Journal of Cultural Heritage 16 (2015) 597–601

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Case study

Load and effectiveness of the tie-rods of an ancient Dome: Technical and historical aspects

Luca Collini*, Ramona Fagiani, Rinaldo Garziera, Kseniia Riabova, Marcello Vanali

Department of Industrial Engineering, University of Parma, Viale delle Scienze 181/A, 43124 Parma, Italy

ARTICLE INFO

Article history:
Received 22 May 2014
Accepted 15 September 2014
Available online 8 October 2014

Keywords:
Tie-rod
Vibration method
Tensile load
Ancient iron

ABSTRACT

The analysis of the health condition of a Renaissance Italian Dome gave us the unique possibility to study some interesting, ancient tie-rods. The engineering analysis of the efficiency of these rods enables us to draw inferences about the technological evolution of handcraft, which becomes a mirror of the attitude of the time in approaching such technical problems.

1. Introduction

In this work, we try to study a structural device which was very popular during ages of big building constructions, as masonry churches and castles. We refer to a case study, placed the middle of the Renaissance, about the tie-rods of the church "Madonna dell'Umiltà" (*Our Lady of Humility*) situated in Pistoia, Italy. These elements are more or less slender pieces of iron which make the building more stable by tying two or more walls together, and constraining any relative movement among them.

These rods, apparently, are quite simple devices, and anyone can say that they would not constitute a nowadays clue technical problem. In fact, not only they are now quite unnecessary (with the new concrete technology), but if needed they should be quickly engineered. Notwithstanding this facts, in the present work, we try to put under the spotlight some sophisticated detail of these objects. And we have the luck to compare these details for two distinct ages: Renaissance and about 1960. The comparison gives us a wonderful picture, in which some gross misunderstanding and some conceited assumption surprisingly image the modern tie-rods as quite inadequate. This comparison cannot be complete without an explicit insight into the significance of iron crafting in the two ages. Indeed, the historical implications that iron gave during its life is an important key to the comprehension of its use and misuse in these monuments.

* Corresponding author. Tel.: +39521905892.
E-mail addresses: lucaferdinando.collini@gmail.com, luca.collini@unipr.it (L. Collini).

http://dx.doi.org/10.1016/j.culher.2014.09.008
1296-2074/

2. Hints on the Dome history

The construction of the Basilica was approved at the end of 1400 following some evidence of a miracle. The name itself "Madonna dell'Umiltà" was given as the Virgin was thought as the main responsible for the miracle. The geometric design of the system of the church was performed by Giuliano da Sangallo, architect of Lorenzo the Magnificent, together with his brother Antonio, and with Francione and Pollaiuolo; the execution was carried out by Ventura Vitoni and, later, by the most famous Giorgio Vasari, who designed and built the majestic dome [1].

Today, the concern about the state of degradation of the Basilica led the Ministry of Heritage and Cultural Activities, March 5, 2008, to sign an agreement with the Curia Bishop of Pistoia and the Foundation of "Cassa di Risparmio di Pistoia and Pescia" for the start of the restoration of the building, designed and carried out by the Superintendence for Architectural Heritage and the Tuscan provinces of Florence, Pistoia and Prato.

In the framework of this massive restoration of the church, the study of the tensile load of the tie-rods that loop the basis of the dome, see Fig. 1, was addressed as a very important issue in order to evaluate the stability of the whole structure. Precisely, far before the completion of the Dome, architect Vasari acknowledged the urgent needing to tie the base of the dome itself, with an iron ring. This was the first tie-rod order, placed in 1575. Immediately after this, he ordered to place another order. Other three orders were placed more or less 50 years later, and finally two recent orders in 1966. These last two orders not only differ from the ancient because of the material, but they greatly differ because of different manufacturing and different implementation of the tensioning system.

Fig. 1. The octagonal Dome; on the left, the seven orders of tie-rods are visible.

3. Measuring the stress in the tie-rods: technical aspects and results

3.1. Method of measurement

The evaluation of axial load of in-service tie-rods is not directly estimable. The method of measurement should be non-destructive and non-invasive. Some of these methods have been already proposed and documented in the technical literature [2–5]. The present authors developed a simple and efficient approach, in which a very high number of unknown parameters can be considered and determined.

Our staff already successfully carried out such measurements at the Cathedral of Parma in 2008 [6], on the reinforcing rods of an ancient castle in 2007 [7], and in some other experiments.

Our method is based on the measure of the vibration of the tie-rod and in the identification of the axial load in it by the matching of a sufficient number of natural frequencies with the same number of frequencies calculated numerically. The authors developed a special algorithm for the automatic parameter identification [6], and the control of the estimation error.

The unknown parameters to identify for the tie-rods on the Dome of Pistoia were many: the effective free-to-vibrate length, the boundary constraints, the irregular cross-section, the masses of the tightening system. Again, connections and additional joints increased the difficulties in the measures. In Fig. 2, it is shown the place where our staff operated, where four out of the seven orders of rods are visible. It is possible to note the junction systems made to tighten the rods by opposing iron wedges, and some supports. In Fig. 2, the two upper rod orders are of ancient handcraft, the two near the trampling floor are recent.

The experimental measurement of vibration were performed hitting each tie-rod by an instrumented hammer and recording the acceleration signals acquired by two accelerometers glued in 2 points, at about 50 cm from the centre of the rod. More details of the experimental set-up can be found in [6]. The result of each acquisition is a function representing the amplification of acceleration given by the rod at each frequency, namely the frequency response function (FRF). The FRF analysis evidences some clear peaks in the frequency domain, to which the same number of modes and of natural frequencies correspond: these frequencies are of our interest.

Once we have got all the natural frequencies, CAD models can be developed for each tie-rod in order to run the numerical calculation. Models have to be geometrically detailed, since many tie-rods are hand-made with non-uniform cross-section; each structural, massive or stiff element connected with the tie-rods has to be considered too. The main measured geometrical features are summarized in Table 1.

The numerical modeling is here performed by the finite element (FE) method, by the commercial code Simulia-ABAQUS. Beam-type elements with Euler formulation are chosen, mesh refinement is about 50 elements per tie-rods, and added masses of the

Fig. 2. Some orders of tie-rods on the dome.