Safety assessment of temple E7 in Mỹ Sơn, Viet Nam

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ABSTRACT: The present work illustrates the results of structural analyses carried out on one of the temples located in the archaeological area of Mỹ Sơn in Central Viet Nam. The temple is a relatively well-preserved building, hosting two square chambers covered by false vaults. A corner of the temple was destroyed by a bomb, and some passing-through cracks were likely induced by the vegetation. The temple was built using multi-leaf brick masonry in most of the walls, the outer leaves being more regular in texture than the inner one; also, the bricks in the outer leaves are stuck by natural resin, which provides an excellent bonding. Finite element models of the temple were set up, according to an accurate recently performed survey, and to drawings dating back to the beginning of the 20th century, as far as the geometry of the nearly intact building is concerned. The models take the layered nature of masonry into account. The masonry leaves were supposed to be either perfectly or partially connected, allowing for a Mohr-Coulomb's type failure condition at the interface between adjacent leaves. Numerical analyses were carried out to evaluate the presumable stress conditions of the still intact temple and to determine whether or not the self-weight alone might be the cause for the collapse of parts of the temple. Also, the damages induced by bombs and vegetation were taken into account, and the current stress conditions were determined. Some conclusions on the safety of the temple in its past and current conditions are drawn; also, the influence of the models employed to allow for the contact between the different masonry layers is discussed.

1 INTRODUCTION

The archaeological area of Mỹ Sơn is located in Central Vietnam. The site is 15ha wide and was the main holy place of the Champa kingdom. Between the 7th and the 12th century, the Cham people built here more than seventy brick masonry buildings, thirty of which are still recognizable.

After having been abandoned and neglected, the area was rediscovered at the beginning of the 20th century by the French architect Henri Parmentier from the École Française d’Extrême Orient (EFEO), who classified and surveyed most of the buildings. The Parmentier expedition in 1898 found the area completely covered by vegetation. About fifty buildings were classified as groups, each group named from A to L and documented through geometrical and photographic survey (Parmentier, 1904, 1918).

Nevertheless, the heaviest losses were mainly due to American bombs in 1969. Several buildings were completely destroyed; others were indirectly damaged by vibrations and fragments of bomb-shells.

From 1981 to 1986, after the Viet Nam war, a Vietnamese-Polish team lead by Hoàng Đạo Kinhand and Kasimierz Kwiatkowski carried out restoration works on some groups of buildings damaged during the Vietnam war at the end of the sixties (Kwiatkowski, 1985, 1990).

The G group of temples is currently the object of a preservation project on a chosen group of temples, which involves Politecnico of Milan, the Institute for Conservation of Monuments of Hanoi and UNESCO. Since 2000 several inspections were done in Mỹ Sơn, to directly evaluate the damage state of the buildings due to bombs and shells launched during the war and to intensive and continuous biological attach.

The building E7, belonging to group E, was studied by the archaeologists of the Lerici Foundation, Politecnico di Milano. E7 was also surveyed by the Vietnamese and Italian team, and a geometrical model was prepared. Also, tests on bricks and masonry filling were carried out. The present paper illustrates the results of a number of structural analyses carried out on this temple, in order to assess its structural safety in view of a future preservation project.

2 DESCRIPTION OF TEMPLE E7

Group E is located north of groups A and G (Fig. 1). Among its buildings it is worth mentioning E1, one of the most ancient temples (kalan) sited in the Mỹ Sơn archaeological area, whose construction can be dated back to the 7th century. On the contrary, E7 was probably built later on, in the 10th century (Fig. 2). This building is a typical example of annex to the main
temple: its location inside the sacred area is responsible for its designation as “south building”. The function of E7 was probably to preserve the sacred texts and objects used during the religious rituals (*kośa grha*).

When the building was discovered by Henri Parmentier, around 1900, its conditions were fairly good. Nevertheless, Parmentier never carried out any archaeological excavations around and inside the building.

At that time, the only damaged part was the top of the roof, which had lost its original shape. The most relevant damage occurred during the Viet Nam war (1969), when several parts of the main northern entrance and of the roof were lost; moreover, the bombings severely jeopardized the stability of the structure (Fig. 3). During an emergency intervention carried out by the Polish architect Kazimier Kwiatkowski, but never completed, the platform was reinforced. The state of damage increased during the years because of the lack of a regular maintenance, which is the main cause of the vegetation growth: several roots penetrated the masonry, thus worsening the crack pattern (Fig. 4).

During the archeological excavation inside and outside the building, it became necessary to carry out a direct geometrical survey on E7. All the surfaces of the building were thoroughly surveyed and many pictures were taken, to serve both as document of the state of work, and as investigation mean.

