BIODETERIORATION OF THE WOODEN ROOF OF THE PHNOM PENH NATIONAL MUSEUM

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1. Introduction

In the framework of an international training program organized by the University of Palermo in Siem Reap, Kingdom of Cambodia, during a visit to the National Museum in Phnom Penh, the Authors noted signs of termite attack on the external wooden beams of the southern portico of the inner garden (see Figure 1).

Considering the risk connected to the presence of such insects in a wooden structure, a preliminary investigation of the roof was performed in order to verify the presence of termites in other parts, particularly in the bearing elements of the roof structures as, in an anthropic environment, termites represent a high risk level for wooden elements [1-10].

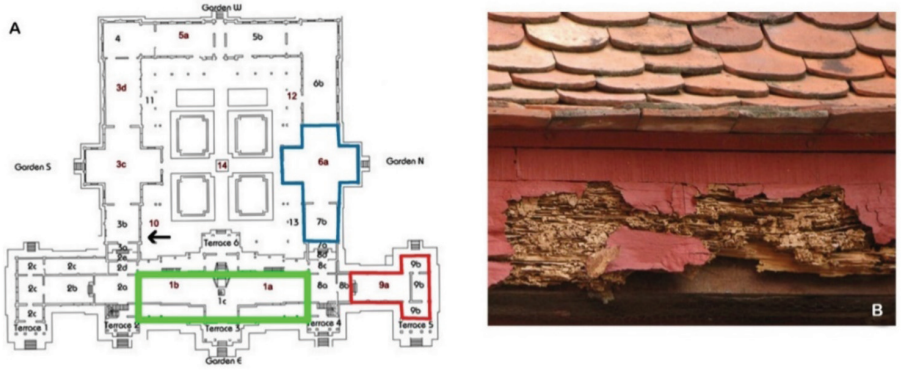

Figure 1. A) Floor plan of the museum; the black arrow indicates the place where signs of termite infestation were noted; the blue frame indicates fungi infestation; the red frame indicates termite infestation; the green area indicates the observed concrete structure. B) The external wooden element damaged by termites.

Identification of the termite species is very important for the proper design of any restoration intervention. In fact, drywood termites (e.g. Kalotermitidae) have colonies consisting of a few thousand individual the various castes and the whole nest is within the wooden element they feed on [11, 12]; on the contrary, colonies of subterranean

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termites (e.g. Rhinotermitidae) consist of several hundreds of thousands of individuals (up to more than one million) and have their nest in the ground. They move back and forth between the nest and the wooden elements they feed on by passing through dark galleries that they build using excrements and soil grains glued together with saliva. The latter are definitely the most destructive [11-15]. These biological differences require different methodologies for disinfestation and preventive conservation.

The National Museum in Phnom Penh is the largest Cambodian museum of cultural history and is the country's leading historical and archaeological museum. The museum roof bearing structure consists of wooden A-frame elements, a drawing of which is shown in Figure 1. The Museum buildings, inspired by Khmer temple architecture (George Groslier), were built between 1917 and 1924. The wood used in the structure has not been identified, as the available samples were too rotten to be observed under the microscope.

2. Previous restoration intervention

It should be highlighted that a recent restoration intervention was performed in the north wing of the building due to the presence of severe termite infestation as reported by a museum restorer.

The intervention consisted in the substitution of the decayed wooden beams, considered unfit to bear the required load, with brand new ones. The latter underwent insecticide treatment performed by brush application of a liquid insecticide, mostly in the end grain or in the joints of the beams (see Figure 2). Signs of this treatment could be easily noted due to the visible brown stain of the product used.

It could be noted that most of the original wooden elements were not substituted in spite of the presence of termite walkways on the surfaces, probably assuming that massive use of the insecticide could stop the ongoing infestation. Unfortunately this assumption is valid only in the case of drywood termites; the pathways were not considered as being used only to move from one feeding place to another, while most of the termite population lived safely within the nest, where it cannot be reached by any treatment performed from the surface. Moreover, this approach would only be effective for drywood termites, as the colony lives in the feeding place, but totally ineffective for subterranean termites, as the colony mostly lives far from the feeding place inside the nest, that could be located dozens of meters away from the roof.

