



Collapse of Khmer stone architecture: was it caused by the lack of structural knowledge or extrinsic environmental factors?

Nuanlak Watsantachad, Ph.D.
Faculty of Architecture, Silpakorn University

Abstract

Angkor Wat is an example of great Khmer stone architecture that was constructed during the Khmer Empire era (802-1432 AD). In Thailand, there are also several major Khmer complexes, such as the Phnom Rung, Phnom Wan, and Phimai complexes, and a number of minor Khmer monuments. They are among the most impressive of man-made structures to be found anywhere in the world. Nevertheless, most of Khmer monuments collapsed, either partially or totally; their materials have deteriorated and weathered; and the entire monuments require urgent conservation. Hence, to propose appropriate restoration approaches, thorough understanding of its construction technique and causes of its failures is mandatory. It is, however, still doubtful whether Khmer masons' and architects' lack of structural knowledge or environmental factors should be the culprit of the failures of Khmer structural performance. Therefore, the main purpose of this article is to study the Khmer construction thoroughly and to analyse the causes of Khmer structural collapse.

Khmer structure failed not only because of its ineffective structural design and misuse of building materials, but also because of the combined effects of several environmental agents that caused different patterns of decay and damage. The ineffective design includes constructing the structure on the foundation that has uneven load-bearing capacity and using stone which is weak in tension as lintels and beams. Being built with drystone load-bearing system, the roofs and upper walls seriously moved and collapsed when the lower walls and door sets began to fail under the loads. Additionally, the error of construction process and the use of incompatible adjacent materials resulted in uneven strength of the walls. Regarding extrinsic factors, when extrinsic decay agents, such as tree root penetration and land sliding, were present, drystone Khmer walls supporting only compressive stresses failed to withstand lateral, shearing or flexural stresses resulting in deformation or collapse of the structure.

Keywords: Khmer architecture / Khmer structural collapse / Khmer construction technique / drystone masonry / stone architecture / stone conservation





Collapse of Khmer stone architecture: was it caused by the lack of structural knowledge or extrinsic environmental factors?

What is Khmer? The term ‘Khmer’ has sometimes been misused by Thai or other Southeast Asian people, and applied only to Cambodia and its culture and people, and in the general perception of the West, Khmer refers to a communist guerrilla organization that opposed the Cambodian government in the 1960s and waged a cruel civil war in 1970-1975. In fact, the Khmer Empire (802-1432 AD¹) is one of the greatest empires to have conquered the Indochina Peninsula since the first century AD. Its art and culture including massive architecture existed throughout the empire, and has since influenced all those present-day countries in this region that once were parts of the empire. These countries includes present-day Cambodia, the greater part of the Indochina Peninsula, the southern part of Laos and the east and north-eastern parts of Thailand (Coedes 1966). Evidence of ancient Khmer culture and civilization, especially Khmer arts and architecture, remains in several parts of these countries today, but only Khmer religious architecture, mainly in stone or brick and laterite with a unique construction technique called ‘drystone masonry’, remains while Khmer houses built of wood vanished.

Built in the twelfth century, Angkor Wat is but one example of great Khmer architecture that was constructed during the Khmer Empire era. (See Figure 1) In Thailand, there are several major Khmer complexes such as the Phnom Rung, Phnom Wan, and Phimai complexes. (See Figure 2)



Figure 1: Angkor Wat from the entrance



Figure 2: The Principal Tower of the Phimai Complex after anastylosis restoration, 1964-1969





There are also a number of minor Khmer monuments called Ku and Arokayasala used as rest houses and hospitals for pilgrims along the Imperial Road which originated from Angkor and led directly to Phimai (a city in the present-day Nakhon Ratchasima Province (Korat) in Thailand). The design concepts of these monuments were based on Hindi beliefs (in combination with Buddhist beliefs in some reigns) and on a cult called Devaraja—or the belief in kings as gods—which originated in Java and became established in Khmer during the reign of Jayavarman II (802-850 AD).

The charm and beauty of Khmer architecture is the result of its well-designed and clear silhouettes, elaborate iconography, and artistic decoration, making it among the most impressive of man-made structures to be found anywhere in the world. Nevertheless, the monuments were abandoned and became hidden by jungles for centuries. As a result, their condition was critical when they were rediscovered. Most of them collapsed, either partially or totally; their materials have deteriorated and weathered; and the entire monuments require urgent conservation.

One of the main conservation activities for Khmer monuments is architectural and structural restoration. In order to propose appropriate restoration approaches to Khmer architecture, thorough understanding of its construction technique and causes of its failures is mandatory. It is, however, still doubtful whether Khmer masons' and architects' lack of structural knowledge or environmental factors should be the culprit of the failures of Khmer structural performance. Could the Khmer structural system sustain its dead load and remain stable through time, or would Khmer monuments have collapsed even if no other extrinsic architectural decay agents, such as wind, water, or root penetration, had been present?

Without a clear understanding of the original construction technology—materials and methods, existing conditions and decay mechanisms, and the environmental context—any appropriate answer for these doubts is difficult, and that becomes the main purpose of this article—to study the Khmer technology thoroughly and to analyse and discuss the causes of Khmer structural collapse.

Khmer construction techniques²

Building Materials

From surviving evidence, it seems that only a limited range of building materials was used in Khmer architecture. In the pre-Angkor period (prior to the late eighth century), fired bricks were a chief building material while sandstone was used only for windows and doorframes, or for decoration of, for instance, pediments and lintels. The bricks were originally covered with a high quality decorative stucco finish made of lime and coarse sand (WMF 1992). Early shrines were rarely built of stone. However, there was rare evidence of the use of lime mortar in either Khmer brick or stone construction. Brick masons used a special mixed organic adhesive as the mortar rather than cement, lime, or clay. Khmer masons had applied lime only as stucco to





430 หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร

brick walls and laterite bases. The dominant building material changed to sandstone by the late tenth century (Rooney 2006), although brick construction techniques also remained in use. Thus, it is sometimes observed that a site is composed of one main stone tower surrounded by minor brick constructions. The bricks of the Pre-Angkor and of the Angkor periods may be differentiated according to size, the former being approximately 12x12x30 centimetres while the latter are somewhat smaller. The dimensions of the stone blocks used in Khmer construction, although various, may have ranged between approximately 25-40 x 38-50 x 65-105 centimetres, according to records, drawings and field survey.

Timber was used for roofs, ceilings, door and window panels, and, in some cases, to supplement stone beams and lintels. Whether or not timber could supplement beams/lintels depends on its position, direction and appropriate thickness. Sometimes, rather than supplementing, timber may weaken the strength of a stone beam/lintel if a part of the stone has been cut away and replaced with an inserted wooden beam. Timber was also a main building material for constructing temporary or common pavilions, dwellings and sanctuaries. Nevertheless, there is little evidence of timber as a construction element remaining today, except for door lintels and posts in a few gopuras. The reason for their survival may have more to do with location than function. Extant examples tend to be in relatively sheltered position where such timber has not been exposed directly to the environment.

Use of metal, such as bronze and iron, was limited to anchors or clamps to tie stone blocks and, possibly, as sheets for lining some sanctuary walls. From the record of Chou Ta-Kuan, a Chinese envoy, during his stay in Angkor from 1296 to 1297 AD, we may see that metal goods had been imported from China since the Funan Period (Macdonald 1987). (However, there is also archaeological evidence of bronze casting in the Khmer Empire in the prehistoric period (ibid).)

Laterite is one of the materials that became prevalent in the Angkorian period and it was often used in the surrounding walls, hidden structures or foundations. In addition, it was used as a main building material for minor monuments, particularly the hospitals and rest houses built during the reign of Jayavarman VII (1181-1220), because of its abundance and the ease of quarrying. These minor monuments generally contained less detail than the major ones because it was difficult to carve laterite. Structurally, Khmer masons often used the construction techniques applied to sandstone masonry to build their laterite architecture.

