1

Electro-Conductive Sensors and Heating Elements Based on Conductive Polymer Composites in Woven Fabric Structures

Irina Cristian[1,2,3], Saad Nauman[1,2],
Cédric Cochrane[1,2] and Vladan Koncar[1,2]
[1]University Lille Nord de France
[2]ENSAIT, GEMTEX, F-59100 Roubaix
[3]Technical University GHEORGHE ASACHI of Iaşi
[1,2]France
[3]Romania

1. Introduction

The use of intelligent materials which are capable of reacting to external stimuli is growing in the field of textiles. Conductive materials, metals as well as conducting polymers, are already being used in many textile applications, like antistatic materials, electromagnetic interference shielding, heating, transport of electrical signals, sensors etc.
Conductive polymers are some of the developments which seem to respond to specific properties of textile materials, like flexibility and deformability. Two sub-classes of conductive polymers can be identified: intrinsically conductive polymers and conductive polymer composites.
Inherently conducting polymers are composed of polymer chains containing long conjugated double bonds which give rise to highly conducting properties, and they have been considered as promising materials (Heeger, 2002; Kumar et al., 1998). Inherently conducting polymers are suitable for applications in many domains of intelligent textiles, but they present some substantial disadvantages, like infusibility or insolubility in common organic solvents, weak mechanical properties and poor procesability. However, advanced solution processing of this class of polymers has been developed significantly over the last decade to improve their low solubility. For example, chemical modification of monomers with dopants has enhanced the solubility in the case of polythiophene and polyaniline (Haba et al., 1999; Gettinger et al., 1995).
For their part, composite conductive polymers are obtained by blending (generally by melt mixing) an insulating polymer matrix (thermoplastic or thermosetting plastic) with conductive fillers like carbon black, carbon fibres or nanotubes, metallic particles or conductive polymers. The presence of filler particles in the matrix may have a negative impact on the mechanical properties of the final composite (Krupa et al., 2001; Novak et al., 2002). Instead of this, the development in the field of composite conductive polymers seems therefore to be a promising approach for intelligent textiles own to simplicity of preparing and to their low cost.

In this chapter, two applications (sensor and actuator) based on coating of textile materials with conductive polymer composites are presented. Several different coating techniques for intelligent textile structures exist - the one chosen for both applications was developed in our laboratory (Cochrane et al., 2007, 2010) based on dispersed carbon black particles (Printex® L6) in a polymer solution (Styren-Butadien-Styren or latex), using a solvent.

In the first part of this chapter, a new approach of NDE (Non Destructive Evaluation) using fibrous sensors inserted inside composite woven reinforcements during their weaving is presented. The use of 3D woven fabrics as the reinforcing medium for composites is becoming a popular choice, due to various advantages such as reduced cost and shorter production cycle, greater design flexibility and superior mechanical properties (Kamiya et al., 2000). Recently, these high performance composites reinforced with 3D structures have found wide applications in various industrial areas such as aerospace, aircraft, automobile, civil engineering etc. Good quality and reliability are basic requirements for advanced composite structures which are often used under harsh environments. To improve their performance, the cure monitoring of technological process is clearly necessary. At the same time, in service NDE is also needed to keep these structures operating safely and reliably.

A novel flexible piezoresistive fibrous sensor has been developed and optimized for in situ structural deformation sensing in carbon composites. Those sensors were inserted as weft in 3D-woven interlock reinforcement, during the weaving process on a special weaving loom. The reinforcement was then impregnated in epoxy resin and was later subjected to quasi static tensile loading. It was found that the sensor was able to detect deformations in the composite structure until rupture since it was inserted together with reinforcing tows.

The morphological and electromechanical properties of the fibrous sensors have been analyzed using tomography and yarn tensile strength tester. An appropriate data acquisition module has also been developed and used for data acquisition and its further treatment. The results obtained for carbon composite specimens under standard testing conditions have validated in situ monitoring concept using our fibrous textile sensors.

The second part of this chapter presents a woven fabric containing an original heating element. Textile actuators like heating fabrics can find applications in numerous and varied fields such as sports, leisure, medical and automotive (Droval et al., 2005; El-Trantawy et al., 2002). Usually actuators need heavy power supplies that are rarely flexible and lightweight which badly affects wearability. Our heating element is designed to adapt to flexible structures. Metallic yarns, used as electrodes are integrated in a woven structure in a comb-teeth arrangement. These electrodes are connected to a power supply. A thin conductive coating is applied on the fabric surface and on the electrode arrangement, in order to ensure uniform heat distribution. The coating is a composite material based on aqueous latex dispersed with carbon black as filler. The heating element (comb electrodes and electro-conductive coating) can thus adopt the desired pattern. This is an important aspect of our heating element as it allows integration of the heating element in various fabrics designed for varied and diverse applications. In our research the distance between electrodes remained unchanged, the only variable value being the percentage of filler. The results regarding the power consumption and textile surface temperature for different filler content were registered. From these results, optimum filler content for heating application was defined. A thermal image of the heating fabric operating at low voltage is given, in order to demonstrate the efficiency of our system. A more precise measurement of surface temperature is thus possible. For applied voltage of 15 V, the maximum temperature gained was about 50 °C. The thermal image also demonstrates the homogeneity of heating provided by our system. Potential applications of these self heating fabrics include garments designed to provide thermal comfort and antifreeze safety.

2. Electro-conductive sensors for on-line measurements of structural deformation in composites reinforced with 3D-woven fabrics

Weaving technique has been used for a long time in order to obtain technical textile products for industrial applications. An important use of this technology is for the manufacturing of 3D reinforcements using high performance fibres (carbon, glass, aramid etc.). 3D reinforcement based composites, in combination with high-performance fibres, are being increasingly used in the aerospace industry (Ko, 2007). Particular advantages of these fabrics mentioned in the literature include better through the thickness properties, better out of plane properties, high impact resistance, enhanced delamination resistance, resistance to crack propagation, impact/fracture resistance, improved post impact mechanical properties, damage tolerance, dimensional stability, ease of fabrication and minimal need of cutting, lay up and joining.

Regarding these properties it can be safely concluded that 3D woven fabrics constitute the most promising class of reinforcements for composite materials for high tech structural applications. To improve their performance, the cure monitoring of technological process is clearly necessary. At the same time, in-service non destructive evaluation is also needed to keep these structures operating safely and reliably. Non destructive evaluation techniques have been developed in the past including ultrasonic scanning, acoustic emission, shearography, stimulated infrared thermography, fibre brag grating sensors and vibration testing etc. (Black, 2009). The challenge today is to develop new low cost techniques which can perform on-line structural health assessment starting from the manufacture of composite structure to the real service of these structures in the field. Moreover, the non destructive evaluation techniques have to be integrated in the design phase and sensors should be inserted during the fabrication of composites, in order to improve accuracy and reduce their costs. The classical non destructive evaluation techniques are difficult to adapt. They are not well suited for on-line structural health monitoring, because of difficulties in making in situ implementation.

