STRUCTURAL CONSOLIDATION AND CONSERVATION OF THE MONUMENTS AT PREAH KHAN - HISTORIC CITY OF ANGKOR - CAMBODIA

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SUMMARY

Amidst the lush tropical jungle in northwest Cambodia near the great lake called the Tonle Sap lies Angkor, the ruins of a grand civilization that flourished between the 9th and 15th centuries A.D. Renowned in its time as a major religious center and the capital of the Khmer empire, Angkor is no less famous today. Cambodians view Angkor with pride as the site of the glorious reign of their forebears, while Cambodians and foreigners alike, impressed by the scale, scope, and artistry of the monuments, hail it as one of the "wonders of the world".

1. INTRODUCTION

The historic temple complex of Preah Khan is related to the turbulent history of the Khmer civilization from the 12th to 14th century. Today it represents a ruined structure - reminiscent of the devastation caused by ground motion, although the actual reasons for damages have been the tropical vegetation, harsh climatic conditions and other factors contributing to the deterioration of the site through the 800 years of its history. Within the frameworks of the project "Preah Khan Conservation Project - Historic City of Angkor Seam Reap, Cambodia" undertaken by the World Monuments Fund, a methodology for structural stabilization and architectural conservation was developed through careful analysis of the style, structural systems, construction methods and conditions of the complex. This analysis enabled a detailed classification of the monuments according to their architectural and structural systems, and priorities in conservation at the site. Methods for permanent and temporary protection have been developed for all the structural components of the Preah Khan complex and the historic

city of Angkor including: beams, columns, vaults, roof structures, towers, enclosure walls, and objects of artistic value such as lanterns, frontons and gorudas. Being in full compliance with modern principles and applications in architectural conservation practice of, the achieved results satisfy the previously set goal of "minimum intervention for maximum protection" including invisible interventions, reversibility and preservation of original structural systems and architectural components. Preah Khan is an extensive monastic complex covering over 55 hectares which was built by the Khmer king Jayavarman VII as a monastery and center for learning. It is located a few kilometers to the North East of the North gate of Angkor Thom. The central sanctuary of Preah Khan which was dedicated in 1191 A.D. has been modified in various ways during the following three centuries. Preah Khan is sub-divided by four concentric enclosure walls, (Fig. 1). The second enclosure wall delineates the principal religious compound of about four hectares within which there is a dense concentration of temples and shrines. The primary central complex is Buddhist whilst the southern sector is dedicated to the worship of the late kings and the eastern sector forms the grand entrance to the central shrine. The northern and western sectors are dedicated to the Hindu sects of Vishnu (West) and Shiva (North), (Fig. 1).