In summary, Khmer construction is mainly composed of sandstone, laterite or brick masonry, with wooden and metal elements used as supplementary structural elements. Although the scale of architecture of the later periods changed, there was no significant change of building materials used in Khmer construction throughout the empire era.





Performances and construction techniques of Khmer structure

Like all buildings, Khmer edifices have their own structure to support and make them stable to withstand environmental impacts. Their structural elements might be broadly divided into three categories according to their functional purposes, i.e. roofs, vertical elements (walls and colonnades) and foundations. The structural performance of Khmer architecture will thus be reviewed according to these elements; the construction techniques of each element will also be considered.

Roof construction

There are various types of roof construction technique which result in different structural performances. One example is the corbelled roof which was widely used in drystone construction, such as in Khmer architecture. This roof is constructed of cantilevered stone: each stone is placed so as to overhang the course immediately underneath it. The reason why some ancient builders preferred constructing corbelled vaults may be the ease and simplicity of construction. For instance, it is easy to cut stones in a roughly parallel shape and place them without, or with only a small, centring (Crocì 2000).

Corbelled roofs act vertically in compression rather than in diagonal thrusts as in true arch constructions. Each stone performs as a compressive support and transforms loads through the stones beneath. Therefore, it acts as a cantilevered beam with limitations on the length of overhang, and when cantilevered effects occur in a stone block, tension created at its upper part and compression developed at its lower part (Gordon 1991 and see Figure 3). However, stone is weak in tension and strong in compression, it is therefore not subjected to support tension or shearing stress and tends to be broken or split easily when used as a beam—either cantilever or normal. Regarding cantilever effects in corbelled arches, the deformation will occur when the strength of the stone has reached its limit due to overloaded stresses, especially tensile stresses. Because of this limitation, corbelled vaults can cover only narrow-spanned spaces—up to three to five metres (ibid).

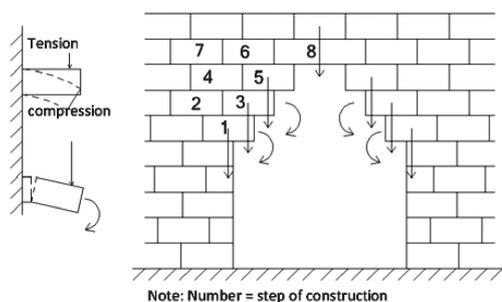


Figure 3: Cantilevered effects in corbelled roofs and openings





Khmer roofs are generally composed of stones placed with a header-bonded dry masonry technique as corbelled vaults. Each stone roof element is placed horizontally, partially projecting over those below, and the loads are then transmitted directly to the lower stones in compression. Interestingly, a characteristic of the working of stone roof blocks is the joggle joints on stretchers (JSA 2000) imitating halved joints in timberwork (see element B in Figure 4). In terms of carpentry, a halving joint joins two pieces of wood by cutting away an end of each to half its thickness and fitting the cut ends together (Agnes 2008). The form and direction of these joggle joints on each roof element can also demonstrate the construction process of Khmer roofing as well as allowing the reassembly of fallen stones to their former positions (see Figure 5). It was the skill of the ancient Khmer people to construct the roof with this special joint both to interlock the stones safely and to prevent rain leakage. The joggle joints vastly increased the friction between the blocks and hence made the roof stable and, with the slope outwards from the joints, drained water away from the building (see element B in Figure 6). However, the drawback of cutting away a half of the stone's thickness is that it might have introduced a zone of weakness to the stone simultaneously. In some cases, wooden beams were inserted into the gables, either to support wooden rafters or to supplement a corbelled vaulted stone roof (see Figure 7 and 8).

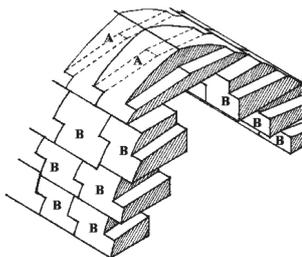


Figure 4: Stone corbelled vaulted roof

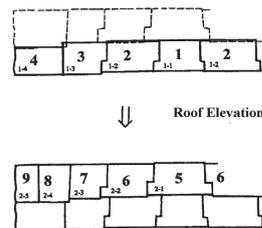


Figure 5: Order and direction of stone roofing (JSA 2000)

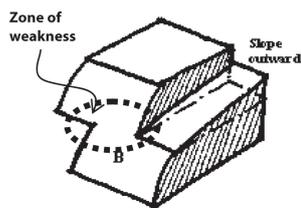


Figure 6: A stone block for roofing

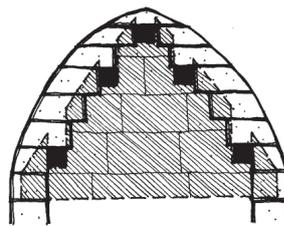


Figure 7: Wooden beams inserted in a gable





Figure 8: Evidence of wooden beams inserted in a gable (Banteay Srei, Cambodia)

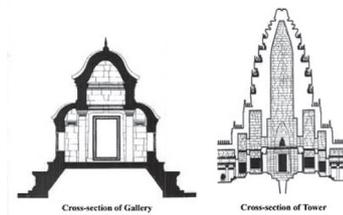


Figure 9: Cross-section of Khmer architecture (JSA 2000)

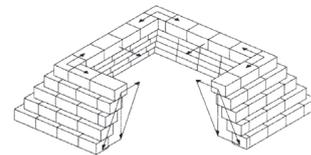


Figure 10: Ring effect in each masonry course of Khmer corbelled tower (Croci 2000)

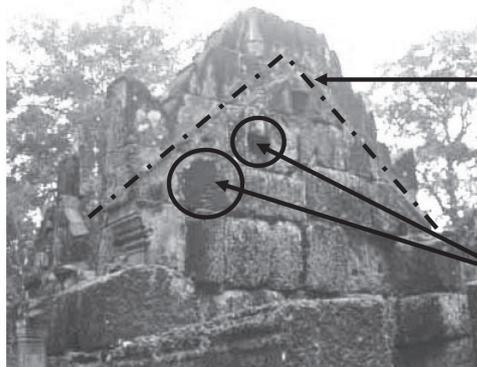


Figure 11: Carved stone blocks with a L-shaped section (Banteay Srei, Cambodia)

Corbelled roofs usually covered only rectangular-planned spaces, such as galleries, libraries or vestibules (mukha), while square-planned towers were constructed with load-bearing walls, which were inclined inward at the top (see Figure 9). With the construction of every horizontal course, a ring was formed which provided a horizontal stabilization³ (Croci 2000 and see Figure 10).

A roof structure, consisting of a wooden tie beam, rafters and purlin, and tile roofing, can sometimes be seen in the internal face of stone gables, for example at Banteay Srei in Angkor; the stones placed on the top are carved beams with an L-shaped section to support wooden rafters (see Figure 11). The curved stone or brick tiles were normally laid convex side downward. Fired clay and stones were both used as tiles. With wooden roof structures, purlins were inserted into the stone pediments, and then the rafters were placed over them (and on the stone wall at the lower ends) to support concave-shaped tiles sitting on wooden cleats (See





434 หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร

Figure 12). As previously described, the farthest end rafters were sometimes also placed on the L-shaped section stone blocks at the gables as seen at Banteay Srei. Unlike the corbelled vaulted roof, the Khmer wooden roof was concave, and a sprocket was inserted at the base of the roof to achieve such a shape. Such a roofing system has been reconstructed from the evidence of gable ends and fallen tiles, for no such roofs survive.

