Two-layers jacketing for column drums

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Abstract

Strengthening and repairing of archaeological handmade are very important issue for structural engineers, and require specific techniques fully consistent with needs of arts prevention. Interventions of rehabilitation are often invasive, they operate directly on the structure changing appearance, so they are not acceptable in application to relevant archaeological constructions. On the other hand, durability of materials used in restoration and preservation of archaeological arts is a very relevant aspect of the design process. In the present paper, a jacketing technique for multi-drum classical columns is presented. In particular, some aspects related to structural design of belts and to limitation of stresses on stone surfaces are discussed. The technique is based on utilisation of metallic belts and elastomeric pads, able to avoid direct contact between belt and stone, reduce localisation of stresses due to surface irregularities and ensure a full reversibility of the intervention.

1. Introduction

Restoration of ancient constructions is a very complex process, and requires a strong and fruitful interaction between different skills; role of engineers in this process is sometimes very relevant when the evaluation of structural performances of ancient constructions is needed. In the past, engineering exerted a strong influence on preservation of monuments and archaeological constructions, since purely rational and technical approach were used to ensure satisfactory safety levels.

As a consequence, common construction materials such as steel and concrete and the related reliability criteria have been extensively used; in this way both aesthetics and original structural schemes have been strongly modified.

This is the reason why damage to archaeological monuments very 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.

A different approach is stated in the Chart of Venice [1,2] that represents the reference document for modern restoration; emphasis is given to design processes able to preserve and reveal the aesthetics and the historical values of monuments and historical buildings. In particular, the basic principles for structural techniques to be used in restoration are based on respect of original material and documents, preservation of all the valid contributions of the different periods of the monument. Any replacement must be harmoniously with the whole, but must be well identified as well, while addition are allowable only if they have not influence on the other parts of the monuments and/or its surroundings.

Traditional materials are clearly essential in restoration, but modern and innovative materials can be used if traditional ones cannot ensure similar performances. In all these cases, durability and full compatibility of interventions are mandatory and adequately proven. However, any intervention must be carried out in a manner that easy corrective actions are possible; in other words, interventions must be fully reversible.

All the above rules result in a rigid framework for structural engineers that can be involved in analysis and design of archaeological constructions at different levels [3]. 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 of damages, that is definitive in nature and is aimed to ensure original structural and physical performances of the construction [4].

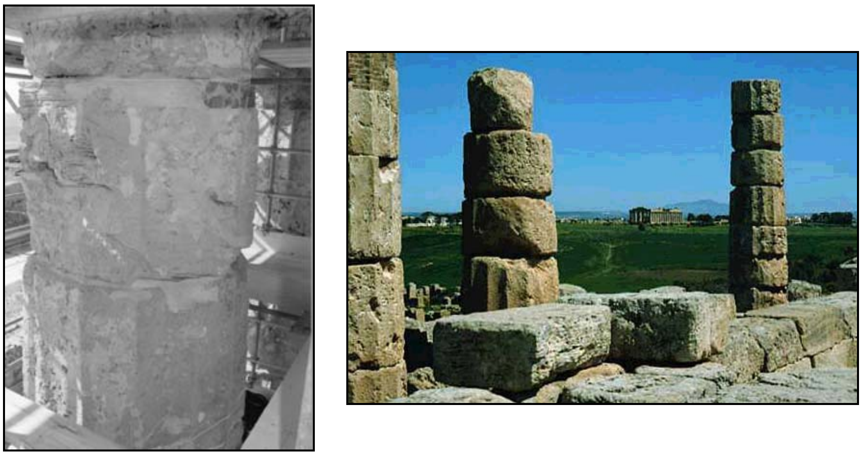

Figure 1: Greek columns in archaeological site of Selinunte (Trapani - Italy)

In the following, the attention is focussed on structural aspects related to preservation and safeguard of ancient columns that characterise both Greek and Roman temples. In Figure 1, a detail of a Greek column belonging to a colonnade identified as Temple C of the archaeological site of Selinunte, South Italy is shown. The picture clearly summarises many aspects discussed before and can be used to explain the main structural features of the constructions.

