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Structural health monitoring of in-service tunnels

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Abstract

This work presents an overview of some of the most promising technologies for the structural health monitoring (SHM) of in-service tunnels. The common goal of damage or unusual behavior detection is best pursued by an integrated approach based on the concurrent deployment of multiple technologies.

Typically, traditional SHM systems are installed in problematic or special areas of the tunnels, giving information on conditions and helping manage maintenance. Deformation of the inner lining, stress variations of the shotcrete and groundwater level, among others, can be monitored either in real time or at periodic intervals. In most cases, the deformation data is compared with the prescribed safety criteria so that, when the deformation exceeds a certain level, alarms are automatically sent to the maintenance engineer.

However, these methodologies often have the drawbacks of forcing the interruption of traffic for SHM system installation and monitoring only selected portions. Alternative solutions that would make it possible to keep the tunnel in normal operation and/or to analyze the entire infrastructure development through successive and continuous scanning stages, would be beneficial.

In this paper, the authors will briefly review some traditional monitoring technologies for tunnels. Furthermore, the work is aimed at identifying possible alternatives and solutions that can be used, limiting or avoiding traffic interruptions. In particular, distributed fiber optical methods, LIDAR and infrared technologies are discussed, and reference is made to existing case-studies. The potential offered by visual based methods is also preliminarily investigated by laboratory testing.

1. Introduction

New and planned infrastructures all over the world often make use of underground development, which remains an ideal and safe solution in many situations, e.g. to overcome mountain ranges, to connect islands to continents, to manage urban and extra-urban roads, for rail and road traffic but also for the management of large hydroelectric plants. Recent examples from the US and Turkey are given in Figures 1a and 1b, respectively.

Figure 1. (a): Miami Tunnel with flood gates (Florida, USA); (b) Ovit Tunnel over 14 km long (Turkey)

A tunnel (Lunardi 2008, Maidl et al. 2013). is a bespoke solution, relying on a variety of tunneling methods optimized against the constraints imposed by the ground conditions and the tunnel's function, as well as the challenges concerning the logistics and the land acquisition. Among the positive aspects in favor of underground structures there is the possibility of coping with scarce land resources, especially in urban areas. Furthermore, underground structures are generally less susceptible to extreme events such as earthquakes, storms/hurricanes, even if they are far more complex and expensive when compared to surface structures.

The Western world has an extensive tunneling heritage. Many of these tunnels have been in service for several decades and are therefore subject to decay and degradation. However, the existing tunnels themselves, despite their advanced age, are still crucial to the development and sustainability of the community life. A decommissioning of them remains an event with a strong impact on the economy, logistics, eco-sustainability and in general on the activities of society. Therefore, the management of existing tunnels, the design and construction of new ones, and the underground infrastructure in general will continue to be a key element to sustainable development, balancing the demands of a growing urbanized population and the desire to preserve the environment. However, insufficient efforts have been made to improve monitoring systems and techniques for underground structures (Richards, 1998; Bhalla et al., 2005; Brownjohn, 2007; Hoult and Soga, 2014; Li et al., 2016; Wang et al., 2017). There are currently no specific codes governing the requirements for monitoring underground structures. Furthermore, there is not a unique solution in terms of instrumentation, technology and algorithms, since each underground structure is unique in itself. Thus, this subject represents an appropriate candidate for research funding to develop innovative solutions in the field of structural health monitoring (SHM).

With respect to other general existing state of the art surveys (e.g. Li et al., 2016), this work is strictly focused on tunnels and innovative SHM solutions and perspectives for such infrastructures. The aim is to analyze the existing monitoring solutions and the possible innovative solutions that can be developed in the light of newly available technologies from other fields of civil engineering but also from related sciences. The emphasis is placed on those innovative solutions that allow monitoring of in service tunnels by analyzing the entire infrastructure development with/without limited traffic interruption. Hence, with respect to the traditional and consolidated monitoring techniques (Lunardi 2008), this manuscript represents a step forward from research to application.

The issues in tunnels can be distinguished as global (e.g. major deformations due to EQs etc) and local (crack and delaminations leading to water seepage). Consequently, there are SHM technologies that are appropriate at the global scale (permanent monitoring solutions using sensors and Fiber Optical Solutions, and intermittent ones such as those using Laser Imaging Detection and Ranging or LIDAR technolology) and local ones (e.g nondestructing evaluation techniques using Infrared spectroscopy).

Fiber optic sensors represent a consolidate and mature technology for SHM of tunnels. In the distributed arrangements for spatial monitoring, it allows static measurements of strains and temperature. Their implementation could be a rather complex process that requires resources and time. However, their functioning is not affected by electromagnetic disturbances or aggressive environment. Different technologies as infrared thermography (IRT) or digital image correlation (DIC) do have the benefit of noncontact requirements for their functioning. The first one is able to detect temperature gradients that could be connected to degradation and damages. On the contrary, digital image correlation allows to detect displacements and strain in both static and dynamic conditions. Furthermore, among noncontact solutions, Laser Imaging Detection and Ranging (LIDAR) can also be used for deformation measure and damage detection without needing light in order to scan and obtain the 3D points cloud. The described noncontact solutions show also the benefit to be mounted on movable vehicles, robot and drones.

The present manuscript is organized as follows. The most traditional monitoring solutions for in-service tunnels are briefly reviewed in Section 2. Distributed fiber optical methods are then discussed in Section 3, whereas LIDAR and infrared technology are presented in Section 4. Reference is made to existing case-studies. In Section 5, the potential offered by visual based methods is investigated by laboratory testing. Finally, some conclusive remarks are drawn.

2. Traditional current practice

Existing monitoring solutions can be classified in those ones adopted during the construction and those in-service ones (Lunardi 2008, Maidl et al. 2013). Moreover, they can be also classified in permanent and portable solutions. The present paper focuses on the in-service monitoring solutions that are aimed to monitor the behavior of the tunnel over the service time, in order to be able to plan indispensable maintenance prudently and guarantee safety over the whole of its service life.

The purpose of long term monitoring is related to (i) verify the functioning of the construction and all the interventions (e.g. maintenance), (ii) track the deformation of the cavity over the time, (iii) assess the impact of the construction on the surrounding environment (e.g. the pre-existing hydrogeological equilibrium). Nowadays, automatic permanent devices are available with which remote measurements of most of the parameters needed to monitor the health of an underground construction can be performed. This means that a monitoring system can be activated during construction which is able to continue furnishing data for many years after a tunnel is commissioned without interfering with the tunnel service. Such type of devices are usually installed in certain critical locations and the provided information is therefore related to such tunnel sections (local monitoring). There are several considerations strictly related to underground structures that also affect the monitoring systems development. Indeed, these structures are characterized by a harsh and rough environment therefore sensors should be particularly durable and robust. Earth pressures, ground movements due to construction, underground formations and ground water fluctuations, dust and dark ambient conditions affect the efficiency, durability and reliability of the monitoring systems. An efficient structural monitoring system can only be achieved if the structure to be monitored is instrumented with sensors networks at all critical points. At the same time, complete monitoring requires the use of complementary sensor systems with sufficient redundancy, so that some sensors can fail without the collapse of the whole monitoring system. In general, SHM sensors can be classified as surface-bonded type and embedded type. The surface-bonded sensors have the benefit to be easily replaceable at any stage. On the contrary, embedded sensors have very limited possibility to be repaired or replaced. Therefore, the latter ones should be more robust and durable.

