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Epistyles Connected with “I” Connectors Under Pure Shear

S. K. Kourkoulis*, E. D. Pasiou

National Technical University of Athens, School of Applied Mathematical and Physical Sciences, Department of Mechanics, 5 Heroes of Polytechnion Avenue, Theocaris Building, 157 73 Zografou, Athens, Hellas
Email: stakkour@central.ntua.gr
**Corresponding author*

Abstract

An ambitious scientific project started in 1983 (and it is still in progress) aiming to the solution of a series of structural problems of the Parthenon Temple. One of them is the restoration of the damaged joins of the epistyles due to the corrosion of the iron and their intense mechanical strain. In the frame of this effort, a parametric numerical analysis was undertaken, using the finite element method, in order to investigate the mechanical behaviour of the “I” shaped connectors and of the marble body surrounding them in case the epistyles are subjected to shear. The models simulate two identical prismatic blocks made from Dionysos marble joined together with one titanium connector. The connector is embedded in a groove sculptured on the blocks and filled with suitable cementitious material (mortar). Synoptically the parameters studied included the boundary conditions, the existence or not of the mortar surrounding the connector and finally the existence or not of relieving space. The study indicated that the presence of both mortar and relieving space is of paramount importance. In addition in some cases the stress field developed may cause fracture of the marble blocks (either in the immediate vicinity of the interface of the two blocks or at the corners of the connector) rather than failure of the connector. Such a result is unacceptable according to the “Venice Chart” and supports existing approaches indicating the need for revision of the design of the connectors.

Keywords: Monuments, Dionysos marble, “I” connectors, Titanium, Shear, Finite Element Method

1. Introduction

The Parthenon Temple of the Acropolis of Athens was built in the 5th century BC by Iktinos and Kallikratis as an offer to goddess Athena. Phedias complemented it with masterly sculptures. It constitutes an enduring symbol of superiority of ancient culture and specifically of Ancient Greece and Athenian Democracy. After a long and tumultuous history (fires, changes of use, earthquakes and restoration attempts - not always successful) the Temple remained roofless and partly demolished. It was only in 1983 when the Committee for the Conservation of the Acropolis Monuments launched an ambitious conservation and restoration program based on the latest achievements of scientific research (Korres & Bouras, 1983). The program is still in progress.

The Parthenon is a dry stone wall construction consisting of marble blocks joined by means of iron connectors ("I" shaped connectors and dowels) placed in grooves filled by ancient Greeks by molten lead. The marble blocks of each layer are joined together with "I' shaped connectors (Fig. 1) while dowels join together marble blocks of sequential layers. The corrosion of iron and the intense mechanical strain led the connectors and/or the marble surrounding them to fracture. Therefore the restoration of the damaged joins was inevitably included in the restoration project of the Parthenon (Toumbakari, 2004, 2008, Vrouva, 2007).

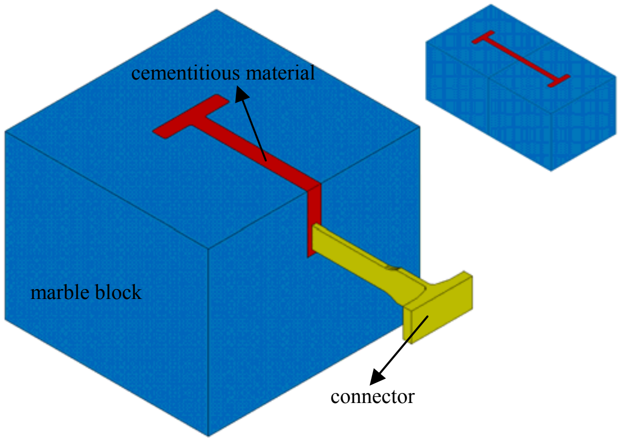

Fig. 1. The connection of epistyles by means of "I" shaped connectors.

This specific problem is nowadays confronted by replacing the corroded iron connectors with new ones made from titanium (Korres & Bouras, 1983). The new connectors are embedded in grooves sculptured on the marble blocks and filled with suitable cementitious material. The project is realized following the general principles of "Venice Chart" according to which the authentic marble must be protected and the new material must fail. For the case of the structure studied here it is desired that under excessive loading the connectors are deformed absorbing strain energy and protecting thus the marble body (Zambas, 1994).

In general the connectors are subjected to shear and tension. Bending within the vertical plane is not considered here since the parts of the members joined rest on the respective abacuses (Fig. 2). On the other hand bending within the horizontal plane, which could appear in case of seismic loading, is not included in the analysis, since the present work is devoted to static loading cases. The tensile behaviour of "I" shaped connectors and the shear behaviour of dowels has been already studied thoroughly (Zambas, 1994). On the contrary there is a lack of knowledge concerning the shear behaviour of the "I" connectors. However, many structural members of the monument could experience translation parallel to their neighbour ones and therefore it becomes obvious that pure shear of "I" connectors is one of the load cases that should be studied carefully.

The commonly used experimental methods for pure shear tests (shear boxes and "push-out" tests) cannot be used for the present study because they impose additional constraints to the specimens that affect the areas of interest, the failure mode and perhaps the location of yield's or fracture's origin. In a recent work Zambas (2004) studied the shear behaviour of dowels paying attention to the influence of the thickness of the dowel and the length of the relieving space. The specimens used consisted of three prismatic blocks of marble joined together with two dowels and mortar. The specimens were asymmetric due to the presence of the dowels. A transverse force was applied normally on the middle block and every effort was made to avoid torsion moments during loading. The other two marble blocks were fixed on the ground. Fracture of the marble was observed to all specimens in the form of a quarter of a cone. It was also concluded that the existence of relieving space enables the connectors to deform further absorbing additional strain energy.

Fig. 2. A typical case of epistyles of the Parthenon temple connected with “I” connectors.

In this context the present paper is an attempt to investigate the behaviour of titanium “I” shaped connectors and of the marble surrounding them under pure shear. The study is carried out numerically using the finite element method. The results of the present numerical analysis will hopefully enrich and complete the existing data and contribute to a better understanding of the reasons leading the connections of epistyles to failure.

2. Materials

The material used by the ancient Greeks for the erection of the Parthenon Temple of the Acropolis of Athens was Pentelic marble. It is an extremely durable white marble quarried from Mount Pentelicus in Attica. The ancient quarries are nowadays exhausted; therefore, the needs of the conservation and restoration program are covered almost exclusively with Dionysos marble due to its physical and mechanical similarity to the authentic marble. The cementitious material used by the scientists working for the restoration project on the Parthenon Temple as groove’s filling material was proposed by Skoulikidis (1971). His decision was based on the mechanical and chemical state of the old cement (that of previous restoration attempts in the beginning of the 20th century) and the absence of any mechanical or chemical decay effects on the marble in contact with it. Finally, the use of titanium connectors was initially proposed also by Skoulikidis (1971). Its main advantages, compared to other metals, are its resistance to all types of corrosion as well as its physical and mechanical compatibility with marble.

