

Monitoring Large Railways Infrastructures Using Hybrid Optical Fibers Sensor Systems

Philippe Velha¹, Tiziano Nannipieri, Alessandro Signorini, Mirko Morosi, Massimiliano Solazzi,
 Francesco Barone², Antonio Frisoli, Luca Ricciardi, Ricardo Eusepi, Marco Icardi,
 Giuseppe Recchia, Margherita Lupi, Giuseppe Arcoleo,
 Paola Firmi, and Fabrizio Di Pasquale

Abstract—In this paper we propose a hybrid fiber optics sensor system, based on Fiber Bragg Gratings (FBG) and Raman distributed temperature sensing (RDTs), for monitoring essential sites within large railway infrastructures like bridges, viaducts and slopes potentially subject to landslides. The geometrical rail track condition is monitored in real-time using fiber optic sensors, providing early warning if pre-defined thresholds are exceeded in terms of longitudinal, horizontal and cross-level defects. The sensor reading units can be remotely located from the monitored zones, without requiring active elements on the tracks and ensuring high immunity to electromagnetic interference. The proposed technology has been first validated in railway laboratories and then in field trials confirming its capability to detect defects over pre-established thresholds and the absence of false alarms with regular train circulation.

Index Terms—Bragg grating, finite element analysis, optical fiber sensors, railway engineering, railway safety, Raman scattering.

I. INTRODUCTION

AS THE railway industry is receiving large investment for development and upgrading, the management of rail infrastructures is becoming increasingly important to guarantee safety, reliability and maintenance. Condition monitoring is a key part of the management process and must be properly implemented to identify deterioration in structures and infrastructures before failures happen, seriously affecting the rail operation [1], [2]. The use of sensors is becoming in this contest a key point to move toward an intelligent infrastructure in which potential problems are detected in an early stage avoiding false alarms and missed failures [3]–[7].

Optical fiber sensors have rapidly evolved in recent years for condition monitoring in a wide range of industrial

applications [8], including Oil&Gas, energy production and distribution, structural health monitoring, automotive and transportation. In particular distributed [9]–[14] and quasi-distributed optical fiber sensor [15] systems are particularly attractive for monitoring large infrastructures such as pipelines, electrical power cables, tunnels, dams and bridges. In distributed sensing the fiber itself is used as a sensing element; optical pulses are sent down to the sensing fiber and the backscattered light, including Raman [9], [10], Brillouin [11], [12] and Rayleigh [13], [14] spectral components, are detected and processed to obtain external physical parameters affecting their properties. While the elastic incoherent Rayleigh scattering can be used for optical cable characterization, the coherent Rayleigh scattering can be used for distributed acoustic measurement along the sensing fiber. On the other hand, spontaneous Raman scattering is exploited for temperature measurement while Brillouin scattering for strain and temperature measurements. Fiber Bragg Grating (FBG) [16] can also be used as point sensors, not only for strain and temperature measurement but also for measuring several other physical parameters using suitable transducers (for example pressure, radiation dose, humidity, acceleration, force and torque). Also arrays of low reflectivity FBG sensors (Ultra Weak FBG) can be used for quasi-distributed measurement of vibrations along large infrastructures. Specific FBG applications in the railway industry include characterization of the pantograph-catenary interaction [17], structural health monitoring of railway bridges [16], train identification [18], dynamic weight and speed measurements [19], [20]; also distributed sensing has been proposed in the railway industry for fire detection in tunnels [21] and for acoustic measurement [22] along the infrastructure to detect intrusion and identify abnormal conditions on both rail tracks and trains [23]. In general optical fiber sensors offer several advantages compared to conventional electronic sensors, such as immunity to electromagnetic interference, suitability to operate in harsh environments, including explosive atmospheres and presence of nuclear radiation, low invasiveness, large multiplexing potential and distributed sensing capabilities using frequency and time domain reflectometry techniques [24], [25]. However, monitoring large railway infrastructures, like bridges and viaducts, can be challenging as it is difficult to decide a priori where and how to install the point sensors. The system

Manuscript received June 23, 2018; revised November 26, 2018, May 2, 2019, and August 28, 2019; accepted October 2, 2019. The Associate Editor for this article was X. Cheng. (Corresponding author: Philippe Velha.)

P. Velha, M. Solazzi, F. Barone, A. Frisoli, and F. Di Pasquale are with Scuola Superiore Sant'Anna, TECIP Institute, 56124 Pisa, Italy (e-mail: philippe.velha@santannapisa.it).

T. Nannipieri and A. Signorini were with Scuola Superiore Sant'Anna, TECIP Institute, 56124 Pisa, Italy. They are now with INFIBRA TECHNOLOGIES Srl, 56121 Pisa, Italy.

M. Morosi was with Scuola Superiore Sant'Anna, TECIP Institute, 56124 Pisa, Italy. He is now with Arup, 20122 Milan, Italy.

L. Ricciardi, R. Eusepi, M. Icardi, G. Recchia, M. Lupi, G. Arcoleo, and P. Firmi are with Rete Ferroviaria Italiana S.p.A., 00161 Roma, Italy (e-mail: m.lupi@rfi.it).

Digital Object Identifier 10.1109/TITS.2019.2949752

proposed in this paper overcomes this issue by continuously monitoring the rail tracks deformation instead of the structure itself; optical fiber sensors are directly installed on the rail tracks at specific potentially critical sites like bridges, viaducts and unstable slopes, in order to identify geometrical defects harbingers of abnormal behavior of the underlying structure supporting the tracks. Alignment, longitudinal and transversal defects can be related to track buckling, subsidence and slide events [26] providing an evidence of abnormal conditions; the railway network management system can reduce the train speed and eventually fully stop the train circulation when such geometrical defects exceed pre-defined thresholds. Visual inspections can then be arranged to check the structural health of the infrastructure only when really needed. In this paper, the rail track deformation is monitored in real-time combining discrete and distributed optical fiber sensors. The trade-off between cost and performance is obtained by installing multiplexed Fiber Bragg Grating (FBG) sensors and Raman distributed temperature sensors (DTS) directly on the rail tracks, allowing to directly extract the track deformation and verify if the pre-defined thresholds are exceeded. A linear elastic model is used, based on the static strain and temperature distributions provided by the hybrid fiber optic sensor system. The sensor reading units can be conveniently located up to several tens of km distance from the monitored zones, allowing distributed sensing from a remote location, avoiding active elements on the tracks, also ensuring high immunity to electromagnetic interference. Note that installing optical fiber sensors directly on the whole railway tracks would be non-practical in terms of compatibility with maintenance procedures; to avoid this issue, the basic idea behind this work is that the hybrid optical fiber sensor system will only be installed within critical sites, such as bridges, viaducts and slopes potentially subject to landslides and not on the whole infrastructure. This will make the system deployment realistic also considering that the monitored zones can be reached from the remote control rooms using optical cables in ducts, limiting the optical fiber installation on the tracks only within essential sites.

The paper is organized as follows. After the introduction, Section II describes the hybrid sensor system and the rail track linear elastic model. Section III describes the Finite Element Method (FEM) analysis and the model validation performed in railway laboratories; both optical fiber sensors and conventional electronic sensors are used for comparison. Section IV describes the field trials, one on decommissioned tracks and one in operation with real train circulation. In the field trial on the decommissioned tracks, different geometrical rail track defects have been induced on purpose using specific mechanical actuators. The data acquired by the proposed optical fiber sensor system are consistent with the measured displacements performed on the field using precision electronic calipers, fully validating the sensor system performance on the field. Real-time measurements on the live second field trial are also carried out, confirming the absence of false alarms with regular train circulation and the capability to clearly identify abnormal conditions such as conditions in which the

fastening system of the track is broken in specific locations. Section V concludes the paper.

II. METHODOLOGY: HYBRID OPTICAL FIBERS SENSOR SYSTEM DESIGN AND REALIZATION

This section describes the hybrid optical fibers sensor system specifically designed and developed to monitor key masonry bridges within the Italian railway network. We aim to a real-time geometric rail track condition monitoring system able to provide early warning in case of abnormal behavior of the underlying structures supporting the tracks. The system is meant to only monitor potentially critical infrastructures and not the whole railway network as this would be unpractical and incompatible with standard maintenance procedures. The real-time track deformation is directly calculated from the static strain distribution along the specific rail section, which is measured using arrays of FBG sensors directly glued or welded to the tracks; pure mechanical strain must be separated from the strain contribution induced by thermal expansion of the material [27]. Due to the well-known strain-temperature cross-sensitivity affecting the FBG sensors, a second loose FBG should be added to each sensing point to perform strain independent temperature measurement; straightforwardly, the pure mechanical strain distribution can be extracted after removing the strain contribution induced by thermal expansion. In our system, instead of using loose FBG sensors at each sensing point roughly doubling the price of the system, we add a second fiber for distributed temperature sensing (DTS), which is based on Raman scattering, resulting in a cost-effective solution very attractive in terms of distributed measurement capabilities over long distances. Considering the track as an ideal beam, a linear elastic model is used to calculate in real-time the track deformation directly from the pure mechanical static strain values. The proposed methodology, although specifically validated for masonry bridges, is general and can be applied for condition monitoring of several large infrastructures in the railway industry, like for example reinforced concrete bridges, viaducts and slopes potentially subject to landslides. In the following, we describe FBG and Raman DTS (RDTS) sensing technologies and show how they can be combined for rail track condition monitoring based on a linear elastic model.

