PREAH KHAN CONSERVATION PROJECT
HISTORIC CITY OF ANGKOR
Siem Reap, Cambodia

REPORT V
FIELD CAMPAIGN II

APPENDIX V/A
STRUCTURAL REPAIR & CONSOLIDATION METHODS

WORLD MONUMENTS FUND
PREAH KHAN CONSERVATION PROJECT
HISTORIC CITY OF ANGKOR
Siem Reap, Cambodia

REPORT V

FIELD CAMPAIGN II
November 1993 - May 1994

APPENDIX V/A
STRUCTURAL REPAIR & CONSOLIDATION METHODS

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South Section of East Gopura III, Preah Khan, Showing Portico Before Repair, March 1993.
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FOREWORD

This report records activities and accomplishments relating to the structural stabilization and repair of the architectural ruins of Preah Khan, a 12th-century Buddhist monastic complex at the Historic City of Angkor in Cambodia. The information was gathered during the World Monuments Fund Field Campaigns I & II in March 1993, and January and March 1994.

Research and conservation interventions undertaken in previous WMF missions are recorded in three volumes: Report I: Considerations for Conservation and Presentation of the Historic City of Angkor, Report II: Preah Khan Conservation Project - Project Identification and Report III: Preah Khan - Conservation Plan. These reports provide historical data and information relating to the conservation and presentation of the site and a description of the principles and procedures to be used in repair and conservation interventions at Preah Khan. The concepts for the various structural stabilization and reconstruction measures referred to herein have been developed following the principles and procedures stated by WMF in Report III: Preah Khan - Conservation Plan and Report IV - Preah Khan Field Campaign I - Project Mobilization.

This report, the Appendix of Report V: Preah Khan Field Campaign II, is the result of three separate three-week missions to Preah Khan in 1993 and 1994 during which the author focused on the identification of structural problems, the definition of a basic analytical approach and the initial identification of methodologies for structural stabilization and/or repair of threatened structural systems. Initial research and survey work resulted in the selection of representative structures to serve as prototypes for the demonstration of appropriate structural consolidation technologies. Analytical and practical field work done in connection with these various project activities provided useful training opportunities for both the professional staff and the work force of Preah Khan. It
is WMF's intention that this research will be useful in the conservation of other sites at the Historic City of Angkor.

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.

Structural consolidation is one of many interventions within 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. Such an approach has been used since the commencement of the Preah Khan Conservation Project in 1992. For nearly three years a continuous high level of cooperation among archaeologists, architects and conservators has been a hallmark of WMF's various technical missions to Cambodia when international specialists and their Cambodian counterparts are brought together to advance the project. It is hoped that this approach can serve as a useful model for others to follow in future efforts to conserve Angkor and other sites in Cambodia.
ACKNOWLEDGMENTS

The author would like to express his appreciation to the World Monuments Fund in New York for entrusting him with this work. Special gratitude is extended to Architect John Sanday, WMF Project Manager of the Preah Khan Conservation Project, for his support and cooperation during the missions and also to John Stubbs, WMF Program Director, for his assistance in making these missions possible. WMF Program Assistant, Felicia Mayro, and WMF consultant, Martha Flach, are sincerely thanked for their assistance in the preparation of this report.
1. **INTRODUCTION**

The architectural configuration of the historic temple complex of Preah Khan reflects the intense religious atmosphere of the time of its construction. The intermingling of different religions was part of the turbulent history of the Khmer civilization during the 12th through the 14th centuries, which especially requires understanding if one plans to intervene at a key Angkorian site such as Preah Khan.

In addition, any analysis of the masonry structures that comprise Preah Khan must take into account the effects of tropical vegetation, harsh climatic conditions and other factors that have contributed to the deterioration of the site over its 800 year history. The extensive material and structural damage to the buildings illustrates the complexity of the conservation issues at hand, primarily the issue of structural stability and the need for further stabilization.

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. For purposes of identification, nine types or groups of buildings having the same or similar form, structural elements, or materials serve as representative types and are described in detail.

These types have been surveyed to record their existing structural condition and the specific types of structural failure, and the main causes of structural deterioration have been analyzed. This report proposes possible interventions at Preah Khan in compliance with the conservation philosophy defined by WMF for Preah Khan.

Stabilization and conservation techniques developed as a result of the surveys and analyses are outlined in this report. These serve as representative examples of the
different applications and techniques required to repair existing structural elements such as vaults, beams, columns, walls and towers.

A knowledge of the basic material and structural characteristics of the two principal construction materials (sandstone and laterite) is essential for making appropriate decisions regarding the stabilization, repair and strengthening of structures as proposed in the project's objectives. A discussion of some of the capacities of these stones is found in Preah Khan Reports III and V.

An updated program of soil and stone sample gathering and laboratory analysis in collaboration with the Institute of Technology at the University of Phnom Penh is planned for September 1994. This continues an earlier initiative with the Institute in which samples were sent to their laboratory for testing.

The problem of broken stones in statues and ornaments received special attention. ADING Ltd., a laboratory in Skopje, Republic of Macedonia, tested and analyzed samples of fractured stones. ADING Ltd. developed an epoxide mixture as well as proprietary glues (based on cement and admixtures) which were then used for repairing the broken stones.

Based on the author's limited field investigations and the need for the development of a systematic conservation methodology for the Angkor region, this report recommends that a single building be selected to demonstrate the results of the application of modern methodology, technology and equipment, as well as to serve as a vehicle for the necessary training of staff. Detailed analyses of the causes and types of failure are best applied to a single typical structure which can then be applied to other similar structures at the site. The most suitable structure for this purpose at Preah Khan is building No. 11, the Tower, which houses the valuable stone inscription (see Chapter 4.1 for details) and exhibits structural failures typical to the site.

The author also participated with other members of the WMF team in two workshops for the Departments of Architecture and Archaeology at the University of Fine Arts, Phnom Penh. The participants of these workshops discussed the proposed structural interventions along with the problems of architectural conservation and presentation at Preah Khan.
2. OVERVIEW OF STRUCTURAL CONDITIONS
AT PREAH KHAN

2.1. GENERAL ANALYSIS

Today, Preah Khan has the appearance of a structural ruin; some areas have suffered total collapse reminiscent of the devastation caused by earthquakes.

Any analysis of the stability and structural systems of the buildings in the complex ought to begin by identifying the load bearing elements, the structural units which are involved and, finally, entire structural systems.

The Preah Khan complex is constructed of two basic materials: sandstone and laterite. The mineralogical characteristics of these materials is presented in Reports III and V. (See Report III, Chapter 8 for a description of mechanical and bearing characteristics). It should be noted that the characteristics of laterite are essentially different under dry and humid conditions and the bearing capacity of sandstone depends upon whether it is loaded on a vertical or a horizontal bed.

Although sandstone and laterite are materials of variable bearing characteristics depending on local conditions, it appears that the number of failures due to the material's low load bearing capacity are rare. There are instances where load bearing sandstone columns have vertical cracks due to overloading. Also apparent are some examples of beam failure caused by over-wide spans or from overloading.

In most cases, however, failure and damage to the load bearing masonry walls, vaults, and tower structures of Preah Khan were caused by original structural instability which, during its preliminary stages, caused the loss of structural integrity and eventually lead to partial or total collapse.
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. In constructing masonry walls, massive columns and towers, the original builders appear to have overlooked the need for expansion joints; the vaults were not constructed as 'true' arches receiving the logical transfer of compressive forces, rather, corbelling was used. Other structural problems include lintel beams that carry no load ('dead beams'), vault elements that do not withstand horizontal forces, horizontal layers with no bonding connections, etc.

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).

Both the materials and structural designs were intended to sustain static or simple gravitational loads. Defects which occurred were caused by different factors such as horizontal forces (which induced sliding, an initial loss of structural integrity and eventual instability). Such problems might have been prevented were there a greater appreciation at the time of construction of horizontal bonding and other lateral bracing. The lack of such measures in linear temple constructions such as Preah Khan have resulted in the site’s relatively destroyed appearance.

Except for an example at East Gopura Enclosure Wall III, there appears to be minimal deformation or structural failure due to soil settlement, even though there have been changes resulting from alterations to the drainage system at Preah Khan and the presence of water in the surrounding canals. Nevertheless, it is recommended that the possible effects of soil deformations at foundation levels receive further analysis. In general terms, this type of failure can be considered rare at Preah Khan as most of the foundation deformation is attributable to disturbance by tree roots.
In the East Gopura there is evidence of a line of deformations running through the center of the structures on a north-south axis. These are characterized by visible failure and deformation due to the settlement of walls, and are most pronounced at the junction of the south-east section as well as on the free-standing North East Pavilion.

### 2.2. PREVIOUS INTERVENTIONS

The methods and concepts of consolidation applied by the French conservators of the Ecole Française d'Extême Orient (EFEO) during their interventions in Preah Khan (especially in the 1930s and 1950s) deserves mention. EFEO developed the use of reinforced concrete with slender supporting elements which has been successfully applied in several instances to failing vaults by incorporating reinforced concrete beams set under broken stone beams or by the partial concrete encasement of elements and their connections. Other ways of consolidation (with varying degrees of success) can be characterized and evaluated as follows:

- In some cases, a non-reversible material was used so that its replacement in many places might induce additional local damage.