Original columns are generally multi-drum, and can be found isolated, as a part of colonnades or of entire temples. The column consist of heavy stone blocks properly shaped so that each block fits the lower without interface mortar layers.

Stability of columns is due to weight and shape of the cross section and dynamic behaviour is by far different respect to flexible contemporary constructions; therefore, they behave as a number of rigid bodies and can be characterised by sliding and rocking motions [5].

Conversely, current configurations are often characterised by former intervention of restoration, partial and/or global reconstruction resulting in changed constraints between blocks, as shown in Figure 1.

The work discussed in the present paper deals with structural aspects related to safeguard of column drums damaged and affected by crack patterns due to environmental and/or additional constraints. In particular, a specific jacketing technique is proposed; it is in full agreement with the principles of restoration since durability of materials and reversibility of the intervention are the two basic design requirements.

Proposed jacketing method is based on metallic belts made of innovative and durable materials like titanium and elastomeric pads able to reduce localisation of sresses due to surface irregularities and ensure a sufficient distance between metallic belts and the edges of the stone block. The safeguard techniques results in a two-layer jacketing system that can be used to ensure adequate mutual restraints in damaged and cracked blocks and a reduction of the relative displacements of individual parts. Design procedure is oriented to estimate rubber-stone interface stresses that are critical in many applications, since stone block skin is generally deteriorated and affected by complex crack patterns. The main problems related to design of such techniques are due to environmental effects, in particular thermal effects due to day/night and or summer/winter temperature cycles.

2. Traditional design approach for jacketing systems

Traditional jacketing systems for masonry columns are based on direct interaction between metallic belts and stone skin; more in detail, steel belts are shaped in order to fit the column cross section. When square or polygonal cross sections are considered steel ties are connected to specific angular steel profiles.

Role of jacketing system is limiting transverse expansion of stone/masonry compressed elements, improve compressive strength and freezing structural damage process.

Traditional installation procedures for column belts require temperature cycles on the metallic component, so that the increased size of the belt allows free installation, while the consequent cooling process and contraction trigger the interaction between belts and stone blocks.

Jacketing system consist of two or more parts fastened using bolts or mechanical interlock devices. The design procedure is aimed to define a reliable temperature scatter ΔT that results in a tightening force.

In fact belt contraction is controlled by column so jacket final radius is the same of column (r_1) and its value is intermediate between $r_{b,o}$ (belt radius at the reference temperature), and the in situ column radius r. Design approach is based on the assumption of polar symmetry of the system.

Evaluation of system final radius r_1, the same for the column and belt, can be carried out referring to two independent equations:

$$r_1 = r_{b,0} \cdot (1 + \frac{\sigma_b}{E_b}) \tag{1}$$

$$r_1 = r_{c,0} \cdot (1 - \frac{1}{E_c} \cdot \left[\sigma_{c,r} - \frac{\sigma_{c,a}}{m_c} \right]) \tag{2}$$

Equation (1) gives the radius r_1 according to belt's elastic elongation; equation (2) depends on radial and axial column deformation, being $r_{c,0}$ the column radius when axial load is not applied, it can be estimated using stone constitutive relationship.

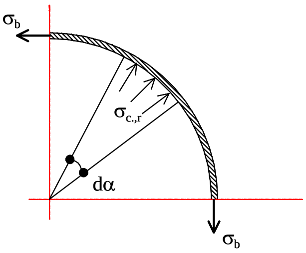

Figure 2. Traditional jacketing system

Symbols $\sigma_{c,r}$ and σ_b are radial stresses in column and belt after belt installation. The above equation state the compatibility between stone block and metallic belts, further equilibrium conditions must be introduced in order to solve the problem. The needed equilibrium equation can be written referring to a part of the metallic belt that is subjected to tensile axial stresses and radial stresses due to interaction with stone block, as shown in Figure 2.

