Cator and Cribbage Construction of Northern Pakistan

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INTRODUCTION

The 'English Movement' for the study of traditional masonry buildings in earthquakes dates from the 1970's. At this time Nicholas Ambraseys had built up an international reputation at Imperial College. Ian Davis, at Oxford, was heavily involved with aid agencies working in disaster recovery. 'Disasters', the journal of the International Disaster Institute, became an outlet to many academics including Francis D' Souza, Fred Cuny and John Norton, and this became a forum for reporting on damage evaluation, earthquake management, disaster recovery.

In 1980 the International Karakoram Expedition brought together many of the above and others including Robin Spence and Andrew Coburn from Cambridge University and myself from Ove Arup. The multidisciplinary team examined earthquake hazards and community vulnerability in Northern Pakistan.

For several years the team then traversed European and Asian earthquakes, applying ever improving investigation techniques. From this resulted ITDG and then EEFIT earthquake research panels. One of the most interesting results was the growing ability to account for damage characteristics related to site specific ground motions. Many engineering techniques were promoted for improving traditional building performance.

These periods of fieldwork have led to 20 years of conserving historic buildings, and developing upgrading techniques for local community housing. It was proposed by Nicholas Ambraseys as early as 1976 that in Northern Pakistan there had historically developed local earthquake resistance construction techniques. This construction comprised roofs separately supported from walls and walls laced together with timbers.

'Cator and Cribbage' is the most elaborate of these timber earthquake techniques, see Figure 1, and dating back here some 1000 years but still to be seen

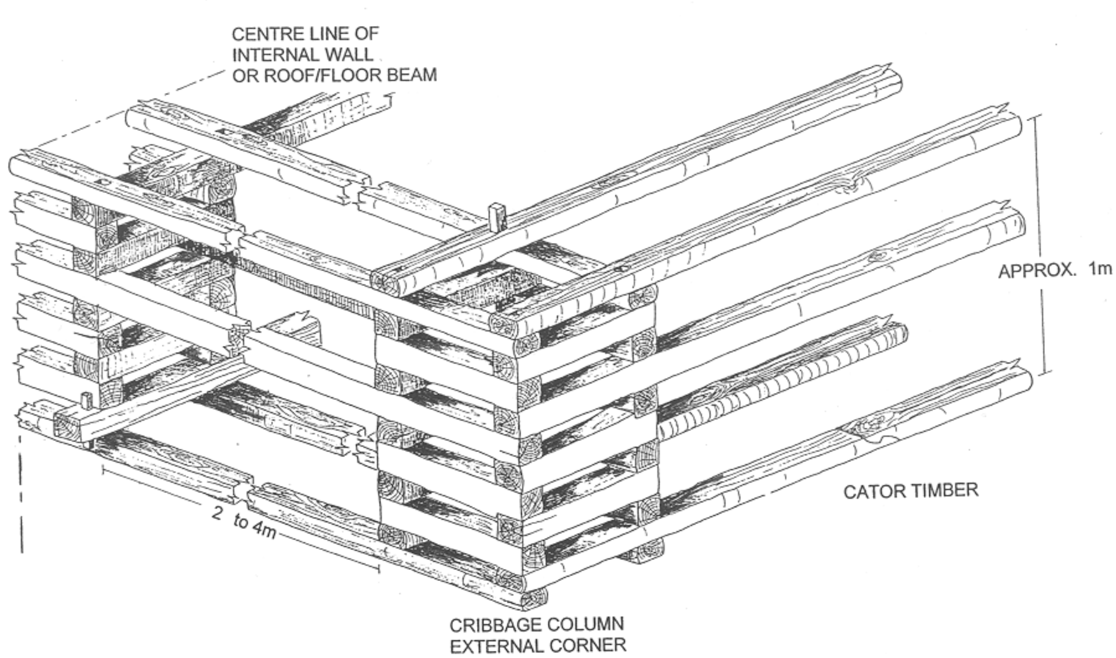


Figure 1: Details of 'Cator and Cribbage Construction

being built in some remote areas for defensive towers. The 'Cator' is the 'Hatıl' of Turkey and in Anatolia with an origin going back some 9000 years.

TIMBER LACING FOR STRENGTHENING WALLS

The use of timber lacing is perhaps first described by Emperor Julius Caesar, as a technique used by the Celts in the walls of their fortifications. Many fine examples, with a lot of variations, are to be noted from archaeological excavations of Bronze and Iron Age hill forts throughout Europe. Examples of lacing have been personally excavated and conserved at Moenjodaro, (Pakistan, 3,500BC), the Little Aton Temple of Akhenaton, (Egypt, 1350B.C.) Baltit Fort, (Northern Pakistan, 800 years BP) and Shigar Fort (Baltistan, 600 years BP). Other interesting examples have been studied in Greece, Macedonia, Turkey, Syria, and Yemen.