2.1 Dionysos marble

Dionysos marble, of almost white colour, is composed by 98% of calcite, 0.5% of muscovite, 0.3% of sericite, 0.2% of quartz and 0.1% of chlorite. Its specific and apparent densities are 2730 kg/m^3 and 2717 kg/m^3 respectively and its absorption coefficient by weight is 0.11%. The thermal expansion coefficient is 9x10^6 /^{o}C between 15 ^{o}C and 100 ^{o}C. Its very low porosity varies between 0.3% in the virgin state to 0.7% after the action of various natural weathering and corrosive agents (superficial porosity) (Tassogiannopoulos, 1986, Perdikatsis et al., 2006).

Concerning its mechanical behaviour Dionysos marble is an anisotropic material, characterized by three different anisotropy directions (parallel to the layers, along the width of the web and along the thickness of the web) and thus it appears to be orthotropic (Vardoulakis & Kourkoulis, 1997). The values of its mechanical properties reported in literature vary between very broad limits (Theocaris & Koroneos, 1979). A series of direct tension and uniaxial compression tests with cylindrical specimens indicated that the mechanical properties along the first two of the above anisotropy directions are very similar to each other (Exadaktylos et al., 2001a,b). Therefore Dionysos marble can be considered as a transversely isotropic material, with two anisotropy directions (Table 1), described adequately using five elastic constants Lekhnitskii (1977).

	E_t [GPa]	ν	σ_f [MPa]	σ_c [MPa]
Strong direction	84.5	0.26	10.8	80
Weak direction	50.0	0.11	5.3	55

Table 1. The mechanical properties of Dionysos marble under direct tension and uniaxial compression (Vardoulakis, Kourkoulis, 1997).

The above tests denoted also that Dionysos marble is slightly non-linear both in the tension and in the compression regime and slightly bimodular, i.e. the elastic modulus in compression is about 15% higher than the respective one in tension. For the needs of the numerical analysis use was made of the actual stress-strain curve obtained by Vardoulakis & Kourkoulis (1997).

2.2 Cementitious material

The cementitious material used today in the restoration project of the Parthenon Temple consists of 1 part white cement and 3 parts silica sand. A series of uniaxial- and diametral- (Brazilian test) compression tests were carried out in order to determine its mechanical characteristics (Kourkoulis et al., 2008). The specimens used were cylindrical (diameter over height ratio ~ ½) and the strains were measured using strain gauge rosettes. The failure mode observed was rather brittle with significant or complete destruction of the specimen. In case of compression, the mechanical characteristics obtained were: Modulus of elasticity E~15.5 GPa, Poisson's ratio ν~0.26, yield stress σ_y~10 MPa and compressive strength σ_u~35 MPa. From the series of diametral compression tests only the tensile strength of the mortar σ_u~2 MPa was obtained. In the present study, the mortar was considered as an isotropic material, obeying the constitutive law dictated by the above experimental study.

2.3 Titanium

Titanium has twice greater weight unit strength than steel and approximately the same Poisson's ratio and thermal expansion coefficient as marble. The last two characteristics protect the structural members of the monument from fracture due to differential lateral shrinkage and differential thermal expansion respectively. Finally, the type of titanium used for the restoration project is characterized by a high modulus of elasticity which enables joins to absorb a significant amount of energy and bear high deformations before fracture (Zambas, 1994). The main mechanical and physical properties of titanium are shown in Table 2. In the present study titanium was considered as an isotropic, linear elastic material due to its high strength compared to the respective one of marble and mortar.

Density (gr/cm^3)	4.51
Modulus of elasticity (GPa)	105
Poisson's ratio	0.32
Thermal expansion coefficient (10^{-6} grad^{-1})	9
Thermal conductivity (cal/cm/grad/sec)	0.007
Hardness (HB)	130
Tensile strength (MPa)	420
Yield stress (MPa)	300
Ductility (%)	20÷22

Table 2. The main physical and mechanical characteristics of titanium (Zambas, 1994).

3. Numerical Analysis

In order to study the mechanical behaviour of both the connectors and the marble surrounding them when they are subjected to shear, a parametric numerical analysis was carried out using the finite element method and the commercially available software ANSYS 10.0.

3.1 The numerical models

The geometrical characteristics of the numerical models matched exactly those of a typical epistyle of the Temple in a scale of 1:3. Each marble block has a cross section area of 20x26 cm^2 and length 25 cm, the groove's depth is 7 cm and the connector's length is 28.6 cm.

Four (4) models were constructed and synoptically the parameters studied included: (a) The boundary conditions (parameter 1), (b) the existence or not of the mortar surrounding the connector (parameter 2) and (c) the existence or not of relieving space (parameter 3), Fig. 3.

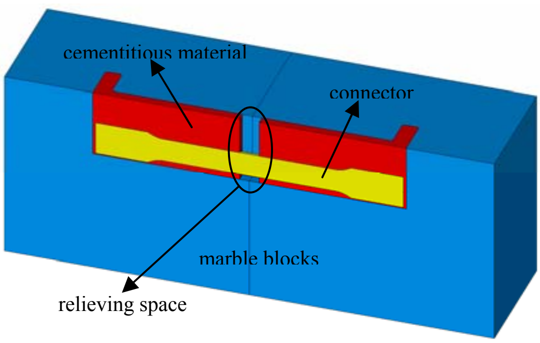

Fig. 3. The relieving space.

The first model, considered as the reference one (Model R), consists of all three materials. The groove has width 1.7 cm and it is filled with mortar (Figs. 4a, 5a). In Model AC an additional constraint is imposed at the block displaced in order to achieve parallel relative translation (Fig. 4b) which is indeed a realistic case as it is seen in Fig. 6. The next model (Model NM) is characterized by the absence of the mortar (Fig. 5b) in order to investigate its influence on the overall mechanical behaviour of the model. Finally, the last numerical model (Model RS1) studies the effect of the relieving space, in other words of the absence of mortar along a part (about 1 cm) of the connector from both sides of the interface between the two marble blocks (Fig. 3).

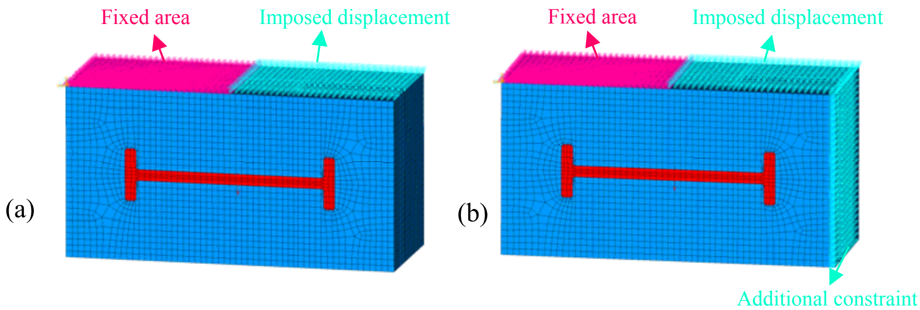

Fig. 4. Change of parameter 1. (a) Model R; (b) Model AC.

