International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Multi-scale monitoring of rock mass deformations in a mid-latitude climatic context through a Fiber Bragg Grating array

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Abstract

Variations in the stress state, influenced by factors like pore water pressure, temperature changes, and freezing/thawing cycles, cause strain in outcropping rock masses. Thermo-mechanical deformations in jointed rock masses can be significant at mid-latitudes, where progressive strain accumulation is controlled by local fracturing and exposure conditions. Consequently, the strain field is strongly scale-dependent. To investigate these topics, the Acuto Field Laboratory (AFL) has been operating since 2016 to investigate those natural processes governing rock mass deformation and acting as preparatory factors of rock slope instabilities. A multi-parametric monitoring system, consisting of seismic, stress-strain and thermal sensors, as well as optical cameras, was installed on a sub-vertical rock wall inside an abandoned quarry. Recent technological advancements have enabled the use of both traditional and innovative sensors, such as Fiber Bragg Grating (FBG) arrays for strain and rock temperature monitoring. Unlike traditional strain devices that provide measurement on a single point or joint, FBG arrays allow for measurements along variable-length baselines. In the case of the AFL, three FBG baselines of increasing length have been installed in three directions (i.e., vertical, horizontal, and diagonal) on a rock mass section exposed to thermal forcing, covering approximately 2 m^2. The strain measured along each FBG baseline represents the cumulative deformation of the rock matrix and fractures intersecting that measuring baseline, thus providing the net strain response of the fractured rock mass. The collected measurements are currently being analysed and will be used to train an artificial neural network to investigate the relationship between environmental factors and rock mass deformations.

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Keywords

Rock masses, rock slope deformation, FBG monitoring, Acuto Field Lab

1 Introduction

Thermomechanical effects heavily influence the stability of rock slopes, as they can result from continuous and transient thermal stresses interacting with rock masses. Local climatic regions strongly control the intensity and effectiveness of thermal stresses, as well as the induced thermomechanical cracking (Aldred et al. 2015). Temperature fluctuations exert slight yet repeated perturbations of local stress fields over daily and seasonal cycles, leading to progressive mechanical weathering and deterioration of rock matrix and fracture properties (Merrien-Soukatchoff and Gasc-Barbier 2023). Thermomechanical effects can cumulate over long timescales, aiding in the destabilisation of rock masses over time and thus determining an increase in the probability of slope failures.

Rock slopes with pervasive fracturing conditions are particularly susceptible to thermomechanical effects because fracture density and orientation significantly constrain the propagation of thermal stresses and the accumulation of irreversible deformations (Marmoni et al. 2020). Environmental factors such as solar radiation, heavy rainfall, and ambient vibrations can further exacerbate near-surface fatigue processes (Gunzburger et al. 2005). However, the role of thermally induced stresses and their interaction with other triggers still need to be better understood, especially because they can operate in both critical and subcritical stress states (Eppes and Keanini 2017).

Advancements in sensing technologies, such as Fiber Bragg Grating (FBG) optical fiber arrays, have provided new opportunities for high-resolution monitoring of structural responses. FBG sensors allow for the real-time detection of stress variations and irreversible deformation processes due to their sensitivity to subtle strain and temperature changes. These systems have been successfully used for monitoring engineering structures, offering valuable insights into the spatial and temporal evolution of stress and strain fields (Marazzi et al. 2010). Nowadays, the application of FBG technology has expanded from structural engineering applications to the monitoring of fractured rock masses (Liang et al. 2022; Zhu et al. 2023; Ren et al. 2024). Monitoring the long-term thermomechanical behaviour of rock masses is particularly promising for capturing the cumulative effects of daily and seasonal thermal cycles and detecting precursor instability signals.

A comprehensive analysis integrating multi-parametric monitoring with advanced numerical modelling is critical for understanding these complex natural processes (Marmoni et al. 2020). This integrated approach is essential for accurately predicting the timing and location of slope failures, offering significant insights into developing strategies for geological risk mitigation and protecting natural and cultural heritage sites.