Traditional stone walls of domestic rural structures are generally weak:

- Shallow foundations without footings - which are highly susceptible to differential movements.
- Most walls are built with variable quality rubble found immediately to hand.
- Stones are placed in a haphazard point to point contact.
- Between the stones are thick irregular mortar (lime or mud) beds.
- Rubble stones are placed out of equilibrium and rely on the mortar and/or internal 'wedging' to maintain a stable position.
- Large stones are used for the inside and outside wall faces. These stones are adjusted by internal wedges to give a vertical face. There is also frequent change of stone sizes up a wall; as the wall approaches shoulder height the stones get smaller because they are manually lifted. The internal core of the wall is progressively infilled with small loose rubble, stone chips discarded from knapping, and leftover mortar. In domestic buildings 'through' stones and long 'quoins' are only occasionally used.

It is for these reasons that timber lacing is normally incorporated into the wall during its construction. Where the system is particularly elaborate the frame and roof can be built first and walls completed later.

The timber, which is added to walls, is clearly a strengthening aid used for its excellent tensile and elastic properties. For example, the British army during its 1891 military campaign in the Northern Areas of Pakistan noted that, "the seven pounder had no effect on the Nilt Fort walls". As this suggests, many structures that use timber lacing are of a military character. In Northern Areas of Pakistan the technique goes well back to the pre - Christian architecture of the eastern Mediterranean. Alexander the Great is known to have made use of the technology in his Asian Campaigns. From a general appreciation of warfare at this time, the military advantages of timber lacing were seen to be:

- Cannot be easily breached by ballistics - from catapults (and cannon, see above).
- Cannot be toppled and subsided by mining the foundations - the timber allowing for walls to span soft spots and for corners to be cantilevered.
- Can be built very quickly with inferior stone and no need for lime mortars (slow to make and slow to set) - the face being random rubble with loose rock core with the timber being the structural tie along and through the wall.
- In rugged terrain can be built quickly - ordinary stone walls need to be tied in to slopes and cliffs with foundation works - the system allows for spanning crevices.
- Walls can be very thin - for speed of getting maximum height with minimal volume of material.
- Local failure can be rapidly repaired - the timber considerable limits areas of stone face/core collapse.
- Can generate overhangs in upper storeys.
- Additional walls can be easily structurally be tied in.
- Timbers can be dismantled and reused - a 'Lego' modular approach.
- Cribbage work allows for the frame to rise more quickly than the stone work - do not have to rely on active carpentry on the top of the stone construction work.

The ability to resist dynamic forces was clearly appreciated and therefore it is not surprising to see its use in domestic architecture in earthquake prone settings. World-wide, it is such traditional housing that is becoming a rapidly dwindling heritage resource.

Photograph 1: Altit Fort Tower, Hunza, showing 'Cator and Cribbage' Construction

The timber is generally of 50 to 120mm square section and horizontal beams are placed into the inside and outside wall faces at 0.3 to 1.3m vertical intervals. In less well-built walls, the timber is infrequent and may only be reinforcing corners. Often the timber lengths are not jointed or nailed together. In better constructed walls the face timbers are tied together through the wall thickness with joined/nailed cross pieces at 1 to 4m intervals. Where the beam is of insufficient length for the whole length of the wall, two or more pieces are connected with tension resisting scarf joints. The beams at the corners are also jointed so that the whole building is strapped together. Breaks in the integrity of the 'ring beam' may occur at doors and windows.

The advantages of constructing an ordinary building with horizontal timbers are:

- The ease of creating straight sided walls.
- The need not to have the typically over designed foundations.
- Corner joints and long timbers providing tensile resistance to out of plane movements.

The disadvantages of timber lacing are:

- Can catch fire.
- Cannot form curved walls.
- Can decay rapidly, due to micro and macro organisms, usually at remote and hidden locations and beyond the site of visible distress.
- Can continually change shape and size due to fluctuating moisture content.
- Decay causes the wall fabric above to be dislodged.

EARTHQUAKE EFFECTIVENESS OF TIMBER LACING

When an earthquake strikes a building it progressively collapses and does so through a commonly occurring failure sequence. The process may all occur within a few seconds or over several minutes. A typical collapse sequence is:

- Ground strains and stresses develop that cause possible structural problems in future - not visible.
- Opening up of existing cracks, new cracks on renders, loose soil falls out. Odd stones fall out.
- Skin splitting in mid wall locations, inside render falls off.
- Small holes and cracks parallel to walls appear on roofs.
- New cracks develop up walls particularly at corners - direction depends on quoins, ring beams and foundations.
- Corner wedge failure.
- Detachment of roof from walls
- One non-load-bearing wall collapses.
- Collapse of roof from one side.
- Roof failure without wall collapse.
- Granular disintegration of walls.
- Overturning of whole walls.
- Rear wall failure where built into soil slopes.
- All walls and roof disintegrate.