One possible solution is to use intelligent textile materials and structures which provide real possibility for on-line and in situ monitoring of structural integrity. Such intelligent materials are made by coating or treating textile yarns, filaments or fabrics with nanoparticles or conductive & semi-conductive polymers giving them special properties.

A review of piezoresistive sensing approaches already being applied to measure strain in fabrics/composites shows that several sensing mechanisms exist (Dharap et al., 2004; Lorussi et al., 2005; Scilingo et al., 2003; Fiedler et al., 2004). These approaches may be categorized on the basis of manufacturing technology as nanotube networks, use of carbon tows for self-sensing and semi-conductive coatings.

Nanotubes have been investigated in detail for use as sensing mechanisms, both for smart textile applications and for structural health monitoring of composites. Significant challenges still exist in their development, for example the efficient growth of macroscopic-length carbon nanotubes, controlled growth of nanotubes on desired substrates, durability of nanotube based sensors and actuators, effective dispersion in polymer matrices and their orientation. Therefore, there is a need to develop both experimental and analytical techniques to bridge the

nano and macro scales towards optimization so as to use nanotube networks as sensors inside macroscale (fabric) or mesoscale (tow) composites (Li et al., 2005).
Carbon fibre reinforced composites offer a unique possibility of using carbon tows as sensing network because of their conductivity. However such an approach can only be used for conductive fibre based composites. Moreover, before applying such an approach for structural health monitoring it is imperative to understand the deformation mechanism of the reinforcement. Any anomaly in the deformation mechanism can threaten the sensing mechanism's validity and efficacy.
Concerning semi conductive coatings, they are easy to realize and can be made wash resistant. Their use as percolation networks for sensing in structural health monitoring applications is quite promising and needs to be further investigated.
Present study is aimed at designing, developing and optimizing piezoresistive fibrous sensors realized from semi-conductive coatings, suited for composites structural parts containing 3D reinforcement. Our sensors can be embedded inside the reinforcement during weaving and they have all the characteristics of a traditional textile material (flexible, lightweight and are capable of adopting the geometry of the reinforcement and become its integral part).
Embedding such an intelligent piezoresistive sensor inside the reinforcement during weaving process is the most convenient and cost effective way of insertion of a sensor for structural health monitoring.
Development and optimization of such piezoresistive sensors has been carried out in order to render them sensitive enough to measure in situ strains inside the composite part. Sensitivity is important as the targeted application usually undergoes very low strains and even such low strains and/or vibrations during the life time of composite parts are critical. Often they are used in areas where structural integrity can not be compromised (aircraft wings, bodies etc).

2.1 Sensor design and optimisation

As coating solution, the conductive polymer composite based on dispersion of carbon black particles (Printex® L6) in polymer (Evoprene® 007) solution, using chloroform as a solvent was chosen (Cochrane et al, 2007, 2010).
In order to characterize the sensitivity and adherence of the coating on different substrates, the 35 % carbon black solution was coated on different yarns (71 tex cotton spun yarns; 482.3 tex polyethylene monofilament and 25 tex polyamide monofilament). Visual inspection of the surfaces of the coated yarns shows that the coating is more uniform for synthetic monofilaments compared to cotton yarns. The cotton yarns absorb the conductive solution, which penetrates inside the pores and interstices much like a dye. This particular phenomenon could be a source of non homogeneity in sensor electrical and mechanical properties, as the spun yarn is non uniform as compared to filaments, the coating and thus the resistivity achieved could be non uniform. Moreover the greatest inconvenience with coated cotton spun yarns is their low sensitivity during the initial tensile loading phase.
The resistance values were measured on 12 coated samples of each variant using a multimeter. The resistivities were then calculated using the yarn/filament fineness, yarn/filament lengths and these measured resistance values. Fig. 1 gives a comparison of calculated resistivity values of conductive layer deposited on different fibrous substrates. It can be seen that coated polyethylene filaments show relatively lower dispersion of resistivity as compared to coated poyamide filaments.

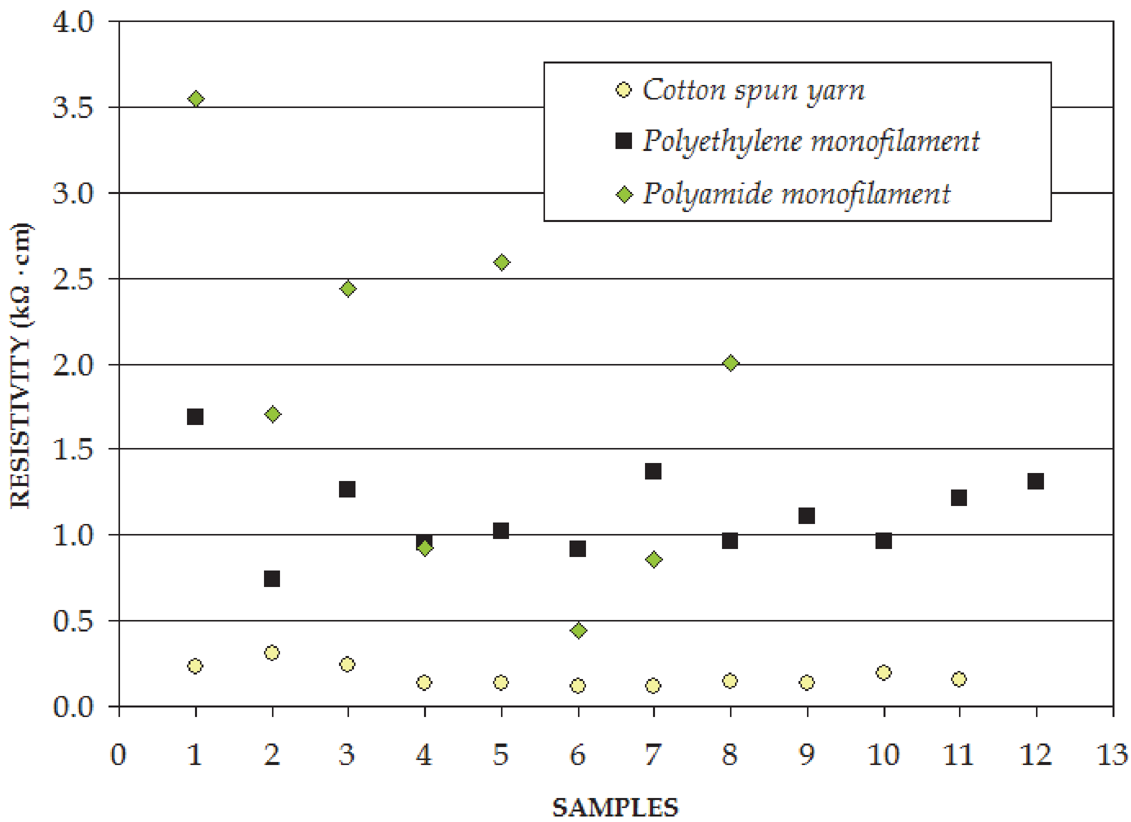
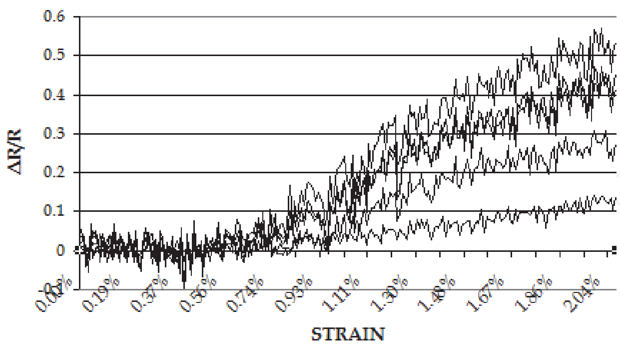