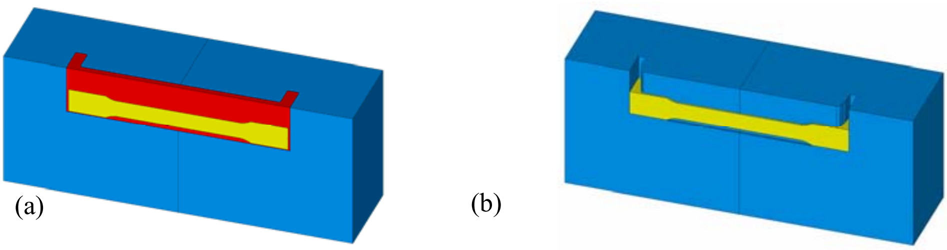

Fig. 5. Change of parameter 2. (a) Model R; (b) Model NM.

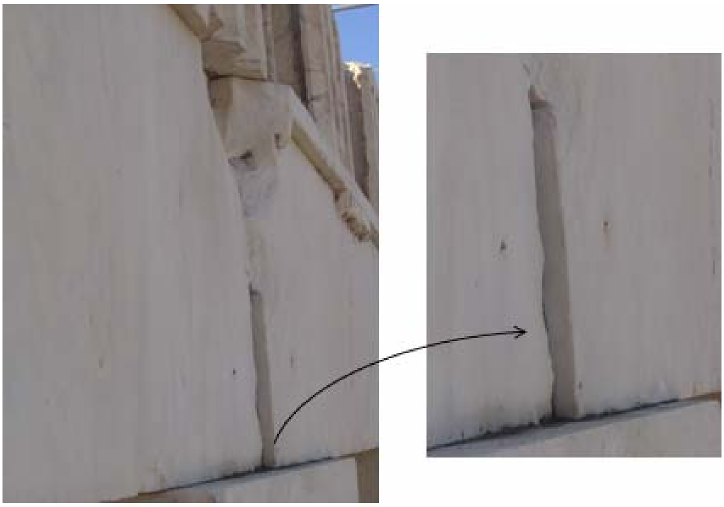

Fig. 6. Parallel relative translation of two marble epistyles of the Parthenon temple.

3.2 Meshing

All numerical models were meshed in the same way. The element used is the *SOLID185*, commonly employed for 3-D modeling of solid structures. It is defined by orthotropic material properties and eight nodes with three translational degrees of freedom each. It supports also plasticity and large strain considerations, necessary for the needs of the present analysis.

A uniform meshing was chosen for the whole model. The titanium connector and the mortar were meshed using the *Mapped Meshing* Technique according to which the elements produced have the shape of a brick, a wedge, a prism or a tetrahedron. Another meshing technique, the *Volume Sweeping* one, was used for the meshing of the marble. The elements produced have the shape of a hexahedron or a wedge when the source mesh consists of quadrilateral elements or triangles respectively.

A series of preliminary "runs" were carried out in order to choose the optimum element size. The study of the stresses at characteristic points of all materials in relation to the number of elements indicated as sufficient a number of about 40 000 elements. In Fig. 7 the values of the various stress components developed at the central point of the central section of the connector are plotted vs. the number of elements indicating satisfactory convergence.

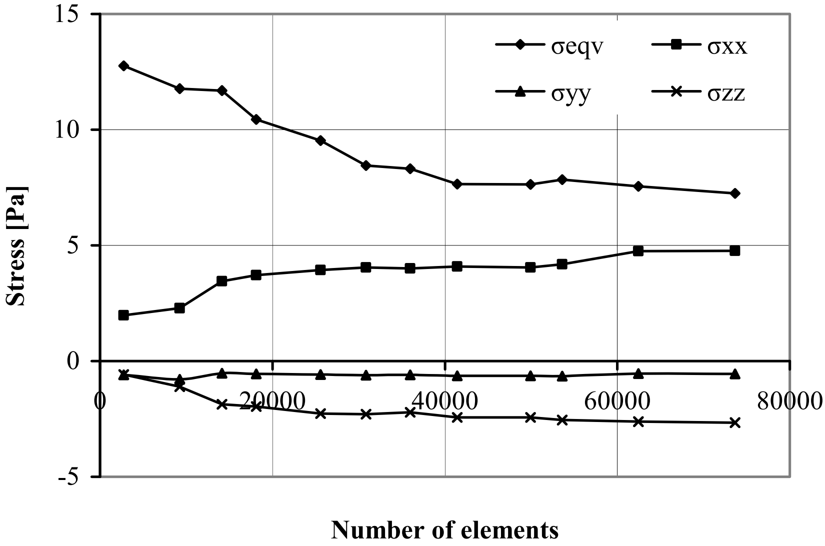

Fig. 7. The variation of the stress components at the central point of the central section of the connector vs. the number of elements.

3.3 Material interfaces

All material interfaces characterizing the sequence of materials were taken into account during the construction of the models. Analytically the interfaces considered are:

1. "titanium connector -mortar" (interface-i) which has the shape of the connector since the cementitious material encloses the connector, Figs. 8(a,c)
2. "mortar-marble" (interface-ii) which has the shape of the groove, Figs. 8(a,c)
3. "marble -marble" (interface-iii), Figs. 8 (a,c)
4. "titanium connector -marble" (in case the mortar is absent) (interface-iv), which has the shape of the perimetric area of the connector and the basis of its heads, Fig. 8b.

