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INVESTIGATIONS USING CSIRO HI TRIAXIAL CELLS FOR MEASURING THE STRESS STATES OF ROCK MASSES SUBJECT TO MINING EXTRACTION: NUMERICAL MODELLING OF IN-SITU EXTRACTED CORE SAMPLES

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EXTENDED ABSTRACT

La misura dello stato di stress agente nella roccia è importante per comprendere le condizioni geostrutturali e migliorare la sicurezza sia nei versanti naturali che nelle cave a cielo aperto e in sotterraneo. Questa ricerca ha l'obiettivo di fornire un contributo innovativo alle attuali metodologie di misura dello stato tensionale della roccia, affrontando in modo specifico le difficoltà legate all'interpretazione della prova di sovracarotaggio 3D denominata CSIRO HI Cell in caso di carote di roccia con forma irregolare. Infatti, le formulazioni analitiche usate normalmente per l'interpretazione della prova presuppongono che i campioni siano perfettamente cilindrici ma è possibile, in ammassi rocciosi molto fratturati, che si producano forme irregolari dovute alla presenza di discontinuità nel campione.

La prova CSIRO utilizza una cella dotata di 12 estensimetri elettrici variamente orientati nello spazio. La cella viene incollata in un foro pilota di diametro nominale 38 mm e viene poi sovracarotata. Gli estensimetri registrano le deformazioni indotte del rilascio tensionale legato al sovracarotaggio. Dopo avere determinato i parametri elastici del materiale roccioso, viene calcolato il tensore degli sforzi attraverso formulazioni analitiche basate sull'ipotesi di un campione cilindrico. Nel caso di campioni di forma irregolare non esistono però formulazioni analitiche e la presente ricerca propone una metodologia basata su:

- ricostruzione Fotogrammetrica e Mesh Editing: viene costruito il modello 3D della carota mediante tecniche fotogrammetriche digitali; la ricostruzione geometrica tridimensionale fornisce una rappresentazione dettagliata del campione irregolare dopo una fase di mesh editing;
- analisi agli Elementi Finiti (FEM): il modello della carota, contenente la cella CSIRO, è sottoposto ad analisi tridimensionale simulando la prova con il campione a geometria complessa;
- determinazione dello Stato di Stress: un'analisi di regressione lineare multipla calcola il tensore degli sforzi. La matrice dei coefficienti del sistema sovradeterminato è derivata dalla simulazione FEM sulla carota irregolare, estendendo così l'applicabilità della misura oltre l'ipotesi di campione cilindrico.

Lo studio mira a comprendere come le variazioni nella forma del campione di roccia influenzino il comportamento del rilascio di tensione. I risultati di questa ricerca contribuiscono al perfezionamento delle tecniche di misurazione degli stress in situ, migliorando la capacità di valutare le condizioni statiche dei fronti di cava e, di conseguenza, migliorando le condizioni complessive di sicurezza sui luoghi di lavoro.

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ABSTRACT

The measurement of the stress state of rock, carried out in-situ using the overcoring CSIRO HI Cell technique, provides valuable information about the rock mass geo-structural and stress conditions. This is particularly useful for calibrating the numerical model of natural slopes and excavations fronts and for assessing their static conditions. Thus, it allows to improve workplace safety conditions in both open-pit and underground quarries. During an in-situ CSIRO test, the stress release strains are measured by 12 strain gauges differently oriented in the space and the stress tensor and the material elastic parameters are then computed. The classic interpretative procedure of stress release test refers to analytical formulations that assume an extracted sample of regular cylindrical shape. However, during overcoring, it may happen that a discontinuity is intercepted, causing the extracted core to break and to assume an irregular shape. To address this challenge, in this work, a Finite Element numerical simulation of stress release was conducted basing on a 3D digital model of the irregular sample resulting from a Photogrammetric Survey. This allowed for the computation of the stress tensor for both irregularly shaped and ideal cylindrical samples. The research proceeded as it follows: *i)* three-dimensional modelling of the irregularly shaped core using Photogrammetric Techniques and Mesh Editing, which enabled the accurate representation of complex geometries; *ii)* numerical Modelling of the irregularly shaped core containing the CSIRO HI Cell through Finite Element Analysis, providing insights about stress and deformation distributions; *iii)* stress State of the rock calculation using a Multiple Linear Regression Procedure by using the coefficient matrix as determined by the core numerical modelling. The implementation of this procedure may facilitate the determination of stress state for irregularly shaped cores, and it enhances to understand how shape and rock elastic properties may influence the stress release behaviour.

This comprehensive approach could allow to address challenges associated to stress assessment for irregular shaped rock cores and to improve the accuracy and applicability of geotechnical engineering methods.

Keywords: CSIRO HI Cell, FEM numerical modelling, photogrammetry, core sample, multiple linear regression analysis.