Finally, the removed beams were stored in Garden S of the building (see Figure 1), very close to the new wooden beams, acting as a decoy for a new infestation.

3. Results of inspection

The main goal of this investigation was to verify the phytosanitary condition of the wooden roof of the National Museum in order to prepare, where needed, suggestions for its safeguard and the proper precautionary steps for its conservation. Starting from a preliminary observation in the south colonnade of the inner garden, the investigation moved to the main and secondary wooden structures of the north wing of the Museum roof.

Before starting the inspection of the wooden structures the concrete structures were observed to evaluate their conservation state in relation to environmental conditions. The conservation state of the concrete was surprisingly quite good and only some mi-

nor corrosion was detected at the top of the roof, despite the structure being 40 years old (see Figure 2). The presence of corrosion was probably caused by water condensation occurring at the top of the roof.

Study of the wooden structures was in two parts. The first was an *in situ* visual examination, primarily focused on the heads of the primary and secondary beams, as they usually suffer biologically induced decay due to water condensation which forms on the wood as a result of its contact with walls. The second part was a microscopic investigation of samples collected during the inspection, consisting of powdered material taken from all meaningful parts of the structure.

Figure 2. Concrete structure of the roof: A) base of the concrete structure with no visible corrosion of reinforcing steel bars; B) top of the structure with clear signs of corrosion.

At first sight, the previous insecticide treatment was easily individuated as the wood appeared darker where the insecticide had been applied, as shown in Figure 3; moreover, signs of the termites' walkways were identified both on the original wooden beams and on the new ones (Figure 4 A and B), highlighting that termite infestation was active after the restoration and had spread to the recently introduced wooden beams. The presence of the ghost trace of a termite walkway (probably removed in the past intervention) beside the new walkways, highlights the ineffectiveness of the insecticide treatment.

Figure 3. A) Insecticide used in the previous restoration intervention; B) treated end grain of an old rafter; C) sign of insecticide treatment on new beams of the roof.

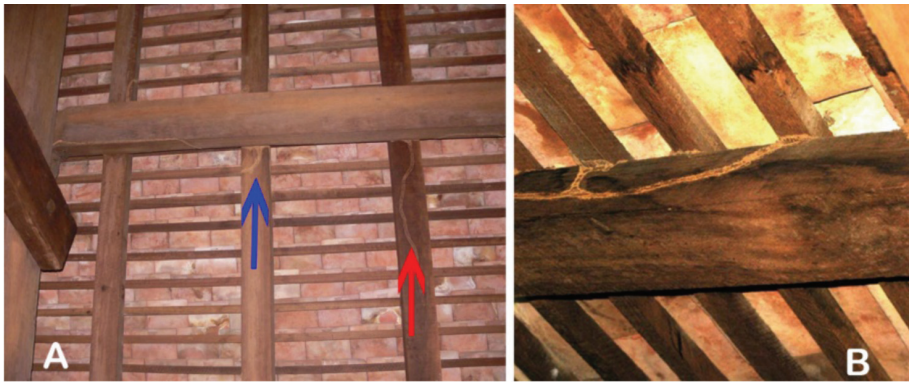

Figure 4. A) The blue arrow indicates a termite walkway on an old rafter, the red one indicates ghost traces of the walkway removed during the previous intervention; B) termite walkways on newly installed rafter.

As the bearing structures of the roof are installed over large tie beams going from one wall to the opposite one, forming the base of the A shape structural truss element bearing the whole roof, particular attention was paid to these elements. Some of the large tie beams resting on the brick walls showed severe deterioration of the end grain, induced by termites, while the remaining part of the beams appeared to be in good condition (Figure 5B); unfortunately, even though the external wooden surface appears sound, termites can act inside the wood. In particular, when the wood was hammered, the resulting sound clearly indicated the presence of large voids within: widespread termite galleries could be observed by removing the thin wooden film on the surface along the whole beam (Figure 5C). The decay appears to be quite severe as the galleries pass over the support area indicating a clear risk of failure (Figure 5F).

On closer examination, it was possible to observe that the termites had hollowed out the wood, severely reducing the section and consequently its mechanical properties. In the north-east corner of the roof structure (Figure 5D), there was some evident danger, as the wooden bearing tie beam was filled with recently constructed termite cells (Figure 5E); moreover, several termites were noted, indicating an ongoing active infestation (Figure 5C).