One of the most common technology is the ***single and multipoint extensometers*** to measure ground movement along the axis of a drill hole with respect to the mouth of the hole at a certain number of measurement points located at various depths. An extensometer is defined as single point or multipoint depending on the number of measurement points installed in it (it can have a maximum of seven points). Typical use of single and multipoint extensometers is for measurement of deformation around the cavity (Figure 2a, radial extensometers). The system consists of installing anchor points in the ground inside drill holes connected to the surface by steel, invar steel or fiber glass rods.

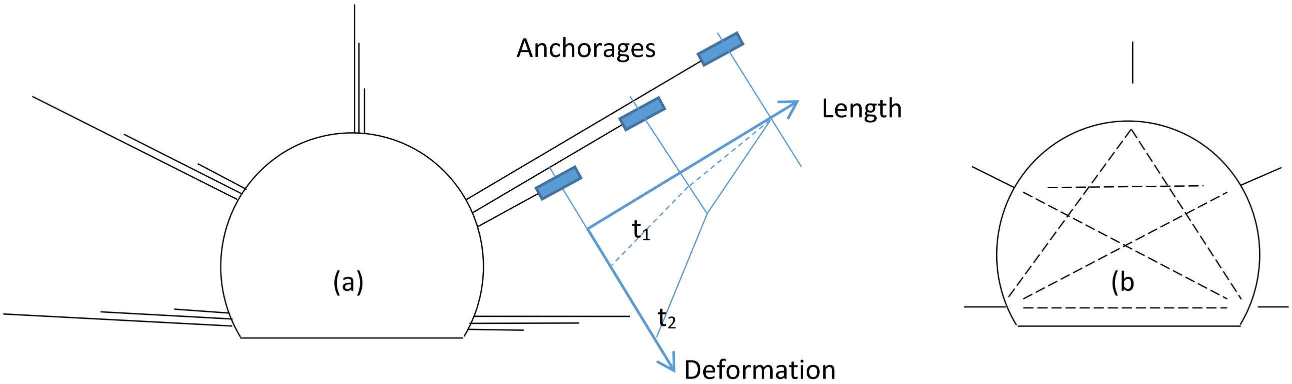

Figure 2. Extensometers for deformation measures around the cavity (a). Distometer nails (b).

Convergence measurements, as those provided by radial extensometers, are critical to evaluate the internal profile of the lining and verifying that it does not deform over time. The instrumentation already installed at the construction stage can be used to furnish directly, and not by deduction, the distribution of the pressures acting on the preliminary and final linings. Special attention to asymmetrical loads should be payed because they may arise as a result of particular pre-existing stress states in the ground, which are not normally predicted by numerical models (e.g. finite element models).

Another monitoring technique that is adopted in current tunneling to evaluate convergence are the ***distometer nails***. They are simple nails with threaded or eyebolt heads used as reference points for the measurement of convergence in a tunnel. Up to five nails can be used into the cavity (Figure 2b). Measurements are performed by comparing the current distances with the reference ones taken immediately after the distometer nails are placed.

Inclinometers are another widely used technology for monitoring vertical and horizontal displacements of the ground and also for measuring variations in the position of surrounding structures. They function by measuring variations from the vertical at significant points. Numerical integration is used to obtain the movements from the inclination.
Pressure and load cells are extremely useful for measuring the total pressure that builds up in the ground, in the lining or at the interface between the ground and the lining.

Another monitoring instrument that can be used is the ***tunnel scanner*** that produces a “stereo-photogrammetric” image of the tunnel surface, which means that all areas of the tunnel surface are scanned simultaneously from two different positions to enable 3D reconstruction. The position of the instrument is fixed by surveying, for example with auto-targeting theodolites.

If a tunnel runs through substantial aquifers, then it is very important to monitor the transition periods (generally long and occupying large physical areas) when the water table first dries and is then replenished. This can be done by installing a network of ***piezometers*** before construction actually commences, which should remain in operation for the whole working life of a tunnel.

Data from the monitoring sensing units applied to all monitored tunnel sections are collected by the ***acquisition and transmission systems***. They usually integrate a series of sub-systems, each used to manage a measurement station by means of a computerized control unit located in a protected place inside a tunnel near the measurement unit. Furthermore a number of central units each controlled by a micro processor which controls and interrogates the various sub-systems via a telephone signal according to set schedules can be installed. These are usually placed near tunnel portals and are connected by modem to the network (Lunardi 2008, Maidl et al. 2013).

3. Distributed optical fiber sensing

Distributed optical fiber sensing (Glisic and Inaudi, 2007; Bursi et al., 2016; Wang et al., 2018) is a recently introduced technology allowing the full monitoring of deformations and temperatures along the whole length of a tunnel. Unlike electrical sensors and localized fiber optic sensors, distributed sensors offer the unique characteristic of being able to measure the physical parameters (in particular, strain and temperature) of thousands of points from a single read-out unit. This technology is based on the use of distributed sensing cables that are installed along the tunnel vault and follow its deformations (Inaudi and Glisic, 2007). The sensing cable is fully passive and does not require power supply. The interrogator, placed at a convenient location, e.g. close to the entrance or in a niche, sends optical signals into the sensing cable and demodulates the returned scattered light, providing strain and temperature information, meter-by-meter, along the whole length of the sensing cable that can reach tens of kilometers.

The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. Both systems make use of a non-linear interaction between the light and the glass material of which the fiber is made. If an intense light at a known wavelength is shone into a fiber, a very small amount of it is scattered back from every location along the fiber itself. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are higher and lower than the original signal (called the Raman and Brillouin components, respectively). These shifted components contain information on the local properties of the fiber, in particular its strain and temperature.

When light pulses are used to interrogate the fiber it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber through the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light one can obtain the complete profile of strain or temperature along the fiber.

Typically it is possible to use a fiber with a length of up to 30 km and obtain strain and temperature readings every meter.

The aquired distributed strain and temperature information can be used to identify and localize damage such as concrete cracks, abnormal differential settlements, deformations, water ingress, fire and others. The cable can be installed in different patterns and directions, as in the examle depicted in Figure 3. Typically, sensors are installed parallel to the expected strain direction or perpendicular to the expected cracks (Iten et al., 2015). The measurements are carried out automatically every few minutes and alerts can be generated based on predefined threshods or more complex alarm criteria.

