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Damage mitigation by innovative materials for Temple C at Selinunte

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Abstract

Greek temples are made of overlapped heavy stone blocks shaped to form columns and entablatures. Preservation of these constructions requires specific structural engineering effort. Present conditions of remains basically reflect centuries of loads and environmental actions, but also undesired effects of former restorations. The latter, if not properly designed, may affect the value and life expectation of these monuments.

In the present paper, a novel interpretation of the jacketing technique for temporary interventions and the application to the Greek Temple C of the Selinunte's (Sicily) archaeological site are presented. Purpose of jacketing is to avoid worsening of the crack pattern by light confinement of stone blocks. Titanium belts and elastomeric neoprene pads are combined to attain the above-mentioned performances. Simplified design model is proposed and a 3D finite elements analysis is performed to evaluate local effects of jacketing; finally information about in situ application are given.

Keywords: Innovative materials; Structural restoration; Damage mitigation; Archaeological structures; Structural jacketing

1. Introduction

Restoration of ancient constructions is a challenging topic for structural engineering requiring strong and fruitful interaction between different skills [6,3]. The task is more difficult, when survival of construction is concerned and the safety of visitors has to be given. Approach to preservation of the monuments was formerly based on solutions and materials shared with common structures, resulting generally in an ineffective answer to critical field applications. Therefore, damages to archaeological monuments are often not only due to deterioration of materials, seismic and environmental effects, but also to improper repair.

Documents as the Chart of Venice [7] give comprehensive guidelines for the modern restoration and can be addressed as the reference documents in the field. The basic principles for structural techniques are the respect of the original materials; required replacements need to be harmoniously integrated with the whole, but has to be easily identified as well; additions are accepted if their influence on the other parts of the monuments and/or its surroundings is negligible. In other words, the minimum destruction theorem applies [10].

Preservation of ancient construction can be carried out at different levels; the first step is the safeguard of the artifact, consisting in temporary measures to ensure satisfactory stability levels meanwhile final interventions are properly designed and executed. The next step is restoration, i.e., reparation of damages, which is definitive in nature and is aimed to ensure original structural and physical performances of the construction [12]. In all these cases, durability and full compatibility of interventions are compulsory and need to be adequately proven. Any applied system

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should be designed to be reversible; all the components could be removed with limited or no damage in order to leave the structure as it is and allowing substitution by new techniques with greater effectiveness. Traditional materials have been and are essential for structural restoration, but modern and innovative ones can be used to give better performances fitting the discussed principles.

In the present paper, the theme of the preservation and structural damage mitigation in archaeological sites is analyzed with respect to ancient temples which are precious evidence of Greek architecture in southern Italy (Magna Graecia), as it was a colony from XI century to the Roman conquer of the region in year 240 BC. These constructions consist of stone rectangular buildings erected on a stone base and with tiles on the roof. Columns and entablatures are made of heavy stone blocks simply overlapped with dry connections or even made of single properly shaped blocks.

In this framework, a jacketing technique for column was developed and installed to the Temple C of the worldwide famous Selinunte (Sicily) archaeological site. Innovation consists of the development of a procedure able to fit the requirements of restoration keeping the effectiveness of traditional jacketing. To achieve the research goals the technique is based on titanium belts and elastomeric pads. The whole system avoids contact between belt and stone, localization of stresses due to column's surface irregularities and mitigates thermal variations' effects, providing full removability.

2. Intervention framework

The famous Italian archaeological site located in Selinunte, close to Trapani (Sicily island) represents one of most beautiful and evocative expressions of the classic civilization of Magna Graecia Tito Livio, I sec. BC. Among all the remains, Temple C is the most ancient temple in the acropolis and is a worldwide symbol of Sicily and Italy; it is a hexastyle peripteral Doric style and had 17 columns along its longer facades (Fig. 1). The columns are about 8.60 m high including capitals with a base diameter of 1.94 m. Environmental actions and degradation of materials are evident on the structure, and in particular on the column #7 that can be identified in the survey reported in Fig. 1.

The present configuration results from the reconstruction of the collapsed original building; in fact a number of columns along the northern part of the temple was reassembled between 1925 and 1927 [11], giving to the construction the appearance that is well known today. The columns along the northern facade are made of heavy stone blocks (drums) properly shaped so that each block fits the lower without interface mortar layers. During the reconstruction, fragments had to be assembled using mortars and reinforced concrete; furthermore missing parts of the drums were filled by red bricks, therefore original configuration has changed significantly.

