Electronic textiles for geotechnical and civil engineering

13

D. Zangani, C. Fuggini, G. Loriga
D'Appolonia S.p.A., Genova, Italy

13.1 Introduction

Smart multi-functional materials represent the construction elements of tomorrow. These materials offer the possibility to provide their traditional function, for instance as structural elements in a construction or protection/barrier layer or performing many different other functions and, at the same time, to carry and transmit information concerning the status of the structure where they are embedded for structural health monitoring (SHM). These materials will also employ sensors, have communication capabilities, and contain self-healing agents and other characteristics to make them multi-functional. As we progress towards this future, there are many challenges to identify and solve. Several include the integration of independent technologies into systems, cooperation between multiple disciplines, the formulation of standards and guidelines, and the development of business models that convince both engineers and end users to adopt them.

Textiles provide an excellent candidate for a multi-functional smart material. They are mass produced and inherently low cost, making them appropriate for wide-area and large-volume civil engineering applications. The industry is extremely competitive, meaning new innovations are sought after and welcomed because they provide a competitive advantage. The textile-manufacturing process itself is sensor-integration friendly. Integration techniques include the weaving or warp knitting of sensitive fibres, stitching-based sensors, printable sensors, and coating. Lastly, textiles have broad applications in engineered structures. In structural engineering, they are utilised for structural retrofit, seismic upgrade, and blast mitigation/hardening. In this chapter, the attention is focused on application of smart multi-functional textiles in the construction sector for the reinforcement of masonry structures and in geotechnical applications. Masonry structures, and in particular unreinforced masonry structures in areas of seismic hazard, provide the market need for multi-functional reinforcing textiles. Although modern codes, materials, and construction techniques are better adapted for seismic forces, hundreds of millions of existing masonry structures are vulnerable to seismic risk. In many cases, such structures populate urban centres and have cultural heritage value. Retrofit is the only desirable solution. In geotechnical engineering, technical textiles are utilised for soil stability, load distribution, and as filters or membranes. The capability of sensing and monitoring the status of geotechnical constructions such as dams or embankments completes the traditional functions and provides insight into the real soil behaviour during the life of the structure.

Electronic Textiles. http://dx.doi.org/10.1016/B978-0-08-100201-8.00014-X

This chapter will provide information on the latest development of advanced multi-functional textiles for the construction sector. A large part of the work presented comes from the research project 'POLYTECT: Polyfunctional Technical Textiles against Natural Hazards,' supported by the European Commission under the Framework Programme 6 with grant number NMP2-CT-2006-026789 (Zangani, 2008), and from the research project 'MULTITEXCO: High Performance Smart Multifunctional Technical Textiles for the Construction Sector,' supported by the European Commission under the Framework Programme 7, GA 606411 (Loriga et al., 2013).

The contribution of the companies and research institutions performing this work is acknowledged, especially those directly in support of the work mentioned in this chapter, which include Selcom Multiaxial Technology and Alpe Adria Textil from Italy; and Glötzl, BAM, STFI, and the Karlsruhe Institute of Technology from Germany.

13.2 Technical textiles suitable for geotechnical and civil engineering

Technical textiles are special structures made from fibres that are specifically designed to perform a variety of functions, different from aesthetics. Functions span from protection, such as in protective clothes used in harsh or industrial environments, to reinforcement, such as in composites, to filtration, such as in geotechnical applications, and many others. The materials used for the fibre are also many, including glass and carbon, which are the most diffuse in construction (e.g., for the external reinforcement of columns and beams), but also Kevlar and other polymers, basalt, and their combination in hybrid structures. The density, orientation (warp, weft, diagonal), and material composition of the fibres determine the textile's strength and performance characteristics as an integrated system. Synthetic raw materials such as polyethylene, polypropylene, polyester, and polyamide are generally used for geotextiles and geotextile-related products to comply with stringent cost and durability issues.

13.2.1 Textile structures for building reinforcement

As anticipated, technical textiles found the application for seismic retrofit of masonry structures, particularly of historical buildings, to increase the structural ductility and the ability to sustain the dynamic loading transmitted by an earthquake over a longer time. For such application, both reinforcing strips and full-coverage strategies can be adopted (Zangani et al., 2007; Messervey et al., 2010). The use of reinforcing strips in grid-like or crossing patterns is more commonplace, and building code provisions for its use are available in many countries. Typically, reinforcing strips are a uniaxial textile made of a high-strength, high-stiffness material such as carbon. They are intended to carry loads along their length and are applied with a resin (e.g., epoxy) to create a stiff bond to the underlying structure (Messervey et al., 2010). The second retrofit strategy is to employ a wide-area or full-coverage textile using a biaxial or multi-axial textile structure to carry loads in multiple directions. This strategy is not as commonplace and is maturing in various research programmes. Full-coverage solutions aim to employ a low-cost fabric of flexible high-strength fibres that dissipate energy through increased structural ductility. For this reason, full- or wide-area coverage solutions are applied with an epoxy mortar to form a textile composite with the underlying structure. Textile architectures used for such applications are generally woven structures. Structures characterised by higher mechanical properties (strength) are non-crimp fabrics (NCFs), a particular textile construction manufactured using warp-knitting technology. The particular feature of non-crimp fabrics is, as their name suggests, that yarns used in the construction are not crimped, as is the case for traditional woven textiles. NCFs consist of one or more layers of long fibres oriented along preferred directions, held in place by a secondary non-structural thread. The mechanical properties of NCF composites are controlled by the type, amount, and orientation of the fibre being used. The stitching process allows a variety of fibre orientations, beyond the 0/90 woven fabrics. NCFs therefore offer characteristics of oriented strength along the different yarns' orientations, something that is preferred in high-performance applications. Moreover, multiple orientations can be exploited to obtain a quasi-isotropic reinforcement, which is beneficial for some applications where the main loading directions are unknown. The ability to tailor the fibre architecture allows for more optimised performance, which translates into weight and cost savings.

NCF is the candidate textile architecture for the incorporation of optical sensor fibres because of the absence of crimp in the fibres, which reduces the risk of micro-bending of the optical fibre. This would create losses in the fibres and would endanger their function. Another advantage with respect to conventional woven structures is that several layers can be stitched together, including the layer oriented at 0°, where the optical sensor fibres can be placed, and the fabric can be made as thick as desired for the application, so that one single fabric is sufficient. Also, the stitch can be designed to obtain a stable fabric, even with open structures.

Figure 13.1 shows three examples of NCF textiles produced by Selcom Multiaxial Technology, Italy. The structure in Figure 13.1a shows a biaxial structure with carbon fibres along the weft direction and glass in the warp direction (corresponding to the longitudinal direction in the roll). Figure 13.1b shows a triaxial structure, with fibres aligned along ±45° and 90°. Similarly, as the structure shows in Figure 13.1a, the fabric is characterised by an open structure in order to allow a proper wetting of fibres, in combination with a dense matrix. Figure 13.1c shows a quadriaxial hybrid fabric, with fibre orientation ±45/0/90, with a closed structure suitable to be used in combination with more fluid types of resin (like epoxy resin or similar).