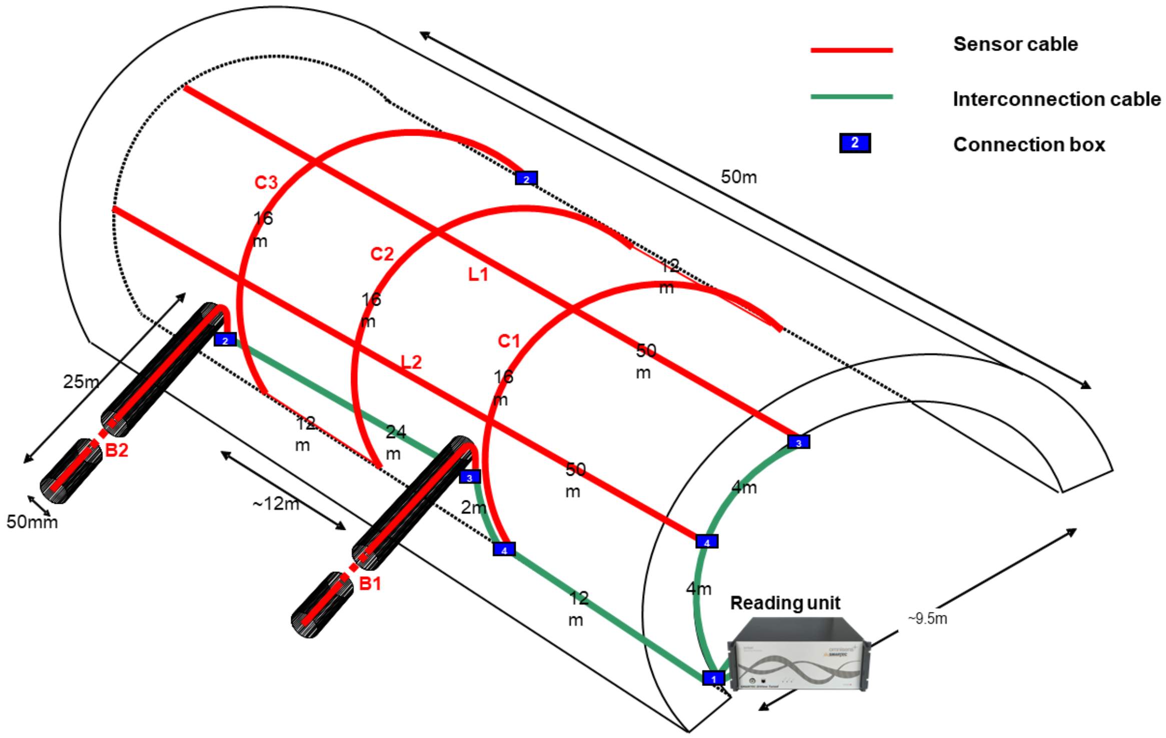

Figure 3. Example of distributed sensing instrumentation for longitudinal tangential and radial directions.

The main advantage of distributed sensing compared to conventional instrumentation, is that it does not require to pre-define monitoring cross-sections and therefore covers the whole length of the tunnel. Once movement zones are detected and localized, it is easier to concentrate inspection, instrumentation and maintenance actions on those zones. The main limitation of distributed optical fiber sensing is that it requires a physical deployment of the sensor in the tunnel. This requires accurate planning of the sensor installation, to make sure that it does not get damaged during construction, operation and maintenance interventions.

3.1 Case Study: the San Salvatore Tunnel (Switzerland)

A portion of the concrete lining of the San Salvatore tunnel collapsed in June 2017 due to water accumulation (see Figure 4). Immediately following that event the Swiss Federal Roads Office defined urgent measures deemed to mitigate the risk that a similar event could be repeated elsewhere in the tunnel. Among all the urgent safety measures to be taken, it was decided to install distributed fiber optic sensors onto the tunnel liner for a continuous, remote and automatic monitoring of the tunnel structural condition.

Figure 4. Local collapse of the San Salvatore Tunnel vault.

The A2 motorway, so-called Gotthard route, is one of the most important north-south transport arteries in Europe and one of Switzerland’s busiest motorways. Thousands of car and lorry drivers use the route on a daily basis, which runs from Basle via Lucerne, then through the Gotthard tunnel to Lugano and continues on the Italian side in the direction of Milan. This heavily traffic stressed route passes through the San Salvatore Tunnel in Ticino.

The tunnel built in 1968 is currently under restoration and this represents a challenge for the two 1,730 m long twin-lane bores, particularly regarding the construction materials used at that time.

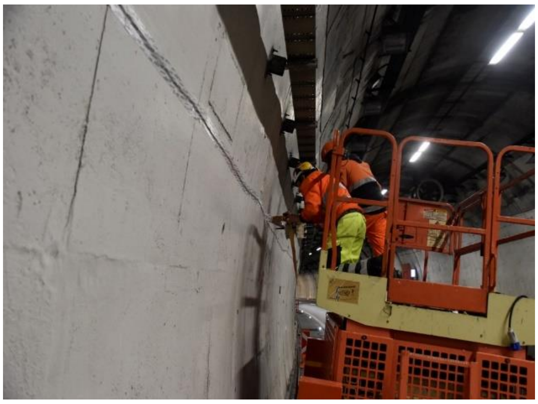

Figure 5. SMARTProfile Sensor Installation on the tunnel lining

Two lines of distributed fiber optic sensors are now tightly affixed onto the tunnel lining and allow detection and localisation every 1 meter of concrete lining deformation and cracks formation due to any hydrostatic pressure behind the lining. The sensing cable (Figure 5) is glued to the concrete surface along the whole length, allowig continuous transfer of strain from concrete to the sensing fiber. In case of cracks, the sensor partially debonds and provides evidence of the crack formation through the apprition of a localized strain peak. The monitoring system allows a fully automatic and continuous monitoring of the tunnel integrity and provides a rapid and effective response to potential defects and failure/collapse, thus increasing the safety of the structure and its users.

In particular, the monitoring system installed in the control room at the entrance of the tunnel performs a measurement automatically every 15 minutes approximatelly. The recorded strains are compared to a baseline and significant variations are immediatelly reported via email to the responsible engineers. The effects of temperature variatins, both seasonal and daily are compensated using a temperature sensing cable installed in an existing cable tray.

An example of result is illustrated in Figure 6. For most of the sections under exam, approximatelly 250m long, the strain variations are in the order of 100-200 microstrains and well correlated with temperature variations. At some locations, the strain peaks are clearly visible and indicative of small crack mouvements. Since craks produce a very concentrated strain, the recorded values are very high even if the cracks only open by a fraction of mm. The data analysis software is able to identify and localize the onset of new crakcs that were not previously identified.

