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Critical aspects of the mechanical behaviour and failure of dionysos marble under direct tension (*)

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(*) The paper is dedicated to the memory of late Professor Ioannis Vardoulakis (1949-2009)

Abstract

The mechanical behaviour and failure of Dionysos marble under direct tension is explored both experimentally and numerically. Intact cylindrical "dog-bone" specimens and also "U-notched" plates were used in the experimental protocols. The components of the strain field were obtained with the aid of suitably positioned arrays of strain-gauge rosettes. The failure of the material was modelled within the frame of the Flow Theory of Plasticity. The experimental data were then used to validate a numerical model aiming at a thorough full-field study of the strain field in "U-notched" marble plates. Moreover the applicability of a simple and easy-to-use single-parameter criterion (based on the concept of the critical Notch Opening Displacement) for the prediction of fracture of structural elements made of Dionysos marble was assessed. Finally the limitations imposed by the non-isotropic behaviour of marble were explored also.

Keywords: Dionysos marble, direct tension, "dog-bone" specimens, notched plates, orthotropic materials, notch opening displacement, finite element method

1. Introduction

In many engineering applications, the tensile strength of rock and rock-like materials (although much smaller in comparison to the compressive one) plays an essential role in the design process and the failure risk assessment. In general the study of such materials under direct tension is among the most difficult tasks of Strength of Materials. The main obstacles are related to: (i) the difficulties in preparing standardized specimens of complex geometry (either "dog-bone" or plates with pin-holes), (ii) the difficulties in applying the tensile load (due to local fragmentation either during gripping the "dog-bone" specimens or when applying the load in plates through holes with the aid of a pins) and (iii) the development of parasitic bending or torsional moments caused by even the slightest non co-axialities and misalignments (which cannot be "self-corrected" by the specimens themselves due to the high brittleness of these materials). The problem seriously concerns the engineering community long ago. The state-of-the art of the problem is thoroughly described in a comprehensive review paper by van Mier and van Vliet (2002).

The techniques proposed to overcome the above mentioned difficulties include, among others, the use of: (i) Pre-notched cylindrical specimens with conventional grips (the stress concentration around the notch decreases the required remote fracture load reducing the gripping difficulties), (ii) Intact specimens with jaw-type grips which under tension center themselves and constrict the specimen, (iii) sophisticated zero-eccentricity devices which apply a uniform pressure throughout the lateral surface of the specimens rather than pulling apart the ends of the specimens (Toutanji and al., 2003) and (iv) Cylindrical specimens, without any additional processing, loaded through flexible grips (cables) which permit the self-alignment of the specimens. Moreover substitute tests were introduced (Fairhust 1964; Hobbs 1964, 1965) like indentation, diametral compression of spheres, three- or four-point bending of prisms and diametral compression of discs. The latter, commonly known as the Brazilian-disc test (Carneiro 1943, Akazawa 1943), is perhaps the one most widely used mainly due to its simplicity.

Obviously, the stress state during these tests is far from being characterized as uniaxial, and the results obtained are often subjected to serious criticism (Fairhurst, 1964). Moreover additional difficulties are introduced by the orthotropic nature of Dionysos marble (Vardoulakis and Kourkoulis, 1997). The latter renders the detailed experimental analysis expensive since the number of tests increases dramatically. On the other hand analytic solutions of the problem are very few and of complicated nature (Kotousov and Wang 2003). In this context it was decided to study here the problem experimentally, by carrying out a relatively small number of direct tension tests (using specially designed gripping systems) and then to use the data of these tests for the validation of a numerical model which will permit thorough exploration of the strain field developed all over the specimen for various values of the geometrical and mechanical parameters.

The numerical analysis permitted an in-depth study of the strain field and quantification of the influence of the orthotropy characterizing Dionysos marble. Moreover critical quantities like the Notch Opening Displacement (NOD) were determined. Based on these data it was possible to explore the applicability of a simple fracture criterion using a single mechanical parameter for the safety assessment of structural elements made of Dionysos marble. Such a flexible and easy-to-use criterion is of increased practical importance especially for engineers working in restoration projects of various stone monuments of the Cultural Heritage all over the world.

2.The material and the specimens. Experimental procedure and results

2.1Intact cylindrical “dog-bone” specimens under direct tension

The study is focused on Dionysos marble which is the material extensively used for the needs of the restoration project of the Parthenon Temple on the Acropolis of Athens since its physico-mechanical properties are very close to the respective ones of the authentic marble of the monument (Zambas, 1994). The target of the study is to gain in-depth knowledge of the overall mechanical behaviour of the substitute material to ensure mechanical compatibility between the substitute and the authentic building stones, as it is demanded by the restoration principles of the “Venice Charter”. The decision to focus on the behaviour of Dionysos marble under tension (either in intact specimens or in the presence of notches) was dictated by an older thorough experimental study of the Parthenon’s stability by Theocaris and Coroneos (1979) who concluded that (at least for the present state of the temple) the critical stresses in case of excessive loading are the tensile ones that will be developed at the upper part of the columns of the monument.