Figure 13.2 shows NCF structures with embedded fibre optic sensors designed for the seismic reinforcement of masonry walls. In particular, the fabric shown in Figure 13.2c, with code SENTEX 8300, produced by POLYTECT partner Selcom Multiaxial Technology, Italy, is made of glass and polymer fibres in three directions, has a density of 460 g/m^2, and polymer optical fibres inserted in the 0° direction during the warp-knitting process. These textiles are the result of a design and optimisation process conducted by the Sächsisches Textilforschungsinstitut (STFI), and more than 120 wall tests conducted at the Karlsruhe Institute of Technology to compare performance under different load scenarios and for different mortar types. The structure of

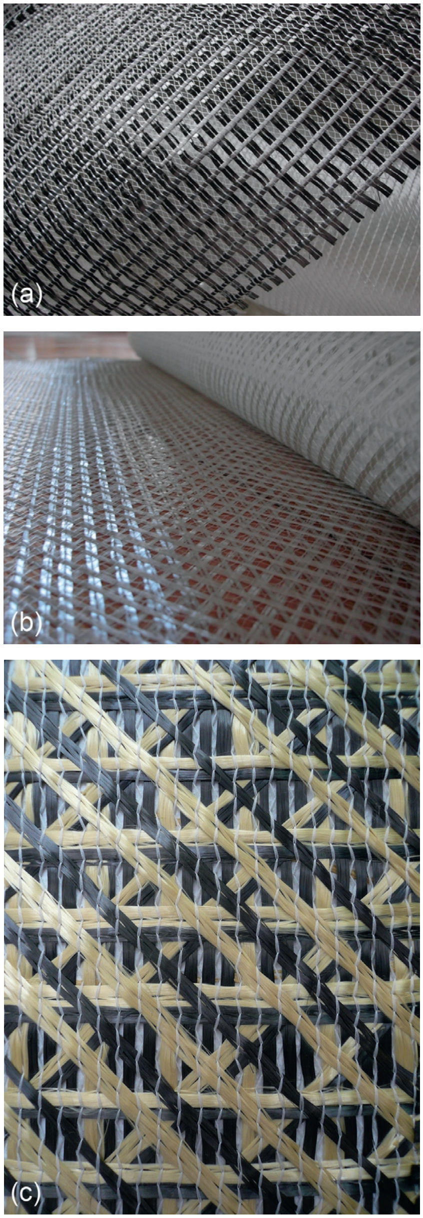

Figure 13.1 (a) Biaxial fabric from Selcom Multiaxial Technology, Italy. (b) Triaxial fabric structure from Selcom Multiaxial Technology, Italy. (c) Quadriaxial hybrid fabric from Selcom Multiaxial Technology, Italy.

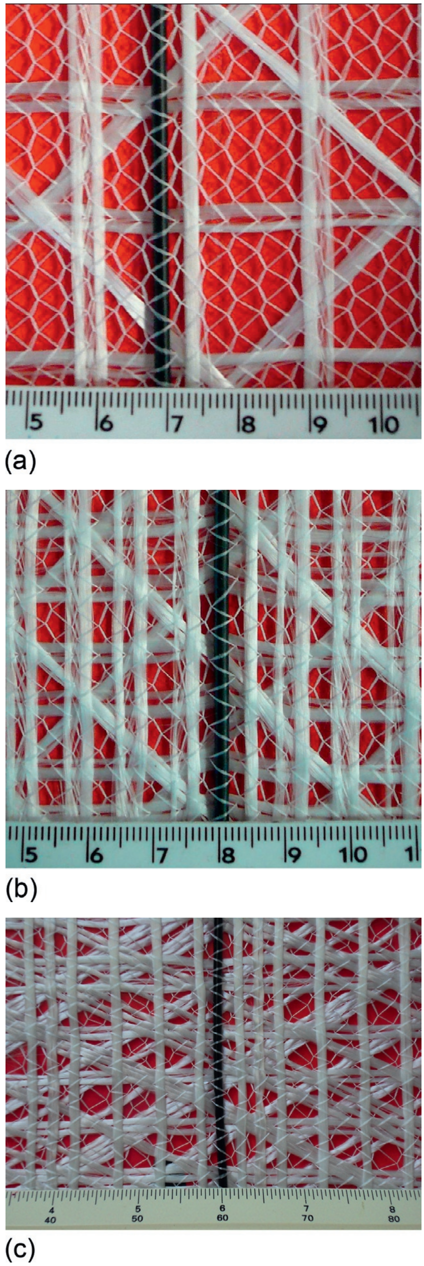

Figure 13.2 (a and b) Examples of NCF multi-functional textile developed by Sächsisches Textilforschungsinstitut (STFI), Germany. (c) SENTEX 8300 triaxial NCF for masonry applications, produced by Selcom Multiaxial Technology, Italy.

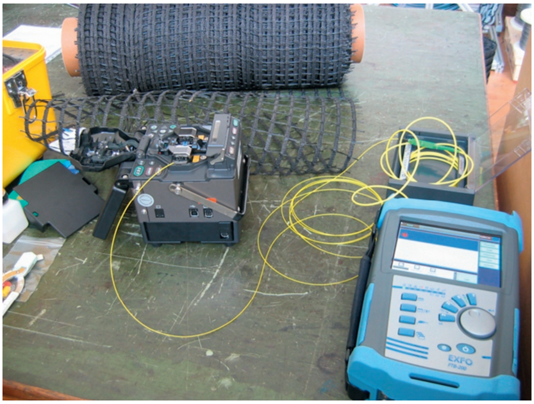

Figure 13.3 Quality check during production of a multi-functional geogrid.
Courtesy of Sächsisches Textilforschungsinstitut (STFI), Germany.

SENTEX8300 is characterised by a balanced fibre density along the three main directions (warp, weft, and bias) and by an open structure for easy impregnation with the mortar and application to the masonry substrate.

An important step in the production of those structures is the quality check, which needs to be performed at the end of production, before final delivery of the material to the customer. A similar equipment to the one used in the field for the interrogation of the sensors is used to check the integrity of the sensors embedded in the structure, as shown in Figure 13.3.

13.2.2 Geotextiles and geogrids

Geotextiles are those fabrics used in geotechnical applications, such as road and railway embankments, earth dikes, and coastal protection structures, designed to perform one or more basic functions such as filtration, drainage, separation of soil layers, reinforcement, or stabilisation. Therefore, almost every geotextile application is multi-functional.

To perform the above functions and satisfy the demanding requirements of cost and resistance for the intended applications, geotextiles are generically made from plastic materials, mostly polypropylene and polyester, but also polyethylene, polyamide (nylon), polyvinylidene chloride, and fibreglass (e.g., in roadway substrates) are used. Sewing thread for geotextiles is generally made from any of the above polymers. Using warp-knitting technology to construct geotextiles makes it possible to provide reinforcement with easy sensor incorporation, thus opening up new design opportunities for multi-functional geotextiles (MFGs).

Figure 13.4 shows an example of an MFG produced by Alpe Adria Textil in Italy. In this example, the structure is a grid with warp (0°) and weft (90°) fibres, where the warp fibre is characterised by a much higher linear density than the weft yarns and is, therefore, the major load-bearing component of the fabric. The sensor fibres aligned along the warp direction are incorporated into the structure, which is designed to not only carry them, but also to protect the sensing fibres from the external environment.

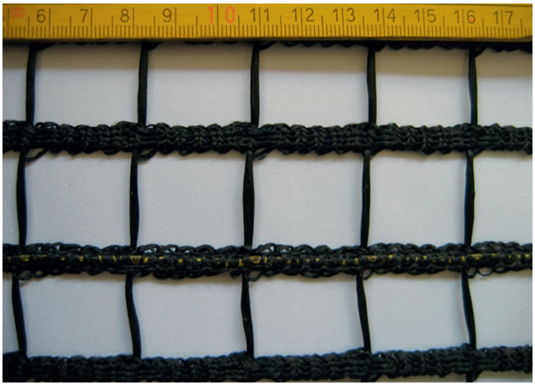

Figure 13.4 Example of multi-functional geogrid with embedded optical fibre sensor, developed by Sächsisches Textilforschungsinstitut (STFI), Germany, in cooperation with Alpe Adria Textil, Italy.

