DAL SISMA ALLA PREVISIONE:

A COLLEPOSTA NASCE L'INGEGNERIA CHE "ASCOLTA" GLI EDIFICI

La Chiesa di Santa Maria delle Grazie a Colleposta
diventa il simbolo mondiale della nuova sicurezza strutturale

di Ing. Diego Dell'Erba



Dopo il terremoto del 2016 nel Centro Italia, la Chiesa di Santa Maria delle Grazie a Colleposta (Accumoli) è diventata il teatro di un intervento ingegneristico rivoluzionario.

Non si è trattato di un semplice consolidamento di emergenza.
Si è trattato del passaggio da una sicurezza strutturale tradizionale a una ***sicurezza continua, misurata e intelligente****.*

Anno 2026

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C'è un luogo, nel cuore ferito del cratere sismico del 2016, dove l'ingegneria ha smesso di aspettare il danno.

E ha iniziato a prevederlo.

Quel luogo è **Colleposta**, frazione del Comune di Accumoli.
E il simbolo di questa rivoluzione è la **Chiesa di Santa Maria** delle Grazie

Non un laboratorio.
Non un prototipo.

Ma un edificio reale, colpito dal sisma, che oggi rappresenta una delle **prime applicazioni concrete al mondo** di monitoraggio strutturale continuo con tecnologie avanzate.

COLLEPOSTA: QUI È NATA LA SVOLTA

Dopo il terremoto del 2016, la domanda era una sola:

come evitare che la sicurezza si limiti a un controllo iniziale?

La risposta è arrivata proprio da Colleposta.

Sulle murature della Chiesa di Santa Maria è stato installato un sistema innovativo basato su **sensori in fibra ottica** capaci di:

- rilevare deformazioni invisibili
- registrare variazioni nel tempo
- misurare effetti dinamici e ambientali
- monitorare lo stato reale della struttura

Ma soprattutto:

TRASFORMARE L'EDIFICIO IN UN SISTEMA CHE "PARLA"

UN CASO UNICO CON RISCONTRI INTERNAZIONALI

L’esperienza della Chiesa di Colleposta non è rimasta un episodio locale.

È diventata:

- oggetto di **pubblicazioni scientifiche internazionali**
- caso studio nel campo dello **Structural Health Monitoring (SHM)**
- riferimento per l’applicazione reale della sensoristica nel costruito storico

Non una simulazione.
Non un modello teorico.

UN’OPERA VERA CHE GENERA DATI REALI

LE UNIVERSITÀ CONFERMANO: NON È TEORIA

A rafforzare questa esperienza arrivano tre tesi universitarie tra:

- **Sapienza Università di Roma**
- **Università Roma Tre**

Che studiano proprio applicazioni concrete come:

- il monitoraggio con fibra ottica
- l’integrazione con Digital Twin
- l’analisi dei dati strutturali nel tempo

E ancora una volta emerge un elemento chiave:

l’Ing. Diego Dell’Erba è correlatore
ma soprattutto è **protagonista operativo delle applicazioni**

Questo significa una cosa sola:

IL CANTIERE HA ANTICIPATO LA RICERCA

IL NUOVO MODELLO DI SICUREZZA

Per decenni l’ingegneria ha funzionato su un principio semplice:

- si costruisce
- si controlla

- si interviene dopo

Oggi, a Colleposta, questo schema è stato superato.

Perché la Chiesa di Santa Maria delle Grazie dimostra che è possibile:

- monitorare continuamente
- comprendere l’evoluzione della struttura
- intervenire prima che il problema diventi danno

IL RUOLO DELL’ING. DIEGO DELL’ERBA

Dietro questa applicazione c’è una visione precisa.

L’Ing. Diego Dell’Erba ha portato nel cantiere:

- la sensoristica avanzata
- l’integrazione con i dati
- un approccio operativo alla sicurezza

Non ha introdotto solo strumenti.

Ha introdotto un principio:

LA SICUREZZA NON È UN MOMENTO. È UN PROCESSO CONTINUO

NASCE LA CYBER–PHYSICAL STRUCTURAL SAFETY

Da Colleposta prende forma un nuovo paradigma:

CYBER–PHYSICAL STRUCTURAL SAFETY (CPSS)

Un sistema in cui:

- la struttura reale
- i sensori
- i dati
- l’intelligenza digitale

operano insieme in tempo reale.

Non più edifici statici.

MA SISTEMI VIVI CHE SI RACCONTANO

DAL REATINO AL MONDO

Ciò che è nato a Colleposta oggi ha un valore più ampio.

Non è solo un intervento locale.

È:

- ***un modello replicabile***
- ***una base scientifica***
- ***una nuova cultura della sicurezza***

IL MESSAGGIO PIÙ FORTE

La Chiesa di Santa Maria lo dimostra ogni giorno.

Un edificio può:

- ***essere ascoltato***
- ***essere compreso***
- ***essere protetto nel tempo***

E allora la domanda cambia:

possiamo ancora accettare edifici che non vengono monitorati?

CONCLUSIONE

Dal sisma del 2016 è nata una nuova ingegneria.

Non quella che interviene dopo.

