Journal of Cultural Heritage 13 (2012) e70–e81

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The roof of the Church of the Nativity in Bethlehem: Structural problems and intervention techniques

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ARTICLE INFO

Article history:
Received 20 October 2012
Accepted 22 October 2012
Available online 21 November 2012

Keywords:
Wooden truss
Seismic vulnerability
Damage analysis
Roof reinforcement
Timber end-beam repair

ABSTRACT

In the present paper, the roof of the Church of the Nativity in Bethlehem is investigated. The lack of maintenance for many years has determined a copious infiltration of rainwater causing serious damage to the wooden structural elements. The damage, both on the main trusses and on the secondary structure, is first analyzed. Then, the stress state is checked on the basis of the surveyed damage. Finally, an intervention of restoration is designed in order to recover the damaged parts and to increase the seismic strength of the entire structure.

1. Introduction

The present work is a summary of the investigations carried out on the roof of the Nativity Church in Bethlehem, commissioned and funded by the Palestinian National Authority. The main goal of the project was to establish the level of damage on the roof, to assess its safety level and to suggest some interventions of consolidation/restoration. At the same time, it seemed to be useful to check the masonry structures in order to point out possible reductions of strength/stiffness, some of which due to rainwater infiltrations.

On the basis of previous experiences (see for instance Mallardo et al. [1]), the Authors investigated the masonry structures and the grottoes under the Church floor [2]. In the present paper the damage on the structural elements of the roof is first analyzed; then, some rehabilitation solutions are presented, in agreement with all European Charts of Restoration and with the specific aim of recovering the damaged parts and improving the seismic behavior of the whole Church.

The system of the timber roof of the Church of the Nativity is different between nave and aisles. A general three-dimensional (3D) view of the timber structure of the roof and a detailed description of each member of the trusses are given in Macchioni et al. [3] (see for instance its Fig. 1).

In the nave the roof is supported by 17 trusses (five in the apse), span approximately 10.3 m, distance 2.8 m; each truss is made of two rafters, one horizontal tie beam, one vertical king-post and two couples of struts. The latters are connected on one end to the king-post and on the other end to the rafters by another element (called sleeper in Macchioni et al. [3]). Furthermore, the tie beam is connected to each wall by a wooden cantilever (length 135–150 cm) anchored to the external part of the wall by an iron tie rod. A sketch of the typical truss in the nave is depicted in Fig. 1 along with the dimension of the main members.

The same truss typology is located also in the transepts (five trusses at each transept) but with a distance of around 1.7–1.8 m. The trusses in the nave and in the transepts are all connected by one longitudinal timber beam through their king-post – tie beam joint.

The roof at the crossing area between nave and transept is more complicated but it is clearly described in Macchioni et al. [3].

In the aisles the truss has a different shape. Its typical geometry and size are depicted in Fig. 2. One rafter, one tie beam and three struts compound the truss that is supported in three points, i.e. at the middle and at one end by two rows of columns and at the other end by the boundary masonry wall. The distance between two consecutive trusses is about 2.70 m and each truss span is approximately 7.70 m.

Due to the lack of maintenance and to the repeated removals of lead sheets from the roof over time, copious rainwater infiltrations have damaged some structural components. The damage has involved mainly the rafter-tiebeam joints, many purlins and

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http://dx.doi.org/10.1016/j.culher.2012.10.013

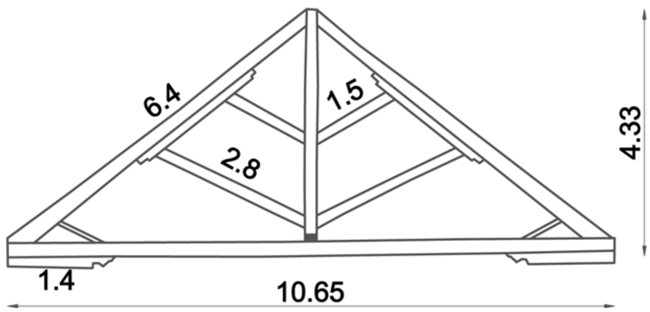

Fig. 1. The typical truss of the roof of the nave.

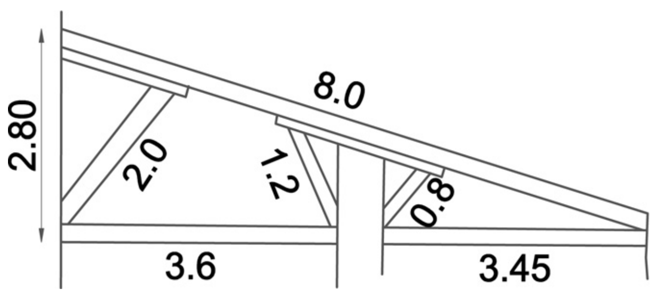

Fig. 2. The typical truss of the roof of the aisles.

boards as well as some parts of the masonry walls. In Fig. 3, the slopes of the different zones of the roof, the horizontal and vertical pipes collecting the rainwater and some viewpoints of the photos taken (A, B, C illustrated in Fig. 4 and D illustrated in Fig. 5) are depicted. The rainwater is mainly collected by a system of horizontal pipes located along the longitudinal walls of the Church and by two vertical pipes located at each apse-transept corner.

