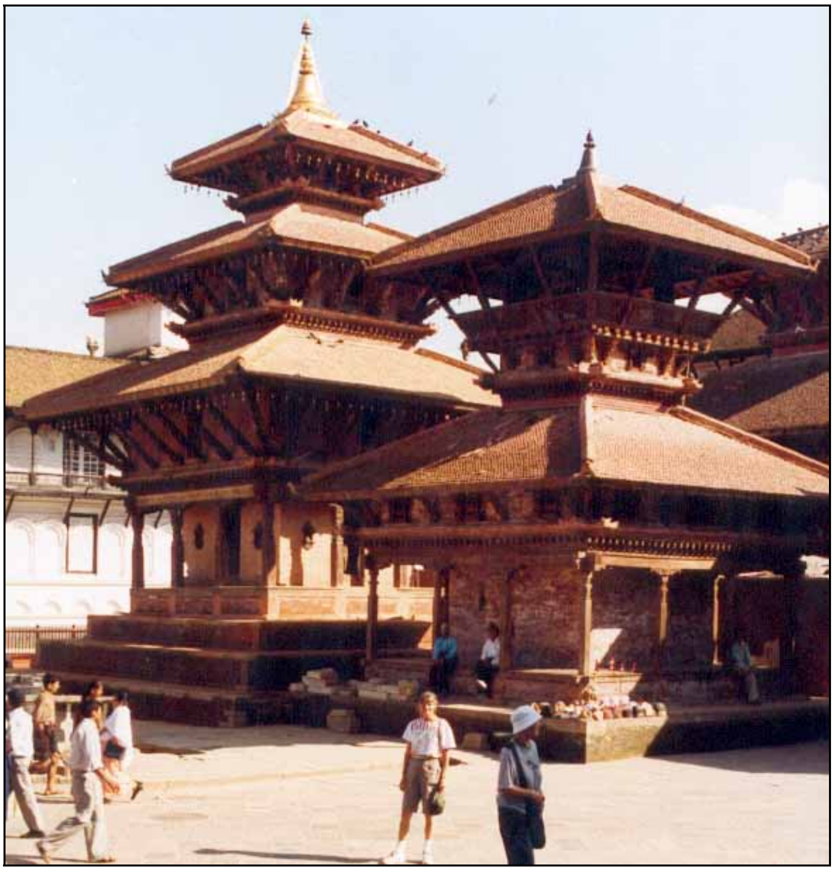
HUYS ADVIES

Options for Reconstruction and Retrofitting of Historic Pagoda Temples

(Example of the Narayan Temple, Kathmandu Durbar Square)



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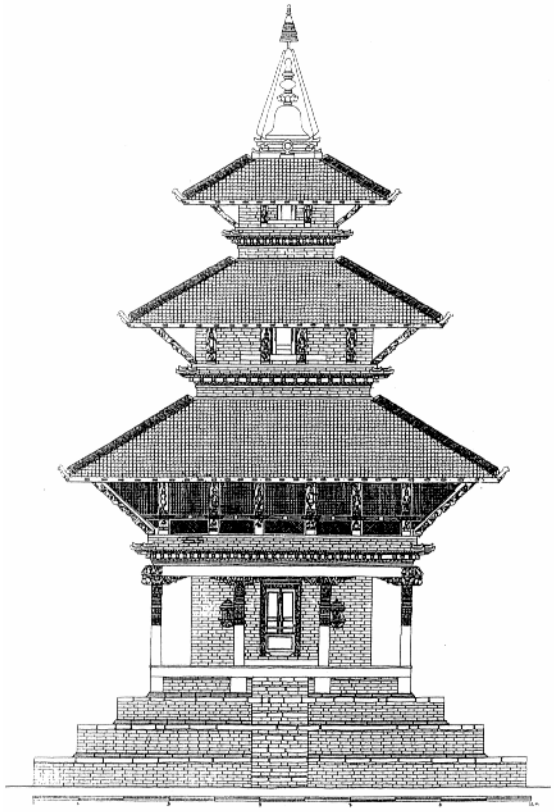
Report date: Kathmandu, September 2003

ABSTRACT

Description of options for reconstruction and retrofitting techniques for historic pagoda-type temples in Kathmandu, many of which collapsed or were heavily affected during the 1934 earthquake and later reconstructed. Deterioration due to lack of maintenance, combined with new research on the original designs, motivated full reconstruction and restoration, along with structural strengthening. Technical details of possible reconstruction and retrofitting options based on temple visits and drawings from several ongoing retrofitting activities and planned reconstructions. An analysis of the building mass of the Kathmandu Durbar Square Narayan Temple. Design options given for improved floor diaphragms, tiled roofs, internal strengthening frame and anchorage.



Narayan Temple
KATHMANDU DARBAR SQUARE INITIATIVE

Photo Front Page:
Completely restored Narayan temple (left) with earlier reconstructed Indrapur temple (right), September 2003.

Substantial information about the reconstruction from:
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Note:
This document is based on several site visits by the author and the staff of KVTP during the ongoing reconstruction activities, but only reflects the findings and opinions of the author. The current document does not necessarily reflect the opinion of Dr. Rohit K. Ranjitkar.

In each reconstruction process (retrofitting, repair, maintenance or restoration) different options are possible depending on its historic value and the proposed value or function of the building after the intervention. It also depends on the available funding and technology at the time. In 2002, for the KVTP, full restoration following the traditional design, without technical improvements (being visible or invisible), was the selected method.

The following paper presents some small alternative earthquake retrofitting options that would not be visible externally but would substantially improve the stability of the building, as well as the durability of the roof construction. As such, it would also substantially extend its lifetime.

ABBREVIATIONS AND EXPLANATIONS

HMG/N	His Majesty's Government of Nepal
KVPT	Kathmandu Valley Preservation Trust
Lakh	One hundred thousand Rupees
NBC	Nepalese Building Code
NGO	Non-Governmental Organisation
NRs	Nepalese Rupee (1 Euro = NRs. 85 at report date)
RCC	Reinforced Concrete Construction
UV	Ultra-violet – short frequency solar radiation destroying binders in plastics
UBC	Uniform Building Code – American code on seismic resistant construction

<u>Reconstruction</u>: The complete rebuilding of a construction, following the original design and historic architecture as much as possible. During reconstruction strengthening techniques can be introduced to enhance resistance against earthquakes or to improve the durability of the building against erosion and climate influences.

<u>Retrofitting</u>: The repair of a standing building, fitted with technical reinforcement measurements that make the building more earthquake resistant. These measurements can be placed externally or internally (or both) and in some cases may considerably change the appearance of a façade when design features are accentuated.

<u>Restoration</u>: The repair of a building or an artwork to its original architectural and decorative appearance. High importance is given to the authenticity of the design elements as originally conceived by the first builders.

<u>Preservation</u>: Maintaining the status of the current situation, avoiding further deterioration of the building. This can possibly include its ruined aspects. It does not include the replacement of entire constructions or construction members.

<u>Conservation</u>: A synonym of preservation.

<u>Efflorescence</u>: The formation of (white) crystals on wall surfaces as a result of evaporation of water containing salts. This is common above foundations that absorb groundwater through hygroscopic action of porous brickwork.

<u>Adobe</u>: Sun-dried earth blocks for building houses and temples. An adobe block consists for about 60-70% of pure clay and for the rest of sand and stone particles and a little silt. In large adobes, straw is used to allow even drying and coherence. For low-cost houses and temples, small adobe blocks measuring 8cm x 15cm x 25cm were often used. Using bricks on the outside and adobe on the inside of the same wall usually causes separation inside those walls.

<u>Adobe Walls</u>: When adobe blocks are used for the outside (bearing) walls, they need to be either well protected from rain by extended roofs or plastered and annually maintained. Well-dried adobe blocks masoned with soft clay have a considerable compressive strength after drying, allowing constructions of three storeys in height (10 meters). The base area of exterior walls constructed in adobe requires an all-natural stone plinth construction of at least 2½ feet high (75cm) to avoid up-splashing rainwater from eroding the wall. The Indian style Shikhara temples are an example of plastered and white-washed adobe wall constructions.

1. INTRODUCTION

By invitation of Dr. Rohit K. Ranjitkar, the Nepal Programme Director of the Kathmandu Valley Preservation Trust (KVPT), a visit was made to the KVPT office and some already completed retrofitted buildings and others in the planning.

Explanations were given about the realised retrofitting, including partial reconstruction, of three temples and the proposal of one house:

- Indrapur Temple, Kathmandu Durbar Square (completed)
- Narayan Temple, Kathmandu Durbar Square (completed)
- Jagannath Temple, Kathmandu Durbar Square (completed)
- Shops on the corner behind the KVPT office, off Patan Durbar Square

Some common retrofitting techniques for buildings were presented in two papers prepared by a young German engineer for the KVPT in February 2002. A collection of existing techniques was presented in the paper entitled “Manual for the Strengthening of Historic Buildings Against Earthquakes”, while the other, “Seismic Strengthening of the Temples on Kathmandu Durbar Square”, contained a few proposals for temples. In these two papers reference is made to a calculation report from Robert Silman Associates (RSA), New York, who visited the temple sites in May 2000.

The present paper gives an overview of some other technical improvements that can be realised in the reconstruction, restoration or retrofitting of the dozens of Newari pagoda-type temples of Kathmandu. The drawings of the Narayan Temple (in this paper) were prepared by the KVPT and have been taken as a basis to explain the possible techniques. The reconstructions of the Indrapur and Jagannath Temples have recently been completed, whereas the Narayan Temple was in its last phase of reconstruction, nearing completion, when this report was made. The plans and approval for the Narayan Temple were made long before this report. The suggestions worked out in this paper may therefore be useful for future restorations, reconstruction or retrofitting exercises of similar temples.

In preservation projects of old buildings, reconstruction work is sometimes frowned upon by local conservation specialists, such as replacing entire wooden components or restructuring internal walls. On the other hand, one of the objectives of retrofitting is to regain a durable (seismic resistant) and attractive building, showing the visitor the architectural and culturally important components. This objective implies that the building should not collapse again with the very next earthquake or require costly annual maintenance repairs. Consolidating or maintaining ruins may not be very attractive for tourists. Many temples have been reconstructed after the several earthquakes or upgraded through the ages because of the living religion and their social importance.

The KVPT must balance the various options between restoration, reconstruction and retrofitting, taking into consideration culture, heritage, technical feasibility, construction and maintenance costs (among others). In some cases, where retrofitting techniques are visible on the inside, it may be interesting for visitors to have the reconstruction techniques explained as part of a heritage conservation tour.

I hope that this paper contributes to the technical improvement of future repair and reconstruction processes of houses and temples and allows considerable cost reductions in both construction and maintenance requirements, without seriously affecting the beautiful architectural heritage of Kathmandu and Nepal in general.

Sjoerd Nienhuys
Architectural Engineer
September 2003

2. HOUSES OF GODS

Before looking at the specific design of the Newari pagoda temple, it is important to first consider the main points that lead to an improved and better earthquake resistant construction. Secondly, an assessment needs to be made whether or not the principles can be applied (technically and cost-wise). Thirdly, it is up to the KVPT to decide whether or not the suggestions will be applied, taking into consideration restoration practices, cost and final presentation of the building, as well as future maintenance.

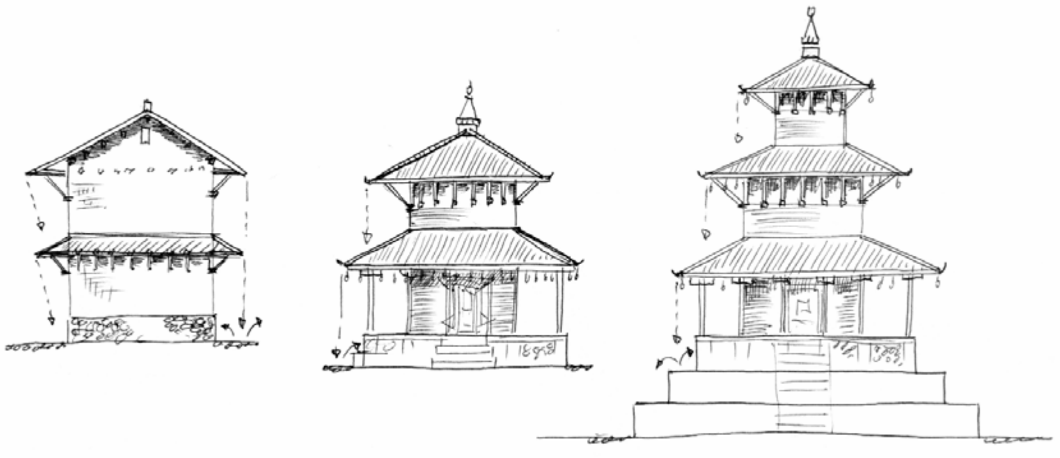
The Newari pagoda temple is the house of a God or Goddess. For that reason it is built in the style of the traditional Newari houses and its vernacular architecture, with its main features being emphasized, such as the roof overhangs, height and decoration.

Not long ago most houses were only one storey and built from adobe blocks. However, with the high cost of land and city development, the richer people started to build two-storey houses from burned bricks for durability, strength and appearance. Multi-storey brick houses with burned-clay roofing tiles are automatically associated with wealth. A typical two- or three-storey Newari house has a roof overhang of about one meter, protecting the wall from rain erosion. At each floor level another roof is fitted to the wall, especially on those sides where rain may affect the walls. In between two houses, in narrow alleyways, such intermediate roofs are not constructed because there the rain falls straight down and the walls will not be affected. Splash protection at the bottom of the walls is achieved by either stone plinth constructions or building the house on a high basement that remains inside the roof projection.

A cross section of a Newari pagoda temple reveals that these functional house designs are exaggerated by extending the roofs and adding more pyramid steps and pagoda roofs, depending on the importance of the God or Goddess and the wealth of the community members building the place of worship. Because temples are free standing, the large roof overhangs are on four sides, giving them their unique pagoda appearance.

Houses and palaces of the wealthy were often decorated with beautifully carved wooden doors, windows and lattice work, a feature which has been even more elaborated upon in the temples, giving them their astonishing appearance. The large roof overhangs help preserve the expensive woodwork from the damaging affects of both rain and sun.

Considering these main features, many of the solutions proposed for retrofitting or the improvement of temples can also be applied in houses.



3. COMMON DETERIORATION

The ancient cities of Kathmandu and Bhaktapur are full of old, dilapidated houses that are in the process of falling apart due to poor original design, lack of maintenance and/or non-repaired damages from earlier earthquakes. Non-maintenance of a house, such as not repairing leaking roofs, will eventually lead to its total collapse. When that happens, the old two- or three-storey houses are usually replaced by five- or six-storey high houses constructed with concrete columns with infill masonry; better utilizing the high land value of the terrains in the inner city. A number of typical examples of deterioration are mentioned below.

Protection of Lower Walls from Rain

Not protecting the lower walls from rain can have a devastating erosion effect. In addition, when the intermediate roofs (skirts) are not maintained, the effect will be that the adobe block wall or poor-quality burned brick wall below will rapidly erode, affecting the strength of the walls.