The mineralogical composition of Dionysos marble is analytically described by Tassogiannopoulos (1986) and Perdikatsis et al. (2006). From the Strength of Materials point of view it is an orthotropic material. The values of its mechanical constants adopted were obtained from a long series of direct tension tests, implemented with the aid of specially designed grips transferring the load from the frame to the specimen through shear instead through friction. The geometry of the grips and their assemblage are shown in Fig.1 together with typical specimens before and after they were tested. The axial and transverse strains were measured using four strain- gauge rosettes glued at the end-points of two diameters of the cross section normal to each other (Figs. 1(b-e)). The system of four strain measurement points permitted accurate quantification of the parasitic axial stresses developed due to bending moment generated by inevitable small misalignments between the loading axis and the geometric longitudinal axis of the specimens.

Characteristic experimental results can be seen in Fig.2a where the conventional axial stress is plotted versus the axial strain for a small number of loading-unloading-reloading loops of a typical specimen cut and loaded along the strong anisotropy direction. An isolated loop is shown in Fig.2b in order for the gradual accumulation of plastic strain to be clear. The average values of Young's modulus, E, Poisson's ratio, ν, and of the tensile strength, σ_f, are recapitulated in Table 1.

Analysis of the experimental data revealed that Dionysos marble is a slightly bimodular material (its elastic moduli in tension and compression are not equal) and also non-linear. What is perhaps more important is that the behaviour of the specific type of marble under direct tension is not purely elastic: Permanent deformation is observed upon unloading and as a result a portion of the total work is dissipated, as it is clearly shown in Fig.3, in which the elastically stored

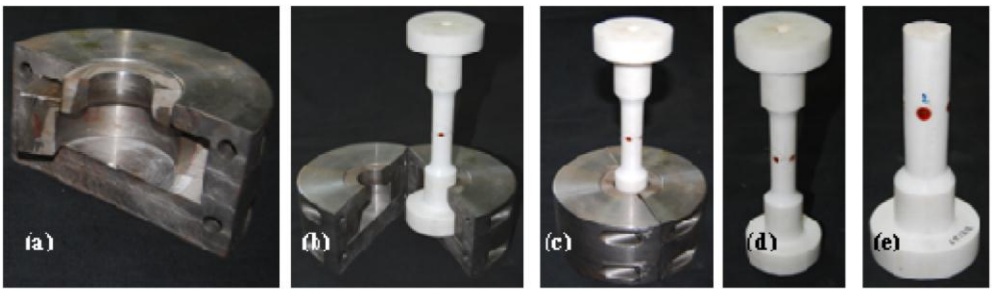

Fig. 1. The grips, their assemblage and typical specimens before and after they were tested.

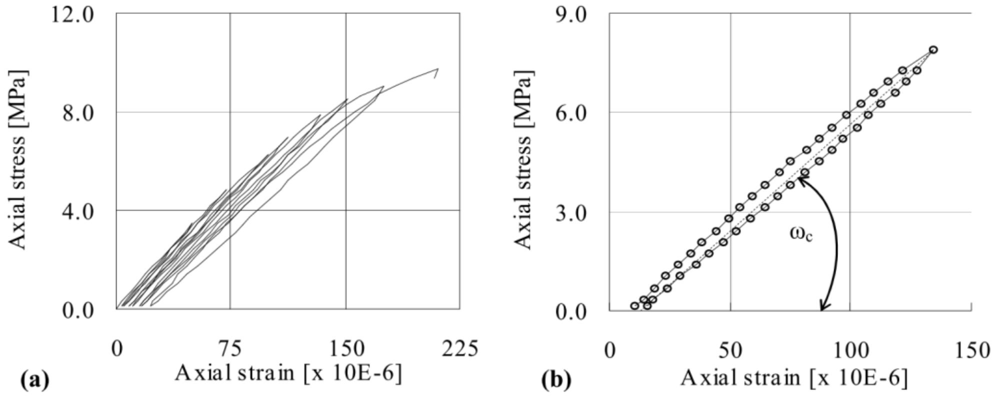

Fig. 2. (a) The axial stress - axial strain curve for a typical specimen cut and loaded along the strong anisotropy direction. (b) An isolated loading - unloading loop and the technique adopted for the determination of the current Young's modulus.

Anisotropy direction	E [GPa]	ν [-]	σ_f [MPa]
Strong	78.4±6.3	0.27	8.9±1.8
Intermediate	74.2±7.1	0.26	8.0±2.1
Weak	48.0±5.4	0.11	5.3±1.7

Table 1. Mechanical constants of Dionysos marble

volume energy, W_e, is plotted versus the dissipated one, W_p. The experimental data indicated that almost one third of the elastic energy is dissipated. For simplicity in the analysis following all energy dissipation during the unloading-reloading loop is disregarded and the corresponding hysteresis loop is replaced by a straight line connecting the point of unloading on the primary loading curve with the intersection of the unloading path with the ε-axis (see Fig.2b). The slope ($\tan\omega_c$) of this simplified unloading-reloading axial stress-axial strain curve is considered as the actual current Young's modulus. It was definitely concluded that the specific modulus decreases during the loading process, as it can be seen in Fig.4. Therefore one is forced to adopt a coupled model that could connect Young's modulus to the state of internal damage of the material.