Fig. 1. Resistivity values calculated for different substrates coated with 35 wt.- % carbon black solution

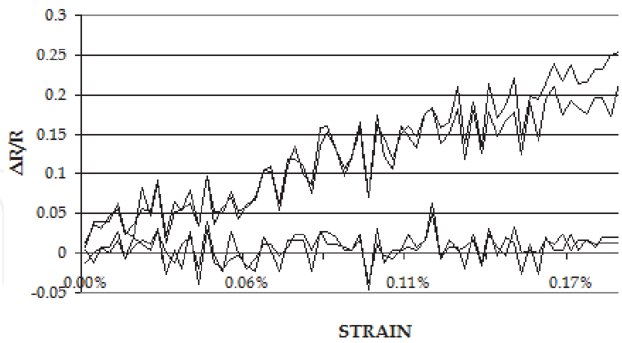
In order to carry out tensile tests on coated yarns and monofilaments, MTS 1/2 tester was used. Samples underwent quasi static tensile loading at a constant test speed of 5 mm/min. For the purpose of electrical resistance variation measurement during the tensile testing, a simple voltage divider circuit and Keithley KUSB-3100 data acquisition module were employed. Fig. 2 shows some of the results for electrical resistance variation, expressed as normalised resistance (ΔR/R) during tensile testing, obtained using different substrates for coating.

Initial resistance of the coating on cotton yarns is much lower then monofilaments. But since the cotton spun yarns are inherently irregular, the coatings obtained are not homogenous and the results for different coated yarns vary widely in their response to tensile loading (Fig. 2-a). Due to particular fineness of the polyamide monofilament it was found that slight non homogeneity in coating on the surface can result in breakdown of conductive path as is obvious from Fig. 2-b. As a result, the behaviour of polyamide is highly inconsistent. Polyethylene monofilaments provide a reasonably good compromise as the substrate. The coatings on polyethylene are easy to achieve due to good substrate/conductive solution interfacial properties. As the curves in Fig. 2-c show, the polyethylene coatings are reproducible as the curves for all the four samples are nearly identical as opposed to polyamide and cotton. Therefore, polyethylene monofilament was chosen for sensor development.

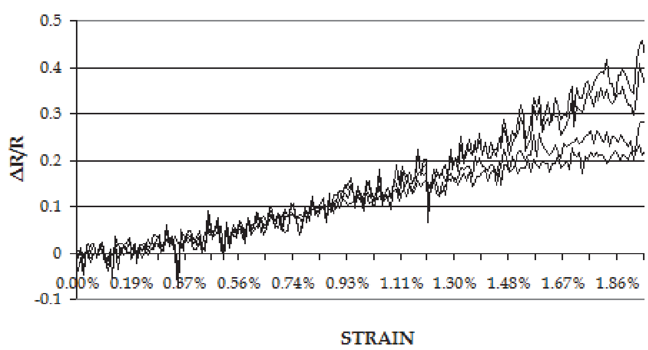
The two ends of the coated polyethylene filaments were additionally coated with silver paint and fine copper wire was attached to the two ends with the help of this paint (as shown in the Fig. 3). In this way, secure connections were realized enabling the reduction of the contact resistance to the minimum.



a) Cotton spun yarns



b) Polyamide monofilaments



c) Polyethylene monofilaments

Fig. 2. Electrical resistance variation during tensile strength tests on different yarn and filament substrates coated with 35 wt.-% carbon black solution

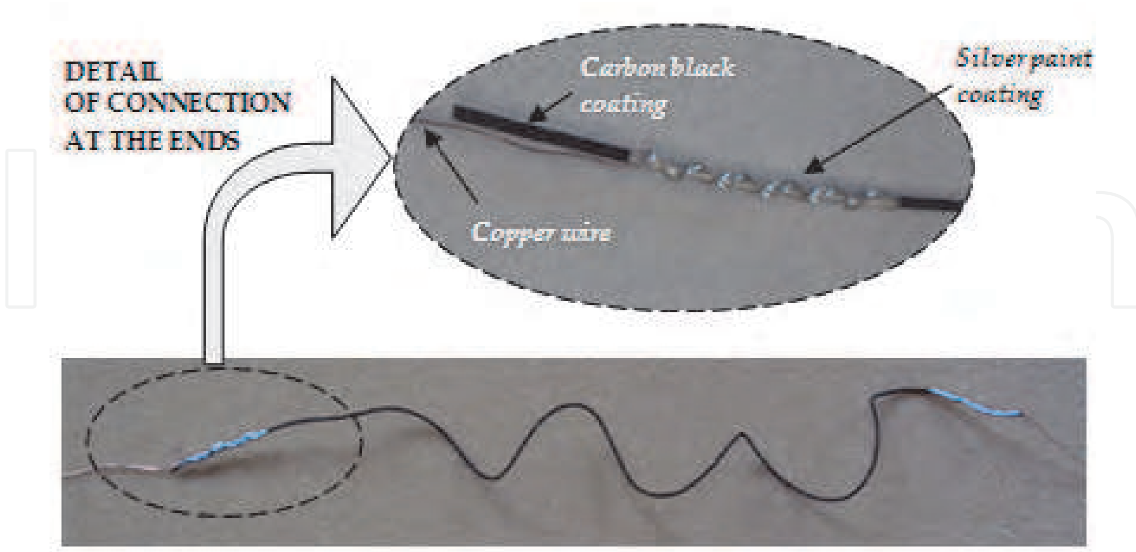


Fig. 3. Carbon black coated sensor with polyethylene substrate

Sensor structural and geometrical parameters along with initial electrical resistance are shown in Table 1.

No.	PARAMATER	UM	VALUE
1	Linear density of the filament	g/km	48.23
2	Diameter of the filament	mm	0.70
3	Average width of the sensor cross section	mm	1.68
4	Average thickness of the sensor cross section	mm	1.26
5	Aspect ratio of the sensor (width/thickness)	-	1.33
6	Initial resistance of the sensor	kΩ	43.3

Table 1. Sensor properties

For insertion in conductive fibre based reinforcements like that woven using carbon multifilament tows, the sensor was coated with Latex Abformmasse supplied by VossChemie® so as to insulate the sensor from surrounding carbon tows.

