causes expansion and shrinkage of finer particles, which in turn causes fine cracks in the masonry and plaster. Water gets into these cracks and causes further deterioration every season. Not only has rainwater washed out the mortar from the masonry, it has also reduced the compressive strength of the historic adobe blocks by washing away the finer particles. High-velocity winds in the western Himalayan region have abraded the external surface, displacing finer particles from the external render and causing voids in the plaster (Warren 1999, 88). The impact of rain, particularly in the presence of high-velocity winds, has been fatal to these water-dispersible earthen structures. In addition, air movement extracts water from the structures by evaporation that has not only changed the surface volume but has also made the surface brittle. Excessive moisture swells the binder (clay), and sudden evaporation leaves voids between the platelets of the clay. Loss of moisture due to excessive evaporation leaves very little adhesion between the binder and the aggregates; hence the walls are vulnerable to erosion (Warren 1999, 95).

FIGURE 4 Vertical structural crack between buildings and the adjacent hill. This significant detachment was caused by the earthquake.

The wooden structural members (rafters, beams, and wooden ceiling panels) are also affected by the induced humidity and water ingress. The damaged wooden structural members removed during the process of investigation and conservation revealed that high moisture content had rendered the wood susceptible to insect attack. The roofing members—ceiling panels and wooden rafters and beams—were partially or completely eaten, so that structural elements are rendered hollow. The lack of ventilation inside the temples has caused dry and wet rot in the wooden members, diminishing their structural strength and increasing their vulnerability to insect attack.

First Response to Earthquake Disaster

Immediately after the earthquake of 1975, local residents responded to the building movements and structural cracks by instituting remedial measures. The corners of the buildings, which had separated because of the outward movement of the walls, were either filled and stitched with rubble stone masonry, or they were supported externally with piled stone (fig. 5). The piles of stones acted as buttresses to halt further outward movement of the load-bearing walls. The rubble stone buttresses at the temples in the upper Kinnaur village of Nako are not coherent, and since they were added later, they are not interwoven with the load-bearing walls. During an earthquake, the rubble stone buttresses vibrate independently of the main structure because of the lack of cohesive bonding between the buttresses and the walls. This might eventually cause damage to the outer surface of the adobe wall. Furthermore, the buttresses at the Nako Temple trap moisture inside the gap between the walls and the rubble stone buttresses. The moisture eventually seeps into the walls, causing several other problems of masonry deterioration. Similar adobe or dressed stone buttresses were added to the historic earthen structures at Tabo in Spiti.[5]

FIGURE 5 Piles of rubble stones stacked against the corners of the buildings after an earthquake in Nako village, to serve as buttresses to halt further outward movement of the masonry walls.

After the earthquake, the sagging structural beams inside the temples were immediately supported with additional props. In some villages, entire roofs were demolished, and new wooden beams were laid that again rested directly on the wall, without wall plates. Instead of repairs with adobe block, the damaged masonry at the intersection of the roof and the walls has been repaired with rubble stone masonry and mud mortar. Stone blocks, although more resistant to moisture, are unable to provide a compatible bond with the historic material. At the same time, the excessive weight of the stone masonry laid over the low-compressive-strength adobe blocks to support sections of the heavy roof has resulted in large-scale detachment and bulging of the masonry walls. Repairs conducted after the earthquake could not do much to heal the heritage buildings, as their structure is now far more vulnerable to another earthquake than previously.

Response to the structural disintegration has to be planned and should be carefully designed, especially when the buildings are being used every day. The historic Buddhist temples have weathered over a period of nine hundred years and have lost some of their original strength. To develop retrofits for such buildings to increase their ability to resist future seismic waves, it is essential to evaluate the current condition of each structural component to be supported and strengthened.

Research Results for the Upgrade of Adobe Structures Against Earthquakes

The research results discussed in this section address each building component and possible new installations that contend with the inherent defects responsible, both directly and indirectly, for the overall stability of the buildings and their behavior during a seismic vibration. Each component that could be used for conservation or repair work has been upgraded and tested separately in the field with similar material and environmental conditions.