$$s_b \cdot \sigma_b + r_1 \cdot \sigma_{c,r} \cdot \int_0^{\frac{\pi}{2}} sen\alpha \cdot d\alpha = \sigma_b \cdot s_b - r_1 \cdot \sigma_{c,r} = 0 \tag{3.a}$$

$$r_1 \cdot \sigma_{c,r} = \sigma_b \cdot s_b \tag{3.b}$$

It is worth noting that right-hand member in equation (3.b) gives the applied force on belt, depending only on belt thickness s_b. Equations (1);(2);(3.b) are independent and build up a non-linear system, characterised by the unknowns: $\sigma_{c,r}$, σ_b, r_1. Final design of metallic must take account of the discontinuous nature of belts respect to a film covering the column, therefore thickness of belts depend on s_b as well as on required increased failure axial load of the column.

2.1. Thermal loads

Solution of the equations reported above allows to estimate the stress conditions of jacketing system at a given reference temperature. However this is not the only critical condition for stone block. In fact, variations of environmental conditions and related changes of external temperature lead to different interaction levels at the stone-rubber interfaces. In particular:

- loss of tensile stresses in the belt are expected when temperature increases; in this case the critical point is keeping the contact between jacketing system and the stone block and ensuring the needed lateral confinement of the column;
- increased local stresses on the stone skin are expected when temperature decreases; in this case the critical point is adequate check of stone stresses in order to avoid stress concentration and local stone failures.

Development of design calculations for jacketing system under changes of environmental conditions is based on the hypothesis that belts and elastomeric pads do not lose contact with stone block; as a result, interaction radial stresses on stone decrease, but cannot be zero.

After the transition phase, thermal variation ΔT leads to a steady state characterised 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 the jacketing system and drum interface; assuming that $r'_1 \approx r_1$ system became linear. From an analytical point of view, equations governing the problem are the following:

$$\Delta r_{b,1} = \Delta r_{c,1} \tag{4}$$

$$r'_1 \cdot \sigma'_{c,r} = \sigma'_{b,r} \cdot s_b \tag{5}$$

where:

$$\Delta r_{b,1} = r_{b,0} \cdot (\alpha_b \cdot \Delta T + \frac{\sigma'_b - \sigma_b}{\mathrm{E}_b}) \tag{6}$$

$$\Delta r_{c,1} = r_{c,0} \cdot (\alpha_c \cdot \Delta T - \frac{\sigma'_{c,r} - \sigma_{c,r}}{\mathrm{E}_c}) \tag{7}$$

Equation (4) and equation (5) represent the compatibility and the equilibrium respectively at the at the column-belt interface in the changed configuration.

3. Two-layer jacketing system

The previously described design approach for traditional jacketing systems is based on the assumption that the outer surface of structural elements to be safeguarded are regular, so that the interaction develops all over the lateral surface of the belt. Whenever it is admissible, the stone surface is treated in order to avoid stress concentration, or thin elastomeric sheets are used.

However, the stiffness of the intermediate components can be generally neglected. Conversely, two-layer concept has to be introduced when specific elements are concerned; in fact, classical multi-drum stone columns are generally characterised by outer surfaces that are not regular not only due to flutes used as decoration of the members, but also to damage often resulting in many missing parts. A way to solve such problems is the to introduce an elstomeric pad, able to fit the outer profile of flutes and hollows due to deterioration, as shown in Figure 2. In all these cases, the stiffness of rubber pads can be not so high, therefore an intermediate component has to be introduced.

Furthermore, the interaction between belt and stone skin cannot be continuous, since the stone corners have to be preserved and aim of rubber pads is to avoid local damage to emerging parts of flutes, as shown in Figure 3.

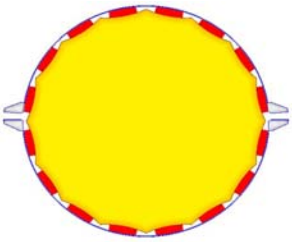

Figure 3. Two-layer jacketing system.