Holes and the missing parts mainly on the south elevation can be recognized. Signs and damages related to environmental effects and former interventions can be observed; detachments of limestone layers, not only along stone stratification direction, and large cracks all over the drum are reported; these data are more comprehensively reported in Fabbrocino et al. [5]. The extension of damage led the Archaeological Survey of Trapani to undertake experimental safeguard measures for structural damage mitigation. In particular the objective was related to slow down the evolution of the crack patterns of drums. As application the third drum (from the top) of column #7 was chosen due to its present conditions (Fig. 2). Jacketing seemed to be adequate for the purpose, however, with some specific features: (1) moderate levels of lateral confinement; (2) appropriate fitting of cross section shape and surface irregularities by means of low flexural stiffness belt even in different environmental (thermal) conditions. As a consequence, a novel jacketing technique was developed to fit such design constraints.

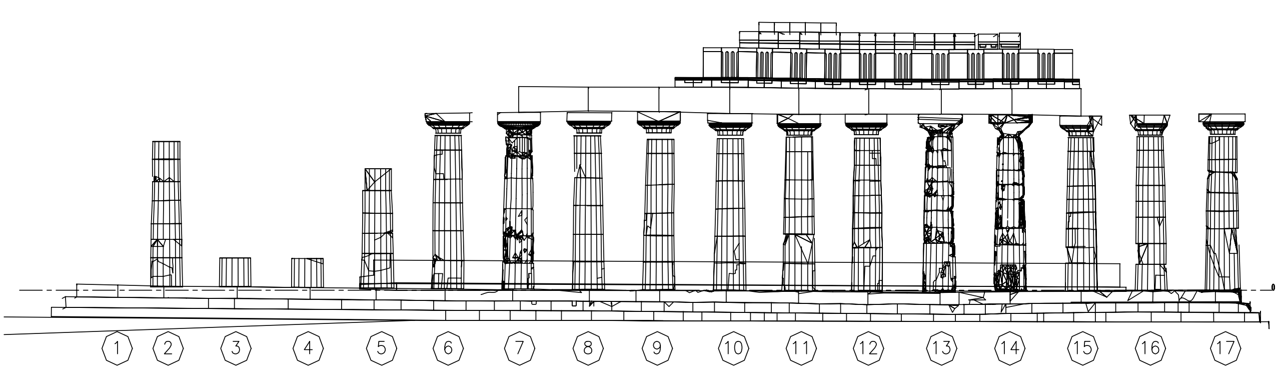

Fig. 1. Northern elevation of the Temple C.

Fig. 2. View of southern elevation of column #7 and the drum chosen for the application.

2.1. Multi-layer jacketing

Traditional jacketing systems for masonry columns are based on confinement due to direct interaction of metallic belts and stone skin; more in detail, steel belts are shaped in order to fit the column cross section. For non-circular columns, steel ties are connected to specific angular steel profiles. Restraining the transverse expansion of compressed elements, jacketing systems improve compressive strength and reduce structural damage propagation. Common procedures of installation for belts prescribe dilation on the metallic components by heating [8], while the subsequent cooling process triggers the interaction between belts and stone blocks. Therefore, design procedure is aimed to define an effective temperature of the belt that results in a tightening force during the cooling process. The design approach for traditional jacketing systems is based on the assumption that the outer surface of structural elements to be preserved are regular and the environmental temperature variations have the same effect on the column and the belt keeping constant the relative interaction. This procedure does not allow but a gross control of the systems at the installation time.

Multi-layer jacketing, herein discussed, has been conceived to fulfill the main requirements of structural interventions on classical columns as control, reversibility durability, and mitigation of damage. The approach is based on explicit modeling of elastomeric pads interposed between belt and columns avoiding direct contact and adapting belt shape to lateral surfaces of ancient columns, generally irregular due to flutes and to damaging aging processes resulting in missing parts. Introduction of elastomeric pads able to fit the outer profile of flutes and hollows, as shown in Fig. 3, leads to considerable rubber volumes and moderate stiffness of the intermediate structural component. Furthermore, the interaction between belt and stone skin cannot be continuous, since the stone corners have to be preserved; as a result primary aim of rubber pads is to avoid local damage to emerging parts of column profile. Whenever hollows and flutes change the column radios point to point, as for the application herein described, the needed elastomeric volume can be divided into a series of thin sheets.

Since increase of compressive performances of column is not critical in this type of application, the ratios between metallic belt and drum volumes are not high. The low flexural stiffness of each sheet enables an easy on-site installation of the system. The proposed technique is, in summary, useful when temporary shoring of columns is needed and long time elapses between damage detection and the final execution of structural interventions. It can be removed if other more effective intervention are developed. Its main goal is to maintain the conditions of the remains in their present configuration. However, the durability is the same as a permanent application since technical life should be virtually undefined.