13.3 Sensors to be embedded in smart textiles

In the technical report 'Textiles and textile products—smart textiles—definitions, categorisation, applications and standardization needs' that has been drawn up by Technical Committee CEN/TC 248, smart textile materials are defined as 'functional textile material, which interacts actively with its environment, i.e., it responds or adapts to changes in the environment.' More specifically, a smart textile system is defined as 'a textile system which exhibits an intended and exploitable response as a reaction either to changes in its surroundings/environment or to an external signal/input.' As can be seen from the definition, the 'sensing capability' is one of the enabling features of smart textiles.

In the last decade, several monitoring systems based on the innovative smart textiles with embedded sensors have been developed, targeting different sectors such as biomedical, construction, tele-assistance, sports, and fitness. As far as the construction sector is concerned, in particular for geotechnical applications and for civil engineering, the integration of optical fibre sensors for monitoring purposes in technical textile structures having reinforcing capabilities has been reported in recent years, with one of the solutions raising an increased interest in the scientific research. As a matter of fact, optical fibre sensors present a relevant number of advantages for civil engineering applications, such as being intrinsically safe, non-conductive, and lightweight, being characterised by insensitivity to electromagnetic radiation, robustness in harsh environments, and easy integration in textile structures. Additionally, they are capable of performing a wide range of physical measurements (or functions), such as strain, stress, load, temperature, displacement, PH, crack detection, and pressure, that make them a suitable solution for structural health monitoring (SHM) applications (Kuang et al., 2009).

A first broad classification of optical fibres can be carried out according to the sensing location, by distinguishing between intrinsic and extrinsic optical fibre sensors. The extrinsic optical fibre sensors are characterised by the fact that the fibre is simply used as a means to carry light to (and from) an external optical device where the sensing takes place. In intrinsic sensors, perturbations act on the fibre, and as a consequence, the fibre in turn changes some characteristic of the light inside the fibre (Fidanboylu and Efendioglu, 2009). In this case, basically the physical parameter or effect to be sensed modulates the transmission properties of the sensing fibre. According to the operating principle, the fibre optical sensors can be classified in the following four categories:

- intensity modulated,
- phase modulated,
- polarisation modulated,
- wavelength modulated.

In the literature, there are some other classifications based on the specific applications (physical, chemical, biomedical sensors, etc.) that we will not consider in this work (Ghetia et al., 2013).

13.3.1 Intensity-based fibre optical sensors

This category of sensors is based on a signal undergoing some loss. There are different ways to produce the attenuation of a signal, such as through absorption or scattering of a target. As these sensors require more light, they usually use multi-mode large-core fibres. A measurand-induced change in the optical intensity propagated by an optical fibre can be produced by different mechanisms, such as micro-bending loss, attenuation, and evanescent fields. The advantages of this category are easy implementation, low cost, multiplexing, and the possibility to implement distributed sensors. Disadvantages include the measurements and variations in the intensity of the light source, which could determine false readings if a reference system is not used (Fidanboylu and Efendioglu, 2009).

13.3.2 Phase-modulated fibre optical sensors

In this category, the physical phenomenon to be measured affects the phase shift between two coherent-propagating lights having different paths. The phase modulation is detected interferometrically, by comparing the phase of the light in the signal fibre with respect to the reference fibre. As a matter of fact, in an interferometer, the light is divided in two beams: the first is subjected to the sensing environment that determines a phase shift, whereas the other is isolated from the sensing environment because it has to be used as reference. When the beams are recombined, they interfere with each other (Fidanboylu and Efendioglu, 2009).

Common interferometers are

- Mach-Zehnder,
- Michelson,
- Fabry-Perot, Sagnac,
- Polarimetric,
- Grating interferometers.

13.3.3 Polarisation-modulated fibre optical sensors

If the fibre is subjected to any kind of strain or stress, there is a change in refractive index, and consequently there is an induced phase difference between different polarisation directions (this phenomenon is called photo-elastic effect). The change in the refractive index due to stress or strain is also known as induced refractive index (Fidanboylu and Efendioglu, 2009).

13.3.4 Wavelength-modulated fibre optical sensors

In this category of sensors, the changes in the wavelength of light are used for detecting the variations in the measuring parameters. Among the sensors belonging to this group, it is worth mentioning the fluorescence sensors, the black-body sensors, and the Bragg-grating sensors. Concerning fluorescent-based fibre sensors, they are used in different sectors, and in particular in biomedical applications, chemical sensing, and physical parameter measurements (e.g., temperature, viscosity, and humidity). As far as the black-body sensors are concerned, the black-body cavity can be placed at the end of an optical fibre, and when the cavity rises in temperature, it starts to glow and act as a light source. In order to define the profile of the black-body curve, detectors in combination with narrow-band filters are used. The scope of this sensor that is commercially available is to measure temperature within a few degrees centigrade under intense radio frequency (RF) fields. Probably the most widely used wavelength-based sensor, in particular in civil engineering, as illustrated in the following, is the fibre Bragg-grating (FBG) sensor. Basically, FBGs present periodic changes created by an intense interference pattern of ultraviolet (UV) energy in the index of refraction in the core of a single-mode optical fibre. This change in the refractive index determines an interference pattern, which acts as a grating. In other words, the Bragg grating acts as an effective optical filter. When a light from a source having a centre wavelength close to the Bragg wavelength is launched into the fibre, the light propagates through the grating, part of the signal is reflected at the Bragg wavelength, and a small sliver of signal is removed from the total transmitted signal (Fidanboylu and Efendioglu, 2009).

After this general overview of the different kinds of fibre optical sensors, it is worth introducing the concept of ‘distributed sensing.’ As a matter of fact, a fibre optical sensor could be sensitive to the measurand at any of its points, and therefore a unique optical fibre-distributed sensor could replace several discrete sensors. In this case, the low fibre attenuation allows monitoring over extremely long distances, enabling the distributed sensing technique particularly suitable for civil engineering, and geotechnical applications where we deal with the monitoring of very large or long structures.

Two different kinds of distributed fibre optic sensors can be distinguished:

- intrinsic distributed fibre optic sensors,
- quasi-distributed fibre optic sensors.

13.3.5 Intrinsic distributed fibre optic sensors

Intrinsic distributed fibre optic sensors find a large application where the monitoring of a single measurand is required at a large number of points or continuously over the path of the fibre. In this case, the optical time-domain reflectometry (OTDR) principle can be used based on different approaches:

- OTDR based on Rayleigh scattering,
- OTDR based on Raman scattering,
- OTDR based on Brillouin scattering.

As a matter of fact, three different scattering processes may occur in an optical fibre sensor, generating a back propagating light that can be exploited to receive information on the local properties of the fibre and consequently on the surrounding environment: Rayleigh, Raman, and Brillouin scattering.

Concerning OTDR based on Rayleigh scattering, in an optical fibre, the light is subjected to attenuation due to this scattering, which is determined by random, microscopic variations in the index of refraction of the fibre core. If a narrow optical pulse is launched in the fibre, it is possible to determine the spatial variations in the fibre-scattering coefficient or the attenuation by monitoring the variation of the Rayleigh-backscattered signal intensity. The scattering coefficient of a particular location is influenced by the local fibre status; therefore, by analysing the reflection coefficient, it is possible to localise the external stimulus.

As far as Raman scattering is concerned, it is worth specifying that this phenomenon involves the inelastic scattering of photons. The incident light pulse causes the molecular vibrations of the optical fibre, which determines the scattering of the incident light. In the case of OTDR based on Raman scattering, a high-input power is requested, as the Raman-scattering coefficient is about three orders of magnitude lower than the Rayleigh-scattering coefficient.

