In-situ investigations for structural assessment of Temple C in Selinunte (Italy)

Giovanni Fabbrocino, Gaetano Manfredi and Elio Giangreco

University of Naples Federico II, Department of Structural Analysis and Design, Naples, Italy

ABSTRACT: Preservation of archaeological handmade is a very relevant task for structural engineers, which are often responsible for safety of ancient constructions and design of interventions aimed basically to mitigate structural damages, rather than strongly improve structural performances of constructions, as for ordinary structures. Concept of mitigation of structural damages is only recently applied to structural restoration; in fact, many interventions made on archaeological constructions in the past were very invasive, operated directly on the structure changing its appearance and original resistant mechanisms. Thus evaluation of present structural performances of ancient constructions is very complex and must be based on an accurate review of former interventions and an analysis of actual structural mechanisms governing the behaviour of the construction. In the present paper, this topic is discussed with reference to an amazing construction: the Temple C, placed in the Greek archaeological site of Selinunte, south-western Sicily, Italy.

1 INTRODUCTION

Preservation of archaeological constructions is a very complex task, involving different skills. Structural engineer has often an important role due to the need to ensure safety of constructions against total or partial collapse (Giangreco, 2000). Furthermore, satisfactory structural performances are not only needed to avoid loss of cultural heritage, but also to protect visitors of archaeological sites from injuries. As a consequence, in the past engineering exerted a strong influence on restoration of ancient monuments and constructions, referring to purely rational and technical approach, resulting in solutions directly derived from current practice and the related reliability criteria. This is the reason for extensive use of materials, i.e. reinforced concrete, and resistant mechanisms, i.e. frames, that led to change appearance and original structural arrangement of the construction. Thus, damage that is observed on archaeological monuments often is not due only to deterioration of materials, seismic and environmental effects, but also to improper use of materials and techniques used to repair and/or rebuilt. Current conditions of many archaeological constructions show clearly the effects of interventions carried out in the early decades of twentieth century. Modern approach to maintenance and preservation conversely is based on the Chart of Venice that stated the basic principles of restoration. The guidelines of Chart of Venice emphasise some peculiar aspects of restoration and safeguard of monuments and historical buildings, with specific reference to structural techniques for restoration that have to respect original materials and documents and also preserve all the valid contributions of the different periods of the monument. Durability and full compatibility of interventions are mandatory. Furthermore, any intervention can be carried out so that corrective actions are possible, resulting in its full reversibility. All the above rules result in a rigid framework for structural engineers that can be involved in analysis of archaeological constructions and design of structural interventions.
at different levels (Penelis, 2000). In any case, the first step is the safeguard of the artefact, consisting in temporary measures aimed to ensure adequate safety levels meanwhile final interventions are carried out. The next step is restoration, i.e. reparation and/or mitigation of damages, that is definitive in nature and is aimed to ensure original structural and physical performances of the construction. However, the fundamental step of the process is the knowledge of the actual structural pattern governing the response of the construction to external loads and of the mechanical and physical properties of materials. The present paper is aimed to discuss the possibility to perform in situ investigations able to define the structural conditions of a construction and support the analysis and design of interventions to maintain satisfactory structural performance for the construction. The paper deals with the investigations carried out on the Temple C, placed in the Greek archaeological area of Selinunte, South-West Sicily, Italy (Tusa V., 1991).