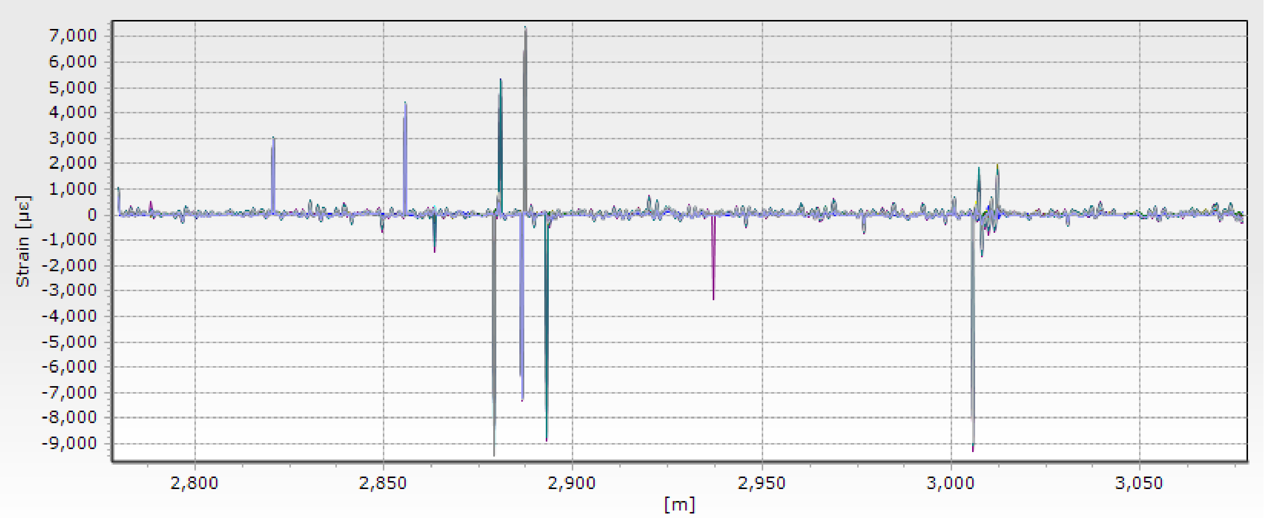

Figure 6. Strain variations in a localized section of the San Salvatore Tunnel. Strain peaks are correlated with small crack mouvements.

4. Non-contact Infrared and LIDAR technologies

There are other technologies to determine water infiltration and crack/efflorescence such as the ones based on ***infrared thermography*** (IRT) and portable cameras. Infrared technology (Holst, 2000) is a non-contact technology to detect temperature difference of water infiltration due to a number of reasons such as deterioration, damage due to settlement etc. Such technologies make it easy to scan structures for localized damage.

In addition to localized issues, large scale problems such as geometric changes due to settlement can also be captured deploying ***Laser Imaging Detection and Ranging*** (LIDAR) technologies using 3D point cloud (Figure 7). The scanner works by emitting a light signal (laser) through a transmitter and receiving the return signal by a receiver. Today, there are two typical scanner types used which are defined by the technique they adopt for their distance calculation. The first scanner type is known as ‘Time of Flight’ which uses a distance calculating technique based on the time elapsed between the emission of the laser and the reception of the return signal. The second scanner type is the ‘Phase-Based’ one which calculates distance by comparing the phases of the output signal and the return signal (3DSCAN, 2018). Overall, time of flight scanners tend to scan slower than phase-based scanners but can scan farther, whereas phased based scanners tend to scan faster but are limited in the scanning range (*SurvTech Solutions, 2019*). The emitter is seated on the body while the body rotates around the axis vertically and also consists of a horizontally rotating mirror. This mirror reflects the laser and directs it towards a detected surface point. These movements occur at extremely high speed which then lead to accelerated data acquisition. This ability entices the use of these tools, since they can collect both millions of data points in seconds while also providing powerful accuracy.
The resolution of a scan can be established by the speed and pitch of rotations given by the user. The slower a scanner rotates, the denser the point cloud becomes due to the amount of grid points acquired. The denser a point cloud is, the better is the quality of data collected. The computed distance, vertical angles and horizontal angles are based on the position of the mirror and body for each measured point. The value of reflectance of the surface is also acquired, and is usually higher when the surface is white. Reflectance can at times become a hindrance when scanning highly reflective materials such

as windows or mirrors. This issue with shiny surfaces is what is known as ‘noise’ (Absolute Geometries, 2018).

A digital camera is integrated within the laser scanner in order to collect images of the scanned areas. The purpose of these cameras is to allow a user to use the color collected through the captured images and input them into the point cloud. This option is ideal for the archiving of structures since it allows the point cloud to have a greater photo-realistic look. Once all these capabilities have been applied by the users, depending on their goal, they can use the point cloud to output 2D and 3D deliverables.

The application of LIDAR technology for tunnel monitoring can offer a number of benefits as given in the following:

- Faster data capture times when compared to typical structural measuring techniques inside large tunnels.
- Effective data collection reducing the amount of on-site visits. The tunnel data can easily be scanned and then compared with respect to past visits.
- Unobtrusive data collection method, thus eliminating the need for hands-on or invasive techniques. This approach allows minimum interruption to tunnel traffic.
- Highly precise and accurate measurements. With advances in technology, the measurement technologies provide sufficient resolution and accuracy to capture movements in tunnels.
- Leads to a lower transfer cost due to the small number of resources needed for data acquisition, thus leading to a higher productivity.
- Illustrates the structural space in 3D as opposed to the normal 2D display of measurements in structural plans. LIDAR with such displays makes it very easy to conceptualize the findings in the structures. This leads to rapid decision making as well.

Research into the feasibility of point cloud technology as a tool for model reconstruction has been and still is being completed. Jafari et al (2017) evaluated the accuracy of deformation of a structure using two point clouds, one with the undeformed shape and the other with its deformed shape. The study concluded that this point clouds comparison gave a measurement accuracy of ± 0.2 mm (95% confidence interval). Much research has been completed on the accuracy of the scanner itself, its ability to obtain real-life measurements and what factors contribute to the accuracy of the results. Li and Cheng (2018) explain that decisions made during the ‘registration’ of a point cloud have a direct impact on the accuracy that the point cloud dimensions can produce.

Currently, surveying equipment is used to study tunnels in order to see what needs maintenance but the use of LIDAR technology (Wang et al., 2014) has potential benefits when considering the cost-effectiveness of the time saved. Research completed by Jãuregui et al (2006) showed the percent differences found when digital photogrammetry techniques, such as laser scanning, were compared to traditional measuring techniques, including both typical hand measurements and structural plan designs. The study found that photogrammetry only differed from a range of 0.06% - 1.43% when compared to hand measurements, and 0.23% - 8.00% when compared to structural plan dimensions (Jãuregui et al, 2006).

One of the more prominent advantages of LIDAR is that they do not need light in order to scan and obtain data which is not the case for surveyors who must be able to visually inspect the tunnel using their equipment. The purpose of using this technology for engineers is to accurately measure if any deformations and/or damages are found within tunnels. Deformations and/or displacements can be determined when comparing measured geometric models of tunnels using two or more epochs (Han et al., 2013a; Han et al. 2013b).

Figure 7. Color/Filtered Point Cloud of Tunnel

While technologies such as LIDAR can provide global deformation and geometry changes for tunnels, also local defects need to be determined for mitigation and repair purposes. As mentioned above, one of the practical and effective technologies for tunnel monitoring is to use infrared thermography (IRT) (Hiasa et al, 2017). IRT is a non-destructive evaluation (NDE) method, and has been developed to detect invisible subsurface defects, including delaminations and voids, in concrete structures with reasonable accuracy. Such a technology can be employed to track tunnel surfaces for possible cracks, delaminations and seepage. IRT also helps to avoid the time and expense of gaining immediate access to the concrete surface in order to conduct traditional sounding tests (Hiasa et al, 2016).

A short description of the IRT technology and theoretical background is given to better understand its implementation. Human eyes are able to see only visible light that is in a limited electromagnetic spectrum; however, infrared has a longer wavelength than visible light. On the spectrum of infrared, every object that has a temperature higher than 0 K° emits heat. This fact forms the basis to the method of infrared thermography, which, with the help of infrared cameras, captures infrared energy and turns it into the electronic signals in order to have a thermal image/video.

