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Nonlinear finite element analyses for the restoration study of Xana, Greece

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ABSTRACT

The object of the present research concerns the structural response of Xana, one of the earliest khans in the Balkan area, located in the archeological site of the municipality of Traianoupolis, Evros, Greece, due to static and seismic loading. The main research question is twofold: (a) what are the causes of nowadays structural pathology; and (b) what is the most adequate restoration scheme. The main methods used for the research refer to historical and bibliographical survey, experimental testing of the monument's materials and nonlinear numerical analyses conducted by the used of the finite element code ADINA. Therefore, two 3D nonlinear finite element models were constructed by the use of 'birth' and 'death' element option. The first model refers to the initial monument's stage till its current stage and the second model refers to its current stage till the restoration proposal. The results refer to the displacement field and failure figure due to static and dynamic loading, under the prism of a pushover analysis. Taking into account soil-structure interaction, the accurate structural geometry and staged construction proved to be essential for the correct estimation of the structural behavior. The absence of wooden tendons in combination with the large self-weight of the structure is the main reason of the monument's pathology. Therefore, the restoration proposal includes the construction of a light-weighted roof and the function of steel tendons.

1. Introduction

Historical structures represent a reservoir of the cultural heritage and the historical memory of a country. Their preservation constitutes a duty not only to the past but to the future generations as well. Furthermore, heritage tourism could enhance the economic development of a country [1–3].

In many occasions however, the preservation and restoration of historical structures is synonymous with the study of their static and seismic behavior, which is a very demanding and difficult task. Important aspects that must be taken into account are: the complexity of the geometrical and morphological configuration [4–7]; the scattering of the mechanical properties of the materials throughout the structure [7]; the uncertainty in the arrangement of bricks/blocks and mortar joints of the structural elements [7]; the various uncertainties affecting the geometrical and the mechanical characteristics of the structural elements [1,8]; the heterogeneity anisotropy, and non-linearity of the masonry materials [4–6,9]; the incomplete experimental characterization of the mechanical properties of masonry structural elements [4–6,10]; the difficulty in numerical modeling of the complex mechanical behavior of masonry materials [4–6]; the existing pathology, such as cracked elements, associated with different events (settlements and/or excessive displacement loadings) [11,12].

Therefore, the prediction of the structural response of historical structures is a much more challenging task than the design of a new structure or the study of usual constructed facilities [13–16]. In general aspects, the conservation of historic buildings requires the understanding of their structural behavior, and consequently of: (i) their boundary conditions, (ii) the characteristics of the constitutive materials, (iii) the origin of the damage that the building suffers and (iv) their vulnerability [11,17]. Therefore, the creation of accurate and sophisticated numerical models is considered to be a necessity in order to reproduce historical pathologies [18] and to obtain the most adequate restoration system [4].

In the present paper some of the most important aforementioned points were taken into account during the progressive steps of the restoration study of Xana by the use of the finite element method. The research aims can be divided into two main categories. The first one refers to the study of the present state of the monument and the second one to the study of the restoration proposal. Therefore, understanding and recognizing the transfer mechanisms of the loads and the overall static system of the monument was the first goal, which was accomplished via in situ inspection. The second aim refers to the experimental testing of the monument's construction materials and the estimation of their bearing capacity. The third goal was the explanation of the monument's pathology which was achieved via correlation of in situ

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Fig. 1a. Xana, present state (S-W and S-E illustration).

inspection; historical records related to Xana and finite element analyses. Particularly, a finite element model of the initial geometry of the monument was constructed according to the graphical architectural representation. The option of "birth" and "death" provided by the ADINA code [19] was used in order to study the stress field developed during the construction stages of the monument and during the decay of its materials. The next goal refers to the investigation of the appropriate measures used for the strengthening of the monument according to the architectural proposal of restoration. Therefore, the finite element model of the monument containing its current pathology was used as basis in order to evaluate the architectural restoration proposal. The "birth" option was used in order to add new members and loading in the present static system.