A. Fiber Bragg Grating Sensor Technology

The FBG sensor is a very sensitive and versatile optical device for measuring several physical parameters including strain, temperature, pressure, vibration and displacement. The FBG technology has rapidly evolved and is today extensively applied in several industrial fields. In its simplest form, a FBG sensor is obtained by a periodic refractive index modulation inscribed in the optical fiber core through photo-sensitivity. FBG based sensors exploit the presence of a resonant condition which reflects the incident light at the so-called Bragg wavelength λ_B , defined as $\lambda_B = n_{eff} \Lambda$, where n_{eff} is the effective refractive index of the fundamental optical fiber mode and

Λ is the grating pitch. The operating principle of FBG sensors exploits the property that any change in either the effective refractive index or the grating pitch, caused by external effects like local strain or temperature, will result in a relative Bragg wavelength shift ($\Delta\lambda_B$) given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = k\epsilon + \alpha_T \Delta T \quad (1)$$

where $\Delta\lambda_B = \lambda - \lambda_B$ is the change in the Bragg wavelength λ with respect to reference Bragg wavelength λ_B , k is the gage factor and α_T the thermo-optic coefficient; the Bragg wavelength shift depends linearly on the longitudinal strain ϵ and temperature change ΔT , with sensitivity values of approximately 1.2 pm/ $\mu\epsilon$ and 11 pm/ $^\circ\text{C}$ for silica fibers at around 1550 nm. As the rail track deformation is extracted only from the static strain values along a cascade of FBG sensors installed on the track, it is necessary to compensate for spurious temperature variations experienced by the FBG during operation. This compensation can be done expanding eq. 1 into:

$$\frac{\Delta\lambda_B}{\lambda_B} = k(\epsilon_M + \epsilon_T) + \alpha_T \Delta T = k(\epsilon_M + \alpha_{SP} \Delta T) + \alpha_T \Delta T \quad (2)$$

where $\epsilon = \epsilon_M + \epsilon_T$ includes two contributions due to pure mechanical strain ϵ_M , and strain induced by thermal expansion ϵ_T (α_{SP} is the thermal expansion coefficient of the material). Indicating by λ_B and T_0 the reference Bragg wavelength and reference temperature and with λ and T the real-time wavelength and temperature values, we can write:

$$\begin{aligned} \frac{\Delta\lambda_B}{\lambda_B} &= k(\epsilon_M + \epsilon_T) + \alpha_T (T - T_0) \\ &= k[\epsilon_M + \alpha_{SP}(T - T_0)] + \alpha_T (T - T_0) \end{aligned} \quad (3)$$

from which we obtain the pure mechanical static strain ϵ_M as:

$$\epsilon_M = \frac{1}{K} \left(\frac{\lambda - \lambda_B}{\lambda_B} \right) - \alpha_{SP}(T - T_0) - \frac{\alpha_T}{K}(T - T_0) \quad (4)$$

In the proposed system, the real-time temperature value T is obtained using a RDTS [9], [10] connected to a multi-mode (MM) fiber cable installed along the rail track in close proximity to the FBG sensors chain. For monitoring large infrastructures, many FBG sensors are required. Therefore, they must be multiplexed along the same single mode optical fiber. In order to enhance the sensing distance we have decided to use Time Division Multiplexing (TDM) techniques in which the response of many low reflectivity FBG sensors at the same central nominal wavelength along a single fiber link can be identified from the known signal time-of-flight. Commercially available FBG reading units based on TDM techniques can measure up to 100 FBGs multiplexed on the same optical channel. Moreover, several channels can also be multiplexed in space domain using optical switches or splitters, enhancing the multiplexing capabilities up to 400 FBGs per reading unit. The following subsection briefly describes the RDTS technology used in this work to eliminate FBG strain-temperature cross-sensitivity, providing a pure mechanical static strain ϵ_M as shown in eq. 4.

B. Raman Distributed Temperature Sensing (RDTS)

The first demonstration of Raman distributed temperature sensing goes back to 1985 [9] and RDTS systems are nowadays commercially available, finding wide applications in strategic industrial sectors like Oil&Gas, transportation and energy. The basic principle of a RDTS is similar to a radar systems and is often based on optical time-domain reflectometry (OTDR) techniques; optical pulses are sent down into the sensing fiber and the backscattered Raman light is detected from the same fiber end. The temperature-dependent backscattered Raman Anti-Stokes (AS) signal is usually normalized to the Raman Stokes (S) backscattered signal component to compensate for spurious losses along the sensing fiber:

$$R(T) = \frac{P_{AS}}{P_S} \propto \left(\frac{\lambda_S}{\lambda_{AS}} \right)^4 \exp\left(-\frac{h\Delta\nu}{k_B T}\right) \quad (5)$$

where P_S (P_{AS}) and λ_S (λ_{AS}) are the power and wavelength for the Stokes (S index) and anti-Stokes (AS index) components respectively, h is the Planck's constant, $\Delta\nu$ is the Raman frequency shift, and k_B is the Boltzmann constant. The temperature profile $T(z)$ along the sensing fiber can be obtained from $R(T)$ by a suitable calibration. Note that the spatial resolution of the measurement depends on the pulse width and fiber types; MM fibers are preferred to single mode (SM) ones due to their larger permitted peak power and larger backscattering coefficient, leading to longer sensing distances (up to a few tens of kilometers). However, inter-modal dispersion in MM fibers induces pulse broadening along propagation, ultimately limiting the achievable spatial resolution. Several commercial RDTS products are today available on the market operating on both SM and graded-index MM fibers, with sensing distances ranging from a few kilometers up to several tens of kilometers. In our system, we use single-ended RDTS, in which a graded-index MM sensing fiber is interrogated from one end only. Double-ended interrogation schemes, able to guarantee robustness in specific harsh environments [28], are not considered here. The main advantage of using a RDTS system for temperature measurement instead of a long array of loose FBG sensors consists of the possibility to obtain a continuous temperature profile over several km distances with meter scale spatial resolution at a reduced cost.

C. Rail Track Linear Elastic Model

Once the pure mechanical strain ϵ_M has been obtained using eq. 4 removing the spurious contribution due to material thermal expansion and thermo-optic effect, a simplified rail track model is used to calculate in real-time the track deformation. The track is considered as an ideal beam and represented by a linear elastic model. Figure 1 reports the coordinate reference system used for the calculation.

Assuming an FBG strain and temperature sensitivity of 1.2 pm/ $\mu\epsilon$ and 11 pm/ $^\circ\text{C}$ respectively at 1550 nm and, a thermal expansion coefficient $\alpha_{SP} = 1.15 \times 10^{-5}/^\circ\text{C}$ for steel type R260, the pure mechanical local strain ϵ_M on the track is calculated from eq. 4 using the measured the FBG wavelength shift $\Delta\lambda = \lambda - \lambda_B$ and the corresponding measured temperature change ΔT obtained by the RDTS

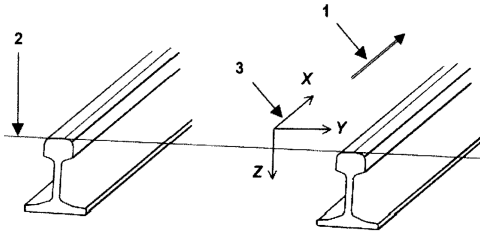


Fig. 1. Cartesian reference system for the rail track (from RFI specifications).

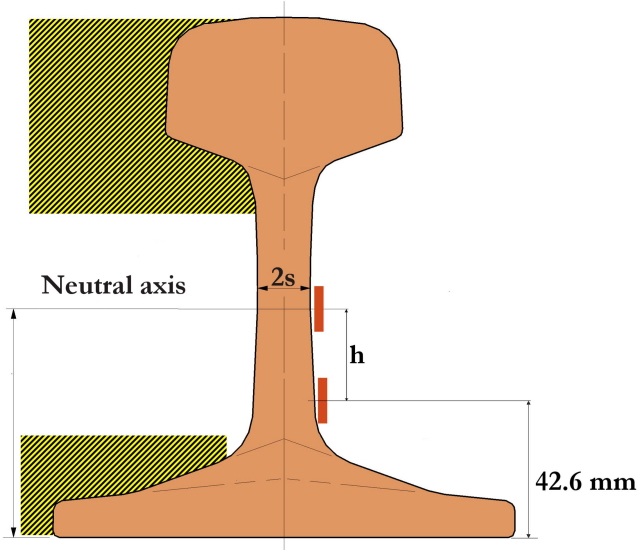


Fig. 2. Characteristics of the 60E1 rail track used in the experiments, showing the FBG positions and neutral axis.