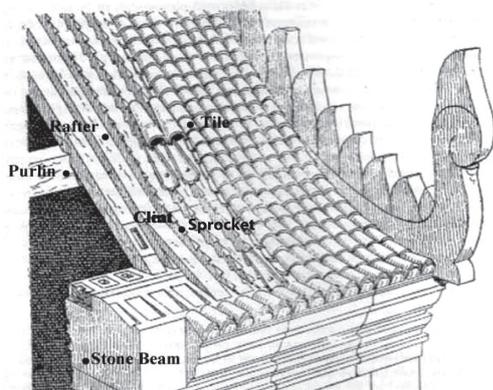


Figure 12: Wooden roof structure (Parmentier 1936)

Like other corbelled roofs, the Khmer roof structure uses only compressive thrusts down to its support—load-bearing walls and stone colonnades—but creates tensile stresses from a cantilever effect in each stone block. However, the problem of the cantilever effect on stone is solved in wooden roof structures by using wooden purlins and rafters to support compressive and tensile stresses caused by the weight of tiles. Then, all the loads are transferred to stone pediments and walls through their supporting joints. Nevertheless, the wooden structure eventually rotted and decomposed, and consequently caused the roof to collapse.

Vertical elements

Vertical elements (walls and columns) provide a weatherproofing skin around the interior and support upper floors and roofs. In drystone buildings, the main structural components of enclosures are load-bearing walls and columns. To create openings, post and lintel or corbelled arch systems were used. The unique character of drystone walls or columns lies in the fact that they are built of stone blocks, or sometimes of rubble, without any cement or mortar. Friction leading to the stabilization of buildings is obtained by the neat cutting of each stone block face, called 'ashlar', to ensure a tight joint. To assure and increase the strength and stabilization of stone walls, stone wedges or iron cramps were sometimes used.





A post-and-beam system was also widely used in stone masonry although stone has a limitation of tensile strength. Columns perform the same structural support as load-bearing walls: they support roof loads and transfer them to the ground. Since stone is weak in tensile strength, ancient masons often solved the problems by reducing the weight loading over beams, increasing the width of beams, narrowing the span between two column supports, or inserting iron or wooden beams to strengthen the stone beams.

In Khmer architecture, walls of towers or rooms were usually built of mass wall construction—either sandstone, laterite or bricks.⁴ However, in this article, only stone and laterite masonry, which have the same construction techniques, will be considered. Since the walls bore many loads of self-weight (or dead load in engineering term) and superstructure, they were generally solid and thick, as thick as the length of the stretcher of one stone block. Regarding the ratio of slenderness (that is the ratio of effective height to effective thickness of the wall), and because the greater the slenderness ratio, the weaker the wall, Khmer walls were sufficiently thick to prevent wall buckling under heavy compression loads. With a drystone masonry technique, the remains of the walls display the patterns of their masonry bond. Generally, the stones were laid without any consistent jointing patterns. However, Khmer masons tried to place the stone with overlapping vertical joints and even horizontal courses. In terms of stone orientation, the basic pattern of masonry laying for the walls is header bond, in which the stretcher of a block is used for the thickness of the walls. However, there are some places where a mixture of headers and stretchers is used.

The dimension of the walls was usually predetermined by the number of masonry courses. The first two courses of masonry normally formed the base of the wall up to the sill of the window frame. Window frames were four or five courses in height with three courses above to the springing of the corbelled roof. However, the height of the wall may have varied from monument to monument. At Bateay Srei in Cambodia, the monument is not human-scaled but smaller, so that the entire wall is only three or four courses high. Interestingly, at Banteay Srei, the walls were composed of vertical stones at each corner to frame the wall; the spaces within the frames were filled with stone blocks. The wall construction, therefore, was built as if it were a post-and-beam system rather than a wall bearing system (see Figure 13).

The stone blocks were often not cut in a regular rectangular shape. As in the corbelled roofing system, there are some blocks with joggled angles to yield interlocking joints to the masonry. Hence, the order and direction of the laying of the stone wall can also be investigated (see Figure 14). A keystone—a small reverse trapezoid-shaped stone—sometimes appears to have been the last stone piece to be inserted to complete each course of the wall. It seems to have been placed downward from the top or horizontally from the front. Noticeably, most of the keystones were laid in edge-bedded orientation (see Figure 15), possibly because of the availability of the



blocks. These pre-cut blocks might have been fitted in the gaps only when laid in edge-bedded direction. Practically, edge-bedded stone should not be constructed for both walls and architectural details due to its weathering susceptibility (Maude 1997). Again, despite their skilfulness, this seems to be further evidence showing the lack of material properties knowledge of Khmer masons.

Wall corners appear not to be bonded, possibly because of the lack of structural knowledge of ancient Khmer masons, or because of the addition of a secondary wall in later periods. It appears that the Khmer masons usually first built a main wall; after that, the secondary wall was constructed and joined to the main one with a straight joint. (Figure 16) That is the reason why the corner of the wall was usually the first part to be torn apart when uneven soil subsidence occurred. However, occasionally, the masons built the corners of walls with a masonry-interlocking joint or sometimes even used metal or stone clamps to tie the stones from different directions together. Moreover, in a few cases, the stones at the corners were cut in a special shape to fit the joints and then tied with clamps.

In order to make a perfectly fitting joint, the faces of blocks in contact with each other were generally treated carefully to form a smooth surface, called a 'rubbed face' (JSA 2000). Traces of rough chiselling on the other faces can sometimes be found. In many cases, however, there are small traces of chiselling on the upper face. According to a field trip to some Khmer complexes in Siem Reap with Professor Shinichi Nishimoto in 2002, he suggested that these seemed to be the result of the following procedure: a lower block was laid and an upper one placed above it. The mason would then observe the closeness of the fit, remove the upper block, and chisel the upper face of the lower block to improve the fit. The upper was then replaced. It seems clear from the presence of holes in the blocks that they were manoeuvred horizontally using timber levers, and not turned over (Figure 17). Nevertheless, these holes are so small that they might not weaken the stone blocks.

There are two types of opening—real and false. The false ones were blocked with stone. False and real windows sometimes have mullions, or the stone blocks were sometimes carved as a trompe l'oeil wooden door or window panel. In the case of doors, both types of openings are supported by stone frames. Adjunct Professor Anuwit Charernsupkul (1998) considers all the elements composing a doorframe as a 'Door Set'. It usually comprises a set of lintel and colonnettes at the front, a set of stone doorframes placed behind the former set, and, sometimes, a huge stone slab beneath them (see Figure 18). The set of the doorframe supports the load of the superstructure and the dead load of the door head, and then transfers them to the threshold through the doorjamb while the colonnettes transfer the lintel weight to the ground or slab (see Figure 18). (Tensile stresses were created at the lower half of the lintel and door head and they consequently cracked the stone.) However, it can sometimes be found that there is a supplemental stone beam placed above the frame to support the upper loads while the threshold is sometimes composed of a





shorter horizontal element, which means that it is not as long as the actual opening. At the entrance or main doors vertical sandstone pieces with vertical bedding planes are used for the jambs of the door, whereas the jambs of some minor doors are not made of a single piece of stone (see Figure 19).

For windows, the head was often composed of double lintels while the sill was composed of the upper face of stone blocks that also formed parts of the course beneath the window. Moreover, in many cases, long vertical elements with vertical bedding planes (edge-bedded stone blocks rather than face-bedded), that were normally used for jambs, did not stretch the full height of the window, possibly because of the reduction in strength in edge-bedded stone. Thus, one or two stone blocks—sometimes they were parts of the wall masonry—were added to supplement the jambs (see Figure 20). Hence, it may be concluded that the constitution of the window frames varied from one window to another, although they were parts of the same monument, and that there was no uniformity. Noticeably, in some early periods of construction like those in the Angkor period, the frames were more precisely constructed than those of the monuments constructed in the Post-classical Angkor period. In the latter, the window frames were usually made only to fit into the wall, but not as a part of the wall structure.

