Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 3 (2017) 316–325

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XXIV Italian Group of Fracture Conference, 1-3 March 2017, Urbino, Italy

Monitoring the mechanical response of asymmetrically fractured marble epistyles after restoring their structural integrity

Stavros K. Kourkoulis* and Ioanna Dakanali

Laboratory of Testing and Materials, School of Applied Mathematical and Physical Sciences, Department of Mechanics, National Technical University of Athens, Zografou Campus, 157 73 Athens, Greece

Abstract

An experimental protocol is presented aiming to monitor the mechanical response of restored structural elements of marble monuments. An accurate copy of a typical epistyle of the Athens Parthenon Temple was constructed by experienced technicians of the Parthenon's worksite under a 1:3 scale. It was composed by two asymmetric fragments and it was restored with the aid of three pairs of titanium bars. It was subjected to ten-point bending, in an attempt to simulate uniform loading conditions. Various techniques, both innovative and traditional ones, were used to monitor strains and displacements: Acoustic Emission (AE), Pressure Stimulated Currents (PSC), Digital Image Correlation (DIC), Optical Fibers, clip gauges, dial gauges and LVDTs. The data recorded from all techniques were in very good mutual agreement. What is more important, however, is that the AE and PSC techniques provided clear and mutually compatible data which can be safely considered as indicators of upcoming failures.

Peer-review under responsibility of the Scientific Committee of IGF Ex-Co.

Keywords: Marble monuments; structural integrity; epistyles; acoustic emission; digital image correlation; asymmetrical fault.

1. Introduction

The unique cultural value of ancient monuments renders continuous health monitoring of any restored structural element of them one of the most serious problems of engineers working in conservation/restoration projects. The nature of these structures imposes a series of limitations to the sensors that can be used for this purpose. For example, the materials used to attach the sensors should not cause any kind of damage to the material of the monuments while for

* Corresponding author. Tel.: +30 210 7721263; fax: +30 210 7721302.
E-mail address: stakkour@central.ntua.gr

Copyright © 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of IGF Ex-Co.
10.1016/j.prostr.2017.04.059

obvious aesthetic reasons the magnitude of the sensors should be the smallest possible. Moreover, the fact that quite a few sensors are required for continuous and effective monitoring dictates the lowest possible cost of each sensor.

The need for efficient monitoring becomes imperative in case the restoration techniques used create interfaces between incompatible (from the Mechanics of Materials point of view) materials. A typical example is the technique, adopted nowadays by the scientists of the "Committee for the Conservation of the Acropolis of Athens Monuments" (Korres et al. 1989). According to this technique fractured epistyles are restored by inserting bolted titanium bars into holes predrilled on the marble blocks and filled with suitable cement paste. The interfaces created (marble-to cement paste and cement paste-to-titanium) are very prone to fail and their continuous monitoring should ideally provide timely data indicating the need to undertake proper actions that will protect the member and therefore the monument.

The design of the connection (number of reinforcing bars, their diameter and exact position, the anchoring length etc.) is inevitably based on several assumptions and simplifications since the complicated geometry of the restored complex, the nature of the three totally different materials and the interfaces created, render exact analytical solutions for the mechanical response of the restored member prohibitively difficult. The most critical among the as above assumptions are the linearity of all three materials involved, the planarity of cross sections and their normality to the beam's longitudinal neutral axis, the perfect compatibility of strains across the interfaces, the transverse isotropy of marble and the assumption that the loads act normally to the material layers of marble (Kourkoulis & Ganniari 2008). The influence of relatively small inclination of the fracture planes of the assembled fragments is also neglected during the design of the connection. Obviously the nature and seriousness of these assumptions dictates increased safety factors (due to the unique cultural importance of these monuments), which in turn lead to increased intervention and damage of the authentic material (increased anchoring length, increased number of reinforcing bars) which is in contrast to the principal guide lines of the Venice Charter (1968) for the restoration of monuments.

The only way to escape from this closed loop is to minimize the as above design assumptions by safely assessing the mechanical response of the restored epistyle. Given that the analytic solution of the problem is beyond any discussion, the experimental and numerical studies appear as the only way out. It is to be mentioned at this point that the respective experimental protocols are also very difficult: The size of the specimens must be quite large to avoid shadowing the results by the size effect which is extremely pronounced in marble and other rocks and rock-like materials (Vardoulakis et al. 1998). In addition the bending load applied must resemble as close as possible uniform distribution (Kourkoulis et al. 2010) since the actual load acting on restored epistyles is mainly the weight of superimposed structural elements. This is achieved, by means of sophisticated assemblies of beams and bars increasing further the complexity of the experiments. Moreover, the construction of specimens which simulate asymmetrically fractured and restored epistyles needs very experienced technical personnel. As a result the number of experiments that can be carried out is usually very restricted and one has to pump the maximum possible amount of data by using combinations of sensing techniques. These techniques should be capable of pumping data from the interior of the three-material complexes (marble-cement paste-titanium) since the failure mechanisms are first activated at the two interfaces (marble-to cement paste and cement paste-to-titanium). Given that these interfaces are not accessible by traditional sensing techniques it is obvious that the use of innovative ones becomes imperative (Kourkoulis et al. 2015) increasing the cost of the experimental protocols. Unfortunately, most of these techniques provide qualitative rather than quantitative data and their proper calibration becomes a decisive non-trivial step (Triantis et al. 2008).

In this direction, an experimental protocol is designed, aiming both to monitor the mechanical response of restored marble structural elements and also to assess the effectiveness of sensing techniques, which could be potentially used for in-situ structural health monitoring of stone monuments. For the needs of the protocol, a copy of a typical epistyle of the Athens Parthenon Temple was constructed by experienced technicians of the Parthenon's worksite. It was composed by two asymmetric fragments the fracture plane of which was inclined with respect to the member's axis in order to study also the role of the fracture plane's inclination. The epistyle was subjected to multi-point bending and its response was monitored with the aid of both traditional and innovative sensing techniques including clip gauges, dial gauges, LVDTs and Acoustic Emission (AE), Pressure Stimulated Currents (PSC), Digital Image Correlation (DIC) and Optical Fibers. The data gathered permitted comparative evaluation of the sensing techniques and indicated that the AE and PSC techniques provide valuable pre-failure indicators. In addition, critical aspects of the mechanical behavior of the restored epistyle were enlightened. Furthermore, the data gathered permitted validation of numerical models which will be used (research in progress) for a detailed parametric study of the problem (Kourkoulis 2017).