Prepared in this way, the sensor with polyethylene substrate was tested again on MTS 1/2 tester, under quasi static tensile loading at a constant test speed of 5 mm/min. The same Keithley® KUSB-3100 data acquisition module was employed for the purpose of voltage variation during tensile testing. This time, a special set-up containing a Wheatstone bridge and an amplifier was used to measure unknown variable resistance of the sensor as a function of output voltage. As is obvious from curves presented in Fig. 2-a, b and c, the simple voltage divider circuit is not adequate for the measurement of resistance change in case of sensors developed here. These piezoresistive sensors produce a very small percentage change in resistance in response to physical phenomena such as strain. Moreover the output signal has considerable noise. Generally, a bridge measures resistance indirectly by comparison with a similar resistance. Wheatstone bridges offer an attractive solution for sensor applications as they are capable of measuring small resistance changes accurately (Wilson, 2004).

Fig. 4 shows schematic diagram of the data acquisition module developed and used for data acquisition and its further treatment.

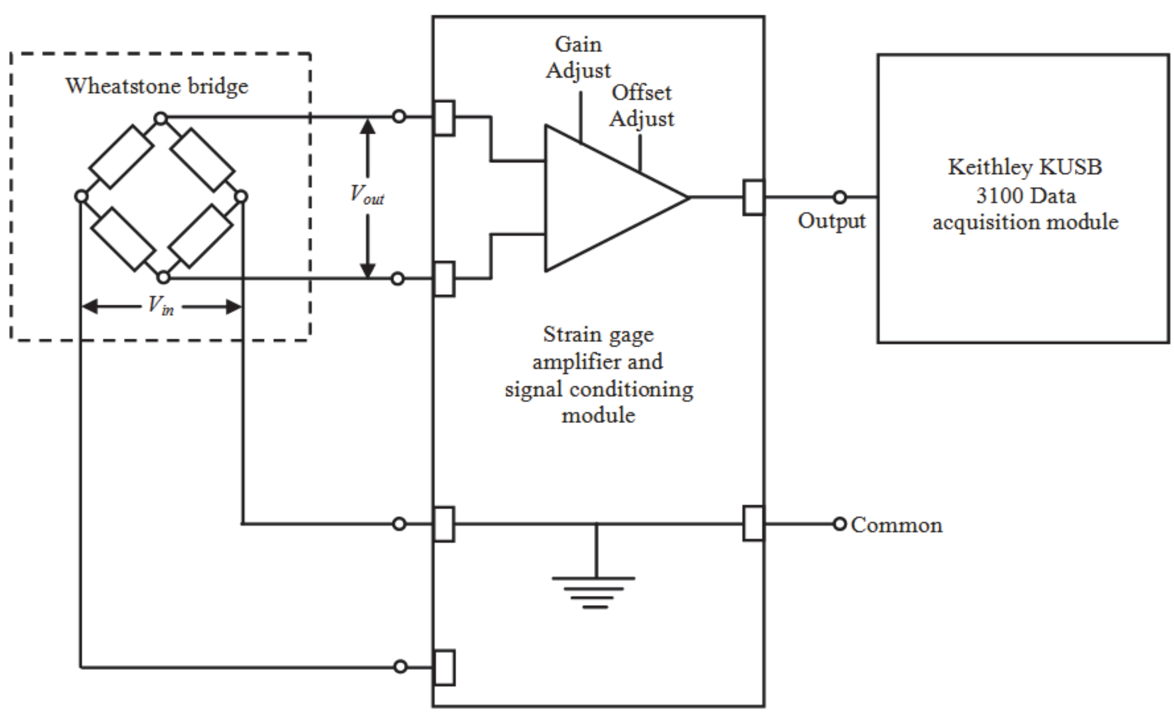


Fig. 4. Schematic of instrumentation amplifier (INA 101) connected to Wheatstone bridge

The resistance variation data thus obtained for different test results was treated for noise reduction using a low pass filter. The resultant stress-strain-resistance relationship curve up to 2.75 % elongation of the out of composite sensor (before insertion in the reinforcement) is shown in Fig. 5.

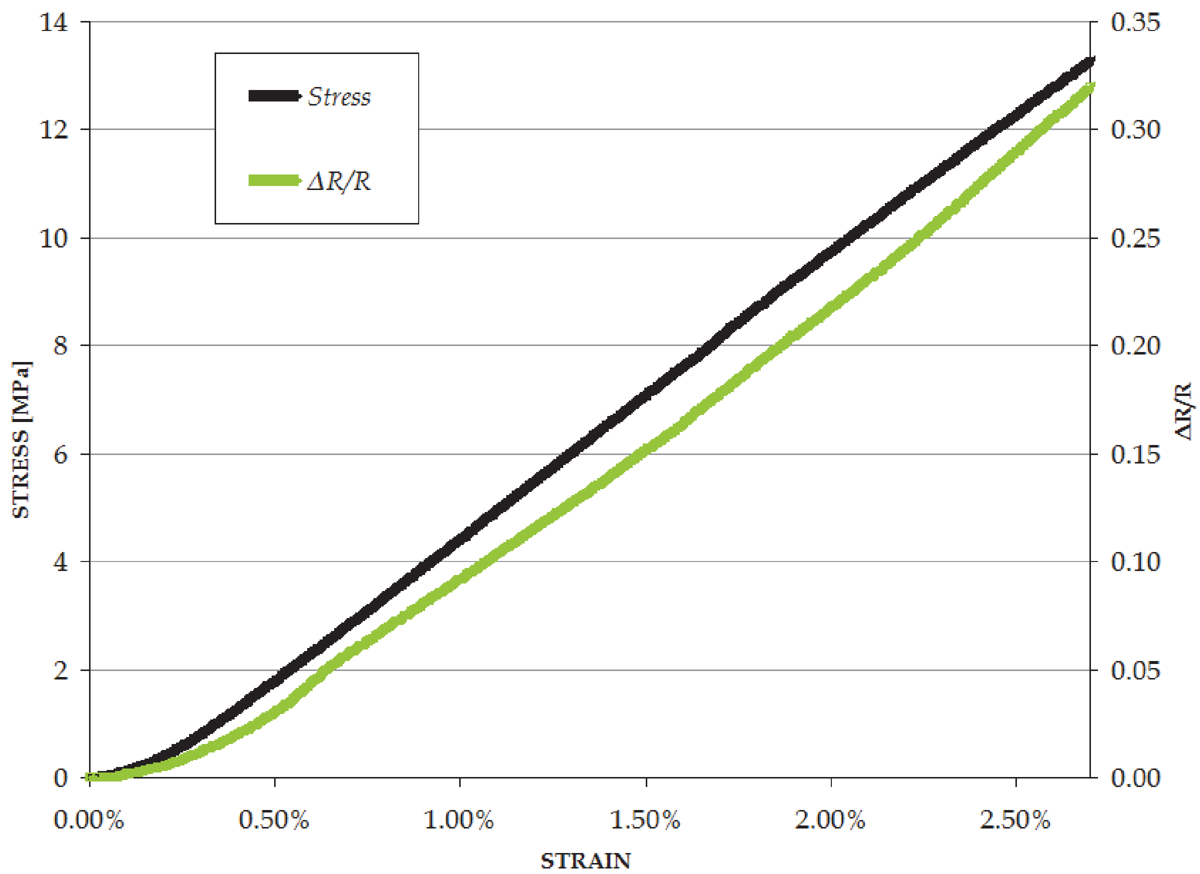


Fig. 5. Normalized resistance and stress against strain for sensor outside composite

It may be noticed in Fig. 5 that the stress vs. strain curve has the same shape as normalised resistance (ΔR/R) vs. strain curve. This validates electromechanical properties of our fibrous sensor for strains ranging from 0 to 2.75 %.