QUELLA CHE PREVEDE PRIMA

Le università lo confermano.

Le pubblicazioni lo dimostrano.

Ma soprattutto:

COLLEPOSTA LO RACCONTA, OGNI GIORNO, ATTRAVERSO I SUOI DATI

Il futuro della sicurezza non è più una promessa.

È già installato sulle nostre murature.

IN APPENDICE ARTICOLO INTERNAZIONALE E IMMAGINI TESI UNIVERSITARIE IN INGEGNERIA STRUTTURALE MAGISTRALE ASSEGNATE DALLE UNIVERSITA' LA SAPIENZA E ROMA3

Journal of Civil Structural Health Monitoring
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APPLICATION BASED

Use of fibre optic sensors for structural monitoring of temporary emergency reinforcements of the church S. Maria delle Grazie in Accumoli

Michele Arturo Caponero[1] · Diego Dell'Erba[2] · Corrado Kropp[2]

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Abstract
After natural disaster, damaged buildings need emergency reinforcements to recover to a stable structural condition. Since emergency reinforcements are components whose tension/compression is affected by the evolution of the static equilibrium of the supported structures, they can be instrumented to perform quasi-static structural monitoring. Fibre optic sensors based on the Bragg grating technology are well suited to instrument emergency reinforcement, as they allow easy installation, simple in-series cabling, and reliable long-term discontinuous monitoring with no unpredictable bias drifting in between successive monitoring campaigns. In this paper, we present an application on the early emergency reinforcements of the church Santa Maria delle Grazie in Colleposta, a small renaissance church damaged after the earthquake which interested central Italy in August 2016. As an emergency reinforcement, the church perimeter walls were confined by external wrapping. Sensors acting as strain gauges in temperature compensation regime were prepared custom, ready for installation on wrapping cables and along a vertical section of the wall. Results from monitoring campaigns in a 5-month time-span, seismic settling-down activity still being present, are presented, showing the easy installation and the effectiveness of the proposed procedure to monitor the working condition of the temporary emergency reinforcements.

Keywords Fibre optic sensor (FOS) · Fibre bragg grating (FBG) · Smart structures · Smart emergency structures

1 Introduction

Emergency intervention on damaged buildings after disaster events starts with technical survey, usually addressed by referenced methodology and form filling. Structural damage is then evaluated, usually based on the identification of macro-elements and kinematic mechanisms activated by the occurred events [1, 2]. After structural damage has been evaluated, the design of emergency shoring and strengthening is prepared, to avoid structural collapsing and damage worsening. Line guides and prescriptions issued by technical bodies and governmental authorities usually address technical questions about design, construction and dimensioning of shoring, confining wrapping and other suggested reinforcements [3]. As a matter of fact, according to experienced past disaster management, the emergency interventions often assume medium- or even long-term character because of reasons spanning from technical to budgetary. Definitive intervention in the long term is quite frequent in case of earthquakes because of the recurrent settling-down activity. Moreover, if earthquake occurred in populated area, activity of ruin removal can be difficult and time-consuming because of the presence of materials previously allowed for construction and later banned for health and environment protection. One more cause of delay for definitive intervention after earthquakes is the necessary seismic retrofitting, which can necessitate complex technical solutions, especially in case of partially collapsed buildings not to be fully demolished. Ruin removal and planning seismic retrofitting is of particular concern in case of cultural heritage and

✉ Michele Arturo Caponero
michele.caponero@enea.it

Diego Dell'Erba
info@ingdiegodellerba.it

Corrado Kropp
info@ingdiegodellerba.it

[1] ENEA Research Centre Frascati, via Enrico Fermi 45, 00044 Frascati, RM, Italy

[2] INGEGNERIA INTEGRATA di Ing. Diego Dell'Erba, via delle Ciliegie 141/B, 00172 Rome, RM, Italy

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historical buildings. In fact, highly conservative interventions usually require 'ad hoc' solutions and ruin removal must be done aiming at conservation and reuse of materials with preservation of external appearance. Planning seismic retrofitting often requires experimental investigations since reference structural models are not reliable for cultural heritage, particularly in case of large architectural complex partially rebuilt and modified in past centuries [4].

After emergency reinforcements, the use of structural monitoring is a common practice: to warn about damage worsening thus providing safe working condition; to identify residual structural integrity thus best addressing the final repair intervention. Structural monitoring is often done by use of valuable procedures and permanent monitoring systems which are laid out on the damaged building itself [5–7] and, to the best knowledge of the authors, do not usually take advantage of the potential usefulness of the temporary reinforcements. Emergency reinforcements are devices whose tension/compression evolution is directly related to the quasi-static behaviour of macro-elements of the damaged building. Monitoring the working condition of the emergency reinforcements cannot provide full evaluation of the evolution of the structural condition of the damaged building. Nonetheless, in the after disaster emergency, it can effectively provide information about the quasi-static structural behaviour of macro-elements whose residual integrity, because of the constraints due to the reinforcements themselves, is quite difficult to be evaluated by use of dynamic techniques and non-distributed static measurements. Instrumented emergency reinforcements can be most useful in case of earthquakes with important settling-down seismic activity. In fact, they can provide immediate and direct information about the effect of new seismic events occurring after the emergency intervention, either calling for further strengthening or confirming unchanged static condition.