In order to model the irreversible deformation within the framework of Flow Theory of Plasticity, the plastic work, W_p, was chosen as the most adequate plastic hardening parameter after proper data regression. Accordingly, both elastic and plastic properties are expressed in terms of W_p. Young's modulus was found to be accurately described by a decreasing function of W_p as:

$$E_c = E_0 + E_\ell \left(1 + \frac{W_p}{W_{p,ref}}\right)^n \quad (1)$$

The numerical values of the parameters appearing in Eq.(1) were found equal to: E_0=5.95x10^4 MPa, E_ℓ=1.87x10^4 MPa, $W_{p,ref}$=1.46x10^{-4} MJ/m^3 and n=-1.83. Concerning Poisson's ratio, ν, it was also found to be a decreasing function of W_p. However the specific dependence is rather weak and in a first approximation it can be ignored. Therefore an average value was assigned to Poisson's ratio, which for the strong and intermediate anisotropy axis was equal to $\bar{\nu}_{s\text{-}i}=0.265$.

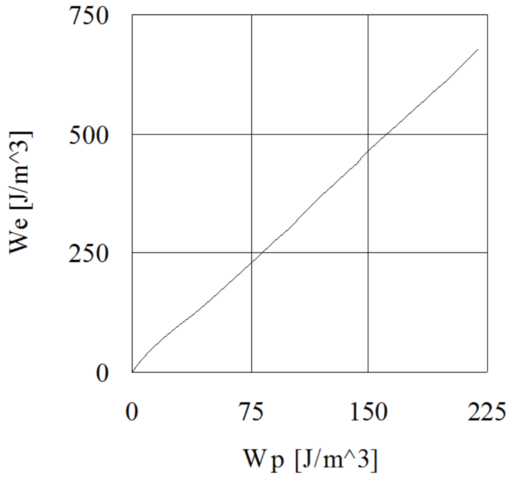

Fig. 3. The elastic volume energy versus the dissipated one.

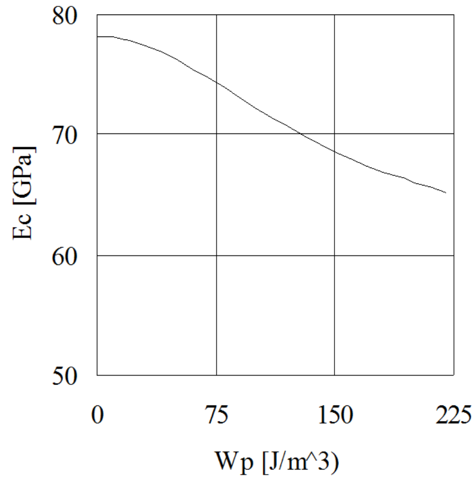

Fig. 4. Young's modulus versus the dissipated energy.

In the frame of the Flow Theory of Plasticity plastic deformation is modelled by utilising the concepts of the yield surface $F(\sigma_{ij},W_p)=0$ and the plastic strain potential $Q(\sigma_{ij},W_p)$. The results of the experimental protocol suggested a simple hyperbolic yield function of the form:

$$T = c(q-p)\sqrt{1-\left(\frac{q-p_o}{q-p}\right)^2} \tag{2}$$

$$p = \frac{I_{1\sigma}}{3} = \frac{\sigma_{kk}}{3}, \quad T = \sqrt{J_{2s}} = \sqrt{\frac{s_{ij}s_{ji}}{2}} \tag{3}$$

where the conventional notation is adopted for the stress tensor, σ_{ij}, and the deviatoric stress tensor, s_{ij}. Recall that $\sigma_{ij}=s_{ij}+(\sigma_{kk}\delta_{ij})/3$. In Eq.(2) q is a material constant while c and p_o are functions of the plastic work, W_p. After suitable curve fitting the experimental data suggested that:

$$c = a + bW_p, \quad p^* = \frac{p_o}{q} = \kappa + \frac{(1+d_1W_p)}{d_2 + d_3W_p}W_p \tag{4}$$

The numerical values of the constants of Eqs.(3,4) are summarized in Table 2, while the dependence of the parameters c and p^* on the plastic work, according to Eq.(4), is shown in Fig.5.

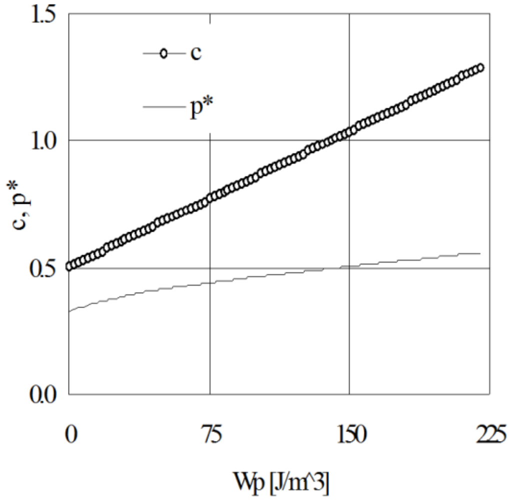

Fig. 5. The dependence of constants c and p* on the dissipated energy.

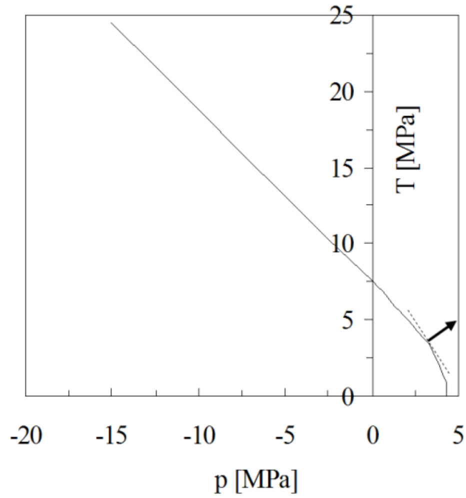

Fig. 6. The yield envelope for Dionysos marble.