- In many places, especially where beams have been consolidated, the capabilities of reinforced concrete beams were undersized (i.e., slender beams with inadequate reinforcement or insufficient anchorage were used). Many such concrete stabilization repairs have failed and have not prevented the development of new deformations and failures.

- The interventions performed were most efficient in the upper parts of the vaults while in other elements (beams, columns, etc.) the stabilization efforts will need to replaced.
3. BUILDING CLASSIFICATIONS ACCORDING TO STRUCTURAL SYSTEMS

In order to fully understand the design and performance of the structural systems of Preah Khan, the structures were classified into different groups in order to analyze representative structural elements. Approximately nine typical groups of structures were identified and classified according to typological and structural systems [Fig. 3.1]. 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.

1. *Tower Buildings:* unique structures with a central space or shrine, surrounded by towers of different sizes having the same basic structural systems [Fig. 3.1, No. 11 (central towers) to 19].

2. *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 [Fig. 3.1, No. 21 to 25].

3. *Halls:* structures that connect the central towers, but are separated by construction joints which may have been consciously planned expansion joints [Fig. 3.1, No. 31 to 37].

4. *Entrance Halls:* vaulted structures with longitudinal bearing walls which form the entrances (gopura) on each of the four sides of the temple complex [Fig. 3.1, No. 41 to 47].

5. *Vestibules:* elements that form an entity of the central shrines and relatively small attached porches [Fig 3.1, No. 51 to 53].

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6. **Corner Towers:** towers located at the corners of Enclosure Wall I [Fig 3.1, No. 61 to 64].

7. **Cloisters:** corridors [Fig 3.1, No. 71 to 73] associated with Enclosure Wall I, and the corridor system [Fig 3.1, No. 74 & 75] which is part of Enclosure Wall II.

8. **Single Shrines:** 24 single temples representing isolated structures of a relatively small size located within Enclosure Wall I [Fig 3.1, No. 81 to 86].

9. **Special Building Types:** unique structures such as the pavilions [Fig 3.1, No. 91] and the Dharmasala ('pilgrim's resthouse') [Fig 3.1 No. 92]. Within this category are free-standing Enclosure Walls III & IV which are also of particular structural interest.

WMF has already prepared an initial study on the extent of damage at Preah Khan and has recorded its findings in *Report III: Preah Khan Conservation Plan*. This analysis is sufficient for present needs but a more detailed one is planned for a later mission. This is to be accompanied by a definition of degrees of damage so that there might be a standard grading of the structures from Level 1 (non-damaged buildings) to Level 5 (collapsed buildings). This detailed classification will develop a definition of criteria as well as a methodological approach probably using a computer database and will be researched by a team of Cambodian students as an educational exercise.
CLASSIFICATION OF BUILDING TYPES

1. Tower Buildings (No. 11 - 19)
2. Entrance Towers (Gopura) (No. 21 - 25)
3. Halls (No. 31 - 37)
4. Entrance Halls (No. 41 - 47)
5. Vestibules (No. 51 - 53)
6. Corner Towers (No. 61 - 64)
7. Cloisters (No. 71 - 73)
8. Single Shrines (No. 81 - 86)
9. Special Building Types (No. 91 - 93)
4. ANALYSIS OF REPRESENTATIVE BUILDINGS

Following the systematic classification of building typologies, one representative building from each group was analyzed in-depth. This analysis presents an assessment of the structures and their structural systems and provides concepts and recommendations for the conservation, repair and strengthening of the selected structures.

4.1. TOWER BUILDINGS (No. 11 - 19)

General Description

The tower building type is one of the most common at Preah Khan and throughout the Historic City of Angkor. The East Tower [See General Site Plan and Classification of Structures in the Preah Khan Complex, Fig 3.1, No. 11] has been selected as the best example of this type. As nearly all the structural elements noted elsewhere in the Preah Khan complex are present in this tower, it was selected as the most representative building to demonstrate various proposed techniques for conservation and structural repair.

The structural system of the East Tower is easy to understand [See Figs. 4.1 - 4.5]. It consists of central massive sandstone columns on which the tower structure stands. From the central columns, walls (supporting vaults) extend in four directions to form the central hall. These vaults are constructed of corbelled sandstone [Fig. 4.3]. The central columns, the walls and the vaults are constructed of dry laid sandstone masonry. The walls of the corridors, at the point where they meet the halls forming massive columns [Fig. 4.4, Fig. 4.5], are of unique design: the relevant wall is independent of the wall-vault structure. The lintel consists of a non-load bearing beam ('dead beam') with specially shaped stones above which
express the shape of the vaults behind. The weight of the wall is transmitted through the 'vault' stones directly onto the columns. This particular structural system represents the straight-forward approach which Khmer builders used when supporting relatively high and broad roof structures. It brings to mind the dead loading of 'true' arches that was done in other cultures.

**Present Condition**

It is important to observe that the force transmission of the corbelled vault is completely different from that of the 'true' arch type vault and that this is a main reason for its frequent failures. In terms of the level of damage, this building can be classified as having partially failed elements in need of structural repair with its vertical bearing structure being in good condition.

The central tower is partially collapsed - above the level of the central vaults there are only two or three rows of stone masonry [Fig. 4.2, Fig. 4.3]. The bearing vaults of the tower are in relatively good condition, with little damage and deformation. This means that the tower failed due to local horizontal uplifting and sliding of the masonry along the level of its horizontal expansion joints, which, in turn, caused failure of the upper parts. It can therefore be concluded that the central part did not become unstable due to the horizontal movement of the walls.

The entrance vaults have partially or totally collapsed due to deterioration of their original form. They became unstable because of the development of horizontal uplifting from the transfer of dead loading and the lack of elements to counteract such forces.

Besides its main bearing elements, this structure also has portal frame elements with classically shaped columns and beams. EFEO repaired local damage and deterioration to the bearing capacity of these beams and their supports in the 1950s.

**Structural Repair Recommendations**

The following conservation activities, including partial restoration and structural repair, are proposed:
1. Rebuild the tower up to the level of the sixth row of stones by reassembling the original stones. The topmost row should be rebuilt with stone blocks connected by metal clamps and vertical dowels to prevent movement (sliding). In this way, the topmost layer will act as a belt course and ensure the integrity of the upper structure. This should be the basic principle of consolidation of the tower walls.

2. Conserve the deformed corridor vaults in their existing state. Reassemble the end rows of corbelled stones to ensure their structural integrity. If it is decided to completely rebuild the vaults, new elements of color and finish matched lightweight concrete should be used.

3. Strengthen the portal beams through the careful placement of reinforcing steel.

4. Consolidate and strengthen the beam elements of the lateral vaults using steel reinforcement and epoxide.

4.2. ENTRANCE TOWERS (No. 21 – 25)

General Description

The eastern entrance (East Gopura) at Enclosure Wall III consists of a group of buildings which have the appearance of a single entity, but are actually independent structural units with hidden construction joints [Fig. 4.6, Fig. 4.7]. It is important to identify the different structural units as this will affect the method of repair and retro-fitting of each unit. The limits and the connection lines are easy to determine and, based on the damage patterns, it is usually obvious where the divisions between units are placed. Within such groups, there are towers placed on center which, according to their construction methods, are similar to those in the 'tower building' group, with certain specific differences.
Present Condition

Fig. 4.6 shows the plan and the structural system of the building. The central columns are connected by vaults supporting the tower and the vestibules on the four sides enclosed by walls and vaults. The central columns and their connecting vaults are in good structural condition, although the tower itself has failed at its upper level and the existing (about 2.5 m.) upper section has deteriorated with large displacements of stonework [Fig. 4.8]. The vestibule vaults are in far worse condition. In particular, the northern vault has partially failed while the southern vault has suffered heavy deformation. This condition was caused by deformation in the soil tilting the walls and causing failure in the vaults [Fig. 4.9]. The external vaulted corridors have suffered heavy damage due to beam failure [Fig. 4.10].

Structural Repair Recommendations

To ensure structural stability, the following measures are recommended:

1. Reassemble and consolidate the stones of the upper few rows in the tower (at a height of approximately 2.5 - 3.0 m.) with dowels and connecting plates.

2. Completely stabilize the southern vault as it currently has an inclination of 15 - 20 cm. and is detached from the connecting wall along its length. If the vault is not connected, it will be necessary to carry out local stabilization and to reassemble the upper stones of the vault by sealing the opening using lightweight concrete blocks and incorporating steel ties at two levels. The northern vault has also failed and it is necessary to carry out stabilization or to rebuild the vault in its original shape.

It is recommended that stabilization of the vestibules also be carried out by strengthening the beams with the insertion of steel reinforcement and the partial reconstruction of the vaults.
4.3. HALLS - CORRIDORS BETWEEN TOWERS (No. 31 – 37)

General Description

The corridor buildings, which link the towers and the temples, have a structural system consisting of longitudinal walls and vaults [Fig. 4.11].

Present Condition

It is apparent that the original profile of the corridor has deteriorated causing heavy deformation and failure. One particular structure [See Fig. 3.1, the General Site Plan, No. 31] has suffered deformation of the lateral walls and detachment of expansion joints at the vault footing [Fig. 4.12].

Structural Repair Recommendations

The method of stabilization consists of increasing the height of the vault until connection through the stone has been achieved. Due to the serious tilting of the walls, steel ties should be placed. This example represents one of the more drastic cases of damage. Other buildings with similar failures [No. 38, No. 39] do not require interventions as complex as using steel ties. The vaults need to be re-set to their original shape by using methods similar to those used in roof re-setting in corridor structures.