Continuing further with removal of the termites' nest, it was possible to observe that no wood was left in the beam head (Figure 5F). In these conditions, the whole roof was clearly in danger of collapsing.

In addition, some of the roof prop beams showed clear signs of termite attack. One of the prop beams in particular was found to be broken in the middle as a result of the weight of the vertical poles connected to it, with no residual mechanical function, which indicated the presence of a large number of termite galleries within (Figure 6c).

Finally, the pitches of the lateral colonnade of the inner garden were slightly sloped; according to this geometrical consideration, it would be possible for water to reach the wooden structures under the roof in the case of heavy rain and strong winds. These wooden beams in effect showed clear signs of fungi infestation, due to high water content, even if transient (Figure 7a).

It is well known that a high water content in wood, particularly in the presence of fungi, attracts insects and particularly termites. Taking this point into consideration, the

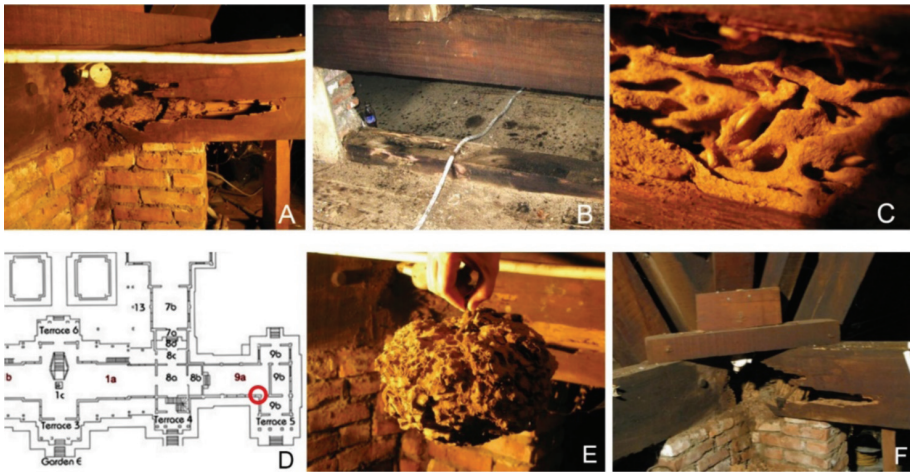

Figure 5. A) End grain of a tie beam decayed by termites; B) apparently sound tie beam, C) after removal of the thin wood surface layer; D) the red circle indicates the position of the structural corner element in the Museum floor plan; E) termite gallery extracted from the end grain; F) hollowed out wood in the end grain of the corner tie beam.

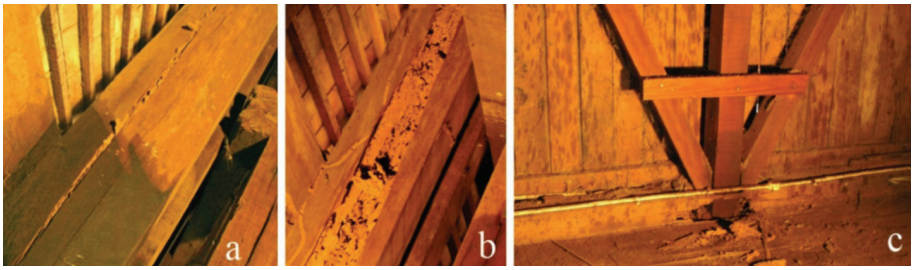

Figure 6. a) Termite pathways on a roof bearing beam; b) the same beam after the removal of the wood surface; c) collapsed horizontal prop beam, caused by termite infestation.

presence of termites in the tie beams of the trusses of the colonnade roof was investigated. It was possible to note that all the shrinkage cracks were filled with a granular material (Figure 7b). Sampling and direct observation of this material were performed and identified as termite faeces, commonly used by termites to build their tunnels or walkways. In general, these walkways or tunnels have to be perfectly sealed as termites are scared by light. The termite population was large and active (Figure 7c), as clearly observed when the walkways along the whole beam were broken; in all investigated points, a large number of living insects were seen to spread out from the wood. This observation confirmed that termite presence was widespread and abundant.