The practical role played by timber in counteracting the above effects is supported by field observations from recent earthquakes for example, Turkey 1976, Pakistan 1981, Yemen 1982 and by model testing on seismic 'shaking tables'.

In support of the timber lacing having been purposely incorporated for earthquake resistance it is found in areas traditionally devoid of timber, for example desert areas of Iran and Egypt. This suggests that timber, an expensive commodity, may have been specifically imported as a building material for a specific purpose that resolves an exceptional problem, namely to withstand wall earthquake shaking. Table 1 defines the roles of timber cators.

TABLE 1

THE ROLE OF TIMBER CATORS IN NORTHERN PAKISTAN

PROBLEM	CAUSE OF THE PROBLEM, OFTEN RELATED TO THE EFFECT OF AN EARTHQUAKE	TIMBER CATOR ACTION
Vertical crack, tending towards uniform width, often connecting through windows and doors	Horizontal extension of wall. Outward bowing of wall	Mobilisation of the excellent tensional and elastic properties of timber baulks. The timber acting as an independent tie or as a ring beam
Vertical cracks, wide at the bottom and narrowing up the height of the wall	Dishing/settlement along the central length of the wall	As above
Vertical cracks, narrow at the bottom and widening up the height of the wall	Hogging or heaving of the central section of the wall. Leaning out of the ends of the wall.	As above
Tilting inwards or outwards of the wall, with or without cracking	High centre of gravity, Differential thermal strains, foundation rotation, lack of cross wall buttressing	As Above
Diagonal cracking up the wall with lateral displacements	Differential foundation movement. Corner and between window shearing	Resistance provided by tensional and elastic restraints, lateral stability provided along wall length.
Vertical splitting up the centre of the wall	Lack of through stones, loose rubble infill, external fabric decay, differential foundation movement and excess loads loaded on one of the external skins.	Tensional restraint of numerous cross wall ties that are pinned into ring beam
Diagonal cracking across wall thickness	Overloading of wall on too weak a material, tilting walls or swaying walls	Tensional restraint of numerous cross wall ties that are pinned into ring beam
Corner cracking often wedge shaped	Lack of quoins, roof splaying, softening of foundation soils at corner, thermal expansion	Tensional restraint of corner bracing ties
Torsional distortion of whole building	Differential ground movement, swaying and rotation of structure	Tensional resistance or ring beams with elaborate corner joints
Spalling of external or internal wall face	Loose mortar, eroding wall core, poor mortar, poor mortar bonding strength.	Limiting of the vertical extent of stone fall, more even spread of load down the wall face, damping of vibration

Timber reinforcement is also still common in the Himalayas where road retaining walls traverse across cliffs. The dry stone walls on convex bends and around spurs are reinforced with odd bits of branches and major timber baulks. Here, the timbers go back into the rubble fill and on the face are jointed into longitudinal ones.

THE USE OF TIMBER CRIBBAGE

Timber cribbage appears to be a wall building technique that is only commonly found in an area spanning Nuristan to Baltistan. Hunza is approximately central to this area. Whether it's use in buildings originated in one place and spread or independently evolved in several location is unknown.

Timber cribbage is used for other sorts of structure:

The technique of 'Cogs' is a well-known technique in the 19th century coal mines and recently used for roof support in old Limestone mines.

- Only short lengths of wood are used.
- The roof bearing surface is larger than for a pit prop.
- Greater bearing surface area on roof and floor.
- Less bowing of structure under load.
- Ease of recovery.

It was once common in Canada for the construction of river and lake quays. In winter a system of cribbage columns are built onshore. The completed structures were then dragged out across the frozen water surface to the required site and sunk as the ice melted. In Australia, timber houses when being sold and moved are stored on cribbage columns. The cribbage technique was extensively used in Roman and Medieval London for quay construction. The major bridge at Shrinigar also used the lacing technique and archaeological evidence suggests that Roman London Bridge was of the same form. The same use of infilled timber 'boxes' is the classic Murus as described by Caesar. The box structure in fort walls has many military advantages over an ordinary rampart, again able to resist large magnitude dynamic forces:

- The rampart can be made taller and narrower for the same quantity of rubble infill and with a corresponding same degree of structural stability as a simple rubble one with better quality stone faces.
- The transverse timbers can be used to tie back the front breast work timber.
- The system can withstand natural or man induced rotational landslides in loose rubble.
- It is very difficult to pull the system apart. Rather, it has to be slowly undone by an attacker and this has to be done in long lengths to fully breech it.