4.4. ENTRANCE HALLS - VESTIBULES TO THE ENTRANCE COMPLEXES (GOPURA) (No. 41 – 47)

General Description

The vestibules to the Gopura such as building No. 41 (which was selected as a representative example of this type) are basically the same as those previously described, having the same structural system and pattern of damage.
Present Condition

Building No. 41 has been damaged due to soil settlement. The weaknesses of the 'corridors between towers' buildings (item 4.3) are even more pronounced when combined with the effects of soil settlement.

Structural Repair Recommendations

Building No. 41 should be stabilized in the same manner as the southern vault of building No. 21.

4.5. VESTIBULES (No. 51 – 53)

General Description

The buildings of this group are smaller in size and proportion and consist of central and peripheral temples connected by and attached to temple corridors. This distinguishes them as a special group of buildings.

Present Condition

Unlike the other building groups, the connection of temples or shrines to the corridors is well integrated and the structural behavior of the building is considered as a complete system [Fig. 4.13]. Thus, the damage patterns noticed in structurally integrated corridors and vestibules reflect problems which usually originate at the larger adjacent structure.

Structural Repair Recommendations

The method for stabilization (especially for building No. 51) will consist of reconstruction of fallen sections and local stabilization of the vaults as described in Chapter 5.
4.6. CORNER TOWERS (No. 61 – 64)

General Description

These are structures at the corners of the massive walls along which the corridors run [Fig. 4.15]. Their structural systems are basically composed of columns and vaults with a tower.

Present Condition

The four corner towers presently vary in condition ranging from stable (as in the case of the structure located in the southwest side [Fig. 4.15]), to severely damaged, to total failure.

Structural Repair Recommendations

Depending on the existing state of the structures, it is recommended that parts of the walls be partially rebuilt and that partially demolished buildings be conserved. Structural stabilization of the remaining buildings should be carried out in the same way as the corner towers.

4.7. CLOISTERS - CORRIDORS AND ENCLOSURE WALLS
(No. 71 – 73)

General Description

Although these buildings have a simple form, they require complete structural analysis and investigation to ascertain the reason for their high structural failure rate in order to determine the best method of structural stabilization and repair.

In general, the corridors are connected to the massive walls. There are special cases where, according to architectural and conservation features, they are
classified as galleries [No. 75]. The corridors are vaulted structures supported by walls (on one side) and/or a system of longitudinal beams and columns on the other. In the Preah Khan complex, there are different types. Fig. 4.16 and Fig. 4.17 show a typical structure in transverse section. Fig. 4.18 and Fig. 4.19 show the basic proportions and cross section. The massive enclosure wall [Fig. 4.20] was constructed of dry laid laterite stone.

Present Condition

The vaults and walls of the corridors forming part of Enclosure Wall II are constructed of laterite stone with a capping layer of decorated sandstone.

The main cause of damage noticed in this group of buildings is due to their minimum resistance capability against horizontal forces. The degree of damage noticed in such structures ranges from a relatively stable condition to total collapse.

Enclosure Wall II West, originally constructed with the corridor, has been considerably altered from its original shape (except for a section of wall along the west side). In principle and for stabilization purposes, this wall should be considered an independent structural entity, especially since areas along its length indicate foundation instability.

The massive Enclosure Wall I West is an independent structure whose stability in areas is endangered by dense vegetation and trees growing alongside [Fig. 4.21 and 4.22].

Structural Repair Recommendations

Methods for consolidation and reconstruction of cloisters and corridors will require resetting of fallen and dislodged vault stones by hydraulic lifting and local stabilization for horizontal resistance [see Chapter 5].

Considering that a relatively small portion of the wall has remained in a condition that allows structural stabilization, it is necessary to be clear on what procedures need to be carried out. First, the stability of the wall needs to be carefully checked. The walls with a vertical inclination of less than 20 cm. are considered stable and
require only the removal of vegetation. In the case of larger deformations, taking into account general conditions, special stabilization measures should only be considered under dire conditions or when, for example, one of the many sandstone garudas along Enclosure Wall IV is threatening collapse. Otherwise, the amount of work involved in the reconstruction of these walls is not feasible.

4.8. SINGLE SHRINES (No. 81 - 86)

General Description

A large number of small individual temples are located within or adjacent to Enclosure Wall I. The buildings of this group characteristically have much smaller proportions (eg. 3.5 x 6.5 m. with a height of 3 - 5 m.) and were constructed as independent buildings with massive walls and a vaulted structure [Fig. 4.23].

Present Condition

Based on the degree of damage, most of these structures, which were not reconstructed by EFEO, are classified as being in a state of total collapse. None of these buildings show only moderate damage, indicating that most must have collapsed soon after initial deterioration commenced. The most common failure can be attributed to lateral pressure to walls which caused the vault to collapse under the concentration of heavy loading in the upper section of the structures.

Structural Repair Recommendations

The majority of these buildings will require improved connections of the exposed end vault stones and at the corners to principal walls. Stabilization can be achieved by the placement of metal plates where stones form a belt course.
4.9. SPECIAL BUILDING TYPES (No. 91 – 93)

The Two-Story Pavilion and the Dharmasala can be classified as examples of exceptional buildings.

**The Pavilion**

**GENERAL DESCRIPTION**

The Two-Story Pavilion is unique in that it has two stories and the upper floor is supported by cylindrical drum columns [Fig. 4.24]. In 1954, EFEO conservators undertook its complete reconstruction using the technique of anastylosis and consolidated the structure using steel plates and old railway track.

**PRESENT CONDITION**

The building is not endangered. Before undertaking any further consolidation measures, it will be necessary to study archival material to ascertain, in detail, what other work was previously done.

**The Dharmasala**

**GENERAL DESCRIPTION**

Another unusual building found at the Preah Khan is the Dharmasala, which is referred to by some as either the *Pilgrim's Resthouse* or the *House of Fire* [Fig. 4.25 and Fig. 4.26 show plans and sections]. The Dharmasala is a temple style building with massive walls supporting the typical vaulted roof structure. A tower is constructed over the west end and a portal wall with an entrance vault is located at the eastern entrance [Fig. 4.27 to Fig. 4.30].
PRESENT CONDITION

Although the building appears to be a single unit, its structural design divides it into three units which can be clearly distinguished by its present pattern of damage. The central vaulted hall suffered deformation due to the outward rotation of the foundation and walls, where the discrepancy from the vertical axis is between 12 and 19 cm. This deformation has created pressure on the vaulted structure and caused sliding along the horizontal expansion joints. This then caused clearly formed vertical detachments between the three sections. The entrance section has a central vault with a smaller span and a facade wall which, due to inadequate connections in the masonry, has detached completely and is no longer in a stable condition. The highest part of the tower has large inclinations and detachments of the walls from the tower as well as local displacements of the masonry walls.

The masonry construction is dry laid sandstone, similar to the other buildings, with all the inherent weaknesses described above (masonry with no satisfactory bonding, lack of vertical expansion joints, etc.). Generally considered, the building is unstable and even a small amount of further damage or deterioration may cause partial or total collapse.

STRUCTURAL REPAIR RECOMMENDATIONS

During the March 1993 mission, the structure was inspected in detail by the WMF team and the Cambodian students to determine how to structurally strengthen the building and bring it to a usable state as a possible site office or exhibition hall. Based on the team’s survey and analysis, the following major and necessary interventions are anticipated to consolidate and make this structure safe. The following three options are given as general solutions:

i) Stabilization, Re-use and Conservation.
ii) Stabilization and Conservation.
iii) Conservation with Minimum Stabilization.
i) Stabilization, Re-use and Conservation

Based on a structural condition analyses made in January and March 1994, the WMF field team proposed the following set of recommendations that, if executed, would render the structure fit for re-use as a working building:

- Strengthen the central and entrance halls with reinforced concrete foundation beams connected at intervals with ties.

- Re-establish the profile of the central hall section and the entrance section by inserting a reinforced concrete ring beam. Reassemble the displaced stones incorporating steel dowels and plates.

- Build in longitudinal steel beams at specific locations supported by transverse beams at the level where the shape of the vault changes. If necessary, the insertion of external beams should be investigated at the time of reconstruction.

- Reconstruct the facade wall over the east entrance and connect the wall to the vault using steel tie plates.

- Counteract local failure in the window openings by placing a steel frame within the perimeter of the window opening.

- Reconstruct some sections with horizontal steel ties as required.

After such repairs and strengthening, the building will be safe for extended usage.

ii) Consolidation, Stabilization and Conservation

As an alternative, the following measures should be undertaken to simply stabilize and consolidate the structure:

- Shore with steel supports before partially reconstructing elevations and reassembling damaged vault areas.

- Rebuild the eastern facade, and provide support within the tower.
• Stabilize the tower, paying special attention to the displacement of its large stone blocks.

These interventions will provide emergency stabilization only. They are not permanent and are not sufficient to enable the building to be used for fully safe public access.

iii) Conservation with Minimum Stabilization

The minimum intervention which will provide sufficient stability to the building in order that it can continue to stand in its precarious state would include the following measures:

• Construct temporary supports on the eastern entrance facade using an external steel scaffolding system.

• Perform similar interventions along the middle of the central vault and to the tower.

This type of stabilization would be done utilizing structural scaffolding designed to support the failing structure in its present position. Only minimal reassembly and replacement of stones will be necessary though unsightly modern structural shoring would need to be left in place indefinitely.