In this paper, we present a demonstrative monitoring system based on fibre optic sensors installed on early emergency reinforcements of the church Santa Maria delle Grazie (Accumoli Colleposta, IT). The custom fibre optic sensors allowed easy installation by epoxy resin and simple in-series cabling. The peculiar features of the adopted FBG (fibre Bragg grating) technology allows reliable and stable long-term data taking, both continuous and discontinuous, in the absence of signal bias drifting. Results from monitoring campaigns in the early after earthquake period are presented. The monitoring systems is still in place and fully operative, used for less frequent periodic monitoring campaign by a private construction company planning to use the collected data to best address the definitive structural recovery intervention to come with the reconstruction activity in that area.

2 Principle of operation of FBG sensors

FBG sensors are fibre optic sensors sensitive to both strain and temperature [8, 9]. We briefly recall that FBG sensors are made by modifying a short segment of a long optical fibre; the segment usually is about 10 mm long. Such modification can be described as a Bragg grating, made by a periodic modulation with pitch Λ of the refraction index n of the optical fibre; the modulation is along the axis of the optical fibre. The modified segment acts as sensor; the non-modified length of the optical fibre acts as signal delivery link. The sensor can be interrogated by use of various techniques. In the following, to recall the principle of operation of the FBG sensors, we consider a technique based on launching some continuous broadband light wave into the fibre. When the light reaches the sensor, some quasi-monochromatic light is back reflected by the sensor. The wavelength λ of the quasi-monochromatic light depends on both the thermal and the mechanical conditions of the fibre at the location of the sensor. Thus, any variation of the temperature ΔT and/or strain ε produces a variation of the back reflected wavelength $\Delta\lambda_{\text{Tot}}$. Signal encoding is given by the linear relationship:

$$\Delta\lambda_{\text{Tot}} = \Delta\lambda_{\text{Temp}} + \Delta\lambda_{\text{Strain}} = \beta \times \Delta T + \alpha \times \varepsilon. \quad (1)$$

β is the temperature sensitivity of the FBG sensor; it is mainly due to the photo-elastic features of the optical fibre (dependence of the refraction index n on temperature T); common value is about 1.0 pm/K. α is the strain sensitivity of the FBG sensor; it is mainly due to the geometric deformation of the pitch Λ; common value is about 1.2 pm/microstrain. The over-specified common values of β and α refer to the FBG sensor in 'bare configuration' (i.e. neither coated with special materials nor inserted in special mounting devices and housing enclosures). Different values of both temperature and strain sensitivity can occur if the FBG sensor is not in 'bare configuration'. Equation (1) applies to the signal encoding of the FBG sensor with no regard to the adopted interrogation technique; any interrogation technique provides the measurement of the wavelength shift $\Delta\lambda_{\text{Tot}}$.

3 Experimental set-up

The church Santa Maria delle Grazie in Accumoli Colleposta is a renaissance building, with one nave and simple rectangular plan, random rubble masonry walls and a bell turret on the front facade. After the severe earthquake which interested central Italy in August 2016, the church was soon reported as damaged by early visual inspection made by the municipality technical office. Subsequent survey was made by qualified technicians following a referenced methodology and filling inspection forms issued by the Italian Civil

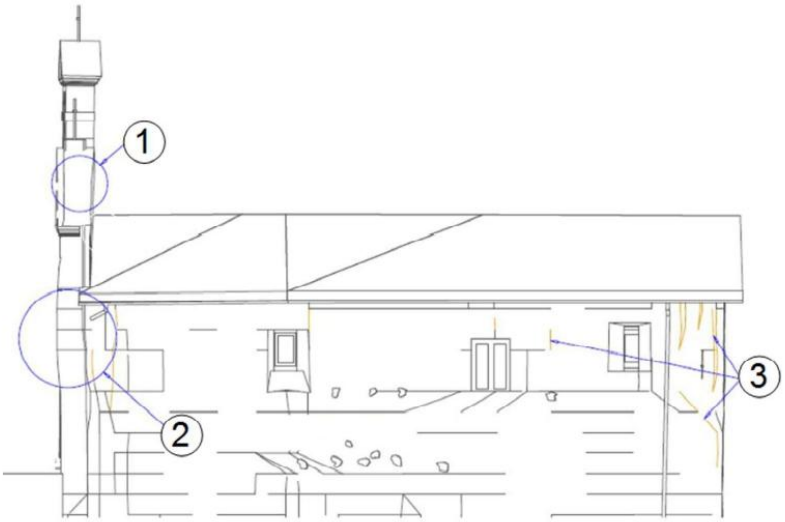


Fig. 1 Elevation of the south wall with evidence of reported flows: cracks and local crush of masonry (1); cracks at walls intersections, out of plumb (2); diagonal and vertical through cracks, cracks at walls intersections (3)

Protection Department. The survey pointed out a severe damage condition: various diagonal and vertical through cracks on the walls; long vertical cracks at walls intersections; evidence of out of plumb at the front facade; local crush of masonry at the bell turret. Figure 1 shows elevation of the south wall with evidence of the reported flaws. After evaluation of the survey report, risk of wall outward-overturning was declared and an emergency intervention was planned.