Noticeably these stone window- and doorframes were skeuomorphs of their timber precursors; some were cut to look like mitre joints. However, these joints are special because, for example, although they appear as 45°-degree angles, the inner hidden part of the joint is a normal right angle as shown in Figures 21a, 21b and 21c. With regard to the doorframes, there are traces that a wooden header may have been inserted into the upper portion of the inner pilasters while there may have been pivot holes on the sill used as door hinges. The complex structure of a multi-order door arrangement is shown in Figure 22. In addition, a pair of opposing square holes could sometimes be found in the walls at the level of the door head or of the threshold. These may be assumed to have taken wooden beams as a frame to hang door panels from (see Figure 23). From this evidence, it could be assumed that there used to be a wooden double swinging door opening inward or outward depending on the locations of the holes. As far as window openings are concerned, their frames are similar to those of the doors, except that there is no trace of mortises for window panel tenons. There are, however, mullion holes—either circular or square—remaining on the head and sill of window frames. Additionally, some stone mullions still exist in their original positions. These mullions were not only used as a decorative element, but they may also have reduced the load that the beam supported. False doors and windows that were filled with stone blocks were possibly built for these purposes as well.

Since stone is weak in tension, Khmer masons tried to decrease the loads over the doorframe or lintel with various techniques. Most commonly, the upper wall above the head of the doorframe is composed of two blocks with a 45°-angle



cut only at the base to form a triangular-shaped hole (See Figure 24c). Consequently, fixed loads over the head could be dispersed to the sides with this technique. This technique can be seen in several monuments built in the Post-classical Angkor period, for instance the Northern Library of Bayon and Banteay Chmar in Cambodia. The other technique that was applied to the frame structure is the separation of two door heads—one laid on top of the other—with a gap in the middle of the upper head (Figure 24b). Again, this technique helped divide the loads from the upper part onto two sides of the lower head which decreased the risk of tensile cracking of the door head. However, this technique may lead to the weakening of the upper head due to its loss of thickness. Another technique that can be found on doorframe structures is the combination of the post-and-beam and the corbelled-arch system. Since a lintel in drystone masonry generally supports only triangle-shaped loads over it because of the corbelled structural effect (see Figure 26) and most of the upper loads are transferred to the ends of the upper head and to the jambs, leaving the middle or most of the head free of loads, the blocks in the triangle may be removed. Figure 24d shows how the stone blocks were placed in the corbelled-arch system over the head of the frame to eliminate the load in the triangle (see Figures 24d and 25d). Khmer masons sometimes used forcing wedges to reinforce vaults above lintels (see Figure 27). This solution gave a fairly successful result in decreasing loads over lintels by yielding an arch-like load effect (Gordon 1991).

Strengthening lintels was also one of the Khmer structural solutions for weakness in the tensile strength of stone. Since stresses usually occurred mostly in the middle of lintels, wooden beams were inserted to strengthen them. However, the Khmer masons applied their solutions without theoretical structural knowledge resulting in unsuccessful strengthening. As seen in Baphon complex, the technique of wooden beams inserted inside the lintels was applied by hollowing out more than three-quarters of the lintels' thickness (see Figure 28). The result was not satisfactory and led to a weakening of the stone lintels due to their lack of sufficient proportion to withstand the thrusts. In addition, wood degradation over time resulted in the loss of its strengthening capacity. Thus, these mistakes may be considered as evidence for the lack of knowledge of material strength and structural mechanics of ancient architects and masons. Their structural successes seem to have been the result of intuition and experience, rather than theoretical understanding.

In using these various techniques, it can be observed how Khmer architects and masons tried to solve structural problems without damaging the aesthetic design. The special techniques of frame construction described above can only be observed from the interior or after dismantling because they are hidden behind a stone lintel placed in the front. When viewed from the exterior, only the double doorframe structures—an actual doorframe and a set of lintel and colonnettes—are exposed (As seen in Figures 18).





Figure 13: Wall of Banteay Srei, Cambodia

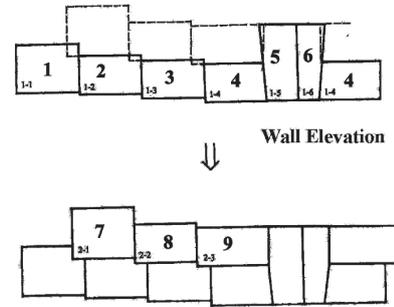


Figure 14: Order and direction of stone laying (JSA 2000)

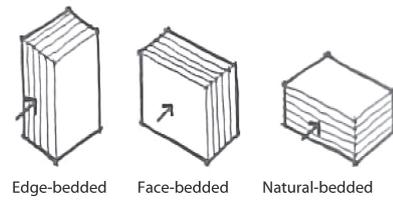


Figure 15: Stone orientation in masonry



Figure 16: Construction of a wall corner with an addition wall added to the original wall with an overlapped decorative craved stone. (Banteay Chmar, Cambodia)

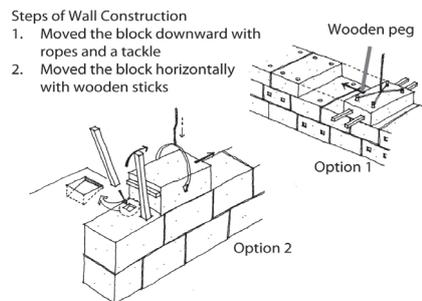


Figure 17: Process of wall construction

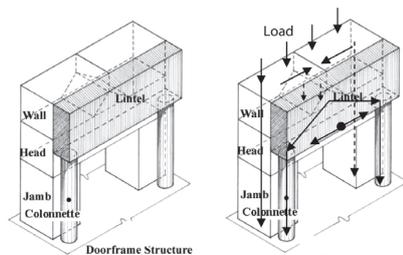


Figure 18: Schematic drawing of Khmer doorframe and thrust diagram in door set





440 หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร



Figure 19: Door jambs composed of stone blocks (Banteay Chmar, Cambodia)



Figure 20: Window jambs with supplementing stone blocks (Banteay Chmar, Cambodia)

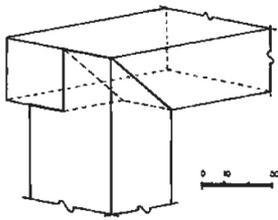


Figure 21a

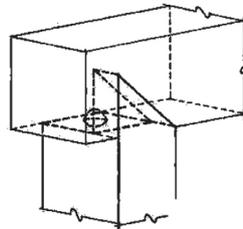


Figure 21b

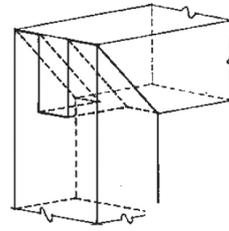


Figure 21c

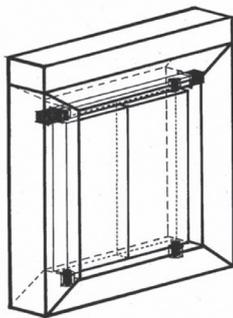


Figure 22: A wooden beam holding door panels



Figure 23: Square holes on the walls near a door head (Banteay Chmar, Cambodia)