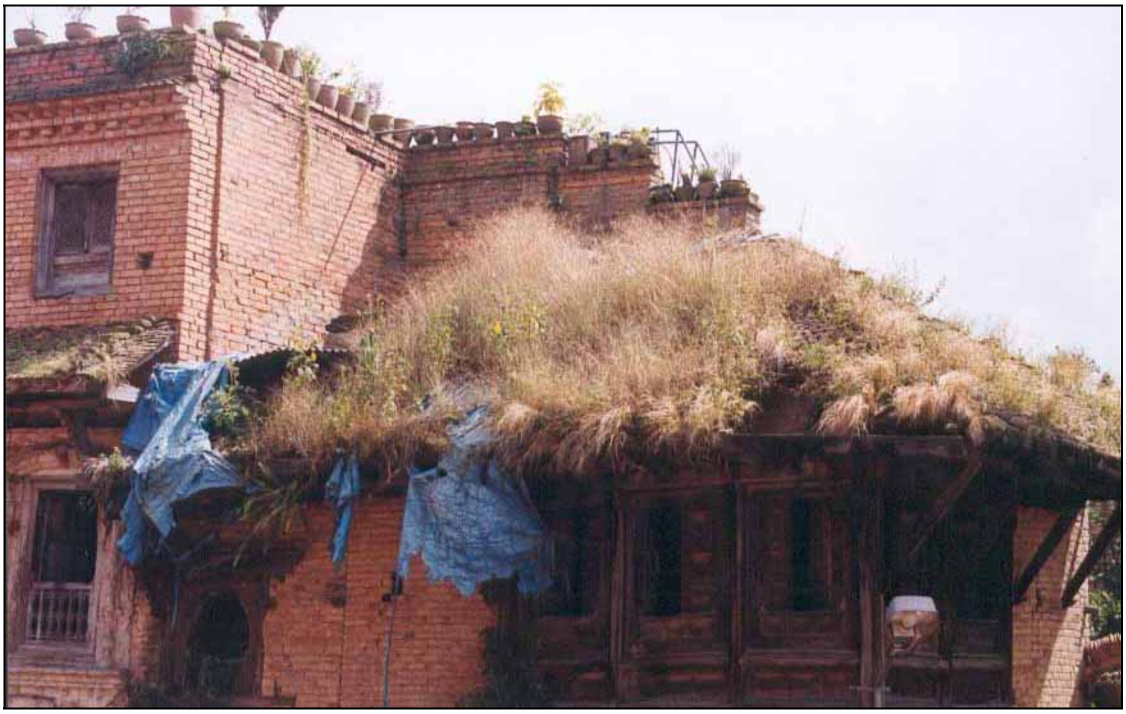
Burned brick wall deteriorated due to rain. Algae growing on lower side due to humidity.

Keeping Roofs Waterproof

Improperly maintained tiled roofs (for example, when broken or lost roofing tiles are not replaced before the rainy season) will definitely allow large quantities of rainwater to enter in between the tiles and into the underlying clay pack, first causing vegetation to grow and subsequently the roofing timber to rot.

Recently repaired roof already falling apart and with grass growing.

Ample examples exist in Kathmandu and Bhaktapur of extensive vegetation on roofs, rotting roof constructions and collapsed traditional houses.



Almost collapsed roof with heavy vegetation.

Rotting roof beams and planks as a result of leaking roof and permanent humidity in the soil layer under the roofing tiles.

Protection of Basement of Columns

Columns, where the bottom part are not protected from rain, up-splashing water or permanent contact with moist masonry work, will be affected within a few seasons, start rotting and cause collapse of the upper structure. Water easily rises up inside burned clay bricks, caused by hygroscopic action.

Column with base starting to rot due to up-splashing water.

Protection of Lintels from Water

Wooden lintel constructions over columns, doors or windows that have lost their protection from the rain may also rot and become compressed by the load from the walls and stories above. The same situation of rotting of the lintel applies when masonry work above the lintel, which is in contact with the wooden beams and soaks up water, becomes wet and is not adequately ventilated.

Beam over columns completely pressed flat due to wood rot.
Infill walls are made in the window openings to support against collapse.

Roof Struts

An outstanding feature of the Newari pagoda temples is the use of elaborately carved wooden roof struts, telling a story of Gods and Goddesses. Structural failure of one or more roof struts will cause the large roofs to collapse and allow rainwater to enter into the walls from above, causing further damage if not immediately repaired. Weakened roof struts are often supported along their sides with new secondary supports. A new plain strut was constructed only in the event when the original roof strut was lost and no pictures were available of the original design (as part of the story).

Where the lower part of the roof strut was damaged, possibly because of moisture emanating from the wall, a new piece was fitted/glued to repair and strengthen its connection to the wall. In many retrofitted temples the struts have been connected with long bolts anchoring them to the wall.

Old carved roof strut supported with two new side supports (left).
Bottom of roof strut support repaired with a new piece of wood (right).

With suggesting improvements for retrofitting or reconstruction of buildings, the following points should be considered:

First, the common aspects of good material use and building design must be kept in mind. This includes making sure that wood remains dry and masonry does not keep its moisture, especially not when the masonry is in contact with the wood.

Secondly, the (climate-proof) material use should go together with technical improvements to obtain coherence of the building to better withstand earthquakes.

Thirdly, the historic aspects of religious or Newari architecture should be considered. Interestingly, good material use and the structural design aspects are usually well taken care of in the original temple design, but new materials, such as cement, (stainless) steel and plastic, may further improve and enhance the building's durability.

In reconstruction it is not recommended only to look at the third aspect because water infiltration will rapidly destroy the high capital and labour investments made.

4. DESIGN PRINCIPLES

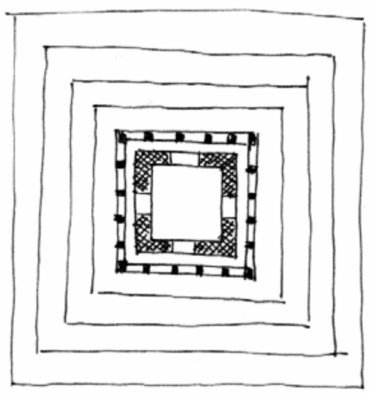
The following guideline principles apply for an improved earthquake resistant design:

A. **Reduce the weight** of the overall construction and construction elements. The force of the earthquake is directly related to the mass of the construction. Lowering the weight will reduce the horizontal and vertical forces and make the building relatively stronger.
B. **Tie everything together** in such a way that it holds together, also when minor shifts occur inside the construction. The effect of the tie-together principle is that the building will not start falling apart or lose supporting wall pieces, columns or struts. The strength of a construction is a combination of pressure and stress forces. When the pressure forces cannot be resisted, the construction starts crumbling.
C. **Allow some movement** in order to absorb some of the horizontal impact and with that the acceleration of the earthquake. The temples were originally built on this principle, but with large forces and shifts, the lack of connectors made them fall apart. Small movements are possible because of high material elasticity, such as wood. In this respect, reinforced concrete or steel framing have very little elasticity.
D. **Use local construction materials** that are easily available or can be locally manufactured, but still make durable and strong constructions. Local construction materials are not only less costly but were also used in the original designs.
E. **Use local construction techniques** that are easy to apply, be it in Kathmandu or other towns in the country having similar problems with the retrofitting or reconstruction of old and dilapidated temples.

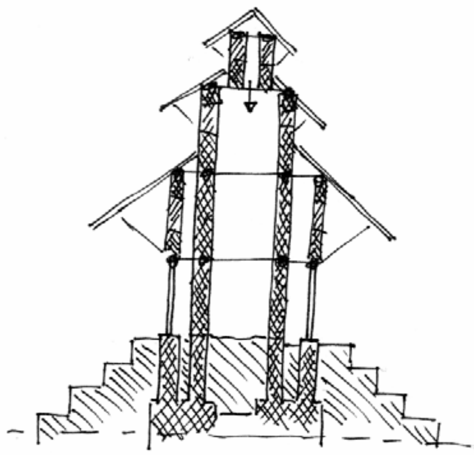
The traditionally built pagoda temples have evolved through many years of experience of the building masters from the 12th to the 18th centuries. A lot of practical earthquake experience has been incorporated in the design during those centuries. The conical building shape with the thick concentric inside walls of dry brick masonry and the balancing of the (heavy) roof structure on these walls is one aspect. Internal diaphragms providing support between the walls and a top storey providing a central load are other important characteristics that allow the buildings to sway slightly during an earthquake.

- A symmetrical construction (square floor plan of the pagoda temple) has a stronger resistance during earthquakes than a rectangular form.
- A large massive basement avoids shear in that foundation. Such a basement may redistribute soil forces to the building above, thus partly absorbing the impact of strong earthquake jolts.
- A conical mass distribution with a wide base is difficult to push over. When a mass needs to be pushed over a leaning support, it will withstand most earthquakes[1].
- A concentric support structure with interconnected columns will function like a table on slightly movable legs.
- A lightweight upper construction (copper-plated roofs) results in smaller horizontal earthquake forces on the storeys below than heavy constructions (tiled clay roofs).
- Good anchorage between wooden members and the walls, and well connected between each other, provide coherent diaphragms in the structure. These floors, however, should be connected on all four sides, not only two.
- Dry masoned walls allow some internal settling and small displacements of the bricks during an earthquake jolt and with that absorb some of the impact. With thick walls this is possible, but with thin walls the construction may fall apart without internal bonding.

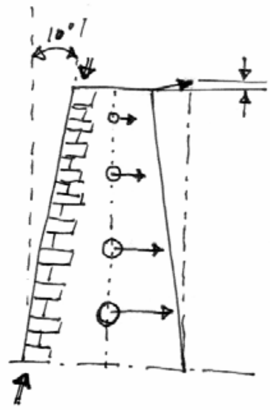
[1] This is because the sideways movement caused by the earthquake tends to result in a lifting force, especially when the side of the walls are built with pressure-resistant blocks or stones well anchored into the wall. The same reclined designs can be observed in ancient stone buildings (and temples) in Peru, a high earthquake-prone area.



Concentric Basement

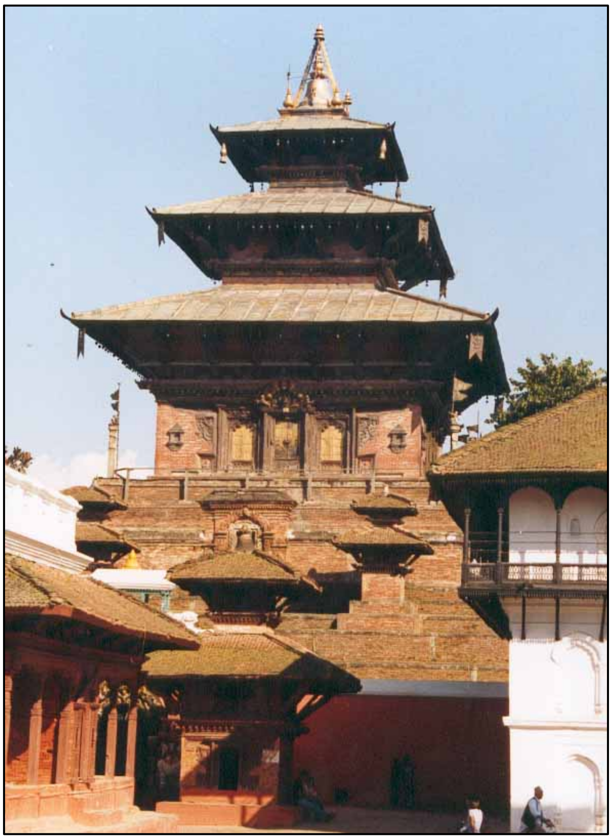


Symmetrical Support Walls



Conical Weight Distribution

The very strong 1934 earthquake, however, was too much for most of these traditional pagoda temple designs. Only a few large temples survived, such as the Taleju Temple (1576) built on a very large base (topped-off pyramid), having a light roof construction (copper-plated) and having a conical mass distribution with concentric walls. These aspects have largely contributed to its stability.



Taleju Temple
Kathmandu Durbar Square

Construction techniques to improve temple reconstruction are:

- Lower the overall weight (mass) of the building construction and its components. This way the overall earthquake forces on the same construction will be reduced. This includes primarily the higher sections of the wall construction and all of the (tile) roofs.
- Apply minor (non-visible) adjustments on the outside of the building to substantially reduce the weight. This includes the elimination of the soil under the roof tiles, waterproofing and fixing of the roof tiles.
- Simplify the application of the reinforcements in the new building and with that reduce the total labour cost and retrofitting time. This includes improving the bonding inside the walls with a cement-lime mortar.
- Improve the horizontal floor diaphragms and assure that floor diaphragms are anchored on all four sides to the walls. Improve anchorage of all wooden elements. Connect the floor diaphragms through the wall to the roof construction.

- Lower the reconstruction cost by lowering the material costs (lesser amount of hardwood), changing the type of materials (introduce plywood and galvanised anchors), eliminating double diaphragm reinforcements (plywood and steel bars) and developing new joint constructions (nailing plates). This includes the replacement of heavy planking in the roofs with a plywood diaphragm and slimming the walls, creating more room inside the temple.
- Apply internal reinforcements and ties to enhance the structural coherence of the building but have no visible impact on the outside. For housing this entails making the outside ties of the floor diaphragms behind the decorated bricks or plaster lining at each floor level. For temples it means making stress-resistant ties on all four inside corners of the building.

Reduction of Mass

The Newari pagoda temples are all slightly different in design, weight, slenderness and stability. Some have large basements in the shape of pyramids with top, homogenizing the impact of an earthquake movement from below. Most of them have a square floor plan with at higher stories a smaller base for the next storey, providing a rather stable, conical weight distribution. The superimposed pagoda roofs protect the mud-masoned walls and the elaborate wood carvings from rain and sun erosion. Centuries ago, the 2 ft. thick inside supporting walls were laid in clay mortar, having no binding property and allowing some horizontal slip and wall dilatation. During earthquakes slip would probably absorb some of the impact, while the very flexible and well balanced construction possibly allowed the entire building to sway a little. Some temples with light roof constructions survived the large 1934 earthquake.

By strengthening the building's horizontal levels (diaphragms, anchors), this swaying (absorbing) possibility will be maintained. However, by strengthening the walls in the vertical direction (diagonals), this swaying will be reduced by the stiffening of the walls. Stiffer walls need to be stronger than flexible walls or additionally reinforced. When a very stiff additional vertical reinforcement is applied against the old walls (such as reinforced concrete or steel frame), the flexible building mass will cause all the forces to be transferred to this stiff bearing construction, requiring the bearing construction to be excessively strong (and costly), while the traditional walls will do nothing to absorb the impact.

When temples are reconstructed keeping most of their characteristic elements, a combination must be sought between strengthening and allowing some impact force absorbing movements. This will be extremely difficult to calculate or even estimate. The design suggestions presented in this paper are therefore based on reduction of weight and knowledge of material behaviour, allowing some movement in the event of excessive forces.