In this study, we present a pioneering application of FBG arrays on a fractured rock mass outcrop at the Acuto Field Lab (AFL), a natural laboratory designed for investigating preparatory and triggering factors of rock fall phenomena (Grechi et al. 2022). Using this advanced technology, we aim to better understand the 3D deformational behaviour of an intensely fractured rock wall exposed to a wide range of environmental stresses, the most significant of which are the near-surface temperature fluctuations.

2 Acuto Field Laboratory

The AFL, which has been operating since 2015, is a research pilot site dedicated to investigating rock mass instability and its influencing preparatory and triggering factors through long-term multi-parametric monitoring approaches. The AFL is located inside an abandoned limestone quarry within the municipality of Acuto, Lazio (Italy), and it is managed by the Department of Earth Sciences of Sapienza University of Rome and the Research Centre for the Prediction, Prevention, and Control of Geological Risks - CERI.

The field laboratory features a sub-vertical quarry rock wall, 200 m long and 50 m high, composed of intensely jointed Cretaceous micritic limestones. The quarry, which ceased operations in the late 1970s, was initially developed to excavate inert rockfill, with the vertical cliff shaped by manual excavation and controlled explosions. This combined excavation approach determined a high predisposition to block detachments from the quarry rock wall, with individual blocks of several cubic meters in volume

(Fiorucci et al., 2020). Due to these specific geohazards, the site has been repurposed for research, education, and risk dissemination activities without invasive structural interventions, hence exemplifying a sustainable recovery model.

The AFL is divided into three distinct monitoring sectors for ongoing experiments: i) the Rock Block Sector (RBS), which targets a 20 m^3 block prone to fall; ii) the Rock Tower Sector (RTS), characterized by a detached 150 m^3 toppling rock slab; and iii) the Stable Rock Mass Sector (RMS), where no significant block instabilities are evident. Extensive instrumentation has been deployed across these sectors, including fully equipped weather stations, rock thermometers, heat flux cells, strain gauges, crack meters, FBG arrays and geophysical sensors, such as geophones and acoustic emission sensors. Multiple data acquisition systems support continuous and triggered monitoring modes, with power supplied by local infrastructures, solar panels, and back-up batteries. Real-time data transmission is ensured via a radio link connection to a cloud server hosted at the Department of Earth Sciences of Sapienza University.

In situ and remote geomechanical surveys allowed the identification of five fracture sets, with their kinematic compatibility assessed for rockfall, planar and wedge sliding, and toppling mechanisms. The susceptibility of the rock wall to these failure mechanisms decreases from rockfall to toppling, which feature the highest and lowest probability of occurrence, respectively. In order, starting from the bedding, the fracture sets have the following orientations (dip direction/dip): J0 (130/17), J1 (300/84), J2 (350/90), J3 (200/84), and J4 (94/85). The physical and mechanical properties of the rock matrix were determined through geotechnical laboratory analyses (Marmoni et al., 2020), while fracture parameters were directly measured in situ (Fiorucci et al., 2020).