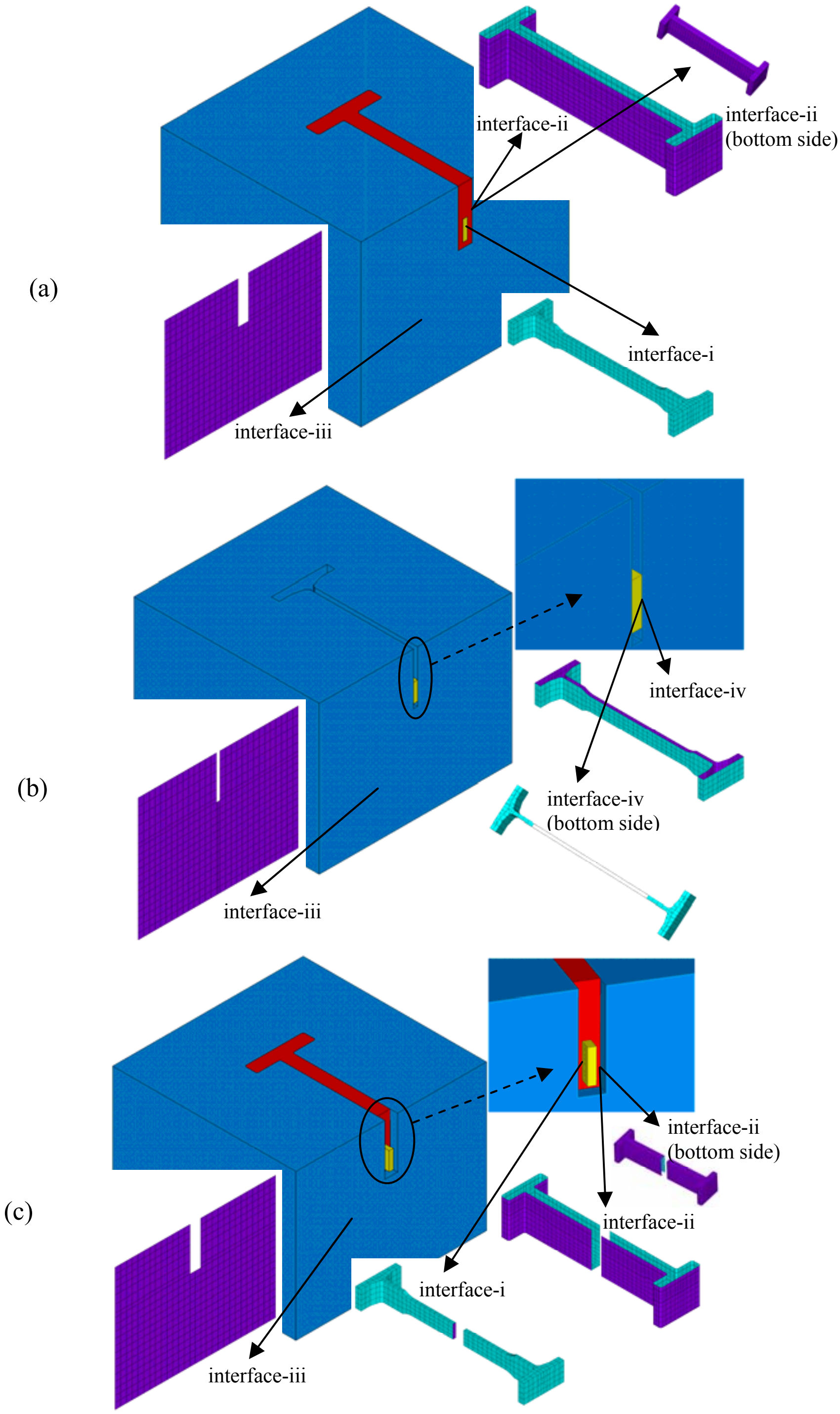

Fig. 8. The position and the shape of the material interfaces for (a) Models R and AC; (b) Model NM; (c) Model RS1.

In order to simulate the interfaces, pairs of contact elements were used, each one of them consisting of "contact" and "target" elements. The "contact" element used was *CONTA173* that simulates contact and sliding between 3-D "target" surfaces and a deformable surface, defined by this element. It is applicable to 3-D structural analyses. It is located on the surfaces of 3-D solid elements without midside nodes, it is defined by four nodes (the underlying solid element nodes) and it has the same geometric characteristics as the solid element face with which it is connected. Contact occurs when the element surface penetrates one of the target segment elements on a specified target surface. The respective "target" element was *TARGE170*. Therefore, for the present analysis the following areas were defined as "target" surfaces:

- the titanium connector for the interface-i (titanium connector-mortar)
- the marble for the interface-ii (mortar-marble)
- either of the two marble areas for the interface-iii (marble-marble)
- the titanium connector for the interface-iv (titanium connector-marble). It appears only in Model NM where the mortar does not exist.

The status of these interfaces was the simple contact one and the friction coefficients were 0.25 for the interface-i, 0.50 for the interfaces-ii and -iv and finally 0.70 for the interface-iii.

3.4 Loading mode and boundary conditions

The shear loading was realized by fixing one of the marble blocks while imposing parallel displacement on the second one. The immobilization of the block was achieved by means of translational and rotational constraints imposed on the nodes of the upper surface (Fig. 4). In Models R, NM and RS1 the block displaced is free while in Model AC an additional constraint is imposed on it restricting rotation of the lateral surface, in order to simulate better pure shear conditions, Fig. 4b. The displacement imposed was 5 mm, as dictated by preliminary tests (Pasiou, 2008). It could be anticipated here that a more realistic model should contain four marble blocks mutually connected with the aid of three connectors. Such a model becomes rather inefficient for a parametric study due to the number of elements and the increased "running time" required.

4. Results and discussion

For the model where the groove is filled with mortar and the translated marble block is not subjected to additional restrictions (Model R) the distribution of displacements of the moveable block is non-uniform, indicating generation of additional bending and torsion moments, Figs. 9(a,b). The maximum displacement is observed either on the front (longitudinal) or the rightmost transverse side of the moveable block and is equal to about 25% of the imposed one. The deformed shape of the connector is shown in Fig. 9d.

The generation of moments was expected since it is known that producing pure shear is among the most difficult problems of Strength of Materials. In the specific case studied here the situation is more difficult due to the inevitable asymmetries caused by the presence of the titanium connector. Indeed the connector is placed asymmetrically both with respect to the centroids of the marble blocks and also with respect to the axis of the imposed displacement. In an effort to eliminate the rotation tendencies of the moving marble block an additional constraint is imposed in Model AC, in the form of a fixed rigid plate in simple contact with the vertical side of the moving block. This constraint indeed forced the moveable block to be translated parallel to itself, eliminating the rotation. The general response and the areas of the structure most affected are almost identical to those of the reference model (Figs. 9c and 10). The magnitudes of the stresses developed, however, are considerably higher in the case of the model with the additional constraint, obviously due to the friction forces developed.

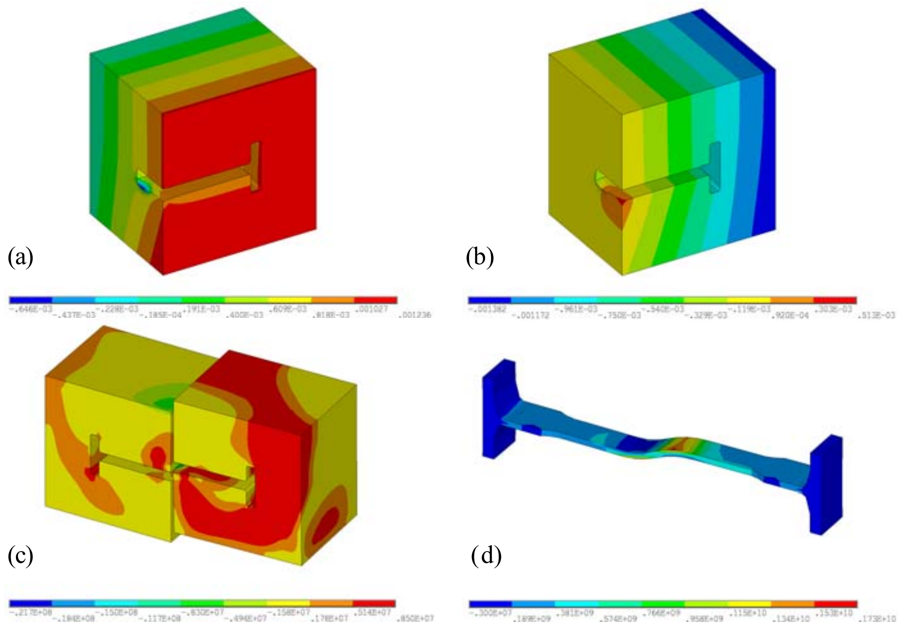

Fig. 9. Model R. The distribution of displacements along (a) x-axis [m] and (b) y-axis [m]; (c) the maximum principal stress σ_1 [Pa]; (d) the equivalent Mises stress in the connector [Pa].