2.2. Materials

It is easy to understand how materials are the key factor for the execution of this kind of intervention. In particular, durability of metallic jacketing and rubber are critical, so that mechanical properties become, if possible, less relevant than physical and chemical performances. This circumstance is related to the hard environmental conditions of the site which is in front of the sea, thus high resistance to generalized corrosion and to aggressive environment are required.

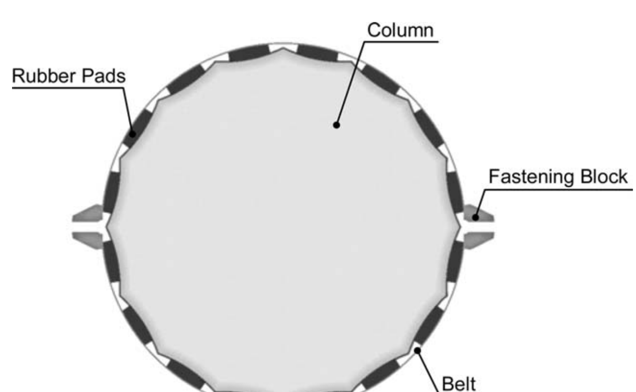

Fig. 3. Multi-layer jacketing system.

Among metals, titanium alloys show high resistance to generalized corrosion and to and polluting agents [2]. Mechanical properties of titanium, i.e., commercially pure titanium Grade 2, according to ASTM, fit the proposed application. It is characterized by a lower weight (4.5 g/cm^3) and a low thermal dilation factor, 8.8 E-6 1/K, compared with other metals, but similar to those of many natural stones. The Young modulus, 103 GPa, is low compared to steel; good are yielding and ultimate strength, 280 and 370 MPa, respectively and ductility as well, since ultimate strain is about 20%. In the last years, titanium has been frequently used in architecture and for preservation and restoration of archaeological constructions, i.e., of Athens temples [4,13,14].

The same durability features are required for elastomeric pads. Neoprene is a synthetic rubber characterized by a balanced combination of properties [9]; it resists to degradation due to sun, ozone, and weather, performs well in contact with oils and many chemicals; in addition it exhibit very good resistance to damage caused by flexing and twisting. Main properties of materials used in this application are given in Table 1.

3. Jacketing design approach

Aim of design procedure, on the analogy with traditional jacketing formulae, is to set the tensile stress of belts, which basically is the only control variable. Jacketing should provide acceptable system's performances also if subjected to environmental temperature variations; such features is given by rubber pads. Therefore, the procedure described in the following enables to evaluate the belt's fastening stress, but is also able to give a rough but conservative estimation of interface stresses between stone and neoprene pads.

Table 1
System material properties

	Specific weight (kN/m^3)	Young's modulus (MPa)	Thermal dilation factor
Titanium (belt)	45	103,000	8.8 E-6 1/K
Limestone (drum)	18	1000	7.0 E-6 1/K
Neoprene (pads)	9	0.5	5.5 E-5 1/K

The design approach of multi-layer jacketing system is schematically reported in Fig. 4. The presence of the flutes is neglected due to the role of the rubber pads, this simplification leads to define an equivalent radius of column assumed to be equal to the radius of base circumference of column cross section. Therefore, the system is polar-symmetrical. The development of a behavioral model is based on the hypothesis that both belt and drum after deformation keep the initial shape.

The belt tensile stresses are constant and elastomeric pads are subjected only to compression. Rubber pads are modeled as independent linear springs transferring tensile force in the belt to compression of drum.

Radius for belt at the equilibrium with the column after installation ($r_{b,1}$) can be expressed as the elastic variation of the original radius ($r_{b,0}$) as in Eq. (1)

$$r_{b,1} = r_{b,0} \cdot \left(1 + \frac{\sigma_b}{E_b}\right), \quad (1)$$

where E_c is the Young's modulus of the belt and σ_b is axial stress in the belt assumed constant along the circumference due to the symmetry. Column radius ($r_{c,1}$) at equilibrium is given in Eq. (2) as sum of vertical load, which tend to enlarge it, and belt confinement

$$r_{c,1} = r_{c,0} \cdot \left(1 - \frac{1}{E_c} \cdot \left[\sigma_{c,r} - \frac{\sigma_{c,a}}{m_c}\right]\right), \quad (2)$$

where $r_{c,0}$ is drum's radius without lateral expansion due to vertical loads; E_c is drum's material Young's modulus; $\sigma_{c,r}$ is radial compression of stone due to jacketing action; $\sigma_{c,a}$ is axial stress compression on the drum due to vertical loads; $1/m_c$ is Poisson modulus of the column. System's compatibility is given by the equality of the belt's radius and the column's radius plus the deformation of the pad (Eq. (3))

$$r_{b,1} = r_{c,1} + (s_g - w_g), \quad (3)$$

where s_g is the pad thickness and w_g (Eq. (4)) is its radial displacement depending on the compression of the column