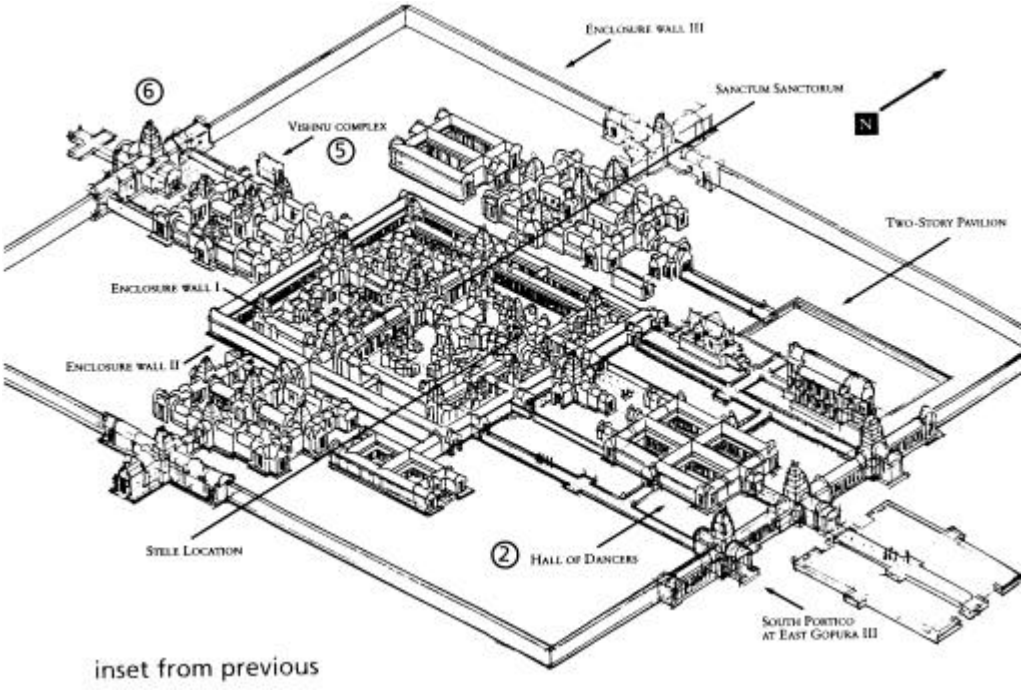

Figure 1. Preah Khan Temple Complex

2. BUILDING TYPES, CONSTRUCTION MATERIALS, DAMAGES AND PRESENT CONDITION

A methodology for structural stabilization and architectural conservation was developed through careful analysis of the style, structural system and method of construction of the complex. This analysis engendered a detailed classification of the monuments according to their architectural and structural systems. Approximately nine typical groups of structures were identified and classified according to typological and structural systems. This classification was undertaken in advance of a more detailed analysis and to enable WMF to present a set of representative proposals for each group as a standard approach for similar structures in the future. These types of buildings are: *Tower Buildings:* unique structures with a central space or shrine, surrounded by towers of different sizes having the same basic structural systems. *Entrance Towers:* similar to the towers described above, they are a part of the entrance complex (gopura) and have a greater central space which often contain supporting columns. *Halls:* structures that connect the central towers, but are separated by construction joints which may have been consciously planned expansion joints. *Entrance Halls*: vaulted structures with longitudinal bearing walls which form the entrances (gopura) on each of the four sides of the temple complex. *Vestibules:* elements that form an entity of the central shrines and relatively small attached porches. *Corner Towers:* towers located at the corners of Enclosure Wall I. *Cloisters:* corridors associated with Enclosure Wall I, and the corridor system which is part of Enclosure Wall II. *Single Shrines:* 24 single temples representing isolated structures of a relatively small size located within Enclosure Wall I. *Special Building Types:* unique structures such as the pavilions and the Dharmasala ('pilgrim's resthouse'). Within this category are free standing Enclosure Walls III & IV which are also of particular structural interest. The Preah Khan complex is constructed of two basic materials: sandstone and laterite. The buildings of Preah Khan are constructed of dry masonry in large stone blocks which form structural components such as walls, columns, vaults, beams, towers, etc. Many of these structures appear to have been built without a full understanding of the principles of the mechanics of logical distribution of forces. Generally these characteristics are not the main reason for inherent structural failure, but they have proven not to have been the best deterrent to the principal factors of deterioration which are: the invasion of vegetation into the structures and the presence of high humidity (which in turn has caused erosion and deterioration, and has contributed to the accelerated process of structural failure).

3. STRUCTURAL STABILIZATION, REPAIR AND STRENGTHENING

The methods for the consolidation, repair and strengthening of the structures of Preah Khan have taken into account existing structural systems, the causes of damage and the types of failure found in the structural elements as well as the characteristics of stones used in construction. The WMF team's objective is to design standard techniques for consolidation, repair and/or strengthening of each type of structural element (beam, column, vault, etc.) found at Preah Khan. Principles to be used in these conservation interventions are summarized below:

?? Minimum possible intervention at all times to the basic structural system;
?? Application of invisible methods of structural repair and consolidation;

?? Application of materials of high durability and minimum interaction with the principal structural materials;
?? Application of reversible materials wherever possible, taking into account climatic and other local conditions;
?? Techniques and methods of implementation should be simple and conform to local conditions and the capabilities of the local work force.