Thermal radiation theory is the fundamental of IR cameras and IRT. The IRT method measures the heat radiation which is emitted from the investigated material, and shows the surface area of the material as a colored thermal image which is related to the temperature distribution (Avdelidis and Moropoulou, 2003). Hence, the IRT concept leans on the heating of the investigated material that is heated naturally or artificially with sources such as the sun or thermal heaters, and observation of the materials during its heating and cooling periods. In many cases, the surface temperature of the material is recorded and compared within its medium in order to recognize the difference of temperature, which usually refers to phenomenon such as delamination, detachment and cracks in civil engineering structures. On the other hand, the IRT method may have a disadvantage on structures with more than one type of material such as a Masonry Arch Bridge, since different materials have different emissivity values and that would cause temperature differences regardless of deteriorations (Clark and Forde, 2003).

IRT surveys' performance depends on many factors such as *data collection time, size of delamination, IR camera specifications, and data collection speed* (Catbas et al., 2015). In addition to that, there are some physical properties that require attention and they are directly related with the investigated material. According to Avdelidis and Moropoulou (2003), these physical properties can be counted as the following: *"*Conductivity, effusivity, and specific heat as thermal properties, emissivity, absorption, reflection, transmission as spectral properties, and porosity, volumetric mass, physiological water content as other properties*"* (p. 120).

Infrared cameras' specifications play a huge role on IRT surveys. There are many research studies which focus on how specifications of IR cameras affect the decision of deterioration detection over thermal images. The main specifications of cameras which influence IRT results can be given as detector type, thermal sensitivity, accuracy, pixel resolution, spectral range, frame rate, field of view.

There is a better visibility of the damage indication with IR cameras which have higher thermal sensitivity and resolution. In addition, the camera angle influences the temperature reading of IR cameras, because the images that are not taken from a perpendicular angle are more sensitive than the perpendicular ones (Hiasa et al., 2016a).

IRT consists of two methods as active and passive. Passive IRT is applied under natural circumstances while active IRT is conducted with thermal excitation. The main heat sources are solar radiation and ambient temperature for passive IRT, and heat generators for active IRT (Kashif et al, 2016; Theodorakeas et al, 2015). Active IRT is chosen when thermal equilibrium exists. IRT methods need a heating source in order to investigate heating and cooling periods of the material and when there is no natural heating source, it is possible to use an external, artificial heating source, and this method is called active IRT. Passive IRT is used when natural heating source which is the sun already breaks the thermal equilibrium around the test material. Passive IRT method is so efficient to use in order to evaluate the structural integrity. Also for many years, it has been used to detect moisture on historical structures (Theodorakeas, 2015). On tunnel structures, it is important to detect water leakage, moisture, delamination on covers for timely repair and rehabilitation before any major damage. It will be shown later in the paper that the passive IRT can be conveniently applied for tunnel structures especially identifying issues at the local level.

The principle of passive IRT is as follows: solar loading heats up the concrete surface. If there is a subsurface defect, air fills that area and acts as a thermal insulator by preventing heat from penetrating to the concrete beneath the delamination due to the different thermal conductivities between air (0.0241 W/m ◦C) and concrete (1.6 W/m ◦C). Thus, the concrete above the delamination becomes warmer than the surroundings during the daytime (heating cycle) since that area conducts the heat faster from the surface to the delamination than the surroundings from the surface to the undersurface. The same area cools down faster than the surroundings during the nighttime (cooling cycle). The above described daily heating-cooling process is depicted in Figure 8

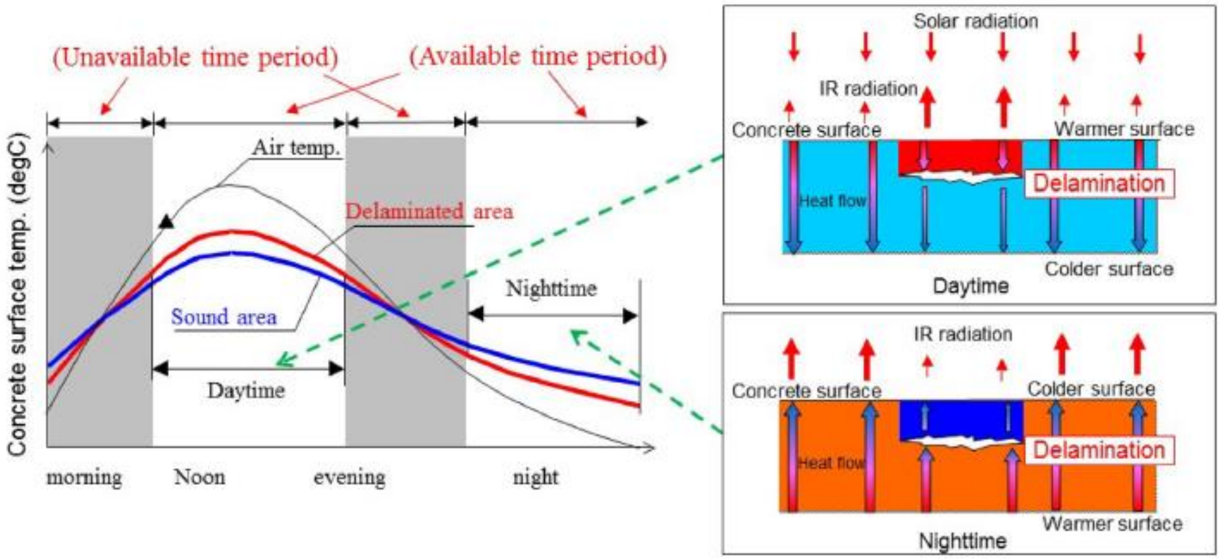

Figure 8. IRT Application Times During a Day and Heat Transfer Mechanisms (re-elaborated from from Hiasa et al, 2017)

In order to assess the conditions of a medium and the high priority areas designated by experts, ***mobile imaging technology*** can be used. The imaging methodology enables the rapid identification of structural deterioration within both concrete and steel tunnel liners. The technology is applicable to both liner types because both surfaces exhibit a temperature differential when water is present. Resulting data assist engineering experts in determining localized tunnel ranges to be revisited, the quantity of structural repair needed, and the as-is condition of the target surfaces. The resolution and type of sensors utilized are purposefully selected to provide the expert staff a level of insight which inform their decision-making for design recommendations. The data may also serve as a historical record of the structural condition at the time of the scanning. IRT with camera setup can be a fast and effective way to determine the cracks and delaminations. Passive infrared can also be applied, as discussed below with reference to a case study, along with high resolution camera to detect water infiltration, efflorescence, concrete deterioration and repaired leaking crack that are commonly observed in tunnels that are aged over time.

4.1 Case-Study: the Washington DC Tunnel (US)

One of the major tunnels in the USA is in the capitol city, Washington, DC. The tunnel system not only serves the passangers but also has a critical impact in govermental work since many federal employees, officials use this public transportation system. The first short stretch of Metro tunnels opened to the public on March 27th, 1976 with five stations. Central Washington sits on a coastal blend of sand, gravel and clay, where "cut and cover" tunneling offers the cheapest method of shallow excavation. Due to heavy traffic on the metro lines, it is not possible to close the lines and carry out routine visual inspections. As a result, a special vehicle (Figure 9) equipped with a customized frame that holds three infrared cameras and a ladybug 360 camera was developed by Nexco West USA (www.w-nexco-usa.com) for rapid scanning of the tunnel during the time window when the metro is not operating.