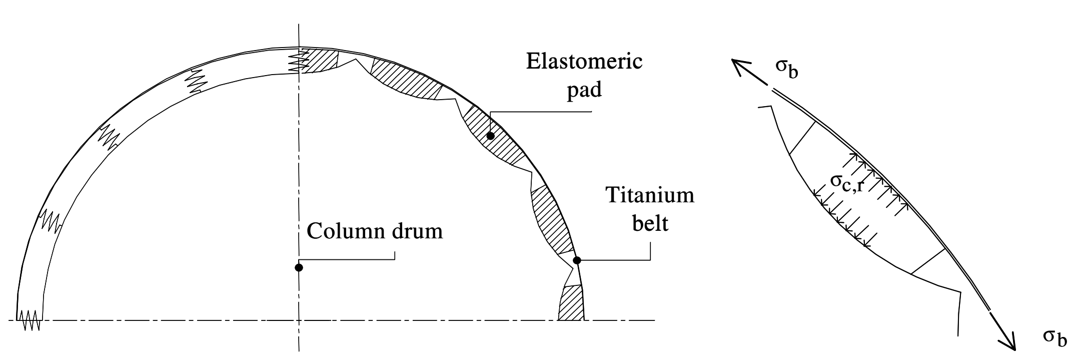

Fig. 4. Jacketing system mechanism.

$$w_g = \frac{\sigma_{c,r}}{E_g} \cdot s_g, \tag{4}$$

where E_g is the Young's modulus and of pad's material. Equilibrium of forces gives on the jacketing belt

$$s_b \cdot \sigma_b = k \cdot \sigma_{c,r} \cdot r_{b,1}. \tag{5}$$

In Eq. (5), $\sigma_{c,r}$ and σ_b represent radial stresses in column and belt axial stress, respectively; k represents the efficiency of jacketing system. In traditional design for circular columns $k = 1$ because the interaction between belt and stone is continuous and not limited to the pad areas. Discontinuous interaction gives a coefficient lower than 1, as in the present application. In the case of multi-layer jacketing k factor can be evaluated by integral in Eq. (6) which refers to a quarter of the system's circumference

$$\sigma_b \cdot s_b + r_{c,1} \cdot \sigma_{c,r} \cdot \sum_{i=1}^{4} \int_{\alpha_i}^{\alpha_{i+1}} \text{sen}\alpha \, d\alpha = s_b \cdot \sigma_{b,r} + 0.629 \cdot r_{c,1} \cdot \sigma_{c,r} \tag{6}$$

In Eq. (6), α_i and α_{i+1} are the initial and final angle defining the zone in which the belt seats on a pad. This integral leads to $k = 0.629$ if the column has 16 flutes. The right-hand member in Eq. (5) gives the applied force on belt, depending only on its thickness s_b. Eqs. (1)–(5) are independent and make up a nonlinear system in the unknowns $\sigma_{c,r}$, σ_b, r_1 . Solution of these equations allows controlling stress conditions of system at reference temperature. Variations of environmental conditions and related changes of external temperature lead to different interaction at the stone–rubber interfaces; loss of tensile stress in the belt are expected when temperature increases hence confinement effectiveness of jacketing system to the stone block decrease. Increased local stresses concentration and stone failures may be expected when temperature decreases. Therefore, design should take into account such variation to ensure adequate performance of jacketing.

3.1. Thermal variation accommodation design

Efficiency of jacketing system under changes of environmental conditions means that belts and elastomeric pads do not lose contact with the stone block; as a result, interaction radial stresses on stone may decrease, but cannot be zero. After the transition phase, thermal variation ΔT leads to a steady state characterized by a new equilibrium condition with different stresses and strains ($\sigma'_{c,r}$, $\sigma'_{b,r}$, r'_1). These parameters can be evaluated again by means of compatibility and equilibrium conditions at drum interface; assuming that $r'_1 \approx r_1$ system of equations become linear. Elastomeric pads installed between belt and stone block can improve the response of system to environmental temperature variations due to differences in terms of thermal dilation factor that is one order of magnitude greater then other materials involved in the system.