A basic principle used by WMF in nearly all of its field projects is to use only locally available materials and equipment, except stainless steel and epoxide. Beams of sandstone are structural members having relatively low bearing capacity and, therefore, are generally only suitable for short spans. Two types of failure occur:

?? Shear failure which is diagnosed by the presence of diagonal cracks, noticed most commonly at beam ends (door- and window- lintels).
?? Bending moment failure evidenced by vertical cracks in the mid-span areas of the beams.

Based on an analysis of the various types of beam failure at Preah Khan where consolidation and strengthening was required, the most suitable methods of structural intervention are proposed using stainless steel and epoxy mortar or/and epoxy resin. The proposed methods for permanent repair and strengthening are practically invisible. Shear failures will require filling of the cracks with epoxy mortars or injection of epoxy resin. Various methods are developed (about 15). A very simple and effective method for repairing failures due to bending moments - usually a vertical crack midway along a span (Fig 2). Columns are common elements at Preah Khan and throughout the Historic City of Angkor. The most frequent pattern of damage to monolithic stone columns, such as those found at Preah Khan, is vertical splitting as a result of bedding plane separation. The evidence of vertical splitting of columns differs, ranging from localized hairline cracks to large fissures running the full height of columns. A combination of different methods of repair, strengthening and consolidation is recommended for splitting columns depending on the degree of damage and whether a temporary or a permanent solution is sought. For consolidation and strengthening, steel belting is presented on Fig. 3.