Study Models for Designing Roof Load

The static load of the roof increases several times due to earthquake acceleration forces. These loads should be kept to the minimum possible and should be distributed evenly over the load-bearing walls. It was therefore decided to calculate the current actual roof load to further assess the total strain on the load-bearing walls.

To ascertain the roof load exerted on the adobe blocks, a model of the historic roof was constructed using materials obtained locally and following traditional construction methods. The model was assembled inside a cardboard box 1 ft. 3 in. × 11 in. × 11 in. (0.39 × 0.29 × 0.26 m) and weighed with a spring balance. The roof assembly was composed of a layer of willow twigs about 2 in. (0.05 m) in diameter laid at the bottom, with a layer of local shrubs laid in a perpendicular direction on the top to form a denser mesh. These layers of shrubs were then covered with a layer of wet mud approximately 1.5 in. thick (0.04 m), followed by a 6 in. (0.15 m) layer of dry compacted mud. The final layer was covered with a thin layer (1 in., 0.03 m) of local clay. The layer of clay was then covered with a 1.5 in. (0.04 m) mud slurry. The total height of the mud roof model was 10.25 in. (0.26 m), which is approximately equal to the height of the historic as well as the vernacular roofs existing in the region.

The roof was weighed after it was completely dry and was found to be 56.3 lb./ft.^{2} (25.6 kg/ft^2 or 273.9 kg/m^2). The weight of the rafters and beams supporting the mud must be added to calculate the cumulative weight. The well-seasoned wooden rafters of local cedar were weighed and measured. The weight of a cylindrical rafter of an average diameter of 4.3–5.9 in. (0.11–0.15 m) and length of 20.7–22.0 ft. (6.3–6.7 m) is 57.2–77.0 lb. (26–35 kg). It is therefore estimated that the average roof load in this region lies between 61.4 and 71.7 lb./ft.^{2} (300–350 kg/m^2). The roof load thus calculated was studied against the compressive strength of the existing mud blocks to assess whether the structure could take the load of the roof (Sikka 2002b). The dry compressive strength of three samples of the historic adobe blocks taken from the Chango Temple, tested at the laboratory in New Delhi, were found to be between 85.3 and 120.8 psi, or 12,283 and 17,395 lb./ ft.^{2} (6.0–8.5 kg/cm^2, or 60,000–85,000 kg/m^2).

Although the historic adobe blocks are able to withstand far more than the load of the historic roof, it is still crucial to make the roof lighter to prevent sagging of structural wood, as well as to promote resistance to earthquakes. Although reducing the thickness of the compacted mud roof may reduce the weight of the roof, it may not be able to withstand the increased precipitation in the region during the last few years. A 1.5 in. (0.04 m) layer of stabilized soil (1:3 parts lime:local sieved [0.7 in., or 0.018 m] soil) was applied to 4 in. (0.1 m) of compacted mud roof, and the model of the roof was weighed (Sikka 2003). The load of the roof thus configured weighed about 20.5–30.7 lb./ft.^{2} (100–150 kg/m^2).

Design of Wall Plates

Interventions made to the building should be minimal in order to preserve as much of the original fabric as possible. Because of the intrusion of moisture, the brackets supporting the beams and the rafters have been lowered from the original position, a change that affects not only the structural integration but also the surrounding wall paintings. To retain the original well-crafted and painted wooden brackets as well as the painted murals around them, the wall plates have to be designed and placed on the walls appropriately. The wall plates can be inserted along the level of the brackets (fig. 6) but slightly higher, so that the load from the beam or the rafter is not directly transferred onto the bracket supporting the structural members (Khosla 2004). The wooden frame with 6 × 3 in. (0.15 × 0.08 m) rectangular sections can be inserted in the wall after the careful removal of top courses of adobe up to the bracket level. As all the brackets are at different levels, it is essential to support the structural member up to the lowest level. This omits the point load and evenly distributes the load generated by the wooden beams (structural members) onto the mud wall. Some of the historic earth structures in the region are fitted with antiseismic retrofits in the form of horizontal continuous wooden ties. Wall plates inserted at the top of the walls, below the ceiling, function as wall-roof connections. These members can then be joined with the rest of the tie beams at the corners of