Solution of the problem at a temperature different in respect to the installation can be performed starting from the equilibrium condition evaluated according to equations given in the preceding section. In this way unknowns are basically $\Delta r_{b,1}$, $\Delta r_{c,1}$, Δl_g, $\sigma'_{b,r}$, $\sigma'_{c,r}$; where $\Delta r_{b,1}$ and $\Delta r_{c,1}$ represents variation of belt and column radius; Δl_g is global rubber thickness variation; $\sigma'_{b,r}$, $\sigma'_{c,r}$ are final stresses in belt and column

$$\Delta r_{b,1} = \Delta r_{c,1} + \Delta l_g. \tag{7}$$

Eq. (7) reports the compatibility of deformation after the equilibrium has been modified due to ΔT ; in fact, the radiuses variation must be consistent. Eqs. (8)–(10) lead to elastic and thermal strain for each system element (belt, pads, drum). Eq. (8) is the radius variation for the belt due to the thermal deformation and elastic equilibrium variation

$$\Delta r_{b,1} = r_{b,0} \cdot \left(\alpha_b \cdot \Delta T + \frac{\sigma'_b - \sigma_b}{E_b} \right), \tag{8}$$

where $\Delta r_{b,1}$ is the radius deformation; $\alpha_b \cdot \Delta T$ is the thermal contribution and $\frac{\sigma'_b - \sigma_b}{E_b}$ is the elastic contribution due to the equilibrium variation of the system

$$\Delta r_{c,1} = r_{c,0} \cdot \left(\alpha_c \cdot \Delta T - \frac{\sigma'_{c,r} - \sigma_{c,r}}{E_c} \right), \tag{9}$$

$$\Delta l_g = s_g \cdot \left(\alpha_g \cdot \Delta T - \frac{\sigma'_{c,r} - \sigma_{c,r}}{E_g} \right). \tag{10}$$

The same applies for the column (Eq. (9)) and the rubber pad (Eq. (10)) with the same meanings of the symbols as Eq. (8). Force equilibrium (Eq. (5)) became Eq. (11)

$$s_b \cdot \sigma'_{b,r} = 0.629 \cdot \sigma'_{c,r} \cdot (r_{b,1} + \Delta r_{b,1}). \tag{11}$$

Substituting Eqs. (8)–(10) in Eqs. (7) and (11), it is easy to recognize that the system becomes linear. The only two unknowns are the final stresses in the belt and stone which are the design variables.

For the application different belt tensile stress levels have been analyzed at different temperature steps. A target stone radial stress equal to 0.36 MPa is chosen as acceptable for design, if compared with uniaxial strength assessed by means of tests on stone specimens [5] that ranges between 5.0 and 13.9 MPa. This target value takes also account of mitigation of thermal effects related to the intermediate neoprene layer and neglect biaxial effects that can improve mechanical properties of base material; as a result, belt tensile axial force is equal to 18.0 kN (Table 2).

Design outcomes show that the system exerts compression to the drum as one order of magnitude lower than the tension in the belt. Effectiveness of the rubber pads can be evaluated changing its thickness between boundary values; 1 mm (≈no rubber) and 80 mm (med-

Table 2
Design approach outcomes (MPa)

	80 mm rubber thickness		1 mm rubber thickness	
	Belt tensile stress	Drum radial stress	Belt tensile stress	Drum radial stress
T_{ref}	36.0	0.362	36.0	0.365
T_{ref} + 40 °C	36.6	0.368	30.1	0.312
T_{ref} − 40 °C	35.4	0.356	40.3	0.481

ium size rubber pad) for a given geometry of the drum (16 flutes). The variation ΔT respect to the reference temperature is assumed equal to ±40 °C. Increased thickness of pads results in low stress scatters for "cooling" processes and slight increase of stress due to "heating" process. This effect is due to rubber expansion factor being greater respect to others and enabling a compensation of temperature effects; thus the intermediate layer is able to mitigate thermal effects and reduce related stress variations, in fact the thermal load mean effect is negligible.

