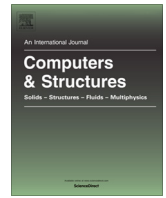




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The narthex of the Church of the Nativity in Bethlehem: A non-linear finite element approach to predict the structural damage

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ABSTRACT

The Church of the Nativity in Bethlehem has a narthex in the front that is as long as the façade of the Church and about six meters wide. Currently, the narthex is covered by five cross vaults, three of which in a dangerous state of decay, and it is internally divided by three walls perpendicular to the façade, which appears to be strongly rotated outwards with a maximum horizontal top displacement of about 40 cm. Inside the central cross vault, the narthex has been heavily damaged and propped since the thirties of the last century. Numerous attempts have been made over the time to identify the causes of such damage. Some archival researches, in-situ inspections of the subsoil and detailed laser scanner surveys, which were carried out during the recent restoration works in the Church and in the narthex, allowed for gaining a deeper insight into the construction features of the cross vaults and for putting forward some hypotheses about the possible causes of damage. This paper provides a scientific validation of these hypotheses by means of finite element numerical simulations, which try to reproduce the seismic response of the Church and the deformation process of a three-dimensional simplified model of the narthex from an assumed initial configuration up to an ultimate state of damage, comparable with the current one. Such models are discretized by means of tetrahedron elements obeying a damage plasticity law that exhibits a softening behavior in both tension and compression. The numerical simulations carried out provide some results that fit reasonably with the actual deformed configuration of the narthex and can be considered as a useful tool for further insights.

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1. Introduction

Very little is known about the history of the transformations of the narthex of the Nativity Church since its construction. The narthex that we see now (or at least the narthex that we can imagine on the basis of the current volumes or the traces of some ancient and still visible openings on the walls) replaced a larger cloister in the second half of the VI century; such a cloister belonged to the previous Church, ordered by Queen Helena, mother of Emperor Constantine, in the IV century. From the outcomes of some archaeological excavations made by Hamilton [1] in the thirties of the last century and from the results of some subsequent studies [2,4], it was possible to go back to the original form of the narthex; differently from now, it was composed of a single volume, had a bigger central door flanked by two smaller side doors in both the principal walls and two windows placed symmetrically with respect to the front door, Fig. 1.

From some traces found in the walls during the restoration works, still in progress, it was possible to deduce that the original roof of the narthex was made of timber, with a single pitch, as in almost all early Christian and Byzantine basilicas with narthex. The typology of the wooden roof is still unclear, although the traces left on the walls suggest that it consisted of a series of simply supported beams having the same slope as the roof; certainly it was a light roof. Over the centuries, especially during the Middle Ages, the Church increasingly took on the appearance of a fortress equipping itself with walls and towers for defense. Some traces of these additions are visible today even in the narthex, in particular in a small protective parapet above the façade and in two thick interior walls, perpendicular to the façade, probably the base of two outer towers, Figs. 2 and 3. Maybe, in order to allow these transformations for protective purposes or as a consequence of some destructive earthquakes, the original timber roof was replaced by a system of masonry cross vaults and some openings were infilled or reduced in size. The two thicker inner walls are made of low quality masonry, surely lower than the one of the external walls, and they are simply adhering to the façade walls of both narthex and Church without any effective connection.

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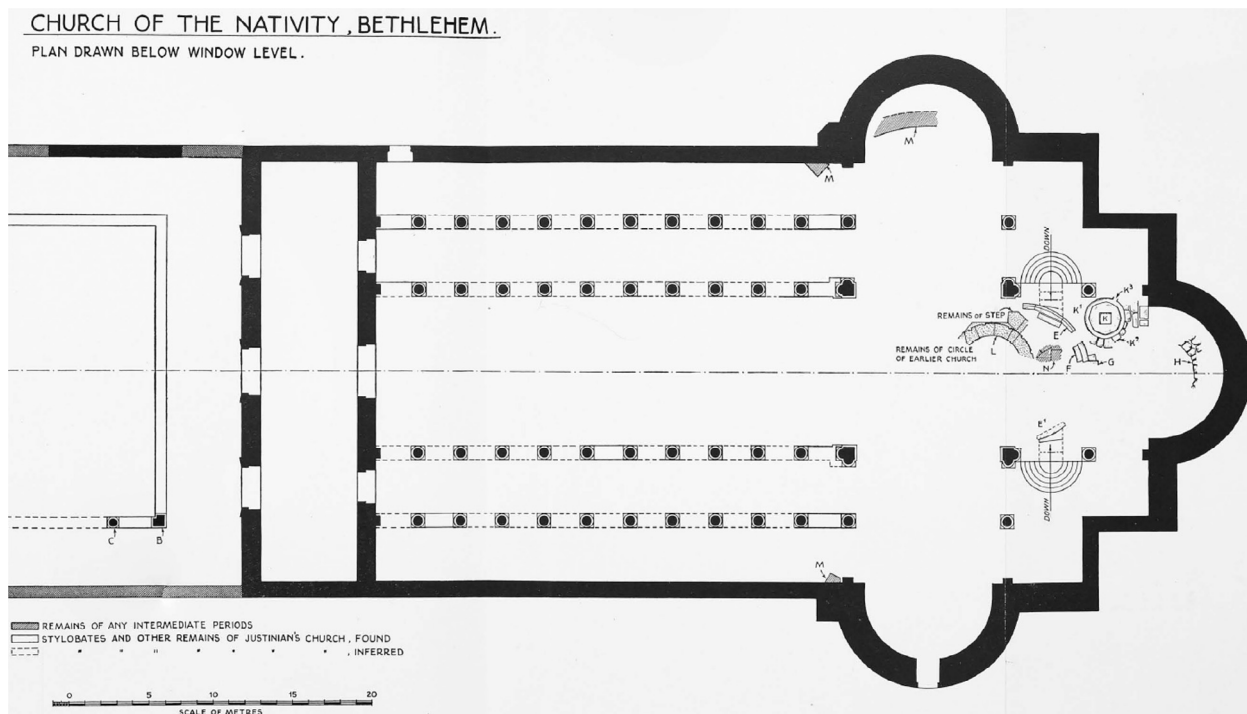