at the specific FBG location (note that the spatial resolution of the RDTS measurement can be set as low as 0.5 m while the separation between consecutive FBG sensors is 1.8 m). As the FBG sensors are installed alternatively on the neutral axis and at 42.6 mm from the bottom of the track, as described in Figure 2, the curvature $\rho_z(x)$ around the z axis along the track longitudinal direction x is calculated from the FBG strain measured on the neutral axis ϵ_{Mn} as:

$$\frac{1}{\rho_z(x)} = \pm \frac{\epsilon_{Mn}(x)}{s} \quad (6)$$

where the positive and negative sign holds respectively for the right and left tracks (considering that FBG sensors are mounted on the inner side of the rail track as shown in Figure 3) and s is the horizontal distance from the FBG at the neutral axes (see Figure 2). The FBG sensors placed away from the neutral axis are sensitive to both curvatures around z- and y-axes, and the measured strain value ϵ_T is given by:

$$\epsilon_T(x) = \pm \frac{s}{\rho_z(x)} + \frac{h}{\rho_y(x)} \quad (7)$$

where h is the vertical distance from the FBG position and the neutral axes (see Figure 2) and the positive and negative sign holds respectively for the right and left tracks. Note that the optimum location of the FBG out of the neutral axes ($h=38.3$ mm in Figure 2), has been identified by maximizing

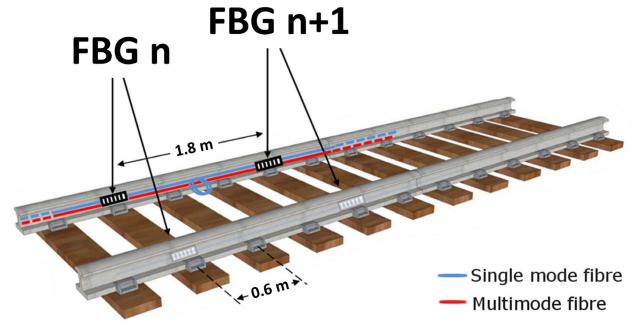


Fig. 3. Scheme of the optical fiber sensors layout on an actual rail track.

the strain sensitivity with several experimental trials, ensuring at the same time compatibility with railway operations and fastening. The curvature ρ_z around z previously obtained by eq. 6 can then be linearly interpolated and the curvature ρ_y around the y-axis can be written as:

$$\frac{1}{\rho_y(x)} = \frac{\epsilon_T(x) - \epsilon_{Mn}}{h} \quad (8)$$

The z and y spatial coordinates of the elastic curve of the rail track can be obtained by integrating the respective curvature along z and y axis:

$$z(x) = \int_0^x \left[\int_0^x \frac{1}{\rho_y(x)} dx + C_1x + C_2 \right] \quad (9)$$

$$y(x) = \int_0^x \left[\int_0^x \frac{1}{\rho_z(x)} dx + C_1x + C_2 \right] \quad (10)$$

where the constants C_1 and C_2 are obtained by imposing both displacement and section rotation equal to zero far from the perturbed rail track section. The interpolation is performed considering 10 FBG, 5 prior and 5 subsequent to each specific FBG position, providing the full rail track deformation in real-time. In order to validate the model, the calculated geometrical values are compared with the data measured on decommissioned tracks using mechanical actuators to induce specific geometrical defects. Note that the sensor reading units can be located several tens of kilometers away from the monitored zones; distributed sensing from a remote location of several key sites, not necessarily consecutive, can be performed without any active elements on the tracks and with high immunity to electromagnetic interference.

Figure 4 shows the structure of the optical fiber sensor system developed to monitor simultaneously both tracks of a rail. Considering a spatial separation of 1.8 meter between successive FBG sensors, corresponding to one FBG every three-railway sleepers, and a maximum multiplexing capabilities of 400 FBGs per reading unit, a single system for monitoring both tracks, including then two FBG and two RDTS reading units, as well as one control unit (CU), will allow to monitor a unique 720-meter long linear infrastructure or several shorter sections placed along the tracks far from the reading unit. Figure 3 schematically shows how the FBG sensors and RDTS fibers can be installed along the rail tracks. Note that the sensors positioned in the internal part of the rail allow for maintenance procedures without damaging

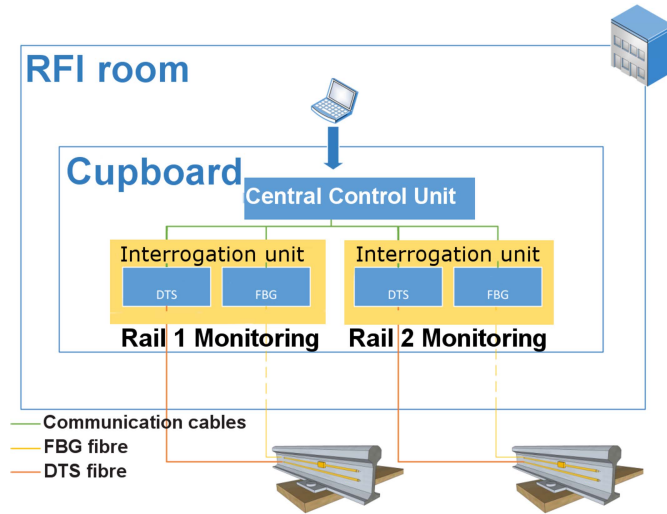


Fig. 4. Schematic structure of the hybrid optical fiber sensor system.

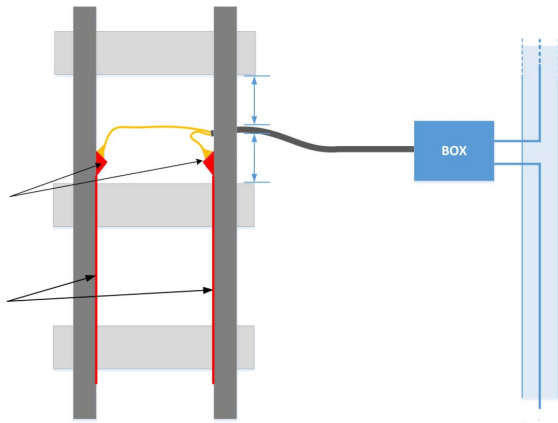


Fig. 5. Example of connection between sensing and communication cables.

the optical fiber sensors. Suitable connectors and junction boxes can be used to connect the sensing fibers to the remote location where the reading units are placed. Figure 5 shows one possible solution where the junction box connects the sensing cables to optical fiber cables within a duct. Note that different, but not necessarily consecutive, sensing zones along the rail infrastructure, corresponding for example to different masonry/concrete bridges and viaducts, can be connected to the reading units within a remote control room using different junction boxes. In each box, a separate TDM channel of the FBG interrogator is dedicated to the specific sensing area on each track while the same MM fiber for Raman temperature measurement can be used in cascade for all sensing zones along the same track. A special plug can be used (for example Fischer connectors) in order to allow maintenance operations on the rails.

III. FEM ANALYSIS AND STATIC MODEL VALIDATION

In this section, the proposed method is validated in the RFI laboratories by comparing with conventional electronic sensors and with FEM static simulations. Note that validation of the optical sensor system in field trials by comparison with

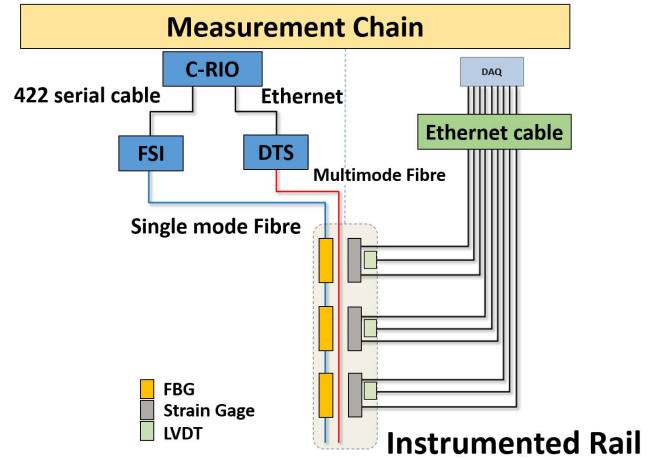


Fig. 6. Scheme of the measurement chain and interface diagram with the detailed cable types.

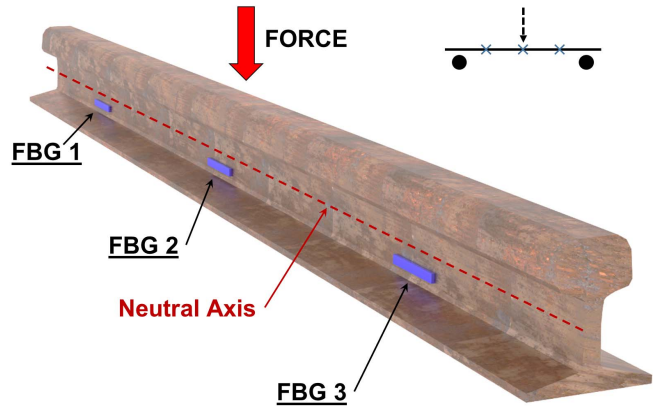


Fig. 7. Layout of the FBG sensors for the lab tests. In the inset on the top right corner: diagram of the setup for applying the load. NB. The RDTS fiber has been installed along the neutral axis.