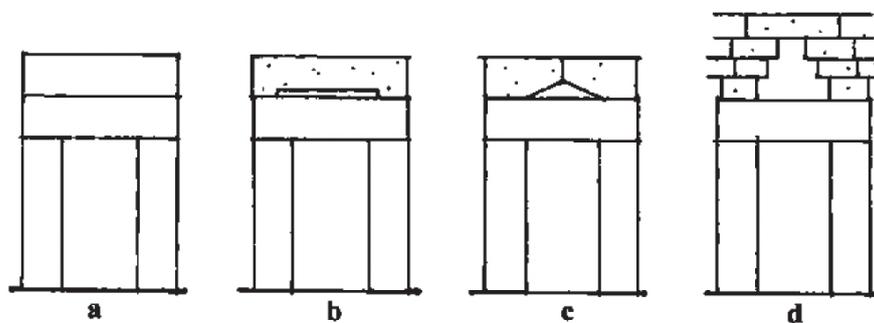


Figure 24: Different types of doorframe structure

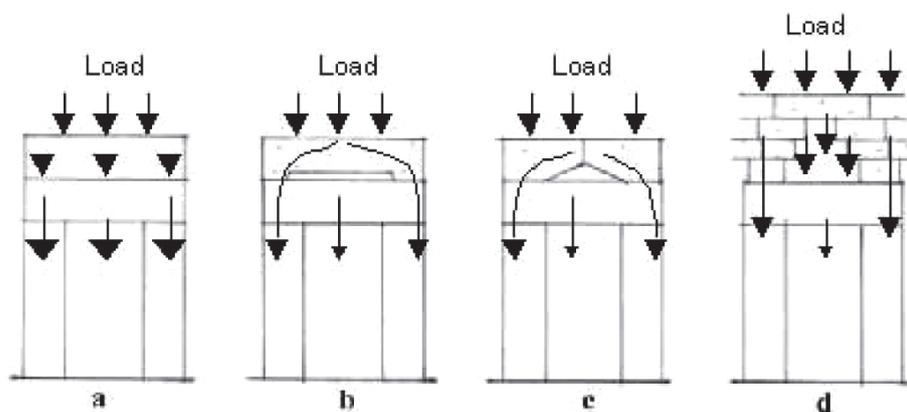


Figure 25: Loads over different doorframes

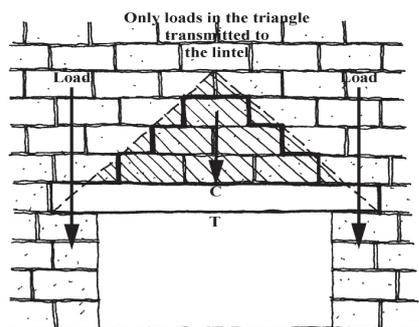


Figure 26: Loads over a lintel with a corbelled-like effect

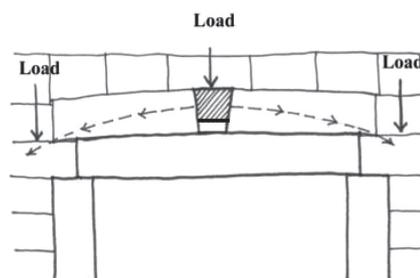


Figure 27: Wedge stone creates an arch-like effect





442 หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร

While the mass walls were constructed with dry masonry technique, a mixed structural construction technique was sometimes applied in the galleries: one side was a solid wall while the other side consisted of nave and aisle columns. (Figure 29) Moreover, like the opening frame, the stone structure connecting nave and aisle columns with a beam was also derived from wooden structures (JSA 2000). There are two types of column used in Khmer architecture. One is the column constructed from a sandstone monolith, the other is composed of sandstone or laterite blocks in dry bond. The latter might be the result of the masons' concern about the orientation of the bedding plane of sandstone. Since the monolith is placed in edge-bedded orientation, it consequently has a lower capacity of loading support than a series of natural-bedded blocks.⁵ Laterite, by contrast, may have strength problems particularly when used together with sandstone columns or walls.⁶

Khmer columns are composed of three parts—a base, shaft, and capital. If the column was a monolith, its capital and shaft were made of one stone piece and its base of another. A mortise and tenon joint technique was applied in order to connect the two parts. The stone tenon, carved from the same monolith, was about 6x6x4 centimetres located on the upper or lower face of each part. However, it is not consistent which element contains a tenon or which one has a mortise. The position of the tenon and mortise is also variable—in some columns, it is in the centre while, in other cases, it is on one side of the face. At the head of the capital, either a tenon or mortise can be found. It might have been used to tie a beam placed over the capital (Figure 30).

Beams comprise of two courses of stone placed horizontally in a lengthwise direction (from east to west since buildings are planned rectangularly with the shorter sides facing east and west). The beams were possibly placed to support the corbelled roof structure. The lower beam was composed of two stone elements placed next to each other horizontally with the stretcher sides facing each other; beams were tied together with metal clamps and processed so as to form one continuous beam (see Figure 31a and 32). The long sides of the elements were placed next to each other with a halving joint (JSA 2000). Then, another beam was placed on top of them. This upper beam has a halving joint on the header as well. In addition, there are traces of clamps having been used in a lengthwise direction to tie the upper blocks of the beams (Figure 31b). However, the structure of the beams could vary, depending on the loads they had to support.

Base and foundation

Khmer structures were usually built on a platform over either a natural or an artificial hill due to the Hindu belief that monuments represented Meru Mountain, the centre of the universe, and that they had to be built on 'pure soil' (Dumarçay and Royere 2001). This conceptual construction has been called 'Temple Mountains'





(WMF 1992). To create an artificial hill, Khmer masons had to deposit large amounts of earth dug from surrounding areas, and, sometimes, additional layers of laterite (Pichard 1972). This kind of hill could be as high as twenty-seven metres at Angkor Wat (Narasimhaiah 1994). Generally, Khmer temples were surrounded by moats resulting from the earth excavation necessary for creating a hill. Not only did these moats serve religious beliefs, but they also show the skill in construction management of the Khmer people, in terms of a cut and fill strategy.

The platforms were generally constructed on layers of several materials over the natural soil: sandstone, laterite, stone fragments and soils, for instance (see Figure 34). Ashlar sandstone and/or laterite masonry is often used as pavement material on the surface, while laterite is used inside the platform. The number of masonry courses of the platform varies from site to site. For example, there are three courses of masonry for the platform construction of the Northern Library of Bayon in Angkor (JSA 2000) while there are only two—one in sandstone and the other in laterite—outside of the Northeast Gate of the Royal Palace (IGT 1996). Generally, the total number of stone masonry courses for platform constructions of each level would have been the same within each building. However, the latter site proves an exception in that the numbers of masonry courses are not equal in the interior and exterior of the building. The exterior platform consists of two layers while the interior consists of five (IGT 1996 and see Figure 35). This might have been because of consideration of the greater loads that the interior platform had to bear.

In addition, Khmer buildings were usually placed on a high and steep platform to give an illusion of greater size and to achieve a sense of monumentality through a false sense of scale (WMF 1992). Since the monuments were built for religious purposes, as the places of gods, and not to be used by people, the stairways leading to the temples are not human-scaled. Khmer stairways are composed of risers of up to 45 centimetres and treads of only 15 centimetres while the size of a comfortable human step should consist of a set of a 15-19-centimeter riser and, at least, a 22-centimetre tread. To exaggerate the false scale even further, the doorways are often smaller than expected as well. Additionally, the majority of the 'temple mountain' structures are set between 50 to 60 degrees while the normal angle of a shape for an unconsolidated earthen structure or mound should be only about 45 degrees. Due to the steepness and height of the platform, retaining walls had to be inserted underneath it. For example, in the case of pyramid-like sanctuaries that are composed of several levels of platforms, stone retaining walls were constructed as boxes that contained earth and sand fill inside. Laterite was normally used for internal retaining walls, but in many cases, sandstone was used as the outer material for both durability and aesthetic effect. In terms of sectional platform construction from the surface to the base, based on the results of excavations carried out at the Northern Library of Bayon (JSA 2000), exposed sections of the floor of the platform