The termites responsible for the attacks on the wooden structures of the roof of the National Museum in Phnom Penh belong to the family of Rhinotermitidae and to the species of Coptotermes gestroi. This species is native to South East Asia but nowadays is widespread in other continents. It is one of the most dangerous species

Figure 7. Colonnade beam: a) fungi signs; b) termite pathways; c) living termites.

for wood. Coptotermes gestroi, as all other species belonging to the Rhinotermitidae family, are subterranean termites, i.e. they build their nest in the soil and the workers spread all around to find wet wood to feed on, reaching places that are quite far from the nest (dozens of meters) [15]. The Coptotermes gestroi species attack only wooden structures with a high moisture content. Once they start infestation, they can spread to nearby dry wooden elements because these termites are able to create by themselves a proper environment for their activity, potentially leading to very serious damage. In the roof environment, the main cause of high humidity is probably the occurrence of condensation phenomena. One way to prevent humidity from condensation is to ensure good air circulation [16-18].

Figure 8. Coptotermes gestroi: A) worker; B) soldiers.

The investigation was also extended to the west wing of the roof. In this part of the structure there was no sign of termites, but a large fungi infestation was clearly present and active (Figure 9). Visual investigation and knocking on the wood beams indicated that the decay was affecting only the surface of all the wooden elements. It should be highlighted that fungi infestation is mostly present at the top of the roof, indicating that the main cause of the high humidity is the condensation occurring when hot humid air reaches the cool top of the roof. Nevertheless, the restoration intervention on the roof must be designed to reduce the relative humidity in the garret ensuring good air circulation throughout the entire roof.

Figure 9. Detail of the fungi infestation found in the west wing of the Museum roof.

4. Proposal of intervention

Suitable measures have to be taken to maintain good air circulation in the Museum garret in order to reduce or avoid the settling of new termite infestation. The first step of the recovery will be the disinfestation of all the termite infested beams in the roof and in the colonnade, by means of Cypermethrin (Cyano-(3-phenoxyphenyl) methyl]3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate) base product. The second step will be the removal of all elements showing signs of termite attack. All the removed wood must be burnt. The insecticide has to be applied by pressure injection, an awkward operation that has to be performed by specialized operators. The beams severely attacked by fungi have to be removed too and all the surrounding wooden elements have to be treated with a 10% solution of Benzalkonium chloride, also known as alkyldimethylbenzylammonium chloride (ADBAC), applied by brushing.

The last step in the recovery intervention will be the sanitization of the soil all around the Museum against the species, Coptotermes gestroi. To achieve this result, a product such as hexaflumuron should be used which is able to affect the growing process of the termites and lead to the destruction of the entire nest [19-21].

4.1 Measures for long term safeguard and conservation

All the new beams should be treated with the same products previously used for the old parts.The heads of the new beams should not be put in direct contact with the walls, in order to facilitate moisture exchange with the air and avoid the settling and development of new termite infestation or fungi infection. It is essential to create in all the garrets, a good system of air circulation in order to avoid condensation phenomena and prevent new settling of biodeterioration agents. It should be sufficient to ensure the presence of open gaps between the beams as shown in Figure 10A, in all parts of the roof. It is also necessary to avoid the mistakes highlighted in Figure 10B and 10C, where the gaps are sealed with tape or mortar, respectively. In order to increase air circulation and prevent a high level of humidity in the garret, a 50 x 50 cm window has to be created at the top of each gable in the roof.These windows will be designed properly to prevent rain water from entering.

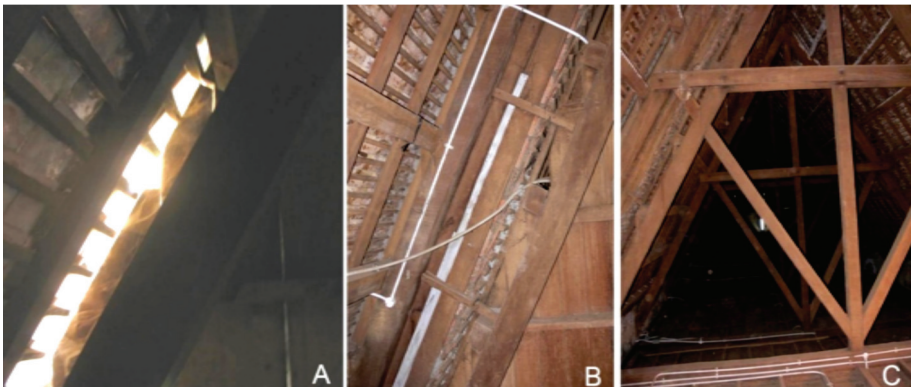

Figure 10. Roof structure: A) open gap between the folds of the roof; B) open gap between the folds sealed with tape; C) open gap between the folds sealed with mortar.