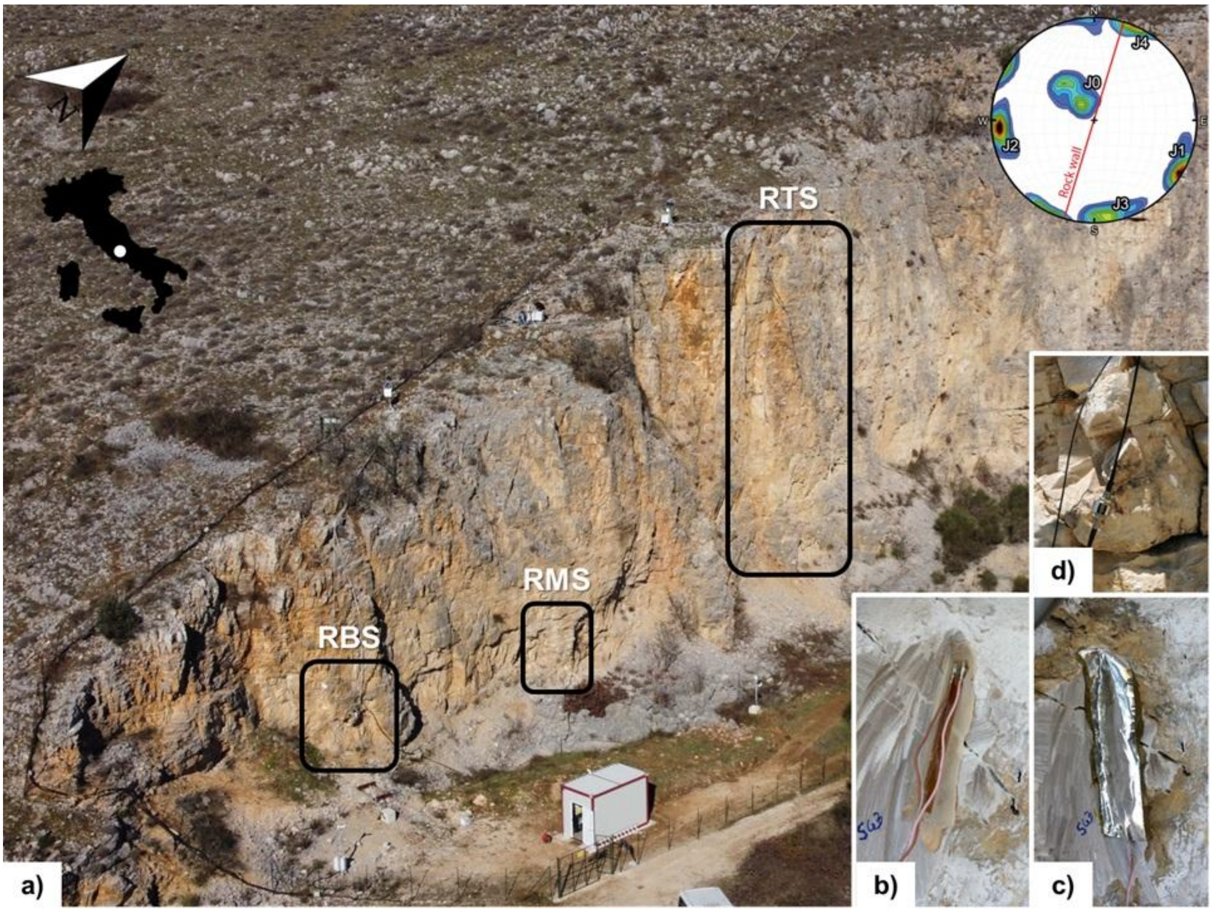

Fig. 1 Panoramic view of the quarry rock wall monitored at the Acuto Field Laboratory. Black boxes highlight the three monitored sectors. The main fracture sets identified are shown by the stereographic projection in the upper-right inset (a). Example of strain gauge installed crossing a single microfracture (b). The same strain gauge is covered by protective aluminium foil (c). An anchor point of the FBG array that splits two segments of the diagonal baseline (d).

3 Materials and Methods

To evaluate the deformational behaviour of the rock mass rather than individual fractures, this research employs an FBG array covering a 2 m² surface through three measurement baselines with different orientations and lengths. While the deformational behaviour of individual fractures can be easily monitored using strain gauges and crack meters, in situ monitoring of rock mass behaviour remains a challenge. This study aims to address this issue by leveraging this advanced technology.