4. Finite elements analysis

The design procedure presented in the preceding section is primarily intended as a rational tool to estimate a tensile belt stress level and to ensure acceptable system performances depending on the temperature variations. On the other hand, it checked the role of the rubber pads during heating or cooling processes due to seasonal and daily temperature variations. However, the design model is based on the assumption that all the components keep initial shape during deformation and that rubber pads are simple springs subjected to concentrated axial loads. Actually, the interaction between elastomeric pads and stone is more complex and needs better understanding. This kind of verification can performed by a 3D finite element analysis. Obviously, it can be carried out at different levels of refinement. Within the scope of the present paper, a FE model design oriented has been selected. This means that it has been optimised to give an estimation of stresses acting after belt tightening, so that specific interface elements to simulate slippage between components have not been used. Fig. 5 reports the FE model of the whole drum with installed neoprene pads and titanium belts. The model was built in the Altair Hypermesh® 3D software environment [1]. The column FE model was characterized by polar-symmetrical, geometry. This is the main simplification since the actual conditions of the drum are far from symmetry due to the aging process. Column drum was assumed as a conical element with a lateral surface slightly inclined (2°) respect to vertical axis characterized by 16 flutes, bottom internal radius about 159 cm, top internal radius is 155 cm.

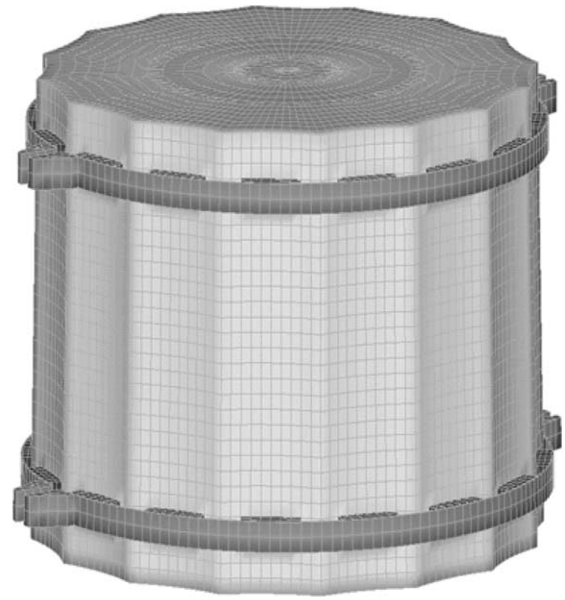

Fig. 5. Drum 3D FE model.

These dimensions have been extrapolated by the actual relief of the column. Drum FE model is a radial 3D mesh using brick elements with six and eight nodes. Mechanical behavior of stone is assumed as linear elastic both in compression and in tension due to the low stress levels induced by the multi-layer jacketing. Each titanium belt is meshed using eight nodes brick elements; anchoring blocks for the belt have been modeled as well in a way that the load has been applied in agreement with the actual installation procedure.

The reliability of the FE mesh of the drum as a whole has been checked by a sensitivity analysis; thus results discussed in the following refer to the most sustainable discretization representing a good compromise between accuracy of results and computational time. This investigation is certainly of interest, since in real cases symmetry and regularity of drums often does not take place, thus reduction of modelled volume cannot be easily carried out. On the other hand, the very low flexural stiffness of the titanium belts makes prevalent the axial deformation mechanisms compared to flexural ones, in compliance with results of sensitivity analysis. In summary, the selected FE model does not affect generality of approach since a negligible effect on drum's interface stress, which is the critical parameter of the system, is observed; no slippage at interfaces of drum, belt and stone is accounted for; modelling of actual geometry of real drums and superposition of neoprene pads to fit drum shapes are by far more complex and require very high computational effort, being out of the aims of the present study.

Thickness of elastomeric pads is about eight centimeters according to the column model. Axial load acting on the stone drum has been obtained by a self-weight analysis of the column and a constant level of compressive stress equal to 0.13 MPa is assumed on the cross section of the drum. The following FE analysis subcases were considered: (1) statical analysis of the free drum; (2) statical analysis at the reference temperature for the jacketing system; (3) statical analysis at $\Delta T = +40$ °C; (4) Statical analysis at $\Delta T = -40$ °C. It is worth to note that the value of ΔT is representative of the thermal effects acting on the system taking into account the sun exposure and the wind actions in an outdoor location close to the seaside in southern Italy.

Every sub-case ran in two parallel conditions: (a) drum only supported on its base; (b) drum firmly constrained at the base. These analysis levels were used to define two limit conditions for lower surface that is restrained by mortar layers and friction. The belts' design axial stress in the analysis at reference temperature can be simulated as the fastening force; in particular, the design tightening force of 18,0 kN, derived from the design procedure, is applied at each fastening element. Due to the nonlinear nature of the problem, the thermal load analysis has to be carried out imposing the fastening blocks displacements and then the thermal loads, in compliance with real system working conditions.

4.1. Results and discussion

In Fig. 6, the main analysis results are summarized; Figs. 6(a) and (b) show radial stone stress at reference temperature and +40 °C analysis for free base sub-cases while Figs. 6(c) and (d) consider a constrained bottom drum.