In Fig. 6, the hysteresis results of the sensor for 10 cycles have been given. The sensor underwent 0.5 % extension at a constant test speed of 5 mm/min, followed by compression in each cycle. The sensor follows the extension and compression patterns in each cycle.

The hysteresis is high for the first cycle which reduces gradually and for the 10^{th} cycle the sensor exhibits almost linear behaviour.

2.2 Sensor insertion in carbon woven reinforcement

An orthogonal/layer to layer warp interlock with 13 weft layers and 12 warp layers was chosen as woven structure (Fig. 7-a) and than was woven on a modified conventional loom (Patronic B60 ARM). 6K multifilament carbon tows (supplied by Hercules Inc.) having 200 tex was used in both direction – warp and weft. Yarn densities were 24 yarns/cm in warp direction and 170 yarns/cm in weft direction. The thickness and areal density of resulted reinforcement were 6.5 mm and 3908 g/m^2, respectively.

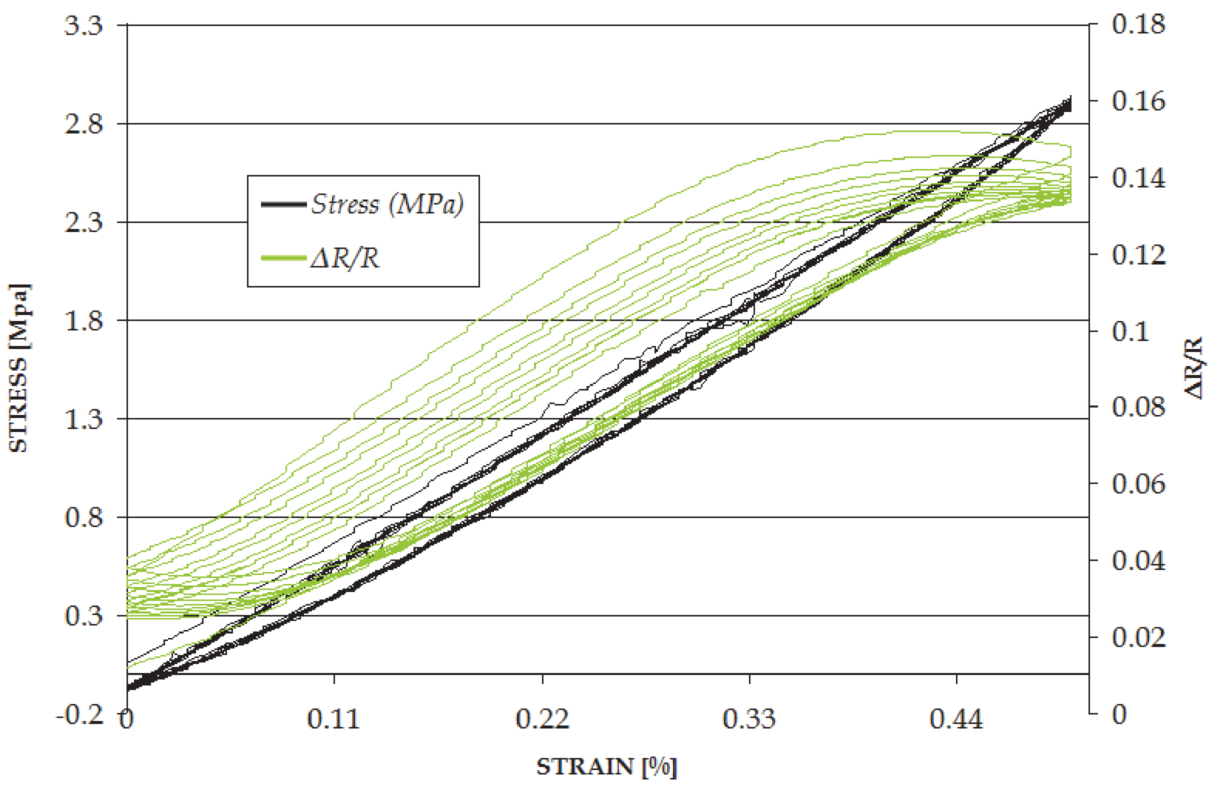
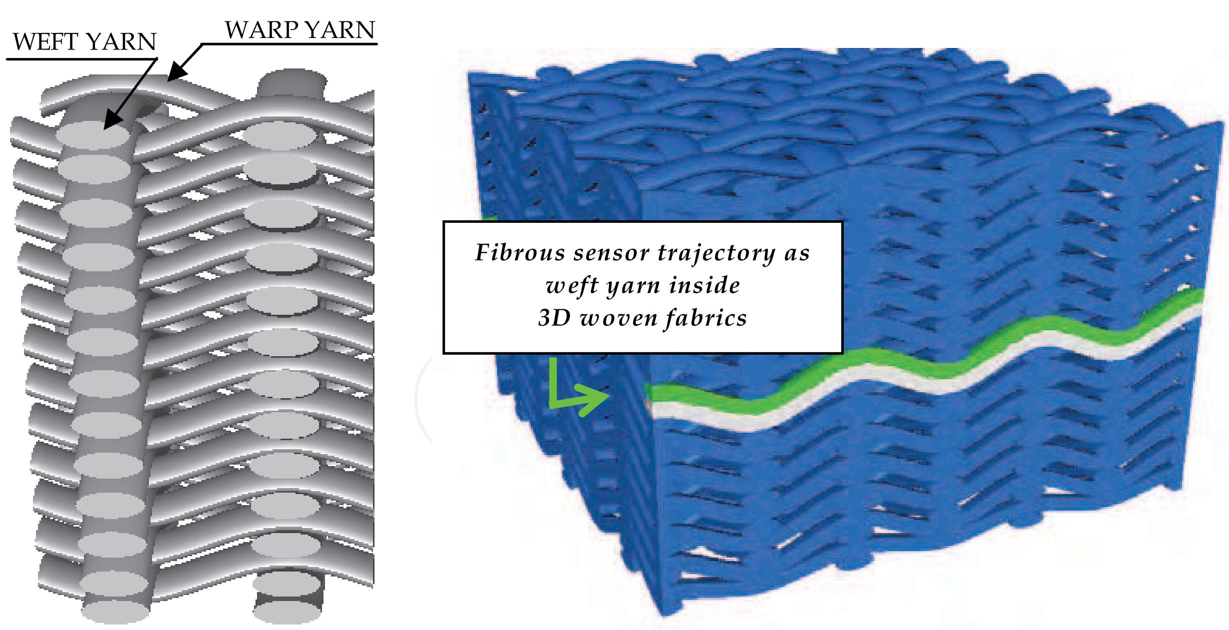


Fig. 6. Normalized resistance (ΔR/R) and stress against strain for sensor (Hysteresis 10 cycles at 0.5 % extension)



a) The weave repeat b) The path of the sensor inside woven fabric

Fig. 7. Interlock weave structure used as reinforcement – graphical representation (TexGen software)

Sensors can be inserted in warp or weft directions during weaving. Given the technical complications associated with sensor insertion in warp direction during weaving on a loom,

insertion in weft direction has been carried out for preliminary studies. The placement of sensor in the reinforcement was decided so that the sensor was inserted in the middle of the structure related to thickness (Fig. 7-b).
The sensor was inserted during the weaving process, as a weft yarn and it follows the same trajectory as the carbon weft yarns inside the reinforcement. In Fig. 8, off the loom dry reinforcement photograph have been shown. Latex coated sensor connections can be seen protruding from the reinforcement.