As emergency intervention, the church perimeter walls were confined by external wrapping, using steel cables, wooden timbers and wooden raker shores. Vertical timbers are placed vertical along the side and the rear facade, spaced about 1 m. Two raker shores brace the front facade at both sides of the main entrance. Steel cables run along the full perimeter of the church, approximately at the height of 2, 3 and 4 m. The bell turret was confined by vertical timber and wrapping polyester belts.

A custom array of sensors, made of four strain-gauge sensors and one temperature sensor was prepared in the ENEA laboratory (Research Centre of Frascati IT), ready for easy in-the-field installation. The strain-gauge sensors are arranged in two chains made by flexible protective tubing, each with two sensors. One chain has sensors for the confining steel cables: the tubing is interrupted at the sensor location, sensors being prepared in saddle-like protective housing which fits the cable surface and allow installation of the sensor by epoxy resin. The other chain has sensors for the wall: the chain is interrupted by a fibre-glass composite tape about 1.5 m long; the two sensors are embedded in the tape, about 1 m far from each other; the tape if flexible and can be stuck on the wall by epoxy resin. Both ends of the two chains are terminated in one cabling box. The temperature sensor is installed on the outer surface of the cabling box. Inside the cabling box all sensors are cabled in series. The two ends of the full series of sensors, protected in thin plastic tubing with inner aramid yarn, exit the cabling box from its rear surface, run inside a conduct through the wall and are terminated with fibre optic connectors at a patch panel inside the church. Figure 2 shows the array of sensors installed, with evidence of positions and assigned labels. Figure 3 shows a close view of the array of sensors in place after installation and during the installation works. Sensitivity of sensors, to be used for data decoding is 1.2 pm/microstrain for the strain-gauge sensors and 10.1 pm/ °C for the temperature sensor. According to the specifications of the optoelectronic unit used for data taking (FS2200 by Fibersensong-HBM), the resulting resolution is about 0.8 microstrain for strain and about 0.1 °C for temperature.

4 Results

Data taking was done by scheduled discontinuous campaigns, the acquisition unit being powered by battery pack (power line was interrupted since the earthquake). For each strain sensor, value of strain ε is given by

$$\begin{aligned}\varepsilon &= \alpha^{-1} \times \Delta\lambda_{\text{Strain}} = \alpha^{-1} \times (\Delta\lambda_{\text{Tot}} - \Delta\lambda_{\text{Temp}}) \\ &= \alpha^{-1} \times (\Delta\lambda_{\text{Tot}} - \beta \times \Delta T).\end{aligned} \tag{2}$$

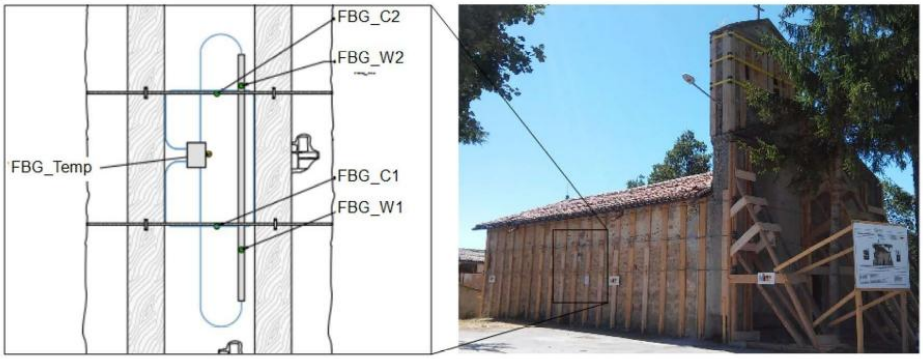


Fig. 2 The north wall of the church with the emergency reinforcements; sketch shows nomenclature, position and cabling of sensors



Fig. 3 The array of sensors in position after installation (left) and during the installation works (right)

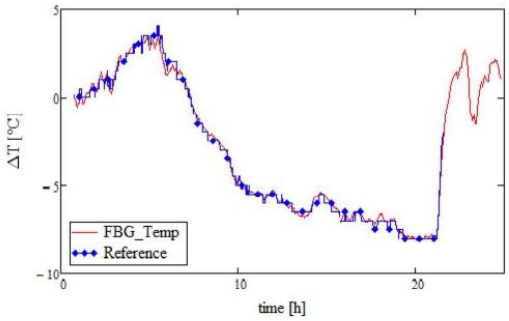


Fig. 4 Comparison of results by FBG_Temp and the RTD reference temperature sensor (colour figure online)

ΔT, α, β, $\Delta\lambda_{\text{Temp}}$, $\Delta\lambda_{\text{Strain}}$ and $\Delta\lambda_{\text{Tot}}$ are defined in discussing Eq. (1). Sensitivity coefficients α and β are known, as they are given by the manufacturer of the sensors; the adopted technique for the preparation of the sensors and their installation did not modify the value of such coefficients. The value of ΔT is given by the compensation temperature sensor (FBG_Temp in Fig. 2). FBG_Temp is made by an FBG sensor stuck on a metallic plate. FBG_Temp is only subject to temperature excitation, both directly and via the thermal deformation of the metallic plate. Thus, signal of FBG_Temp is given by

$$\Delta\lambda^{\text{T}}_{\text{Tot}} = \Delta\lambda^{\text{T}}_{\text{Temp}} + \Delta\lambda^{\text{T}}_{\text{Strain}} = (\beta^{\text{T}} + \rho^{\text{T}}) \times \Delta T = \gamma^{\text{T}} \times \Delta T. \tag{3}$$