2. Description of Xana

Xana (Fig. 1a), is a caravanserai building, situated 13 km far from the city of Alexandroupolis, Evros, Greece. The monument was constructed by Ghazi Evrenos Bey (1375–1385) at a nodal geographical area, close to via Egnatia, the thermal springs of Loutra (Ilica) village and the city of Roman Traianoupolis, which was characterized as an archeological area in 1964 by the Hellenic Ministry of Culture and Tourism.

The monument has a rectangular plan (39.62 m × 13.92 m) [20]. The outer side of the circumferential walls rises at 4.97 m while of the inner side at 2.35 m. Xana is covered by a hemi-cylindrical dome of net height 7.26 m which was protected by a wooden span roof with red tiles. The dome is constructed by bricks and mortars. The circumferential walls consist by three-leaf masonry. The exterior of the walls is constructed as cloissone masonry while the inner leaf is constructed by mortar and stones. The monument consists of two parts divided by an inner wall. The first part was used for the lodging of the travelers while the second part was used as a stable for the animals and is divided in three parts by two stone arches. The heating and cooking needs were being fulfilled by six fire places, F1 to F6 in the first part of the monument (Fig. 1b).

Three stone arches, A1, A2 and A3 were constructed in the second part of the monument (Fig. 1b). The two of them divide its length at almost equal distances and the one was constructed in contact with the northern wall (Fig. 2).

Two square holes (0.15 m × 0.15 m) at a height of 2.60 m, along the length of the walls served for the placement of wooden beams. Four wooden tendons (W1 to W4) of the same cross-section were placed at a height of 4.30 m at equal distances and they were probably used in order to tie down the span roof while other two (W5, W6) were placed at a height of 2.60 m and connected the two stone arches [21]. Xana's physical lighting is accomplished by three windows on the northern side and three windows on the western side of the second part as well (Fig. 1b).

The dome of the first part collapsed in the early 1900s due to its heavy weight [21]. In 1939, the main gate of the monument and the highest parts of the walls collapsed during the construction of a road in front of it [22,23]. In 1968 and 1969 restoration works took place, aiming mainly at the healing of cracks and the monument's protection from rain waters [24,25]. In 1998, the last restoration took place relating to the reconstruction of one part of the western masonry [26].

The identification and the monitoring of the pathology condition of the structure in combination to the knowledge of the actual cracking path, plays an important role in understanding the current state and behavior of the structure as well as in selecting the suitable restoration methods [11,16,27,28]. Therefore, Xana's pathology was thoroughly investigated. One of the main problems is a vertical fracture on the northern wall, which is attributed to soil subsidence due to the combination of clay soil foundation and high water level (thermal baths). Another important aspect is the tensile cracks running along the interior surface of roof and in the vertical direction as well, where the openings are situated. The cracks can be attributed to the action of the large self-weight of the roof in combination with the absence of horizontal tendons. Hair cracks, loss of stone material, detachment of small pieces, exfoliation, mortar pulverization, efflorescence and blistering can be attributed to the action of marine aerosols [29,30], taking into account that the monument is located only 6 km from the Aegean sea; to biological colonization; to drainage problems [30] in combination to unsuitable repair materials, such as cement [31] and to soil moisture.

3. Materials and methods

3.1. Laboratory experiments – Materials

Taking into account that the results derived from a calculation model are sensitive to the material properties and boundary conditions [32], the gathering of experimental data is considered to be mandatory [11]. Due to the lack of financial and technical resources neither the construction of a masonry specimen at the laboratory nor the resistance testing of the masonry in situ was feasible, even though the aforementioned testing methods are proposed by various researchers [11,33]. Therefore, in order to collect all the vital information concerning the materials of the structure, samples of bricks and stone were taken from the damaged parts of external walls and tested in the laboratory [34]. In particular, the density and the compression strength of six brick and four stone samples were determined (Table 1).

The significant diversity of the compressive strength of bricks can be attributed to the lack of production standards in the old days [35].

The material behavior for stone and brick masonry was considered to be isotropic, homogeneous and non-linear. The isotropy assumption is due to the impossibility of evaluation of all the necessary parameters describing the anisotropic behavior in the inelastic range, in absence of ad-hoc experimental characterization [36]. Furthermore, taking