FBGs are periodic microstructures within optical fibers that serve as narrowband filters, reflecting light at the Bragg wavelength (λB), which is determined by the grating periodicity and the refractive index of the fiber core. The light outside this spectral range passes through the fiber with minimal loss. Due to their symmetric structure, FBGs reflect the Bragg wavelength irrespective of the light's direction of incidence. Due to their characteristics, FBGs are widely used to detect strain and temperature variations. Mechanical deformation alters the grating periodicity and the refractive index through the photoelastic effect, resulting in a shift in the Bragg wavelength. Temperature sensitivity primarily arises from the thermo-optic effect, with a minor contribution from silica's low thermal expansion coefficient. As optical fiber-based sensors, FBGs offer several advantages: low signal attenuation, immunity to electromagnetic and radiofrequency interference, compact size, lightweight design, intrinsic safety in hazardous environments, high sensitivity, and long-term reliability. These features make FBGs ideal for precise monitoring in challenging and demanding conditions.

The FBG array installed at the AFL consists of three measuring baselines (designated A, B, and C) with different inclinations relative to the ground surface (Fig. 2). Measurement line A is horizontal and approximately aligned with the rock mass bedding; measurement line B dips 45°, while measurement line C is nearly vertical. Each baseline is further divided into segments between anchor points, along which the system provides deformation values in microstrain:

- Segment A1 (40 cm in length, measured between anchors) contains two discontinuities, while segment A2 (40 cm in length) contains three discontinuities;
- Segment B1 (43 cm in length) contains two discontinuities, segment B2 (40 cm in length) contains three discontinuities, and segment B3 (78 cm in length) contains three discontinuities;
- Segment C1 (43 cm in length) contains five discontinuities, segment C2 (40 cm in length) contains three discontinuities, segment C3 (80 cm in length) contains nine discontinuities, and segment C4 (80 cm in length) contains five discontinuities.

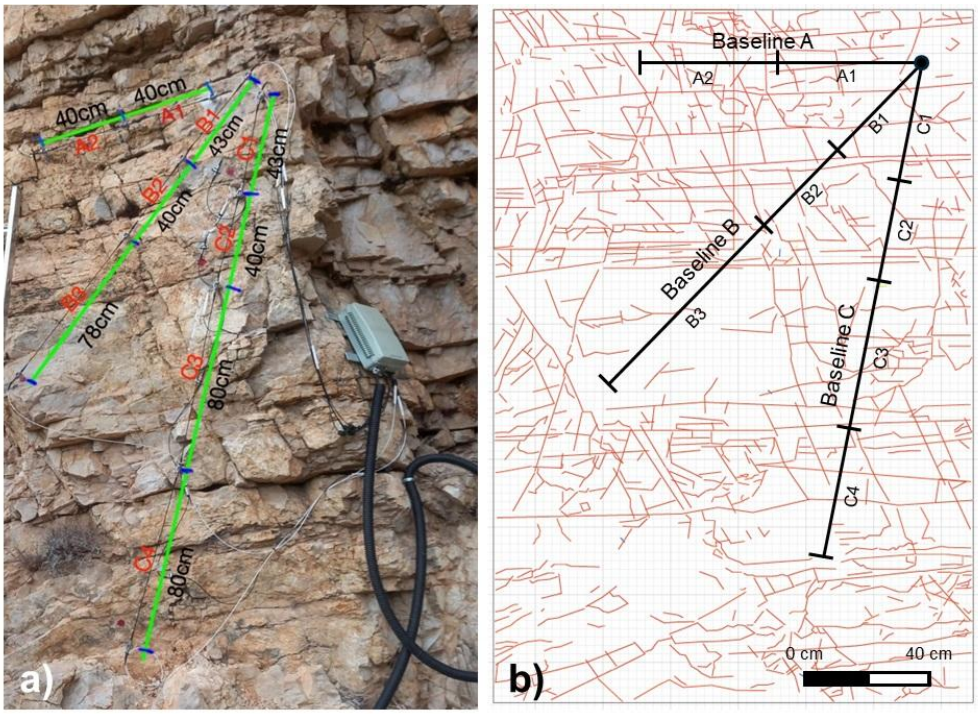

Figure 2. Arrangement of FBG array on the selected rock mass sector (a), and digitised fracture traces identified in the monitored rock mass area (b).