In this way, it is possible to ensure additional restraints to individual parts of damaged stone drums and at the same time to fit the basic requirement of reversibility of the intervention. It is worth noting that fitting of hollows and flutes is a very complex task, so that the needed elastomeric volume can be divided into a series of thin sheets. Due to the low flexural stiffness of each sheet, the shape of the hollow and/or of the flute can be fitted and installation of pads can be effectively performed on site, without complex local surveys.

3.1. Materials

Selection of materials is a critical point of the design process. In fact, durability of metallic and rubber jacketing components is ensured by the chemical and physical properties of the basic materials. The latter are generally subjected to hard environmental conditions, therefore a high resistance to generalised corrosion and to different types of local corrosion is required.

Among metals, it is well known that titanium shows a high resistance to generalised corrosion and to atmospheric and polluting agents [6]. Corrosion resistance results from its stable, highly-adherent, protective surface oxide film. Because the metal is highly reactive and has a strong affinity for oxygen, the beneficial oxide film forms spontaneously when exposed to moisture or air. In fact, a damaged oxide film can generally restore itself instantaneously. Titanium is available on the market as pure Titanium or as Alloy. Mechanical properties of titanium alloys, i.e. commercially pure titanium Grade 2 according to ASTM, fit many aspects related to the proposed application. In fact titanium Grade 2 is characterised by a low weight (4.5 g/cm^3) compared to steel; a low thermal dilation factor, 8.8 μm/(m °K), compared with other metals, so that its performances are near to many natural stones; the Young's modulus, 103 GPa, is low compared to steel; good yielding and ultimate strength, 280 MPa and 370 MPa respectively; good ductility, since ultimate strain is about 20%. It is currently used to build structural components for automotive and air transportation, devices for chemical plants; utilisation in marine application is also regular. In the last years, titanium has been frequently used in architecture, i.e. Guggenheim Museum Bilbao (1997) and also in preservation and restoration of archaeological constructions, i.e. of Athens temples.

Elastomeric pads can be made of neoprene, which is an extremely versatile synthetic rubber, originally developed as an oil resistant substitute for natural rubber. it is characterised by a balanced combination of properties; in fact it resists to degradation due to sun, ozone, and weather, performs well in contact with oils and many chemicals and remains useful over a wide temperature range; furthermore it has outstanding resistance to damage caused by flexing and twisting.

3.2. Design approach

The design approach to multi-layer jacketing system is summarised in Figure 3.

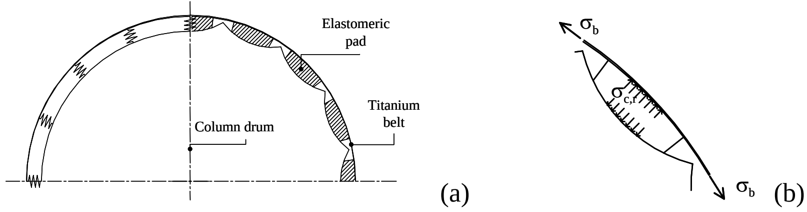

Figure 4. Design model for two-layer jacketing system.

The design simplified model is developed assuming that both belt and drum after deformation keep initial shape, so that tensile stresses in belt are constant and elastomeric pads are subjected only to compressive stresses, Figure 3,b.

Each elastomeric pad behave as an independent spring that allows the interaction between column drum and titanium belt. Spring force-displacement behaviour is assumed as elastic linear.

Final radius, formerly called r_1 in traditional design approach, is not the same for belt and column, but the belt final radius $r_{b,1}$ can be obtained by column final radius $r_{c,1}$ and the pad deformation:

$$r_{b,1} = r_{c,1} + (s_g - w_g) \tag{8}$$

where w_g is the displacement due to pads depends on the radial stress acting on the column:

$$w_g = \frac{\sigma_{c,r}}{E_g} \cdot s_g \tag{9}$$

and s_g and A_g are the effective thickness and area of the pad.