Superscript T specifies that Eq. (3) refers to FBG_Temp only; ρ^{T} is a constant proportional to the thermal expansion coefficient of the metallic plate. The value of γ^{T} was worked out by a simple calibration procedure, having the sensor in a climatic chamber whose temperature was varied following controlled cycles. After installation, FBG_Temp was successfully tested for the assumed calibration using a RTD sensor for reference measurement. The test lasted about 24 h, starting at about 10:00 am. The plot in Fig. 4 shows the time history of the temperature variation measured by the two sensors, assessing the correct calibration of FBG_Temp.

The position of all the installed sensors is such that thermal equilibrium among occurs: all sensors stay on the north wall and under the roof protrusion, direct exposition to the sun never occurs for any of them. Equation (3), which is a particular expression of Eq. (1) for sensors not subject to direct mechanical forces, applies to FBG_Temp. Thus, FBG_Temp is used to evaluate ΔT whose value can be used in Eq. (2) to evaluate the strain measured by FBG_C1, FBG_C2, FBG_W1, and FBG_W2. Figure 5 shows the time history of strain ε values recorded in monitoring campaigns.

Data of the four main campaigns shown in Fig. 5 are given in expanded plot in Fig. 6. Deformation due to temperature circadian cycle can be seen in all plots, although with

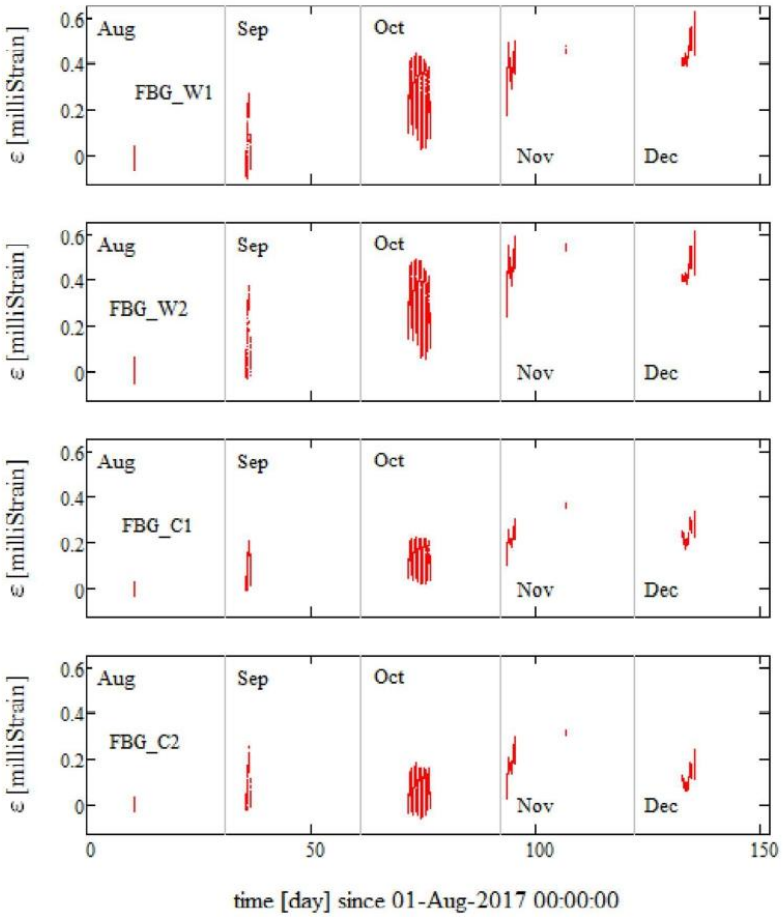


Fig. 5 Time history of strain

minor evidence in November and December because of both missing data (acquisition interruptions due to power failure) and moderate temperature excursion. Plots do not show evidence of neither discontinuities within acquired data nor large variations among different campaigns, which both are features that should warn about possible major worsening of the recovered structural condition. All plots, although with some difference among the four sensors, show a general trend of bias increase with seasonal temperature decrease.

Correlation plots between strain ε and temperature variation ΔT are shown in Fig. 7 where the full dataset of the acquired data is used. Correlation plots allow some insights about the strain time history, which is expected to be due to thermal excitation only in the absence of structural rearrangement. Plots give evidence of much better correlation for sensors at the wall (FBG_W1 and FBG_W2) that strain measured at the cables, with worst correlation for sensor FBG_C2.