4 Results

The strain recorded along different segments of the FBG has been resampled to hourly format and presented as a time series for the observed period that spans almost three years, from July 2021 to March 2024. Long-term deformational trends can be observed for each segment, reaching deformation at least higher than 300 μstrain per segment over the entire monitoring period (Fig. 3). The cumulative displacements calculated for the three baselines of the FBG array and obtained converting strain in displacement according to the total length of the baselines are presented in Figure 4. It is not possible to make a direct comparison with the deformations obtained using traditional strain gauges for two main reasons: (i) in the RMS sector, which is monitored with the FBG array, no strain gauges are installed, whereas they are present in the RBS and RTS sectors (see Fig. 1); (ii) while strain gauges provide the deformation associated with a single discontinuity element, each segment of the FBG array returns a cumulative deformation value along its length, which accounts for the various discontinuities intersecting that specific measurement base. However, beyond this specific distinction, the deformations recorded during the diurnal cycle are comparable in magnitude between the two sensor types (see Fig. 3b). Finally, the quantitative description of displacement along different baselines and their segments, along with the number of fractures cross-cutting these segments, is presented in Table 1. The cross-cutting fractures have been categorised into stratification and vertical joints for further analysis and interpretation.

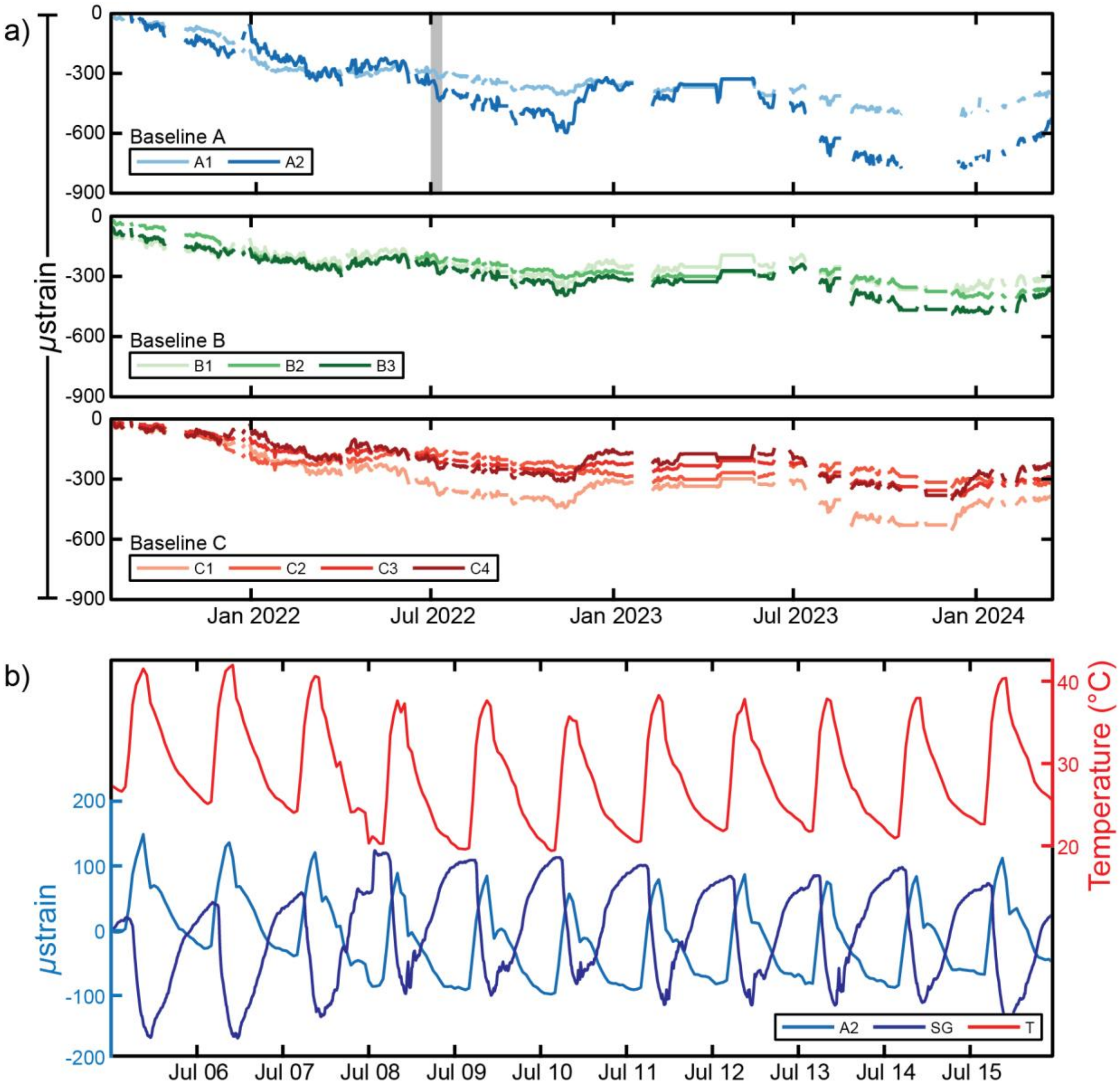

Figure 3. Time series of micro-strain measured along several segments belonging to the three different baselines of the FGB array (a). Comparison among temperature, strain recorded by A2 segment, and strain recorded by traditional strain gauge sensor over a pluri-daily time window.