Constant	a	b	κ	d_1	d_2	d_3
Unit	---	$[m^3/J]$ $x10^{-2}$	---	$[m^3/J]$ $x10^{-2}$	$[J/m^3]$ $x10^3$	$x10^1$
Magnitude	0.504	0.356	0.325	0.497	0.339	0.744

Table 2. The numerical values of the constants of Eqs.(3,4) according to the curve fitting process

Concerning the tension limit, p_o, it can be determined through regression analysis of the plastic dilatancy, in such a way that the experimentally measured plastic strain increment vector to be normal to the yield surface at the current state of the direct tension test, as it is shown schematically in Fig.6. In other words the yield surface is here used as plastic potential surface either (associate plasticity), i.e. $F \equiv Q$.

Concluding Dionysos marble is an orthotropic, stiff and brittle material. Its Young's modulus approaches that of aluminium. The ratio of Young's modulus over the tensile strength varies about $9x10^3$ (depending on the anisotropy axis). The material is non-linearly elastic and during tension a significant portion of the total energy input is dissipated, suggesting the use of constitutive models accounting for irreversible deformation. Moreover Young's modulus decreases with strain, which in connection with the aforementioned energy dissipation results into a fully coupled elasto-plastic model with the plastic work as hardening parameter. It is to be noted that plastic volumetric strains monitored are significant and, in order to model them properly, they were associated with a hyperbolic yield surface utilizing the normality flow-rule. However in case brittle failure under tension is to be modelled the present model should be reconsidered. Preliminary analysis shows that the classical co-axial flow-rule of flow theory should be relaxed, and a more-general, non-coaxial model, similar to that proposed by Papamichos and Vardoulakis (1995) must be adopted.

2.2U-notched "dog-bone" plates under direct tension

The specimens used in the second experimental protocol are shown schematically in Figs.7(a,b). They were plates of overall dimensions 0.3x0.4 m^2 properly machined to resemble the familiar "dog-bone" standardized specimens. U-shaped notches of depth a=10 mm and semi-circular crown of radius R=2 mm were mechanically machined at both sides of the plates. The load was applied with the aid of two steel pins of diameter 22 mm passing through holes of diameter 23 mm. To avoid premature cracking in the immediate vicinity of the load-application arc the "ears" of the specimens were locally reinforced with two pairs of PMMA plates (Figs.7(b,d)) glued on each face of the plate. In this way the direct contact of pins and marble was avoided and the load was transferred from the pins to the PMMA plates and through them to the marble plates in the form of uniform surface shear stress eliminating thus any stress concentration around the loading pins.

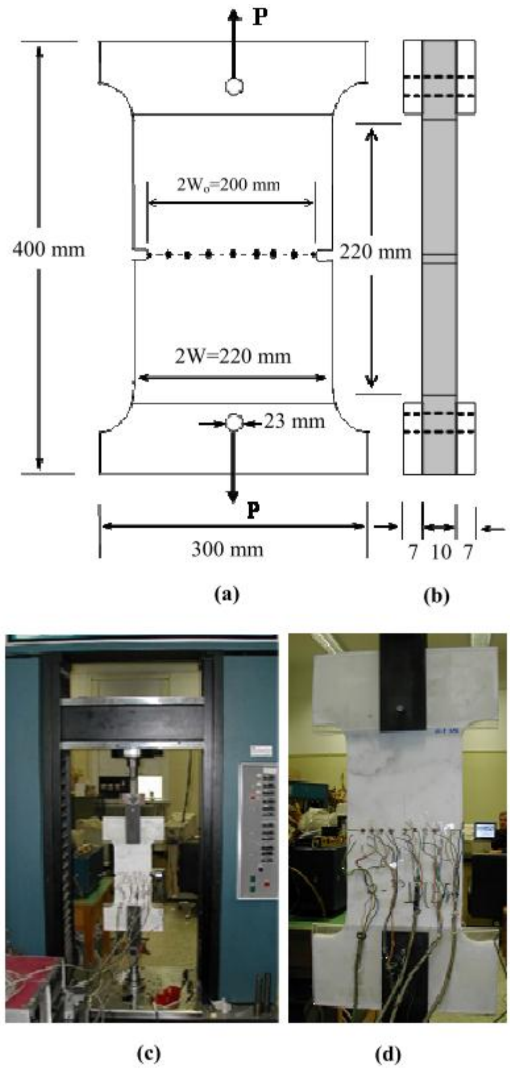

Fig. 7. (a, b) Sketch of the front and side-view of a typical specimen. (c) A wired specimen mounted in the loading frame. (d) Detailed view of the specimen showing the arrangement of strain gauges.

The plates were cut from freshly quarried Dionysos marble and attention was paid for the loading direction to coincide with the strong anisotropy axis. The load was applied statically using a recently upgraded INSTRON/1126 servo-hydraulic loading frame of capacity 250 kN (Fig.7c). The displacement-control loading mode was chosen under a constant rate equal to 0.20 mm/min. The tensile force was measured using an INSTRON/2511-308 tension-compression load-cell properly calibrated with the aid of a verified Wykeham-Farrance load-ring.