THE DECLINE OF CATOR AND CRIBBAGE IN NORTHERN PAKISTAN

It is now rare to see new Cator and Cribbage being constructed due to the following factors:

- Fashion for modern houses in brick and concrete.
- Decline of tribal exchange.
- Deforestation for wood 14000 hectares each year in Pakistan in 1980's and 11300 hectares annually in the 1980's in Afghanistan. The export of wood out of the mountain areas: e.g. 3000 cubic metres from Afghanistan to Pakistan each year in 1980's. In Pakistan the growth timber speculators who take over forests solely for rapid profits. The villages are therefore becoming disassociated with the surrounding wood supplies. To permit transport of timber down the valleys and rivers and for movement on trucks it is cut into short lengths - too short for full length cators in traditional houses. The wood would need to be spliced with scarf or lap joints that are no longer part of the repertoire of the carpenters.
- Wood reinforcement was extensively used on mosques, forts and the houses of the rich. Forts are no longer needed and the rich use fashionable materials. This means that ordinary people no longer copy.
- There has been a dramatic population expansion and mass movements of refuges and all long wood is needed for roof beams.
- Wood burning methods in open fires are inefficient - now addressed with the Aga Khan bukara wood burning stove and the introduction of bottled gas.
- Inhabitants now are willing to live with the decay and structural distress until such times as the whole building is replaced.
- Wood mounted in the front facade is no longer a status symbol - replaced by concrete or paint.
- Lack of skills for replacing decayed members.

- There are no traditions for treating wood with preservatives.
- New buildings in traditional villages are built around the edges. These houses are built by young couples who wish a new sort of life style and form of house.
- After an earthquake people have been unable to see or appreciate the effectiveness of timber reinforcement so its use has been discontinued and aid agencies import new construction techniques.
- Some of the areas where wood was used are no longer seismically active (or are dormant?).
- The quality of the traditional woods are no longer so good and are less durable. Pine is being replaced by willow and poplar. The wood is used when young and green, and therefore is less workable.
- In new houses the same reinforcing effects can be achieved with modern materials that are cheaper - cement mortars/RC ring beams.
- Many more recent examples of cators are as rounded timbers with bark - these are less good for carpentry processes and not as good for holding in place stones - this has given the technique a bad reputation.
- The use of stone is becoming very expensive (when compared with concrete block, for example). The use of soil is not used much today because of durability-image problems.
- Aid agencies have given priority to the arrangement and size of house spaces and keeping costs down. Solving technical problems has focused on foundations (deeper and larger to stop walls cracking) and flat roofs (where long timber for beams is seen as more essential).

THE FUTURE OF CATOR AND CRIBBAGE IN NORTHERN PAKISTAN

The inhabitants in the highly seismic zones of the Northern Areas are being encouraged to resist the recently observed trend to abandon high quality traditional construction techniques. For example, the Aga Khan Housing Board is running carefully considered education and training programmes, showing how structures can be better engineered.

New buildings can be modified by better detailing, taking a new form or change the structural shape, better site selection, the introduction of timber lacing, the use of reinforced concrete/steel-mesh ring beams and by adding non-load bearing vertical reinforcement.

In the Northern Areas one way 'Cator and Cribbage' is being encouraged is through the preservation of historic buildings. One of the great international achievements here has been the conservation of Baltit Fort.

In Turkey, planning authorities must be applauded for their recognition that timber lacing is part of a useful tradition that can still be utilised. 'Adobe Buildings and Construction Methods'- Turkish Standard TS 2515 details the way timber can best be incorporated into ordinary houses, in an uncomplicated way, and where the inhabitants are familiar with the theory behind the technique, and indeed have seen it work!

THE CONSERVATION OF BALTIT FORT

Baltit Fort is the most important historic building of the Northern Areas. Dating back some 800 years it has been at the centre of the 'Great Game', see Photographs 2 and 3. It is now an international tourist attraction and research centre and has been responsible for initiating many other conservation projects and encouraging community development.

The conservation design and implementation fully followed UNESCO approved processes standards and conventions. Related to the 'Cator and Cribbage' structure, the following approach was undertaken in respect of engineering concerns:

- Structural deformation to be left and illustrated as part of the building's history.
- Structural continuity after monitoring of past and active movements and assessment of phases, how the structure works, external dynamic forces, future uses. Some upgrading of the system therefore appropriate.
- Structural readjustment only for severe distress.
- New structural systems to be traditional and modern – each to satisfy a particular case.
- Chemical treatment where significant decay found and where the cause may not be fully remediated.
- Wood replacement to structural members if more than 20% cross section decay.
- Maximum reuse of removed wood – cutting down to new sizes.
- Replacement wood to be old and well seasoned and tested.
- New wood obtained in traditional way at traditional harvesting times.