Equations giving jacket radius and drum radius are the same of traditional method, so they are not shown here; the equilibrium condition is the only one to be modified as follows:

$$s_b \cdot \sigma_{b,r} = k \cdot \sigma_{c,r} \cdot r_{b,1} \tag{10}$$

In fact, discontinuous interaction between stone and belts due to elastomeric pads gives a coefficient k lower than 1 that represents the effectiveness factor of jacketing system. It depends basically on geometry of stone block and thus it depends on the number of flutes; k results from integral (4) written in the following form in the case of sixteen flutes:

$$\sigma_b \cdot s_b + r_{c,1} \cdot \sigma_{c,r} \cdot \sum_{i=1}^{4} \int_{\alpha_i}^{\alpha_{i+1}} sen\alpha \cdot d\alpha = s_b \cdot \sigma_{b,r} + 0.629 \cdot r_{c,1} \cdot \sigma_{c,r} \tag{11}$$

All these equations are parts of a system - equations (1), (2), (8), (9), (10) - that relate tensions in jacket and column.

3.3. Thermal loads in multylayer system

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 greater then other materials of the system.
Solution of the problem at a temperature level different respect to installation one can be performed starting from the equilibrium condition evaluated according to equations given in the preceding section. In this way unknowns are basically $\Delta r_{b,1}$, $\Delta r_{c,1}$, Δs_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.

$$\Delta r_{b,1} = \Delta r_{c,1} + \Delta l_g \tag{12}$$

$$\Delta r_{c,1} = r_{c,0} \cdot \left(\alpha_c \cdot \Delta T - \frac{\sigma'_{c,r} - \sigma_{c,r}}{E_c} \right) \quad (13) \qquad \Delta r_{b,1} = r_{b,0} \cdot \left(\alpha_b \cdot \Delta T + \frac{\sigma'_b - \sigma_b}{E_b} \right) \quad (14)$$

$$\Delta l_g = s_g \cdot \left(\alpha_g \cdot \Delta T - \frac{\sigma'_{c,r} - \sigma_{c,r}}{E_g} \right) \quad (15) \qquad s_b \cdot \sigma'_{b,r} = 0.629 \cdot \sigma'_{c,r} \cdot (r_{b,1} + \Delta r_{b,1}) \quad (16)$$

Substituting equation (13), (14), (15) in equations (12) and (16), the only two unknowns are the final stresses that can be easily evaluated.

4. Application

The design procedure for two-layer jacketing system is utilised on a typical drum of doric style column belonging to Temple C of Selinunte (Trapani) Italy. Column drum is a conical element with a lateral surface slightly inclined (2°) respect to vertical. It is assumed that drum is characterised by sixteen flutes, bottom internal radius about 159 cm, top internal radius is 155 cm. Design process is oriented to prevent damages at the rubber-stone interface, thus low values of radial stress tension on the column lateral surface ($\sigma_{c,r}$) are allowed. In this application study stress target is about 0.2÷0.3 MPa, comparable with axial stress due to weight of the rest of column, but sufficient to give a lateral confinement and mutual restraints between different stone pieces that characterise damaged drums. The latter consist of calcarenite; experimental tests able to give its mechanical performances have been carried out. Elastic modulus, 10000 MPa, linear thermal expansion factor, 7.0 E-6 1/°C, compressive and tensile strength have been defined.
Axial load acting on the stone drum is derived from a static analysis of existing columns; in the following an axial normal stress equal to 0.13 MPa is considered uniformly distributed on the cross section of the drum. Titanium belt is

characterised by a rectangular cross section 5 mm thick and 100 mm wide, anchoring ends are made of thick titanium plates and bolts. It is worth noting that in this specific application, thickness of the belt is not critical, since high levels of confinement are not needed, conversely low belt flexural stiffness allows fitting the shape of cross section and irregularities due to hollows. The resultant of tensile stresses acting on the belt, evaluated according to equations given in section 3.2., is about 12.5 kN corresponding to a tensile stress of about 25 MPa.