N.B. Emergency shoring using structural scaffolding was installed at the Dharmasala in March 1994. It is felt that this measure occurred just in time to prevent the collapse of at least the east end of the building. Next steps must include a determination of the use of the building, which will have a bearing on the method used for its structural repair.
FIG. 4.1. PLAN AND SECTION - EAST TOWER (NO. 11)

FIG. 4.2. NORTH ELEVATION - EAST TOWER (NO. 11)
FIG. 4.6. PLAN - EAST GOPURA

FIG. 4.7. EAST GOPURA
FIG. 4.8. UPPER SECTION WITH DISPLACED STONWORK - EAST GOPURA

FIG. 4.9. PARTIALLY DAMAGED NORTH VAULT OF EAST GOPURA

FIG. 4.10. BEAM AND COLUMN FAILURE - EAST GOPURA
FIG. 4.11. PLAN AND SECTION - CORRIDOR (NO. 31)

FIG. 4.12. EXPANSION JOINT FAILURE ALONG CORRIDOR WALL AND VAULT CONNECTION - NORTH SECTION OF EAST GOPURA
FIG. 4.13. PLAN - VISHNU TEMPLE COMPLEX

FIG. 4.14. PARTIAL COLLAPSE - VISHNU TEMPLE COMPLEX (LOOKING SOUTHEAST)
FIG. 4.15. VIEW OF SOUTH - WEST CORNER TOWER

Laterite Stone

Sandstone

FIG. 4.16. CROSS SECTION OF CORRIDORS AND ENCLOSURE WALLS
FIG. 4.17. PARTIAL COLLAPSE AND DAMAGE - CORRIDOR IN ENCLOSURE WALL II

FIG. 4.18. TYPICAL CORBELLED VAULT WITH DEFORMATION
FIG. 4.20. SECTIONS OF OUTER AND INNER ENCLOSURE WALLS

FIG. 4.21. DAMAGE - ENCLOSURE WALL III
FIG. 4.22. FICUS TREE CAUSING DAMAGE - NORTH ENCLOSURE WALL III

FIG. 4.23. SINGLE SHRINES
FIG. 4.25. PLAN - THE DHARMASALA

FIG. 4.26. SECTION - THE DHARMASALA
FIG. 4.27. SOUTH ELEVATION - THE DHARMASALA

FIG. 4.28. SEPARATION OF EAST FACADE - THE DHARMASALA
FIG. 4.29. SEPARATION OF TOWER STONES - THE DHARAMSALA

FIG. 4.30. DISLODGED VAULT STONES SHOWING SETTLEMENT - THE DHARAMSALA
5. METHODS FOR CONSOLIDATION, REPAIR & STRENGTHENING OF STRUCTURAL MEMBERS

5.1. METHODOLOGY

The methods recommended 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:

1. Minimum possible intervention at all times to the basic structural system.


3. Application of materials of high durability and minimum interaction with the principal structural materials.

4. Application of reversible materials wherever possible, taking into account climatic and other local conditions.

5. Techniques and methods of implementation should be simple and conform to local conditions and the capabilities of the local work force.
5.2. MATERIALS

The following recommended materials and their applications may be modified in the process of application due to availability and local conditions though the general methodology should become standard procedure.

A basic principle used by WMF in nearly all of its field projects is to use only locally available materials and equipment. The two principal non-original materials used at Preah Khan are steel and epoxide. Regular steel is available in nearby Siem Reap although, at the present time, epoxide adhesives are not available within the country. They are, however, available in Bangkok and can be shipped with little difficulty and cost to the site.

Steel: Steel plates, steel reinforced bars and bolts should be set in epoxide mortars. Where possible, stainless steel is preferable to ordinary steel.

N.B. Following an exhaustive search in January 1994 in the local market in Siem Reap, a quantity of 15 mm. stainless steel bars was located. About 30 sections three meters long were purchased (at approximately $1.00 per meter run) and stored for future use.

Epoxide Resins: Epoxide Resins and Epoxide Mortars are the types of adhesives recommended for refixing fractured or broken stonework. Different mixtures of adhesives have been formulated (in collaboration with Dr. Frank Preusser, WMF's materials conservation specialist) to be used depending on the size of cracks and the degree of damage. (See also Reports IV and V.)

The formulae and applications for Epoxide Resins are:

- **Epoxide Resin and Powdered Sandstone:** A ratio of 1:2 Resin/Sand mix is suitable for filling cracks wider than 2 mm.

- **Epoxide Mortar 1-2:** A ratio of 1:2 Epoxide/Sand is sometimes used with a lower or higher ratio of sand mixed with lower or higher percentage of sand.
• *Epoxide Resin*: A neat epoxide formulation for injecting into small cracks and crevices. The maximum sand grain size is 0.5 mm.

• *Epoxide Mortar 1-2*: This typifies a standard mortar with epoxide binders and cement additives (the filler/binder ratio is the same as for standard mortars).

### 5.3. BEAMS

#### Diagnosis

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 lintels and window lintels).

- Bending moment failure evidenced by vertical cracks in the mid-span areas of beams.

#### Methods of Repair and Strengthening

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 as follows:

Methods for temporary lintel repairs are detailed in Fig. 5.1 to Fig. 5.4. Methods for temporary beam consolidation are detailed in Fig. 5.5 to Fig. 5.7. More permanent repairs and strengthening of beams are detailed in Fig. 5.8 to Fig. 5.13.

The methods for temporary repair and consolidation are visible but the interventions are easily removed, if permanent repair and/or strengthening are later desired.
The proposed methods for permanent repair and strengthening are practically invisible [Fig. 5.8 to Fig. 5.13]. The method selected for repair and strengthening is determined by the types of failure, adjacent structural conditions and aesthetic concerns. Shear failures [Fig. 5.8 to Fig. 5.9] will require filling of the cracks with epoxide mortars or injection of epoxide resins in combination with steel bolts that are rust proofed by placement in epoxide resin.

A very simple and effective method for repairing failures due to bending moments - usually a vertical crack midway along a span [Fig. 5.10 to Fig. 5.13] - is the use of post-tensioned steel bars and steel plates with anchorage bolts set in epoxide mortars and/or epoxide resins.

5.4. COLUMNS

Diagnosis

Columns are common elements at Preah Khan and throughout the Historic City of Angkor. Due to their structural significance when standing columns exhibit signs of failure their repair is of crucial importance. 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.

Methods of Repair and Strengthening

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 temporary consolidation and strengthening, steel belting is recommended (as described in Fig. 5.14 to Fig. 5.17). This is a very efficient method which is easy to execute. It is recommended that stainless steel be used. The steel belts can be
easily removed when permanent repair and/or additional strengthening is to be undertaken.

The application of steel staples for temporary consolidation (as described in Fig. 5.17 to Fig. 5.20) is another efficient remedy especially for use on columns, at slipping doors and window frames, and where doors and windows connect to massive walls.

The methods detailed in Fig. 5.20 to Fig. 5.24 incorporate the following materials: stainless steel and epoxies - either resins or epoxide mortars. In cases of severe damage and large cracks, the repair process is undertaken as described in Fig. 5.21.

A simple but effective method (described below and in accompanying drawings) has been introduced to consolidate split or otherwise damaged columns.

• The column is relieved of its load by carefully jacking the lintel or beam above it.

• The fracture is cleaned out using compressed air.

• The joint of the fracture is pulled together using temporary metal clamps (contact between the stone and metal is avoided by using timber wedges).

• Once the fracture is closed, the column is drilled through completely with a drill and 12 mm. masonry bit.

• Spaces on the stone surface are carefully incised (countersunk) to a depth which will accommodate a washer and nut.

• The bolts, which have been cut and tapped to the correct length, are coated in epoxy resin glue, placed in the drill holes and tightened to close the fracture as tight as possible.
• The remaining open section of the fracture is carefully filled with a resin bonded mortar matching the stonework in color and finish. The area is thoroughly cleaned of any residue.

Many small cracks are often found in the lower parts of the columns. An efficient way of injecting this zone is to incorporate (perpendicular to the cracks) 4-5 mm. diameter steel dowels set in epoxies. In this way, the injection zone is 'reinforced' incorporating both mechanical and chemical methods of repair [Fig. 5. 24].

5.5. ROOF STRUCTURES - VAULTS

Diagnosis

The roof structures at Preah Khan are corbelled vaults of sandstone and laterite stone. When laterite stone is used, the capping stone along the ridge of the vault is usually of sandstone.

Conditions of near or total collapse are principally caused by the original shape of the vaults being displaced. This is evidenced by horizontal displacement (sliding), vertical dislocation along vault centerlines and misalignment at vault spring lines [Fig. 5. 25, 5.26].

Methods of Repair and Strengthening

In the case of serious deformation of vault stones, the displaced stones should be brought back to their original form with the use of hydraulic jacks. Connecting elements such as steel shear pins, plates and ties can easily be installed to prevent further slippage.

As a short term solution vaults can be temporarily shored using triangular steel supports (shelves) [see Fig. 5.27]. In cases of serious deformations (especially walls that are bulging or forms leaning), stabilization using steel ties is often the best solution [Fig. 5.28]. The use of any blatantly exposed steel supports should
be considered as temporary measures since they detract from the artistic and historic character of the site.