Local interface stresses are higher than values predicted using simplified design under fastening blocks, as clearly expected; while they decrease to the lower value in under the middle of the belt. However, stone compression they never exceeds 1 MPa in high stress zone and is moderate away (approximately 0.2 MPa) due to loss of load due to shear stresses on the pads.

If the thermal loads are concerned, FE calculations confirm that a negligible stress variation is induced by temperature changes, especially in the case of temperature increase, resulting in a very effective role of elastomeric pads. Furthermore, FE analysis have shown that stress field due to base restraints of the drum is slightly influenced in the present configuration. Results in terms of stone radial stresses are summarized in Table 3, where axial belts tension is not reported because due to the titanium properties maximum stress level is by far lower than yielding point of the material.

In Fig. 7, the global major principal stress in the the upper belt and elastomeric pads is shown. Stress concentration of belts near to the fastening is related to the conservative assumption of negligible flexural stiffness of the fastening bolts; therefore ends of belts are subjected to both axial and transverse displacements producing such stress peak in the titanium. Conversely rigid bolts coerce fastenings to displace quasi-axially mitigating such effect.

FE analysis was intended to estimate local effects which simplified design is not able to take into account and, in the absence of verification, may be remarkable.

Table 3
Results of FEM analysis

	Vertical stress (MPa)	Radial stress far from the fastenings (MPa)	Radial stress near to the fastenings (MPa)
Free drum	0.13	–	–
Jacketed drum T_{ref}	0.13	0.23	1.21
Jacketed drum $T_{ref} + \Delta T$	0.13	0.22	1.21

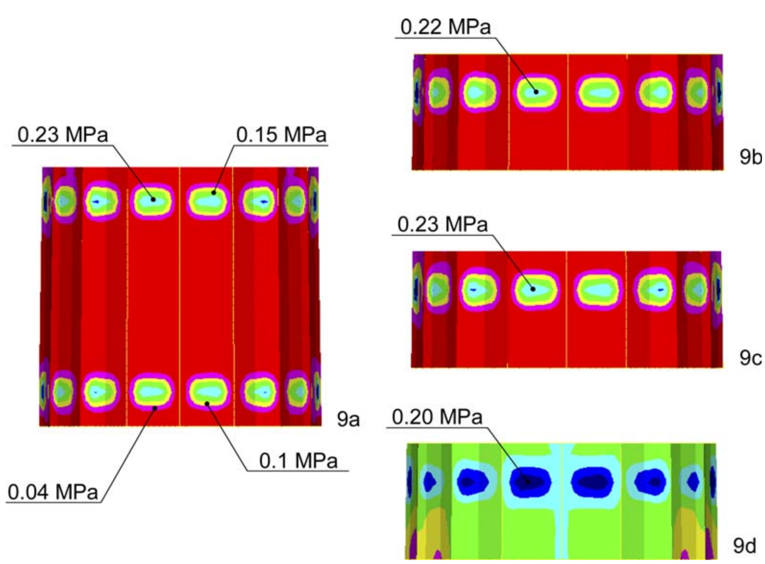

Fig. 6. Result of statical analysis in terms of stone radial principal stress for free and constrained base.

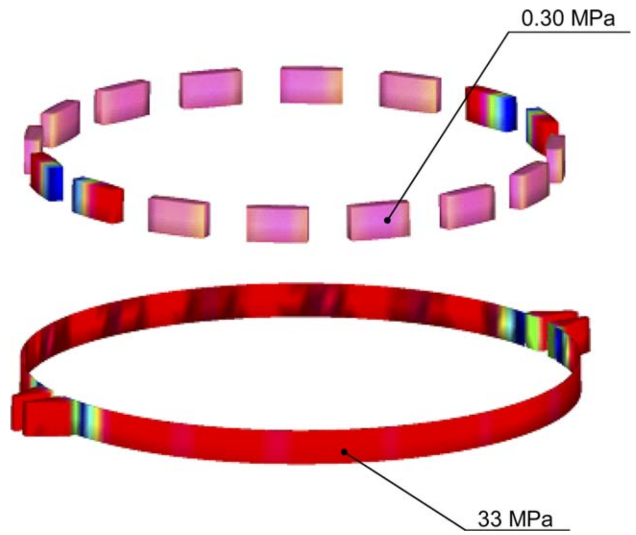

Fig. 7. Result of statical analysis for rubber pads (radial stress) and upper belt (axial stress).

Fig. 8. View of the site application.