INTRODUCTION

Over the years, CSIRO (Commonwealth Scientific and Industrial Research Organisation) Hollow Inclusion (HI) cells have proven to be valuable tools for civil and mining engineering, significantly contributing to the understanding of structural behaviours of rocks and the management of risks associated with slopes stability. The accuracy and reliability of measurements provided by the cells make them useful for a wide range of engineering applications, from preliminary surveys to continuous monitoring of geotechnical structures (Vreede, 1981; Sarwade, 2009; Ouanas *et alii*, 2010;).

CSIRO cells stand out for their ability to withstand extreme environmental conditions and to operate in underground or surface environments, enabling rock deformation measurements in challenging and inaccessible conditions not reachable by conventional methods (Krietsch *et alii*, 2017; Yang *et alii*, 2017; Souley *et alii*, 2018). These cells are equipped with sensors capable of detecting microscopic variations in rock stress, allowing for detailed and real-time assessment of in-situ geomechanical conditions.

The present paper examines the application of the CSIRO HI cell within a marble quarry of the Apuan Alps extraction area, in Italy.

During the stress measurement campaign, a core breakage occurred for the presence of a near vertical joint almost parallel to the direction of investigation. Nevertheless, the CSIRO cell remained intact and provided all the expected output.

To reconstruct the stress state of the extracted irregular sample, it was decided to perform a numerical modeling. A possible solution to this is represented by the Digital Photogrammetry which benefits in capturing three-dimensional details has already demonstrated by several papers in different contexts (Salvini *et alii*, 2014; Eltner *et alii*, 2016; Salvini *et alii*, 2020, León-Bonillo *et alii*, 2022; Casula *et alii*, 2023). The produced digital model represented the starting point for a very precise analysis of deformations thanks to a Finite Element numerical simulation. It allowed to overcome the limitations related to conventional analytical solutions which are applicable only to cylindrical samples (Amadei, 1983; Amadei, 1986). A Multiple Linear Regression Analysis allowed to determine the stress state and to address the role of shape and elastic properties in rock behaviour providing crucial insights for understanding and managing the stability of geotechnical works in similar contexts.

MATERIALS AND METHODS

CSIRO HI cell overcoring technique

The CSIRO HI cell overcoring technique was developed in the early 1970s in Australia. During the years it has gained widespread global adoption as one of the most reliable in-situ stress measurement techniques (Sjöberg *et alii*, 2003). These tests involve the use of strain deformation cells (Figure 1), equipped with 12 strain gauges plus a thermistor for measuring the hole inner temperature, which allow for three-dimensional stress measurements at a specific point of the rock wall. The test procedure requires meticulous gluing of the cell within the rock. The overcoring of the rock volume containing the cell involves real-time measurements of the strain gauges elongation during the overcoring advance, when the sample separates from the rock. Typically, once the overcoring has completed, the extracted intact sample undergoes a radial compression test with the aim of determining the material elastic parameters such as Young's modulus and Poisson's ratio. This methodology is described more in detail in Wortonincki, 1993; Ask, 2006; Salvini *et alii*, 2022.

The measured overcoring strains are interpreted assuming linear elasticity of the material (Amadei, 1983; Amadei, 1986). By the principle of "superposition of effects" a set of 12 linear equations is obtained (one equation for each strain gauge of the cell) as it follows:

$$\{\lambda\} = [C]\,\{S\}_{XYZ} \qquad (1)$$

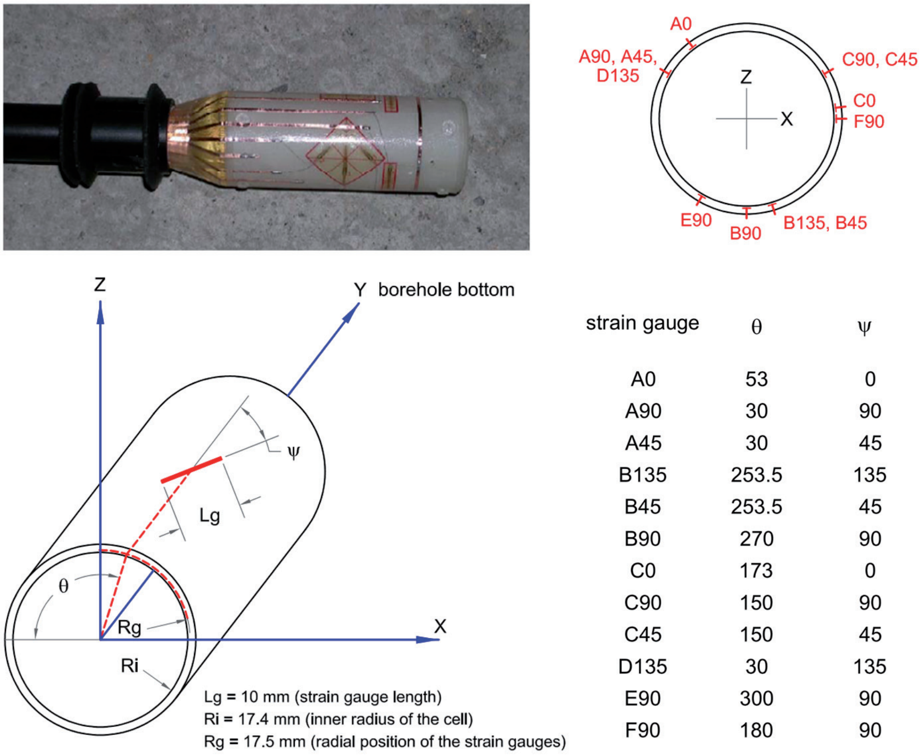
where $\{\lambda\}$ is the array of the 12 measured stress release strains, $[C]$ is the 12 x 6 matrix of coefficients that, for a cylindrical sample, can be computed analytically (Amadei, 1983; Amadei, 1986), and $\{S\}_{XYZ} = [S_{XX}\ S_{YY}\ S_{ZZ}\ T_{XY}\ T_{XZ}\ T_{YZ}]^T$ is the array of the 6 unknown stress components. The overdetermined set of equations (1) is solved by a Multiple Linear Regression Analysis (in the actual case the MATLAB routine MLRA was used) giving the stress tensor $\{S\}_{XYZ}$ that minimizes the residuals sum of squares.