Figure 8 shows the correlation plot of sensor FBG_C2, with evidence of the dataset from each campaign. The slope of the five datasets is quite similar, but some 'drift' is evident for datasets from the different campaigns, the drift being toward lower values of the abscissa with time (from August to December). The dataset from the November campaign shows a complex path, but a main 'trend' and the slope is evident. The observed similar slope shows that the relationship between the environment temperature and the overall deformation of the perimeter walls (as monitored by FBG_C2 through the strain of the wrapping cable) does not change appreciably. Eventually, permanent slope change could be due to severe structural change or to the loosening of the wrapping cable. The observed 'drift' cannot be assumed to be simply due to seasonal temperature decrease since it

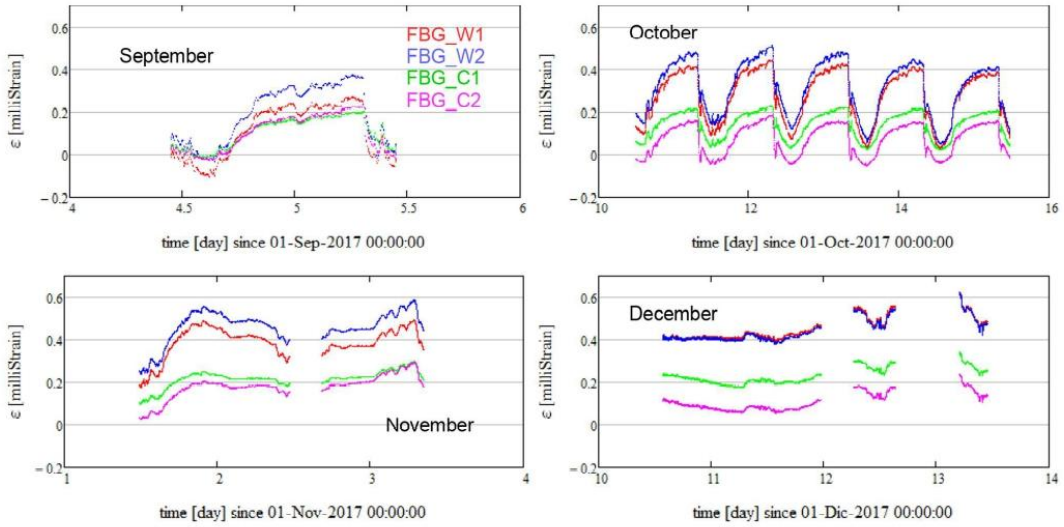


Fig. 6 Time history of data from campaigns in September, October, November and December (colour figure online)

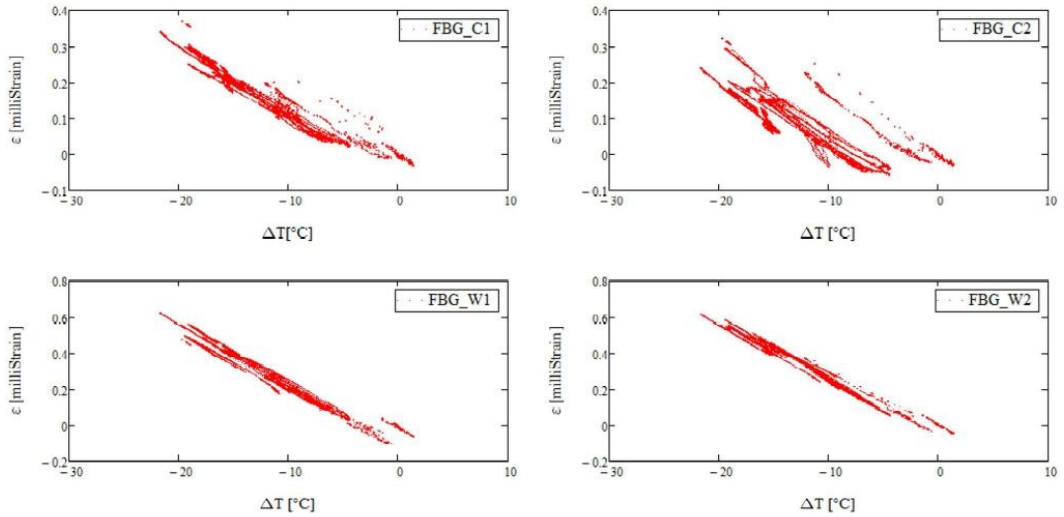


Fig. 7 Correlation plot between strain and temperature variation of data from campaigns shown in Fig. 6

does not apply with similar amplitude to any other sensor. The 'drift' can be assumed to be due to slight structural settlements which vary the 'bias' tensioning of the wrapping cable. Such hypothesis is quite likely in the context of the after earthquake scenario and further analysis of data shows good consistency.

The dispersion of data in the November campaign, which appears to be quite relevant, is further considered in Fig. 9 where highlighted data are acquired during the occurrence of some seismic events. All reported seismic events with epicentre within 5 km from Colleposta and magnitude > 0.5 are considered. The list of the seismic events is from the Italian National Institute of Seismology and Volcanology

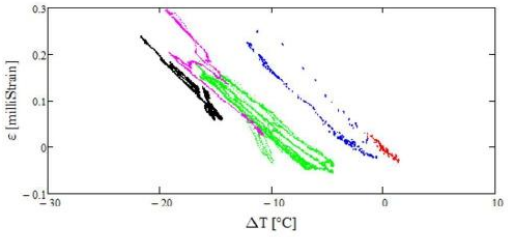


Fig. 8 Sensor FBG_C2. Evidence of correlation of individual campaigns (red: August; blue: September; green: October; magenta: November; black: December) (colour figure online)

(Fig. 10). Correlation plots of sensor FBG_C1 and sensor FBG_C2 are shown to allow comparison between them: it can be observed that most relevant differences between the two patterns arise at the occurrence of some seismic event.