2 THE SITE OF Sselinunte AND THE TEMPLE C

2.1 Brief historical overview

Archaeological site of Selinunte is located in South-Western Sicily close to town of Castelvetrano, province of Trapani. Its name is due to savage parsley, ‘selinon’ in Greek, that was a distinctive plant present also on local coins. It was founded by Megara Hyblea’s peasants in the VII century b.C. It was the most advanced point of Greek colonial expansion, and its history was influenced by this peculiar condition. At the beginning of the V century, war between Sicilian Greeks and Carthaginians broke out and ended with the Himera battle in 480 b.C.; at that time Selinunte joined its forces with Cartagio, so that a large number of hard conflicts against Segesta took place until 409 b.C., year of its destruction caused by the Carthaginians. Selinunte was then subjected to Punic, who fortified and carried out the reconstruction of the city in the same area of the ancient acropolis. Carthaginian dominion went on until the first Punic War, when Cartagio decided to concentrate its strength on Lyliebo, and moved there people from Selinunte that was destroyed, abandoned and went to rack and ruin. The causes of the definitive destruction of the city in X or XI century a.C. are controversial; in fact due to a catastrophic natural event, the ancient town and the monuments became a lot of ruins. In the second half of the XVI century, historian Tommaso Fazello discovered the site, and later in 1823, English archaeologists undertook a number of excavations. Fallen columns, lonely foundations, dismantled towers and ruins of walls are distinctive signs of the site. The archaeological area consists of three different zones: the eastern hill, where the ruins of three temples G, F and E exist; the acropolis that holds the ruins of five temples, O, C, D, A and B; the Malophoros (pomegranate-bearer) in the west 800 m far from the acropolis, consisting of the ruins of an ancient sanctuary located on the country road that leads to the necropolis of Manicalunga. The temples are identified using letters due to lack of knowledge about gods to whom the constructions were dedicated. The city shows orthogonal cross-roads grid plan, after ionic architect Hippodamus from Miloto; twelve functional roads without any monumental character ran from East to West, crossing the main North-South road with a right angle. The acropolis has a plan with a peculiar pear shape and is linked to the new city, Neapolis, via an isthmus. Walls crenulated and strengthened by round towers protected the city in the North, and a network of underground paths useful in case of siege, rapid shifting of troops and sudden sorties can be observed.

2.2. The Temple C

The Temple C, the largest and oldest in the acropolis, was perhaps dedicated to Heracles, and was erected in 6th century B.C.; the longitudinal direction is East-West, in compliance with Greek and Roman tradition. Stone for drums and blocks used for construction come from a place called Cave di Cusa (Tusa S., 1987), 13 km far from Selinunte. The quarries have been probably active for many centuries and their utilization probably was suddenly interrupted around 409 B.C., since today it is still possible to observe blocks and drums at different stages of preparation. The temple is a hexastyle peripteral Doric style and had 17 columns along its longer facades. The stylobate measured 71 m × 26.62 m; the chamber with the pronaos and opisthodome
were lengthened, as was quite common in the archaic temples. Noteworthy is the importance of this temple in the field of Sicilian Greek Temples' architecture, in fact columns are both monolithic, in the south side, and made of superposed drums in the north. The drums of the columns are monolithic, high, cylindrical, without entasis; the number of the flutes is not constant, but varies between twenty on the front columns and twelve. This circumstance probably highlights that construction lasted many years. The columns are about 8.60 meters high including capitals with a base diameter of 1.94 m. Signs of the catastrophic event that destroyed Selinunte can be seen also on the Temple C, since fall of columns happened in a way that they remained in an almost perfect order and on parallel rows from south to north, as shown in Figure 1.b. The Temple C in its present configuration, see Fig. 1.a. results from reconstruction of the collapsed original structure; in fact a number of columns along the northern part of the temple was re-assembled between 1925 and 1927, giving to the construction the appearance that is well known today (Valenti, 1927).

3 THE STRATEGY OF STRUCTURAL ASSESSMENT

In the present section, the in-situ investigations carried out on the Temple C in Selinunte are briefly presented. The activity was completed in June 2000 and was aimed to assess the actual conditions of the temple and analyse from a structural point of view the deficiencies revealed by cracks present on many drums and capitals. The investigations were developed with the support of Italian Ministry of University and Scientific Research and in cooperation with Soprintendenza di Trapani, that is the Regional Government Office for Archaeological and Cultural Heritage and an industrial partner, the Tamburini s.p.a., an Italian construction company. The main objective of the work was the development of a procedure able to give a clear view of the structural conditions of the construction; however, the complexity of the structural configuration and the limited available budget led to focus the attention on some components of the structure. Thus, three columns were accurately investigated, together with the portion of entablature located above them. Scaffolding was erected to allow a close observation of the external surface of columns and capitals, as shown in Figure 1.b.