Photogrammetric reconstruction and mesh editing

When a non-cylindrical sample is obtained from the overcoring, the first aim is to accurately survey its geometry. For this purpose, Close-range Photogrammetry was employed to reproduce the irregularly shaped rock core accurately and faithfully. High-resolution photographs of the rock sample were captured from multiple points of view by using a Nikon^{TM} D7100 camera. Consequently, 94 sequential images were acquired to achieve complete coverage of the sample. These images were processed by using the Structure from Motion (SfM – Spetsakis & Aloimonos, 1991) and Multi-View Stereo (MVS – Gallup *et alii*, 2007; Goesele *et alii*, 2007; Jancosek *et alii*, 2009) techniques, implemented within Agisoft^{TM} Metashape software. This methodology enabled the creation of a detailed 3D point cloud of the irregular shape of the rock core. To account for any variations that have occurred due to core breakage during the overcoring process, the model has undergone to accurate manual editing. The final version of the model, built in a triangular polygon mesh format, consists of vertices, edges, and faces that define the actual shape of the rock sample.

Finite element analysis

Finite Element Method (FEM) was employed to numerically model the stress and strain state within the



Lg = 10 mm (strain gauge length)
Ri = 17.4 mm (inner radius of the cell)
Rg = 17.5 mm (radial position of the strain gauges)

strain gauge	θ	ψ
A0	53	0
A90	30	90
A45	30	45
B135	253.5	135
B45	253.5	45
B90	270	90
C0	173	0
C90	150	90
C45	150	45
D135	30	135
E90	300	90
F90	180	90

Fig. 1 - CSIRO HI Cell and strain gauges geometry

rock core. The analysis was carried out by using the RS3 software (RocScience^{TM}, 2023). The rock is initially subjected to a known state of stress. Then, the FEM model simulates the overcoring process computing the elongation of the strain gauges within the cell. This can be done for the ideal cylindrical sample and for any irregularly shaped sample. Applying unitary stress components to the FEM model, the coefficients of the matrix [C] in equation (1) can be numerically computed. For example, applying a unit stress S_{xx}, the computed strains of the 12 strain gauges are the first column of matrix [C]; applying a unit stress S_{yy}, the second column of matrix [C] is obtained, and this procedure is continued to construct the remaining part of the matrix.

RESULTS

During the stress measurements fieldwork at the marble quarry of the Apuan Alps extraction area (Italy), a test resulted with a core breakage during overcoring. The rock breakage was due to a fracture almost vertical and parallel to the borehole axis, that did not intersect the cell. Throughout the overcoring process the cell remained intact and provided the measurements of the 12 strain gauges and the thermistor (Figure 2). Due to the irregular shape, it was not possible to perform the radial compression test and thus, the elastic parameters measured in an adjacent test were assumed (*i.e.*, Young's modulus "*E*" = 80 GPa, and Poisson's coefficient "*ν*" = 0.38). The unit weight was set equal to 26.5 kN/m^3 from laboratory tests.

During the overcoring, the thermistor of the cell measured an increase in temperature of about 4°C, caused by the friction of the diamond crown and the different temperature between water and rock.

The three-dimensional point cloud obtained from the photogrammetric reconstruction of the overcored rock core consists of 18,023,483 points and it was used to generate a 3D model in mesh format. The latter underwent further refinement through editing techniques up to obtain approximately 10,000 faces. This processing involved refining the digital model to ensure accuracy and completeness, addressing any artifacts or discrepancies resulting from the irregularities in the rock core. Mesh editing produced a reliable geometric representation (Figure 3) to be used for the numerical simulations within the FEM program (*i.e.*, RS3) where the pilot hole and the CSIRO HI Cell were added (Figure 4).