The validation of simplified design approach is performed using a finite element model of the whole drum and two-layer jacketing system, as shown in Figure 5. Drum FE model is a radial 3D mesh using brick elements with six and eight nodes; the drum is considered without cavities or hollows. Mechanical behaviour of stone is assumed as linear elastic both in compression and in tension; such an assumption agrees with low values of tensile stresses that affect the drum under considered loads. Titanium belts is meshed as a two layers model using brick eight nodes elements; anchoring blocks for the belt have been modelled as well in a way that the load has been applied in agreement with the actual installation procedure. Bottom surface of drum is simply supported. Thickness of elastomeric pads is about eight centimetres.

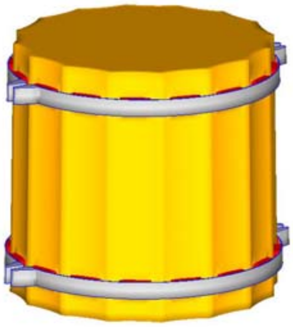

Figure 5. View of 3D F.E. model.

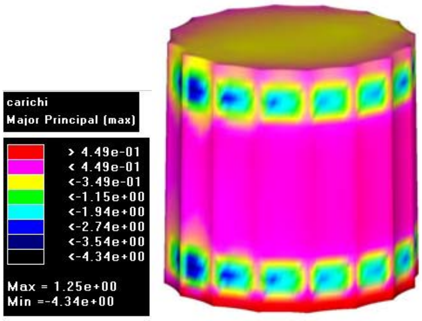

Figure 6. Plot of major principal stress.

Some results of the finite element analysis are shown in Figure 6 and 7. They show the distribution of the drum major principal stress the whole drum. It is possible to recognise that local effect at the ends of the belt are detected. In fact, interface stresses higher than values predicted using simplified design model are present especially in the first and second rubber pad. It is also worth noting that the greater is the distance from the ends, the lower is the belt stress, due to flexural effects and shear type stresses acting on the pads. As a result, the interface stresses under the pads decreases in the middle belt regions.

It is clear that the simplified model cannot take account of the above effects, but is very useful because it gives an good estimation of mean interface stresses.

For what concerns thermal effects, some calculations made using the simplified model are reported in Table 1. In order to show the effect of elastomeric pads on the structural response of the two-layer system, two values of the rubber thickness are considered, 1 mm (≈no rubber) and 80 mm (medium size rubber pad) for a given geometry of the drum (16 flutes). The variation of the temperature, ΔT, respect to the reference one is ±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 seems to be able to mitigate thermal effects and reduce related stress variations.

	80 mm rubber thickness		1 mm rubber thickness	
	Belt axial stress	Drum radial stress	Belt axial stress	Drum radial stress
T_{ref}	25.0 MPa	0.252 MPa	25.0 MPa	0.253 MPa
$T_{ref} + \Delta T$	26.2 MPa	0.259 MPa	19.7 MPa	0.200 MPa
$T_{ref} - \Delta T$	24.2 MPa	0.244 MPa	30.2 MPa	0.306 MPa

Table 1. Temperature effects.

5. Final remarks

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 focussed on safeguard of damaged colonnades and column drums. The basic requirements of reversibility and durability are fulfilled using specific materials and avoiding interventions requiring bonding and anchorages on the stone. The key aspect in the design process is the check of interface stresses due to jacketing devices for column drums. The work is clearly not exhaustive for a very complex task of structural engineers, but is intended as a contribution to the discussion involving multi-disciplinary skills. The results show that the useful assessment of interface stresses can be carried out using a simplified and design oriented model. The introduction of elastomeric pads at the belt-stone interface is useful, since it is able to reduce localisation of stresses due to surface irregularities and the additional deformation due to rubber pads allow to reduce thermal effects on the system due to temperature cycles.

6. References

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