The following inferences can be drawn from the results obtained:

- Strain Concentration: Strain measurements revealed higher concentrations towards the horizontal arm of the rock quarry wall, indicating that structural orientation influences stress distribution. The data suggest that deformation is not uniformly distributed, likely due to the interaction between stress direction and joint orientations.
- Deformation Patterns: The deformation hierarchy illustrates that fracture density significantly impacts strain behaviour. Notably, portions of similar length exhibited different deformation levels, suggesting that factors like fracture density and spatial distribution are key drivers of strain variability.
- Fracture Influence: Comparative analysis between A1 and B2, and A2 and C2 revealed that regions with higher vertical fracture density experience greater deformation. Vertical fractures appear to accommodate more strain compared to horizontal ones, highlighting the critical role of fracture orientation in determining deformation responses.
- Rock Quality Effects: A2 demonstrated higher deformation than A1, despite A1 being characterized by a higher fracture density. This anomaly is attributed to differences in rock quality, with A2 likely having reduced cohesion or increased brittleness, exacerbating deformation. Similarly, C1 exhibited more deformation than C2 due to its higher fracture density and the presence of vertical fractures, emphasizing the combined effects of fracture density and orientation.
- Strain Accumulation: B3 displayed a higher displacement per centimetre than B1, aligning with B3's greater joint density and the presence of additional vertical fractures. This result underscores the proportional relationship between joint density and strain, with vertical joints playing a dominant role in localizing deformation.