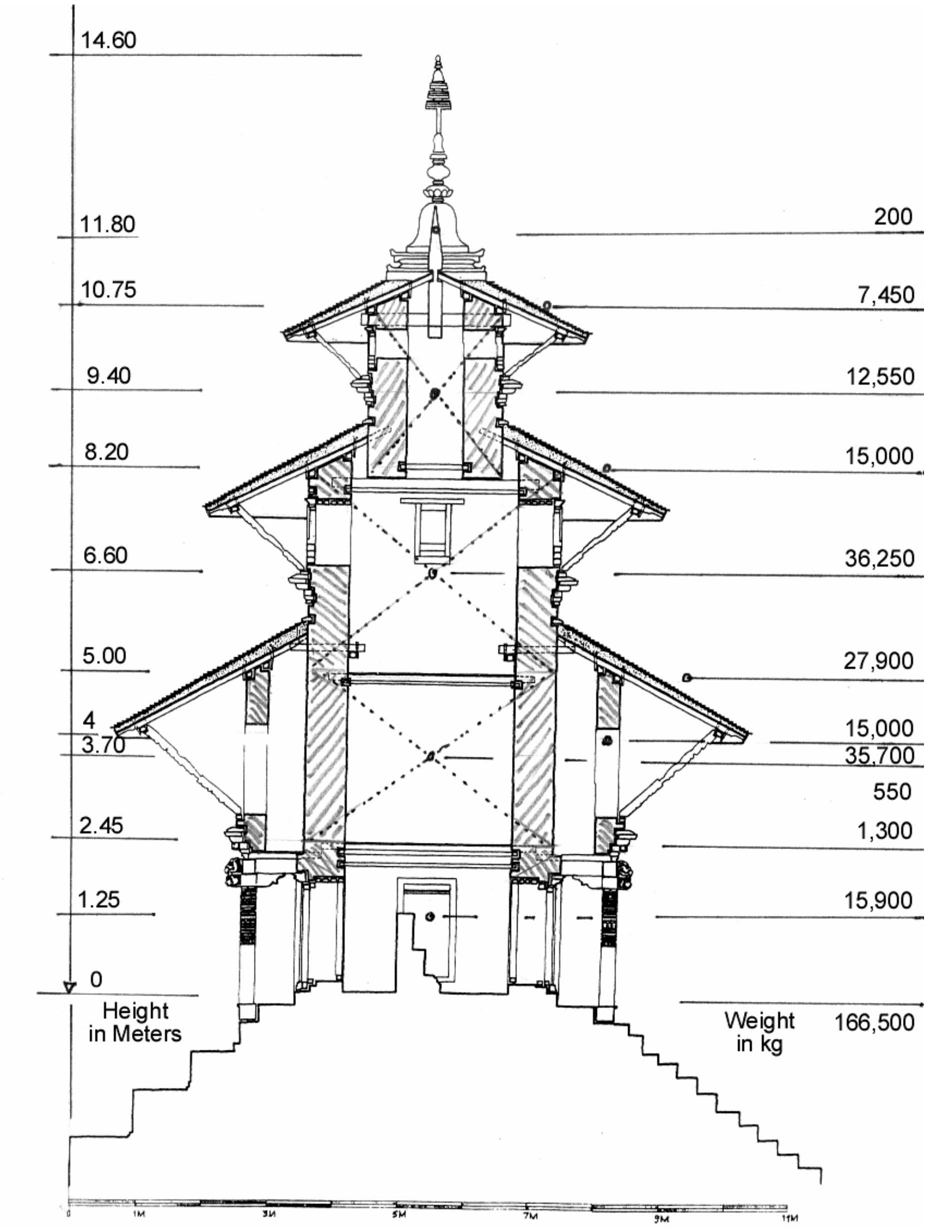
To better understand the impact or the influence of the total mass (weight) of the temple construction, a calculation needs to be made, based on standard earthquake codes. The structural strengthening design can be based on available building codes. However, because no dynamic analysis has been made of the pagoda-style temple constructions and these bear no similarity to conventional houses in their structural design, estimates have been made on the static forces. The recommendations, therefore, are based only on simplified static analysis, using the seismic coefficients of the Uniform Building Code (UBC). The total horizontal load on the building is V = I*K*CS*W, in which:

I = The importance of the building, varying from 1 for normal up to 1.5 for hospitals and control centres. As the temples are unoccupied by people, the importance is taken as standard (1).
K = The type of construction. The value is suggested to be 1.33 for non-ductile construction.
CS = Coefficient of Soil condition. When the 2.5 meter high base of the temple construction acts as a single unit, the CS can be taken as 0.14. This is when the temple is about four stories high.
W = The mass of the building component.

Horizontal force on the building is V = 1*1.33*0.14*W = 0.186*W or about 20% of its own weight (mass). This illustrates that weight reduction of the building, especially in the higher zones, is a very effective method in making a building more earthquake resistant.

The typical mass of burned brick dry masonry is about 1400 kg/m^3, with lime mortar 1500 kg/m^3. Typical mass of dry roof clay is also 1400 kg/m^3 with a thickness varying from 8-20cm and the mass of roofing tiles being also about 1400 kg/m^3, three layers thick, together about 6cm. On average it can be suggested that the typical mass of the construction materials is about minimal 1400 kg/m^3.
The thick, large dimension hardwood construction of the roofs has a mass of 800 kg/m^3.

In order to make a initial assessment of where the weights are in the temple design and to determine the position of the horizontal loads, a section drawing should be made. An example using the Narayan temple is given below.



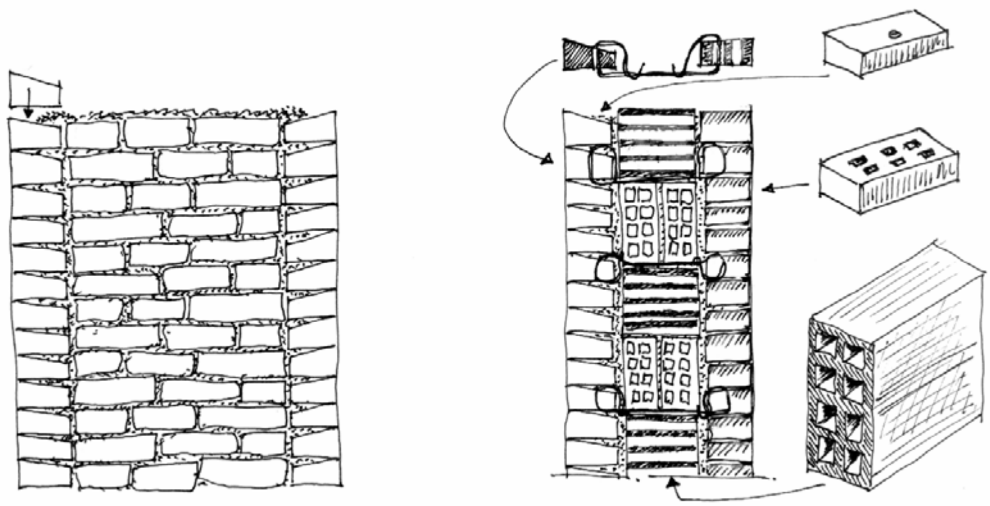
Approximate weight distribution in reconstructed Narayan Temple.

The horizontal load factors above the foundation block are estimated as follows:

Existing or Proposed Traditional Design					**Proposed Design with Weight Reduction**			
Dry Brick Masonry Solid	**Roof Timbers**	**Roof Clay Soil Layer 8-20 cm**	**Roof Tiles Three Layers**	**Level in Drawing**	**Masonry 20 cm Reduced**	**Masonry with Part Hollow Bricks**	**Roof Timbers Reduced**	**Roof Tiles –15%**
1400 kg/m³	*10 cm average*	*0.1x1400 kg/m³*	*5cm1400 kg/m³*	*Top 200 kg*	*1500 kg/m³*	*1200 kg/m³*	*6 cm average*	*1400 kg/m³*
				1300 kg				
–	22 m² 1750 kg	21 m² 3000 kg	20 m² 1400 kg	Roof 3	–	–	22 m² 1000 kg	20 m² 1200 kg
8.5 m³ 12000 kg				Level 3	5.7 m³ 8550 kg	5.7 m³ 6840 kg		
	6.7 m² 550 kg			Floor 3			6.7 m² 550 kg	
	50 m² 4000 kg	50.5 m² 7500 kg	50.5 m² 3500 kg	Roof 2			50 m² 2400 kg	50 m² 3000 kg
25.5 m³ 35700 kg				Level 2	17 m³ 25500 kg	17 m³ 20400 kg		
	6.7 m² 550 kg			Floor 2			6.7 m² 550 kg	
	92.5 m² 7400 kg	93 m² 14000 kg	93 m² 6500 kg	Roof 1			93 m² 4500 kg	93 m² 5500 kg
10.6 m³ 15000 kg				Level 1a outside	9 m³ 13500 kg	9 m³ 10800 kg		
25.5 m³ 35700 kg				Level 1b inside	17 m³ 25500 kg	17 m³ 20400 kg		
	6.7 m² 550 kg			Floor 1			6.7 m² 550 kg	
10.6 m³ 15900 kg				Sanctum inside	7 m³ 10500 kg	7 m³ 8400 kg		
Total 114,300	**Total 14,800**	**Total 24,500**	**Total 11,400**	**Top 1500 kg**	**Total 83,550**	**Total 66,840**	**Total 9,550**	**Total 9,700**

Total traditional design: 166,500 kg + windows is about 170,000 kg (100%)
Total with slimmed walls and adapted roof design: 104,300 kg (60% of original)
Total with slimmed and hollowed walls design: 87,600 kg (50% of original)

Roof construction traditional is about: 50,700 kg (100%)
Roof without clay soil layer is about: 26,200 kg (52%)
Roof without clay and reduced timber and tiles: 19,250 kg (38%) and half the timber cost

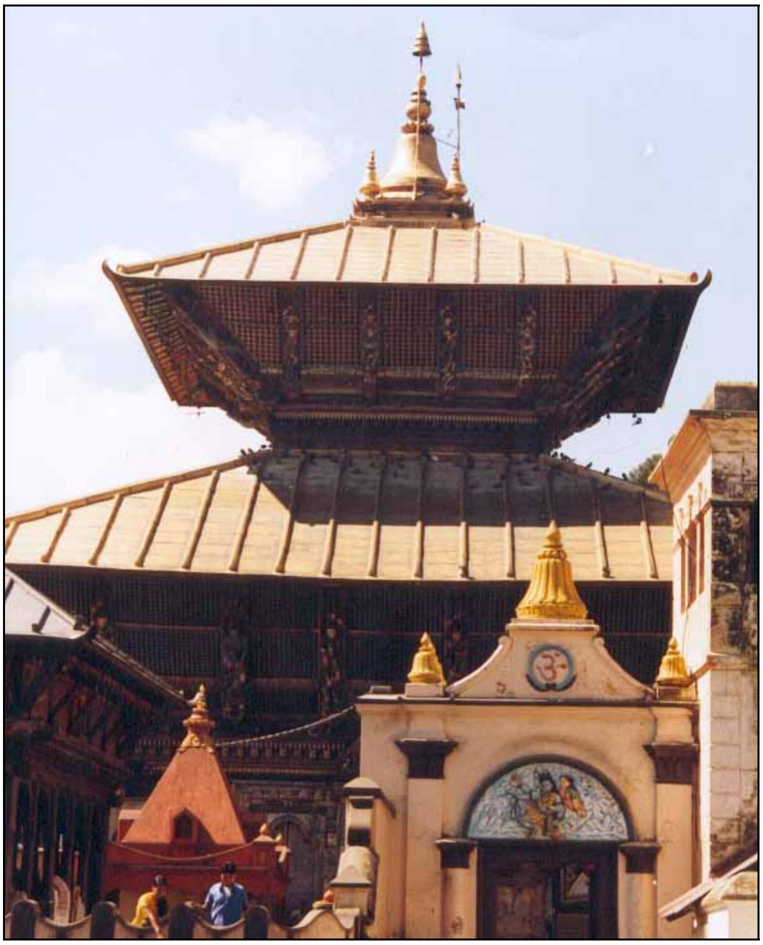


Slimmer and lighter walls made by a combination of solid and hollow bricks.

Where Can the Mass Be Reduced?

The masonry of the 65cm inside walls can be reduced by 20cm, using a binding mortar. In addition, weight can be reduced by masoning hollow bricks into the core of the wall. An important condition for the slimming of the walls is a better bonding between the stones, achieved by applying a bonding mortar (with cement or lime) and introducing internal ties. The typical mass of the hollow bricks is only 800 kg/m^3, while the combination of hollow and massive bricks is estimated at 1200 kg/m^3. The clay soil is totally removed from the roof design, while waterproofing and attachment under the tiles allows a 15% weight reduction by slightly repositioning the tiles.

The weight reduction of the roof deck is further achieved by replacing the 2½" thick hardwood plank roofing deck with ¾" thick waterproof plywood (see sketch page 28). This saves an enormous amount of wood and thereby reduces cost. The result is a strong, light diaphragm which is not visible from below because of the pasted-on strips and the multiple heavy spores. As can be seen from the table above, this roof timber weight reduction is limited as compared to the weight of the entire roof. The estimate for the inside wood floors have been kept the same. The above table demonstrates that by redesigning the building with lesser weight, the horizontal load factor can be considerably reduced (40-50%). When the horizontal load is positioned high above the base, the overturning effect caused by the earthquake is also largest; therefore load reduction becomes most important at the highest levels.



Pashupatinath Temple with a lightweight roof construction with copper plating.
This will cause lesser horizontal forces during earthquakes.

5. RESTORATION STRATEGY

The KVPT has two lines of restoration activities, one for historical temples and one for historical buildings. For temples it may result in a complete reconstructing from the base upwards. After the 1934 earthquake some temples were not entirely reconstructed according to their original design and others had become so dilapidated since their 1936 reconstruction that restoration and retrofitting alone would not be sufficient to produce a durable construction. Old photographs, drawings and architectural details were studied to reconstruct the temples in their most original design and details. The retrofitting of temples may include metal reinforcements, but visible adaptations of the building design and internal strengthening measurements, which are irreversible, are not immediately considered in restoration.

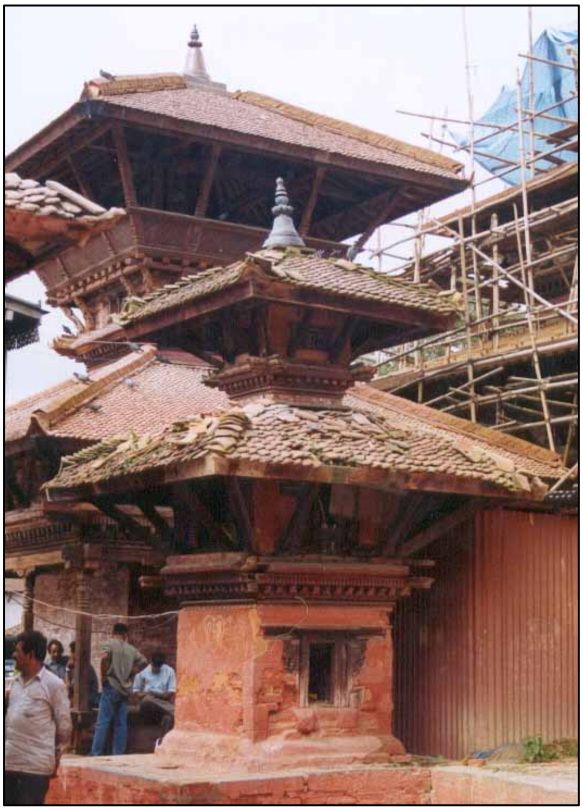
There is a greater tolerance for modification of the external structural details during the reconstruction and retrofitting of old (historical) houses and shops. External details should not be overly modified in order to maintain the historic characteristics of the building, but some details can be substantially improved upon, as long as the historic character is not affected. One of the objectives of the restored or retrofitted houses and shops is that people can live safely in these buildings, while maintaining the beautiful character of the streets or public squares and with that the liveability of the area.