Finally, Brillouin scattering is caused by the acoustic vibrations that occur in the optical fibre when an optical pulse is launched. The acoustic vibrations determine a counter-propagating wave, called a Brillouin-scattering wave, which drains energy away from the input pulse. There is a frequency shift between the Brillouin-scattering wave and the original light pulse frequency in the order of tens of GHz. This is a relevant effect, as the frequency shift of a Brillouin gain spectrum is sensitive to temperature and strain. In order to obtain high spatial resolution, a very narrow light pulse is required, which results in a proportionally lower level of the backscattering signal and an increased receiver bandwidth requirement for detecting these pulses (Gholamzadeh and Nabovati, 2008).

It is worth highlighting some relevant differences between the three categories of scattering. The intensity of Raman scattering has an intrinsic dependence on the temperature of the fibre, and for this reason, the phenomenon has been used in the literature for the development and implementation of reliable distributed temperature sensors. Also, the frequency of Brillouin scattering is intrinsically dependent on fibre density, which depends intrinsically on temperature and strain by favouring also in this case the development of distributed sensors. In the optical fibre sensors based on Rayleigh scattering, the scattering itself is used only to track and to reveal propagation effects, which are considered the real sensing mechanisms. These propagation effects include attenuation and gain, phase interference, and polarisation variation, and they may also affect Raman- and Brillouin-distributed sensors, but in these latest cases, they are usually neglected because both scatterings offer direct sensing mechanisms. Taking into account the above-mentioned features, the fibre optical sensors based on Rayleigh scattering could be sensitive to many different physical parameters, in addition to temperature and strain (Palmieri and Schenato, 2013).

In the situations where distributed sensing is not feasible, as an alternative, it is possible to turn on quasi-distributed fibre optical sensors, and in this case, a finite number of locations is monitored. Among the different solutions for implementing quasi-distributed fibre optic sensors, it is worth mentioning again the FBG sensors characterised by high sensitivity, high multiplexing capability, and cost-effectiveness (Gholamzadeh and Nabovati, 2008).

As a matter of fact, as we shift our focus to practical solutions that can be used in the construction sectors for civil engineering and geotechnical applications, we can see two different kinds of optical fibres that have a wide application as far as their integration in textile structures is concerned:

- polymer optical fibre (POF),
- FBG sensors.

13.3.6 Polymer optical fibre (POF)

Polymer optical fibre (POF) sensors are very suitable for civil engineering applications, as they are characterised by both elasticity and robustness. They can be based on the OTDR technique and present the great advantage of a wide measurable strain range of more than 40%, with a limitation in the measurement length fixed at a few hundred metres. This sensor type is therefore most appropriate for applications where high strains have to be detected and the structures to be monitored are of a maximum length of a few hundred metres. The spatial resolution is between 20 cm and 1 m, depending on the distance of the event to be detected. Typical applications for this sensor type would be the monitoring of mechanical deformation in slopes, dikes, embankments, masonry structures, and so on. (Liehr et al., 2008)

Standard polymethylmethacrylate (PMMA) POFs having a relatively high attenuation of about 150 dB/km and large core diameters up to 1 mm are usually used for distributed strain detection up to about 100 m fibre lengths. The main features of this kind of fibre are strong strain sensitivity, robustness, high strain ability, and the possibility to carry out an easy connection due to the large core diameters and numerical apertures. Most recently, the low-loss perfluorinated (PF) gradient index (GI) POF types based on poly(perfluorobutenyl-vinylether) (this kind of POF is also known as CYTOP) allowed the achievement of higher spatial resolution measurement and extended measurement lengths up to 500 m (Liehr, 2011).

POF sensors can be processed directly by textile machineries and can be embedded in a one-step process in the textile structures (multi-axial fabric) during their manufacturing.

Optical time-domain reflectrometry (OTDR), as has been already mentioned, is a well-known technique in telecommunication for fault analysis and in the fibre optical sensors based on scattering, and it has recently been applied to multi-mode standard

POF for strain-sensing applications. Despite large fibre core size and hence significant modal dispersion, some success was demonstrated for SHM applications. In this case, OTDR sensing exploits the monitoring of the backscatter light in an optical fibre following the launch of a short optical pulse at one end of the fibre. The backscatter signal is recorded as a function of time and then converted to distance measurement. Perturbations, such as strain or defects along the length of the fibre, will result in either a peak reflection or loss in the backscatter signal at the location of the perturbation (Kuang et al., 2009).

13.3.7 FBG sensors

As illustrated in the previous paragraph, fibre Bragg gratings (FBGs) are characterised by periodic changes created by an intense interference pattern of UV energy in the index of refraction in the core of a single-mode optical fibre. This change in the refractive index determines an interference pattern, which acts as a grating. The grating reflects a spectral peak based on the grating spacing; therefore, a variation in the length of the fibre due to tension or compression determines a change in the grating spacing and consequently the wavelength of light that is reflected back. In this way, by measuring the centre wavelength of the reflected spectral peak, it is possible to get a quantitative measurement of the strain.

The response of several FBG sensors can be measured simultaneously by placing several networks in series attached to one lead optical fibre. This is a relevant advantage with respect to traditional strain sensor measurement, which requires an acquisition system for each sensor. By using different wavelengths that are reflected, various FBG sensor signals can be identified, and therefore the space-distributed sensors are identified and distinguished, as each sensor has its own characteristic wavelength. An optical switch must then be used to connect several optical fibres to the light source and the spectrometer that measures the reflected wavelengths. The switch allows the scanning of all the connected lines sequentially, making possible the spatial distribution of the sensors in a monitored structure that can be read by only one measuring unit (Nancey et al., 2007).

Fibre Bragg-grating (FBG) sensors can be used for quasi-distributed measurement of strain. The FBG sensors excel in precise point-wise strain measurements up to 0.8% with a resolution of 3 $\mu\varepsilon$, or temperature determinations with a resolution of 1 K. The FBG fibres exhibit low breakdown strain of only 1%. It has been already seen that POF sensors can be processed directly by textile machineries, whereas FBGs can be embedded in an apposite tube inserted at the production stage into the textile matrix (although other approaches are under study) or directly in the epoxy resin of composites.

The direct embedding of optical fibres with FBG in the epoxy resin of fibre-reinforced polymer (FRP) materials allows exact strain measurement in the material, and in this way, mistakes are minimised during monitoring. Therefore, the epoxy resin is an effective protection for the optical fibre. Alternatively, there is the possibility of realising any design of sensor arrangements by embroidering the optical fibre directly on a carrier material. In this case, the carrier materials are the reinforcing fibres. The direct embroidery of FBG simplifies significantly the fixing. An embroidery machine that uses computerised support is able to fix the fibre optical system accurately, fitting the carbon fibre material. By using computer-controlled machines, it is possible to achieve a very high degree of prefabrication as well as high productiveness (Käseberg and Holschemacher, 2010).

13.4 Smart multi-functional technical textiles incorporating sensors

The EU-funded FP6 large-scale collaborative project POLYTECT (grant agreement NMP2-CT-2006-026789) for small and medium enterprises (SMEs) ended in 2010 pushed the state of the art for technical textiles through the development of large-area sensor-embedded multi-functional textiles employing fibre optic sensors for masonry applications as well as for geotechnical work.