Table 4
Design and FE radial stress (MPa) summary

	Simplified design procedure	Finite element analysis
Jacketed drum T_{ref}	0.13	0.23
Jacketed drum $T_{ref} + \Delta T$	0.13	0.22
Jacketed drum $T_{ref} - \Delta T$	0.13	0.24

Comparison of design outcomes and finite elements analyses (Table 4) shows how design gives a conservative estimation of the interface stress not in the proximity of fastenings (were the model used in design applies). FE analyses also confirm stress compensation due to pads as assumed by design procedure.

5. Field application

Two belts have been installed on the drum as reported in Fig. 8, each one consists of two parts that were assembled using bolts

During the installation phase, strain gauges measures were taken to control the stress level of the system. Both belts have been instrumented by four extensimeter each as in the scheme pictured in Fig. 9, where S1, S2, S3, and S4 are location of sensors to the upper belt, while those on the lower belt are I1, I2, I3 and I4. Measures have been carried out by the data acquisition system P3500 by Measurements Group, Inc. Extensometers are type EA-06-250BG-120 from Measurements Group, Inc.; the measures represent the mean deformation of the belt since measures started before applying tension to the tightening system. Design tension (see above) was 5 N/mm^2.

For each of the two belts control of forces has been carried out by continuous measuring of deformations in the instrument #1 (S1 and I1 for the upper and lower belt, respectively). A number of tightening steps have been carried out in order to attain the design tensile force in belts. When the design stress level is reached, then the deformations are measured. Results for each instrument and belt have been summarized in Table 5 (positive values indicate tension).

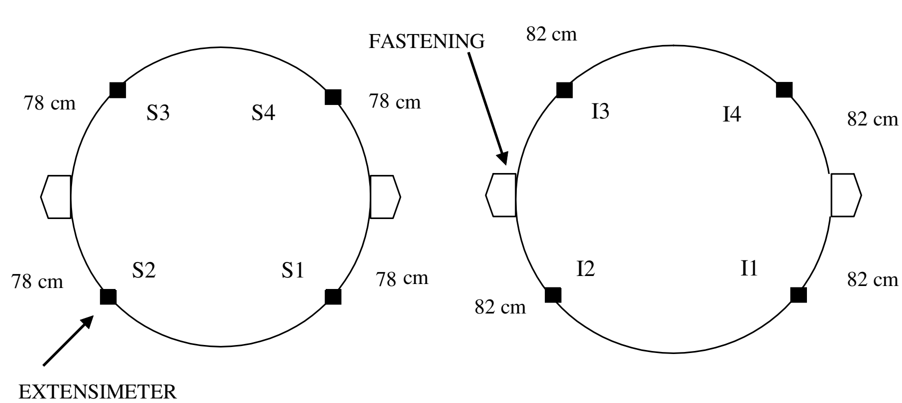

Fig. 9. Jacketing in situ instrumentation (instruments' distances are intended from the nearest fastening block).

Table 5
In situ instruments' fastening

	Belt's measured deformation (m/m E-6)	Belt's axial stress (MPa)	FEM result (MPa)
Instrument S1 fastening steps			
Start	0	0.00	–
I	47	4.84	–
II	87	8.96	–
III	143	14.73	–
IV	191	19.67	–
V	238	24.51	–
VI	351	35.23	36.35
Instrument I1 fastening steps			
Start	0	0.00	–
I	77	7.93	–
II	146	15.04	–
III	242	24.93	–
IV	342	35.23	39.15

6. Conclusions

In the present paper, some aspects related to structural design of safeguard devices for ancient multi-drum columns have been discussed. The attention has been focused on the preservation of damaged colonnades and in particular jacketing solutions for damage mitigation of column drums are analyzed. The case study comes from the need of provisional and durable intervention on one of the most important temples of Italy and world, Temple C at Selinunte, Italy.

A jacketing technique, modified to fit the purposes of arts restoration and damage mitigation, was applied. The development of the multi-layer jacketing system is discussed and a field application is reported. The key aspect in the design process is the check of interface stresses due to jacketing devices for column drums and reliable evaluation of thermal effects. Results show that the control of interface stresses can be safely carried out using a simplified and design oriented model. Introduction of elastomeric pads at the belt–stone interface is useful, since it is able to reduce localization of stresses due to surface irregularities and the additional deformation due to rubber pads allow to compensate the thermal effects on the system due to temperature cycles as well. The belt tightening force is basically dependent upon the required performances of jacketing; design equations can be used to define the belt's tensile stress corresponding to a reasonably low value of the radial stress at the rubber–stone interface.

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