As demonstrated in the earlier table, the weight (mass) reduction during a reconstruction activity is achieved in the traditional Newari architecture by two principal measurements:

1. Reduction of the roof load by eliminating the clay soil layer under the roof tiles (50% of the total roof weight) and slightly reducing the number of tiles (15% of tiles weight). Both measurements are not visible from the outside and can strongly reduce future maintenance. The roof deck can be replaced with plywood (40% of deck weight).

2. Reduction of the mass of the walls by reducing the thickness and weight of the materials used, while strengthening the internal bonding (30% reduction). Rebuilding a thinner wall partly with hollow blocks and providing a better bonding material, such as lime-cement instead of mud, is one option; introducing wall reinforcement is another. Combining the two measurements will further enhance strength (45% weight reduction).

Combining the two mass reduction measurements will reduce the side impact (load factor during an earthquake) on the building and thus make the building relatively stronger. In the case of only a retrofitting exercise on an existing construction, the reduction of the thickness of the bearing walls may not be possible.



Roof of small temple damaged by monkeys. Narayan temple under reconstruction behind. The proposed technology can be tested on small roofs, serving for skill training at the same time.

Four Options of Approach for Repair

When applying these reconstruction measurements to temples, an ideological consideration may come into the picture, even when the changes are not visible from the outside. Generally speaking there are four options of approach possible.

A. **Only restoration.** A temple can be rebuilt exactly as it was 75 years ago, only using some better wood and wood connections or additional tie-beams and straps, but not reducing overall mass or enhancing bonding inside the walls. In this case the construction will most probably be strongly damaged or even collapse again with the next large earthquake. The roofs will have to be repaired every 2 to 5 years, considering climate and monkey attack[2].

B. **Restoration and retrofitting.** A temple can be repaired as indicated above, but at the same time a strengthening and support structure is realised in the interior of the temple that will better resist lateral and vertical forces. The reinforcement structure will be stiffer than the traditional building and therefore would need to be very strong to carry all the mass of the traditional building. This will be costly and is fully visible on the inside (metal or concrete frames). With such reinforcement the temple will better withstand earthquakes, but because the walls are still built with traditional dry mud mortar, they may fall away from the new stiffer support frame. The roofs with the traditional soil layers still require frequent (costly) maintenance.

C. **Restoration by reconstruction using original materials.** A temple is restored by reconstruction using the original materials, with slimmed walls for the higher wall sections and improved bonding and anchorage inside the walls and between building elements. Lighter construction materials are used and the load of clay soil from the roofs is eliminated. This way not only the earthquake forces on the building will be considerably reduced, but also the wall construction will be stronger, providing adequate earthquake resistance to minor quakes. In addition, by applying the modified roofing design, the roofs will not require frequent maintenance, thus almost eliminating this high recurrent expenditure.

D. **Restoration by reconstruction with internal retrofitting.** A temple is reconstructed as mentioned in paragraph C above, and an additional strengthening structure is realised inside the temple. Because the overall weight of the temple is less than before, and the construction of the new walls can absorb part of the forces, this internal structure can be much lighter (and cheaper) than a support structure to the original construction as mentioned in paragraph B.

The technical details in the following chapters are based on the methodologies C and D above, as being considered the most logical, requiring minimum amount of funding and providing maximum durability. The strongly reduced maintenance factor of some of the design options is important for financial reasons.

When a temple or house is not entirely reconstructed, but only retrofitted, the slimming of the walls may not be feasible. Because the traditional roofs and side skirting roofs of the Newari houses and temples are all in very bad shape, they have to be redone anyhow and the suggested design can be applied, eliminating annual maintenance.

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[2] Recently reconstructed or repaired temples show that the roof tiles along the borders are already coming loose. When monkeys have access to the temple roofs (from lower buildings), serious damage will rapidly occur to the traditional (clay soil based) roof tile constructions. Water penetration will accelerate erosion, allowing more roof tiles to come loose. When water penetrates into the clay soil layer, it will negatively affect the wooden support structure because it maintains its moisture for a long time. Grass and weeds easily grow in the clay soil under the roof tiles. In some cases monkeys throw the loose tiles off the roofs.

6. FOUNDATION

As suggested in the two KVPT seismic strengthening reports, the foundation can be made as one large coherent unit, forming the base on which the temple stands. After the 1934 earthquake some temples were rebuilt on the old foundation as these were still in good condition. These massive foundations will largely eliminate the earthquake risks associated with soft soils[3]. To further strengthen the foundation a 30cm x 50cm wide reinforced concrete ring beam was cast all around the foundation. In addition, the 2 meter high pocket between the two concentric foundation walls was filled in with bricks and rubble, making the pyramid base as one unit (see drawing page 32).

First Terrace Floor

The first perimeter terrace floor of the Narayan temple (level with the Sanctum) is built around the central building volume and is supported by both the inner and outside foundation walls. This floor is about 2.20 meters above the excavated ground level of the overall temple foundation.

The reconstruction of this perimeter floor will provide a circumferential bracing of the inner walls of the main support structure. To this effect the hardwood tie-beams are interlocked by half-wood joints, reinforced with bolts. The inner tie-beams (4" x 4") are extended at the corners and connected with dovetails to the exterior (original) large size wooden beam (4" x 8"), which lies in line with the exterior line of columns (see photo page 16). It is planned to reinforce the corner construction with a stainless steel plate, over which the new wooden floor will be nailed.

A well ventilated reconstruction of Sanctum floor.

In the reconstruction of this perimeter floor care has been taken to avoid rotting of the tie-beams and floor by the following measurements:

- Excavating a void under the floor that is well ventilated; avoiding contact between wood and soil, which may cause fungus to develop on the timber.
- Supporting the tie-beam exclusively on thick stones or slate which prevents transmission of humidity from the stone to the wood. In the past some wood sections were supported on the burned brick, by which the hygroscopic action of the brick brought humidity from the ground below to the wood and caused rotting.
- The roof overhang and the terrace steps ensure that water does not splash up against the perimeter beams or the column feet.

[3] It is considered that the one 3-4 meter high traditional pyramid shape foundation, with loose infill and side bracing steps, may have functioned as a shock absorber. This (possible) feature can be further studied by engineers having knowledge of the dynamic behaviour of loosely masoned constructions. An analysis of the extent of past earthquake damage of Newari temples in relation to the size of the pyramid base construction was unavailable.

The above design still has several disadvantages:

1. The inner tie-beam placed with one side against the inside support walls of the temple has no preserving coat against the wall (humid, wet) (second photo below).

2. The dimension of the inner tie-beam is too small to prevent any bulging of the foundation wall when earthquake movements internally loosen and expand the main support walls.

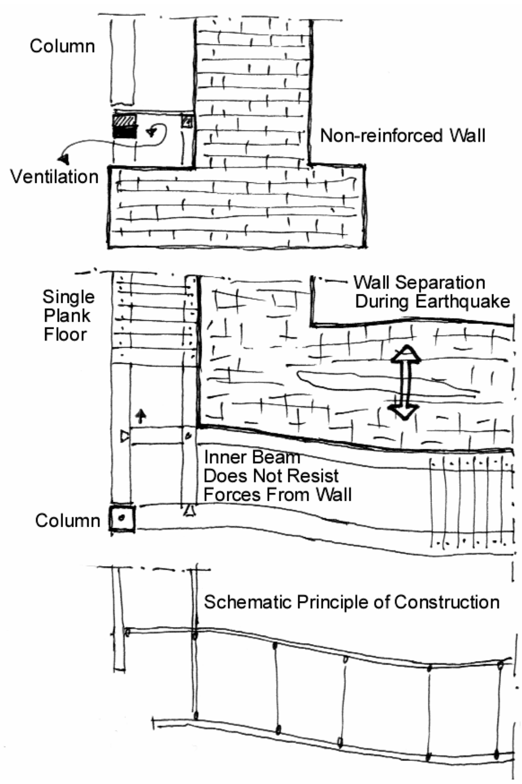
3. The half-wood connection on the inner tie-beam (when fitted with a bolt) is reducing its total resistance to about one-third of the stress force allowable in the solid beam.

4. The dovetail connection at the end of the inner tie-beam transfers few forces to the outside beams. Besides, the dovetail may be subject to shrinking and loosening.

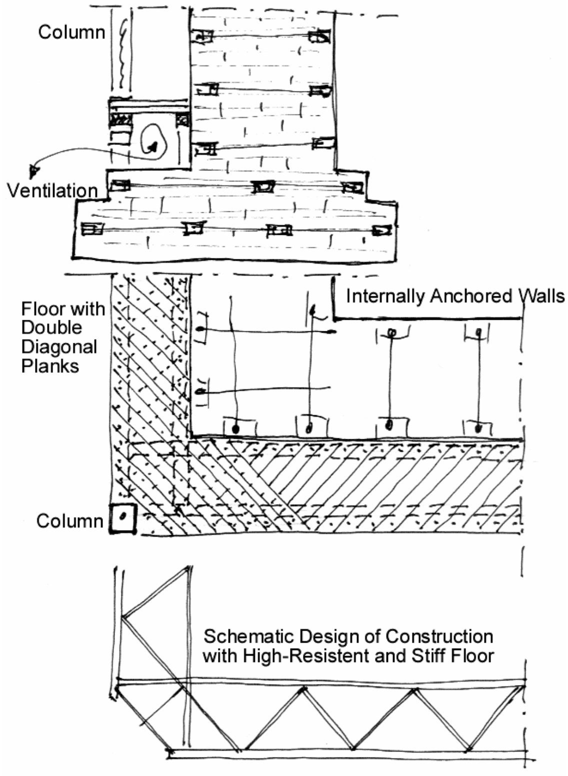
5. The outside perimeter beams will be linked at the corners. This corner plate will not assist the beam against any bulging of the inner wall. Nor will it resist any movement of the underlying external foundation wall.

Reconstruction of the Sanctum floor with dovetail connection
in the outside beam and half-wood connection for the inner beams.
The diagonal beam in the corner supports the floor planks.

The indicated construction may be improved for future temple reconstructions by making a wide truss (in a horizontal position) from the plank floor by nailing two layers of "sal" planks diagonally one over the other (see right-hand sketch below[4]). This will create a stiff and very strong tie-truss-beam that will better resist a possible bulging of the inner walls. The corner construction needs to be able to transfer the forces around the corner.



Existing Situation

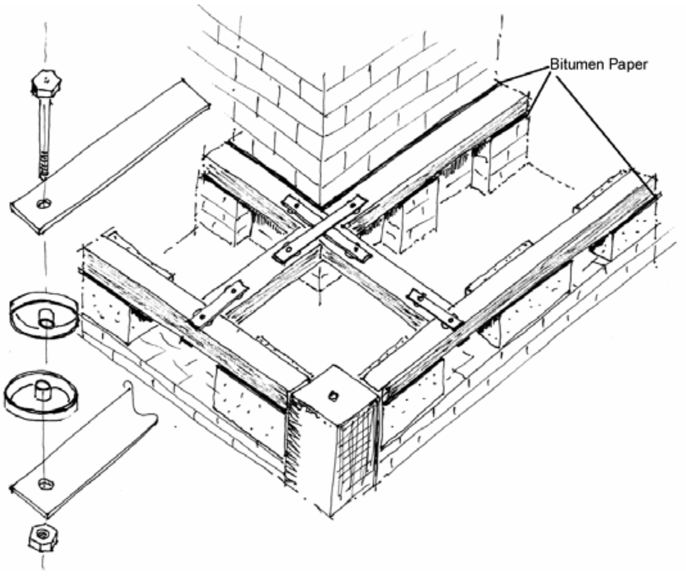


Proposed Improvement

The following are points for improvement of the Sanctum floor:

1. The pasting of bitumen paper between the brick wall and the wood beam, as well as under the beams where these are laid on the stone supports, will extend the lifetime of the beams.

2. The corner connection of the inner tie-beam can be better made with a combination of a bolt with grip-anchor plates, split-ring or toothed ring plates. The split or toothed ring is embedded halfway into each beam. This wood-to-wood connection allows a 30-40% smaller wood dimension than a half-wood connection. A 2½" ring



[4] These truss-type floor beams have been suggested in one of the earlier reports of the KVPT. In this case it is suggested to apply the same technology for the ground perimeter floor as well, holding the basement of the walls together and avoiding any separation at the first level. For higher floors the truss-floors need to be connected to the inner floor diaphragms.

requires a ½" bolt, and a 4" ring requires a ¾" bolt. The application of timber connectors (such as embedded toothed plates with bolts) is much faster to realize than half-wood constructions, thus saving timber and time, whilst enhancing strength.

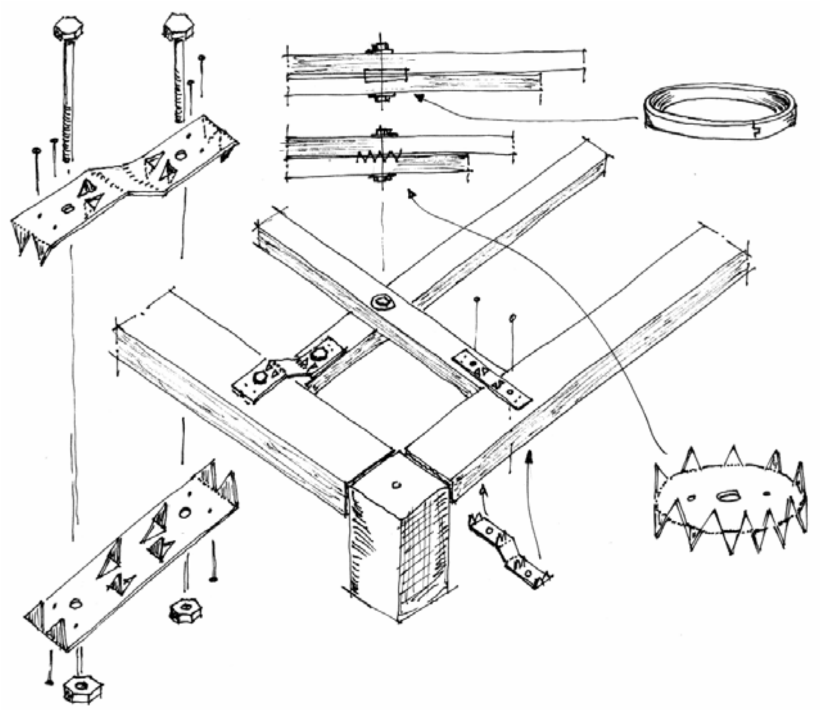
3. The inner tie-beams of the temple terrace have to maintain the half-wood connection in view of the covering plank floor which needs to be level. Also the outside perimeter beams need to be in one level, but can be made half the original dimension.