The roof is now supported by a system of trusses, purlins and boards (Fig. 6a) and it is partially protected by what remains of two overlapped layers of lead and bitumen (Fig. 6b).

As a matter of fact, the infiltration of rainwater has occurred also through the vertical pipe located at the apse-transept corners (Fig. 5), which needs to be rebuilt with a new waterproof protection.

The key issue in the structural investigation of the timber roof structures is the vulnerability of the connections among the elements. In Palma et al. [4] an extensive experimental campaign on structural carpentry connections was conducted to assess their rotational behavior and the effectiveness of some common repair and reinforcement techniques. In Pizzo et al. [5] the reliability of a repairing methodology of old timber truss ends based on wood prosthesis and glued-in iron rods is tested experimentally. In Bareto et al. [6] the tensile strength of adhesively bonded repairs with carbon-fiber reinforced plastic patches on wood members in pure tension is addressed experimentally and numerically; the Finite Element (FE) Method and cohesive zone models are adopted to simulate damage initiation and propagation. In Stehn and Börjes [7] the influence of ductile connections, slotted-in nailed wood to steel joints, on the total load-carrying capacity and deformability of a glulam truss is investigated by experimental and FE parametric studies. In Pantelides et al. [8] glass fiber reinforced polymer composite laminates are investigated for improving the tensile capacity of joint splice connections in the chords of the arch wooden trusses of the roof of a historic structure; the solution is interesting and it may be adopted to increase the stiffness of the roof for anti-seismic purposes.

The structural response under generic loads is also an important and open issue, in some way strictly related to the quality of the connections. In Branco et al. [9] the timber elements of two king-post timber trusses are experimentally loaded with a series of symmetric and non-symmetric cyclic tests to measure the response of the elements and of the connections. In Hansson and Ellegaard [10] probabilistic analysis by Monte Carlo approach of a timber W-truss with punched metal plate fasteners is performed; FE calculations are carried out by including the contact between timber members and the non-linear behavior of the joints. Moreover, the global behavior of roofs is handled in Parisi et al. [11] by classic modal and response spectrum analyses to define the vulnerability of a variety of timber roof structures; the analysis does not include important characteristics such as its in-plane stiffness and the quality of the connections with the bearing vertical walls.

The successive sections are aimed at describing the results of the survey carried out on the timber structures of the roof (Sections 2 and 3), at proposing rehabilitation procedures for the trusses (Section 3) and at explaining the approach that has been followed to increase the seismic strength of the Church (Section 4).

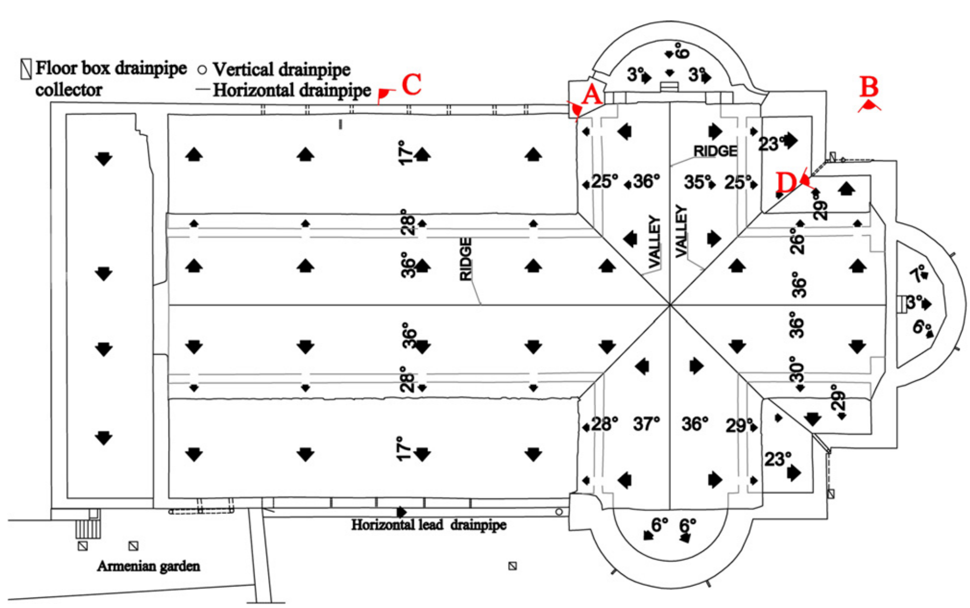

Fig. 3. Roof slopes, drainpipes and photo viewpoints.