444 หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร

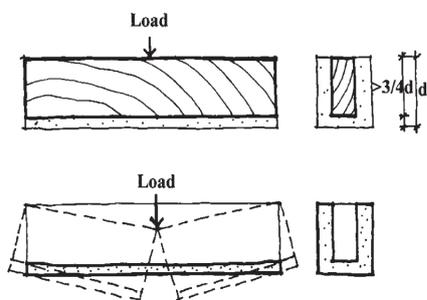


Figure 28: Failure of wooden beam strengthening



Figure 29: A mixed structural construction technique applied in a gallery of Bayon



a. Tenon at the top of a shaft (Ta Phrom, Cambodia)



b. Tenon at the bottom of a shaft (Falling column in Banteay Srei, Cambodia)



c. Mortise at the base of a column (Banteay Srei, Cambodia)

Figure 30: Mortise-tenon of column



Figure 31a: Plan of lower stone beams (JSA 2000)

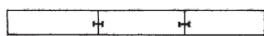


Figure 31b: Plan of upper stone beams (JSA 2000)

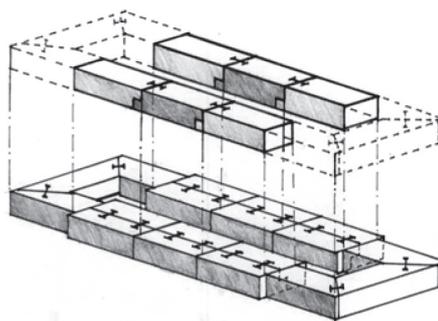


Figure 32: Two-course beam in Khmer architecture



Figure 33: A remaining beam over a pilaster. Generally, a beam is composed of two elements of stone tying together on their stretchers with I- or H-shaped metal clamps. In this structure, one beam is missing (Banteay Chmar, Cambodia)





were generally paved with sandstone blocks while laterite was used where the floor was protected by the wall construction on top of the platform. Wedge-shaped sandstone blocks were often inserted into the small spaces between the floor elements to fill the gaps and complete the floor work, but there are cases in which soil mixed with sandstone fragments was used instead. Beneath the sandstone layer that formed the floor were laterite blocks as the second (and, sometimes, also the third) course. Beneath this, there is normally a layer of compacted soil; however, in some places there is a tier of laterite blocks. Trench excavation at Bayon shows that within the compacted soil layer sand is also found. The depth of this layer is approximately 50 centimetres. Sometimes, it can be found that this layer is as deep as 160 centimetres from the surface of the platform. At this point another layer of hard material, which seems to be laterite, can be found. However, in some cases, such as the south side of the Northern Library of Bayon, evidence from the excavation confirms that laterite blocks had a depth of 140 centimetres from the terrace surface, below which a layer of compacted soil up to a thickness of 170 centimetres was found. Beneath this, a hard material layer, possibly laterite, was found (JSA 2000). The section drawing of the foundation is shown in Figure 36.

At the Northern Library of Bayon, within the compacted soil layers, broken stones were sometimes added to form the artificial fill under the laterite layer. These stone fragments were laid randomly at low density. Some small fragments of earthenware, porcelain pieces and roof tiles are sometimes found in each layer. The ratio of the fragments and the compacted soil was usually the greatest in the layer underneath the laterite layer, i.e. the third layer from the surface. Soil in this layer was more cohesive than that used elsewhere in the foundation. This clay-like soil was also used for filling joints between stone blocks in the platform construction (ibid).

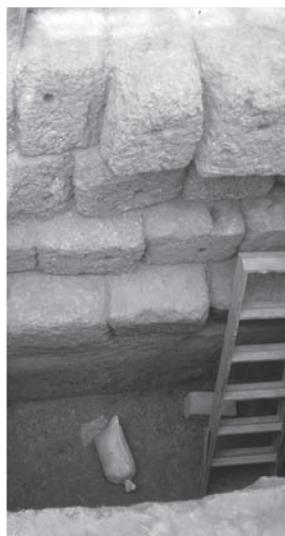


Figure 34: A trench of one of the tower foundation shows layers of different materials starting with sandstone, then, laterite, and finally, soil (Prasat Sao Prat, Cambodia)

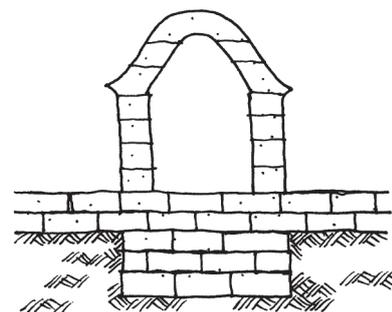


Figure 35: Comparison of courses of platform masonry between interior and exterior



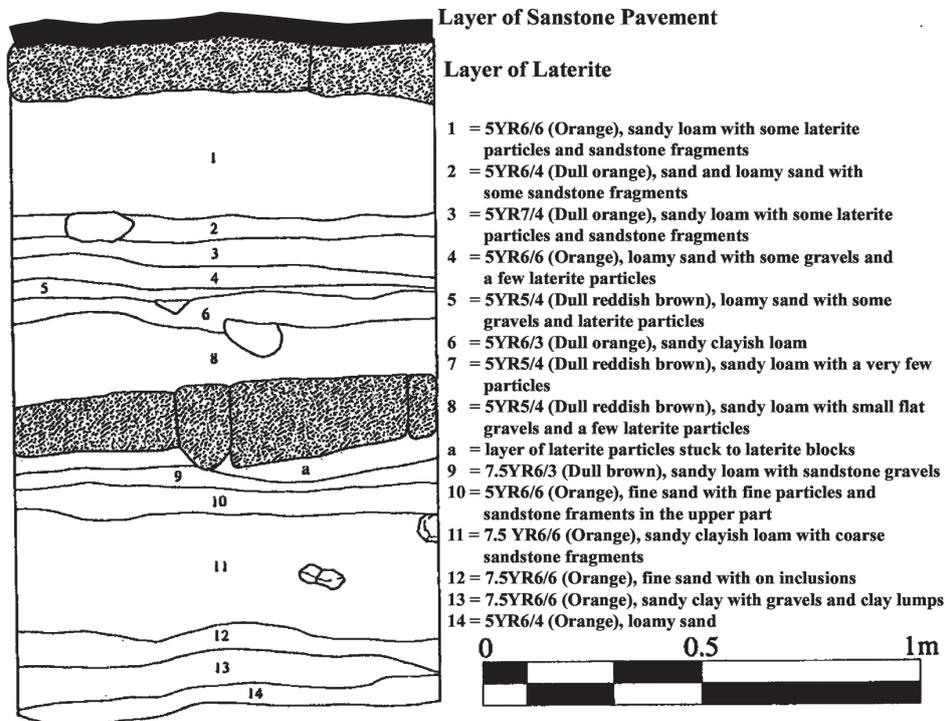


Figure 36: Example of Khmer foundations: Platform of the Northern Library of Bayon, Cambodia (JSA 2000)

Regarding the joints between the blocks, their width and the amount of soil fill varied according to the size of the blocks and the way in which they had been shaped or formed (JSA 2000). The soil varied in thickness from 5mm to several centimetres and filled in the bed joints and vertical joints between sandstone and laterite blocks and in the bed and vertical joints between two laterite blocks. However, there is no evidence that the bed and vertical joints between the sandstone blocks below the column bases were intentionally filled with the soil. Noticeably, unlike Western masonry techniques, Khmer masons filled the joints with soil rather than mortar and this soil fill was found only in the foundation masonry construction. Sometimes, small fragments of sandstone or laterite were mixed into the soil to fill in wide vertical joints—a width of 20 centimetres or greater—between sandstone and laterite blocks. The amount and size of the gravel mixed in the soil also varied according to the width of the joints.

The purpose of joint filling might be for adjustability or cohesion. The JSA report suggests that soil was used to adjust the level in masonry technique for which no standardized blocks were used, and that it was used for connecting and stabilising as well (JSA 2000). However, since the ratio of clay to silt in this kind of soil is rather high, the soil could lose the cohesion of its particles easily when water is present,





resulting in significant subsidence of the platform, and, in the worst case, collapse of monuments. Such an occurrence could happen particularly in cases where the soil in the bed joints was up to 10 centimetres thick (ibid).