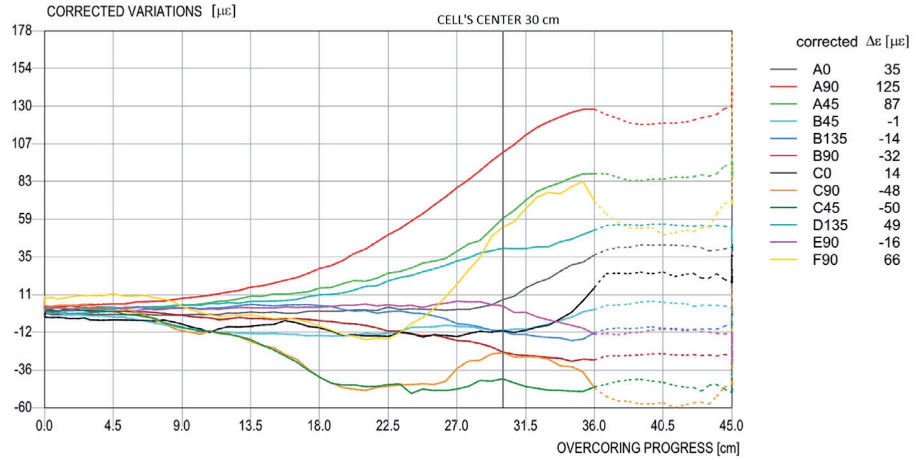


Fig. 2 - Plot of the strain (με) recorded by the 12 strain gauges versus the overcoring progress (cm). The strain is corrected for the temperature variation. The stress release deltas are summarized in the table on the right side of the figure

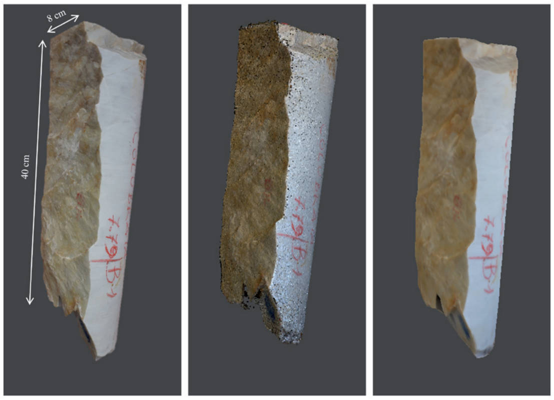


Fig. 3 - Phases of the photogrammetric processing: example of an original photo (on the left); 3D dense point cloud (in the centre); mesh 3D model (on the right)

By means of the FEM model, the matrix [C] of equation (1) was computed both for the ideal cylindrical sample and for the irregularly shaped one.

With reference to Figure 2, strain gauges C0, C90, C45 and F90 show a clear anomaly at about 35-36 cm advance, that is a non-derivability point (edge) of the experimental curve; besides, C45 and C90 show premature variation at the early stage of the overcoring between 5 and 20 cm.

Therefore, two alternative interpretations were carried out and named I and II both for the cylindrical and cracked samples.