A simple and effective method for permanent repair and strengthening of vaulted spaces is the rebuilding and partial reassembling of the topmost layers (after raising with hydraulic jacks) using steel dowels and plates as connectors [Fig. 5.29 and Fig. 5.30].

5.6. TOWERS

Diagnosis

The most frequent type of damage to the tower buildings is the failure of masonry along vertical joints. The vertical joints have insufficient overlap making them vulnerable to any horizontal pressure or the spitting action of plant roots coming down from above. When this occurs the structural integrity of the towers is threatened by long vertical cracks. When the process of the wedging apart and displacement of stones occurs it usually results in partial or complete failure of the structure [Fig. 5.31].

Methods of Repair and Strengthening

Structural consolidation of damaged tower structures can be achieved by preventing the expansion of the vertical cracks and by local stabilization of individual stone blocks using steel ties at different levels in the towers [Fig. 5.32]. Consolidation could be achieved with the use of steel plates, dowels and staples. Belting and post-tensioning are possibilities as well.

In the case of rebuilding and reassembling the topmost layers of the towers, steel dowels and connecting steel plates should be placed at different levels [see Fig. 5.31]. Connection of facade stones and key stones should be done using the same techniques as those used for the repair of large vertical cracks. Consolidation of towers can only be undertaken after the repair and strengthening of the structure's lower vaults, walls and columns.
5.7. VAULTS

Diagnosis

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. In cases where they rest on either columns or insufficiently rigid walls, typical failure occurs due to differential transmission of building weight. Such failure is usually noticed in deformations at both the vault's central vertical axis and at vault spring lines.

Methods of Consolidation and Repair

Bearing vaults as found at Angkor appear to be frequently overloaded by large concentrated masses above them. Therefore, prior to each consolidation and repair intervention, careful investigation of tower superstructures and their stability should occur. Such a precautionary measure is important as even the slightest intervention could cause instability and subsequent structural collapse.

Stabilization of load bearing vaults should be carried out by placing steel members and ties where stone displacement has occurred [Fig. 5.32 to Fig. 5.35]. This intervention will probably require the careful and coordinated use of hydraulic jacks.

5.8. ENCLOSURE WALLS

Diagnosis

Taking into consideration the length of the Enclosure Walls at Preah Khan and their overall condition (each requires major stabilization and rebuilding work), additional
investigations and testing of repair procedures are necessary before a general recommendation is made for the repair and conservation of these important elements of the Preah Khan complex. Thus far, visual inspections and some selected core samples have identified two main reasons for damage and collapse of enclosure walls: damaging vegetation and moisture - either from above or below. The result is the deterioration of laterite wall construction at either the foundation level or at the wall tops.

Wall failure due to ground settlement may, in fact, not be the problem at Preah Khan that it was originally suspected to be. Excavation along wall foundations at East Enclosure Wall IV (some 15m north of the East Gopura) revealed that a large section of wall collapsed due to the heaving action of large tree roots.

Methods of Repair

It is of primary importance to completely remove dense vegetation affecting the walls and to guard against the penetration of rainwater from above. Where a wall is leaning, raking shores should be installed to provide temporary support. Although original materials are preferred for the rebuilding of damaged walls, new or recycled materials will likely have to be incorporated when extensive reconstruction and repair work is undertaken. The return of damaging vegetation should be prevented and where possible foundations should be better protected against water penetration.

The development of standard repair methods for the laterite walls of Preah Khan will require determining an acceptable level of stability since, as is the case with architectural ruins found elsewhere at the site, complete restoration to a level of perfect straightness and serviceability is not practical. A possible repair method for an acceptable level of restoration intervention is presented as a case study in Chapter 7.
5.9. METHODS OF CONSTRUCTION FOR TYPICAL STONE STRUCTURES

Diagnosis

There is not a great deal of variation to be seen in ancient Khmer construction technology, at least as it is found at Preah Khan. Thus, methods for repair and conservation of structural systems and their components can, for the most part, also be limited in choice. This having been said, it should be noted that no two structural conservation challenges in the field are exactly alike, due to a number of variables mainly having to do with condition.

Despite the typical methods of stone construction used in structures such as the South Porch of the East Gopura III or the Hall of Dancers, it is necessary to analyze their present condition in more detail and to recommend solutions which follow the typical repairs as described in this report.

Methodology of Repair and Consolidation

A methodology for repair and consolidation for many of the building conservation challenges faced at Preah Khan is best illustrated by the techniques used by the WMF team to repair the South Portico of East Gopura III. In March 1993, this porch was on the verge of collapsing due to serious structural deformations mainly caused by settlement and ineffective repairs in the 1950's. The entire porch structure was tilting outward at an approximate 20° angle, was disengaged from the jambs of the Gopura vestibule, and its side beams were settling in a way which was wedging the structure further and further apart. The details of the stabilization and repair of the South Portico of the East Gopura during the January and March 1994 field missions are given in Chapter 6.

1. Following the temporary erection of emergency supports using raking shores, a steel scaffolding was erected around the structure to provide support to its unstable columns and to provide working platforms on which to off-load the remaining vault stones and lintels.
2. All stones to be moved were documented on detailed drawings of record with each stone numbered both *in situ* and on the drawings.

3. Stone vaults, beams and lintels were raised by block and tackle and placed on scaffolding platforms as close to their original location as possible.

4. A detailed assessment was made of the structural stability of column and beam structural composition and a plan developed for consolidation.

5. The west pair of columns were individually returned to the vertical position using hydraulic jacks. The east pair, together with its joining lintel, were returned to the vertical position using pairs of jacks. (One column which had fractured at its base was reinforced using temporary steel plates and bands.)

6. Damaged pieces of stonework were refixed (prior to their relocation) using epoxide glues and the below-grade bases of the columns were consolidated using mass concrete.

7. Vulnerable joints and connections in the roof beams were strengthened using stainless steel dowels and steel plates previously coated in epoxide. These interventions can only be detected from above, if seen at all.

The following sequence of work was done to the paved stone floor:

1. The 'as found' condition of the stone paving was carefully documented on archaeological drawings of record.

2. All loose stones and aggregate were removed to expose a laterite substrate. Unfinished stone chips were saved for use in concrete.

3. The sandstone forming the front steps was removed and stacked in order, ready for reconstruction.

4. Foundation stones in the area of the column footings were carefully removed until stable soil was encountered. The excavation was prepared to receive a new concrete foundation.
5. A concrete mixture of (1:3:5) was placed to an elevation of 10 cm. below the original finish paving level in the area of the column bases.

6. The stone steps were rebuilt and structurally enhanced by doweling the stones together. No concrete or mortar was used to bed the stones. A limited number of dowels were also used to secure some of the large substrate stones located near the porch edges.

7. The inside of the stone construction was lined vertically with a heavy duty polyethylene sheet and made ready to receive concrete. No concrete came into contact with the stone.

8. A weak concrete (1:5:9) base was laid at the paving substrate level ready to receive the original paving stones.

9. The top layer of sandstone pavers was reset in its original position as per the documentary drawings and photographs.

5.10. LANTERNS (BORNES) - PROCESIONAL WAY

Diagnosis

A detailed archaeological inventory of the East Processional Way at Preah Khan was undertaken during Field Campaign I. See Report *Preah Khan Conservation Project Field Campaign I* - *Appendix IV/A*. During the January 1994 mission of Field Campaign II, the stone conservation team made an analytical study and conducted some experiments which are described in Appendix O of *Preah Khan Conservation Project - Report V*.

The photos presented in Figs. 5.36 - 5.39 show that there are two main types of damage to the bornes located along the processional way: (i) disturbed stability (overturning, tilting, and damage to the top half of the bornes from falling), and
(ii) cracks in the blocks forming the base or the top portions and separation of these elements.

**Methods of Repair**

The proposed methods for structural repair, strengthening and stabilization of the lanterns depend upon their degree of damage. Recommendations for possible interventions are presented in Fig. 5.40.

Based on consultation with the members of the stone conservation team, epoxies (with possible variants such as epoxide resin for injection, epoxide mortars in different mixtures, etc.) and stainless steel are proposed as the main materials. In the case of connecting larger parts when glue fastening is insufficient, it is necessary to perform mechanical bonding with the additional use of steel dowels. Repair schemes illustrated in Fig. 5.40 show a variety of structural repair techniques using dowels. (See also *Report V, Appendix B, part 5.*)

### 5.11. INDIVIDUAL STRUCTURES

**Diagnosis**

In order to provide specific conservation solutions for some of the special structures at Preah Khan such as the Dharmasala and the numerous shrines within Enclosure Wall II, it will be necessary to generate more detailed analyses of the structures in question. It can be said, however, that solutions which are likely for these structures will probably not vary greatly from the concepts and methods discussed in this report.
FIG. 5.1. REPAIR OF LINTEL BEAM SHEAR FAILURE - TEMPORARY SOLUTION

a) Angle

b) Strap
FIG. 5.2. REPAIR OF LINTEL BEAM SHEAR FAILURE - TEMPORARY SOLUTION

a) Steel Angle 1 12 - 1 16

b) Staple
FIG. 53. REPAIR OF BENDING MOMENT FAILURE WITH STAPLES
(TEMPORARY SOLUTION)
FIG. 5.4. REPAIR OF BENDING MOMENT FAILURE WITH STEEL PLATE (TEMPORARY SOLUTION)
FIG. 5.5. LI NTEL BEAM CONSOLIDATION - SHORT TERM SOLUTION
FIG. 5.6. LINTEL BEAM CONSOLIDATION - SHORT TERM SOLUTION
FIG. 5.7. LINTEL BEAM CONSOLIDATION - SHORT TERM SOLUTION
FIG. 5.8. REPAIR AND STRENGTHENING OF SMALLER SHEAR CRACK IN LINTEL