4. An anchor strip and a bolt fitted through a shear plate will vastly improve the connection between the inner tie-beam with the exterior perimeter beam. It is recommended to use stainless steel or hot-dip galvanised steel plates with an additional preserving coating of tar. The additional coating on the galvanised steel is especially important when the hardwood beams have been treated with a wood preservative. The shear plates are to be pre-drilled/grooved into the hardwood. Time saving is realised by the simplicity of the design.

5. The outside perimeter beam is currently largely over-dimensioned for its purpose. This may have been needed in the past because this beam was exposed to the weather and wood was cheap. With modern wood preservatives and the beam hidden under the plank floor, the beam can have the same dimensions as the inner tie-beam. The two beams having equal sections is relevant when the inner tie-beam and the external tie-beam are working in unison as a truss.

6. The diagonal nailing of the two plank floors (one over the other in perpendicular direction) on the two beams should be done with galvanised nails or screws to avoid corrosion. The nails or screws need to be pre-drilled through the top planking.

The variety of timber connectors can be studied by the KVPT and a special set manufactured for the hardwood connections[5]. For ring or round shear connectors that need to be embedded in hardwood, a special drill-bit can be manufactured that cuts/saws a ring into the hardwood of the exact dimensions of a ring or slightly less deep for a toothed ring. If unavailable, a drill-bit for a ring can be manufactured from a pipe section into which saw-teeth are cut, sharpened and hardened.

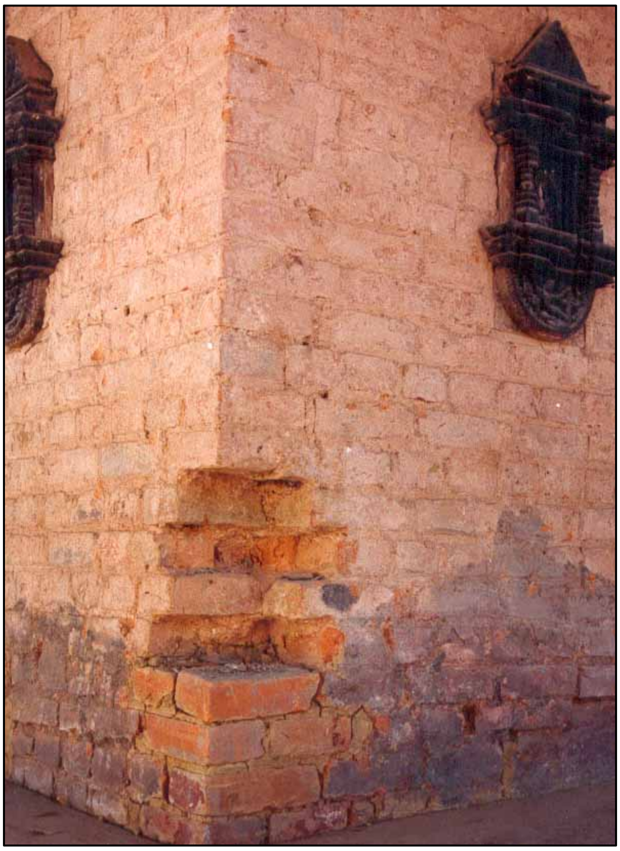


[5] Some details about wood connectors can be obtained from the following web pages: www.tpub.com/integ/1j.htm, www.batcontinental.nl/indexechtsmv2.htm and 3.htm, and with the hyperlinks under www.strongtie.co.uk/catalogue/infosimp.php

7. SUPPORTING WALLS

A recent survey of the Narayan temple determined that after the 1934 earthquake the temple was reconstructed using lime mortar for the first 250cm above the old foundation (Sanctum). Lime mortar has a much better bonding than plain mud mortar. The question arises if future reconstruction activities should still use mud mortar, lime mortar or light lime-cement mortar. Lime-cement mortar has a better bonding than lime mortar, but is also slightly less flexible.

The bonding mortar inside the massive walls is not visible from the outside but has a very large influence on the structural strength and resistance of the temple. With a better bonding material inside the masonry, the walls can be constructed thinner and lighter, having a large influence on the weight and strength of the entire construction. Reducing the weight (mass) of the construction reduces the earthquake forces, and thus enhances the relative strength.



New walls (1963) using adobe bricks with lime mortar.

Adding cement to the mortar will reduce the flexibility, a special feature of the non-bonded dry, thick masonry constructions of the old temples. Because the heavy interior walls have a relatively large flexibility, and the perimeter columns can move sideways with minor movements (without losing their bearing capacity), the entire temple construction can absorb minor earthquake impacts.

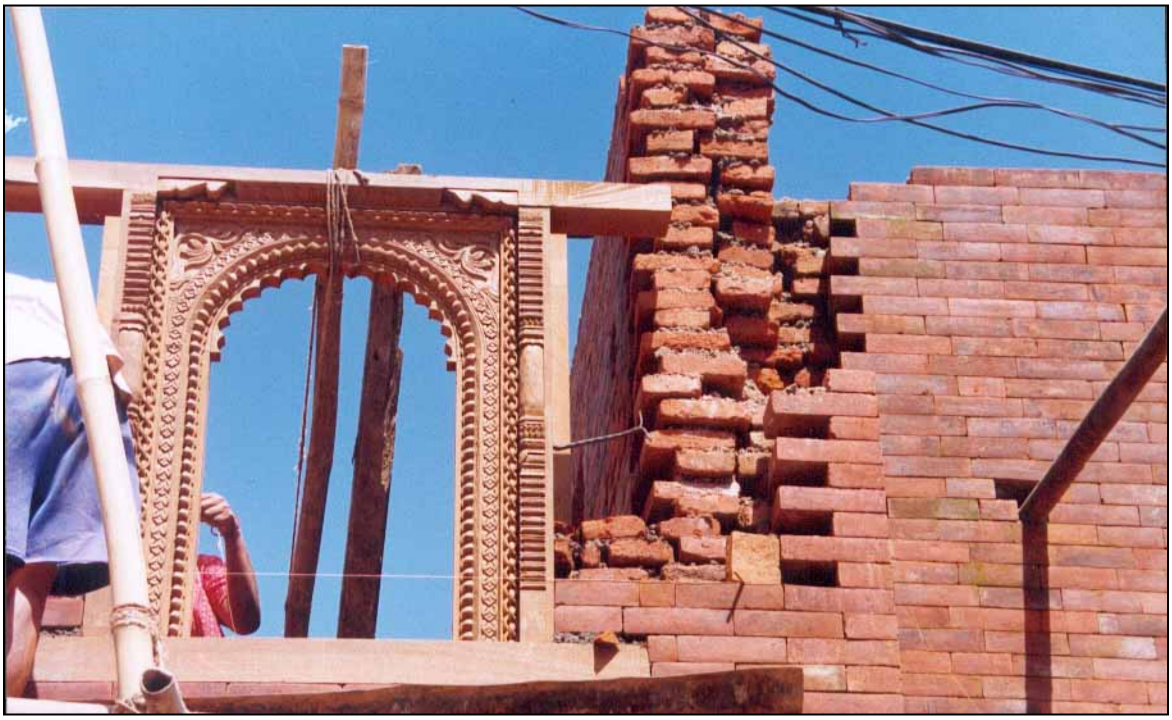
The elasticity module E of concrete and cement mortar is high, indicating little elastic deformation.

Reinforced concrete	$E = 210{,}000\ kg/cm^2$ (good quality)
Cement mortar in brick masonry	$E = 100{,}000$ till $80{,}000\ kg/cm^2$
Cement mortar with lime	$E = 80{,}000$ till $60{,}000\ kg/cm^2$
Lime mortar with cement	$E = 40{,}000$ till $30{,}000\ kg/cm^2$
Lime mortar	$E = 20{,}000$ till $15{,}000\ kg/cm^2$
Dried clay	$E =$ below $5{,}000\ kg/cm^2$

The above means that when a non-mortar-masoned stone construction is combined with reinforced concrete, the reinforced concrete, having a very high elasticity module, will receive all the forces because of its stiffness. The non-masoned construction is therefore dead weight and requires a substantial (over) dimensioning of the concrete construction, adding weight to weight.

Reinforcing the masonry walls can best be done with lime-cement mortar, maintaining a high flexibility, enhancing bonding strength and resistance against erosion. Although the 1936 reconstruction used soil-lime mortar, a stronger mortar is needed with a thinning of the walls.

In the reconstruction or retrofitting of historical buildings, one of the objectives is to improve strength and durability. This can be partly achieved with new materials, provided their use does not change the appearance of the building. Using a better bonding method inside the walls does not affect the architecture. Extreme care must be taken when using lime-cement bonding. If cement gets on the exterior of the brick walls, this will be very difficult to remove. When using light lime-cement mortar, galvanised iron anchors and reinforcements may be slightly affected by the cement mortar and need to be painted with an anticorrosive coating.



Wall under reconstruction using common cement mortar in the inside of the wall.
Exterior bricks are conical and masoned without external joint.

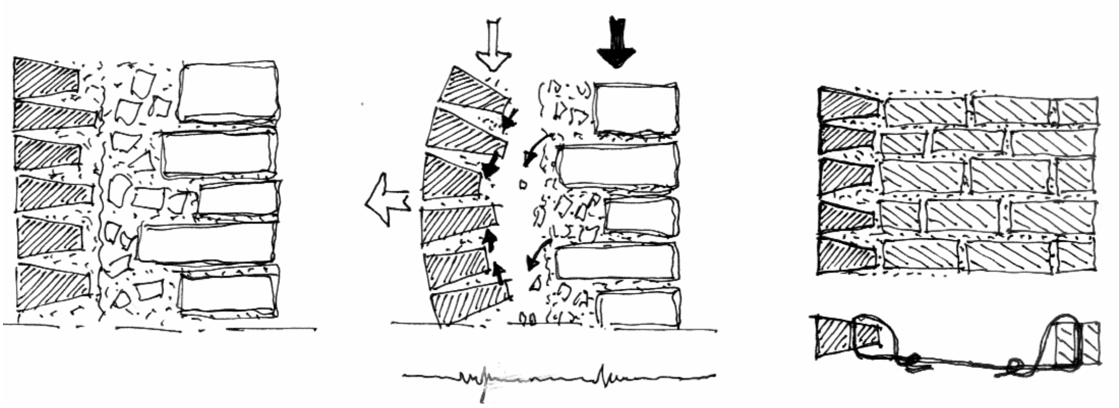
Clay-soil Mortar Masonry

Very pure yellow clay-soil is currently being used for the masonry of the new temple walls. Water is added to the yellow clay and is trampled with the feet until a smooth paste is obtained. When slightly dried, this paste is applied between the burned bricks[6]. The burned bricks absorb part of the moisture from the clay. New layers of burned bricks are pasted over the old layers after one day to allow some drying of the mud mortar. A disadvantage of the wet clay paste is that the burned bricks absorb dissolved salts and lime from the clay water. Through hygroscopic action of porous brickwork, this water will seep to the exterior of the walls and cause efflorescence. These white crystals can be washed off, but will reoccur until the drying process inside the thick walls is completed.

A second disadvantage in using pure clay is that it shrinks during the drying process. Because the burned bricks do not shrink, the clay cracks loose from the bricks. When the bricks are laid in moist clay, the joints will become slightly thinner after drying of the clay. When 50% clean sand is mixed with the clay, the physical property of the bonding is maintained, while the shrinkage will be reduced by 50%. Also the amount of water needed to make the mix plastic enough for its application will be strongly reduced; hence efflorescence will be reduced as well.

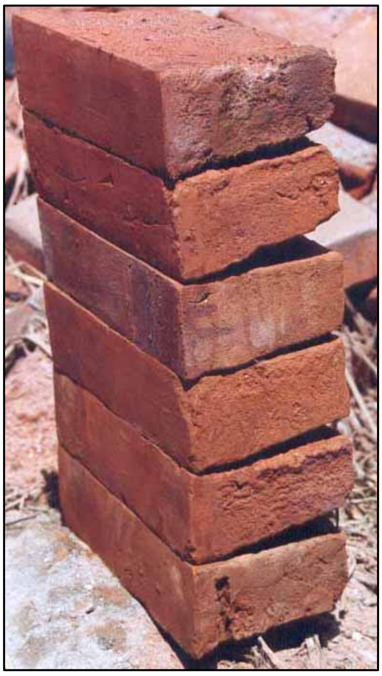
[6] The advantage of using clay is its typical bonding characteristic when dried. Clay consists of flat cells which are lubricated with water. Microscopically, clay looks like a pile of playing cards. When the water evaporates from the clay, it causes high friction between the cells and they become strongly attached between one and another, making the clay shrink and harden.

In the reconstruction of the temples all bricks utilized are burned bricks, reducing a possible imbalance between inner and outer-face of the wall when using two different materials. This is a very important improvement of material use as compared with wall constructions having the outer wall made of burned bricks and the inner wall made of sun-dried adobe blocks. The use of all bricks instead of two materials will also reduce (but not eliminate) de-lamination between the outer brick façade and the inner adobe wall.



The left sketch represents a traditional design with conical bricks[7]. The brick is of another material than the inner wall adobe blocks and will cause cracking due to annual differences in humidity and drying resulting from climate changes between rainy and dry seasons. With the frequent small vibrations of ever-present mini-tremors, grains of soil filling fall into the cracks and prevent the outer façade from moving back, hence the bulging often visible in old houses. When the joint material erodes from between the conical bricks, vertical loads will cause accelerated de-lamination due to the hinging aspect of the conical stones. When this happens, it is only the inner wall that provides the bearing capacity of the construction.

The photo shows how the conical bricks can be aligned on one side, making a closed smooth face. The inside needs to be supported with non-compressible material. When soft clay is used, it will shrink when dry and the bricks will turn inwards. To avoid this turning of the façade bricks, nearly dry clay should be used with a high sand content. Better yet is to use lime or lime-cement mortar, especially for the thinner walls.



De-lamination can be eliminated by the following measurements:

- Minimizing joint thickness in the outer façade to eliminate erosion (done in the Narayan temple).
- Minimizing the conical shape of the outer façade bricks (done).
- Use of the same building material for façade and inner structure (done).
- Minimizing the thickness of the infilling clay mortar (done).
- Minimize possible shrinkage of infill material (not done; only clay is used).
- Enhance bonding/anchorage between inner structure and façade bricks (not done).

[7] In mountain areas large hand-dressed stones are used instead of burned bricks. These stones are ten times larger in volume than bricks and have a conical shape. Nicely dressed stones have more material cut off to make them neatly fit with thin joints in the face of the façade. Small joints reduce erosion of the joint material, but the bearing between these dressed stones is very small and de-lamination becomes a risk. Buildings made with conically cut-back dressed stones which are not masoned with a binding lime-soil mortar are fatally dangerous in the event of an earthquake.