The strategy of the investigations was developed according to the following scheme:

- evaluation of the present conditions of the structure by means of an accurate geometrical survey taking into account the main constructional aspects;
- evaluation of deficiencies by means of the survey of crack pattern;

![Figure 1 : The Temple C, north a), and south b) view points.](image)

| Table 1 : Results of laboratory tests on limestone from Selinunte archaeological site. |
|-----------------------------------|----------|----------|
| Specific weight KN/m³             | Maximum  | Minimum  |
| Compressive strength MPa          | 15.74    | 18.80    |
| Indirect tensile strength MPa     | 5.0      | 13.9     |
| Young’s Modulus MPa               | 0.7      | 0.9      |
| Linear thermal dilation µm/m/°C   | 9302     | 13440    |
|                                   | 6.0      | 8.5      |
c. identification of original works and effects of former structural interventions of restoration;
d. evaluation of the mechanical and physical properties of materials used in the construction;
e. advanced non-destructive tests on the structure to describe internal conditions of massive
blocks and eventual additional constraints.

It is to recognize that the tasks are sometimes complex and need the interaction between different
skills. Results of step and c are summarized in Table 1 and Figure 3 respectively. The tests on
limestone have been carried out on specimens extracted from blocks taken in the archaeological
site, in agreement with Soprintendenza. Thus any intervention on the temple has been avoided.
Geometrical survey, available in 3D Cad digital format gives a representation of the entire struc-
ture and makes an enhancement of a previous archaeological survey (by Studio Di Grazia, 1980),
missing some critical details from a structural standpoint; conversely, a specific attention has
been paid to the three investigated columns #7, #13, and #14 that have been carefully shaped us-
ing high resolution topographic equipments. Longitudinal and transverse section have been also
provided in order to support modeling and NDT investigations.

3.1 Geometry of the Temple C and survey of crack pattern

As already mentioned present configuration of Temple C derives from a reconstruction carried
out in 1920’s. The analysis the main aspects of the geometry points out common irregularities of
drums and presence of large volumes made of bricks, used to fit the original shape and fill the
voids due to missing parts. As a result, at time of reconstruction blocks were already ‘cracked’ in
the sense that not only interfaces between limestone and bricks, but also between different lime-
stone fragments existed. This circumstance is confirmed by Figure 4 that reports a schematic
view of typical interventions based on extensive use of steel bars and profiles and aimed to fasten
together different damaged parts of drums and capitals (Valenti, 1927).

This initial condition of the temple changed due to deterioration of materials used during re-
construction and also to the number of very invasive interventions that took place in the last dec-
ades. Today, signs of a large number of perforations can be identified on the external surface of
the construction. The holes, about 20/30 mm in diameter, were done using drills that caused high
levels of vibrations and therefore often damaged the blocks. This kind of intervention dates back
to 1980’s and can be related to many observed deficiencies. In order to have a complete view of
the construction, a number of drawings have been set, as shown in Figure 4÷7 referring to col-
umn #7, entablature and capital above column #13. Perforations allowed the injection of resins
loaded with sand inside the blocks, in order to bond fragments. On the southern side of the colon-
nade, generalised damage due to wind erosion can be observed, on this subject, an interaction with resin injections has been identified, in fact in many regions, the presence of resin inside the blocks forced the development of erosion, influencing the original sensitivity of blocks to the phenomenon. Longitudinal and quite large cracks have been detected on many drums, as shown i.e. in Figure 6. Entablature has been also perforated and injected with mix of resin and sand; in general it is characterised by the assemblage of different blocks by means of reinforced concrete. The latter has been extensively used in order to bear flexure in the architrave. Corrosion of steel components can be also observed, and results in large zones of concrete or resin spalling, Figure 7.