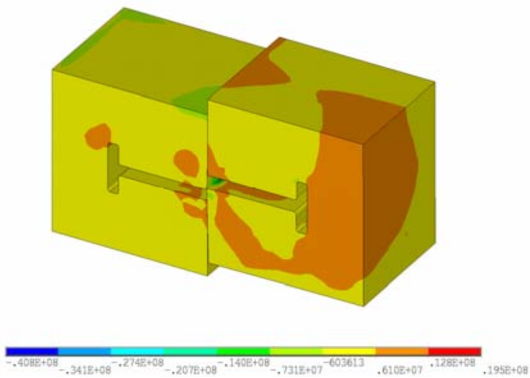

Fig. 10. Model AC. The distribution of the maximum principal stress σ_1 [Pa].

Concerning the influence of the layer of cementitious material interposed between the marble and the metallic connector the analysis of the results proved that its influence is paramount for the deformation and displacement of the moving block. Indeed in case this layer is not used (i.e. the connector is in direct contact with the marble, Model NM) an inverse rotation tendency of the moving block is observed, Figs. 11(a,b), compared to that of the models including all three materials. This tendency could be explained if it is taken into account that in this case the connector is free to deform, in the direction of the existing empty space above it. As a result the back side of the block experiences larger deformations compared to those of its front side.

On the other hand the analysis of the stress distributions reveals considerable changes, with respect to the reference model, concerning both the magnitude of the stresses and also the areas of the structure most affected (most dangerous to fail): High stress concentrations are observed at the interface of the two blocks in the immediate vicinity of the connector (Fig. 11c), contrary to what happened in the reference model (where the maximum stresses were distributed in a more homogeneous manner, prohibiting in this way the marble pieces from local fractures and exfoliations).

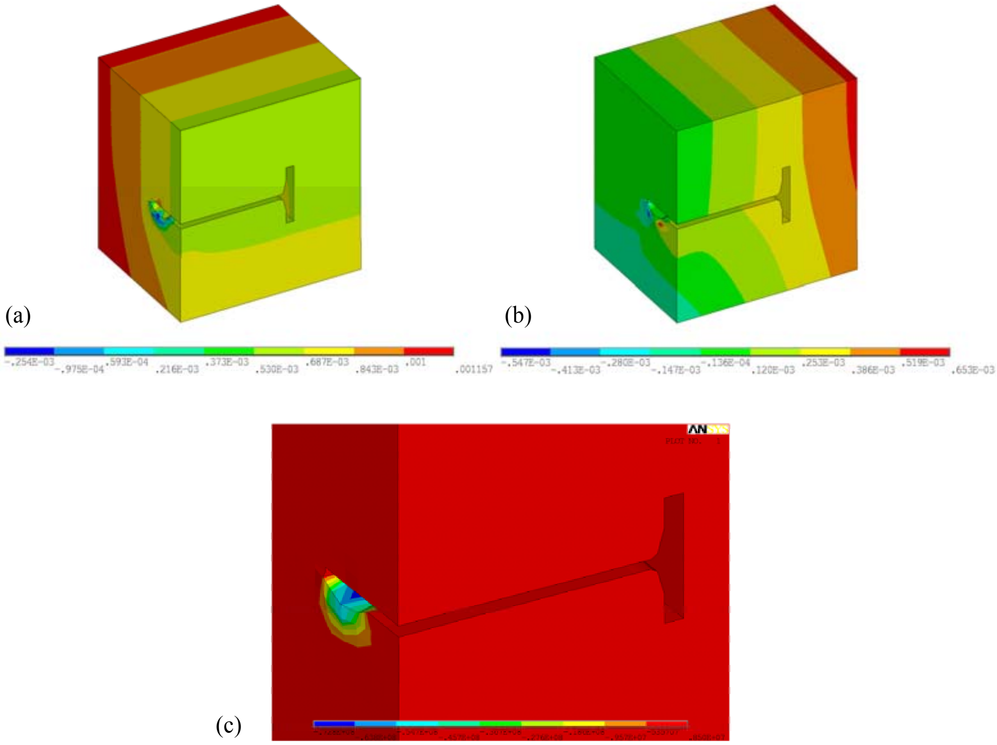

Fig. 11. Model NM. The distribution of (a) displacements along x-axis [m]; (b) displacements along y-axis [m]; (c) the maximum principal stress σ_1 [Pa].

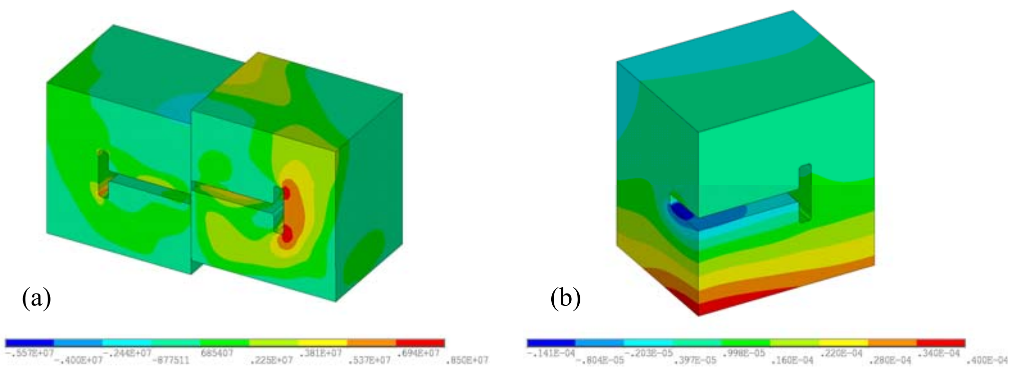

Fig. 12. Model RS1. The distribution of (a) the maximum principal stress σ_1 [Pa]; (b) displacements along x-axis [m].

The results obtained from the analysis of Model RS1, i.e. the one with the relieving space, confirm the positive action of this parameter, as mentioned previously. The first important conclusion is that for the geometry and the size of the empty space adapted here, the connector does not come in direct contact with the marble, at least for the value of displacement imposed. Thus, it becomes clear that the areas of interest of the marble (namely these at the interface of the two blocks in the intermediate vicinity of the metallic connector) are less severely stressed and the stress fields are maximized exactly at the corners of the head of the connector (Fig. 12a). In addition, the moveable block is displaced again along the loading direction, Fig. 12b, although there are not additional constraints. In fact what really happens is that the axial deformation of the connector is now relieved due to the existence of the empty space around its body at the interface of the blocks and therefore no additional moments appear.