The project involved 27 partners from 12 countries, and its aim was to provide reinforcing and monitoring capability for geotechnical and masonry applications through the industrial production of multi-functional technical textiles. In fact, as illustrated in the previous paragraphs, textile materials are extensively used in construction. In masonry applications, textiles are growing in importance, as they provide a non-intrusive technique to provide reinforcing strength to a structure (damaged or undamaged). Common applications include localised crack repair, the reinforcement of critical walls, or the wrapping of existing columns. Across geotechnical and masonry applications, textile materials improve structural performance under service conditions and provide protection in the event of an earthquake, landslide, accident, or other unforeseen loading conditions. Embedding sensors of different types into textile materials enables several important advantages, in particular for measurements able to perform structural health monitoring. Such measurements can be used before or after an event to take preventive measures or to assess the state of the structure. Measurements over time can be used to track changes in structural performance, allowing the activation of maintenance and repair actions when appropriate. The main results of the POLYTECT project included

- The development of new and novel sensors, including fibre optic sensors, piezoelectric sensors, chemical sensors, and sensitive textile fibres (coatings);
- The development of new and novel sensor interrogation systems and data processing techniques;
- The development of nanoparticle-based mortars and adhesives;
- The integration of sensors into warp-knitted textiles for geotechnical and masonry applications (two-dimensional and rope-like structures);
- The development of multi-functional textiles for application in the construction sector to increase ductility and structural strength of masonry structures, to monitor stresses, deformations, acceleration, water level variation, and pore pressure, to detect the presence of fluids and chemicals, and to measure structural health through the innovative developed solutions.

Although different kinds of sensors and solutions have been studied and developed in the frame of the project, the most interesting results that merit further investigation are related to the development of a seismic wallpaper to be used as retrofitting of existing buildings in order to both reinforce and monitor the structure.

Strips of fibre-reinforced polymers (FRPs) are used for reinforcing purposes in construction, particularly for wrapping columns and as a tension member at the intrados of beams. Sometimes the use of strips is not optimal, in particular for the reinforcement of large structures such as walls, as it can result in stress concentrations (force goes first to the stiffest part of a structure) and does not prevent falling debris. Careful analysis may be required to know where to safely apply these strips (tapes), which are generally made by carbon fibres that are inherently expensive compared to traditional construction materials and are not sensor-embedded.

The concept of intelligent composite ‘seismic wallpaper’ for the reinforcement, strengthening, monitoring, and management of civil infrastructures vulnerable to earthquakes has been proposed in the frame of the POLYTECT project.

Multi-axial textile structures, glass, and polymeric or hybrid textiles can be used within this concept, rather than carbon fibres that are characterised by a far higher price and cannot be considered for all applications. The textile has to be coated in an alkaline environment (cement mortar) for durability and to enhance the textile-mortar bond interface. Then, the textiles have to be applied to a structure using a mortar compound. The composite seismic wallpaper has been conceived as a full-coverage or wide-area reinforcing solution for unreinforced masonry buildings and structures. Walls vulnerable to brittle behaviour and collapse were being held together even after they cracked. These composites feature embedded sensors so that measurements can be taken before, during, and after seismic events. In the POLYTECT seismic wallpaper, fibre optic sensors (both POFs and FBGs) have been integrated in the composite structure. These measurements carried out through the seismic wallpaper can be static or dynamic (high frequency). Engineers could utilise such data to control new construction, to assess and quantify the benefit of retrofit actions, and to help manage the structure over time. In particular, from a components point of view, the seismic wallpaper consists of (Fuggini et al., 2011)

- Multi-axial, warp-knitted, anti-reflective (AR) glass, and polypropylene (PP) fibres, which constitute the composite fibres produced by Selcom that were described in the previous paragraph (see also Figure 13.5).
- Nanoparticle-enhanced coatings for the textile fabric.

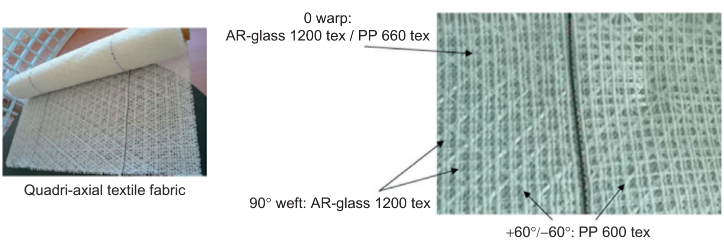

Figure 13.5 Quadriaxial NCF incorporating optical fibre sensors for masonry application, developed by Selcom Multiaxial Technology, Italy.

- Nanoparticle-enhanced mortar (the matrix of the composite) to bond the textile to the structure.
- Fibre optic sensors (Figure 13.6).
- An interrogation system to acquire data from the sensor-embedded textile-mortar composite.

The application procedure that has been followed in the frame of POLYTECT is illustrated in Figure 13.7 and consists of the following steps:

- The matrix has to be applied fresh to the walls' external surface, making the surface as smooth as possible.
- The textile has to be rolled out from the roof, applied to the fresh mortar, and pushed against it until a mortar penetration into the textile fabric structure is reached.
- Finally, a second layer of matrix has to be applied to externally cover the textile.

In addition to the seismic wallpaper concept, sensorised strips to be used as retrofitting have been developed.

The SENTEX 410 (Selcom, Italy) strip seismic retrofit is a sensorised technical textile for the reinforcement of masonry buildings located in areas prone to earthquake events. As shown in Figure 13.8, SENTEX 410 is made by an E-glass unidirectional fabric that is applied on the masonry substrate using an epoxy system constituted by an

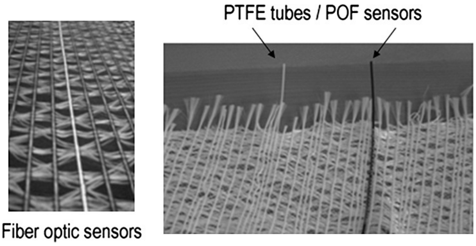

Figure 13.6 Integration of fibre optical fibres in NCFs.
Courtesy of Sächsisches Textilforschungsinstitut (STFI), Germany.

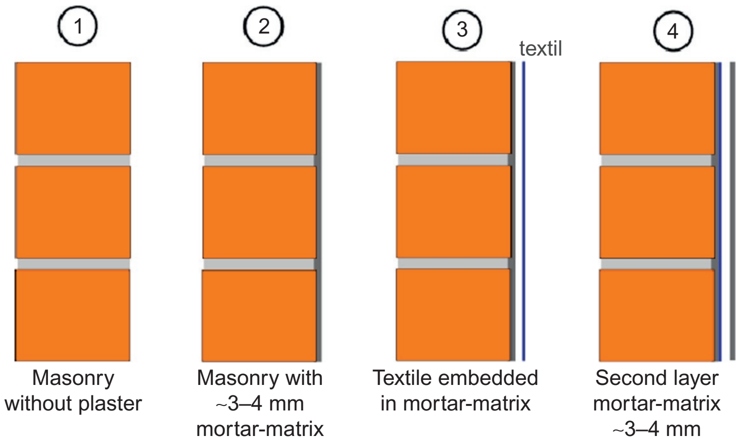

Figure 13.7 Steps of application of seismic wallpaper for the reinforcement of masonry walls.

Figure 13.8 SENTEX 410 (by Selcom, Italy) strip seismic retrofit having embedded optical fibre sensors.

epoxy primer, an epoxy putty, and an epoxy resin. As the seismic wallpaper, the SENTEX 410 multi-functional textile combines reinforcing capability with monitoring information due to the fibre optics.

The POLYTECT project pushed the state of the art for technical textiles through the development of large-area sensor-embedded multi-functional textiles employing fibre optic sensors not only for masonry applications, but also for geotechnical work. In the frame of the project, it has been proved that optical fibre sensors are an excellent solution for geotechnical applications. They enable distributed measurements over kilometres. Cables can be conveniently routed underground to a common receptacle point for interrogation, and activities such as soil displacement generally happen slowly over time (i.e., continuous high-frequency measurements are not necessary). This implies that portable interrogation equipment can be brought to the site at prescribed intervals.