- Community participation in conservation processes.
- Use of some simple conservation techniques, which workers can see applicable and affordable for spinning off to improve their traditional houses.

At the design stage the greatest technical concerns were:

- Stabilising foundation settlement by underpinning in loose glacial soils.
- Removing a long cator and inserting a new one.
- Removing an element of a cribbage column.
- Rectifying a wall distortion without dismantling rebuilding it.
- Tying, or not, the structure together for seismic upgrading.

After the removal of Baltit Fort's render the following complex set of conditions were noted and are very similar to those seen in the traditional housing stock.

- Most wall timbers were in a very sound condition with pegged connections still efficiently working.
- The cators serving as wall plates for roof beam connections were generally decaying on the upper surfaces.
- External cators at and below ground level were decay prone, most evidently where rain was infiltrating. Perhaps most decay was in the cator timbers used in the surrounding retaining walls.
- cators in foundations or in walls buried below internal floor surfaces often were as fresh as the day they were placed there.
- Springing of cators away from the wall face, resulting from stone displacement, Bowing of walls was most evident in the west facade and the builders had at some time attempted to stop the movement by inserting beams with large exposed 'through' pegs - serving as wall tie plates.
- Pulling out of cators from their sockets only occurred where they were part of an additional phase and had been inserted.
- Major wall settlement – up to 400mm along the south façade
- Grain splitting and surface mulching of exposed wood and where the fabric was subject to dry winds and high levels of UV light. The timbers were generally structurally still working well but the decay was found to be the cause rain penetrating the core of the timber and allowing insect attack. On the north facade the rounding off of the cators then allowed for stones and soil blocks above to be dislodged.

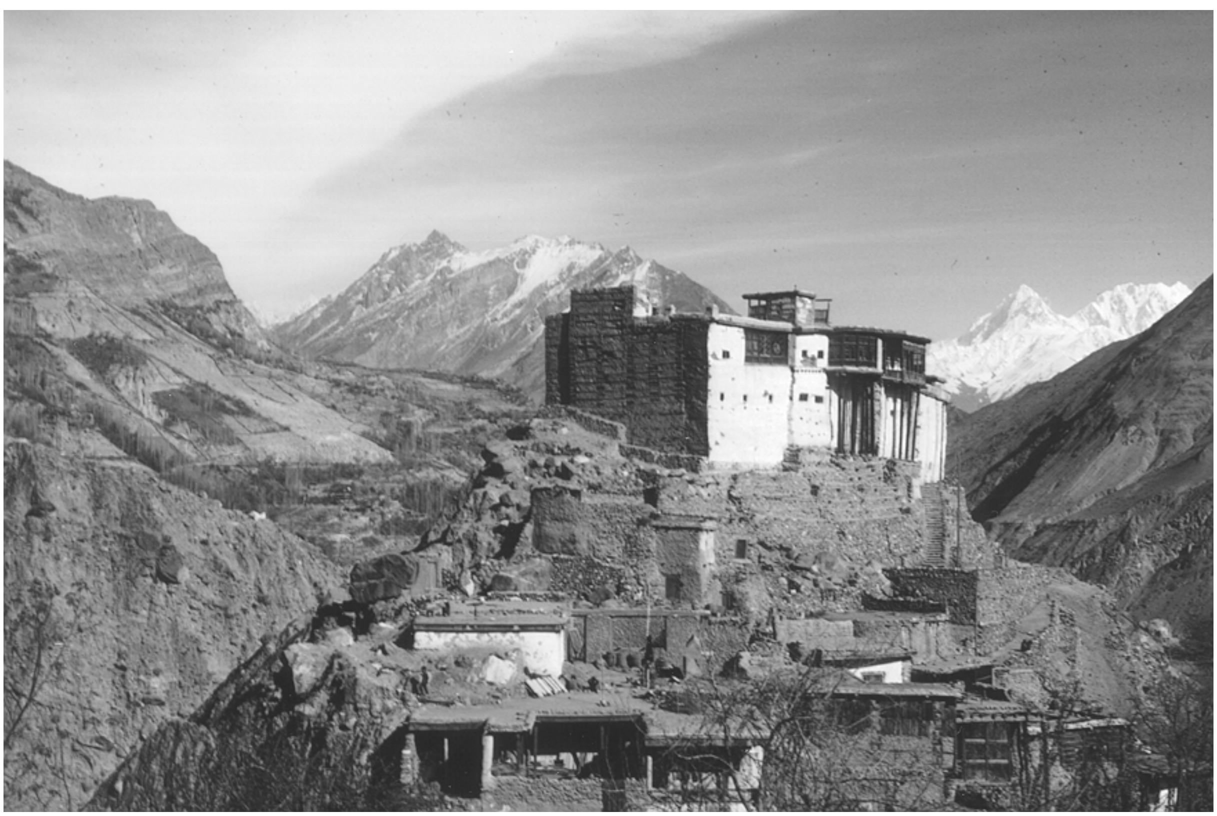
Photograph 2: Aerial view of Baltit Fort, Hunza.