5 Conclusion

We proposed and applied a working procedure which allows effective structural monitoring of damaged buildings subject to temporary emergency reinforcements. The working procedure considers instrumentation of reinforcements, whose tension/compression variation is effectively representative of the static equilibrium variation of macro-elements of the damaged building, although it cannot provide precise mapping of structural displacements, strains and movements. The assumed scenario considers that reinforcements, although being temporary, often stay long in place prior the definitive intervention, especially in case of earthquakes. Monitoring reinforcements allow to collect information about the evolution of the static equilibrium of the macro-elements, which is useful for both actual temporary safety and definitive intervention planning. The working procedure takes advantage of the peculiar features of the fibre optic sensors based on Bragg grating technology, which allows easy installation, simple in-series cabling, and reliable and stable long-term discontinuous monitoring with no concern for signal bias drifting in between successive monitoring campaigns.

The application presented confirms that the proposed working procedure and the adopted sensing technology allow easy of installation in critical operative conditions, providing long-term reliability, temperature compensation, and suppression of drifting among discontinuous monitoring campaigns. Results presented in the paper give evidence that the strain time history of temporary reinforcements can be effectively monitored and analysed to point out the evolution of the structural condition of the reinforced damaged

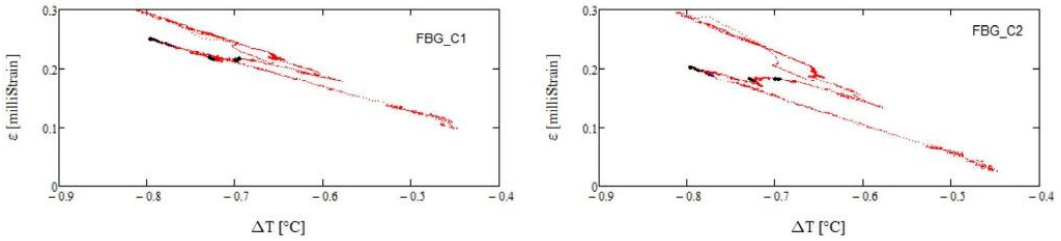


Fig. 9 Data of the campaign of November; correlation plot with evidence (black) of data at seismic events within 5 km from Colleposta (colour figure online)

Timezone: Italy | Since 02-11-2017 to 03-11-2017 | Magnitude greater than 0.5 | Point: (42.66, 13.2) - Radius: 5 km | Custom Search | Map

Showing 4 earthquakes (Sort Time Descending) | Export list (UTC)

Origin time (Italy)	Magnitude	Region	Depth	Latitude	Longitude
2017-11-03 07:40:54	ML 1.5	4 km W Accumoli (RI)	13	42.69	13.21
2017-11-03 04:56:14	ML 0.8	5 km W Accumoli (RI)	11	42.69	13.19
2017-11-02 21:35:55	ML 1.4	5 km N Cittareale (RI)	10	42.66	13.15
2017-11-02 21:18:46	ML 1.4	5 km NW Cittareale (RI)	9	42.66	13.14

Fig. 10 List of seismic events reported by the Italian Nation Institute of Seismology and Volcanology, within 5 km from Colleposta in the period of the November campaign

building. Within the monitored period, analysis correlation between strain and temperature pointed out anomalous behaviour for one sensor (lower correlation to than other sensors) and gives evidence that such behaviour has high correlation with seismic settling-down activity.

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UNIVERSITÀ DEGLI STUDI "ROMA TRE"

DIPARTIMENTO DI INGEGNERIA

CORSO DI LAUREA MAGISTRALE IN INGEGNERIA CIVILE
PER LA PROTEZIONE DAI RISCHI NATURALI – STRUTTURE [LM-23]

TESI DI LAUREA

L'impiego dei sensori di deformazione in fibra ottica FBG per il monitoraggio strutturale di opere provvisionali in emergenza sismica: il caso del Santuario di S. Maria delle Grazie ad Accumoli (RI)