As a next step the variation of some characteristic quantities (stress and displacement components) is plotted along three strategic paths, AA′, BB′ and CC′ (Fig. 13) for all four models, for comparison reasons. In general it is clear that Models R and NM and Models AC and RS1 exhibit well comparable mechanical behaviour.

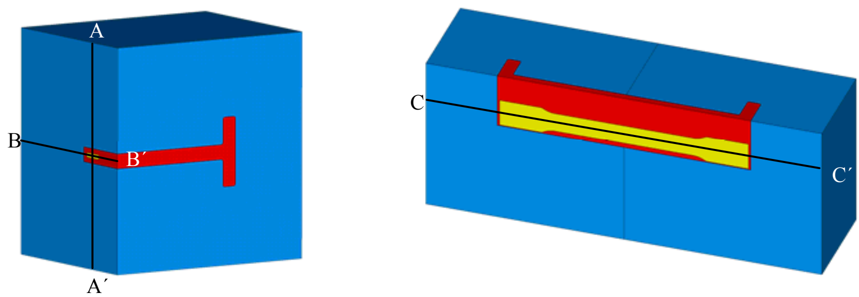

Fig. 13. The paths along which the path-plots are realized.

More analytically the results for the path AA′ are shown in Fig. 14. For models R and NM it is seen that the shear imposed in combination with the lack of additional restrictions (either externally imposed or locally generated by the presence of the cementitious material) permits elongation of the connector which in turn forces the two blocks to move away from each other, Figs. 14(a,b). In models AC and RS1 this tendency is eliminated due to the additional external restriction imposed (u_x=0) and the action of the cementitious material which does not permit free "expansion" of the connector. It is also emphasized that for models AC and RS1 the maximum equivalent stress developed (Fig. 14c) is equal to about 5 MPa (in the body of the connector) almost two thirds of the respective value developed at the same points in models R and NM, indicating again the beneficial action of the relieving space.

In Fig. 15 the path plots related to the BB′ line are shown. It is interesting to note here that for model NM the "bending" tendency is of opposite sign compared to the respective tendency of model R (Fig. 15a). This should be expected if it is taken into account that due to the void space existing in model NM (namely the space normally occupied by the cementitious material) the "expansion" of the connector is unrestricted. In addition it is to be noted that the displacement along axis y is higher in model AC since the additional external restriction, which eliminates the x-displacement, "guides" the expansion of the cementitious material exclusively along the other two directions (Fig. 15b). Concerning the variation of the equivalent stress along line BB′ it is seen again that higher stresses are again developed in models R and NM in good accordance to the results of the previous paragraph (Fig. 15c).

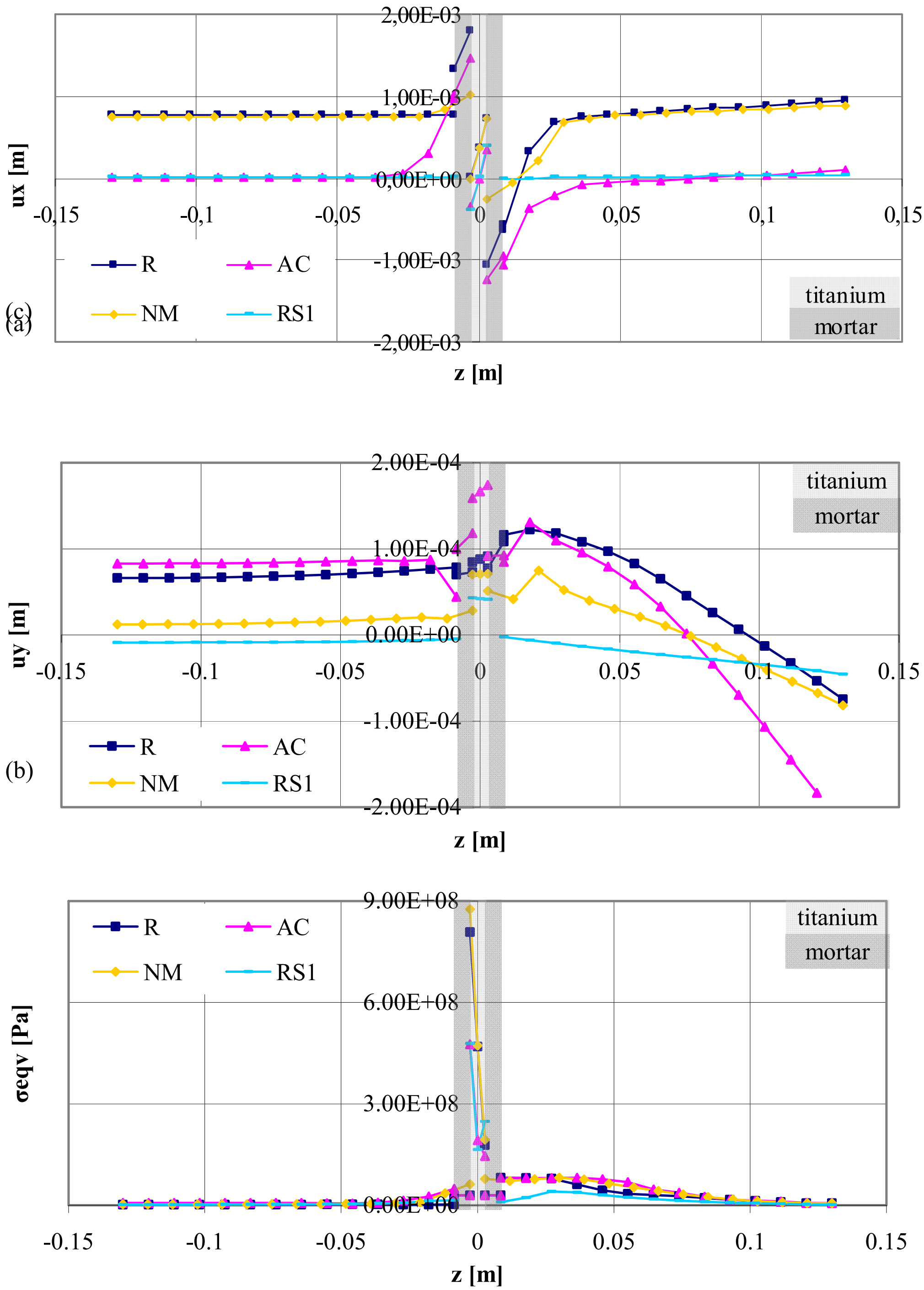

Fig. 14. The variation of the x- (a) and y- (b) components of displacement along the path AA′ and the variation of the von Mises equivalent stress (c) along the same path.