Fig. 1. Original narthex of the Church of the Nativity.

Also the vaults, made of irregular and roughly cut stones, are connected to the façade walls only in correspondence with the corbels at the base of the arches and for a height of about 1.1–1.3 m. Instead, such vaults are well connected with each other in the East-West direction (the longitudinal direction of the Church) by means of arches, orthogonal to the façades and built with greater and more regular stones. Moreover, such stones have two different lengths and they are assembled in such a way that the longer stone and the shorter one are always alternate, so as to allow for a greater connection between arches and vaults. Even the diagonal arches of the vaults are made of quite regular stones, although not so regular as the ones of the arches mentioned before. The thickness of the vaults is not constant everywhere and it varies between 35 and 40 cm. Before starting the restoration, the space between the existing external paving and the extrados of the vaults was filled with sand and remains of a medieval paving. Some inspections made on site have shown that the walls of the narthex continue downwards with a constant thickness up to a depth of 94 cm from the floor; then they have an enlargement of 20 cm on each side up to a depth of 141 cm and continue with a compact layer of stones and mortar for other 150–165 cm before reaching the bedrock. The two side walls of the narthex (North and South sides) are 1 m thick and have an inner core of undefined thickness; the façade wall, like the façade of the Church, is 1.15 m thick, made of regular stones and with a limited or null inner core. The narthex is now connected to the monasteries of the Franciscans Friars (North) and of the Armenian religious community (South), Fig. 2; these monks, together with the Greek Orthodox ones, manage the activities in the Church according to the current *status quo*. On the external front, towards the square, there is a big buttress probably built after the XVI century: in fact, some drawings made by Amico [3] and dating back to 1609 show the façade of the narthex still without the buttress, Fig. 4.

The present paper, which is an extension and a thorough revision of that presented during CC2015 congress [5], Fifteenth International Conference on Civil, Structural and Environmental Engineering Computing, held in Prague, Czech Republic 1–4

September 2015, presents and discusses a wide set of numerical results validating the aforementioned hypotheses of structural damage of the narthex. The results are obtained by means of advanced numerical finite element (FE) simulations, which include non-linear dynamic analyses. Such advanced FE approaches try to reproduce the deformation process on detailed three-dimensional models of both the whole church and the isolated narthex. The FE models consist of tetrahedron elements and masonry is treated as a homogeneous macroscopic material obeying a damage plasticity law, which exhibits a softening behavior in both tension and compression. The numerical simulations carried out provide several results that seem to fit reasonably with the actual deformed configuration and can be considered as a useful tool for further insights, including rehabilitation, strengthening and seismic vulnerability reduction.

2. State of the structural damage and possible causes

Nowadays the structure of the narthex is strongly deformed [6]. The façade wall exhibits a rotation towards the square more pronounced in the middle of its length and starting approximately from the architrave of the Humility door, about one meter above the ground. As a consequence of such a rotation, the façade wall has undergone a maximum horizontal displacement at the top, approximately in the middle of the wall, equal to about 40 cm measured at the base of the parapet. It is a very high value when compared with the height of the wall, about 8.7 m. If any fractures occurred in the past, they were closed by local interventions of cleaning and consolidation made over the centuries. The fact that they have not re-opened ever since shows that the damage evolution is now over and that it was probably over even when the external buttress, now still perfectly vertical, was added. The façade of the Church, opposite to the one of the narthex, exhibits a slight out-of-plane deformation, which starts from the roof of the narthex and achieves 10 cm at the top of the tympanum [6]. As a consequence of the rotation of the narthex façade, the three central vaults, and in particular the one in the middle, underwent

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