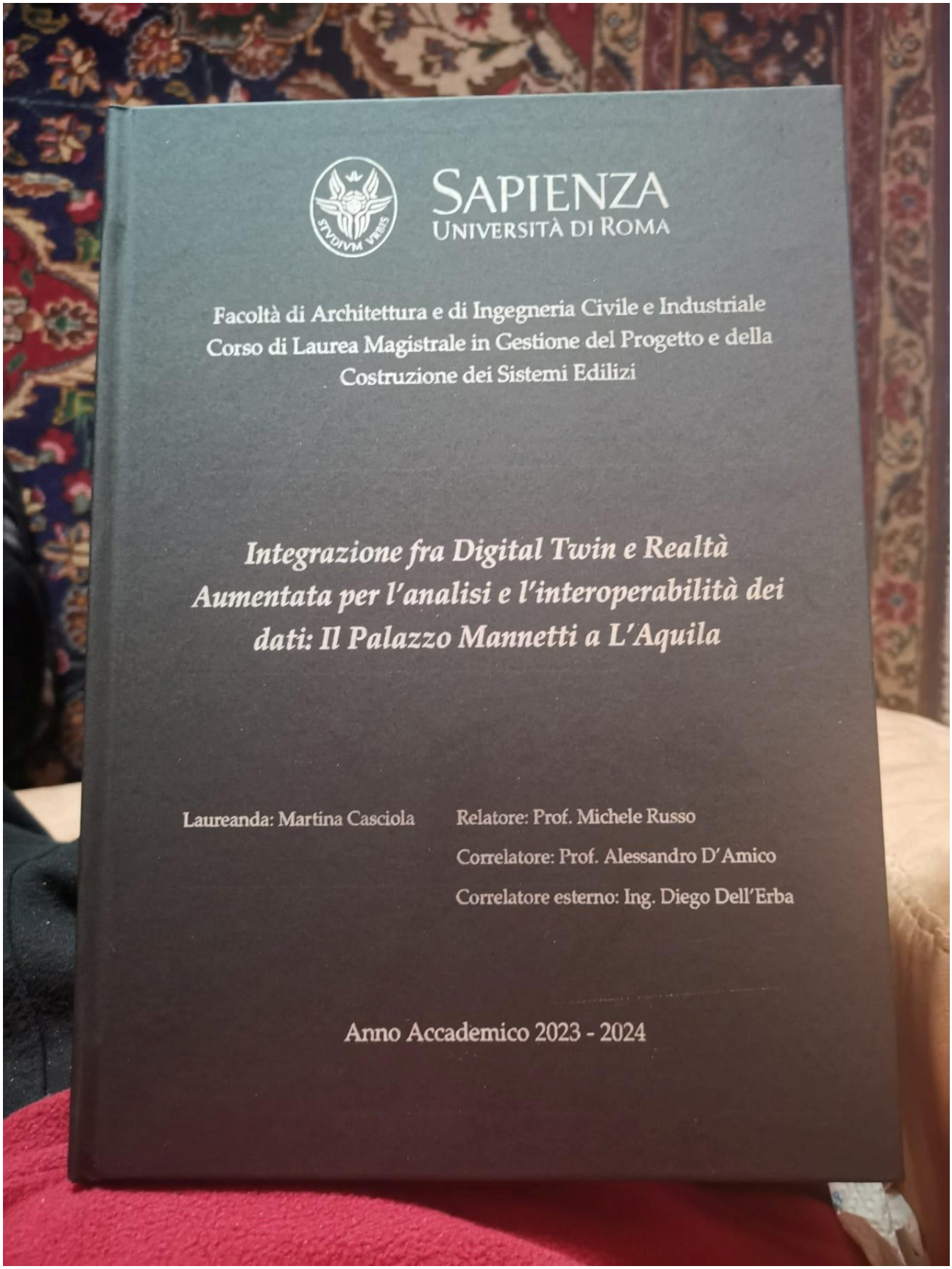
RELATORE:
Prof. Ing. Stefano De Santis

CORRELATORI:
Dott. Ing. Diego Dell'Erba (*Ingegneria Integrata*)
Dott. Michele A. Caponero (*ENEA*)

CANDIDATO:
Alessandro Luciani
MATRICOLA 489180

diego
dell'erba
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Laureanda: Martina Casciola
Relatore: Prof. Michele Russo
Correlatore: Prof. Alessandro D'Amico
Correlatore esterno: Ing. Diego Dell'Erba
Anno Accademico 2023 - 2024

Ing. Diego Dell’Erba

L’Ing. Diego Dell’Erba è un ingegnere nucleare multidisciplinare con oltre cinquant’anni di attività professionale svolta in Italia e all’estero nei settori dell’ingegneria civile, strutturale, geotecnica e della sicurezza delle opere complesse.

Laureato alla Sapienza di Roma, ha maturato una lunga esperienza nella progettazione, direzione lavori e gestione tecnica di interventi su edifici, infrastrutture, territori fragili e ricostruzioni post-sisma.

Nel corso della carriera ha sempre affiancato alla competenza tradizionale una costante attenzione all’innovazione tecnologica, introducendo soluzioni avanzate di monitoraggio strutturale, sensori a fibra ottica, Digital Twin, manutenzione predittiva e modelli di controllo evoluto dei cantieri.

È tra i promotori del paradigma **CYBER–PHYSICAL STRUCTURAL SAFETY**, orientato a una ingegneria capace di prevedere il rischio e proteggere nel tempo persone, patrimoni e infrastrutture.

Ha collaborato con università, enti di ricerca e istituzioni pubbliche, promuovendo eventi, studi e iniziative divulgative finalizzate alla diffusione di una nuova cultura della sicurezza tecnica: dinamica, intelligente e preventiva. La sua attività professionale continua ancora oggi con particolare attenzione alla ricostruzione post-sisma e all’innovazione applicata al territorio.