The bonding inside the wall can be improved by various measurements:

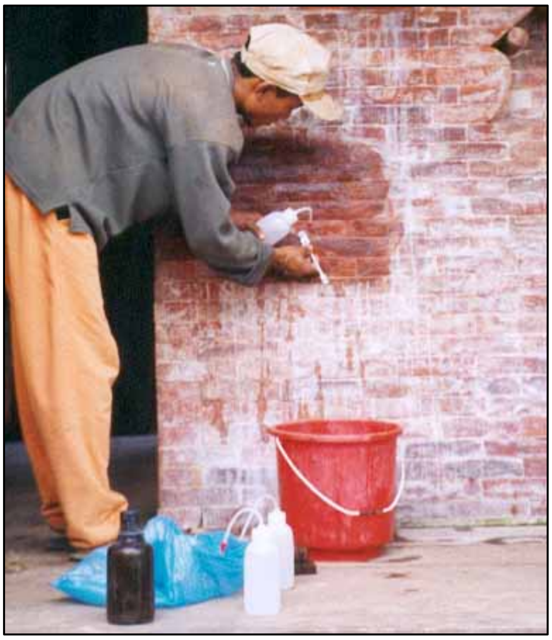
- Reduce shrinkage of the clay mortar by adding 50% sand.
- Apply a bonding mortar, such as lime-soil or lime-cement-sand.
- Apply long through-bricks from the façade into the inner construction. This requires the special manufacture of long bricks.
- Connect the outer façade bricks with the inner façade bricks with a 2.2mm galvanised wire or a 3mm woven Polypropylene (PP) rope, thus providing an anchorage. For this purpose it will be necessary to drill holes in the façade bricks. Anchors need to be placed at 50cm intervals, horizontally and vertically (recommended).
- Place a fishnet mesh of pre-stretched PP rope over the width of the wall. Such a mesh needs to be manufactured with a 5-10cm maze and placed at 50cm vertical interval.
- Place a metal (galvanised wire-mesh or stainless steel wire-mesh) inside the wall at vertical intervals of 50cm.

Reconstruction of new wall in upper part of the Narayan temple using conical bricks in the façade and ordinary burned bricks on the inside. Incomplete clay filling in between joints will result in a loose wall structure highly vulnerable to earthquakes.

Mixing the yellow clay with 50% clean masonry sand can reduce shrinkage of the mortar inside the wall. This will have the following results:

1. Less water is needed to obtain the needed plasticity for filling between the bricklayers.
2. Because less water is used, the bricks will absorb less water and drying will be faster.
3. The lesser amount of water also causes lesser swelling of the clay. Because the sand is an inert material, the overall shrinkage will be about 50% of the pure clay shrinkage.
4. Efflorescence (crystallization) on the outside façade of the brick wall will be reduced as there is lesser water to absorb the lime and salts from the clay during evaporation.

Mixing the sand-clay with lime will further reduce shrinkage and increase bonding.
Making a sand-lime and cement mix will eliminate the shrinkage. Mixing cement in the presence of clay is eliminating the action of the cement and must be avoided.

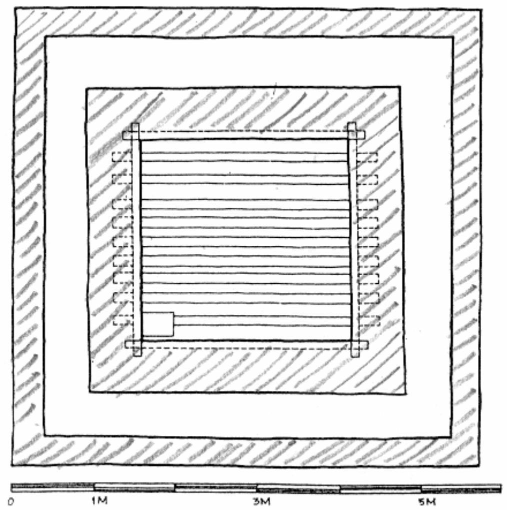


Heavy sedimentation and efflorescence caused by clay is very difficult to remove from the bricks.

8. FLOOR DIAPHRAGMS

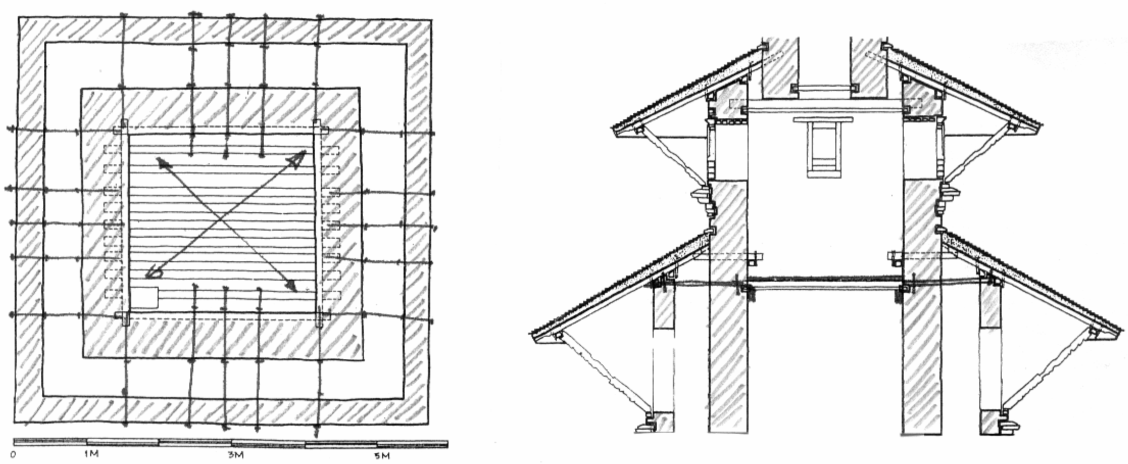
<u>Internal Floor Diaphragms, Existing Situation</u>

The floor constructions for the three temple floors are all of similar design. On the top beams the support walls for the top roof are placed (see vertical section below). The beams are laid in one direction and the anchoring of the beams into the walls is by support only. With dry brick masonry the beams lay loose in the walls and therefore are not adequately attached to the floor diaphragm. The floor diaphragm does only little to resist outward stress forces on the walls. This outward stress resistance needs to be improved in the two horizontal directions. The outside truss tie-beam must be connected to the inner floor diaphragm. Considering the thick wooden construction with beams and hardwood planks, the flooring will resist inward-directed forces.



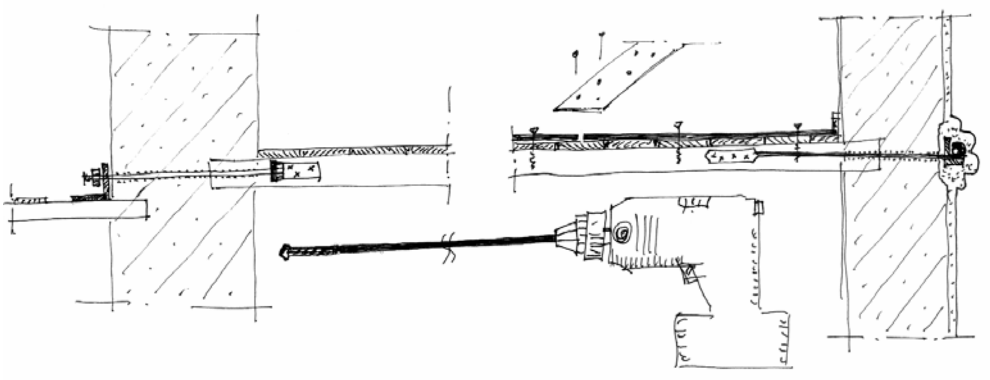
Existing Floors in Narayan Temple

Improvement of the stress resistance between floor and outside wall ties must be made between the floor and the external wood construction of columns and roofs. Where possible the horizontal truss beam should be constructed around the outside of the wall. Reference is made to the overall cross section of the temple. The ties can be made from galvanised steel strips or stainless steel rods.



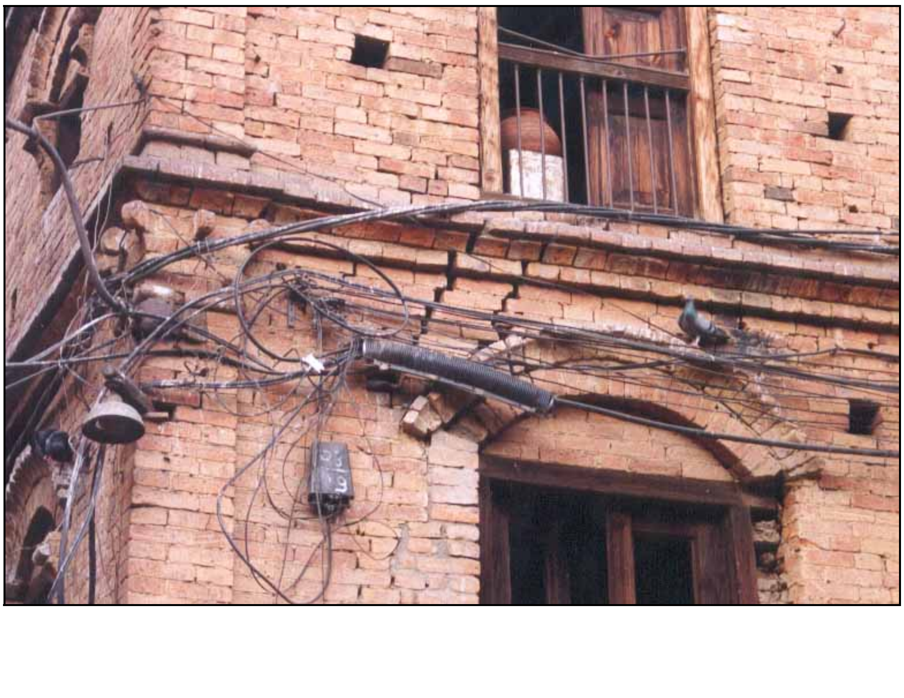
Improved Anchorage from Inner Floor through Main Walls and to Wall Plates and Roof Diaphragms

First Temple Floor: The ties need to be connected from the floor beam, though the wall and onto the first perimeter floor. In this case the drilling of rods is possible. Rod drills 100cm long can be made by welding a high-quality stone drill onto a straight bar of 75cm. Low speed drilling alongside the wooden floor joists and through the soft brick is easy.

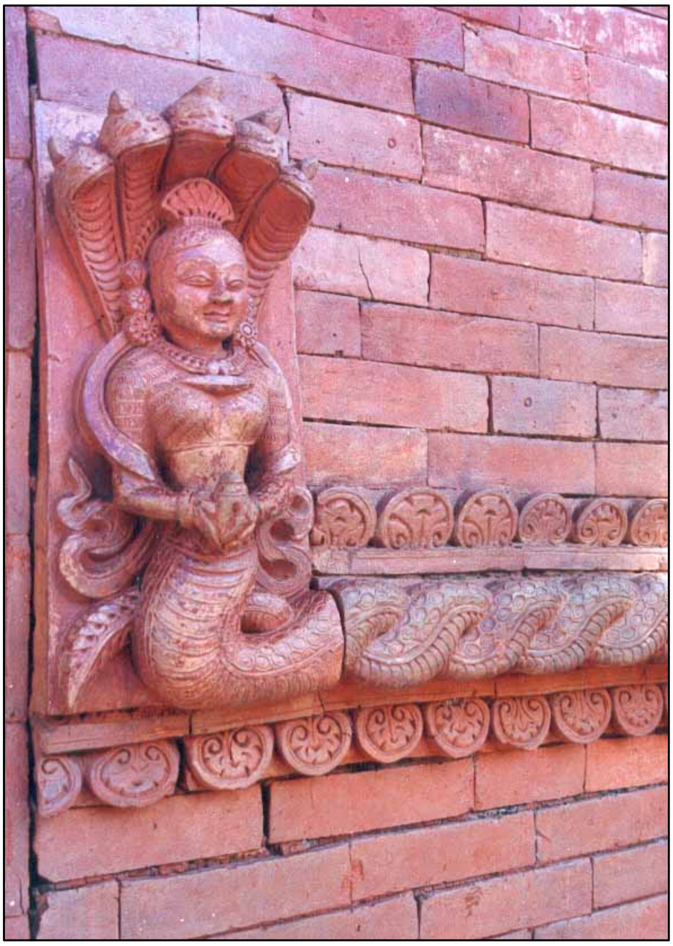


Second and Third Temple Floors: According to the section of the temple, connector bars can be made straight from the floor beams all the way to the wall plates on the exterior walls, just under the roof. This will connect the inner floor to both the exterior wall and to the roof. The two roof constructions, when these are built as four diaphragms that are linked together over the corners, will hold the walls inside, whilst the inside floors will be pressure resistant. Depending on the strength of the tie-beam construction of the combined roof sections, additional floor ties are not necessary.

Housing Floors: Ties in housing floors can be made from 10mm concrete reinforcement bars, flattened on one end for nailing to the floor beams. The section sticking out of the wall (when pushed through from the inside) can be bent to provide outside anchorage to a steel profile. Anchors can be placed at intervals of 60-90cm. Often in housing a brick decoration is made on the outside at each floor level. Other houses have a plastered ridge on the exterior at floor level. These exterior designs can hide the outside floor-tie constructions that perforate the solid outside walls. Floor diaphragms are created by screwing ¾" thick water and insect-proof plywood through the existing floor planks into the floor joists. The panels should be staggered and the sheets well fixed onto the same beam. The use of galvanised sheet metal, nailed to both sheets of plywood where they meet on a floor beam, will provide a good solution. Preferably galvanised nails and screws should be used.



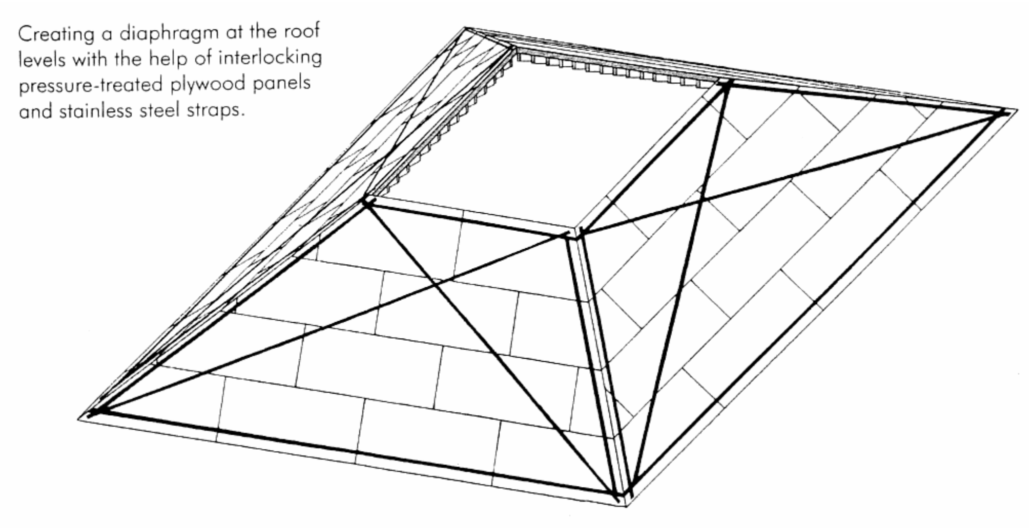
Traditional house being taken apart for reconstruction. The loose bonding of the inside of the wall can be noted. Although the outside wall is bonded with lime mortar, there is hardly any connection with the inner part of the wall that is bearing the floors. To improve this, through-connection from the inner floor to an external tie is essential. This can be done by placing a tie-beam on the joists of the external roof.