conventional electrical sensors was not possible due to practical difficulties to install electronic sensors in remote locations. A 5.64-meter long single rail track section, bounded at the two sides and quasi-statically loaded in the center, has been instrumented with FBGs, Raman sensors as well as with electronic strain gages and linear variable differential transducers (LVDT). Figure 6 shows a schematic of the measurement chain and interface diagram with discrete sensors installed in the center ($L/2$) and at positions $L/4$ and $3L/4$, where $L = 5.64\text{m}$. Three loading and unloading ramps have been considered within the ranges 3-60 kN, 3-80 kN and 3-140 kN respectively; note that the first two correspond to elastic deformation while the last one leads to nonlinear plastic deformation behavior for the steel type R260 used for rail tracks fabrication. While the vertical displacements of the rail track are measured using electronic LVDT sensors, the longitudinal static strain is monitored using FBG sensors and electrical strain gages places on opposite sides of the track. The FBG sensors are installed as reported in Figure 7; the strain gage sensors, not shown in the figure, are symmetrically installed with respect to the FBG sensors on the other side of the track. A RDTS system is also used to measure the temperature and validate

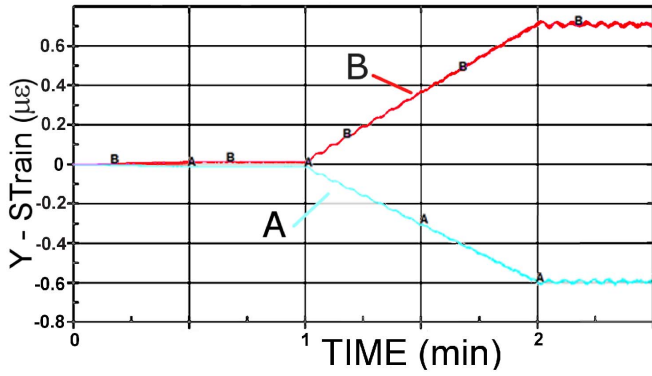


Fig. 8. Longitudinal strain ϵ_y versus time with loading ramp from 0 kN to 140 kN at (A) $z = L/2$ and (B) $z = L/4$.

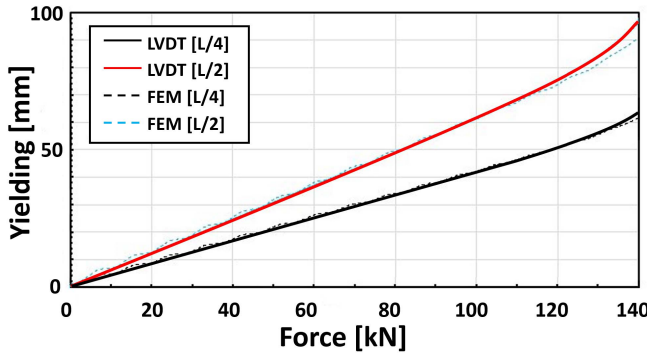


Fig. 9. Comparison between measured and calculated vertical displacements versus applied load at $L/4$ and $L/2$.

the optical sensor system performance while changing the rail track temperature using a heater. A first comparison between FBGs and electrical strain gages measurements, supported by a static FEM analysis, has been performed to validate the optical fiber sensor system at controlled temperature conditions.

The FEM model used in the static analysis assumed an elasto-plastic behavior for the R260 steel, based on the Power Law Hardening Model (LS-DYNA) [29]. The non-linear relation providing the yield stress σ_y is described as:

$$\sigma_y = k\epsilon^m = k(\epsilon_{yp} + \bar{\epsilon}^m)^m \quad (11)$$

where ϵ_{yp} is the elastic strain and $\bar{\epsilon}^m$ the plastic component. The parameters $k=1300$ and $m=0.18$ are evaluated comparing with experimental tests carried out on the R260 steel beam and reported in reference [30]. The elastic modulus and the Poisson coefficient are respectively $E=2.07 \times 10^5 \text{ MPa}$ and $\nu = 0.3$. Our FEM static simulations have been first compared with the experimental results reported in [30], clearly pointing out good agreement and the effectiveness of the Power Law Hardening Model. Figure 8 reports the calculated longitudinal strain ϵ_y versus time at $L/2$ and $L/4$ before, during and after the loading ramp from 0 kN to 140 kN. These results clearly point out tensile strain at the foot position of the track. The FEM static analysis has also been used to validate the vertical displacement measured by LVDT sensors.

Figure 9 compares the measured and calculated vertical displacement values versus applied load up to 140 kN at $L/2$ and $L/4$; a very good agreement can be observed between

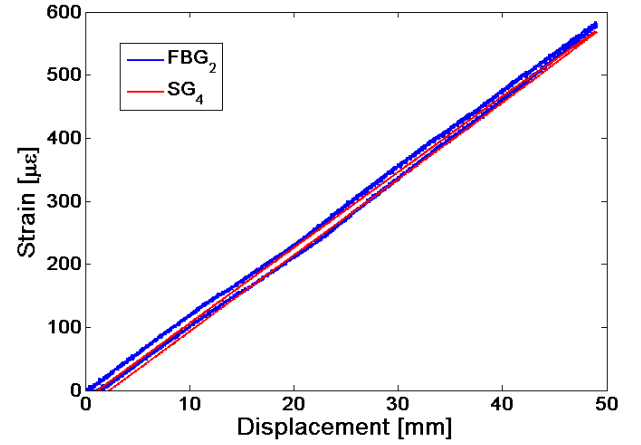


Fig. 10. Longitudinal strains versus vertical displacement due to yielding up to 50 mm obtained at 80 kN of load, using FBG and electrical strain gage installed at $L/2$. The loading and unloading of the force is plotted.

numerical static FEM predictions and experimental data, even in the non-linear regime where the elasto-plastic behavior is clearly evident.

As practical railway operations will never reach such non-linear regime, in the following we will limit the optical sensor system validation to a maximum applied load of 80 kN. A load ramp up to 80 kN has been applied and the strain from FBGs and electrical strain gages installed along the rail section as shown in Figure 7, are compared; note that the strain gages E_1 - E_3 are symmetrically installed with respect to FBG1-FBG3. Excellent agreement can be observed as shown in Figure 10, reporting longitudinal strain versus displacement, measured at $L/2$. Both systems, not only measure equivalent strains but also measure a small hysteresis due to a spurious plastic behavior of the steel. In order to fully validate the hybrid sensor system based on FBG and RDTS, static loads and temperature variations have also been applied simultaneously to the steel rail track. With the aim of comparing static strain measurements performed with FBGs and electrical strain gages under temperature variations, we have also installed a Raman sensing fiber and thermocouples. In the instrumented rail the FBG sensors and strain gages are installed at $L/2$, below the neutral axis. Figure 11 compares the longitudinal strain versus load (up to $F = 80$ kN), measured using FBGs and strain gages at two different temperature values (17°C and 35°C). Note that both FBG and strain gages based measurements are compensated in terms of thermal effects. The comparison between both type of strain sensors in Figure 11 points out good agreement with a maximum differential strain lower than $20 \mu\epsilon$ over the full road ramp up to 80 kN.

In conclusion, this section has fully demonstrated the equivalence of FBG strain sensors to standard electrical strain gages and the effectiveness of the proposed hybrid optical fiber sensor system for quasi-distributed static strain measurement along rail tracks.

IV. OPTICAL FIBER SENSOR SYSTEM VALIDATION IN FIELD TRIALS

The hybrid optical fiber sensor system has also been validated in two railway field trials. The first field trial was set

TABLE I

EXAMPLE OF STANDARD THRESHOLDS FOR GEOMETRICAL RAIL TRACK QUALITY, DEFINED FOR RAILWAY LINES WITH SPEED UP TO 200km/h. THE VALUES OF THE DIFFERENT DEFECTS A, L AND XL ARE EXPRESSED IN mm AND THE MAXIMUM ALLOWED SPEED V FOR TRAINS IS IN km/h

Defects	Description	Max Displacement A,L, XL and Speed Limits V					
Alignment	y direction (A)	$A > 23$ $V < 40$	$A > 18$ $V < 60$	$A > 13$ $V < 80$	$A > 10$ $V < 120$	$A > 9$ $V < 160$	$A > 8$ $V < 200$
Longitudinal	z direction (L)	$L > 22$ $V < 40$	$L > 21$ $V < 60$	$L > 18$ $V < 80$	$L > 17$ $V < 120$	$L > 16$ $V < 160$	$L > 10$ $V < 200$
Transversal	Cross-level displacement (XL)	$XL > 19$ $V < 80$	$XL > 14$ $V < 120$	$XL > 12$ $V < 160$	—	—	—

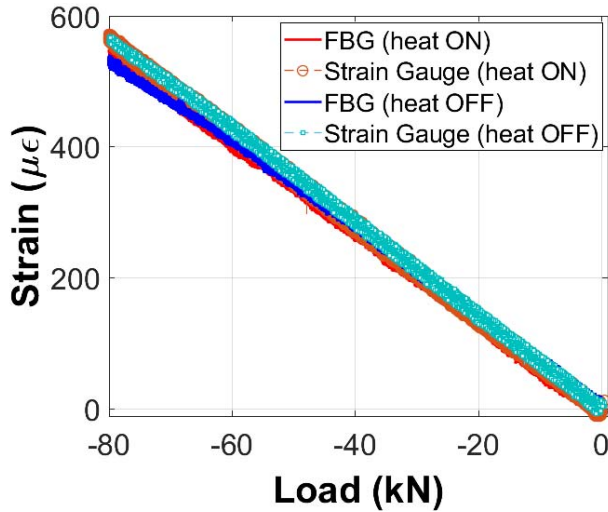


Fig. 11. Longitudinal strain versus applied load for FBG and strain gages with two different temperature (room temperature 17 °C and with heater at 37 °C) at position L/2.

in an out-of-service rail, where different geometrical rail track defects have been induced using specific mechanical actuators. The second field trial was performed on a masonry bridge in service, confirming the absence of false alarms with regular train circulation as well as the capability to identify specific abnormal conditions of the rail track as for example missed clips in the fastening system.