It has been already mentioned that POF sensors have the advantage of being very elastic and robust at the same time. Standard PMMA POF fibres can be strained to more than 40% while fully maintaining their light-guiding properties and presenting relevant advantages with respect to silica fibres. In the frame of the POLYTECT project, POF was investigated as a distributed strain sensor by analysing the backscatter increase at the strained section using the OTDR technique. This sensing ability, together with its high robustness and breakdown strain, made POF well suited for integration into technical textiles for the monitoring of mechanical deformation in slopes, dams, dikes, embankments, and others before critical damage occurs (Liehr et al., 2008).

In the context of POLYTECT, the sensing characteristics of the distributed POF strain sensor by evaluating the Rayleigh backscatter signature using the OTDR technique have been evaluated, as well as the response to strain and possible disturbances and cross sensitivities like bends and temperature. It is important to underline, on the other hand, that geotextiles with integrated FBG sensors enable quasi-distributed measurement of low strain with a limited number of measuring points along the fibre. Some solutions produced by TenCate (Netherlands) are currently commercially available. TenCate GeoDetect® provides soil reinforcement, structural health monitoring, and an early warning system in one package. This multi-functional textile has been designed specifically for geotechnical applications, with the objective of offering a technical solution for monitoring changes in strain and temperature in geostructures. The TenCate GeoDetect® system incorporates a geocomposite fabric, fibre optics, instrumentation equipment, and software to provide solutions for the multi-functional requirements of a geotechnical application (e.g., protection of the optical fibre, capability, and reinforcement in addition to data acquisition). TenCate GeoDetect® is available in three configurations: GeoDetect®, GeoDetect® S, and GeoDetect® S-BR. The basic version (GeoDetect®) is a customisable solution where FBG, stimulated Brillouin scattering, and Raman scattering are used to measure strain, strain and temperature, or temperature-only changes in soil structures. Strain as low as 0.02% can be measured with a spatial resolution of 10 cm. With the proper software, changes in temperature can be monitored at 0.1 °C with a spatial resolution of 10 cm (http://www.tencate.com/emea/geodetect/).

13.5 Application cases in the construction sector

13.5.1 Application of multi-functional textiles for the seismic reinforcement of masonry buildings

In what follows, the results of field trials and on-site tests by applying the multi-function textiles as presented in Section 13.2.1 as seismic reinforcement of masonry buildings are presented. Two case studies are described:

- Seismic tests on a reinforced masonry building carried out within the POLYMAST project (http://www.series.upatras.gr/POLYMAST) at the Eucentre in Pavia (Italy).
- Seismic tests on a reinforced masonry building carried out within the POLYTECT project at the Indian Institute of Technology (ITT) in Madras (India).

13.5.1.1 Seismic tests on a reinforced masonry building at Eucentre (Pavia, Italy)

Shaking tests on a two-story stone masonry building have been carried out in the framework of the SERIES (Seismic Engineering Research Infrastructures for European Synergies) project (http://www.series.upatras.gr) within the POLYMAST (Polyfunctional Technical Textiles for Reinforcement of Masonry Structures) project.

A stone masonry building was considered in three configurations: the unreinforced building (#URB), the damaged building (#DAM), and the reinforced building (#REB), shown in Figure 13.9. The #URB building is a two-story stone building 5.80-m long (*X* direction), 4.40-m wide (*Y* direction), and 5.80-m high (*Z* direction). The building foundation (40-cm tall) is made of concrete, while a wood slab is realised in between the first and the second stories. A double-pitched roof (wood-made) covers the building. The roof structure is made by a longitudinal wood beam and by transversal beams that are simply supported on top of the stone walls. The #DAM building corresponds to the #URB after having been damaged during the experimental tests.

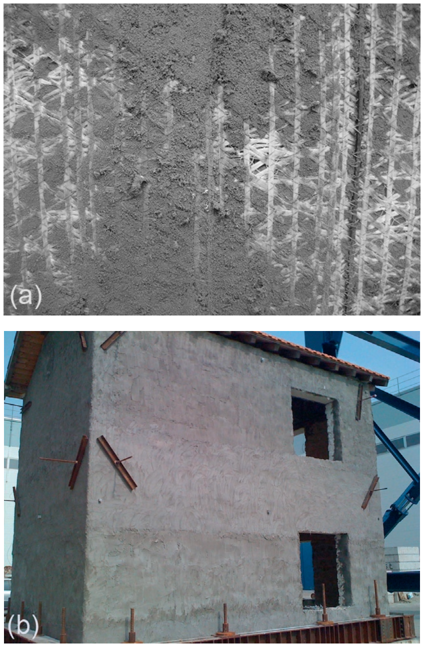

Figure 13.9 (a) Eucentre-POLYMAST full-cover textile reinforcement with the multi-functional textile: mortar + textile as they look when applied to the wall and (b) the building full cover after some days.

The testing phase consisted of the following steps:

- Repairing of the damaged unreinforced building;
- Retrofitting of the repaired building with the full-cover multi-axial sensor-embedded textile solution (Selcom product WP5C8300, E-glass);
- Installation of fibre optic sensors into the textile (during the retrofitting phase);
- Testing the building on the uniaxial-shaking table for subsequent seismic events of increasing intensity.

As reported, the building was subjected to a number of seismic tests of increasing energy for an assessment of the reinforcing solution by means of the multi-functional textile (see Figure 13.2c) and of the monitoring capability of the embedded sensors. Before each seismic test and in correspondence with the main configurations of the building, a number of dynamic characterisation tests were also performed. The performance of the textile was successfully evaluated together with the performance of the sensors and the reliability of the information performed. Indeed, strain measurements from the embedded fibre optic sensors were successful recorded during the seismic tests, allowing the determination of the point of maximum stress after the seismic excitations. Permanent (plastic) deformations and displacements were also detected. This was achieved by comparing the strain and displacement time histories pre- and post-seismic tests, and looking at the reference strain amplitude after the last seismic test.

13.5.1.2 Seismic tests on a reinforced masonry building carried out at the Indian Institute of Technology (IIT) in Madras (India)

Experimental shaking table tests of a two-story full-scale masonry building, tested unreinforced, reinforced with a textile-based striped solution (Selcom UNIE410), and finally reinforced with a multi-functional textile full-cover solution (Selcom product WP5C8300) were carried out at the Indian Institute of Technology, as depicted in Figure 13.10. Shaking table tests of increased seismic intensity up to 0.55 g were carried out for all the different building configurations. The building is 5-m high and 3.4 m × 3.4 m wide.

In the case of the unreinforced building, cracks occurred not only directly in the joints, but also across the stones themselves. In one wall, also an 80-cm-high vertical

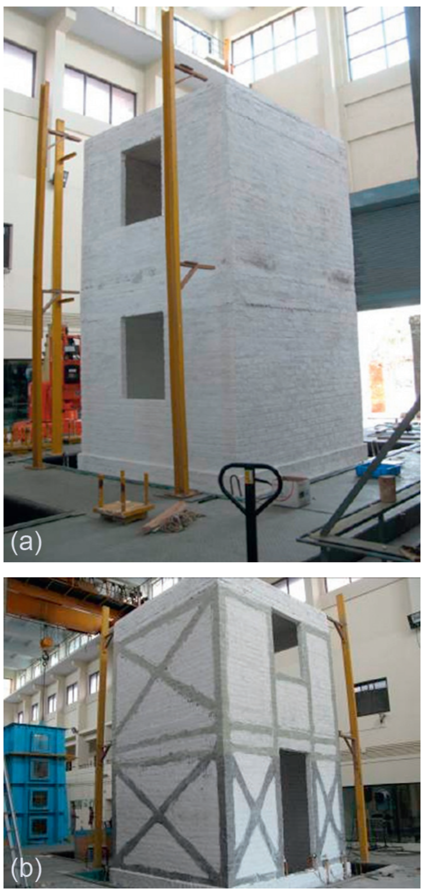

Figure 13.10 (a) IIT Madras unreinforced masonry building and (b) strips reinforced. Courtesy of the Indian Institute of Technology (IIT), Madras (India).

crack occurred in a corner crack mode through big overturning moments after 0.45 g. The sliding was visible, and a collapse was impending.