As most of the buildings of the Mỹ Son area, E7 was built following the typical procedures of Cham architecture. All the monuments are characterized by the presence of four fundamental elements: the foundations, the base, the central body and the roof (Fig. 5). The internal floor level is always located at the end of the base (*cymatium*). In the case of E7, the only remainder of the original floor is a sandish filling. The access was guaranteed by stairs, generally made
of stone. Because of its function inside the complex, and similarly to others in Mỹ Sơn, E7 is composed by two rooms connected by a door with a threshold, stone jambs and a plain lintel. The cover of the two rooms consists of two false pyramidal vaults, which are connected at the top by a single false vault. Externally it appears as a double-curvature vault. The visual double curvature effect was obtained by simply smoothing the external faces of the bricks: therefore, this curvature has no static function. On the east and west sides are located two small windows, with small stone columns.

All the information gathered were instrumental in creating a three-dimensional model of the structure, which was drawn by means of CAD (Figs 6–7).

The structure of the foundations was investigated by means of a pit, located on the south-east side of E7. The pit followed the external profile of the building wall. The trench brought to light three rows of foundation bricks, 18 cm thick, put on a preparation layer of about 15 cm, made of small pebbles and soil (Fig. 8). It is reasonable to assume that, like in the case of other Cham monuments, the foundations of E7 were built inside continuous cavities, without any foundation plate.

The masonries in elevation are composed by three leaves. The two external leaves are characterized by a thickness which is equal to the length of the bricks, and are constituted by whole bricks with very thin (micrometric) joints of organic material, whereas the dimension of the internal leaf, as well as the type of internal filling, varies with the maximum dimension of the masonry. The external leaves consist of horizontal and continuous layers of headers. Only in few cases stretchers are found, to guarantee the toothing between the external leaves and the central leaf. The limited offset observed between the layers of headers,
reduced to few centimeters, implies a weak toofing between the external leaves and the central leaf, and does not guarantee an adequate monolithicity to the masonry, whose behavior tends to be similar to that of three independents leaves (Condoleo, 2007).

Differently from the external leaf, which is homogeneous from the base to the roof, the internal leaf has different characteristics from the base to the principal body. The main difference between the two parts is represented by the dimensions. The thickness of the base is approximately the same as that of the foundations, with a value of approximately 110 cm. The principal body, which rests on the base, has a smaller thickness, with a value close to 75 cm. The internal leaf of the base of the annexes is constituted by layers of entire and half bricks, with irregular arrangement, and a filling of variable thickness made of clay, chamotte and quartzitic temper (Fig. 9).

Before surveying the external and internal surfaces of the walls it became necessary to remove the vegetation layers. This cleaning process made the survey of all surface damages possible, together with a clear identification of the missing parts. The results of the survey process were reported on drawings, in order to facilitate the damage interpretation and the detection of its causes.

The overall structural stability is mainly endangered by several cracks, passing through the entire wall thickness. Moreover, the loss of the lintel and part of the vault of the main entrance jeopardized its stability (Figs 10–11).

For this reason, it was decided to put a timber provisional structure. In order to avoid any modification of the structural behavior, the scaffolding was designed to be passive, which means that its bearing capacity is activated only in case of collapse or movements of the building itself (Fig. 12).
3 FINITE ELEMENT MODELS

The geometric (CAD) model of the temple was defined according to an accurate recent survey and to drawings dating back to the beginning of the 20th century (Parmentier, 1918), as far as the geometry of the nearly intact building is concerned. The geometrical model was later converted into a finite element model, consisting of approximately 24500 4-node constant strain tetrahedra. The total number of nodal degrees of freedom is nearly 23300. The FE model of the intact temple is shown in Fig. 13. In the definition of the FE mesh, account was taken of the heterogeneity of masonry across the wall thickness: each leaf was individually discretized, and the different leaves were given different mechanical properties. The lower base of the model is supposed to be fully constrained to the soil underneath.

To investigate the effect of the damages induced by the bombs and the vegetation, part of the FE model was suppressed and the main cracks surveyed in the existing temple (such as those shown in Fig. 11) were also included. A mesh much more refined than that used for the intact temple had to be defined, to capture the irregularities of the damaged model. The FE model of the temple in its current conditions is shown in Figure 14.

In the analyses, the materials forming the temple were assumed to be linearly elastic and isotropic. According to mechanical tests carried out on samples taken from similar temples (Binda et al., 2006), the outer masonry layers, made of bricks bonded by resin, were given an elastic modulus $E$ of 1530 MPa, whereas for the inner layer $E = 1300$ MPa. All the layers were given a Poisson ratio $\nu = 0.11$ and a density $\rho = 2200$ kg/m$^3$.

Different assumptions were made regarding the connection between the leaves of the brick walls. The less conservative assumption is considering the leaves as perfectly bonded (case A). The most conservative is
neglecting any connection, thus considering the three leaves as fully independent (case C). As a matter of fact, the leaves are likely to be partially connected, according to the construction technique (see Sec. 2), so that stresses can be transmitted from a leaf to the neighbouring ones to a certain extent. To model this situation, the interface between each pair of adjacent leaves was supposed to comply with a Coulomb-type interface (case B). The friction angle was given a value of 30°, whereas the tensile strength of the interface was neglected: the latter is likely to be a conservative assumption.