A. Field Trial in an Out-of-Service Track

The main goal of this field trial has been the evaluation of the sensor system capabilities to identify abnormal track deformations, specifically due to longitudinal, transversal and alignment defects connected to hazardous events such as subsidence, slides and buckling. The railway network management system can reduce the train speed and eventually fully stop the train circulation when such geometrical defects exceed pre-defined thresholds [31]. Table I shows an example of such thresholds defined for the three defects with reference to Figure 1, where A represents the track displacement in the y direction, L the track displacement in the z direction and XL the cross-level displacement between the two racks.

The field trial has been carried out at the *Santo Stefano Magra* railway station on an out of service track which is not used for regular train traffic. Figure 12 describes the field trial set-up in which the reading units, placed within a service

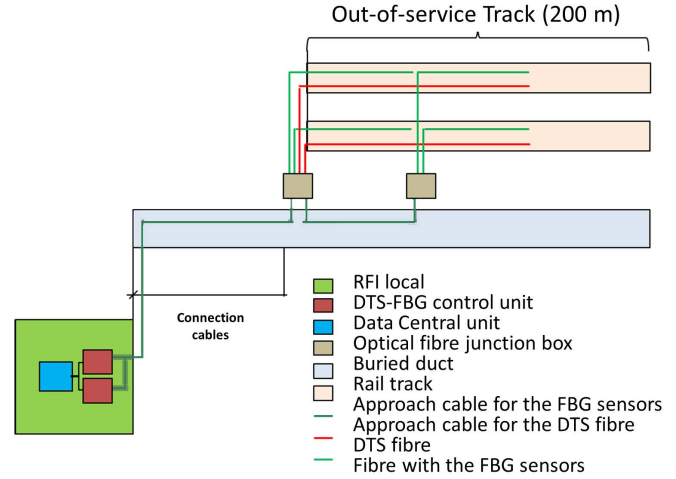


Fig. 12. Field trial layout.

room, are connected to the Raman and FBG sensing fibers along the track through two approaching fiber cables including MM graded-index and SM fibers respectively. A 100 meters long rail section has been instrumented with 55 FBG, spaced 1.8 meter, and a MM fiber cable on each track, for monitoring static strain and temperature distributions. The chosen FBG sensors can operate within the temperature range $-30\text{ }^{\circ}\text{C}$ to $70\text{ }^{\circ}\text{C}$ and are suitable for harsh environment, characterized by low invasiveness and compatibility with railway maintenance operations. They are glued, after carefully grinding and chemically cleaning the steel, thanks to a template that allows to place precisely the sensors using a fast curing adhesive (Z70 from HBM) and then covered by a waterproof protective patch (ABM75 from HBM). Note that consecutive FBGs are installed along the track in different positions as described in Figure 2 (positions top and bottom). This allows one to separate distinctly longitudinal and transversal geometrical defects by processing the acquired data along the full FBG sensors cascade using the linear elastic model described in section II C. Before starting the experimental activities, the geometrical condition of the track section under study has been checked using a precision electronic caliper and a steel wire, confirming absence of significant defects. Different geometrical rail track defects have then been induced using specific mechanical actuators and data were acquired in real-time by the optical fiber sensor system.

1) *Longitudinal Elevation Defect*: The longitudinal defect has been induced on both tracks at the same longitudinal

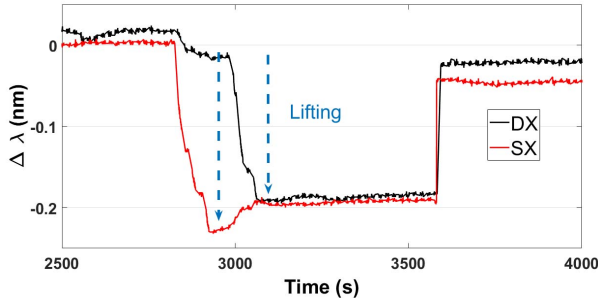


Fig. 13. FBGs wavelength shifts corresponding to a longitudinal defect of approximately 23 mm. (DX: Right; SX: Left).

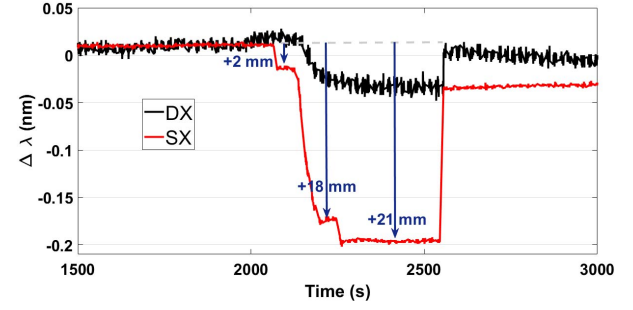


Fig. 15. FBGs wavelength shifts corresponding to a longitudinal defect of approximately 23 mm on one track only. Like in Figure 13 the black curve (DX) is the right track and the red one (SX) is the left track.

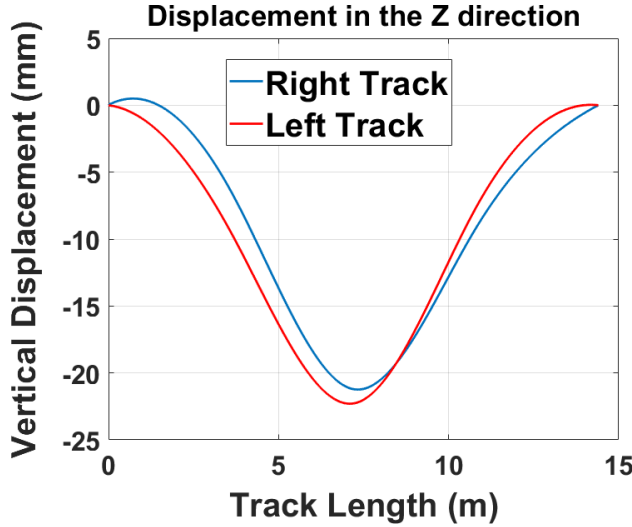


Fig. 14. Vertical displacement values along the z-axis for the two tracks in the case of a longitudinal elevation defect.

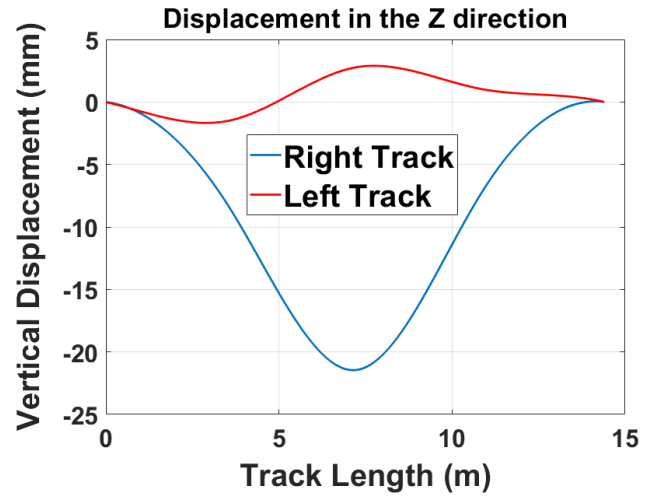


Fig. 16. Calculated vertical displacement values (z-axis) for the two tracks using the experimental strain values obtained during field trials. The arrows indicate the measured manual lifting done during the tests.

x coordinate, simultaneously using two mechanical actuators. The maximum longitudinal defects measured during the actuation along the z axis is respectively 23 mm for the left track and 26 mm for the right track. Figure 13 shows the Bragg wavelength shifts for the two FBG sensors nearest to the actuator position during the actuation process. It is evident that a significant wavelength shift is present on both FBGs during the actuation and that, due to the ballast inertia, the Bragg wavelengths will not completely recover after removing the forces applied to the track. The rails vertical displacements calculated from the FBGs static strain according to the linear elastic model described in section II.C, and reported in Figure 14, confirm a maximum deflection of approximately 23 mm, in good agreement with imposed deformation along the z axis.