Figure 9. Camera Scanning Rail Truck with a single camera (left), and Cameras Scanning the Tunnel with two IR cameras (right)

The mobile system was implemented on different lines during non-revenue hours and early-outs. Equipment was mounted onto Hi-rail vehicles (Figure 10) provided by the client, with setup periods averaging about two hours prior to the scan. On-site preparation and recording procedures shaped into a well-defined and repeatable process following a successful pilot test on one of the line in the first month of the task. The most efficient scanning passes were planned weeks prior to the fieldwork, and the on-site proceedings (setup methods, personnel roles, etc.) were continually optimized throughout the task duration.

Figure 10. Special Nexco West USA Vehicle Equipped with Cameras before field implementation during off-peak hours

The imaging system is comprised of three main components: an infrared camera array, a line-camera array, and a 360 recording device. The infrared camera array excelled at detecting stagnant and active leaks within the shallow surface of the tunnel liner. The cameras also provide high resolution inspection results of the tunnel where both camera images (Figure 11) with cracks and infrared images can be mapped for a better understanding of the tunnel condition. This recent study provided valuable information to the decision makers and data collection did not interrupt the service in the tunnels. Such tests reduce economic loss due to service interruption and also utilize movable monitoring vehicle to scan the entire surfaces of the structure for local defects.

Figure 11. Tunnel Images (VR View-6 Cameras)

The array centered on the crown of the liner was used to determine the presence of active leakage, stagnant leakage, or leaking cracks. Some leaking cracks were noted to have been previously repaired (evidenced from several injection points along the crack), but were leaking again. In some cases, instances of concrete delamination and spalling were noted.

The line-camera array mapped out the location, severity, and size of findings on scaled images. This component was responsible for providing a spatial baseline for the data, and was stitched (orthographically corrected and laid out in a linear fashion) based off a highly sensitive distometer.

The 360 device captured a full 3D recording of the tunnel liner and ballast and was vitally important during the structural reviewing process. It was instrumental in navigating the steel liner sections on certain lines which required further in-depth inspection.

The scans in Figure 12 were able to point out where repairs had to be carried out and infrastructure owners were happy with the results obtained due to objectivity of experimental data and not interrupting the routine operations. One of the other advantages of these systems compared to permament monitoring is that these can be routed to regions and lines deemed more critical.

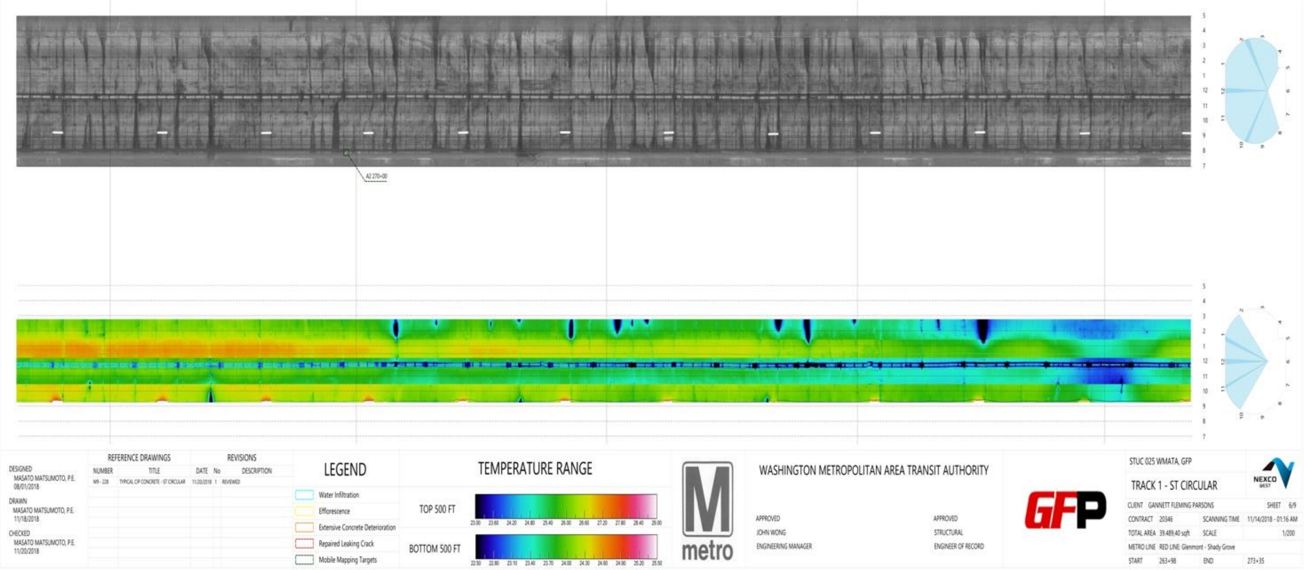

Figure 12. Typical Scan Data.

5. Innovative visual based methods

Digital Image Correlation (DIC) is an effective and widely used non-contact and material independent technique for measuring material deformation (Peters and Ranson, 1982). It was originally developed by Sutton et al. in the eighties (Sutton et al., 1986) and it is widely used for full-field deformation measurement due to its advantages of simple equipment, high precision, and noncontact measurement. The principle of the digital image correlation is based on two key technologies, a camera to take images at different conditions and a digital image correlation algorithm.

Considerable progress (Hild et al., 2006; Roux et al. 2008; Pan et al. 2009; Wu et al., 2014; Dworakowski et al., 2016; Feng and Feng, 2018,; Niezrecki et al., 2018; Pan 2018) has been made in recent decades in both developing new experimental DIC techniques and in enhancing the performance of the relevant computational algorithms. Nowadays, there are some commercial 2D and also 3D digital image correlation systems on the market but these systems are usually too expensive for many research institutes to afford. The development of a low-cost digital image correlation system as NCORR or XJTUDIC is of critical interest (Tang et al. 2010, Blaber 2015). In particular, the high-quality, flexible DIC software package called NCORR (Blaber et al. 2015) can be used to trace the displacement field (*u*, *v*) and the related deformations in small and finite deformations, also accounting discontinuities (cracking).

In DIC algorithms, the reference image is partitioned in subsets that are small subdomains where the deformation is assumed to be homogeneous. The deformed subsets are then tracked in the current image. Within the NCORR process, the subdomains are initially a contiguous circular group of points that are on integer pixel locations in the reference configuration. A linear first order transformation $p=\left\{ u \quad v \quad \frac{\partial u}{\partial x} \quad \frac{\partial u}{\partial y} \quad \frac{\partial v}{\partial x} \quad \frac{\partial v}{\partial y} \right\}$ is used to transform the coordinates of these points from the reference to the current configuration. To find the subset deformation, DIC algorithms employ a correlation function. NCORR, in particular, implements two different correlation criteria to find the initial guess and its subsequent refinement. The initial guess is focused on the identification of the displacements *u* and *v* with integer (pixel) accuracy, then a nonlinear optimization procedure (i.e. Inverse Compositional Gauss-Newton method) is used (Baker and Matthews, 2004). The complete DIC NCORR algorithm description can be found in (Blaber et al. 2015).