Most decay occurred to softwoods particularly poplar and willow - and these being those used only in the more recent phases of construction. Juniper is the most resilient wood and the inhabitants say it never rots and it is cut at special times of the year when the sap is resistant to insect attack. Due to the character of Juniper it was generally used in only short lengths - mostly for high quality cribbage work. Apricot is also reported to be good for cribbage. Most cators were Duadar/Glindour - Himalayan Pine as this was once abundant through the whole area but is now imported. Walnut was used mainly for the carved room columns.

Major structural interventions were at just five locations:

- Along the South Façade, where the foundations were deep but sitting on loose glacial soil powders mixed with straw (thrown off the roof of an earlier phase of the structure). Some of the timbers were found to be decayed and were individually replaced during wall underpinning.
- At the southwest corner, where the walls had only shallow foundations sitting on the loose soils. Here new foundations were built up as cribbage allowing the base cators to become spanning beams.
- At the two southeast towers, which were found to have no foundations at all. Both towers were underpinned on reinforced spread concrete pad footings.
- Around the northeast corner of the fort, where there were found to be no foundations and with the bottom cators decayed. Here the internal floor was to be lowered and an emergency exit door inserted. New foundations were formed here in tradition walling techniques.
- The west façade, found to be 400mm wide 8.5m high and 1.2m out of plumb! The tilt was left in place and the structure tied back.

In the new foundation locations the superstructure was suspended while decayed material was removed and the new inserted. To achieve this required the existing walls to be temporarily propped on needle beams, which in turn were held in place by 'acro props' and/or hydraulic jacks. The temporary propping was straightforward because of the cator beam action.



Photograph 3: Baltit Fort, Hunza, viewed from the North.

There was one exception to using traditional conservation methods and that was the use of an occasional modern structural tie (see below). The building, consisting of 60 or more structural phases of which only a few were linked, meant that there was very little structural continuity and elements were found drifting apart. In some places this has aided in limiting the extent of knock-on damage caused by foundation settlement. Because of the seismic character of the area and because Baltit Fort had experienced many events it was decided to leave it with, as far as possible, its existing ductility. This was supported by the lack of data about seismic ground motions and topographic modification effects. It was for this reason that the southwest tower was left as an independent structure. Just the top level roof beams were joined to the wall plates. This aimed to give a modicum of continuity in the ordinary working state, but in a form that could be disrupted in an earthquake.

Providing an upgraded long-span continuity through the structure would have been possible with timber cators, appropriately jointed, and fully designed to work in tension. The concerns with this approach were as follows:

- The limited supply of well seasoned long timbers.
- The difficulty of insertions through the structure.
- The disruptions to the existing cator system.
- The lack of opportunity to monitor any developing strains within the system.

Because of this, alternative methods were sought. Metal tie rods were not locally available and there was no possibility to have them manufactured. Suspension bridge wire rope was available but the local wire is known to badly stretch under continuous long term loading.

For these reasons a modern alternative was sought - 'Parafil Rope', consisting high strength Kelvar filaments encased in a tough and durable polymeric sheath. It is used for anchoring offshore oil platforms. The parafil rope is regarded as the modern equivalent of a cator and its use at Baltit Fort is the first application in a historic building. The advantages of this material are:

- Long term durability.
- Very high specification - high strength/low creep.
- Very easy to transport.
- Very easy to attach anchor fittings.
- Very small diameter (25mm) and therefore not disruptive to existing structure and visually not noticed when exposed against ceiling joists.
- Very easy to thread through the structure in long runs and even capable of taking bends, etc.
- Can be removed and reused.

It was installed to be a passive element, left slack to become active only if significant movements occurred in the structure (therefore a very valuable safety tool while heavy engineering works were occurring). A series of the ties were installed across the structure to form as regular pattern of back-up supports to the west facade - the one with significant outward tilt.

THE USE OF TIMBER CATORS IN HOUSING

Baltit Fort has been used as a catalyst for improving housing in the Hunza valley, because the structure in reality is just a collection of traditional houses stacked up and wrapped around by a defensive wall. However, the use of ‘Cator and Cribbage’, in the traditional form, has been noted above as no longer feasible. The strategy of the Aga Khan programme has been to address building improvements by:

Existing Housing

- Improving maintenance.
- Reducing rain penetration through flat roofs.
- Connecting beams to columns and wall plates.
- Replacing unstable stones, infilling wall cores and good quality pointing.
- Using structural renders.