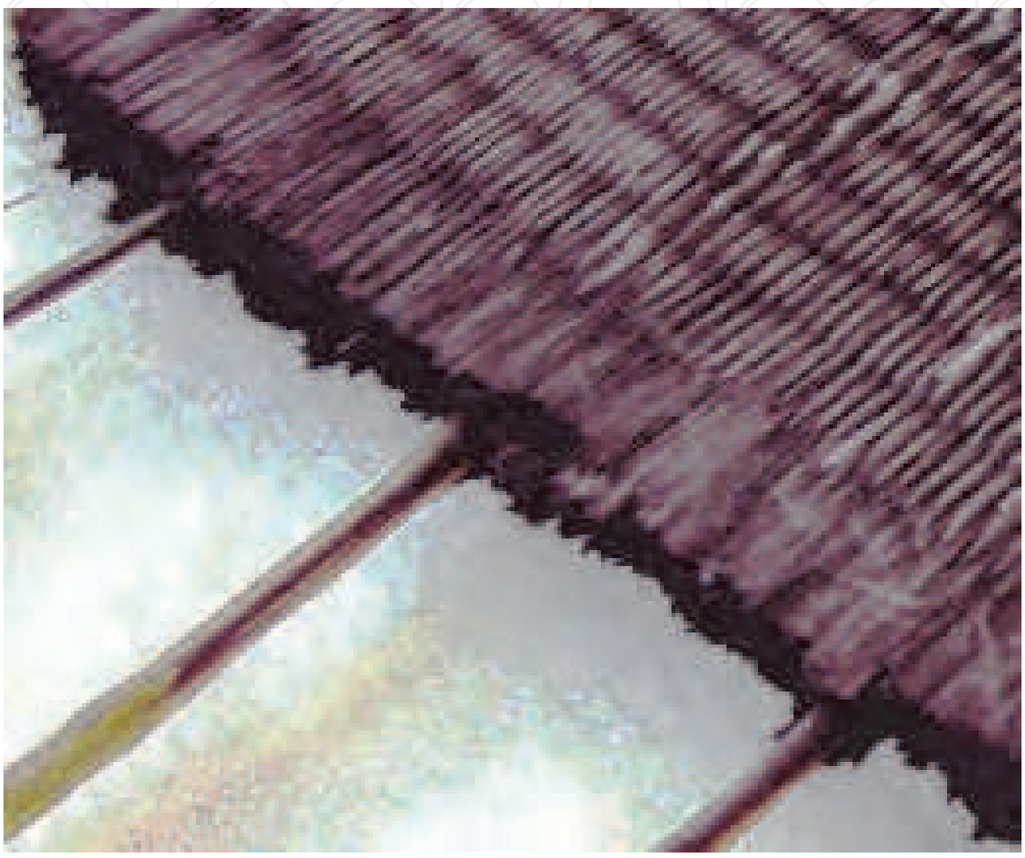


Fig. 8. Reinforcement with protruding sensor connections

2.3 Carbon woven reinforcement impregnation and testing

After weaving, the reinforcement was carefully removed from the loom and was impregnated using vacuum bag infusion process in order to make the composite part stiff. The resin employed was epoxy Epolam® 5015. The two connections of the sensor which remain outside the reinforcement at the two ends were carefully separated from the rest of the mould. This was done by creating two vacuum sub moulds inside the larger mould so that the resin may not impregnate the two connections of the sensor. The impregnated composite samples were cut into slabs of 25 X 2.5 cm (Fig. 9).
The composite specimens were tested on Instron 8500 tester. Tensile strength tests were performed on the composite specimens (according to ISO 527-4, 1997) in the weft direction i.e., the direction parallel to the inserted sensor. The same Wheatstone bridge was used for resistance variation measurement. The configuration of the testing equipment was also kept the same. The composite structural part was tested at constant test speed of 5 mm/min. The composite underwent traction until rupture.