Some interesting application on concrete beams by using random speckle patterns have been presented in (Forte 2018). Optimization and identification issues have been deepen in (Garbowski et al. 2011, 2012). Such techniques represent an interesting development that can be shifted from the laboratory (e.g. beams and specimens applications) to the real world and tunneling in particular. Indeed the method allows to extrapolate the deformation fields from the comparison between the reference image and the current condition that can be updated by following up the structural state. It can be useful for highlighting finite deformation on a tunnel lining surface. Spackle patterns could be disposed for this purpose to improve the effectiveness of the analysis. However it has been also noted that a rough surface with a proper lighting (opportunely shadowing the surface imperfections) naturally introduces a constant pattern that could be usefully employed.

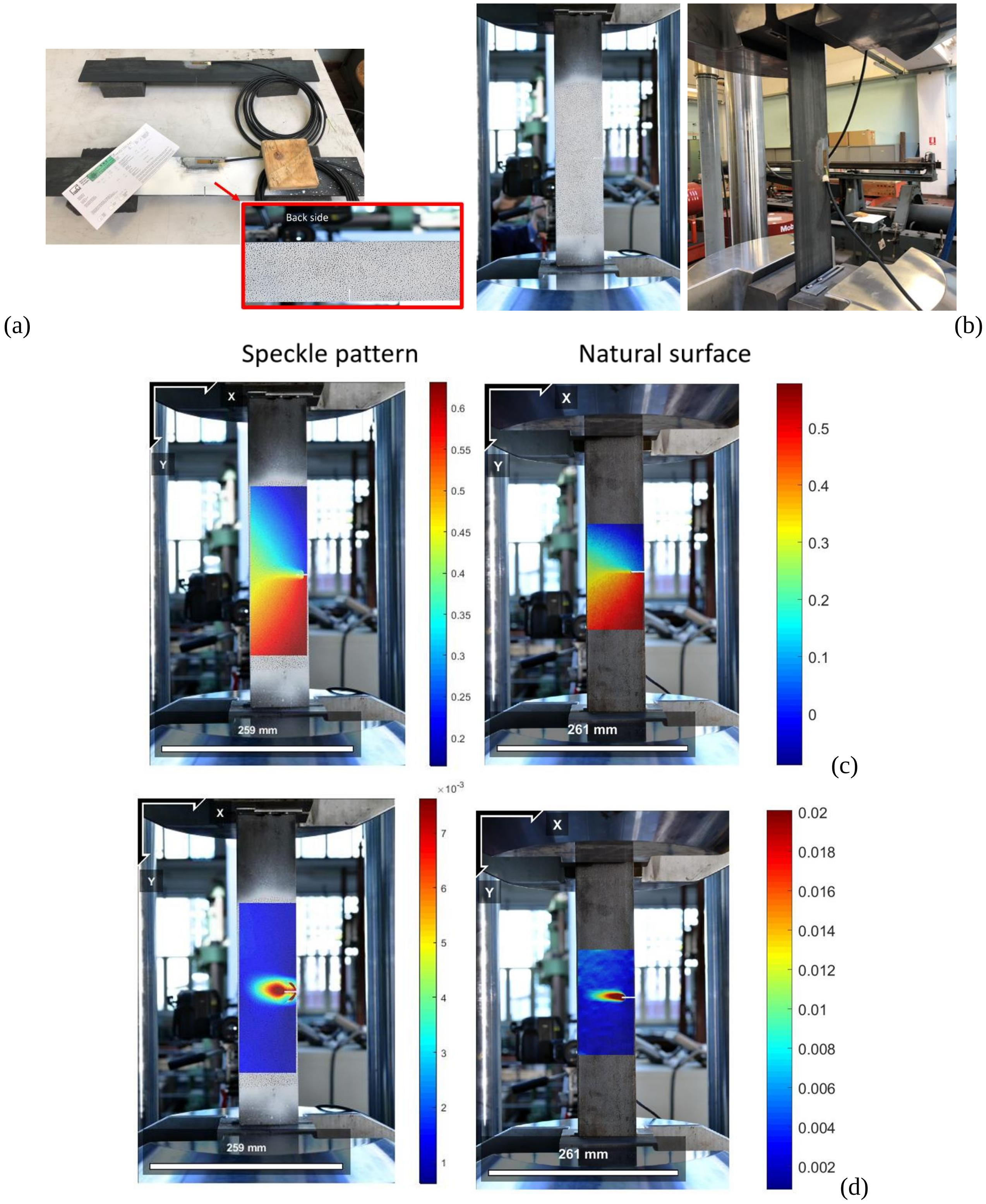

Figure 13. Examples of DIC analysis on steel plates with imperfection: specimens (a) and lab tests set up (b); analysis results in terms of vertical displacements (c) and deformation (d) contour bands, with and without spackle pattern.

Figure 13 reports two essential examples where the DIC analysis has been successfully applied to extrapolate the displacement and the deformation fields in a steel plate with imperfection under simple axial tensile tests. The tests are performed in tensile quasi-static conditions up to the complete crack of the specimens. The axial load is stepped through the following sequence: 0, 20, 40, 60, 80, 100, 105, 110, 115, 120, 125 kN. From 80 to 110 kN the transition from linear elastic to plastic domain is observed.

Figure 13a depicts the steel plates specimens (top one with natural surface, and the bottom one with speckle pattern on the back side) with 62x6mm of minimum cross section (notching), 80x6mm of standard cross section, 625 mm of total length. Figures 13b highlights the tests conditions with the strain gauge applied in half-bridge configuration on the specimen to measure the strain in the longitudinal direction. It is glued across the notched cross section, on the opposite side with respect to the notch. Figures 13c and 13d report the displacement and deformation fields, respectively, as computed by the digital image correlation at 100kN axial force. The measured strain from the extensimeter at 100kN is 1833 μm/m that is consistent with the DIC outcomes (about 2000 μm/m for both natural surface and speckle pattern options).

The DIC camera is a Nikon D800-S, with optic Micro Nikkor lens 60mm focal length (for macro shooting). For samples without speckle pattern the image acquisition took place with a 1/90 s at diaphragm 8. For samples with speckle pattern 1/90 s at diaphragm 9.5. Nikon D800-S is a digital camera with a CMOS 36 mega pixel sensor (full format, i.e. 24 x 36 mm - the photographic film format).

It should be noted that the method has been able to efficiently highlight the strain concentration and the global deformation field both with and without spackle pattern. The plate digital image could represent a scaled representation of a tunnel lining strip (transversal or longitudinal – Figure 14). Big data and machine learning tools may also improve the use of the collected amount of data, to provide damage detection and identification in large sections of underground infrastructures (Farrar and Worden 2013).