Newly reconstructed temple wall with conical bricks. The decorated snake line would be suitable to hide the external horizontal anchorage that connects to the floor beams.

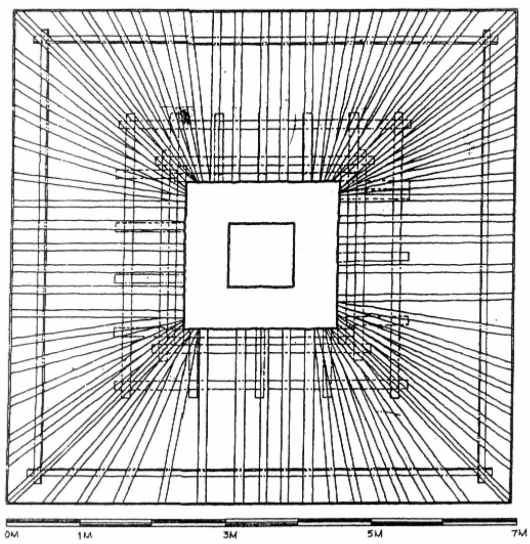
9. ROOF DIAPHRAGMS

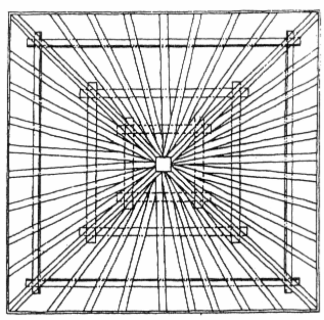
The two KVPT seismic strengthening reports suggest the application of plywood over the roof deck (made of thick hardwood planks) and the application of metal straps around the borders of the trapezium-shaped diaphragms. That principle is correct but requires good detailing.



The following observations can be made:

- The thick wooden deck planking is not visible from below because of the heavy joists (photo page 27). This deck can be replaced with pasted-up[8] plywood panels. If the wooden deck planking is eliminated, a vast amount of costly hardwood can be saved (5000 kg), as well as labour. If eliminated, the total weight of the roofs will also be reduced by about 4½ tons.





Existing Roof Beams of the First Floor and Top Roof Showing Heavy and Dense Support Beam Structure

[8] If plain plywood panels are directly nailed onto the roof joists, a good observer may be able to see from below that no planks are used. The pasted-up plywood panels are nailed with the added strips downward, providing the authentic look. The plywood panels need to be cut to size so that they join together on a roof beam. This is far less costly than the traditional design, but only slightly more expensive than plain plywood panels without paste-up.

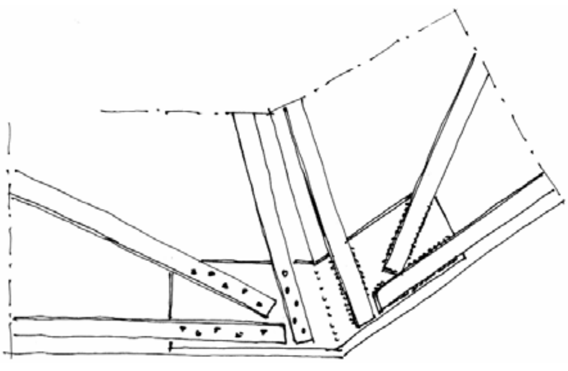
- Instead of the thick wooden deck planks, waterproof plywood can be nailed over the joists. By screwing the plywood to all the joists, making sure the joints are lapped with additional strips (see house floor page 24), each roof trapezium will become a stiff panel.

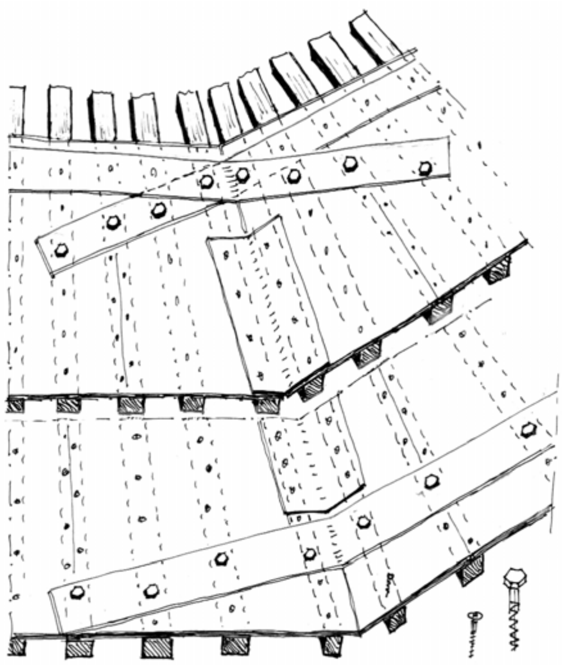
- Connecting the roof trapeziums together with stainless steel straps needs close attention. While three bars are joined in the corner, all forces of those three bars should be transmitted around the corner. A single bar connection of a similar cross section is structurally inadequate (see sketch on previous page of wrong application).

- The trapezoids can be additionally linked over the inclined junctions along their full sides with a nailed strip. This will enhance the total coherence.

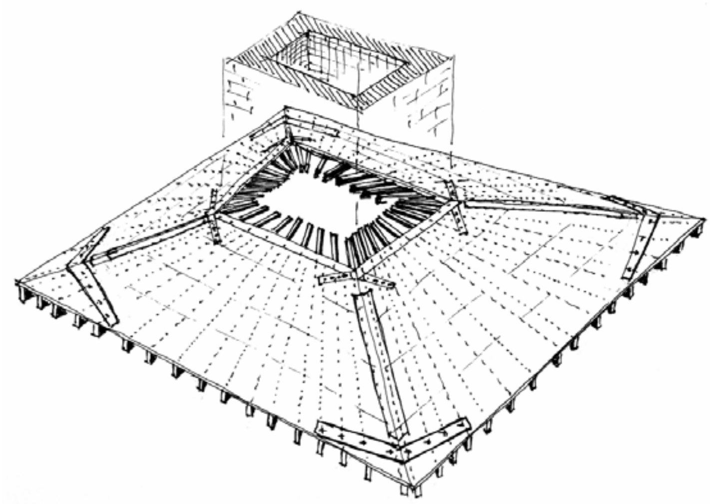
Two possible solutions of applying the reinforcement bars over the roof diaphragms.

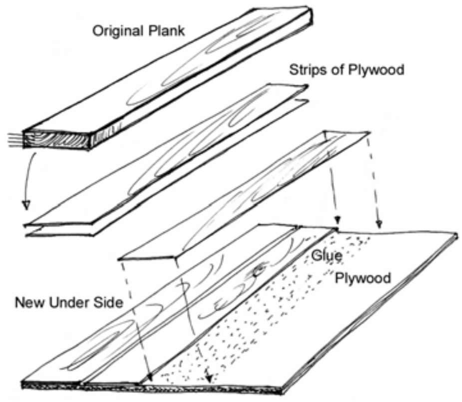
On the right-hand side sheet steel is nailed over the joint between the two roof surfaces.





- A plywood roof top cannot carry a clay layer as this will slide down due to inadequate adherence caused by the smooth plywood surface. The clay layer should be abandoned anyhow because of its weight and negative earthquake characteristics.





- The traditional tiles allow water leakage to pass through, especially with wind or when tiles are broken. Heavy duty plastic foil (PVC 0.10mm new or 0.15mm recycled)[9] should therefore be first placed on the roof panelling to prevent the plywood from becoming wet from water leakage. At the bottom of the roof eventual water leakage must be allowed to drain off easily.

- Over the plastic foil, a heavy-duty galvanised wire-mesh is fixed (stapled) onto the plywood.

- A good connection needs to be realised between tiles and roof diaphragm. Holes can be easily drilled through the soft tiles. The tiles can now be attached with PP ropes to the wire-mesh. PP ropes can also be stapled (machine stapler) with galvanised staples to the plywood when no wire-mesh is used (see sketch page 30).

- Because the waterproofing of the roof will be substantially improved with the plastic foil, the spacing of the tiles can be slightly increased. They do not need to overlap more than two times. This will decrease of the number of tiles by 15%, saving material, weight and cost.

- Because of the low angle of the roof construction when seen from below, the differences in tile angle and tile quantity will not be visible at all. The lowest roof surface is only visible from a distance of 25 meters from the temple base.

It is clear from the weight calculation that the clay padding must be removed entirely and replaced with new techniques utilizing modern materials (not visible).

In houses the clay will assist in keeping the house cooler during the summer, but this can be achieved using several other (lighter) thermal insulation materials.

The photo on page 6 shows the underside of the roof with different colours of planks. The same effect can be achieved with the strips of plywood.

[9] Two types of PVC foil are available in the market; new foil, being transparent and more costly, and foil with partly recycled plastic. The recycled plastic is coloured (grey) and in Nepal commonly used for leak-proofing formwork before casting of reinforced concrete. Both foils have little resistance against UV light, but can be perfectly used in closed building components, such as inside roofs where no sunlight will penetrate. The minimum thickness is recommended.

10. ROOF TILES

As indicated in the weight/mass calculation table, the heavy clay layer under the tiles, combined with the large surface of the several roofs, have a large influence on the total weight of the temple and, consequently, a large impact on the earthquake forces.

The traditional tile-on-clay design is maintenance-wise an economic disaster, requiring frequent (costly) repairs.
With the new design proposal, no difference can be seen from the outside.

Not only is the weight an important factor to consider, but also the maintenance. Monkeys who have access to the roofs are an additional factor causing the loosening of tiles. The recently reconstructed Indrapur temple has already loosened tiles, even without having problems with monkeys. In this temple the ridge tiles are tied together with copper core electric wiring, providing a suitable solution for the ridges, but all the other tiles are still loose.

The traditional tile-over-clay roofs of a large number of houses in Kathmandu and Bhaktapur have abundant growth of grass and weeds between the roof tiles, nurtured by the underlying clay soil and water penetrating in between the tiles (see photos pages 3 and 4).

A theoretical advantage of this green carpet is that its root system holds the tiles and the soil together, whilst at the same time the plants extract moisture from the clay. The more it rains, the faster the plants grow. During the dry season the weeds die first and then the grasses, but the greenery resurges with new rains. In addition the thick roof provides a cool climate inside the house.

The disadvantage is that the roof load is excessive. Moreover, the water penetrating in between the tiles will cause the woodwork under the tiles to rot and eventually collapse under the weight. A lightweight, waterproof roof with well-fixed tiles is preferred in earthquake areas.

The temples least damaged in the earthquakes were those having copper-plated roofs, thus having a lower roof weight because of the absence of the roof tiles and underlying clay soil. When the original character and design of the tiled roofs need to be maintained, then the heavy weight of the tiles will remain, but other weight factors should be reduced.

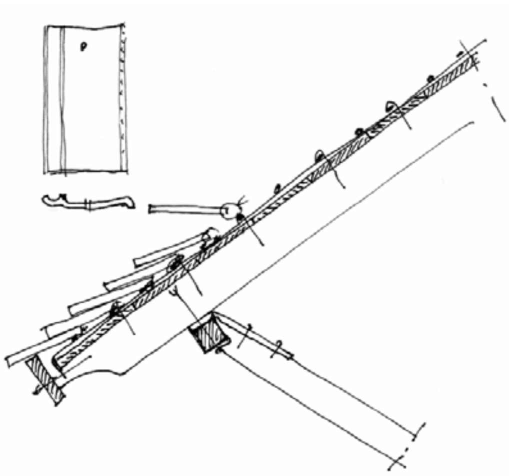
The proposed improvement for the roofs is therefore five-fold:

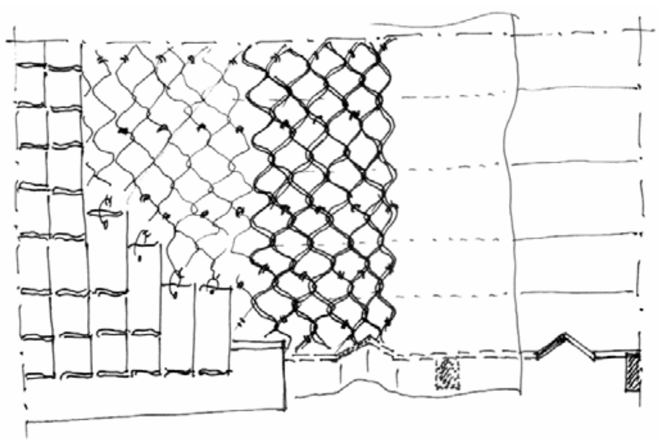
1. Reduce the overall weight by eliminating the clay layer and eventually reducing the thick hardwood deck under the clay layer.
2. Improve the strength of each roof diaphragm by screwing waterproof plywood on the roof joists, preferably instead of the thick hardwood roof deck.
3. Improve the connection between the four roof trapeziums by strips of tie-irons strongly bolted to the first group of purlings around the corners.
4. Improve the water evacuation of the tile roof with a thick plastic foil under the roof. The support structure will remain dry because the 0.10mm (new plastic) or 0.15mm (recycled) thick plastic foil will prevent leaking water from filtering down in between the tiles due to wind and/or broken tiles. The plastic foil must drain at the bottom[10].
5. Provide anchorage for the roof tiles by placing a galvanised wire-mesh over the plastic foil on the roof deck. Holes can be easily drilled into old roof tiles, while new roof tiles can be manufactured with a hole. A PP rope is pulled through the hole and knotted to the galvanised wire-mesh or stapled onto the plywood (when no wire-mesh is used). This way all tiles will be permanently fixed, requiring minimum maintenance for the first thirty years.

The ridges can be fixed with brown copper core electric wire as already done by KVPT.

The suggested design is illustrated below. It is recommended to test this construction first in smaller roofs so that the craftsmen can practice the method of assembling. The short- and long-term savings are considerable, whilst reducing earthquake hazard from heavy roofs and dropping tiles. Capitalizing on this new construction signifies economical savings of many Lakhs for each temple roofing and equally in retrofitting of housing.

The drawing on the second page (Abstract) shows all the roofs of the temple, demonstrating the importance of having a better tiling method, considering the overall surface and weight.





[10] In Europe special roofing foil is available with overlapping ventilation flaps. This can be important for housing when attics are not adequately ventilated and humidity from cooking or people is produced inside the house. This is not relevant for the temples because the bottom side of the roofs are completely open.