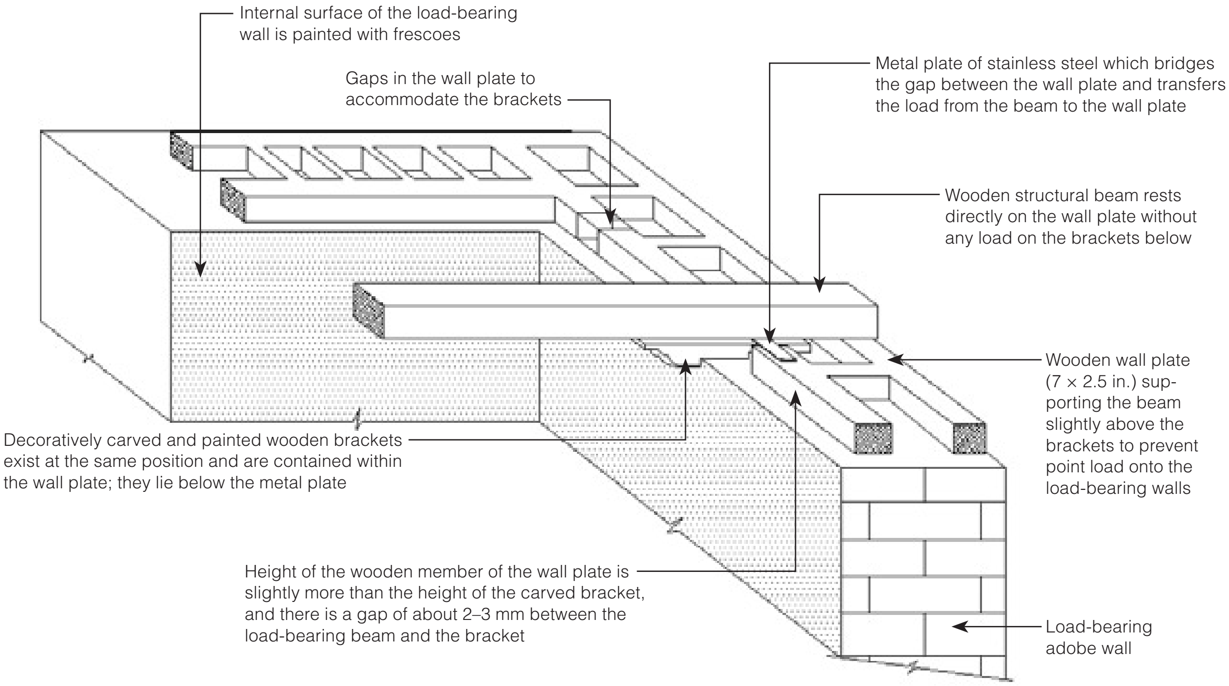

FIGURE 6 Wall plate detail for the historic earthen structures in the Spiti and Kinnaur Valley of the western Himalayan region, giving detail and sizes of the wooden wall plates running all along the length of the load-bearing adobe walls, to evenly distribute the roof load carried by the rafters and beams. Originally drawn by C. Chaudhry; taken from the phase 3 report of the Nako Preservation Project (Khosla 2004), with some modifications.

the building and with the vertical members, to form a frame for the entire building.

Insertion of wall plates in the Buddhist temples in the region could well be an interdisciplinary task, as the mural paintings need to be stabilized and shored before and after the insertion of wall plates. The painted plaster with murals inside these buildings comes almost to the ceiling level. The brackets supporting the wall plates are supporting the beams below the ceiling level. Insertion of wall plates at the bracket level may cause damage to the wall paintings, especially at the point of interface between the brackets, wall paintings, and ceiling. An alternative solution may be to increase the height of the wall and rest the members slightly above the original ceiling level, leaving an unpainted band, thus securing the overall structure and the paintings.