The components of the strain field were measured using a system of nine orthogonal strain-gauge rosettes arranged along the line connecting the tips of the notches (Fig.7(a,c,d)). Moreover the Notch Mouth Opening Displacement (NMOD) of both notches was measured with the aid of two suitable INSTRON/2670-120 clip-gauges (Fig.7d). All data obtained from the load cell, the eighteen (9x2) strain gauges and the two clip-gauges were stored in a commercial PC.

The variation of the axial strain (longitudinal) versus the nominal remote stress is plotted in Fig.8 using data from two strain rosettes: The one closest to the tip of the notch and the one at the geometric center of the specimen. The remote nominal stress is determined by dividing the load applied through the pins over the area of the effective (smallest) cross section, i.e. the one between the tips of the notches. It is seen from this figure that the response at the center of the specimen is almost perfectly linear, as it was expected, considering that the maximum stress level reached is equal to something less than one third of the fracture strength of Dionysos marble (see Fig.2). On the contrary, as one approaches the tip of the notch the behaviour of the material becomes strongly non-linear from almost the very first steps of the loading procedure, since the local stress field is amplified significantly due to the presence of the notch. This very strong non-linearity is attributed to the development of a process zone, i.e. a zone of intense micro-cracking, in the immediate vicinity of the notch tip. The extent of this zone for Dionysos marble was quantified by Kourkoulis et al. (1999) and was found of the order of 5 mm. Considering the size of the respective strain rosette it is concluded that indeed the point under study lies inside the process zone, justifying the strong non-linearity of the stress-strain curve.

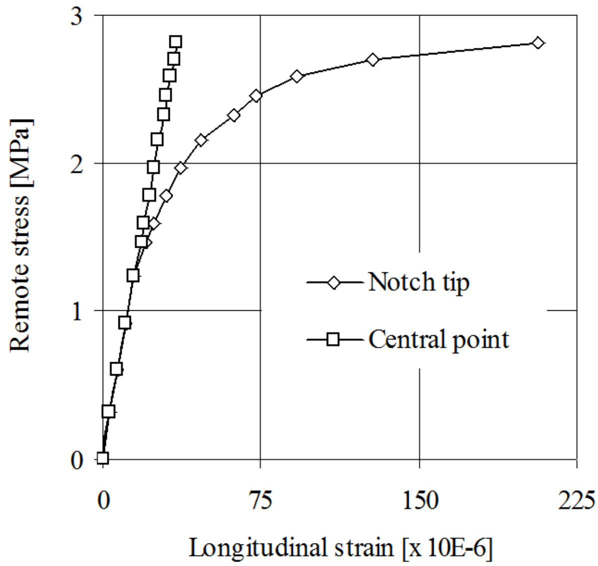

Fig. 8. The remote stress versus the longitudinal strain at the central point and the tip of the notch.

The variation of the longitudinal strain along the line connecting the tips of the notches is plotted in Fig.9. The strain close to the tip is almost six times that at the central portion of the specimen. The mean of the maximum values attained approaches $2x10^{-4}$, almost equal to the fracture strain of the intact specimens (see Fig.2a). Therefore it can be concluded that, in a first approximation, a “maximum tensile strain” criterion could be adopted to describe the fracture of Dionysos marble. The discrepancy from perfect symmetry observed (with respect to the axis of the load) can be attributed either to: (i) Slight misalignment of the load with respect to the geometric axis of longitudinal symmetry or to (ii) Slight inclination of the anisotropy axis with respect to the loading direction. In both cases it is expected that parasitic bending moment is generated rendering the stress field spatially non-uniform.

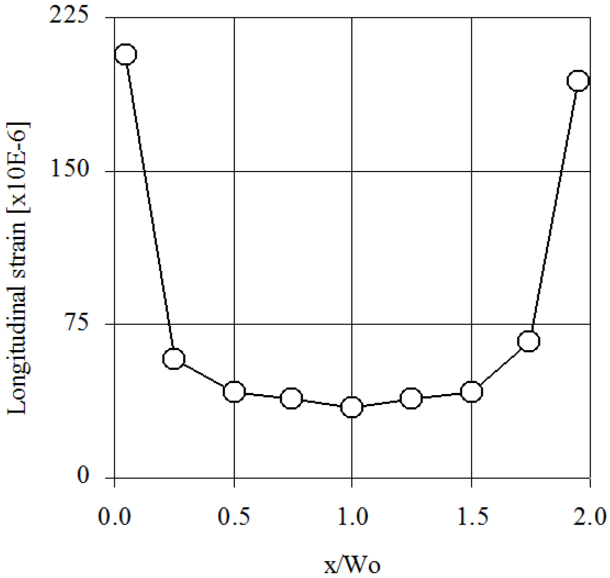

Fig. 9. The longitudinal strain along the line connecting the tips of the two notches.

Additional experimental data, concerning the Notch Mouth Opening Displacement (NMOD), will be presented in next Section 3 together with the respective results of the numerical analysis.

3. Numerical analysis

3.1The numerical model

The numerical analysis was realized using the Finite Element Method and the commercially available ANSYS-12 software. The Plane-182 element was used for meshing the "U-notched" specimens. It is defined by four nodes with two translational degrees of freedom for each one. An extremely fine mesh was created around the areas of increased interest (notches and pin-holes) while a coarse one was used in the remaining part of the specimen. The mesh around the notch is shown in Fig.10. Geometric symmetries were not taken into account and the total number of elements that was finally chosen (after a suitable convergence process) was equal to about 123000. The central node of the model was rigidly clamped. The load was applied either as uniform radial pressure along a small arc of the two loading holes or as a traction, uniformly applied on the lateral surfaces of the specimen's ears. Series of preliminary "runs" indicated that both loading modes give almost the same results all over the surface of the specimen at a reasonable distance from the specimens' "ears". Especially around the tips of the notches the results were identical, as dictated by Saint Venant's principle. The material was modelled either as isotropic or orthotropic, in order to explore the consequences of the assumption (commonly adopted in practical applications) of isotropy. The constitutive law was obtained from the data of Section 2.1 by curve fitting.