In the case of the strip reinforcement, the main effect of the reinforcement was to concentrate all the forces in the corners. The result was localised high damage in the stones at the bottom corners. Also, the thick ground masonry ring was destroyed. The sliding and the opening of cracks though the high overturning moment was visible and a collapse was impending. Because of that, the test was interrupted after 0.55 g ground acceleration as pick value. As a result, the stripe reinforcing increased the global strength of the building about 18.2%.

Finally, for the case of the full-cover reinforced building, the building was able to withstand the seismic action up to 0.55 g without presenting any significant and visible damage. The global strength of the building was increased, as well as the capacity of the building to dissipate energy associated to the energy content of the seismic impulse.

13.5.2 Application of multi-functional geogrids for soil stabilisation of unstable slopes and railway embankments

In what follows, the results of field trials and on-site tests by applying the multi-function textiles as presented in Section 13.2.1 as seismic reinforcement of masonry buildings are presented. Three case studies carried out within the FP6 EU project POLYTECT are described:

- Field test to evaluate the settlement of a railway line close to Chemnitz (Germany);
- Field test to evaluate the slope stability at Belchatow (Poland);
- Field tests to evaluate the benefit of a geotechnical reinforcement of a slope failure at Zimmersrode (Germany).

13.5.2.1 Field test to evaluate the settlement of a railway line close to Chemnitz (Germany)

The location of the test is in correspondence with a curve of a railroad near Chemnitz (Germany), as shown in Figure 13.11. The traffic volume in the nearby rail track is very high. The portion of the embankment we tested is more than 100 years old and was selected because it was under reconstruction. The motivations for the field test were

- Investigation of handling, behaviour, and performance of the textile samples with different types of sensors incorporated into the textile structure;
- Investigation of the influence of weather conditions during installation (the weather was from dry to extremely rainy, and then snowy and with temperatures below 0 °C) and for long-time measurements at time intervals.

13.5.2.2 Field test to evaluate the slope stability at Belchatow in Poland

The scope of this field test was to evaluate the possibility of using an intelligent geotextile to investigate and observe creeping slopes and landslide slopes. The

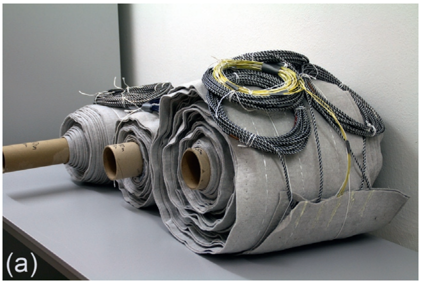

Figure 13.11 (a) Chemnitz railhead: multi-functional geotextiles (MFGs) and (b) railway test site.

multi-functional geotextiles developed within the POLYTECT project represented an ideal candidate for this application because the system is able to measure strain and temperature continuously distributed along the whole length of the fibre that is integrated in the geotextile. The chosen fibre is a standard PMMA POF, which is integrated in the geotextile mat and is able to measure distributed strain behaviour on a length of 100 m. The sensor principle is based on the use of the optical time-domain reflectory (OTDR) technique to obtain the backscatter profile of the fibre. Short laser pulses are given into the fibre, and the backscattered light for each pulse is recorded as a function of time. Standard PMMA POF can observe strain up to 40%.

The field test was the open-pit brown coal mine in Belchatow that presented a creeping slope active with a reasonable velocity, which allows the detection of movements in a reasonable time. Figure 13.12 shows the creeping assessment by means of MFGs.

13.5.2.3 *Field tests to evaluate the benefit of a geotechnical reinforcement of a slope failure at Zimmersrode (Germany)*

Field tests to evaluate the feasibility and the effectiveness of a geotechnical reinforcement to improve the stability of a slope failure and to decrease the failure speed were carried out at an old mining site in Zimmersrode, located about 50 km south of Kassel, Germany (see Figure 13.13). Two types of multi-functional geotextiles (MFGs) were considered: an optical fibre sensor integrated in geogrids and three optical fibre

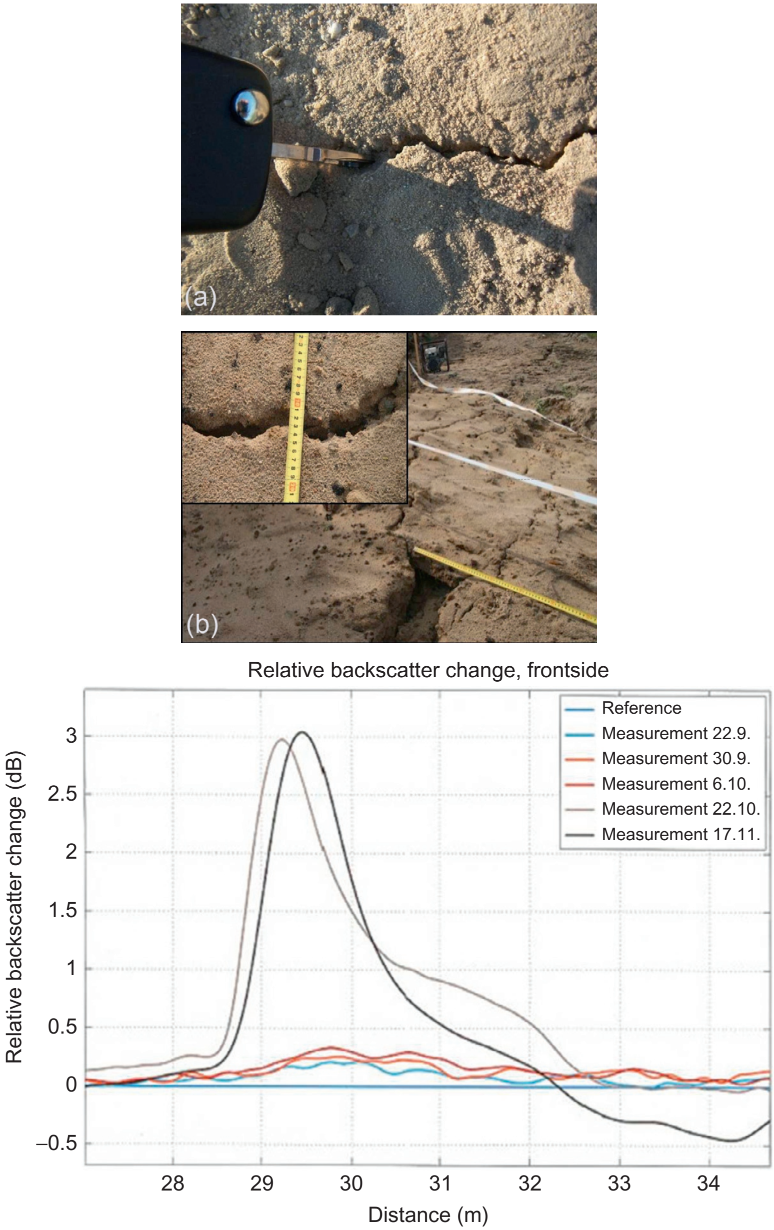

Figure 13.12 Belchatov-creeping assessment by multi-functional geotextile (MFG) sensors. (a) Crack opening (detail) and (b) crack measurement with scale for the calibration of the readings from the optical sensors embedded in the textile.
Courtesy of the Federal Institute for Materials Research and Testing (BAM), Germany.