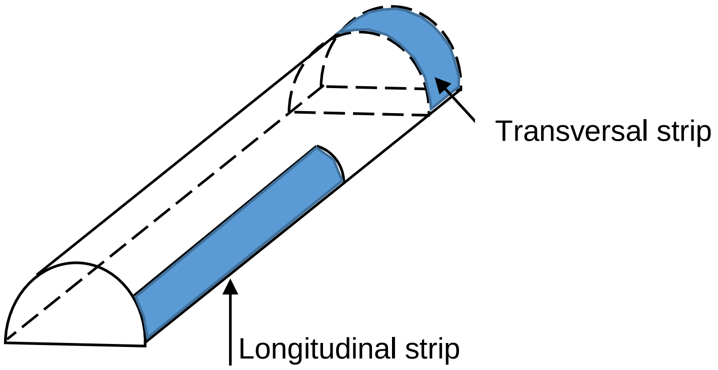

Figure 14. Tunnel lining strips.

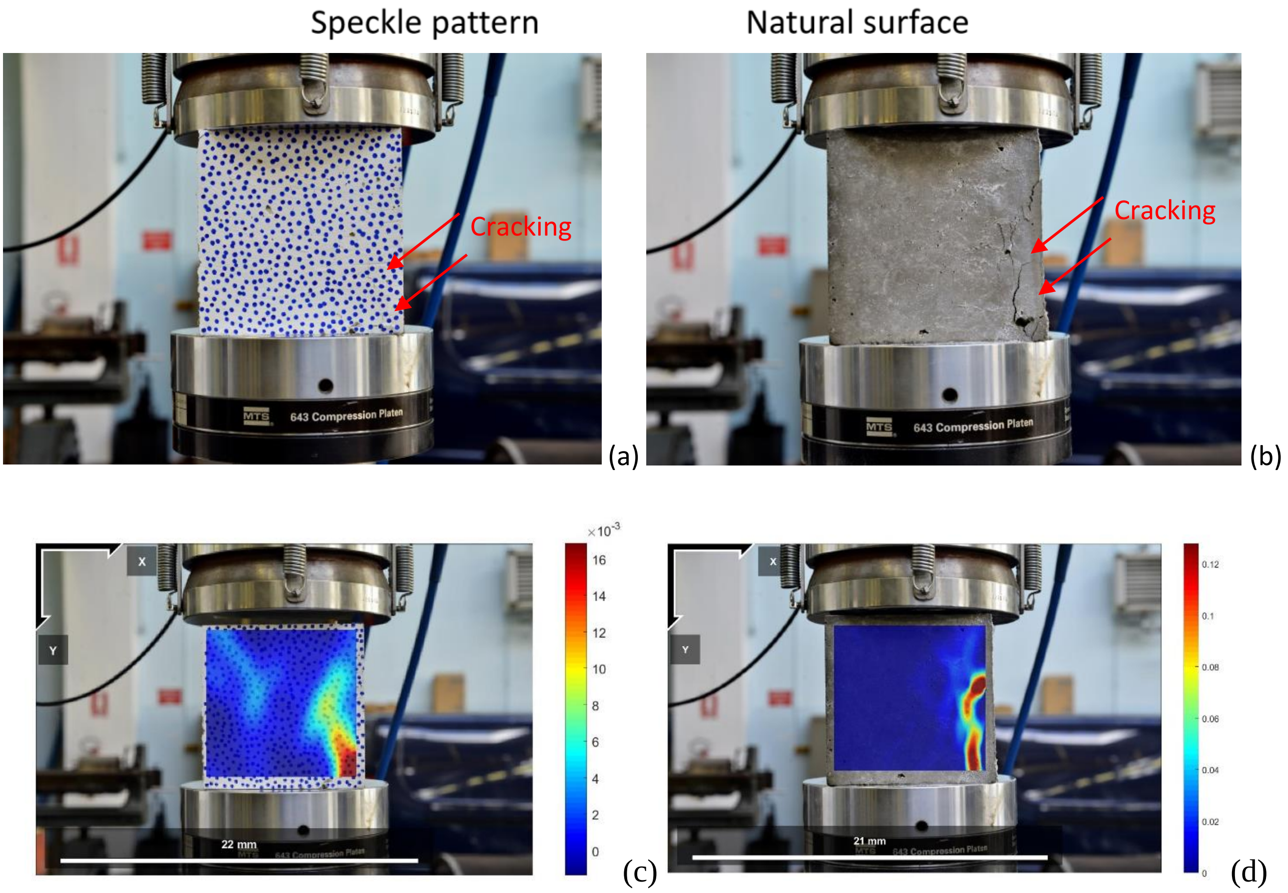

Figure 15. Examples of DIC analysis on concrete specimens: cracking on specimens with (a) and w/o (b) speckle pattern; normal horizontal deformations for specimens with (c) and w/o (d) speckle pattern.

With reference to the typical concrete lining of underground infrastructures, a series of additional compressive tests on concrete specimens with and w/o the spackle pattern are carried out. They are performed in quasi-static conditions by stepping through the following sequence: 0,100,200,300,400,450,500,550,600 kN. The cubes have a standard side of 150 mm and reach the ultimate compressive strength within the 550-600kN range. The specimens with and without speckle pattern are brought up to collapse as shown in Figures 15a and 15b, respectively, where the smeared cracking is visible. The corresponding horizontal deformation fields are plotted in terms of contour bands in Figures 15c and 15d, respectively, where the cracks smearing is clearly highlighted.

5 Final remarks

This work is focused on the in service tunnel heritage that remains essential for the development and sustainability of existing critical infrastructures all over the world. Indeed many of the existing tunnels are in service for several decades and are therefore subjected to decay and degradation. The development of suitable straightforward techniques for monitoring and damage assessment that could be employed without traffic interruption remains a challenge.

Some existing monitoring techniques have been summarized emphasizing possible innovative solutions that could be developed from other fields of civil engineering but also from related sciences. In particular, the benefits that could come from the use of non-contact and material-independent monitoring and damage assessment techniques have been emphasized. As a result, extensive amounts of data are expected and the use of big data and machine learning tools seems mandatory for real tunnels applications. Furthermore, the use of structural codes and procedures as finite element ones in tandem with iterative optimization and identification techniques could also be useful to elaborate on the sometimes changing-in-service material parameters by means of the provided monitoring data, e.g., the ones from digital image correlation.

Structural monitoring systems are evolving mainly from a physical network technology connected by wire to wireless systems. In this transition there are several difficulties in relation to the considered solution: for example, problems related to underground GPS systems, both for positioning and synchronization of sensors networks, or the problem related to obstacles in indoor conditions when referring to Wi-Fi systems. However, with the current technological developments, new solutions can be observed that can help to overcome these difficulties. They are related, for example, to technologies that implement the bridging between sensors in indoor conditions or with obstacles, and bounce the signal to the control unit. Zigbee devices can transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones. Nevertheless, the increasing interest and development in wireless technologies for SHM systems in civil engineering applications, such as in bridges, buildings and infrastructures, can only have a limited impact on underground structures due to the inherent difficulties related to the connections and energy supply. These aspects call for improvements and efforts.

Another solution that is spreading to different types of space structures (large structures such as bridges, tall buildings and tunnels for example) is the use of drones. That is, robots that can fly, climb, run or walk, navigate, etc. This solution can fulfil several roles, from data collection to energy supply, from search and rescue to maintenance. In other words, it represents a physical but disconnected solution for locating, identifying, collecting. New technologies as the use of drones in underground environment, e.g. to harvest data from remote sensors, are currently under development.

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