5. Conclusive remarks

This paper presents the preliminary study for the conservation of the wooden roof of the National Museum in Phnom Penh. The study starts from a visual inspection of the external elements of the roof and goes on to identify the termite species responsible for the decay. Moreover, some proposals have been suggested to improve the environmental condition of the roof and to ensure the long-term safeguard of the structure.

The observations reported in this case study offer the opportunity to develop some interesting advice on termite-decayed wooden structures.

As a first point, it is evident that the old restoration intervention was ineffective, as the termite infestation returned after one year and today is more widespread than before. This fact appears to be related to some controversial decision in the previous intervention such as: old and new timbers being mixed in the structure, regardless of the presence of termite walkways on some old elements; no modification was made in the garret environment, no new openings were created to increase air circulation; old timbers attacked by termites were stored close to the building and the termites' nest was not identified and eradicated. It is very important to note that the use of an effective insecticide is not enough in treating subterranean termite infestation because the insecticide is only able to kill the termites present in the timber elements while the main part of the nest population is safe in the ground.

As a second point, the wood severely attacked by termites shows a clean, apparently healthy surface, even if the infestation is ongoing: it is very important to look for small signs of the termites' presence, such as walkways in the wooden elements or in the walls, filling of shrinkage cracks. As shown in this paper, the infestation could have totally decayed the wooden elements without affecting the surface.

As subterranean termites are quite widespread in Cambodia, the only effective long-term safeguard consists in the environmental control of relative humidity in order to lower wood moisture content in the wooden elements.

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Biographical notes

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Giovanni Liotta former full professor of Agricultural Entomology at the University of Palermo; he has a vast curriculum of research and interventions on cultural heritage subject to entomological attack, especially in wooden structures, library collections, etc.. He is the author of several books on the subject, including: "*Gli insetti e i danni del legno. Problemi di restauro"; "Agli insetti piacciono le opere d'arte"*.

Summary

Within the framework of a training program in Cambodia, during a visit to the National Museum in Phnom Penh, the most important in the Kingdom of Cambodia, the authors noted the presence of some signs of a termite attack in the secondary elements of the roof of an inner garden. Following this observation, a further investigation was performed in order to evaluate the phytosanitary condition of the wooden bearing element of the roof. The inspection highlighted the presence of severe decay, constituting a real danger for the integrity of the roof; consequently, an intervention of restoration, conservation and safeguard was considered to be necessary and urgent. This paper presents the results of the investigation of the conservation state of the load bearing wooden structures of the National Museum in Phnom Penh, Kingdom of Cambodia; moreover, a proposal is put forward for a properly designed intervention to safeguard against the termites in the long term.

Riassunto

Nella cornice di un programma di formazione in Cambogia, durante una visita al Museo Nazionale di Phnom Penh, il più importante nel Regno di Cambogia, gli autori hanno notato la presenza di alcuni segni di attacco di termiti negli elementi secondari del tetto di un giardino interno. In base a questa osservazione, un'ulteriore indagine fu effettuata per valutare la condizione fitosanitaria dell'elemento portante in legno del tetto. L'ispezione ha evidenziato la presenza di un grave decadimento che costituiva un chiaro pericolo per l'integrità del tetto, dunque un intervento di restauro, conservazione e salvaguardia è stato considerato come necessario ed urgente. In questo lavoro sono presentati i risultati del lavoro di indagine sullo stato di conservazione delle strutture portanti in legno del Museo Nazionale di Phnom Penh, Regno di Cambogia; inoltre è riportata una proposta di intervento correttamente progettato per la salvaguardia contro le termiti per un lungo periodo di tempo.