FIG. 5.9. REPAIR AND STRENGTHENING OF SMALLER SHEAR CRACK IN LINTEL
FIG. 5.10. REPAIR AND STRENGTHENING OF BEARING BEAM BY POST TENSIONED STEEL BAR
FIG. 5.11. REPAIR AND STRENGTHENING OF BEARING BEAM BY POST TENSIONED STEEL BAR
FIG. 5.12.  REPAIR AND STRENGTHENING OF BEARING BEAM BY DOUBLE STEEL PLATES
FIG. 5.13. REPAIR AND STRENGTHENING OF BEARING BEAM BY SINGLE STEEL PLATE
FIG. 5.14. TEMPORARY STRENGTHENING AND CONSOLIDATION OF ENTIRE COLUMN BY STEEL BELTING

FIG. 5.15. TEMPORARY STRENGTHENING AND CONSOLIDATION OF UPPER PART OF A DAMAGED COLUMN BY STEEL BELTING

FIG. 5.16. TEMPORARY STRENGTHENING AND CONSOLIDATION OF LOWER PART OF A DAMAGED COLUMN BY STEEL BELTING

FIG. 5.17. TEMPORARY STRENGTHENING AND CONSOLIDATION OF MIDDLE PART OF A DAMAGED COLUMN BY STEEL PLATE AND BELTING
FIG. 5.18. TEMPORARY STRENGTHENING AND CONSOLIDATION OF A DAMAGED COLUMN BY APPLYING EPOXIDE MORTAR AND STEEL BELTING

FIG. 5.19. TEMPORARY STRENGTHENING OF DOOR COLUMNS BY STEEL STAPLES

FIG. 5.20. TEMPORARY CONSOLIDATION OF DAMAGED COLUMN BY STEEL STAPLE
FIG. 5.21. PROCESS FOR PERMANENT REPAIR, STRENGTHENING AND CONSOLIDATION OF HEAVILY DAMAGED STONE COLUMNS
FIG. 5.22. REPAIR AND STRENGTHENING OF DAMAGED COLUMNS BY EPOXIDE INJECTION, EPOXIDE MORTAR AND STEEL BELTS

FIG. 5.23. REPAIR AND STRENGTHENING OF DAMAGED COLUMN BY EPOXIDE MORTAR, EPOXIDE INJECTION AND STEEL BELTS

FIG. 5.24. REPAIR OF COLUMN CRACKS BY EPOXIDE INJECTION AND STRENGTHENING BY STEEL NEEDLES
FIG. 5.25.  DAMAGE AND PARTIAL COLLAPSE OF ROOF STRUCTURE

FIG. 5.26.  ROOF STRUCTURE - CORBELLED VAULT
FIG. 5.27. TEMPORARY STABILIZATION OF ROOF STRUCTURE BY TRIANGULAR STEEL SUPPORTS

FIG. 5.28. STABILIZATION OF ROOF STRUCTURE BY STEEL TIE
FIG. 5.29. REPAIR AND STRENGTHENING OF ROOF STRUCTURE BY STEEL PLATE AND DOWEL CONNECTION

FIG. 5.30. STABILIZATION AND REALIGNMENT OF FAULT USING STEEL PINS
FIG. 531.  TYPICAL VERTICAL JOINT FAILURE - TOWER STRUCTURES
FIG. 5.32. CONSOLIDATION OF TOWER BUILDING
FIG. 5.33. CONSOLIDATION OF BEARING VAULTS

FIG. 5.34. STABILIZATION OF VAULTS BY STEEL TIE

FIG. 5.35. TEMPORARY REPAIR AND STRENGTHENING BY STEEL PLATES AND DOWELS
FIG. 5.36. WEST PROCESSIONAL WAY

FIG. 5.37. DAMAGED LANTERN (BORNE)
FIG. 5.38.  DAMAGED LANTERN (BORNE)

FIG. 5.39.  DAMAGED LANTERN (BORNE)
FIG. 5.40. LANTERN REPAIR

- REASSEMBLY
- CRACK REPAIR
  EPOXY RESIN INJECTION
- SPALL REPAIR
  EPOXY AND PIN
- DOWELING OF PIECES
6. THREE CASE STUDIES OF CONSOLIDATION AND REPAIR

The above mentioned conservation approaches have been applied to four characteristic examples in need of stabilization. This was done in order to test and demonstrate the proposed methodologies formulated by the WMF technical staff and to train field staff by exposing them firsthand to the real experience of in situ architectural/archaeological conservation.

6.1. REPAIR AND CONSOLIDATION OF THE SOUTH PORTICO OF THE EAST GOPURA

Present State and Diagnosis

The porch (portico) is located on the east facade of the south part of East Gopura III and is part of the grand entrance. It is an important element in the design of one of the most important buildings at Preah Khan.

One possible cause for the precarious state of this projecting portico can be attributed to the root system of a large ficus tree that straddles a nearby gallery of this gopura. After clearance of jungle in the area in 1992, it was clearly seen for the first time in over twenty years that all which remained of the structure was four columns, its beams, fragments of a fronton on the east elevation, and a few roof vault stones. The majority of the original roofing stones had collapsed and the portico columns were leaning dramatically in the easterly direction with deflections of 69 to 73 cm. from true vertical.

During the March 1993 mission, the structure was shored with timber props. During the January 1994 mission, it was concluded that this structure was in
urgent need of repair and consolidation in order to save it from collapse. The beam connections were found to be separating and were settling in a way which was forcing the structure further apart at its beam and column joints [Figs. 6.1 and 6.2]. The collapse of this portion of the gopura would have likely destroyed its carved fronton and carved lintels, and a well preserved *singha* (guardian lion) located at the south side of its entrance steps.

**Recording and Measurement**

Prior to any work being undertaken, all stones including two levels of paving stones, lintels, vaults and adjacent wall structure, were extensively photographed, and measured and drawn to scale as part of WMF's standard documentation process. All stones were carefully inventoried with their reference number painted on each stone in order to facilitate their accurate removal and replacement. Stones forming the surround of the portal into the vestibule were also referenced although they were not to be temporarily dismantled.

In addition to the above mentioned graphic documentation, the complete process of dismantling and repairing the remains of the South Portico was extensively recorded by both still photography and video camera.

**Conservation Process**

Structural repair and consolidation commenced on January 4, 1994. A steel scaffold was erected and a timber platform was positioned at the level of the column tops to receive lintels and other stones forming the roof of the structure. The longitudinal beams and roof blocks were lifted and placed on the platforms. The loading on the front portal beam was removed and the beam was left *in situ* attached to the front columns. The paving stones and steps of the porch structure were then carefully removed and laid out in a logical fashion in order to facilitate reconstruction [See Figs. 6.3 to Fig. 6.6]. Stones at the base of the columns were removed down to their laterite stone foundation layer.

Following these preparations, the columns were returned to a vertical position using hydraulic jacks, wooden levers, nylon straps and ordinary rope. The front (easternmost) columns were jacked back into vertical position in tandem with its
lintel and the carved fronton above it. This was accomplished by operating both hydraulic jack systems simultaneously [Fig. 6.6]. After returning the columns to a vertical position, each was stabilized at its base with a pour of a medium strength of reinforced concrete.

Realignment and repair of the north and south vestibule entry surrounds and their returns was undertaken before the lintels and other stonework at the roof level were realigned and reset. During this process broken stone blocks were repaired and strengthened [Fig. 6.9] with the use of steel plates, dowels, epoxide and other means as described in Chapter 5 [Figs. 6.10 and 6.11].

The final phase involved restoring the floor of the terrace which consisted of removing the upper two layers of stone blocks, cleaning roots and earth from the base-course and expansion joints, covering the floor with a mortar layer and sealing vertical expansion joints of the final mortar layer (whereby hydro-isolation and protection against the growth of vegetation was achieved).

6.2. REPAIR AND STRENGTHENING OF A SANDSTONE COLUMN IN THE HALL OF DANCERS

Present Condition

A monolithic square column located in the southeast portion of the Hall of Dancers at Preah Khan was selected for repair due to the representative nature of its damage. In this instance the column supports an intact corbelled half-vault via two beams which meet at the centerline of its capital [Fig. 6.13]. Damage to the column consists of a longitudinal crack along its entire 2.35 m. length and addition small cracks at its base.

Conservation Intervention

The column was repaired and strengthened using two epoxide mixes and steel dowels [Fig. 6.14]. After placement of temporary steel belts to guard against further splitting, hydraulic jacks were used to lift the beams in order to relieve
column loading. After debris in the cracks of the column were removed by compressed air, the steel belts were tightened in order to decrease the width of the longitudinal cracks from 24 mm. to 3 - 4 mm. After this, 15 mm. holes were drilled into the stone, steel dowels inserted and the crack was injected with epoxide resin. Touch-up finishing of the repaired cracks and the countersunk dowel heads was accomplished by using a weaker strength of epoxide with stone dust pressed into it which made the intervention nearly invisible [Fig. 6.15].

6.3. REPAIR AND STRENGTHENING OF LINTELS IN THE VISHNU TEMPLE COMPLEX

Two lintels in the Vishnu Complex in the west portion of Preah Khan were selected for repair in order to demonstrate two different techniques and for purposes of staff training.