Design of Wall Ties

The walls of the historic earth structures can be strengthened against earthquakes using horizontal wooden wall ties in the form of ring beams inserted at a vertical distance of about 5 ft. (1.5 m) around the entire building. Existing wall ties can be carefully joined together with new members to form a continuous ring. These horizontal ties are then connected at the corners of the building with flexible vertical wooden members tied together with wooden pegs (fig. 7).[6] The lengths of the walls of the Buddhist temples are sometimes enormous and unsupported. Absence of any external intermediate vertical ties reduces their ability to resist horizontal earthquake forces, resulting in out-of-plane flexural cracks. Installation of vertical tie members at standard intervals (on the external face of the wall) depending on the height and the thickness of the walls is crucial.[7] The vertical tie members should be fixed, both at the base and at the roof level, to resist in-plane sliding, rotation, and out-of-plane movement, depending on the direction of the oscillations. These ties are installed inside the adobe walls under exterior and interior plasters. They run horizontally all around the perimeter of the building. The horizontal wall ties are laid after every 6.67 ft. (2.00 m) of mud brick wall courses and

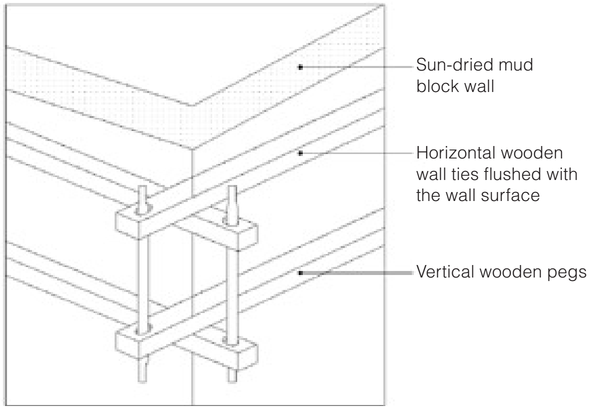

FIGURE 7 Seismic retrofit with horizontal and vertical wall ties, which are fixed like a protective framework, along the external facade of the earthen structures.

are anchored into the masonry with vertical pegs. The horizontal ties are connected to the orthogonal or vertical ties at the corners (see figs. 2 and 7 for connection of vertical with horizontal, as has been done for decades).

Natural Fiber Jackets

Deformations and bulges in adobe structures in the western Himalayan region, the result of prior resistance to seismic vibrations, are the vulnerable areas most likely to collapse in the event of future horizontal force. Close observation of the Buddhist temples in the region of Spiti and Kinnaur revealed flexural cracks and strains developed from compression that are visible both in the mud blocks and in the mortar, mostly near the ceiling level. Unreinforced adobe walls are brittle, with low tensile and flexural strengths, and therefore cannot withstand horizontal forces.

There is an urgent need to reinforce damaged and unreinforced masonry with protective composite laminates or jackets, in order to impart additional tensile and mechanical strength in an effort to avoid the loss of valuable polychrome artwork and wall paintings. Recent work shows that the jacketing of masonry applied on the external surfaces improves the masonry's ability to resist high-energy impact and increases the ability of the structure to further deform, delaying out-of-plane spalling (El-Dakhakhni et al. 2006). Recent publications and examples from research on reinforced concrete structures (RCC) also explain the effectiveness of external composite jackets in providing lateral reinforcement against earthquake forces (Kazemi and Morshed 2005; Perera 2006). Some work has been published on the use of steel and wire-mesh jackets on adobe walls, which have shown good results during an earthquake (Blondet, Garcia, and Brezev 2003).