Only the effects of the self-weight of the materials were investigated in the analyses shown in Sec. 4, failing any evidence of significant ground settlements.

4 NUMERICAL ANALYSES

The main results of the numerical analyses carried out on the two models of the temple are presented in the form of contour lines of the extreme principal stresses plotted on the deformed FE mesh. The stress values are expressed in Pa units. To appreciate the effect of the different assumptions made about the degree of connection of the wall leaves, the same magnification factor for the displacements (=1650) was employed in all the figures shown in the continuation of this Section. Only the results obtained in the cases A and B are shown: the results pertinent to case C were found to be unrealistic, as illustrated in the continuation.

4.1 Analyses of the intact temple

The results of the analyses carried out on the model of the temple at its presumed intact, original state are first described. Figures 15 and 16 show the contour plots of the minimum (compressive) and maximum (tensile) principal stresses, respectively, obtained assuming the leaves to be perfectly bonded (case A). The highest compressions are attained at the base of the vertical walls of narrowest section, and are of the order of −0.25 MPa. The highest tensions are located in the lintel of the north doorway, where they attain +0.05 MPa.

The computed stresses are quite low and compatible with the strength of the materials forming the building. Indeed, according to the available experimental results, the tensile strength of the outer layers measured on couplets of bricks bonded by resin is of the order of 0.25 MPa, whereas the compressive strength measured perpendicularly to the joints is 11.5–12 MPa.

Contrary to case A, where stresses do not significantly differ across the wall section from one layer to the others, in case B the stress is usually higher in the inner layers than in the outer one as a consequence of interfacial debonding. The highest compressive stresses are of the order of −0.42 MPa in the central layer; the highest tensile stresses attain +0.17 MPa above the main entrance. Despite the increase due to debonding, even in case B the stresses estimated in the intact temple are not found to be incompatible with the material strength properties.

It is worth mentioning that in case C (fully debonded leaves) tensile stresses exceeding +0.38 MPa were computed at the base of the upper part of the temple.
4.2 Analyses of the damaged temple

The results of the analyses of the model of the temple at its current, damaged state will be now illustrated. The contour plots of the extreme principal stresses when the wall leaves are supposed to be perfectly bonded (case A) are shown in Figures 19 and 20. Comparing these plots with the corresponding ones referred to the intact temple (Figs 15 and 16), the increase in stress and deformability associated with the damage suffered by the building is apparent. In particular, tension peaks exceeding 0.2 MPa are found, although they are quite localized in limited regions of the damaged temple (Fig. 20).

Much more alarming are the current stress conditions of the temple if computed allowing for interfacial debonding of the wall leaves (Figs 21 and 22). The leaves turn out to have widely debonded, and the global deformation mode of the temple corresponds to a sort of punching of the deck on the lower, weakened part of the temple. An increase in the maximum compressive stress can be noticed (Fig. 21), with the highest values attained at the base of the innermost brick leaf; these
values, however, are of the order of $-0.5 \text{ MPa}$, that is, compatible with the material compressive strength. Wide regions where the maximum principal tensile stress exceeds $0.2 \text{ MPa}$ are found (Fig. 22). They are mostly located at the base of the deck of the temple, where the lower walls collapsed and the deck behaviour resembles that of a cantilever. As these high stresses could not be borne by the material, a scaffolding was duly placed in the opening caused by bombing to prevent the temple deck from failing.

5 CONCLUDING REMARKS

According to the numerical analyses performed, the stress in the temple E7 in Mỹ Sơn archaeological site was found to be compatible with the material strength properties when the temple was still intact, unless the excessively severe assumption of fully independent wall leaves is made. Thus, the possibility that the collapse of the temple might be partially due to the self-weight alone seems to be excluded.

Nevertheless, its current state is the result of the damage caused by the bombings during the war and the lack of repair and maintenance during the last decades. Therefore, the analysis was repeated to address the damaged situation.

As very high tensile stresses were computed in the damaged temple accounting for a limited interface frictional bonding (case B), the building in its current condition is not found to be safe. Provisional scaffoldings have already been put up, to avoid the collapse of the upper part of the building (see Fig. 12). The safety assessment of the damaged building is worth being further analyzed. To this end, it might be appropriate employing more reliable constitutive laws, both for the brick leaves (accounting for their brittleness) and the interface between the leaves (accounting for its non negligible tensile strength, coming from the partial degree of connection of the leaves). Also, an attempt at evaluating the local stress concentrations due to the vegetation that took root in the temple is planned, by introduction of a suitable pressure into some of the main cracks.

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REFERENCES