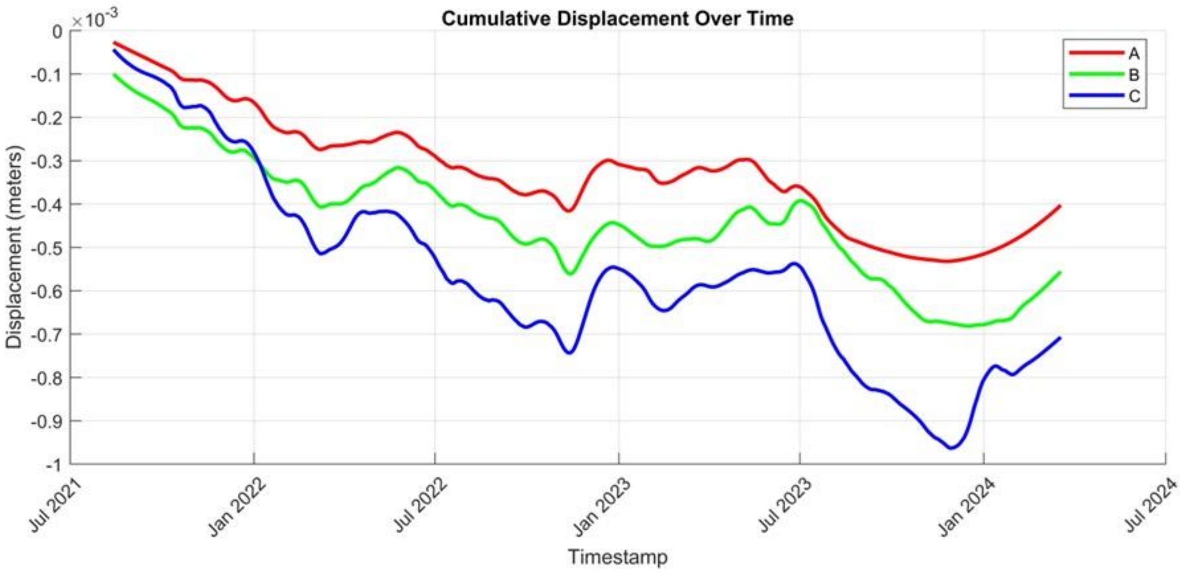

Figure 4. Time series of cumulative displacement calculated along the three baselines of the FBG array.

Table 1. Final cumulative displacement along different baselines and segments of FBG, along with a number of fractures crosscutting specific segments. The asterisk (*) associated with "fractures" indicates the number of fractures crosscutting a particular baseline or segment of FBG.

	Horizontal	**Oblique**	**Nearly Vertical**
Baseline	A	B	C
Length (cm)	80	161	243
Disp(cm)*10 $^{-2}$	-3.545	-4.235	-6.208
Disp/ cm of baseline (*10 $^{-4}$)	-4.43	-2.63	-2.50

Fractures*	7		13			25			
Fractures*/cm of baseline	0.087		0.081			0.103			
Segments	A1	A2	B1	B2	B3	C1	C2	C3	C4
Length (cm)	40	40	43	40	78	43	40	80	80
Disp(cm)×10 $^{-2}$	-1.480	-2.064	-0.839	-1.140	2.255	-1.451	-1.105	-2.018	-1.631
Disp (cm)×10 $^{-4}$ per cm of segment	-3.70	-5.16	-1.95	-2.85	-2.89	-3.37	-2.76	-2.52	-2.03
Fractures*	4	3	2	4	7	6	3	8	8
Fractures*/cm of segment	0.100	0.075	0.046	0.100	0.089	0.139	0.075	0.100	0.100
Stratification	0	0	2	3	4	5	3	5	4
Vertical	4	3	0	1	3	1	0	3	4

5 Conclusion

This study investigated the thermo-mechanical deformations of fractured rock masses using Fiber Bragg Grating (FBG) sensor arrays at the Acuto Field Laboratory (AFL). Despite the preliminary nature of the obtained results, several key points can be highlighted, primarily from a technological perspective. The FBG array has proven to be a useful tool for recording deformations in fractured rock masses exposed to exogenous agents over variable measurement lengths. The analysis of the initial results has shown that the deformation of fractured rock masses is influenced by joint orientation, with higher strain amplitude recorded over horizontal segments, while strain variability is linked to fracture density and spatial distribution, with vertical fractures accommodating more stress; strain accumulation depends not only on fracture density but also on the mechanical properties of the rock mass, and temperature fluctuations play a significant role in mechanical weathering and instability. Finally, it is possible to say that the study underscores the potential of FBG arrays for long-term rock mass monitoring, providing insights into deformation mechanisms, capturing cumulative strain, and offering a broader measurement scope compared to traditional strain gauges.