3.2 Non Destructive Tests: Results of GPR investigations

The objective of the NDT investigations was to collect information about internal conditions of massive blocks of columns drums and capitals, with specific reference to presence of cavities and/or additional steel restraints between blocks. High-resolution GPR tomography has been preferred to use of extensive endoscopic investigations and seismic tomographies, in fact the fundamental requirement for investigations was the minimization of mechanical interaction with the structure. The equipment consisted of GSSI Sir 2 System with 1.5 GHz antenna. Sixteen longitudinal GPR profiles were acquired along the flutes using a specific longitudinal wood slide, able to straightforward the antenna, keep the correct direction and avoid noise and scattering. Transverse circular GPR profiles were also acquired; their location was related to the presence of joint between two superposed drums; another wood. The investigations consisted of 149 GPR profiles, divided as follows: 48 longitudinal and 47 transverse profile on the three investigated columns; 14 profiles on the capitals and 40 on the entablature. Some examples are reported in Figure 8 and 9. The geometrical survey of the structure and the accurate CAD representation of the geometry allowed to obtain a 3D representation of the anomalies and have a global picture of the actual situation. Sample results of the tests are reported in Figure 4÷7 and Figure 10. GPR tomography showed that in some drums of columns metallic bars are present, their direction is sub-horizontal and their structural scope is bond fragments and confine in transverse direction the stone blocks. Conversely, mutual restraints between blocks is ensured basically by mortar and resins, but longitudinal bars across the joint are missing. A few endoscopic tests and high resolution GPR tomographies are reported; the perforation has been done in the brick regions, avoiding works on original limestone. The depth of investigation is limited in order to ensure a higher resolution. A picture of the resin and sand mix injected in column #7 is shown in Figure 11, together with the scheme of layers inside the drums. In Figure 12, the endoscopic profile is compared with GPR one. It is worth noting the capability of GPR to identify the brick/limestone interface and void volumes.

4 CONCLUSIONS

In the present paper the in-situ investigations on the Temple C in Selinunte, south Italy, have been briefly reported. The aim of such activities was the assessment of actual conditions of the structure. A strategy based on the combination of different sources of information has been developed. The results of such a process have been described pointing out some critical aspects concerning archaeological constructions and cultural heritage in general. Identification of former interventions and changes of the original arrangement of the construction are really important, as well as the knowledge of the main mechanical and chemical-physical properties of all the present materials. A very useful tool is the extensive and accurate survey of the crack pattern in combination with a back analysis of the deficiencies can lead to the definition of causes. The contribution to assessment of the structure given by GPR seems to be really encouraging, since results of GPR investigations have a high degree of resolution and reliability.
Figure 4: Column #7, summary of the NDT analysis and crack pattern survey.
Figure 5: Column #7, summary of the NDT analysis and crack pattern survey.
Figure 6: Entablature above Column #13 and #14.

Figure 7: Entablature above Column #13 and #14.
Figure 8: GPR profiles on column #7.

Figure 9: GPR profiles on entablature above column #7.

Figure 10: Results of GPR tests on entablature above columns #13 and #14.
Figure 11: Endoscopic analysis on column #7 at 1.10 m.

Figure 12: Endoscopic analysis vs. GPR tomography on column #13 at 2.33 m.

ACKNOWLEDGEMENT

The authors acknowledge Ministry of University and Scientific Research, Syremont s.p.a and Tamburini s.p.a. for the support in the development of the investigations. They are also grateful to Soprintendenza di Trapani, and in particular to Dr. S. Tusa for documents and fruitful discussions and suggestions. Finally thanks are due to Eng. M. Catanese and the rest of Geolab s.r.l. team, responsible for the NDT investigations and to Eng. F. Iannone for the field activity and elaboration of the drawings related to crack pattern survey.

REFERENCES


International Chart of Restoration or Venice Chart 1964. II International Conference of Architects and Technicians of historical monuments. Venice.