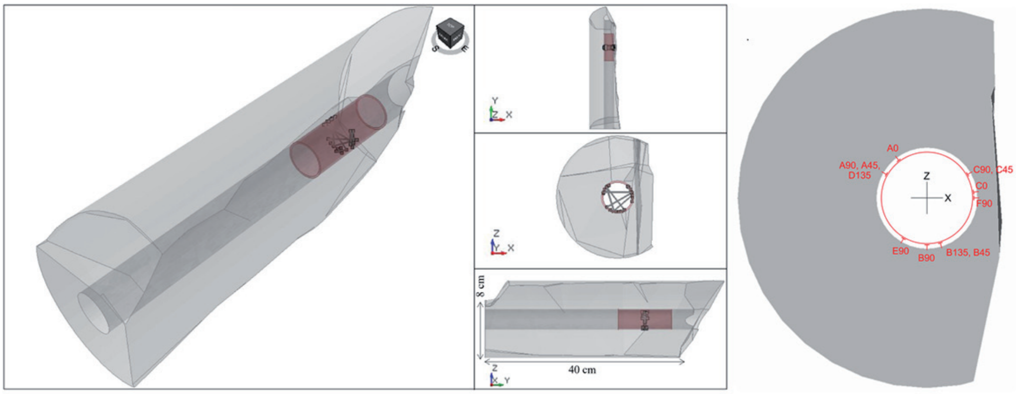
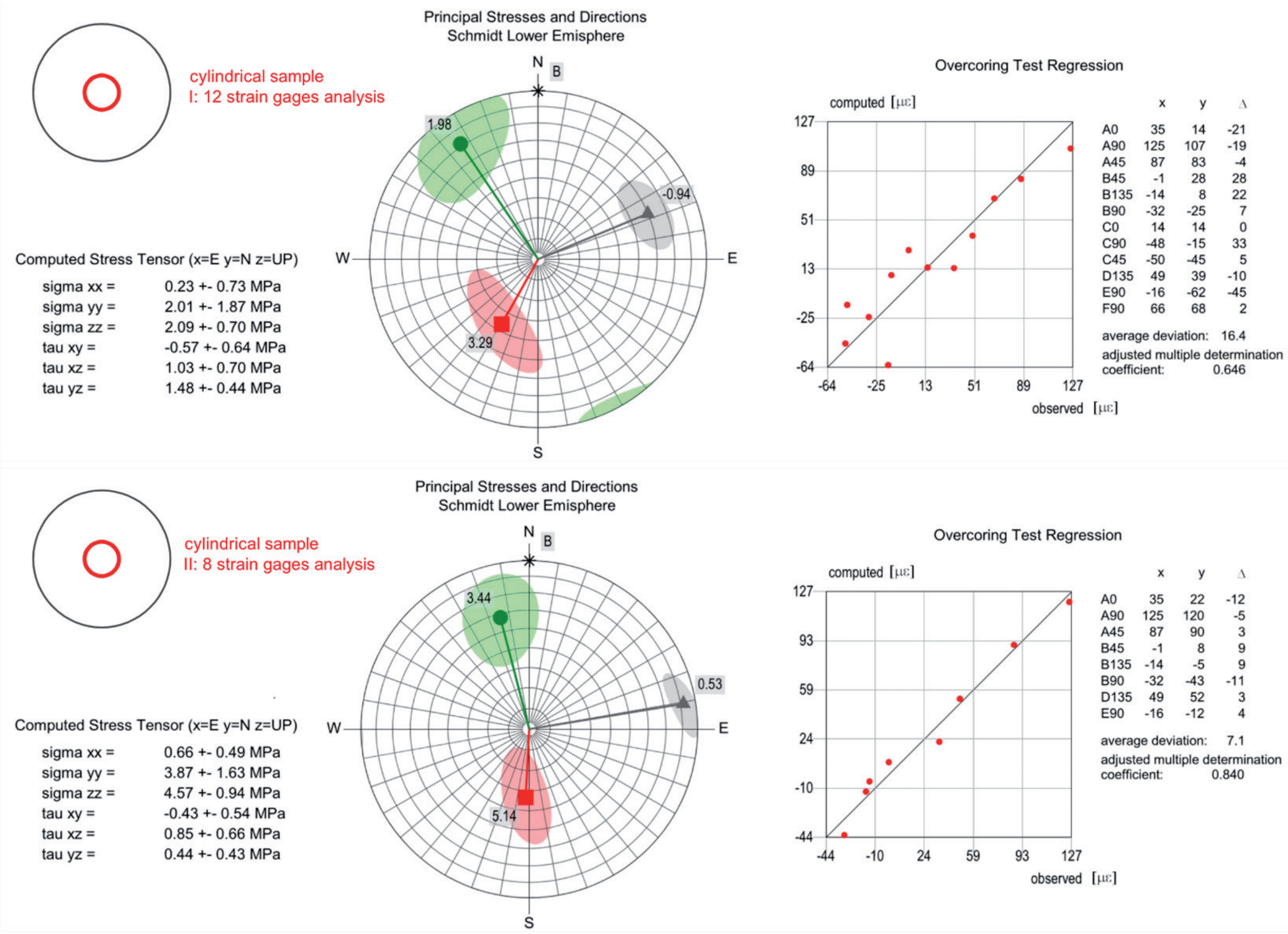


Fig. 4 - Views of the irregular rock sample containing the CSIRO HI Cell as modelled by RS3 software. At right, the cross section located at the centre of the cell



Computed Stress Tensor (x=E y=N z=UP)

sigma xx = 0.23 +- 0.73 MPa
sigma yy = 2.01 +- 1.87 MPa
sigma zz = 2.09 +- 0.70 MPa
tau xy = -0.57 +- 0.64 MPa
tau xz = 1.03 +- 0.70 MPa
tau yz = 1.48 +- 0.44 MPa

	x	y	Δ
A0	35	14	-21
A90	125	107	-19
A45	87	83	-4
B45	-1	28	28
B135	-14	8	22
B90	-32	-25	7
C0	14	14	0
C90	-48	-15	33
C45	-50	-45	5
D135	49	39	-10
E90	-16	-62	-45
F90	66	68	2

average deviation: 16.4
adjusted multiple determination coefficient: 0.646

Computed Stress Tensor (x=E y=N z=UP)

sigma xx = 0.66 +- 0.49 MPa
sigma yy = 3.87 +- 1.63 MPa
sigma zz = 4.57 +- 0.94 MPa
tau xy = -0.43 +- 0.54 MPa
tau xz = 0.85 +- 0.66 MPa
tau yz = 0.44 +- 0.43 MPa