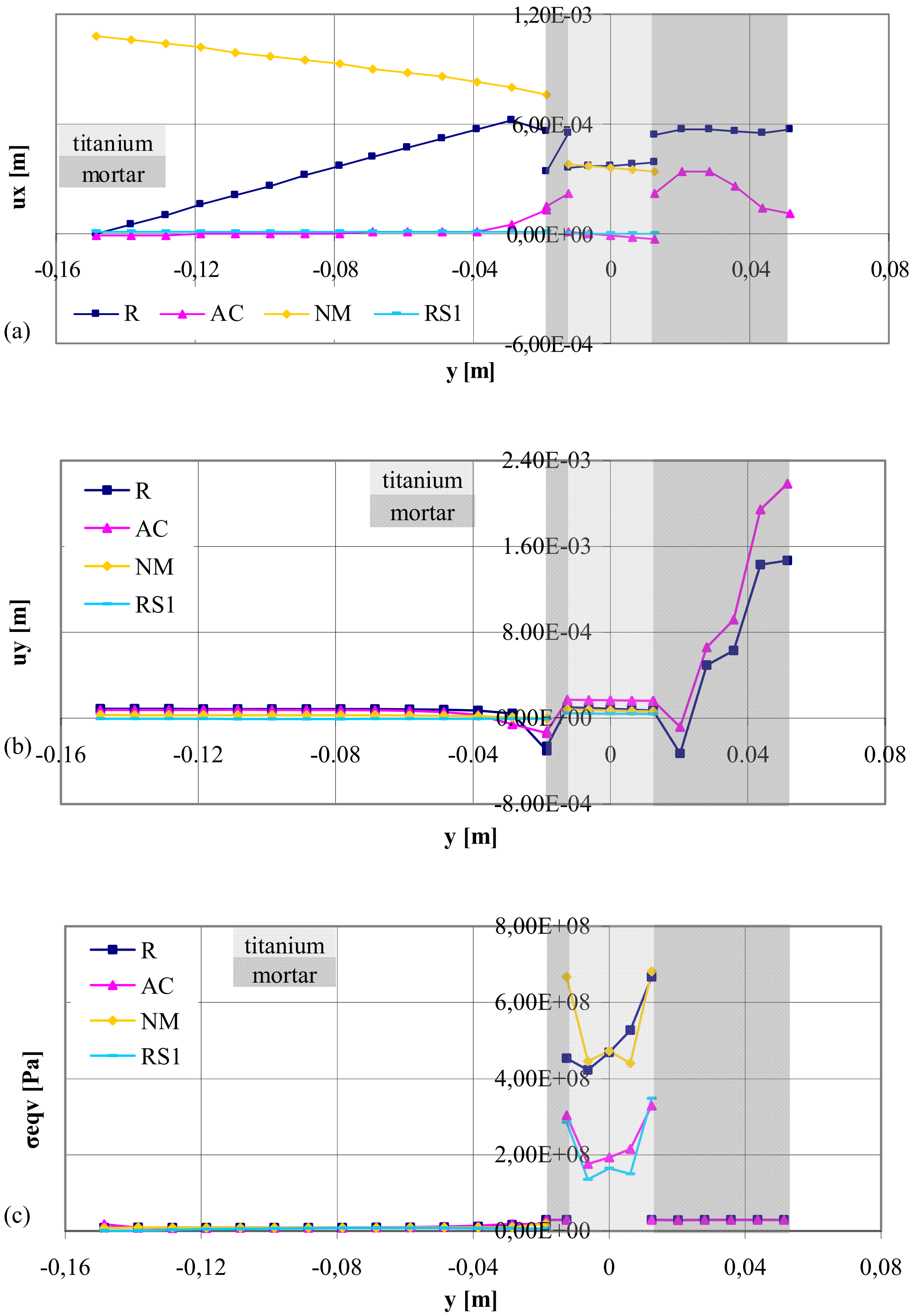

Fig. 15. The variation of the x- (a) and y- (b) components of displacement along the path BB′ and the variation of the von Mises equivalent stress (c) along the same path.

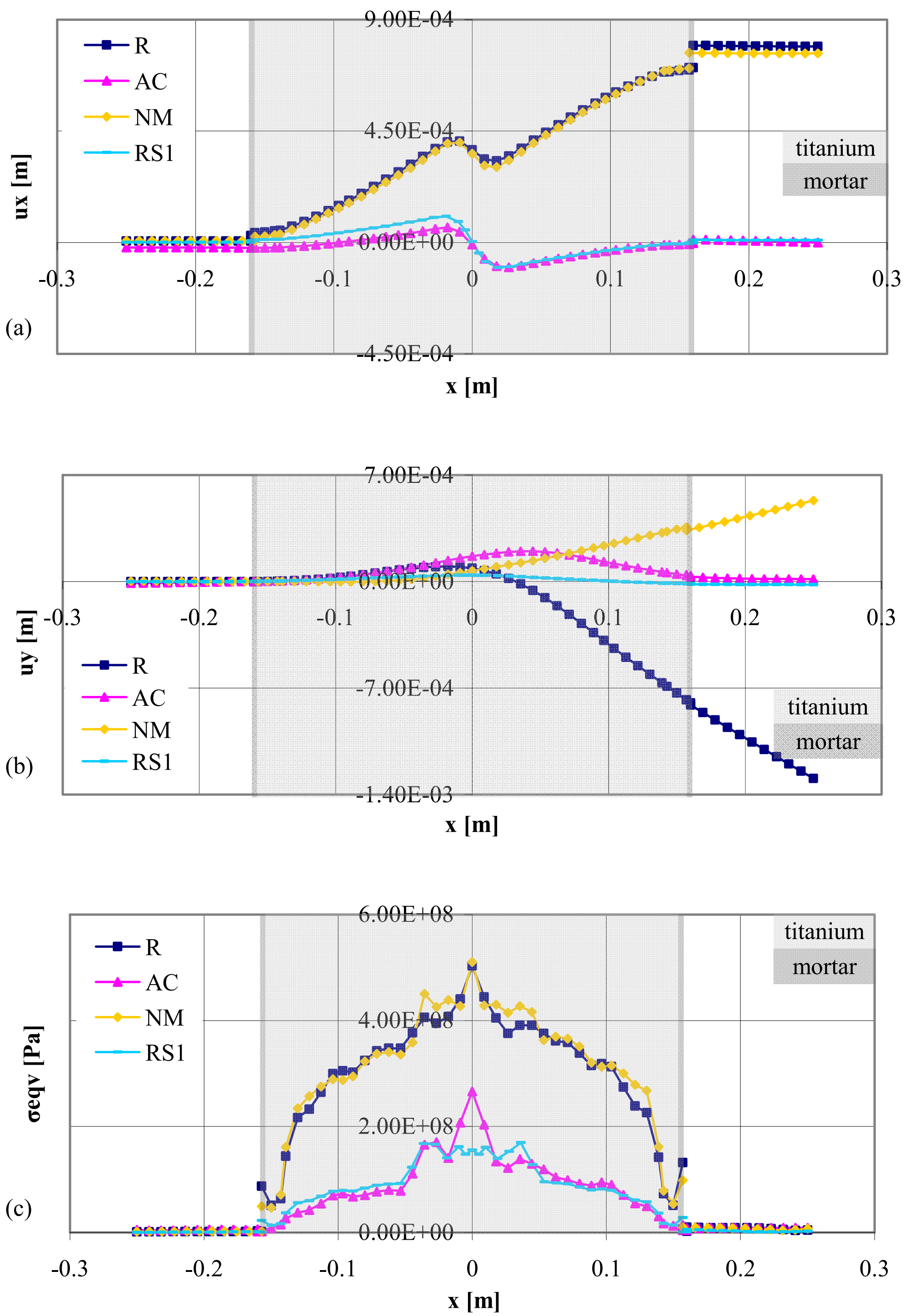

Fig. 16. The variation of the x- (a) and y- (b) components of displacement along the path CC′ and the variation of the von Mises equivalent stress (c) along the same path.