Additionally, in order to construct and support the upper structure, it was necessary to adjust the level of the upper face of the artificially laid soil and to provide a certain amount of strength. Because the weight of the upper structures might cause the soil to subside unevenly, inclusions were added to strengthen the mix. Noticeably, more stone fragments are found near the laterite blocks in all layers. Furthermore, a clay-rich mixture was sometimes added to the sandy soil matrix to provide better support (JSA 2000). This also helped to prevent differential settlement thus ensuring reliable horizontal levelling—although it is later proved that the foundation still unevenly subsided possibly because of the poorly-compacted layers of soil, or because the loss of the cohesion in the soil.

In conclusion, Khmer architecture was usually constructed on a spread footing acting as a platform over a hill—either natural or artificial. The foundation of the artificial platform was generally composed of at least four layers of material, i.e. sandstone, laterite, compacted soil and hard materials such as stone, to support the load of the buildings. It is also possible that the compacted soil and hard materials were alternately placed, and ended with the hard material layer. However, the depth of each foundation layer varies with each construction site. The variation in depth and materials might be the result of the conditions of the natural soil where monuments were constructed, the size or importance of monuments, or the availability of materials at the period of construction.

Like other spread footing constructions, the loads of Khmer superstructures were transferred down to the ground through their platforms to the soil hills. These platforms were their footings and supported all compressive loads above them. The stabilization of the structure could therefore be achieved with the equilibrium of the compression of the superstructure and the reactive forces of the soil. However, since Khmer masons built the foundation with one or more layers of laterite and clay under a course of sandstone, it might have been the cause of defects in the foundation. Due to the infiltration of rainwater and the fluctuation of underground water, along with the heavy superstructure loads and the tree root penetration, the laterite foundation became crushed, disaggregated or broken while the clay layers did not uniformly subside resulting in uneven load-bearing foundations. Such failure in the foundations consequently led to the overall structural deformation of Khmer monuments. The deformations of superstructure and foundation are probably a chain-cycle—once the foundation unevenly compacted, the superstructure lost its equilibrium and inclined outward or inward resulting in the change of load distribution. Because of the latter phenomenon, the ground and foundation then subsided irregularly because of uneven pressure of loads further destabilising the superstructure.





Outward movement is generally much more severe than an inward one because, due to the movement of their supports, lintels or beams can slip out from their supports or corbelled roofs can lose their stability (Figure 37). In contrast, inward movement may cause only minor damage to the structure because the structural elements can adjust themselves to be stable in new equilibrium conditions and support a deformed but surviving structure (Figure 38). In this case, only some patterns of deformation occur in the structure until further forces appear and exceed the limit of structural equilibrium, and then the structure may collapse (Crocì 2000).

Failures of Khmer Structural Performance

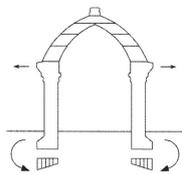


Figure 37: Outward movement of roof support because of uneven subsidence of foundation (Crocì 2000)

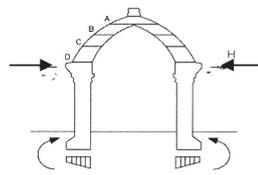
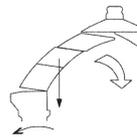
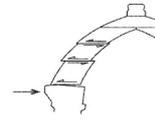


Figure 38: Inward movement of roof support because of uneven subsidence of foundation (Crocì 2000)



The main failure of the Khmer structural system was the failure of its foundation (Picard 1972). Being built of such a weak and partly soluble and erodible material as soil, it would inevitably subside. The use of laterite in construction was possibly the other principal cause of the failure. Uneven load-bearing capacity of the foundation resulted in non-uniform movement of the structure leading to overall structural deformation (see Figure 39). For instance, the outward movement of columns and walls consequently caused unbalanced and collapsed corbelled roofs. However, this failure was caused not only by the misuse of material and ineffective design of Khmer architects and masons, but also by the environment, especially the presence of water—either the infiltration of rainwater or groundwater—when the soil becomes saturated the soil begins to behave like a fluid.

The misuse of material includes the incompatibility of adjacent materials. Each material has its characteristics and durability, which are different from one to another. Iron clamps inserted in the stone have different thermal expansion from the stone and consequently break the stone when expanded. Iron clamps, when rusted, also break the stone by their increasing volume. Wood has much less durability than stone and degrades over time, and thus should not have been used as any main structural element in stone masonry structures. Consequently, wooden roofing structure or wooden beams inserted in stone beams rot and decompose resulting in collapse of the roofs or weakening of the beams. Again, this problem is aggravated by the material decay mechanisms, mainly the result of the presence of





water and salts. The difference in load-bearing capacities of sandstone and laterite is a further example of material incompatibility. Problems occurred when they were used together to support structural elements resulting in uneven structural support and thence the deformation.

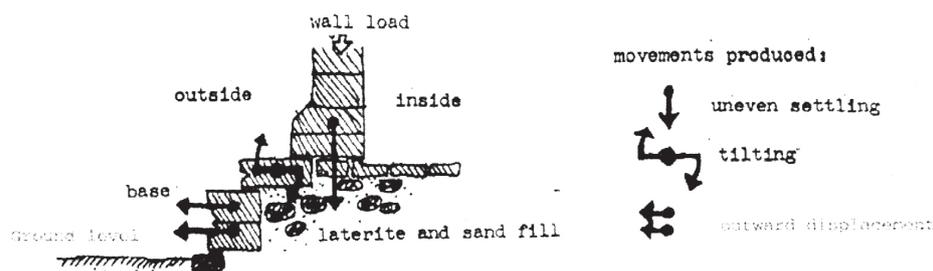


Figure 39: Movement of Khmer Foundation (Pichard 1972)

Stone is weak in tension and therefore should not be used as any tensile structural element. In Khmer structure, stone was used as lintels and beams resulting in tensile stresses created in the bottom half of the stone, mostly at the centre of the span. Cracks were usually found in the area where tensile stresses were greatest. Although Khmer masons tried to solve the problem by decreasing or dispersing the loads over the beams or lintels, the results were relatively successful. This problem was caused by the inappropriate structural design of Khmer architects. The roofs and upper walls depended on door sets as well as columns for their supports; consequently, serious movements and even collapse occurred when these elements, which were unsuitable for the purpose, began to fail under the loads. (Since stone lintels were broken at the bottom creating an arch-like effect, the structure, however, may have been stabilised and survived.)

Regarding drystone masonry construction, sandstone blocks in Khmer walls were sometimes laid in different orientation—or mixed with laterite blocks—resulting in uneven strength of the walls. Since the compressive strengths between natural-bedded, edge-bedded and face-bedded sandstones are dramatically different, when some blocks were vertically laid, they created weak spots within the walls resulting in uneven load-bearing walls. This failure was caused by the error of the construction process which is an intrinsic cause. In addition to the presence of water and salts, such vertical blocks tended to deteriorate more easily than the natural-bedded ones with a resultant weakening of the mechanical strength of the blocks. Regardless of the orientation of the stone, the decay mechanism of stone over time has caused the stone blocks to lose their perfectly sharp edges; the wall has lost its perfectly fitted joints resulting in the reduction of surface friction between the blocks. This might have caused the wall to have less stability.