11. INTERNAL BRACING

When the walls are in their original non-bonded brick masonry without adding lime or other binder, it is highly recommended to construct some additional bracing inside the temple. With the reconstruction and restoration of the Chyasilin Mandapa Temple in Bhaktapur Durbar square, a light metal frame support structure is visible from the ground floor. Because of the rather low weight of this entire temple, the support structure is not very heavy and somehow blends in with the woodwork. The weight of the Narayan temple would require a heavy metal framing if it was to carry the full weight of the construction. The massive metal framing constructions suggested in one of the earlier KVPT reports is an illustration of the engineering problem with a stiff support structure. In such a case it is suggested to make a flexible bracing that will work together with the original stone construction and allows some movement.

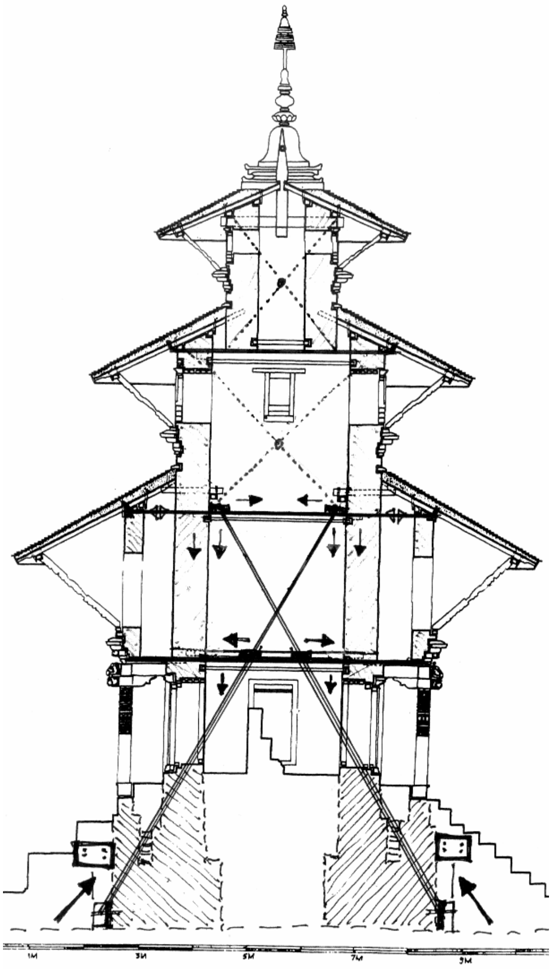
Chyasilin Mandapa Temple in Bhaktapur Durbar Square
with internal metal bracing in reconstructed and restored temple.

Three internal reinforcement or retrofitting bracing options are possible.

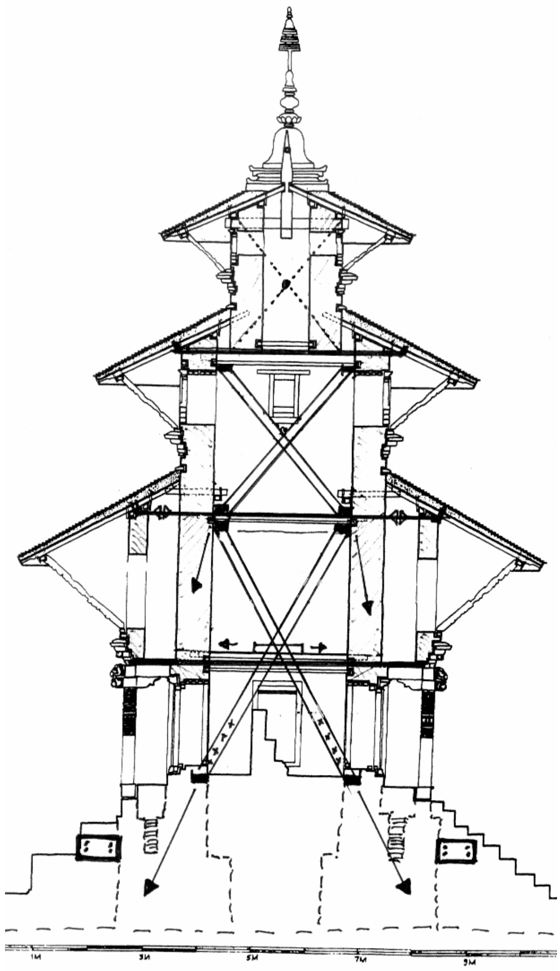
1. **<u>Stress/stretch</u>.** This is based on resisting the outward swaying of the temple walls (with roofs) by applying stress cables to the floor diaphragms. This supposes that the floor diaphragms hold the building together at every level, connecting the outward moving walls to the inward moving walls, and that the forces from the walls can be transferred to these stress cables. For this it is essential that the floor diaphragms are through-connected to the roofs. A possible problem with this design is that the diagonal stress cables need to be anchored deep inside the foundation.

2. **<u>Support</u>.** This is based on wooden supports fitted under the floor diaphragms, resisting the inward movement of the external walls. This also supposes that the floor diaphragms hold the building together at every level, connecting the inward moving walls to the outward moving walls, and that the forces from the walls can be transferred to these supports.

3. **<u>Support/stress</u>.** This is based on a combination of the above two systems. The wooden members provide the support, while in the other direction supply stress connection. Although the support is simple to realize from the foundation upwards, the stress resistance from the foundation upwards can only be realised following the mechanism described under 1 above, thus making the reinforcement technique double.



Drawing of Stress Reinforcement



Drawing of Support Structure

Stress/Stretch-Ties

The stress cables need to be fixed at the lowest part of the foundation, below the ring beam. This can be done by drilling holes right through the stone work. This will be easy when the foundation walls are made of burned brick, but almost impossible when the foundation is made from large natural stones. The cables need to be tied to the top of the second floor diaphragm, one set in each corner and stretched to the required tension. Either suspension bridge cables can be used or 3mm galvanised wire fixed in all of the four corners.

The advantages of the stress-ties are the minimal amount of (visible) material and the possibility to make tension adjustments after installation. Both cable and steel bar stress-ties are possible. Woven suspension bridge cables can be used (with high elasticity) that gradually build up resistance with increase of stress. The stress on the cable or bar is developed when walls (with the floor diaphragms) flex outward because of seismic movements. The more stress applied to elastic cables, the more they will resist and absorb the impact. When the cables exceed the elastic stress capacity, they will deform slightly, with that absorbing part of the impact. With the second earthquake movement they will again resist forces from their new elastic point to deformation. Suspension bridge cable has a higher elasticity than galvanised wire, but galvanised wire has a longer deformation trajectory. For low-cost application, the commonly available 3mm hot-dip galvanised (Gabion) wire can be used.

Cables can be made of 3mm galvanised wire (200 kN/cm²), having a higher tensile strength than mild steel and can be easily brought into the narrow temple building. Car tire rubber strips must be placed between the wood and the wire to avoid damage of the galvanised wire. The wires can be stretched by twisting the bundle; once on tension, the twist-point needs to be locked and the wires painted. Placing the wires through a black HDP water pipe is recommended.

The total load of the Narayan building above the second floor is 76 ton; 18% = 13.7 ton.
Two diagonal bundles together (at 60°) require about 14 ton resistance.
One 3mm wire (7mm²) has a total tensile resistance of about 14 kN or 1500 kgf. This means that in total only 10 wires of 3mm are necessary, five on each side.
To tie the entire floor diaphragm in its four directions, eight 5-wire bundles are recommended to fix to the second floor diaphragm.
The weight of the section between the second floor diaphragm and the first floor diaphragm is 56 ton, requiring 10 ton additional resistance or three extra wires per bundle.
When the temple would have been reconstructed in a lower weight, a much lesser number of wires would have been required.

The advantage of the wire-bundle reinforcement is that by overstressing, the wires will start to deform but will not break. During that deformation process the impact of the earthquake is partly absorbed. This can be important when there is only one big shock, followed by a series of smaller shocks. The resulting downward forces need to be absorbed into the main supporting walls, and the lifting forces need to be countered from the heavy foundation. When the support walls are structurally not strong enough to take this load, the stress wires would not be a good solution.

Support Frame

The second option is a wooden support frame, also connected to the two floor diaphragms, that works to resist sideways and vertical pressure, being the result of the lifting factor[11]. In this case an excessive horizontal inward force from the top and middle part of the building is resisted by the diagonal supports standing diagonally on the foundation. When the wall wants to move inwards against the floor diaphragm, the diagonal struts will tend to lift the floor diaphragm, but this lifting is resisted by the above mass; thus deflecting the force downwards along the diagonals. This construction requires a rather stiff load distribution beam under the floor diaphragm, and a floor diaphragm that is well anchored into the wall. Where the floor beams are laid into the wall, this is easy to achieve; but where the floor beams are parallel to the wall, the floor beams should be fully connected to the walls to make a stiff platform. The eight support diagonal beams must be well supported by the foundation on the bottom.

To reduce the buckle length, the diagonal wooden struts are firmly joined together at their crossing with the first diaphragm floor. A moment-stiff connection will shorten the theoretical buckle length, requiring smaller wood dimensions than with a loose connection. In the case of the Narayan temple, the inclination of the supports can be about 60°, making a diagonal from the foundation to the second diaphragm, allowing a free door passage at the Sanctum. The maximum recommended inclination is about 75°.

The minimal cross section of the diagonal hardwood supports beams, each carrying about 7 tons (resistance hardwood about 10 N/mm² = 100 kg/cm²) is about 10cm x 10cm or 100cm², considering a buckle length of only 240cm. This buckling length takes into consideration that the junction of the diagonal beams is fixed in a moment-resistant design, reducing the theoretical buckle length.

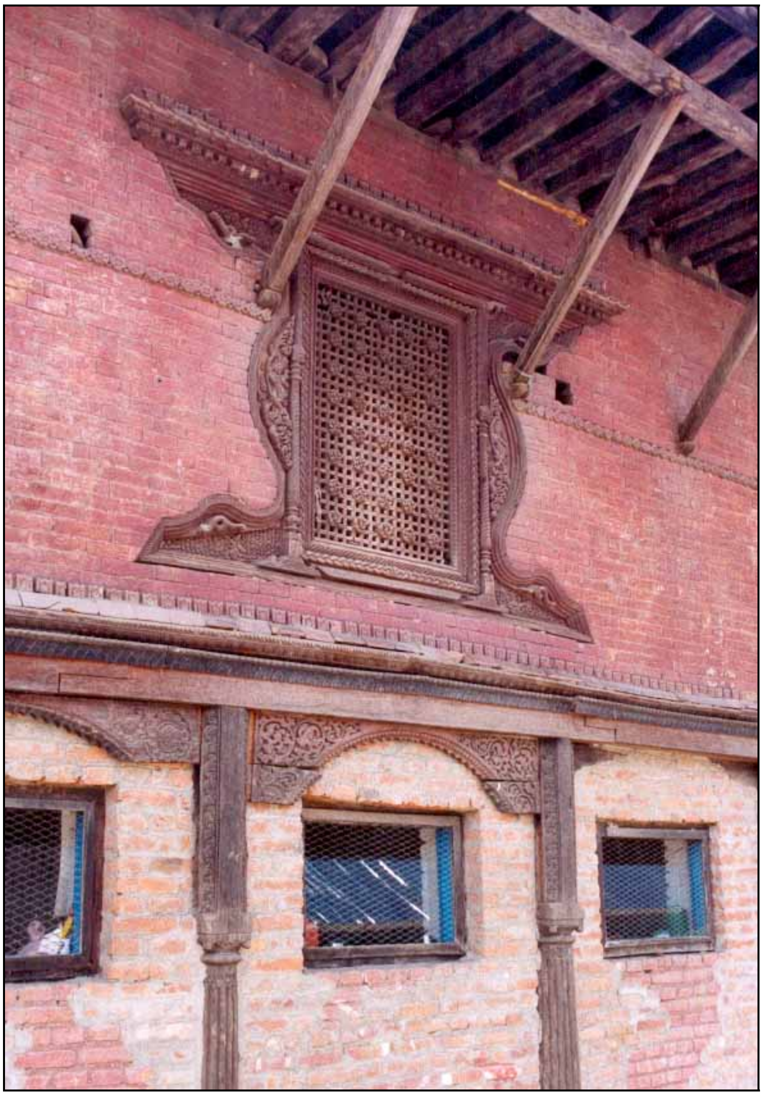
This wooden support frame can only absorb some stress forces when it is attached to the foundation as indicated with the cable design. When stress is taken on one side of the temple, the pressure force on the other side will be reduced in the event that the temple is a rather stiff construction. With dry masoned walls this may not be the case. Therefore, reducing the dimensions of the wooden support to calculate for a combination of both stress and support resistance of opposing beams may not be

[11] The lifting factor is caused when a sideways earthquake force pushes the mass against a fairly upright diagonal. This diagonal will start to move to a more vertical position, needing to lift everything above it. The above-located mass creates the counterforce. With an angle of minimum 10 degrees from the vertical, this still works very well.

logical. For this reason it may be more simple to calculate only on the basis of the stress or the support reinforcement; not both.

An advantage of the hardwood support frame is that the material is locally available and the framing can be applied at a later stage after the restoration of the temple. In contrast, the making of the anchors inside the foundation requires extensive digging and reconstruction work on the foundation.

The support or stress designs are not irreversible, but both require good floor diaphragm constructions that are well anchored to the walls and the roofs. Care must be taken to ensure that any wood construction is well preserved and direct contact is avoided with the masonry because this may cause rot. This can be done by placing bitumen mastic paper between wood and masonry. Especially the footing of the wooden supports need to be protected from rot or humidity. The disadvantage of the wood construction is that it requires a substantial amount of tropical hardwood.



Above the columns and lintel a built-out ridge can be noted.
The ridge partly protects the lintel and can hide floor anchorage.

12. RESUME

When we observe the traditional architecture of the pagoda-type Newari temples, two important elements are outstanding: the large roof surfaces all around the building in several layers, becoming smaller at the top, and a dry-masoned core and support structure. This dry-masoned core structure has very thick walls and traditionally has a slightly flexible but balanced structure. The Narayan temple has at its first level a line of wooden column supports around the dry-masoned core structure. All outside roof borders are supported with decorated diagonal wooden struts to the wall below.

In some of the pagoda-type temples, the roof structures are covered with copper plating instead of burned clay roofing tiles in a clay soil layer; in relation to earthquake forces providing an important advantage by its lower weight.

New materials and construction techniques have been developed since the temples were first built centuries ago. Improved bonding with cement mortar, stainless steel and metal wood connectors, bituminous paper and PVC foil for water proofing, galvanised nails, screws, staples and wire-mesh are only some examples. In reconstruction or retrofitting, the technologies can be used to lighten the construction and to improve resistance as well as coherence.

The technical recommendations provided can be used for both temple and building reconstruction (or retrofitting). These recommendations are based on the three basic principles of earthquake engineering:

- Reducing the weight (mass) of the construction.
- Improving the bonding (cohesion) of structural elements and improve the connections between several building components.
- Improve the overall resistance to alternating lateral forces and load impact.

Applying these techniques will enhance the durability of the building, especially during earthquakes, lower maintenance and reduce construction costs.

In general the technologies are an aspect of better local and natural resources management, not only in the building industry, but also in the tourist industry.

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