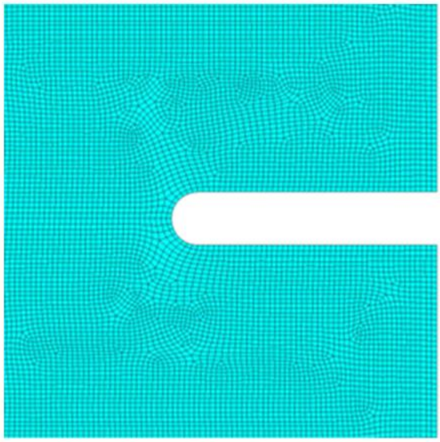

Fig. 10. Detail of the mesh around the notch.

3.2Validation of the model

The validity of the numerical model was assessed by comparing its predictions for the Notch Mouth Opening Displacement (NMOD) against the respective data obtained from the two clip-gauges mounted on the specimens (Section 2.2). The comparison is shown in Fig.11. The agreement is very satisfactory almost for the whole range of the load applied. Discrepancies appear for loads approaching the ultimate one. Indeed as it was previously mentioned the stress field is inevitably slightly non-uniform. It is seen from Fig.11 that while the readings of one clip-gauge decrease the readings of the one mounted at the opposite notch increase abruptly. In any case the deviation between the experimental data for NMOD and those of the numerical model were below 8% (excluding the last two points).

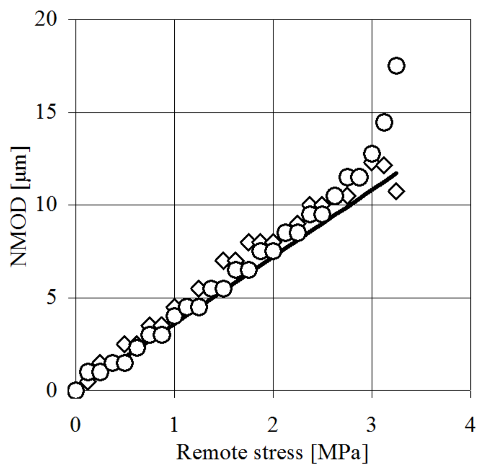

Fig. 11. The NMOD for the two notches vs. the remote stress for a typical test and the prediction of the numerical model (continuous line).

3.3Results

The distribution of the axial strain in the vicinity of the notch is shown in Fig. 12. As one moves away from the tip of the notch the extreme values of the axial strain are translated away from the horizontal symmetry axis, i.e. from the line connecting the tips of the two notches.

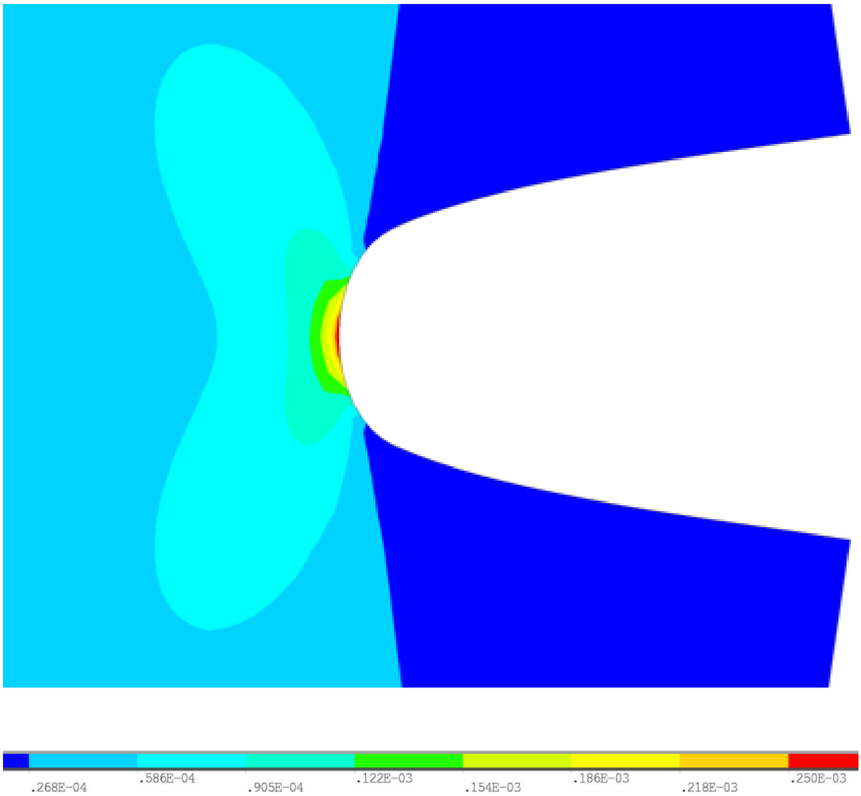

Fig. 12. The distribution of the axial (longitudinal) strain in the immediate vicinity of the notch.