2) *Transversal Defect or Cross-Level Defect*: A single mechanical actuator has been applied to induce a cross-level defect displacement of approximately 24 mm in the z direction on right track only. Figure 15 reports the Bragg wavelength shifts for the two FBG sensors closest to the actuator position during the actuation process. The vertical displacements calculated from the FBG sensors readings are reported for the two tracks in Figure 16, confirming that the right track is moved by about 22 mm while the left one is almost unchanged. This further confirms the capability of our

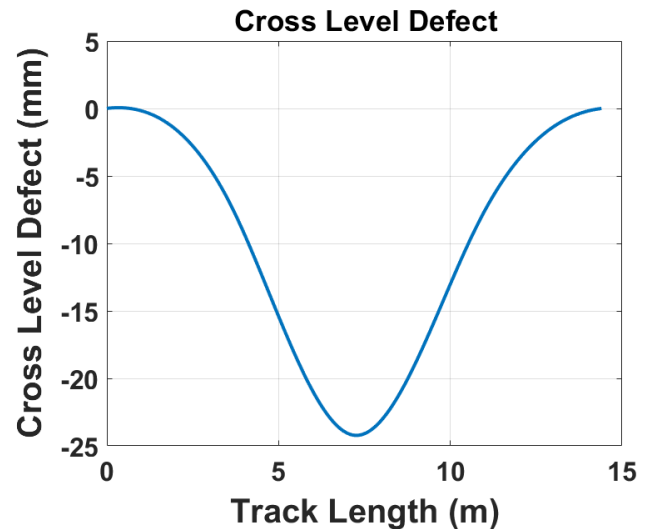


Fig. 17. Calculated transversal defect XL versus distance along the rail track using the experimental strain values obtained during field trials.

hybrid sensor system to predict effectively railway geometrical defects in real-time.

Figure 17 reports the level difference between the displacements values on the two tracks, defined as transversal defect (XL), confirming the results of Figure 16. This further

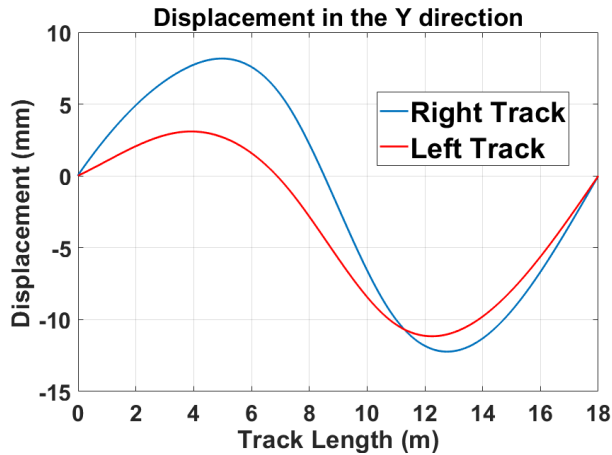


Fig. 18. Calculated displacement of the track along the y-axis using the experimental strain values obtained during field trials.

confirms the capability of our hybrid sensor system to predict effectively railway geometrical defects in real-time.

3) *Defect of Horizontal Alignment:* Finally, in order to induce horizontal alignment defects, the ballast below 10 sleepers instrumented with FBG sensors has been partially removed on one side of the track and a transversal force on the opposite side has been applied by a mechanical actuator. The induced displacement has been measured at the same point where the force has been applied. Figure 18 reports the displacement along the y-axis for both right and left tracks, showing a complex behavior which however confirms the 15 mm maximum deflection measured while using the mechanical actuator. We observe both positive and negative lateral displacements along the y-axis; this can be explained by the difficulty of manually removing the ballast in a uniform way for all the modified trail length, resulting in different constraint forces on the sleepers.

It is evident that the proposed sensor system can provide extremely useful data in real-time about the geometrical rail track conditions and consequently can provide early warning for the train circulation, also limiting the need for visual inspections only when really needed.

B. Field Trial in Service With Train Circulation

This second field trial has been performed to monitor in real-time the track deformation with regular train circulation, fully confirming the absence of false alarms. The layout of the field trial on the Italian railway line Parma/Fidenza-Arcola/Vezzano, between the railway stations of Scorsetoli and Filattiera, characterized by intense freight train circulation due to the connection of La Spezia harbor to the northern part of Italy, is similar to the one described for the field trial not in service (see Figure 12). In this case, 170-meter long rail section has been equipped with an array of 95 FBGs (1.8 meter spacing) and with a MM fiber cable on each track; this rail section is over a 130-meter long masonry bridge. In order to check the geometrical condition of the rail section before performing our measurement we have analyzed the data provided by the diagnostic train Talete [31], [32], which has monitored the line at the end of November 2017. Although

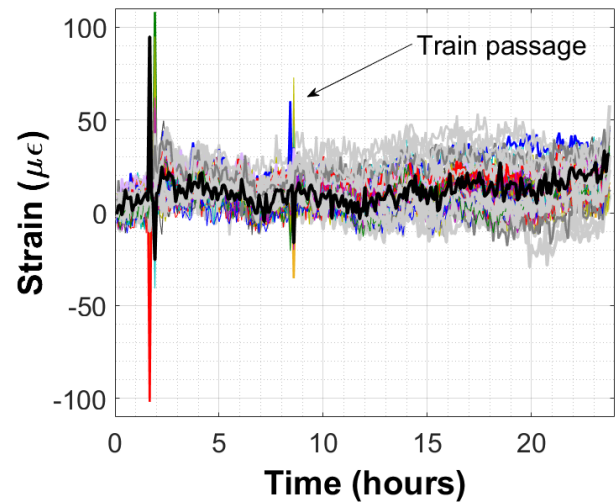


Fig. 19. Measured strain values versus time of all the 188 FBGs installed on the tracks.

a few local defects have been identified, the alignment, longitudinal and transversal misalignments are all below the first level of threshold defined by the RFI regulation, as reported in table I, and the rail track can therefore be considered in good shape. Figure 19 reports the strain measured in all FBG sensors along the monitored rail section, with an average measurement time of 5 minutes. Note that for most of the sensors the strain values are changing within a limited range $\pm 20 \mu\epsilon$, confirming the effectiveness of the temperature compensation. However, a few peaks can be observed in Figure 19, which are likely due to very long freight trains passing on the rail section. Such trains can take more than one minute to go through the monitored zone and the accumulated error may be such that is not vanishing on a 5 minute average measurement time. These peaks are located to specific single time sampling points and can then be easily identified and ignored as not related to static geometrical defects. Figure 19 also points out a few sensors in which the static strain trend is changing over a larger range compared to the $\pm 20 \mu\epsilon$. We have checked that such sensors correspond to non-consecutive positions in which the track is not properly fixed to the sleepers or the fastening is broken. The larger strain variation is due to the fact that in these locations the track can slightly move due to temperature induced deformation.

We can conclude that the system is not affected by false alarms as local peaks in specific locations can be easily identified with train passing events, then ignored, and not considered for static strain analysis. The proposed optical fiber sensor system can well identify significant defects in the track geometry and provide then early warning.

V. CONCLUSION

In conclusion, we have presented and experimentally verified a hybrid optical fiber sensor system, based on combine FBG and RDTS technologies, for monitoring large railway infrastructures. The sensing fibers are directly installed on both rail tracks at key infrastructures like bridges, viaducts and slopes potentially subject to landslides. Combining static strain measurement over long FBG sensor arrays and distributed

RDTs allows one to obtain the rail track deformation in real-time in order to identify significant defects and verify if pre-defined thresholds are exceeded. The proposed technology has been first validated in railway laboratories and then in field trials. Two full system have been installed on rail tracks over a 100m long section not in use and on a live track over a bridge. The field trials have allowed confronting a simple model based on beam theory to actual measurements of deformation and both are in very good agreement. The field trial on the live track with heavy traffic has confirmed that the system was able to detect anomalies (like broken fastener) without raising false alarms. We are aware that a large scale deployment of the proposed hybrid fiber optic sensor system is not straightforward. In particular the main issue hindering this deployment is related to the fact that installing optical fiber sensors directly on the railway tracks can be unsustainable in terms of compatibility with maintenance procedures. However the idea behind this work is that the proposed sensor system should not be installed on the whole infrastructure but only within essential sites, such as bridges, viaducts and slopes potentially subject to landslides. The proposed system has demonstrated its effectiveness for rail infrastructure monitoring and can effectively contribute to the development of intelligent railway transportation systems.