Figure 13.13 Zimmersrode multi-functional geotextile (MFG) installation.
Courtesy of Kassel University, Germany.

sensors integrated first in a thin rope-like geotextile and then placed between two layers of non-woven filter mats. The aim was to collect valuable information as well as the performance of the MFGs against the weather and mechanical straining. Several measurements were made by interrogating the optical fibre sensors using OTDR (POF) and Brillouin scattering (glass optical fibre (GOF)) techniques. The field tests were successful because they provided feasibility in the use of MFGs more than 100 m in length. Although some local bending had occurred in the POF sensors during manufacturing, the production of MFGs of such length was itself a demonstration of feasibility and success.

13.6 Standardisation issues

As illustrated in the previous paragraphs, in the last decade, advanced textile materials have been developed as a result of a number of research and innovation projects addressing the construction sector. Despite the benefits introduced by this new generation of multi-functional materials, many building practitioners are unfamiliar with the behaviour and characteristics of these materials. The lack of information about the uses and properties of these materials from the design and construction community limits their capability of achieving the highest possible standards in quality assurance and control of construction projects.

For these high-performance materials, coming both from modification of existing materials and from newly developed high-performance textile materials, the current design codes or regulations may or may not be applicable. In general, new codes or specifications, or guidelines for their use or testing procedures, are required to be developed for the purpose of design, construction, and testing.

Standards allow manufacturers, technology providers, and suppliers to develop their businesses, as standards support the removal of trade barriers and the acceptance of new products by the market by guaranteeing that the required levels of quality and performance are respected (Rijavec, 2010).

In recent years, several European cooperation projects on smart textiles have produced a variety of outcomes with high market potential in three target domains: personal protective equipment (PPE), construction products, and consumer goods. SUSTA-SMART (grant agreement 319055) is an FP7-funded project supporting standardisation for smart textiles to boost their use in the market (http://www.susta-smart.eu/), focused particularly on the above-metntioned three application sectors:

- By mapping the relevant standardisation organisations and issues in FP6/FP7 projects;
- By defining a standardisation audit procedure;
- By synthesising and prioritising the needs for standards with a broad consensus and leading to a standardisation road map;
- By producing standardisation input documents (including new work item proposals) to be presented to the relevant standardisation committees.

The main objective of the project was to develop a detailed road map for smart textiles in the three domains comprising the construction sector.

The road map included the identification of the smart textile products for the three target domains, the analysis of trends and drivers, the specifications of the major technology areas, and the technology alternatives. An analysis of barriers (legal, economic, and technological) that hamper the standardisation process for smart textiles was carried out, as well as an analysis of critical system requirements. Then, the identification of means necessary to overcome the barriers was performed. The analysis considers different aspects: further research developments, capital investments, lobbying and networking, and others. Finally, actions, recommendations, and a timeline for fostering the standardisation process of smart multi-functional textiles were established.

The analysis of the standardisation needs for the construction sector underlined that key issues are related to the identification of relevant properties for the characterisation and evaluation of the technical textile-based systems, the performance evaluation of the new generation of multi-functional textiles, the durability of these products in harsh environments, the identification of appropriate tests and testing procedures, and the definition of application guidelines. The road map provided at the end of the project highlighted the need to achieve short-term targets as a priority, provide definitions in the field of smart textile-based products for the construction sector, and categorise different types of products according to their features by updating the CEN/TR 16298 'Textiles and textile products smart textiles—definitions, categorisation, applications and standardization needs.' The main categories to be considered for these products are (1) building applications and (2) earthwork applications. The second step in the short-term period is to develop a technical report related to an official road map 'for standardisation of smart textile-based products for the construction sector with integrated technology.' The starting point for this road map should be the SUSTA-SMART road map that has been provided as a supporting document to the relevant standardisation committee. For the medium term, the focus must be moved to the development of suitable test methods and guidelines for the new generation of multi-functional textiles for the construction sector.

For this purpose, the ongoing FP7 project MULTITEXCO (grant agreement 606411) mentioned in the previous paragraphs and started in October 2013 aims at supporting the competitiveness of the European SMEs of the construction by developing testing procedures, guidelines for design and use, and codes of practices for the novel smart textiles for the construction sector.

13.7 Conclusion

Research on multi-functional textiles embedding sensors for the structural health assessment of buildings and infrastructures is very active, and many commercial products are emerging in the market. EU projects such as POLYTECT, MULTITEXCO, and SUSTASMART have open the way towards this development and represent the state of the art of this technology. The current developments are focused on the standardisation of those products for a wider and more diffuse application in construction.

References

Fidanboylu, K., Efendioglu, H.S., 2009. Fiber optic sensors and their applications. In: 5th International Advanced Technologies Symposium (IATS'09), May 13–15, 2009, Karabuk, Turkey.

Fuggini, C., Chatzi, E., Zangani, D., Messervey, T.B., 2011. Innovative multifunctional reinforcement technology for masonry buildings: numerical validation and damage detection investigation. In: COMPDYN 2011 III ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Corfu, Greece, 25–28 May 2011.

Ghetia, Shivang, Gajjar, Ruchi, Trivedi, Pujal, 2013. Classification of fiber optical sensors. Int. J. Electron. Commun. Comput. Tech. 3 (4), 442–445.

Gholamzadeh, Bahareh, Nabovati, Hooman, 2008. Fiber optic sensors. World Acad. Sci. Eng. Technol. 2, 281–291.

Käseberg, S., Holschemacher, K., 2010. Smart CFRP systems—fiber Bragg gratings for fiber reinforced polymers. In: CICE 2010–The 5th International Conference on FRP Composites in Civil Engineering, September 27–29, 2010, Beijing, China.

Kuang, K.S.C., Quek, S.T., Koh, C.G., Cantwell, W.J., Scully, P.J., 2009. Plastic optical fibre sensors for structural health monitoring: a review of recent progress. J. Sens. 2009, 13, Article ID 312053.

Liehr, Sascha, 2011. Polymer optical fiber sensors in structural health monitoring. In: Mukhopadhyay, S.C. (Ed.), New Developments in Sensing Technology for Structural Health Monitoring, vol. 96. Springer, Berlin/Heidelberg, pp. 297–333.

Liehr, S., Lenke, P., Krebber, K., Seeger, M., Thiele, E., Metschies, H., Gebreselassie, B., Münich, J.C., Stempniewski, L., 2008. Distributed strain measurement with polymer optical fibers integrated into multifunctional geotextiles. In: Berghmans, F., Mignani, A.G., Cutolo, A., Meyrueis, P.P., Pearsall, T.P. (Eds.), Optical Sensors. Proceedings of the SPIE, vol. 7003. p. 700302.

Loriga, G., Fuggini, C., Zangani, D., 2013. Smart multifunctional technical textiles and composites. Compos. Mag. 30, 21–28.

Messervey, T.B., Zangani, D., Fuggini, C., 2010. Sensor-embedded textiles for the reinforcement, dynamic characterisation, and structural health monitoring of masonry structures. In: Structural Health Monitoring 2010, Sorrento, Naples, June 28-July 4.

Nancey, A., Lacina, B., Henderson, J., 2007. Geotextile and optic fibers: feedback after four years of use in soil. In: Proceedings of the Geosyntetichs 2007, January 16–17, 2007, Washington, DC.

Palmieri, L., Schenato, L., 2013. Distributed optical fiber sensing based on rayleigh scattering. Open Opt. J. 7 (Suppl.1, M7), 104–127.

Rijavec, Tatjana, 2010. Standardisation of smart textiles. Glasnik hemičara, tehnologa i ekologa Republike Srpske 4, 35–38.

Zangani, D., 2008. Multifunctional textiles for protection against natural hazards. Adv. Sci. Technol. 56, 601–608.

Zangani, D., Scotto, M., Corvaglia, P., Münich, J.C., 2007. Rehabilitation and seismic reinforcement of masonry structures with multifunctional composites. Compos. Mag. 5, 52–56.