6.3.1. Temporary Consolidation of a Lintel Beam

Prior to repair which occurred on March 26, 1994 a 20 mm. diagonal crack was evident in the easternmost lintel of Room Seven (7) of the gopura of the West Vishnu complex. Temporary consolidation was accomplished by lifting the lintel so that its parts were realigned and placing a steel angle at the juncture where the horizontal lintel joins its vertical support. An hydraulic jack raised the lintel and the steel angle was anchored to the jamb of the opening using stainless steel bolts [Fig. 6.16]. An epoxide coating was used to protect all metal parts against corrosion.

6.3.2. Permanent Consolidation of a Lintel Beam

Permanent consolidation of a completely cracked lintel in Room Four (4) of the same building was performed by filling the crack with epoxide mortar, repositioning the beam and inserting steel dowels at diagonals [See Fig. 6.17]. The particulars of the procedure are listed below:

- Where possible relieve all loading on a lintel by inserting temporary supports.
• By careful jacking, carefully close the fracture as much as possible and keep shored in position for drilling.

• Drill two (2) 12 mm. holes at right angles to the fracture line. If possible, expose the point where the hole comes through the uppermost part of the lintel.

• Cut and thread stainless steel bolts.

• After coating bolts in epoxy resin, position in holes and fit inner washer and bolt in order to anchor the dowel.

• Tighten outer nut with washer so that the dowel firmly draws the two stone pieces together. If it is not possible to fit an anchor bolt or plate, plenty of adhesive should be pushed into the hole to ensure good adhesion between the threaded dowel and the stone.

• Fill the fracture with epoxide mortar allowing filling tubes for injection grouting. Inject with filling mortar from bottom to top. (An alternative, if possible, is to inject filling mortar into the crack before the tightening of the tension rods.)

• Once injection is complete, allow drying before the application of a weak epoxide mortar mixed with stone dust to the exposed joint. The matching of the color and texture of the cleaned stone pieces being restored, and careful craftsmanship is very important during this stage of the procedure.

6.4. ANALYSES AND REPAIRS AT EAST ENCLOSURE WALL IV

During the March 1994 mission a typical collapsed section of Enclosure Wall IV located just north of the northern end of East Gopura IV was examined in order to understand the reason for its collapse and its repair potential. Some 21 meters of the massive laterite wall had fallen in the direction of the moat to the east. Fortunately this section of wall did not contain any of Preah Khan's famous
monumental protective garuda sculptures which are to be seen at regular intervals along this outermost enclosure wall of the site.

The first actions of work in this area involved vegetation removal and disengaging most of the half buried laterite blocks. Each stone was cleaned, referenced and relocated to an adjacent lay out area.

The results of core samples of the foundation revealed that no natural soil settlement had occurred in this area. It appears that the failure of the wall was due to deterioration of the laterite at the point where the wall meets the ground (immediately above the foundation) due to poor drainage, and because of large tree root disturbance.
FIG. 6.1. SOUTH PORCH OF EAST GOPURA
PRIOR TO RECONSTRUCTION (JANUARY 1994)

FIG. 6.2. DAMAGE TO SOUTH PORCH OF EAST GOPURA
FIG. 6.4. STONE SURVEY AND NUMBERING - FLOOR
FIG. 6.5. STONE SURVEY AND NUMBERING - ROOF
FIG. 6.6. SURVEY AND NUMBERING - PORTICO ENCLOSURE WALLS
FIG. 6.7.  SCAFFOLDING AND SHORING DESIGN FOR PORTICO RECONSTRUCTION
FIG. 6.8. SOUTH PORCH OF EAST GOPURA - WORK IN PROGRESS (MARCH 1994)
FIG. 6.9. REPAIR OF BROKEN SANDSTONE BLOCK

FIG. 6.10. DESIGN FOR RESTORED PORCH
FIG. 6.11. RESTORED SOUTH PORCH OF EAST GOPURA

FIG. 6.12. CRACKS IN COLUMN - HALL OF DANCERS

FIG. 6.13. COLUMN - HALL OF DANCERS
FIG. 6.14. REPAIR AND STRENGTHENING OF COLUMN - HALL OF DANCERS
FIG. 6.15. REPAIRED COLUMN - HALL OF DANCERS
FIG. 6.16. TEMPORARY STABILIZATION OF LINTEL BEAM - VISHNU COMPLEX

FIG. 6.17. PERMANENT STABILIZATION OF LINTEL BEAM - VISHNU COMPLEX
FIG. 6.18. EAST ENCLOSURE WALL IV
FIG. 6.19. EAST ENCLOSURE WALL IV - FOUNDATION

FIG. 6.20. EAST ENCLOSURE WALL IV (LOOKING WEST)
7. RECOMMENDED URGENT TEMPORARY PROTECTION MEASURES AND CONSERVATION INTERVENTIONS AT PREAH KHAN'S MOST ENDANGERED BUILDINGS OR PARTS THEREOF

7.1. URGENT MEASURES FOR TEMPORARY PROTECTION

An intensive effort was undertaken throughout 1993 to disengage the structures of Preah Khan from the jungle and surface debris which was followed by a survey for the purpose of identifying structures which were in danger of collapse, rapid further deterioration and/or were considered hazardous to visitors. For this reason, inspections were carried out to identify the most critical areas of concern and instructions were given to the work force to temporarily brace buildings of building elements which threatened to fall.

Special plans made of the site by both the archaeologists and the structural engineer denote the structures requiring urgent temporary shoring and repair. It should be noted that structural shoring using locally cut timber is only temporary and while in place it must be carefully monitored on a regular basis. Where the timely repair of these structurally unstable features of the site cannot be affected (due to the shear number of problems) more durable supports should be installed until proper attention can be given to all of the some 135 specially propped structures or components.

7.2. RECOMMENDATIONS FOR URGENT INTERVENTIONS

The critical structures requiring urgent action to prevent collapse were again inspected during the March 1994 mission. The buildings and zones of the site
identified below are considered dangerous and require urgent intervention. A decision on the scope and level of protection (whether only remedial solutions or longer term interventions) should be made on the basis of funding availability.

7.2.1. The Dharmasala Hall

A detailed description of this structure and a survey of its condition are contained in Report IV, Preah Khan Conservation Project, Field Campaign I, Appendix IV/C, as well as Chapter IV of this report. The structural stability of the Dharmasala Hall is in a critical state. In March 1993, vegetation was removed from within and around the structure and it was shored using timber props. Further inspection in March 1994 revealed that the shoring was insufficient and that further deterioration had occurred: fallen blocks in the central area, new cracks in walls and beams, and separation of portions of the building, most notably its east facade.

As a first and most urgently needed measure, carefully designed metal scaffolding was erected on the east and west sides to augment existing timber supports [see Fig. 7.1]. The scaffolding was designed so that it can be used when the actual conservation intervention is undertaken. There is a good probability that the structure will collapse in the near future - during the heavy monsoons - unless urgent measures are taken for its protection. Chapter 4 of this report proposes an approach for deciding whether to undertake repair, consolidation and conservation. A detailed design for repair and conservation of this structure must be developed before any long term conservation work is undertaken.

7.2.2. Structure in the Hall of Dancers

A rare almost complete corner of an important Khmer building type remains in the southeast corner of the Hall of Dancers. [See Fig. 7.2.] At present it is highly unstable and likely to collapse. This part of the Hall of Dancers is one of the few areas of Preah Khan that was not repaired during French administration of the site. Permanent consolidation by strengthening the primary structural elements (columns, beams) and partial reconstruction of the vaults is recommended.

Considering its location on the main visitor route through the complex, urgent measures should be undertaken. These repair and consolidation activities could
also easily serve to indicate methods of conservation for visitors of the site and
interested others.

7.2.3. Portico at East Gopura IV

During the French administration, the inner North Portico of the East Gopura
underwent some intervention utilizing reinforced concrete elements and steel
anchors. At this time the anchors are corroded, concrete parts are deteriorated and
the structure itself is threatening collapse. It is necessary to carry out measures for
stabilizing this structure by partial reconstruction of the roof vaults and the
strengthening of structural elements (beams, columns and foundations) [Fig. 7].
FIG. 7.1. ERECTION OF STRUCTURAL SCAFFOLDING - EAST FACADE
DHARMASALA HALL
FIG. 73. SOUTH PORCH - EAST GOPURA IV (LOOKING WEST)
8. INVESTIGATION OF BUILDING MATERIALS

It is essential that additional investigations be carried out to assess the basic mechanical and load carrying characteristics of sandstone and laterite materials. In March 1993 test samples in the shape of cubes and prisms of both sandstone and laterite were prepared for tests of compressive and tensile strength, bending resistance, porosity and bulk density. The cubes (20/20/20 cm. and 10/10/10 cm.) and prisms (4/4/12 cm. and 40/10/10 cm.) were taken to the laboratory of the Institute of Technology at the University of Phnom Penh to be investigated. However, due to subsequent changes in administration at the Institute, these tests were not performed.

In order to define possible methods for structural repair and strengthening, some basic mechanical and load bearing characteristics of Preah Khan's sandstone and laterite were tested at the Laboratory of ADING Ltd. in Skopje, Macedonia. Adhesive materials to possibly be used in the repair process were tested on the original Kulen sandstone samples.