New Housing

- Foundations designed in relationship to ground conditions, particularly soil strength.

- Reinforced concrete ring beams at ground and roof level.
- Symmetry of form and architectural elements.
- Careful positioning of windows and doors.

In Baltistan, to the east of Hunza, new construction of earthquake resisting architecture is already comprehensively undertaken but fully with traditional techniques. Here, cator and cribbage construction was only used for the forts, mosques and astana. Domestic architecture was and still is built with each floor and the roof each independently supported off very large posts - separately founded in the ground when the foundations are formed and then set within the core of the wall. Prior to occupation a building is shaken to test its performance.

THE AGA KHAN SELF HELP SCHOOL CONSTRUCTION PROGRAMME

For the last decade the Aga Khan Housing Board, Pakistan has been implementing a self-help school construction programme in the Northern Areas/Chitral region of Pakistan. Given that the schools were to be 'engineered structures' responding to a high seismic resisting requirement of His Highness it was found that the structural design needed further consideration. Ove Arup and Partners were appointed to carry out the engineering design for a proposed hollow concrete block prototype school and traditional variation types in Stabilised Soil and Stone, see Figure 2.

The structural approach employed was based on three main design criteria. The first criteria was to have some continuity of ‘Cator and Cribbage’ tradition, as a feature the inhabitants were familiar with and had confidence in. The second was dominated by need to provide safe performance of the structure under extreme earthquake loading, with the maximum design event being Ms = 7.0 (and based on a hazard study for the whole area). The third criteria focused on the durability requirements to meet the proposed design life of 50 years.

The foundations for the single storey school building were designed to resist a maximum load of 40kN/m, including dead loads and assumed live loads. It was assumed that as a result of the site selection the founding soils could be highly variable but granular or cohesive soils with the appropriate bearing capacity are common throughout all settlement locations. As the school structure was to consist of load-bearing walls, the optimum foundation solution in terms of performance, constructability and cost was unreinforced strip foundations. The foundation calculations provided for unreinforced strip footings 0.6m wide. A minimum founding depth was required to prevent foundation movement due to heave of frost susceptible soils. The following minimum founding depths were adopted for the schools and taking account of the local soil character - Chitral region = 1m and Gilgit region = 0.75m

It was necessary to ensure that there was sufficient lateral strength to resist the forces induced by strong ground shaking, and this is particularly important for masonry buildings where the amount of available ductility is necessarily limited. The US Uniform Building Code (UBC:1988) was chosen to provide lateral force requirements because it is well respected and commonly used in Pakistan.

The lateral force requirement in the code for masonry buildings is 25% of the weight, and this appears consistent with the Indian seismic code for the Himalayas (about 32%). A possible objection to the use of US code to establish minimum lateral strength is that the masonry clauses for areas of high seismicity require more uniform spacing of horizontal and vertical steel through the masonry walls than determined for the schools. This concept is very similar to the regular spacing of timber ‘Cator and Cribbage’ work in traditional walls.

The structural analysis considered the worst possible cases of seismic force distribution ignoring any beneficial interaction between the different structural systems and load sharing. The structural continuity, with good quality detailing of connections minimised on potential failures so enhancing the ultimate performance of the structure under earthquake loads.

The design was undertaken to as far as possible to also conform to the requirements of Eurocode EC8, for confined masonry. The principal features are horizontal and vertical tie beams at the top and bottoms of walls, at the ends of walls or major intersections and around major openings.
Ground ring beam provides the structural continuity of the loading path to the foundations by bridging across door openings. The effects of local concentrations of load such as uplift forces are re-distributed by the ring beam into the wall panels. In addition, the ring beam also helps to resist local differential foundation settlement and any variable hill creep.

Cator tie beams are positioned at windowsill level and at top of window/door levels. The beams, including the roof and ground beams, create structural continuity in the building by providing ties, which bridge weaknesses in blocks or blockwork joints. The tie-beams also help to control the cracking induced in the walls by the thermal and shrinkage movements and so improving the durability performance of the walls. In the traditional structure the high level of ductility of wood and dimensional changes, responding to climate, have always meant considerable cracking and given this the method allows for ease of stone panel replacement.

The walls are hollow concrete block partially filled with reinforced concrete. The remaining voids aid thermal performance. Special consideration was given to the mix design, given the extreme climatic conditions, soil gradings and very high soil mica content.

The uplift, bending and shear forces imposed on the wall elements were determined assuming an earthquake load at the centre of mass of the structure in two orthogonal directions. Here, the structure is a regular prism with a material/building quality homogeneity throughout. The same type of calculations for determining the live forces are not possible for complex buildings like Baltit Fort but as the text below shows the detailing to resist them is very similar.