As a next step a single-parameter and easy-to-use fracture criterion was sought for the prediction of fracture of structural elements made of marble. In this direction the applicability of the critical Notch Opening Displacement (NOD) concept was considered. Initially the NMOD was determined numerically (taking into account that the latter is easily measured experimentally even for structural elements already placed in their position or in service). A maximum tensile strain criterion was adopted and the critical NMOD was obtained numerically for various values of the notch length. As a last step the critical values of NMOD were reduced to the respective ones of the critical NOD by considering that the quantities for the case with a=10 mm are the reference values. The results of the above procedure are plotted in Fig.13 where the critical NOD is plotted versus the length of the notch, normalized with respect to the effective width of the plate, W_o (see Fig.7a). It is safely concluded from this figure that the critical NOD could be used as fracture criterion (at least under specific conditions) considering that after a critical limit, it is the presence of the notch itself that plays a crucial role rather than its exact length. The results of the present analysis are in excellent agreement with the respective ones by Vayas et al. (2009) although in their work data from three- and four-point bending tests were used to evaluate the critical NOD.

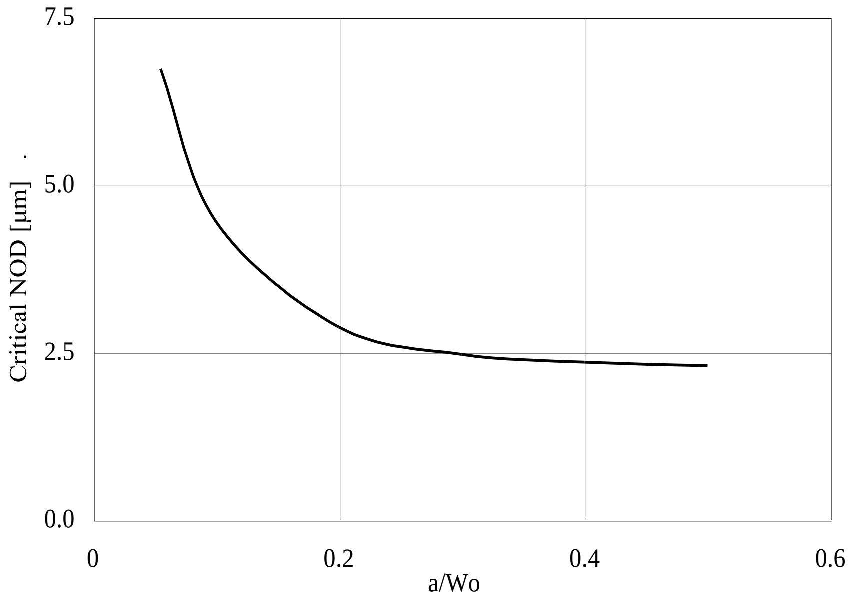

Fig. 13. The dependence of the critical Notch Opening Displacement on the normalized (over the effective width of the plates) notch length.

As a final step the variation of the axial (longitudinal) and transverse normal strains (according to a Cartesian reference system with its axes parallel and normal to the loading direction) is

plotted in Figs.14(a,b) for two cases concerning the constitutive behaviour of Dionysos marble: (i) Isotropic and (ii) Orthotropic. Both plots are realized along a geometric locus similar to the boundary line of the notch at a distance equal to 5 mm from this boundary. For comparison reasons strains are normalized over their overall maximum value detected while the distance along the path was normalized over the length of the perimeter of the notch.

It is clear from Fig.14 that both strain components obtained in case marble is considered as orthotropic material systematically exceed the ones determined according to the isotropic model. The difference is much more pronounced for the transverse strains. For the line connecting the tips of the two notches the difference approaches 200%. At the same point the difference for the axial strains is about 15%. From the same figure it is again noted that the distribution of axial strains exhibits two distinct off-axis maxima, symmetric with respect to the axis of symmetry. These maxima exceed the corresponding value along the line of symmetry by about 27.5% and 25% for the isotropic and orthotropic models, respectively. The exact position of these two maxima is estimated at an angle equal to about 60^o with respect to the line connecting the tips of the two notches.