8.1. SANDSTONE

For testing of the strength characteristics of typical sandstone from Preah Khan, four prisms with dimensions of 40/40/160 mm. were tested under laboratory conditions using standard procedures. The compressive and bending strength of the samples were determined to be normal and parallel to the layers. The results of these tests are presented in Table 1.
Table 1. Characteristics of Preah Khan's Sandstone

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dimensions [mm]</th>
<th>( \gamma ) [kg/m(^3)]</th>
<th>( \beta_c ) [N/mm(^2)]</th>
<th>( \beta_b ) [N/mm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35/40/160</td>
<td>-</td>
<td>61.6</td>
<td>5.67</td>
</tr>
<tr>
<td>2</td>
<td>39/40/160</td>
<td>2575</td>
<td>0.9</td>
<td>5.52</td>
</tr>
<tr>
<td>3</td>
<td>40/40/160</td>
<td>2639</td>
<td>30.94</td>
<td>5.51</td>
</tr>
<tr>
<td>4</td>
<td>40/40/160</td>
<td>2623</td>
<td>19.15</td>
<td>4.75</td>
</tr>
</tbody>
</table>

\( \gamma \) - density  
\( \beta_c \) - compressive strength  
\( \beta_b \) - bending strength

Based on these results, it may be concluded that the sandstone used at Preah Khan is a typical fine-grained sedimentary rock, i.e., sandstone. The mechanical and bearing characteristics of sandstone vary depending on the stretching direction of the layers. The bulk density is uniform in all samples. The tensile strength, i.e., \( \beta_b \) - bending strength is also within the allowable limits with allowable deviations \([\beta_b = 5.67; \beta_b = 4.75 \text{ MPa}]\).

However, the results relating to the compressive strength are different - the difference being up to 300%, i.e., \( \beta_c = 61.6 \text{ MPa} \) in respect to \( \beta_c = 19.15 \text{ MPa} \) (which is expected and due to the stretching direction of the main sedimentary layers). The experimental results thoroughly correspond to the failure types found in columns at the site.

**8.2. LATERITE STONE**

As laterite was seen primarily as a secondary construction material at Preah Khan, it had not generally been considered in previous analyses. Considering that laterite
stone is a volcanogene-sedimentary rock of a complex chemical content involving substances of different origin, and that the samples tested had been used as a construction material, more detailed information as to its chemical-physical and strength characteristics is necessary. Some preliminary analyses of this material have been made, however, in order to explain some phenomena of damage and behavior of structures in the Historic City of Angkor. The strength characteristics of this material are given in Table 2.

Table 2. Characteristics of Preah Khan's Laterite Stone

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dimensions [mm]</th>
<th>$\gamma$ [kg/m$^3$]</th>
<th>$\beta_c$ [N/mm$^2$]</th>
<th>$\beta_b$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40/40/160</td>
<td>327</td>
<td>10.08</td>
<td>2.65</td>
</tr>
</tbody>
</table>

$\gamma$ - density  
$\beta_c$ - compressive strength  
$\beta_b$ - bending strength

The strength characteristics i.e., $\beta_c = 10.08$ MPa (compressive strength) and $\beta_b = 2.65$ MPa (bending strength) and the bulk density $\gamma = 2327$ kg/m$^3$ indicate that it is a good construction material for its intended purpose (as a comparison, laterite's main characteristics are very close to those of modern bricks).

In response to the need of establishing reasons for failure related to laterite construction, as well as to assess whether failures identified at Preah Khan were entirely due to soil deformation, it was essential to do a petrographic and microscopic analysis of the laterite stone. The results of this preliminary analysis performed on a limited number of samples are as follows:

**Petrographic Analysis of a Sample Taken from Preah Khan**

*Macroscopic Description:* The rock is colored yellow-brown. It consists of cemented larger and smaller fragments of a prevailing limonitized form (most probably from some group of mitotic minerals).
The cemented mass consists mostly of a limonite component. Also observed are cavernous formations which most probably represent altered feldspar grains, the feldspars being pre-transformed into kaolin which has been washed away.

Microscopic Description: An easily recognizable breccioid structure with relatively more dispersed fragments (in respect to the cemented mass) is observed in the sample subjected to petrographic analysis. The fragments are represented by sharp polygonal grains of quartz (rarely of feldspar) as well as numerous larger sharp and slightly rounded grains of completely limonitized (most probably mitotic) grains.

The cemented mass which represents 60% of the rock consists of a limonite-clastic component which, apart from the limonite which dominates, also contains small sharp grains of quartz and feldspars of a volcanogene, i.e., pyroclastic genesis. The clayey component is almost not present, i.e., it is found in some negligible quantities, however, processes of slight silification are observed.

Definition: Volcanogene-sedimentary breccia

Applicability: Fresh material can be used as a construction material. However, deterioration is possible under conditions of variable humidity and other factors. To that effect, further investigations are necessary.

The analysis was performed by Dr. J. Jancevski in cooperation with experts from the Institute of Geology - Skopje. The analysis was ordered by Prof. Dr. P. Gavrilovic.

8.3. INVESTIGATION OF REPAIR MATERIALS

Taking into account the need for modern conservation, the use of new materials at Preah Khan ought to be considered seriously. Tests of two basic materials produced by ADING Ltd. - Skopje were done to provide a basic orientation and evaluation. These materials are ADINGPOKS - an epoxide resin - and HIDROKOL - additive, a bonding material based on cement. The sandstone
samples that have been previously tested under bending were refixed using both of these materials. The main results are presented in Table 3.

Table 3. Characteristics of Repair Materials

<table>
<thead>
<tr>
<th>Type of Materials</th>
<th>Base of Adhesives</th>
<th>$\beta_c$ [N/mm$^2$]</th>
<th>$\beta_b$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Repair Original</td>
<td>Repair Original</td>
</tr>
<tr>
<td>ADINGPOKS</td>
<td>Epoxide</td>
<td>- 27.9 - 61.6</td>
<td>5.67 5.52</td>
</tr>
<tr>
<td>HIDROKOL</td>
<td>Cement</td>
<td>27.9 61.6</td>
<td>1.94 5.67</td>
</tr>
</tbody>
</table>

$\beta_c$ - compressive strength
$\beta_b$ - bending strength

Fig. 8.1 presents types of failure. In the case of refixing sandstone by epoxies, failure occurs in the main materials under conditions of repeated loading [Fig. 8.1] which means that the bonding material is stronger than the basic material and pasting 'along the layer' is efficient.

In the case where bonding has been performed using mortar, i.e., 'HIDROKOL,' it is clear that the bonding material is weaker than the original one. However, in the case when only ordinary gluing, i.e., compressive strength, is required, this material satisfies the design criteria.

Recommendations for Application:
- For elements expected to sustain bending loads, epoxide based glue should be injected, including epoxide resin and strong epoxide mortar.
- For elements expected to sustain compression, HIDROKOL-S glue (with a cement base) should be used, or epoxide mortar with cement additives.

On the basis of these results, the following conclusions can be drawn:
- The compression bearing capacity of the basic material (sandstone) varies depending on the direction of load application: parallel or normal to the layers, i.e., due to its lack of cohesion.
• The bearing capacity of laterite stone varies depending on the local conditions and can deteriorate in time.

• In the case of application of epoxide base glue [Fig. 8.1], failure occurred in the sandstone itself parallel to the refixed area, and the strength is the same as that of the original material. The adhesion is efficient and the application is stronger than the original material, while the failure mechanism is the same as in the original material.

• In the case of the cement based glue material HIDROKOL S, the bending resistance is about three times lower than that of the original material, while failure occurs in the connections [Fig. 8.1].

• Investigations of the characteristics of the main materials and their interaction with the new materials will be necessary.
FIG. 8.1. REPAIR AND STRESS TESTING OF STONE SAMPLES USING HIDROKOL-S AND ADINGPOKS-T
9. EQUIPMENT AND MATERIALS

The following is a list of the equipment required to undertake the interventions proposed in this report:

- Hydraulic jacks of 10 and 20 ton capacities 6 pcs
- Hydraulic jacks for pre-stressing, 20 ton capacity with accessory equipment 1 set
- Post-tension system with accessory equipment 1 set
- Steel workshop and accessory equipment 1 set
- Cable crane bearing capacity 5 - 10 tons 1 pc
- Vertical transportation platform system 1 pc
- Equipment for epoxy injection 1 set
- Carts etc., platforms for horizontal transportation
- Light metal scaffolding towers
- Epoxy resin: SIKADUR 752 100 kg.
- Epoxy mortar additive: SIKA-LAT EX 100 kg.

It is recommended that a small steel workshop be established which, in addition to the preparation of the structural elements, could be used for maintenance activities.
10. CONCLUSIONS AND RECOMMENDATIONS

The analyses contained in this report have identified and investigated the different types of failure, their principal causes, and subsequent damage to the structures of Preah Khan.

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.

If funding can be realized, it is recommended that Tower Building No. 11 be used as a demonstration project for testing WMF's best efforts at structural consolidation. During this process the procedures can be even further refined. This project in particular will provide the practical examples necessary for the preparation of the proposed handbook for architectural conservation and structural consolidation at Angkor.

A wider discussion of the techniques for stabilization proposed in this report will greatly assist in the final determination of suitable methodologies and technologies for use at Preah Khan. It is recommended that as an extension of the present mobilization effort, each specific recommendation for structural repair be undertaken as soon as possible.