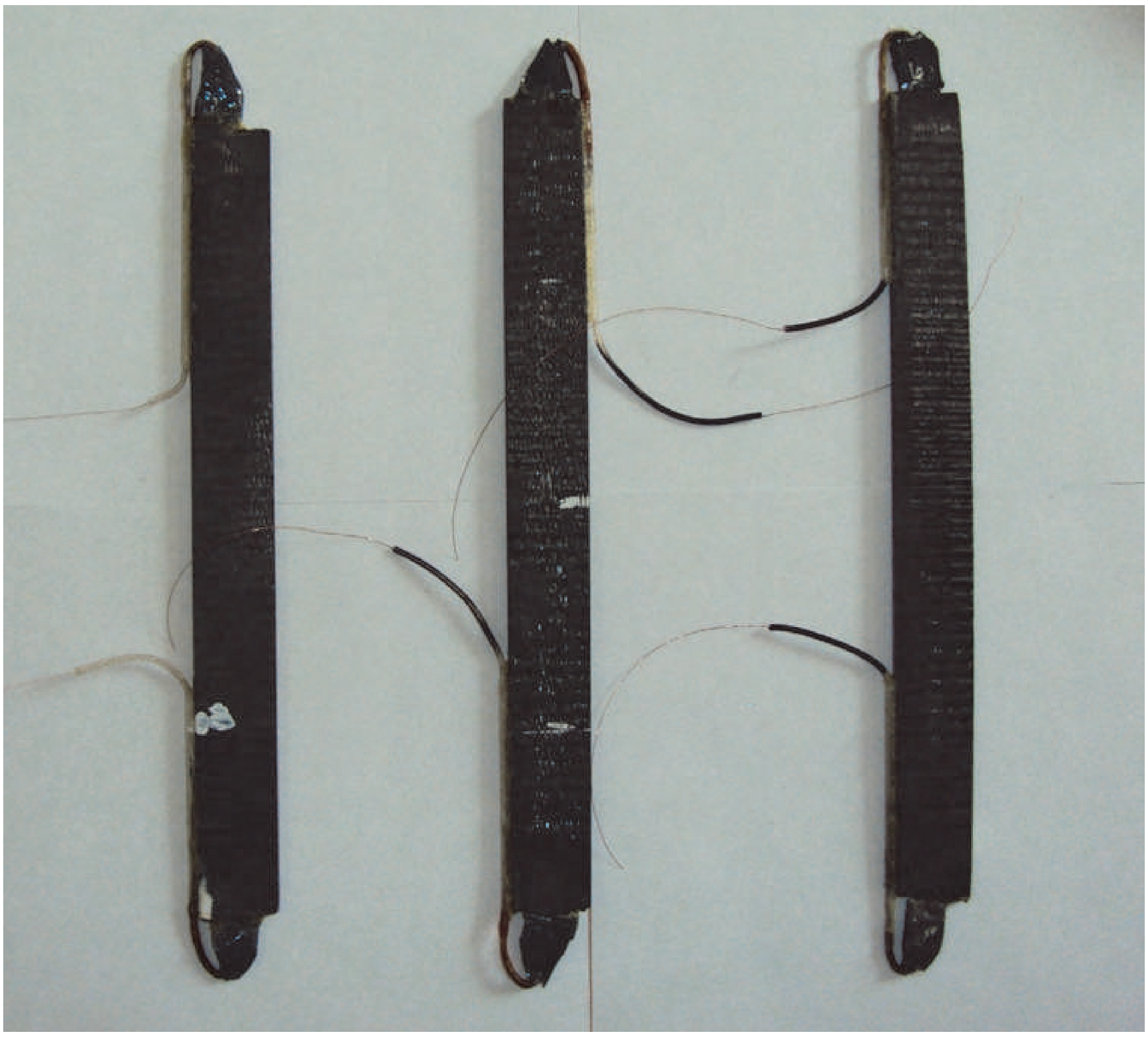


Fig. 9. Textile composite sample containing fibrous piezo-resistive sensor

2.4 On-line measurements of sensor in woven fabric composites - Results

Resultant stress-strain-resistance relationship curve is shown in Fig. 10. It can be observed that the normalized resistance follows the stress-strain curve. The stress-strain-resistance curve can be divided into four regions: *the initial stiff region* - where the composite exhibits toughness against the applied load represented by high slope; *the tows straightening region; the second stiff region* and the *zone of rupture*. The rupture occurred at the strain of 0.52 %, after which the tensile strength tester came back to its initial position at the same speed (5 mm/min). Since the fibrous sensor has not been broken, the normalised resistance ($\Delta R/R$) decreased until zero as the tester returned to its initial position. However this decrease was not linear because the sensor was still intact while the resin-sensor interface was partially damaged which caused its non linear behaviour.

Due to the high difference in yarn densities (24 warp yarns/cm vs. 170 weft yarn/cm), the weft tows are highly crimped. In the initial stiff region micro-cracks start appearing as the composite specimen undergoes traction but the interface at resin and multifilament tows is still intact. That is why the composite exhibits rigid behaviour. In Fig. 10 it can be observed

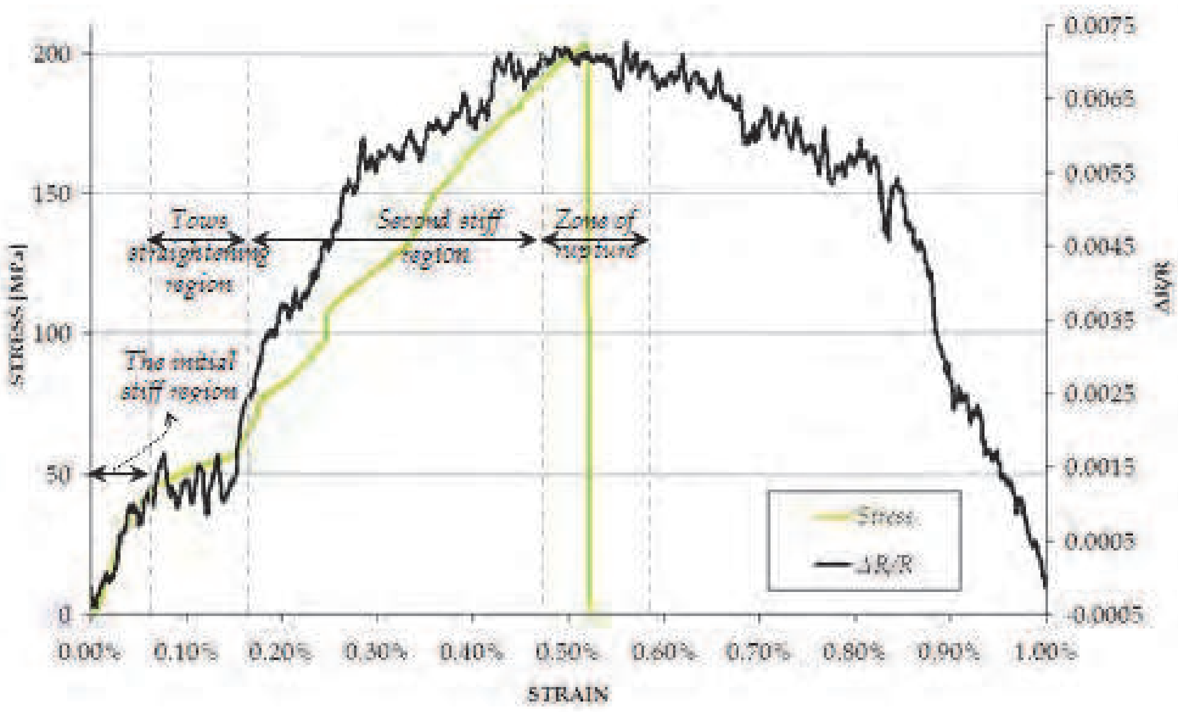
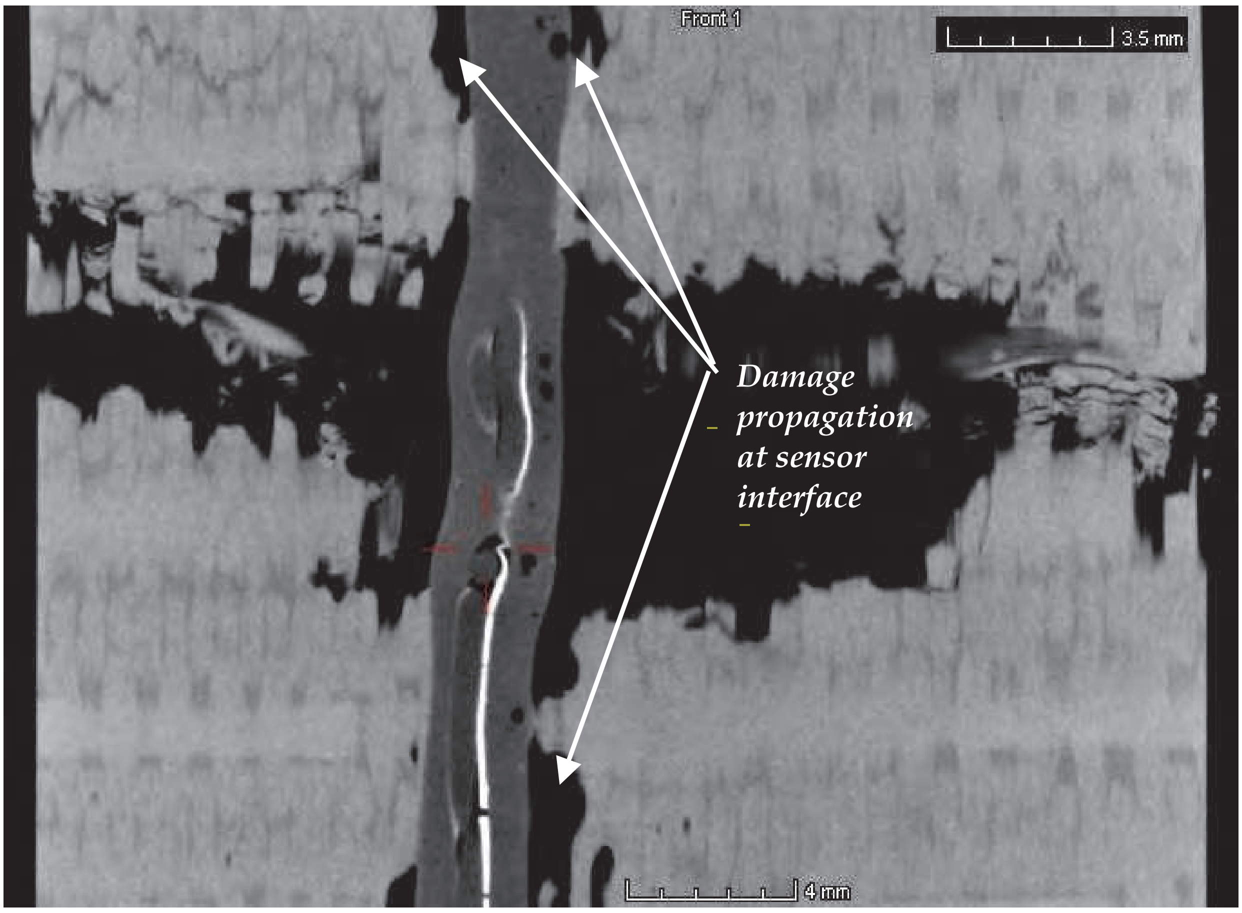