REFERENCES

- [1] E. Bernal, M. Spiryagin, and C. Cole, "Onboard condition monitoring sensors, systems and techniques for freight railway vehicles: A review," *IEEE Sensors J.*, vol. 19, no. 1, pp. 4–24, Jan. 2019.
- [2] S. Jovanović, D. Bovžović, and M. Tomivčić-Torlaković, "Railway infrastructure condition-monitoring and analysis as a basis for maintenance management," *Gradevinar*, vol. 66, no. 4, pp. 347–358, May 2014.
- [3] V. J. Hodge, S. O'Keefe, M. Weeks, and A. Moulds, "Wireless sensor networks for condition monitoring in the railway industry: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1088–1106, Jun. 2015.
- [4] H. Alawad and S. Kaewunruen, "Wireless sensor networks: Toward smarter railway stations," *Infrastructures*, vol. 3, no. 3, p. 24, Jul. 2018. [Online]. Available: <http://www.mdpi.com/2412-3811/3/3/24>
- [5] J. Wang, J. Wang, C. Roberts, and L. Chen, "Parallel monitoring for the next generation of train control systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 1, pp. 330–338, Feb. 2015, doi: 10.1109/its.2014.2332160
- [6] B. Akpinar and E. Gulal, "Multisensor railway track geometry surveying system," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 1, pp. 190–197, Jan. 2012.
- [7] J. J. García *et al.*, "Efficient multisensory barrier for obstacle detection on railways," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 702–713, Sep. 2010.
- [8] B. Culshaw and A. Kersey, "Fiber-optic sensing: A historical perspective," *J. Lightw. Technol.*, vol. 26, no. 9, pp. 1064–1078, May 1, 2008.
- [9] J. P. Dakin, D. J. Pratt, G. W. Bibby, and J. N. Ross, "Distributed optical fibre Raman temperature sensor using a semiconductor light source and detector," *Electron. Lett.*, vol. 21, no. 13, pp. 569–570, Jun. 1985.
- [10] M. A. Soto *et al.*, "Raman-based distributed temperature sensor with 1 m spatial resolution over 26 km SMF using low-repetition-rate cyclic pulse coding," *Opt. Lett.*, vol. 36, no. 13, pp. 2557–2559, Jul. 2011. [Online]. Available: <http://ol.osa.org/abstract.cfm?URI=ol-36-13-2557>
- [11] X. Bao, J. Dhlwayo, N. Heron, D. J. Webb, and D. A. Jackson, "Experimental and theoretical studies on a distributed temperature sensor based on Brillouin scattering," *J. Lightw. Technol.*, vol. 13, no. 7, pp. 1340–1348, Jul. 1995.
- [12] M. A. Soto, G. Bolognini, F. Di Pasquale, and L. Thévenaz, "Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range," *Opt. Lett.*, vol. 35, no. 2, pp. 259–261, Jan. 2010. [Online]. Available: <http://ol.osa.org/abstract.cfm?URI=ol-35-2-259>
- [13] J. Park and H. F. Taylor, "Fiber optic intrusion sensor using coherent optical time domain reflectometer," *Jpn. J. Appl. Phys.*, vol. 42, pp. 3481–3482, Jun. 2003, doi: 10.1143/jjap.42.3481
- [14] Y. Muanenda, S. Faralli, C. J. Oton, and F. D. Pasquale, "Dynamic phase extraction in a modulated double-pulse Φ -OTDR sensor using a stable homodyne demodulation in direct detection," *Opt. Express*, vol. 26, no. 2, pp. 687–701, Jan. 2018. [Online]. Available: <http://www.opticsexpress.org/abstract.cfm?URI=oe-26-2-687>
- [15] Y. Wang, J. Gong, B. Dong, D. Y. Wang, T. J. Shillig, and A. Wang, "A large serial time-division multiplexed fiber Bragg grating sensor network," *J. Lightw. Technol.*, vol. 30, no. 17, pp. 2751–2756, Sep. 1, 2012.
- [16] A. Kerrouche *et al.*, "Strain measurement on a rail bridge loaded to failure using a fiber Bragg grating-based distributed sensor system," *IEEE Sensors J.*, vol. 8, no. 12, pp. 2059–2065, Dec. 2008.
- [17] P. Boffi *et al.*, "Optical fiber sensors to measure collector performance in the pantograph-catenary interaction," *IEEE Sensors J.*, vol. 9, no. 6, pp. 635–640, Jun. 2009.
- [18] C. Wei *et al.*, "A fiber Bragg grating sensor system for train axle counting," *IEEE Sensors J.*, vol. 10, no. 12, pp. 1905–1912, Dec. 2010.
- [19] G. Kouroussis, D. Kinet, V. Moeyaert, J. Dupuy, and C. Caucheteur, "Railway structure monitoring solutions using fibre Bragg grating sensors," *Int. J. Rail Transp.*, vol. 4, no. 3, pp. 135–150, 2016, doi: 10.1080/23248378.2016.1184598
- [20] H.-Y. Tam, S.-Y. M. Liu, W.-H. Chung, K. Cheng, and K. K. Lee, "Fibre Bragg grating sensors for smart railway monitoring," in *Proc. Photon. Fiber Technol. (ACOFT, BGPP, NP)*, 2016, Paper BM4B.4. [Online]. Available: <http://www.osapublishing.org/abstract.cfm?URI=BGPP-2016-BM4B.4>
- [21] A. Signorini, T. Nannipieri, F. D. Pasquale, E. Fedeli, and E. Marzilli, "Fire detection in long railway tunnels using high performance Raman based optical fiber sensors," in *Proc. 11th WCRR*, Jun. 2016.
- [22] D. Hill, "Distributed acoustic sensing (DAS): Theory and applications," in *Proc. Frontiers Opt.*, 2015, Paper FTH4E.1. [Online]. Available: <http://www.osapublishing.org/abstract.cfm?URI=FO-2015-FTH4E.1>
- [23] M. L. Filograno, P. Corredera, M. Rodríguez-Plaza, A. Andrés-Alguacil, and M. González-Herráez, "Wheel rail detection in high-speed railway systems using fiber Bragg gratings," *IEEE Sensors J.*, vol. 13, no. 12, pp. 4808–4816, Dec. 2013.
- [24] W. Eickhoff and R. Ulrich, "Optical frequency-domain reflectometry in single-mode fibers," *Appl. Phys. Lett.*, vol. 39, no. 9, pp. 693–695, 1981. doi: 10.1063/1.92872
- [25] K. Kikuchi, T. Naito, and T. Okoshi, "Measurement of Raman scattering in single-mode optical fiber by optical time-domain reflectometry," *IEEE J. Quantum Electron.*, vol. QE-24, no. 10, pp. 1973–1975, Oct. 1988.
- [26] X. Li, M. Ekh, and J. C. O. Nielsen, "Three-dimensional modelling of differential railway track settlement using a cycle domain constitutive model," *Int. J. Numer. Anal. Methods Geomech.*, vol. 40, no. 12, pp. 1758–1770. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/nag.2515>
- [27] B. Lee and Y. Jeong, *Interrogation Techniques for FGSs and the Theory of Fiber Gratings*. Boca Raton, FL, USA: CRC Press.
- [28] M. A. Farahani and T. Gogolla, "Spontaneous Raman scattering in optical fibers with modulated probe light for distributed temperature Raman remote sensing," *J. Lightw. Technol.*, vol. 17, no. 8, pp. 1379–1391, Aug. 1999. [Online]. Available: <http://jlt.osa.org/abstract.cfm?URI=jlt-17-8-1379>
- [29] *LS-DYNA Livermore Software Technology Corporation (LSTC)*. Accessed: Oct. 31, 2019. [Online]. Available: <http://www.lstc.com/dynamat/>
- [30] N. Larijani, C. Kammerhofer, and M. Ekh, "Simulation of high pressure torsion tests of pearlitic steel," *J. Mater. Process. Technol.*, vol. 223, pp. 337–343, Sep. 2015. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0924013615001843>
- [31] *Standard di Qualità Geometrica del Binario e Parametri di Dinamica di Marcia Con Velocità Fino a 300 km/h*, document RFI-TCAR ST AR 01 001 D Del, Rete Ferroviare Italiane, Rome, Italy, Nov. 2011.
- [32] M. Elia, *Healthy Tracks Mean Healthy Operations*. Accessed: Oct. 31, 2019. [Online]. Available: <https://www.globalrailwayreview.com/article/18570/healthy-tracks-mean-healthy-operations/>

Philippe Velha received the degree in engineering and the M.Sc. degree in integrated digital electronics from the Ecole Centrale Lyon, France, in 2004, and the Ph.D. degree in physics from the Université Paris-Sud XI, in 2008. Over the years, he has been involved in the supervision of over 10 Ph.D. students. In 2013, he has joined the Scuola Superiore Sant'Anna, Pisa, Italy. He is the coauthor of more than 90 publications and is a Senior Member of the OSA.

Tiziano Nannipieri received the degree in telecommunication engineering from the University of Pisa. From 2009 to 2017, he was with the Institute of Communication, Information and Perception Technologies, Scuola Superiore Sant'Anna, in the optical fiber sensors and integrated photonics subsystems research area. From 2010 to 2017, he was involved in joint industrial projects between Scuola Superiore Sant'Anna and industrial partners operating in transportation and Oil&Gas sectors aimed to the development and validation of a fiber optic-based sensor system for multiphysical sensing. He is currently a Co-Founder and a CTO of INFIBRA TECHNOLOGIES Srl a start-up company involved in designs and providing fiber optic sensor systems for many industrial sectors spanning from transportation and automotive to Oil&Gas. His current research interests include fiber optic sensing, especially in design and development of distributed and discrete fiber optic sensor systems for static and dynamic measurements based on spontaneous Raman and spontaneous/stimulated Brillouin scattering and fiber Bragg gratings.

Alessandro Signorini received the M.S. degree in electronic engineering from the University of Pisa, Italy, in 2008. From 2008 to 2010, he was a Research Engineer with Scuola Superiore Sant'Anna (SSSA), Pisa, for the study, design, and development of a Raman-based distributed temperature sensor. From 2010 to 2016, he has been a Research Fellow at SSSA. He is Co-Founder and a CEO of INFIBRA TECHNOLOGIES Srl, a high-tech startup company operating in the field of fiber optic sensors. His main research activities were focused on fiber Bragg point sensors and distributed optical fiber sensors based on Rayleigh, Brillouin, and Raman scatterings, particularly on the study and development of new measurement methods and new application techniques in the fields of oil&gas, transportation, safety, power, and environmental monitoring. He is the author and coauthor of more than 30 international publications in journals, conferences, and patents in optical fiber sensing and their applications. He was involved in several joint projects between Scuola Superiore Sant'Anna and Rete Ferroviaria Italiana (RFI) and General Electric for the development and field trial of fiber optic sensor systems.