Acknowledgements

The study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

References

Aldred J, Eppes MC, Aquino K, Deal R, Garbini J, Swami S, Tuttle A, Xanthos G (2016) The influence of solar-induced thermal stresses on the mechanical weathering of rocks in humid mid-latitudes. Earth Surface Processes and Landforms 41(5), 603-614. https://doi.org/10.1002/esp.3849.

Eppes MC, Keanini R (2017) Mechanical weathering and rock erosion by climate-dependent subcritical cracking. Reviews of Geophysics 55(2), 470-508. https://doi.org/10.1002/2017RG000557.

Fiorucci M, Martino S, Bozzano F, Prestininzi A (2020) Comparison of approaches for data analysis of multi-parametric monitoring systems: insights from the Acuto test-site (Central Italy). Applied Sciences 10(21), 7658. https://doi.org/10.3390/app10217658.

Grechi G, Fernandes JR, Jean-Pierre H, Le Gallais AC, Sampieri H, Amato G, D'Angiò D, Fiorucci M, Iannucci R, Marmoni GM, Martino S (2022) Explorative data analysis from multiparametric monitoring at the Acuto Field Laboratory (Central Italy) for detecting preparatory conditions to rock block instabilities. Italian Journal of Engineering Geology and Environment (2), 59-77. https://doi.org/10.4408/IJEGE.2022-02.O-05.

Gunzburger Y, Merrien-Soukatchoff V, Guglielmi Y (2005) Influence of daily surface temperature fluctuations on rock slope stability: case study of the Rochers de Valabres slope (France). International Journal of Rock Mechanics and Mining Sciences 42(3), 331-349. https://doi.org/10.1016/j.ijrmms.2004.11.003.

Liang M, Fang X, Song Y, Li S, Chen N, Zhang F (2022) Research on three-dimensional stress monitoring method of surrounding rock based on FBG sensing technology. Sensors 22(7), 2624. https://doi.org/10.3390/s22072624.

Marazzi F, Tagliabue P, Corbani FM (2011) Traditional vs innovative structural health monitoring of monumental structures: A case study. Structural Control and Health Monitoring 18(4), 430-449. https://doi.org/10.1002/stc.382.

Marmoni GM, Fiorucci M, Grechi G, Martino S (2020) Modelling of thermo-mechanical effects in a rock quarry wall induced by near-surface temperature fluctuations. International Journal of Rock Mechanics and Mining Sciences 134, 104440. https://doi.org/10.1016/j.ijrmms.2020.104440.

Merrien-Soukatchoff V, Gasc-Barbier M (2023) The Effect of Natural Thermal Cycles on Rock Outcrops: Knowledge and Prospect. Rock Mechanics and Rock Engineering 56(9): 6797-6822. https://doi.org/10.1007/s00603-023-03420-1.

Morcioni A, Apuani T, Cecinato F (2022) The role of temperature in the stress–strain evolution of Alpine rock-slopes: thermo-mechanical modelling of the Cimaganda rockslide. Rock Mechanics and Rock Engineering 55(4), 2149-2172. https://doi.org/10.1007/s00603-022-02786-y.

Ren C, Sun X, He M, Tao Z (2024) Application of FBG Sensing Technology for Real-Time Monitoring in High-Stress Tunnel Environments. Applied Sciences 14(18), 8202. https://doi.org/10.3390/app14188202.

Zhu Y, Wang S, Liu B, Liu X, Kang Y (2023) Monitoring Technology of Surrounding Rock Deformation Based on IWFBG Sensing Principle and Its Application. Lithosphere 2023(1): lithosphere_2023_278. https://doi.org/10.2113/2023/lithosphere_2023_278.