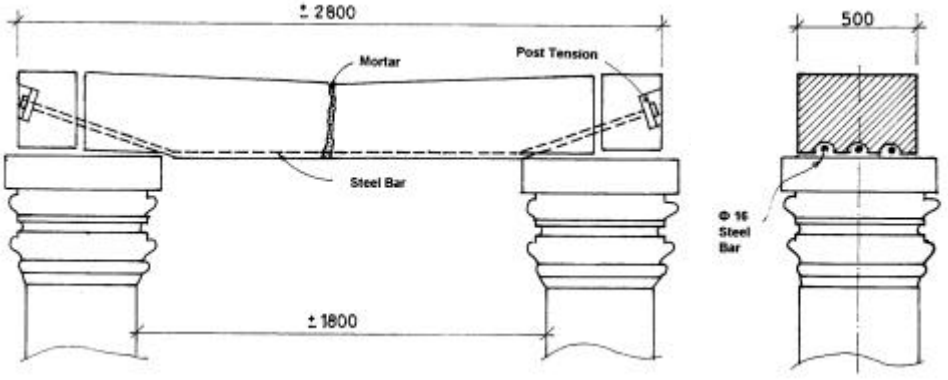

Figure 2. Repair and strengthening of bearing beam by post tensioned steel bars

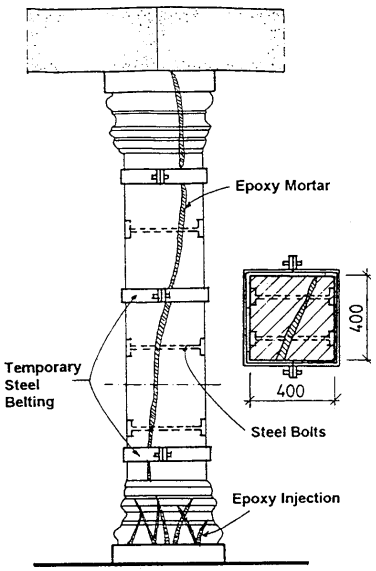

Figure 3. Strengthening of columns

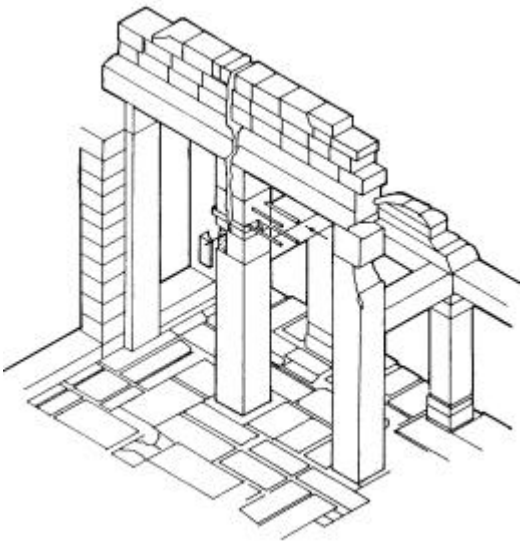

Figure 4. Consolidation of Hall of Dancers

Bearing vaults in ancient Khmer architecture are constructed of large sandstone blocks that support the loads from tower superstructures. When well-connected with the massive walls, thus forming a sound tower base, the large corbelled vault stones remain in place and suffer minimal damage. Stabilization of load bearing vaults should be carried out by placing steel members and ties where stone displacement has occurred. This intervention require the careful and coordinated use of hydraulic jacks. As a example fo consolidation of an assembley will be presented section of Hall of Dancers. The south east sector of the Hall of Dancers has been identified as being in critical need of consolidation. If the column adjacent to the axial route, which is severely distorted, should fail it would cause the collapse of the largest intact corbelled vault assemblages remaining in this building, (Fig. 4) Following WMF's standard procedures, the structure was measured, drawn and photographed by the student team prior to the commencement of any work. The initial stage of the process of conserving this portion of the Hall of Dancers involved the construction of a sound tubular steel scaffolding. The first task was to repair and realign the column in the most dangerous condition by repair with a newly carved stone insert. This step was followed by realigning the capital. Although part of the capital was missing, it was not replaced, because it played no structural role (Fig 4).

Repairs to the damaged column utilized a technique which was tested on a column in the South West Sector of the Hall of Dancers during Field Campaign II. To unload the column, hydraulic jacks were used to raise the beams. Steel belts were temporarily placed around the upper part of the column to close the cracks. The column was then drilled across the crack and stainless steel dowels were inserted. "Sikadur 732" epoxy mortar was used to seal the edges of the cracks, after which the cracks were injected and flooded with "Sikadur 752" epoxy resin. Later a new stone patch was cut to replace the spalling stone, then drilled and fixed in the same way with stainless steel pins and epoxy resin. As a result of the large deformation of the stone half

vaults in this section of the Hall of Dancers, the whole section, which was for the most part intact, was carefully dismantled and documented during the process. After the repair and reconnection of the column and lintel, the vaults were reassembled, ensuring proper connection to the main portal frame. Damaged sections of structural stonework were replaced with new stones. Due to structural necessity, one particular keystone in the vault was replaced with a newly cut stone. Where bearing ends of existing vaults had vailed, a new section of stone was spliced to the old, then bolted and glued using stainless steel and epoxy resin (Fig 4).

4. CONCLUSION

The concepts for structural consolidation at Preah Khan comply with the basic principle: "minimum intervention - maximum protection". The proposed procedures employ methods and materials which are both appropriate and reversible. These analyses are a prerequisite to establishing a finalized concept and methodologies for repair, consolidation and conservation. The classification of the buildings at the site and their characteristic structural elements together with the proposed recommendations for consolidation, stabilization, repair and strengthening provide a solid base for more specific studies which will be undertaken as each project is undertaken and developed in the coming years. Structural consolidation is one of many interventions with the full range of possibilities in architectural conservation. The use of a multidisciplinary approach which recognizes a carefully developed set of conservation priorities for a given site has proven to be the best procedure to follow at complicated architectural and archaeological conservation projects such as those found at Angkor. It is WMF's intention that this research and application be useful in the conservation of other sites at the Historic City of Angkor.

5. ACKNOWLEDGMENT

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