The main steel bars are inserted at the edges of the walls to resist the bending moments and possible uplift forces. The shearing forces are resisted by the walls themselves.

The roof beam edge was designed to provide a connection between the walls and the roof, and as a horizontal frame restraining the perimeter of the roof and ensuring the roof's performance as a diaphragm, capable of distributing effectively the horizontal forces to the walls. In the traditional structures of the Northern Areas the main roof beams rest on the wall plates and so cannot aid in resisting uplift and shear forces. In the conservation programme for Baltit Fort the beams joists and wall plates were all pegged together to introduce a little continuity.

To provide adequate structural continuity in the roof fabric, between the roof hollow concrete blocks and the precast roof T-beams, the use of tapered sides (to generate accurate block location) and mortaring of blocks into the beam sockets were introduced. There is no parallel for this in vernacular structures.

Reinforcing the roof screed which overlies the hollow roof blocks was another area where detailing was determined to be of great importance
as it greatly contributes to the roof structure and it role in resisting shear and uplift forces. This could be achieved with reinforcing bars or wire mesh and the preference was to the former option.

The main aim of the school development commission was to provide an engineering solution that was seismically efficient and also economically viable. Here the concrete block appeared, from costing analysis, to be the best option. However, the programme for architectural purposes also allowed for village choice of traditional materials - dressed stone being more expensive and stabilised soil being cheaper than the 'concrete' alternative. In both cases, it was recommended that cator reinforced concrete ring beams be incorporated at the same levels proposed for the hollow concrete block wall system and tied through the wall thickness to ensure earthquake resistant performance over the 50 year design life.

Terracrete is a material made up of soil stabilised with a small percentage of cement. It is a very variable material largely dependent on the type of soil used and the mixing techniques employed. It was widely used firstly in Baltit Fort, to enhance durability of conservation adobe blocks, mortars, and renders.

The strengthening features aim to reduce the need for vertical reinforcement. This is a good policy for Terracrete walls as vertical reinforcement is difficult to detail and may be of minimal structural value. This type of structure is very much more like the timber lacing - cribbage work approach in that the product is a hybrid form of construction.

The experimental school at Mohammadabad had walls built of squared stone and achieved to a very high construction standard. Here only minor modifications were appropriate to allow for more accurate placing of the concrete ring beams and roof lintels. The provision of through stone ties would provide further continuity between the outer and inner stonework skins.

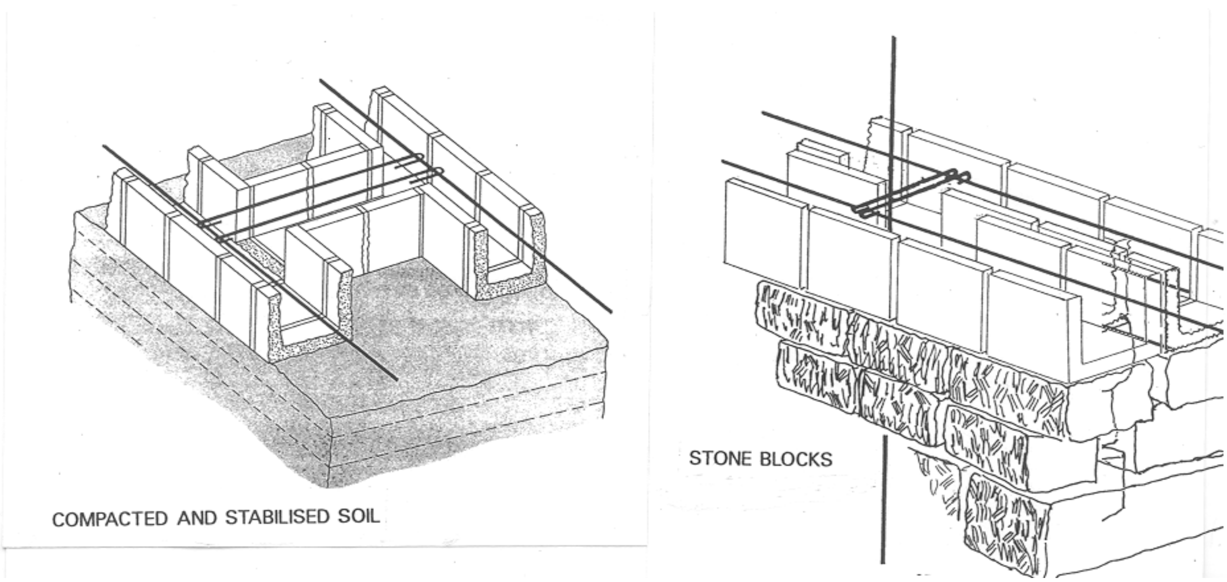


Figure 2: Some Construction Details of the Northern Areas Self Help Schools