450

หน้าจั่ว: สถาปัตยกรรม การออกแบบ และสภาพแวดล้อม
วารสารวิชาการ คณะสถาปัตยกรรมศาสตร์ มหาวิทยาลัยศิลปากร

The other errors of construction work can be found in other parts of the structure, such as the lack of bond at the wall corners. Such corners were easily torn apart, especially when the foundation was unstable. However, this lack of corner bond may make the structure flexible and able to move partially without any critical structural damage when the soil subsides. Where the walls supported a superstructure, the displacement of such walls resulted in the deformation or collapse of the superstructure. The other inappropriate design is the skeuomorphs of carpentry joints in window- and doorframes. When cut back to make such joints, the strength of the stones was weakened, and, when heavy loads were applied, the heads of the frames tended to displace downward more easily than the ones which were simply laid over the jambs.

In terms of extrinsic factors, when extrinsic decay agents, such as tree root penetration and land sliding, were present, drystone Khmer walls supporting only compressive stresses, failed to withstand lateral, shearing or flexural stresses. Pressures caused by tree root penetration were much greater than the friction between blocks of a wall resulting in displacement, deformation or, at the worst, collapse of the wall. The failure of withstanding combined forces tended to be the most important cause of the collapse of Khmer structure.

In summary, Khmer structure failed not only because of its ineffective structural design and misuse of building materials, but also because of the combined effects of several environmental agents that caused different patterns of decay and damage. However, despite their lack of structural knowledge, Khmer architects and masons have shown the world their excellency of architectural aesthetic and design and their skillfulness of craftsmanship; and that is the most significance.



Note

¹ It was the generally accepted period when the Khmer empire reached its greatest territorial limits and cultural and artistic achievements (Rooney 2006).

² This article considers Khmer construction techniques as gathered from drawings, photographs and secondary bibliographical sources. Some information is gained from the author's observations and interviews with experts; and from site visits and surveys with the Japanese Government Team for Safeguarding Angkor (JSA) in Siem Reap in Cambodia in 2002 and at some selected Khmer monuments in Thailand.

³ According to a discussion with Associate Professor Dr. Piboon Jinawath in June 2011, he suggested that, while being constructed, load-bearing walls of square-planned towers might have needed temporary wooden supports to stabilise them before all full rings were enclosed and they could gain the stabilization. Similarly, regarding Dr.

Jinawath's discussion with Dr. Suvit Rasamephuti, an ex-director of FAD of Thailand, they assumed and agreed that there might have been a wooden falsework supporting the temporary loads of stone blocks during the construction of a corbelled roof.

⁴ Generally, in Khmer construction, the walls and roofs are in the same plane and material—in other words, the roofs are corbelled. In this article, the 'wall' is everything from the ground up to the spring of the corbelled roofs.

⁵ Dry sandstones can bear about 11% more loads perpendicularly to the natural bed planes than parallel to the bed lines or rifts (Watsantachad 2001).

⁶ Sandstone, even ferruginous one, when wet, has about 3 times greater capacity for compressive load bearing than laterite, and, when dry, has about 9 times greater compressive load bearing than laterite (Watsantachad 2001 and Watsantachad 2006).

References

- Agnes, M (ed.) (2008) **Webster's New World College Dictionary**, 4th edition. Ohio: Wiley Publishing, Inc.
- Chandler, David P. (1983) **A History of Cambodia**. Colorado: Westview Press.
- Charernsupkul, Anuwit (1998) **ปราสาทเมืองต่ำ การศึกษาทางประวัติศาสตร์สถาปัตยกรรม (The Architectural Design of Prasat Muang Tam)**. Bangkok: Dhamasat University Press. (in Thai)
- Coedes, G (1966) **Angkor, an Introduction**. translated and edited by Emily Floyd Gardiner, London: Oxford University Press.
- Croci, G (2000) **The Conservation and Structural Restoration of Architectural Heritage**. Southampton UK: Computational Mechanics Publications.
- Dumarçay, Jacques and Pascal Royere (2001) **Cambodian Architecture, Eight to Thirteenth Centuries**. Boston: Brill.
- Feld, Jacob (1968) **Construction Failure**. London, UK: John Wiley and Sons, Inc.
- Fine Arts Department (2003) **The Summary of the Archaeological Excavation Project at the Ban Prasat Complex**. Bangkok: Fine Arts Department.



- Finot, Louise et al (2000) **A Guide to the Temple of Banteay Srei at Angkor.** translated by J.H. Stape, Thailand: White Lotus Co., Ltd.
- Fitchen, J (1996) **Building Construction before Mechanization.** Massachusetts: The MIT Press.
- Freeman, M and Jacques, C (2009) **Ancient Angkor.** Bangkok: Amarin Printing.
- Gordon, J.E. (1991) **Structures: Or Why Things Don't Fall Down.** London: Penguin.
- Heidhues, M S (2000) **Southeast Asia: A Concise History.** London: Thames and Hudsons Ltd.
- ICOMOS (2003) **ICOMOS Charter- Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage** http://www.international.icomos.org/charters/structures_e.htm. Page consulted 14 March 2011.
- Indonesian Government Team for Safeguarding Angkor (IGT) (1996) **Report on Technical Study for the Preservation of the Royal Palace Site, Angkor Thom (III).** unpublished.
- Japanese Government Team for Safeguarding Angkor (JSA) (2000) **Report on the Conservation and Restoration Work of the Northern Library of Bayon, Angkor Thom, Kingdom of Cambodia.** Tokyo: Interbooks Co., Ltd.
- Macdonald, M (1987) **Angkor and the Khmers.** Oxford: Oxford University Press.
- Maude, T (1997) **Guided by A Stone-Mason.** London: I.B.Tauris Publishers
- Morgan, W. (1987) **Elements of Structure,** 2nd edition. U.K.: Longman Publishing Group.
- Narasimhaiah, B. (1994) **Angkor Vat: Indian's Contribution in Conservation.** New Delhi: The Director General Archaeological Survey of India, Government of India.
- Parmentier, H. (1936) **"La Construction dans L'Architecture Khmère Classique"** Bulletin de l'École Française d'Extrême-Orient: TOME XXXV, 1935.
- Pichard, P (1972) **Restoration of a Khmer Temple in Thailand.** Paris: Unesco.
- Polivka, J.J. and Polivka, M (1958) **Philosophy of Structure.** Berkeley and Los Angeles: University of California Press.
- Robertson, E C (1982) **"Physical Properties of Building Stone" in Conservation of Historic Stone Buildings and Monuments: Report of the Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission of Engineering and Technical Systems,** National Research Council, 62-86. Washington D.C.: National Academy Press.
- Rooney, D (2006) **Angkor: An Introduction to the Temples,** Fifth Edition. Hong Kong: Odyssey Publications.
- Salvadori, M (2002) **Why Buildings Stand Up.** New York: W.W. Norton and Company.
- Siribhadha, Smitthi and Elizabeth Moore (2001) **Palace of the Gods: Khmer Arts and Architecture in Thailand.** Bangkok: River Books
- Suksawasdi, S (1995) **"Khmer Culture in Cambodia and Traces of Khmer Culture in Thailand"** in **Khmer-Thai Cultures: The Inseparable Ties,** 31-52. Phnom Penh: Rama Printing International. (in Thai)
- Torroja (1958) **Philosophy of Structures.** Berkeley: University of California Press.



World Monuments Fund (WMF) (1992) **'Considerations for the Conservation and Presentation of the Historic City of Angkor, Siem Reap, Cambodia: Report I, Overview.'** unpublished report.

World Monuments Fund (WMF) (1994) **'Preah Khan Conservation Project, Historic City of Angkor, Siem Reap, Cambodia: Report V, Field Campaign II, Appendix V/A: Structural Repair and Consolidation Methods.'** unpub-

lished report.

Watsantachad, N (2001) **'An Investigation of Consolidation Material for the Northern Gopura of the Phimai Sanctuary in Thailand'**, unpublished MS thesis, University of Pennsylvania, U.S.A.

Watsantachad, N (2006) **'A Study of Laterite Used in Khmer Architecture in Thailand'**, unpublished PhD thesis, University of York, U.K.