The properties and efficiency of jute as a material have been explored recently. Published results regarding jute's use in reinforcing cement concrete and natural soil drains show that these natural, organic, polymer fibers have high tensile strength, as well as good thermal and mechanical resistance (Aziz, Paramasivam, and Lee 1981; Mansur and Aziz 1982; Lee et al. 1994). Its interface with other materials as composites increases its mechanical strength and resistance to environmental aging (Gassan 2002; Doan, Gao, and Mäder 2006; de Albuquerque et al. 2000). Jute and coir have been used in traditional building construction. More recently, many industries are using these environmentally friendly natural fibers as a reinforcement material for doors, wall panels, and partitions. Introduction of jute textile as a superficial wrapping, covering the walls underneath the protective external plaster, not only may help in improving adherence of new plaster to historic earthen surfaces in the western Himalayan region, but may also provide increased resistance to earthquakes. Its performance on ancient adobe structures as a seismic retrofit and its ability to provide additional tensile strength against seismic vibrations are yet to be tested. This solution could present some problems if it is used for historically significant decorated surfaces.

Additional Diagonal Bracing and Buttresses

Documentation of the sizes of cracks on the external and internal surfaces of the Buddhist structures revealed that additional diagonal bracing, preferably 1 × 1 ft. (0.30 × 0.30 m) with a cross section of 4 × 2 in. (0.10 × 0.05 m), can be used to support the few upper courses of the load-bearing exterior walls, to increase the structural torsion strength.

The piles of rubble stone masonry used for supporting the load-bearing walls at the corners of several buildings in the region must be reinforced or reconstructed with stabilized adobe blocks on a stable foundation. Careful detailing of masonry joints between the buttresses and the load-bearing walls will not only make a coherent structure but at the same time prevent intrusion of water into the historic masonry during the rainy season. The buttresses have to be plastered eventually with lime-stabilized local soil (1:3 lime:sieved local soil) to keep them dry (Bilham, Gaur, and Molnar 2001).

As weathering agents do not act alone on a building, the action of one may render the materials more susceptible to the subsequent action of another. Efficiency and performance of all the installation and seismic retrofits discussed in this paper depend on many other factors—including wind velocity, snow load, site drainage and bearing capacity of the soil after the recent change in climate, condition of the wall and its present moisture content, changing humidity and temperature in the interiors and outside the building, distance of the building from the epicenter, intensity and direction of seismic waves, and, most important, how the building is used and maintained in the future.

Conclusion

Conservation of this living heritage raises two important conflicting issues. On the one hand, the preservation of the ancient architecture and its features in their original form is of the utmost importance as a document of history. On the other hand, this living heritage poses a serious threat to the safety of the inhabitants during an earthquake. To a certain extent, retrofitting would alter and interfere with the historic fabric and poses a serious threat to its authenticity. The practical design and development of seismic retrofits for such ancient existing earthen buildings in the region should keep in mind the potential hazards to life safety, the present condition of the structure, and its materials and their behavior.

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Notes

1 Test pits dug next to the outer wall to the bottom of the foundation of the buildings revealed that the foundations generally rest on either rocky outcrops or solid ground.

2 The seismic zones in India are divided into five zones, V to I, with respect to the magnitude of the earthquakes on a decreasing scale: Zone I (no risk), Zone II (low risk), Zone III (moderate risk), Zone IV (high risk), and Zone V (very high risk).

3 The vertical ties are present in some, while missing in others.

4 Because of its precarious condition, the temple of Dhangker in Spiti was included on the 2005 World Monuments Fund Watch List of the hundred most endangered sites in the world.

5 The buttresses were plastered externally with mud, and there is no photographic record or published literature that tells us about the core material.

6 The vertical pegs are not rigidly fixed into the horizontal ties. This will provide leverage during a seismic vibration and at the same time prevent outward movement of the horizontal ties. Horizontal ties may or may not move together in the event of an earthquake, depending upon the type of seismic waves under the building wall. They are tied together with the help of vertical pegs, so that one prevents the other from dislodging from the wall and becoming independent.

7 Determination of standard distance for the installation of vertical tie members may depend on several factors, including the thickness and height of the walls, the strength of the masonry and the mortar, the intensity of the earthquake, and the closeness to the epicenter.

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