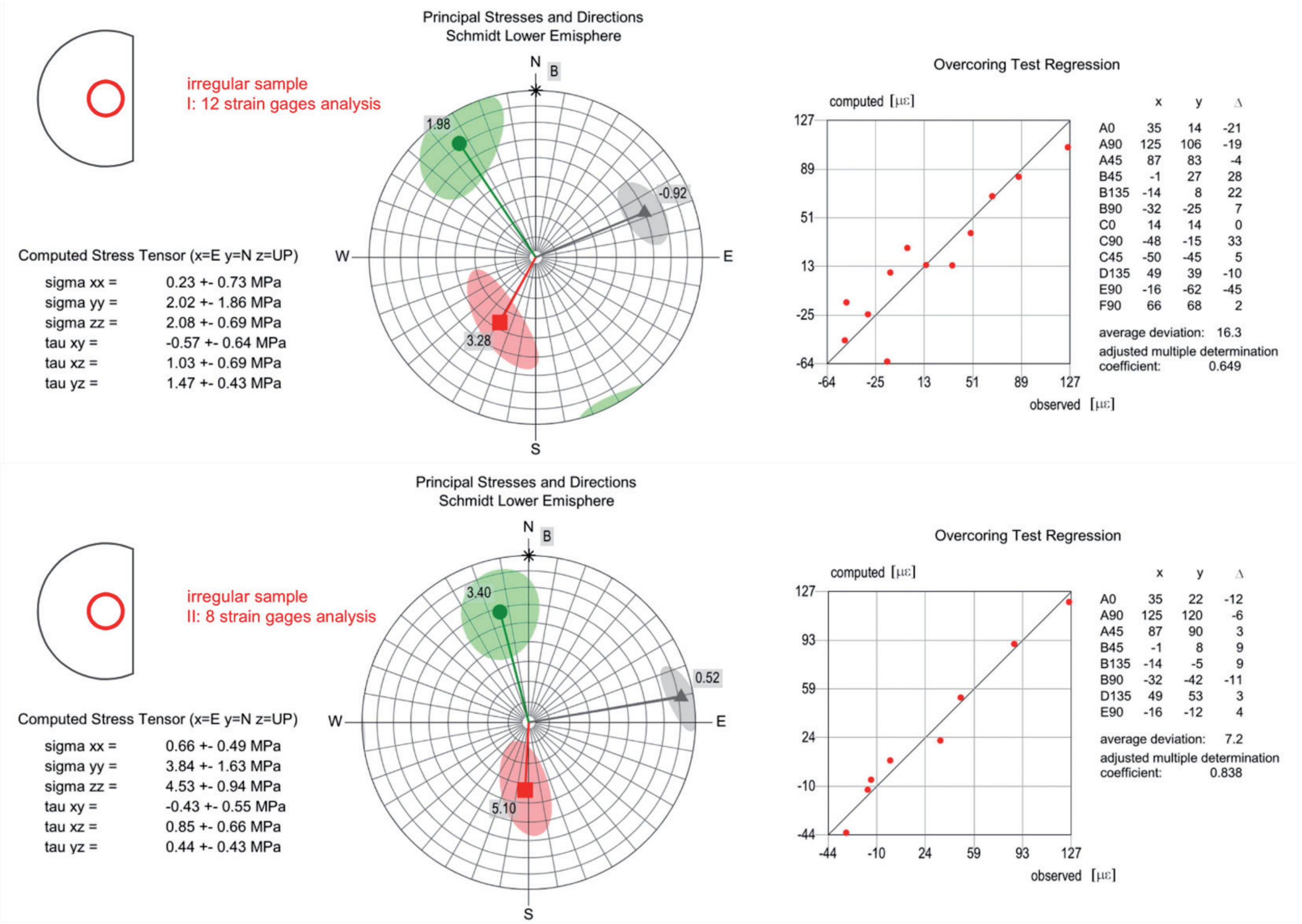
	x	y	Δ
A0	35	22	-12
A90	125	120	-5
A45	87	90	3
B45	-1	8	9
B135	-14	-5	9
B90	-32	-43	-11
D135	49	52	3
E90	-16	-12	4

average deviation: 7.1
adjusted multiple determination coefficient: 0.840

Fig. 5 - Results of the regression analyses I and II – the matrix [C] of the cylindrical sample is used. The adjusted multiple determination coefficient (R^2_a) is equal to 0.646 and to 0.840 in the analysis I and II, respectively. Red, green, and grey zones in the stereographic projection at the centre of the image represent Sigma 1 (S1), Sigma 2 (S2) and Sigma 3 (S3), respectively

In interpretation I, all the 12 strain gauges were considered in the multiple linear regression analysis; in interpretation II, the 4 anomalous strain gauges were discarded, and the regression analysis involved a set of 8 equations only.