Mirko Morosi received the degree in engineering from the University of Perugia, Italy, in 2001, the M.Sc. degree in earthquake engineering from the Rose School, IUSS, Pavia, in 2010, and the Ph.D. degree in geotechnical and earthquake engineering from IUSS in 2015. He has collaborated with Scuola Superiore S. Anna, Pisa, Italy for a year and a half after his Ph.D. degree. Before his Ph.D., he was a consultant engineer in the construction and infrastructure industry for more than ten years. He is a structural engineer with strong experience in seismic design. Since 2017, he has been with Arup, Milan, as a Senior Engineer and Analyst.

Massimiliano Solazzi received the Ph.D. degree in innovative technologies from Scuola Superiore Sant'Anna, Pisa, Italy, in 2010. He is currently an Assistant Professor in applied mechanics with the Scuola Superiore Sant'Anna, and carries out his research with the PERCRO Laboratory, TeCIP Institute. His research interests include the design of robotic interfaces for virtual reality, teleoperation and rehabilitations, the design and control of arm exoskeletons, the development of control systems for manipulators, and the psychophysical validation of HMI.

Francesco Barone received the bachelor's degree in computer and automation engineering and the master's degree in automation engineering from the Polytechnic University of Bari, Italy, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. degree in emerging digital technologies with Scuola Superiore Sant'Anna, Pisa, Italy. He is currently involved in the study of compressor stability control with the Oil&Gas Testing Laboratory, Baker Hughes, a GE company (Florence). His interests include control systems, photonic sensors, signal processing, artificial intelligence, and machine learning. His current research interests include optical fiber sensors, advanced sensors for industrial compressors, and turbines monitoring. He previously involved in robotic exoskeleton control and electromyographic (EMG) signal processing for neurorehabilitation.

Antonio Frisoli received the M.Sc. degree in mechanical engineering, minor robotics, from the University of Pisa, Italy, in 1998, and the Ph.D. degree (Hons.) in industrial and information engineering from Scuola Superiore Sant'Anna, Italy, in 2002. He is currently a Professor of robotics and mechanical engineering with Scuola Superiore Sant'Anna, Pisa, Italy, where he is also the Head of the human-robot interaction area with the PERCRO Laboratory, TeCIP Institute.

He is the author of more than 200 articles in peer-reviewed international conferences and scientific journals. His research interests include design and control of haptic devices and robotic systems, rehabilitation robotics and human motor control, virtual reality, advanced human-computer interfaces for training, and brain-computer interfaces. He is currently involved in the study of new designs for exoskeletons systems, portable fingertip haptics, and new brain-robot interfaces.

Dr. Frisoli has been the Chair of the IEEE Technical Committee on Haptics and the General Chair of the Eurohaptics 2018 conference in Pisa and Human-Machine Interaction summer school HMISS 2017. In the field of robotics and haptics, he acts as an Associate Editor in numerous international conferences, such as the IEEE WORLDHAPTICS, the IEEE ROMAN, and the IEEE Haptic Symposium, and journals, such as the IEEE ROBOTICS AND AUTOMATION LETTERS and MIT Press Presence.

Luca Ricciardi graduated in mechanical engineering from the La Sapienza University of Roma, Italy, in 2001. From 2000 to 2002, he was with mechanical and environmental private companies. Since 2002, he has been with Rete Ferroviaria Italiana S.p.A. (RFI), the Italian Railway Infrastructure, where he is currently the Infrastructure and Environment Laboratory Manager. In RFI, he is involved as a Technical Consultant in legal disputes resulting from presumed noise pollution and electromagnetic fields. He is the author and coauthor of different scientific journals and conference articles. He was a member of the Expert Group Noise and Vibration, International Union of Railways (UIC). He is also a member of the Acoustics and Vibrations Committee, Ente Nazionale Italiano Unificazione (UNI), which studies, develops, approves, and publishes technical rules.

Ricardo Eusepi graduated in mechanical engineering from the Tor Vergata University of Rome, Italy, in 2011. In 2012, he was with Photovoltaic private companies. Since 2012, he has been with Italcertifer, the Italian Certification Body of Subsystems that make up the European rail system. Since 2015, he has been with Rete Ferroviaria Italiana S.p.A. (RFI), the Italian Railway Infrastructure, where he is currently an Infrastructure Laboratory Testing Engineer. In RFI, he is involved in testing and calibration accreditations according to European Standards. He is also with the Research and Development Laboratory for the study of railway infrastructure components.

Marco Icardi graduated in electrical engineering from the Montani Technical Institute of Fermo in 1972. Since 1973, he has been with FS Group, Rete Ferroviaria Italiana S.p.A., as a Chief Engineer, responsible for the electrical systems sector. Since 2009, he has assumed the functions of responsible of the Department. During his working life, he deals with the maintenance of the railway infrastructure in its various aspects with particular regard to electric traction and safety systems. He is currently with the Territorial Unit of Pisa. As a voluntary activity, he has been a Technical Director of the Railway Section of the National Museum of Transport of La Spezia, since 2005.

Giuseppe Recchia received the degree in electronic engineering from La Sapienza University of Rome in 1998. He was hired at the Italian Railway Network in Florence for the activities of Design and Works Management of technological systems in 1999. He took on the role of Responsible of Specialty Operations (SO) Technology Systems, Genoa, in 2008. In 2009, he was Responsible of SO Technologies, Florence and since 2011, he has become Responsible of SO Territorial Operational Management. In 2014, he has assumed the position of Responsible of SO Engineering, within the production territorial direction of Toscana. Since 2014, he has been Responsible of the territorial unit that manages the railway lines referring to the Pisa, Livorno, and La Spezia nodes.

Margherita Lupi received the degree in mechanical engineering (energy sector) from the University of Rome La Sapienza, Italy, in 1995. From 1996 to 2010, she was with TAV—Treno Alta Velocità, a company of FS Group (Italian Railways) taking on the role of the Responsible of Technologies (Center and South Area), carrying out coordination activities in the design, realization, and activation of the first Italian high speed lines (Rome- Naples and Bologna - Florence). She is currently an In-charge of coordination activities of study, research, and experimentation of innovative systems and measurement systems (connected to the railway track and monitoring of the relative geometric dimensions) with the Technical Department of Rete Ferroviaria Italiana S.p.A. (RFI).

Giuseppe Arcoleo received the degree in civil engineering from the University of Palermo, Italy, in 1995, and since 1981, he has been with the FS Group, Italian Railway, covering more jobs, designing and managing works for the maintenance and construction of railway lines. He has been a Manager of Rete Ferroviaria Italiana S.p.A. (RFI) - Italian Railway Network, since 2002, he has assumed the responsibility of the Track Equipment and Civil Works structure of the Production Department in Palermo and two years later, he held the position of the Head of the Efficiency Maintenance Structure - Territorial Operational Management of Sicily. Since 2010, he has been the In-charge of Track Equipment and Civil Works of Production Direction Headquarters of Rome, and Program Contact for the maintenance work and railway track equipment construction on the entire network. Since 2015, he has been a Production Manager of Sicilia and then in 2016, he held the position of the Head of the Track Equipment Structure in Rome, where he has conducted experimental projects and issued technical documentation of Track Equipment. In 2018, he has left the FS Group.

Paola Firmi received the degree (Hons.) in civil engineering (Transport specialization) and the Ph.D. degree in town planning and infrastructure environmental design. Since 1993, she has been with the Rete Ferroviaria Italiana S.p.A. (RFI), where she was first an Inspector with the Engineering and Constructions Department and then Environment Responsible (from 2003 to 2007), Civil Infrastructures, and then Experimental Standards Responsible (from 2008 to 2016). She is currently the Director of the Technical Department, with the task of promulgating regulations for the safety of railway operation and technical standards for the whole railway infrastructure, comprising civil constructions and tracks and technological equipment. The Technical Department also ensures the definition and the development of innovative solutions, and the infrastructures components certifications and approvals. She has been involved in several projects and committees for investment directions, regulations for constructions and related monitoring procedures, and technical verification of civil works. She has been a monitoring member of the Panel of Structural Experts (PoSE), UIC Rail System Forum, Track and Structures Sector, since 2014, a member of the UIC Rail System Forum Steering Board, since 2014, and a member of JNS (CER Key Contacts), CER Safety Sector, since 2016.

Fabrizio Di Pasquale received the degree in electronic engineering from the University of Bologna, Italy, in 1989, and the Ph.D. degree in information technology from the University of Parma, Italy, in 1993. From 1993 to 1998, he was with the Department of Electrical and Electronic Engineering, University College London, U.K., as a Research Fellow, involving in optical amplifiers, WDM optical communication systems, and liquid crystal displays. After two years with Pirelli Cavi e Sistemi and two years with Cisco Photonics Italy, he moved to Scuola Superiore Sant'Anna, Pisa, Italy, where he is currently a Full Professor of telecommunications and a Deputy Director of the Institute of Communication, Information and Perception Technologies (TECIP). His current research interests include optical fiber sensors, silicon photonics, optical amplifiers, and WDM transmission systems and networks. He has filed 20 international patents and he is the author and coauthor of over 210 scientific journals and conference articles. He is on the Board of Reviewers of the IEEE PHOTONICS TECHNOLOGY LETTERS, the IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY, the IEEE SENSORS journal, *Optics Communications*, *Optics Express*, and *Optics Letters*.