Finally in Fig. 16 the results for the variation of displacements and stresses along the line AA′ (namely along the longitudinal axis of the connector) are shown. The main point of interest is the "opening" (i.e. the removal of the vertically displaced block away from the fixed one along the axis of the connector) observed for models R and NM, the models without additional restrictions (Fig. 16a). The "opposite" bending tendencies between models R and NM, mentioned previously, is again detected clearly in Fig. 16b. The variation of the equivalent stress along line CC′ is almost perfectly symmetric with respect to the plane including the common section of the two blocks. All along line CC′ the magnitude of the stress for models R and NM exceeds significantly the respective ones for models AC and RS1.

5. Conclusions

A parametric numerical analysis was carried out with the aid of finite element method in order to investigate the mechanical behaviour of "I" shaped connectors and the marble surrounding them under shear. The conclusions drawn can be shortly summarized below.

- The realization of pure shear test of two epistyles connected with a single "I" connector is extremely difficult from an experimental point of view: Bending and torsion moments inevitably appear due to the asymmetry imposed by the position of the connector. Retraction of these phenomena can be achieved only by imposing additional constraints. However this is to be avoided (if it is possible) because any additional constraint affects the areas of interest and changes both the failure mode and the region where failure appears.

- The placing of suitable cementitious material around the body of the connector and the providence for an adequate relieving space around the connector in the vicinity of the central cross section are of paramount importance concerning both the stress and the deformation fields: They not only influence the magnitude of the equivalent stresses developed but they dictate also the regions where fracture occurs.

- However the most interesting conclusion of the present study is the observation that in some cases the stress field developed could cause fracture of the marble blocks (either in the immediate vicinity of the interface of the two blocks or at the corners of the connector) rather than failure of the metallic connector. Such a conclusion is unacceptable according to the principles of the "Venice Chart" and it emphasizes the need for a thorough revision of the design of the connectors.

Before coming to an end, it is mentioned at this point that intense additional research is necessary before definite conclusions are drawn concerning the optimum combination of the magnitude of the relieving space and the composition (i.e. its mechanical properties) of the cementitious material interposed between the marble and the connector. Preliminary experimental investigation of the problem (Pasiou, 2008) indicated that the margins for improvement are rather wide compared to what is presently adopted. In any case, the intensity of the stress field developed in a restored or conserved structural member (somehow characterizing the "quality" of the intervention) depends also on many other parameters, as for example the damage of the original material of the monuments, the exact shape of the fragments, the existence or not of the adjacent structural members (dictating the boundary conditions) etc. It is therefore clear that the final decision concerning the optimum combination of the parameters influencing the stress field developed depends among others on the irreplaceable experience of the technicians and scientists working for a specific restoration project since they are the only ones who have an overall view of the specific problem they deal with.

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References

Exadaktylos GE, Vardoulakis I, Kourkoulis SK (2001a). Influence of nonlinearity and double elasticity on flexure of rock beams – I. Technical theory, *International Journal of Solids and Structures*, 38, 4091-4117.

Exadaktylos GE, Vardoulakis I, Kourkoulis SK (2001b). Influence of nonlinearity and double elasticity on flexure of rock beams – II. Characterization of Dionysos marble, *International Journal of Solids and Structures*, 38, 4119-4145.

Korres M, Bouras H (1983). *Study for the Restoration of the Parthenon*, Ministry of Culture and Science, Committee for the Preservation of the Acropolis Monuments, Athens, Greece.

Kourkoulis SK, Papanicolopulos S-A, Marinelli A, Vayas I (2008). Restaurierung antiker Tempel: Experimentelle Untersuchungen zum Ausziehverhalten von Verankerungen im Marmor, *Bautechnik*, 85(2), 109-119.

Lekhnitskii SG, *Theory of Elasticity of an Anisotropic Body*, Mir, Moscow, 1977.

Pasiou ED (2008). Experimental and numerical study of a double "T" shaped connector under pure shear. Thesis for the Inter-Departmental Program of Post Graduate Studies: Protection of Monuments, National Technical University of Athens, Greece (In Greek).

Perdikatsis V, Kritsotakis K, Markopoulos Th, Laskaridis K (2006). Discrimination of Greek marbles by trace-, isotope-, and mineralogical analysis, Symposium on Fracture and Failure of Natural Building Stones, 16th European Conf. on Fracture, Alexandroupoli, Hellas, July 2006. Published in: "Fracture and Failure of Natural Building Stones - Applications in the Restoration of Ancient Monuments", S.K. Kourkoulis ed., Springer, Berlin, 497-515.

Skoulikidis ThN (2000). *Corrosion and Conservation of Building Materials of Monuments: the Acropolis Case*, University of Crete Publications, Heraklion, Crete.

Tassogiannopoulos AG (1986). A contribution to the study of the properties of structural natural stones of Greece (in Greek), Ph.D. Dissertation, National Techn. Univ. of Athens, Greece.

Theocaris PS, Coroneos E (1979). Experimental study of the stability of Parthenon, *Publications of the Academy of Athens*, 44, 1-80.

Toumbakari EE (2004/2006). *Study for the Structural Restoration of the Orthostates of the North Wall of the Parthenon's Main Temple, Vol. 1*, Ministry of Culture, Committee for the Preservation of the Acropolis Monuments, Athens, Greece.

Toumbakari EE (2008). Structural Pathology of the Capitals & the Entablature of the Parthenon Opisthodomos and the Effect of the Connectors. Proc. 3rd Nat. Congress of Antiseismic Engineering and Technical Seismology, Athens, Greece.

Vardoulakis I, Kourkoulis SK (1997). Mechanical properties of Dionysos marble, Final report of the Environment Project EV5V-CT93-0300: Monuments Under Seismic Action, National Technical University of Athens, Greece.

Vrouva A (2007). *Investigation for the Interconnections of the Epistyles of the Parthenon's North Colonnade*, Ministry of Culture, Committee for the Preservation of the Acropolis Monuments, Athens, Greece.

Zambas K (1994). *Study for the Restoration of the Parthenon, Vol. 3b*, Ministry of Culture, Committee for the Preservation of the Acropolis Monuments, Athens, Greece.

Zambas C (2004). *Mechanical Properties of Pentelik Marbles*, Committee for the Restoration of Parthenon Publications, Athens, Greece