The Figure 5 shows the results of regression analysis I and II, for the cylindrical core sample. The adjusted multiple



Computed Stress Tensor (x=E y=N z=UP)

sigma xx = 0.23 +- 0.73 MPa
sigma yy = 2.02 +- 1.86 MPa
sigma zz = 2.08 +- 0.69 MPa
tau xy = -0.57 +- 0.64 MPa
tau xz = 1.03 +- 0.69 MPa
tau yz = 1.47 +- 0.43 MPa

	x	y	Δ
A0	35	14	-21
A90	125	106	-19
A45	87	83	-4
B45	-1	27	28
B135	-14	8	22
B90	-32	-25	7
C0	14	14	0
C90	-48	-15	33
C45	-50	-45	5
D135	49	39	-10
E90	-16	-62	-45
F90	66	68	2

average deviation: 16.3
adjusted multiple determination coefficient: 0.649

Computed Stress Tensor (x=E y=N z=UP)

sigma xx = 0.66 +- 0.49 MPa
sigma yy = 3.84 +- 1.63 MPa
sigma zz = 4.53 +- 0.94 MPa
tau xy = -0.43 +- 0.55 MPa
tau xz = 0.85 +- 0.66 MPa
tau yz = 0.44 +- 0.43 MPa

	x	y	Δ
A0	35	22	-12
A90	125	120	-6
A45	87	90	3
B45	-1	8	9
B135	-14	-5	9
B90	-32	-42	-11
D135	49	53	3
E90	-16	-12	4

average deviation: 7.2
adjusted multiple determination coefficient: 0.838

Fig. 6 - Results of the regression analyses I and II – the matrix [C] of the irregular sample is used. The adjusted multiple determination coefficient (R^2_d) is equal to 0.649 and to 0.838 in the analysis I and II, respectively. Red, green, and grey zones in the stereographic projection at the centre of the image represent Sigma 1 (S1), Sigma 2 (S2) and Sigma 3 (S3), respectively

determination coefficient (R^2_a) turns out to be equal to 0.646 and to 0.840 in the analysis I and II, respectively.

The Figure 6 instead shows the results of linear regression I and II conducted on the irregularly shaped sample. In this case, the adjusted multiple determination coefficients were found to be 0.649 and 0.838 in analyses I and II, respectively.

DISCUSSION

The CSIRO HI Cell overcoring test represents an advanced and reliable methodology for obtaining information of in-situ stress state of rock masses, significantly contributing to the understanding and management of geotechnical slope and walls stability in critical engineering projects (Sarwade *et alii*, 2008; Lin *et alii*, 2019). The accuracy of these measurements is essential for studying the stability of open pits and underground mining sites, where rock stress can significantly influence the structural behaviour, the material yield and, primary, put at risk the quarrymen safety (Ferrero *et alii*, 2013; Gullì *et alii*, 2013; Salvini *et alii*, 2022).

During a stress measurements campaign at a marble quarry in the Apuan Alps extraction area (Italy), a core breakage occurred during overcoring due to a sub-vertical joint, parallel to the borehole axis, that, however, did not intersect the CSIRO HI cell. In fact, throughout the overcoring process the cell remained intact and provided the measurements of the 12 strain gauges and the thermistor.

Photogrammetric reconstruction and mesh editing techniques were utilized to precisely map the geometry of the irregularly shaped sample. High-resolution photographs taken from various angles facilitated the creation of accurate three-dimensional replicas of the rock core, providing an essential data for the numerical modelling. It is important to highlight how the value of a 3D model depends on the quality of the acquired images and the accuracy of the photogrammetry process: lighting conditions, image resolution, and the presence of shadows, for example, can highly influence the results.

The resulting mesh from the photogrammetric survey was employed to develop a procedure able to compute the stress tensor even in irregularly shaped samples. Meanwhile the classic interpretative procedure of a CSIRO stress release test refers to analytical formulations that assume the extracted sample is cylindrical (Amadei, 1983; Amadei, 1986), and no analytical solutions are available for irregular shaped samples, a Finite Element numerical simulation was set-up in this work to interpret the stress release. Usually, in the presence of a broken rock core, test results cannot be interpreted. Therefore, the methodology described in this paper could represent a significant advancement in CSIRO overcoring tests, allowing, for the first time, to interpret the results even in these conditions.

Using unitary stress computations, a matrix was computed for both the ideal cylindrical sample and the irregularly shaped one.

Examination of the experimental data revealed that the behaviour of the four strain gauges closest the crack (rosette C and strain gauge F90 of Figure 1) was most affected by this disturbance during the overcoring progress. Thus, two different analyses were conducted: one considered all the strain gauges of the CSIRO HI Cell in the multiple regression analysis, while the other discarded the anomalous strain gauges.

Comparison of results for the cylindrical core sample confirms that C0, C90, C45 and F90 strain gauges, showing anomalies in the overcoring plot of Figure 2, were the most affected by the core breakage. In fact, removing their equations from the overdetermined set significantly improves in R^2_a (Figure 5). Similarly, the multiple linear regression analysis applied to the cracked rock sample did not highlight significant differences: removing C0, C90, C45 and F90 strain gauges from the overdetermined set produces a significant improvement of R^2_a (Figure 6).