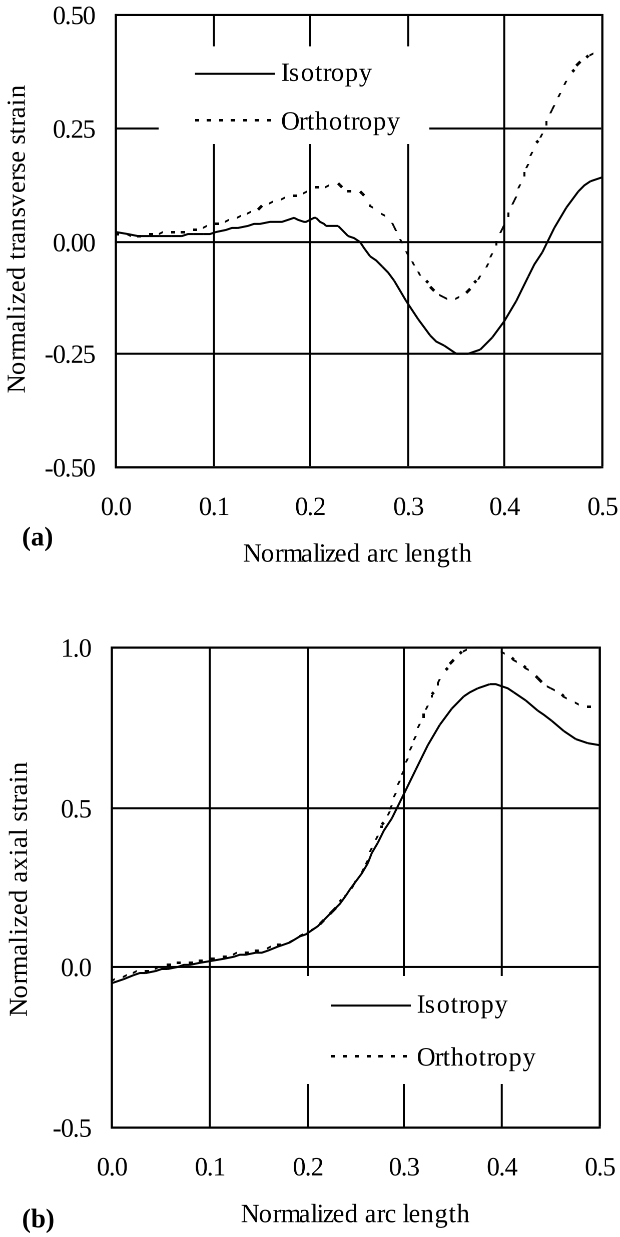

Fig. 14. The variation of the normalized transverse (a) and axial (b) strains along a contour similar to the boundary of the notch at a distance 5 mm from it. The graph is plotted only along the lower half of the contour for obvious symmetry reasons.

4. Conclusions

The mechanical behaviour and fracture of Dionysos marble was studied both experimentally and numerically. Attention was focused to the behaviour under tension considering that due to the difficulties in the experimental implementation of direct tension tests the specific behaviour is up to now studied using substitute tests (like for example the Brazilian disc test). However the interpretation of the results of such tests is not always unique and therefore ambiguities enter often into the analysis (Markides and Kourkoulis, 2012).

Based on the results of long series of experiments with cylindrical "dog-bone" specimens various critical aspects of the behaviour of Dionysos marble under tension were explored. It was concluded that this marble is of orthotropic nature with three distinct anisotropy directions, namely one along the grain plane, a second one along the head-grain plane and a third one along the rift plane (Kourkoulis et al., 1999). Therefore nine mechanical constants are required for the complete description of its mechanical behaviour (Lekhnitskii, 1977). However the mechanical properties along the strong and intermediate anisotropy directions are sufficiently close to each other and one could consider Dionysos marble as transversely isotropic material described with the aid of only five mechanical constants. In addition it was found that the axial stress - axial strain curve is non-linear from the early loading steps. Moreover if subjected to loading - unloading - reloading loops plastic strains are accumulated and the modulus of elasticity degrades according to a more or less sigmoid law (Vardoulakis et al., 2002).

The failure of Dionysos marble was found to be rather accurately described within the frame of Flow Theory of Plasticity by utilizing the concepts of yield surface $F(\sigma_{ij},W_p)=0$ and plastic strain potential $Q(\sigma_{ij},W_p)$ in connection with a simple hyperbolic yield function.

In the presence of notches it was concluded that a zone of intense micro-processes is developed around the tip of the notch. Moreover the strain field is strongly amplified locally. For example the axial strain at a distance equal to a/2 from the tip of the notch is almost six times higher compared to the respective strain at the central region of the specimen. However this amplification is rapidly eliminated and at a distance higher than 2.5a the strain field becomes almost homogeneous.

For the prediction of fracture of Dionysos marble it was demonstrated that the critical NOD concept could be safely used assuming that the length of the notch exceeds a critical limit equal to about $a=0.25W_o$. Although it could be argued that a single-parameter fracture criterion based on a critical length can hardly be a fracture criterion (with a sound basis from the physical point of view) for practical purposes it could be accepted, at least for structural elements already placed in their position.

Finally it was concluded that the commonly accepted assumption that Dionysos marble can be approximately described as an isotropic material should be critically reconsidered given that for the transverse strain component differences approaching 200% were detected between the isotropic and orthotropic versions of a plate with a notch under direct tension.

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Извод

Критични аспекти механичког понашања и лом дионисовог мермера под директним оптерећењем

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Извод

У овом раду је испитивано механичко понашање и лом Дионисовог мермера под директним оптерећењем како експериментално тако и нумерички. У протоколу експеримената коришћени су интактни цилиндрични “dog-bone” узорци епрувета као и плоче са „U–зарезом“. Компоненте поља оптерећења добијене су уз помоћ одговарајуће позицинираних низова розета за мерење оптерећења. Лом материјала моделиран је у оквиру Теорије течења пластичности („Flow Theory of Plasticity“). Експериментални подаци су затим коришћени за валидацију нумеричког модела са циљем темељног проучавања целог поља оптерећења у мермерним плочама са „U–зарезом“. Додатно, процењивана је примењивост једноставног и лаког за коришћење једнопараметарског критеријума (заснованог на концепту Notch Opening Displacement критичног померања зареза) за предвиђање прелома структурних елемената направљених од Дионисовог мермера. Коначно, испитивана су и ограничења која настају услед анизотропног понашања мермера.

Кључне речи: Дионисов мермер, директно оптерећење, “dog-bone” узорци епрувета, плоче са „U–зарезом“, ортотропни материјали, критично померање зареза, Метода коначних елемената

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