Both simulations demonstrate that removal of the equations related to the strain gauges closest to the fracture from the overdetermined sets produces a significant improvement in the adjusted multiple determination coefficient. No significant differences were found in the results of the regression analysis for the intact rock sample and the cracked one. Thus, in the actual case of this paper, the reduced rock stiffness of the cracked side of the sample did not affect the strain of the cell in a meaningful way. Due to the high ratio between the elastic modulus of the rock (80 GPa) and that of the cell material (2.6 GPa), the cell behaved as practically perfect "soft inclusion "and did not significantly hinder the strain of the surrounding rock sample. This leads to the conclusion that the anomalies of the strain gauges closest to the crack cannot be justified by the mechanical behaviour of the irregular shape of the sample and that, probably, they are due to non-uniform thermal effects caused by the variable thickness of rock present between the flushing drilling water and the strain gauges. That is, where the thickness was smaller, the thermal effect during overcoring was higher.

A question arises: what is the rock elastic modulus when the influence of the inclusion becomes evident? To answer this, Figure 7 summarizes the results of some more FEM simulations that were carried out assuming variable elastic moduli. In the typical range of the rock material elastic modulus (E = 10 – 100 GPa) the mechanical effect of the irregular shape is negligible and the classical interpretation, based on analytical formulation for the cylindrical sample, gives reliable test results. It provides that the anomalous strain gauge responses can be detected in the overcoring plots and excluded from the regression analysis.

The analysis carried out shows that, when rock material elastic moduli exceed 8 GPa, the difference in the first stress invariant "I1" (*i.e.*, S1+S2+S3 in Figure 7) between the cylindrical and irregular sample has an order of magnitude of 1%. Only for rock material moduli below 8 GPa the delta exceeds 1%. In other words, for most of the typical rock materials the mechanical effect of the irregular shape is negligible.

CONCLUSIONS

The conducted research demonstrated the effectiveness of an innovative methodology based on the utilization of CSIRO HI Cell overcoring technique for assessing the stress state in

E rock [GPa]	Shape	S1 [MPa]	S2 [MPa]	S3 [MPa]	S1+S2+S3 [MPa]
80	cylindrical	5.1	3.4	0.52	9.02
	cracked	5.14	3.44	0.53	9.11
				Δ[%]	1
8	cylindrical	5.1	3.35	0.66	9.11
	cracked	5.2	3.4	0.43	9.03
				Δ[%]	1
0.8	cylindrical	5.1	2.93	-0.09	7.94
	cracked	5.61	3.11	-0.02	8.7
				Δ[%]	10

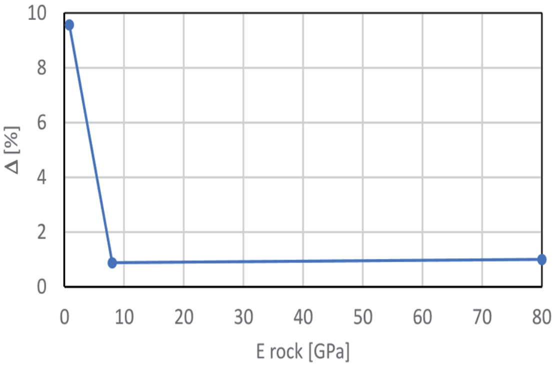


Fig. 7 - Results of the FEM simulations with variable rock material elastic moduli. The table and the plot show the delta (Δ%) of the first stress invariant "I1" versus the rock material's elastic modulus E

rock masses, even in the presence of irregularly shaped rock cores. Through the implementation of methodologies such as digital photogrammetry and finite element modelling, it was possible to obtain a detailed representation of a cracked rock sample complex geometry, enabling to accurately assess the stress and deformation distribution. The applied multiple linear regression procedure extended the applicability of stress state determination beyond the traditional cylindrical shaped samples, allowing the analysis even to irregularly shaped cores.

A final and fundamental conclusion can be drawn: in the typical range of the rock material elastic moduli (E = 10 – 100 GPa) the mechanical effect of the irregular shape of the sample is negligible, and the classical interpretation based on analytical formulation for the cylindrical sample give reliable results, provided that: *i)* the cell does not break prematurely during the overcoring; *ii)* eventual anomalous strain gauge responses can be detected in the experimental plots and excluded from the regression analysis. The classical interpretation, based on analytical formulations for cylindrical samples, remains reliable, provided such considerations are taken into account.

In conclusion, the integration of CSIRO overcoring tests, photogrammetry, 3D modelling, finite element and multiple linear regression analyses constitutes a robust methodology for assessing the stress state, even in irregularly shaped rock cores.

This study establishes a strong groundwork for future research to explore the applicability of the presented methodologies to different rock types with varying elastic parameters. The methodologies outlined here provide valuable tools for geotechnical engineers and researchers in rock mechanics, particularly in addressing challenges related to irregularly shaped and fractured rock samples.

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