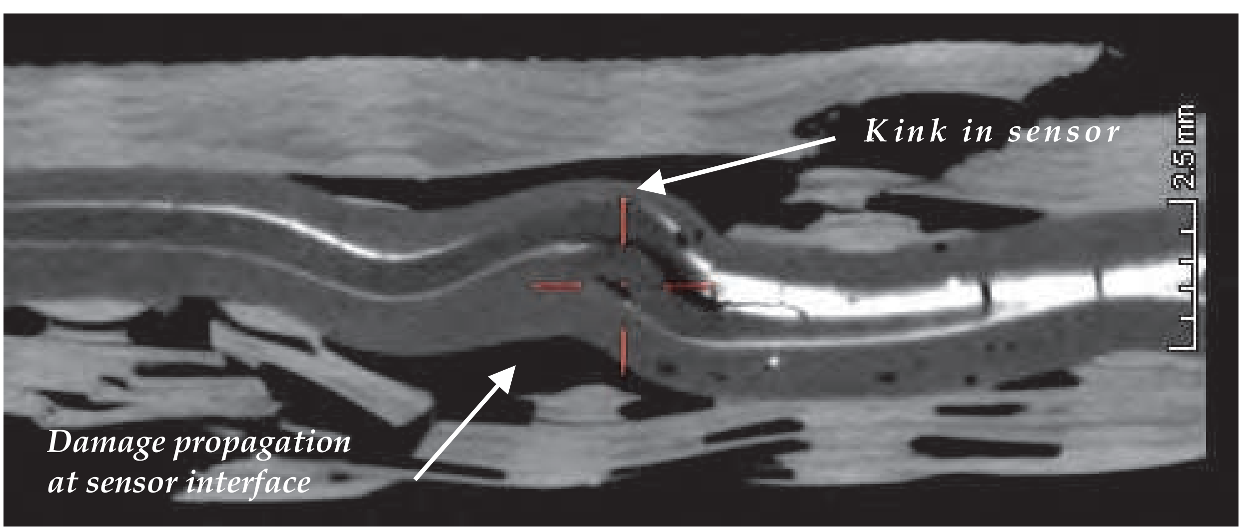
Fig. 10. Normalized resistance and stress against strain for sensor inside composite

that after the initial stiff region the highly crimped tows tend to straighten due to increasing tensile load in the second region. In this region the micro-cracks give way to relative slippage of highly crimped tows in their sockets i.e., the resin-tow interface is relatively weakened. It can also be remarked that the sensor resistance follows the stress strain curve, but in the second region the electrical resistance curve is noisier as compared to other regions of the curve which might signify the slippage of tows as well as the sensor in their sockets. This second region is followed by the third region called the second stiff region where the tows are locked in their sockets. In this region the tows resist the applied load and exhibit stiff behaviour as they regain some of their initial stiffness after the straightening of tows in the second region. The electrical resistance varies almost linearly with the applied load, in this region. The third region is followed by the zone of rupture of the composite in which the electrical resistance, having attained the highest value starts dropping down. The normalized resistance starts dropping after the rupture. The fact that the sensor resistance attains its initial value after the rupture signifies that the sensor, owing to its elastic properties, is not destroyed with the composite. This fact was confirmed by tomographical image of the samples which underwent traction, shown in Fig. 11-a) and b). Sensor cross section and its path at and near the zone of rupture can be observed.

In Fig. 11-a) and b) it can be observed that the sensor-resin interface has a lot of voids. These are caused by poor resin-sensor interfacial properties. The insulating medium on the sensor surface needs to have good adherence with the epoxy resin and carbon fibre reinforcements. Damage that occurred at the main rupture zone has propagated along the sensor boundary giving rise to de-bonding of the sensor. A kink in the sensor can be observed which is caused by the relaxation of sensor as it tries to regain its original dimensions after the tensile loading damages the composite sample. The insulation coating around the sensor renders it thick as well which is undesirable for high performance composite materials as thick insulation coatings might adversely affect the mechanical properties.



a) Frontal view



b) Longitudinal section

Fig. 11. Tomographical images of sensor inside a tested sample near the zone of rupture

3. Heating elements based on conductive polymer composite

The second part of this chapter presents a woven fabric containing an original heating element. Textile actuators like heating fabrics can find applications in numerous and varied fields such as sports, leisure, medical and automotive (Droval et al., 2005; El-Tantawy et al., 2002). In garments, wearability is affected because of the use of metallic components (heating wire and/or heating track on polymer flexible substrate), that are rarely elastic, flexible and lightweight. Nevertheless, these metallic, non-textile elements can be replaced by other conductive fibres such as silver plated polyamide fibres. In that case, the heating textile becomes lightweight, but very expensive (WarmX GmbH). In all the cases, heating systems need heavy power supplies. Thus, it is very important to develop heating textile systems able to work at low voltage.

Our heating element is designed to adapt to woven flexible structures. Additional metallic yarns, used as electrodes, are integrated in a woven structure (or sewn into textile) in a comb-teeth arrangement. Function of these electrodes is to connect heating textile to a power supply and to distribute the current in the conductive coating layer applied on the fabric surface. The comb-teeth electrode arrangement is specially designed to ensure uniform heat distribution. The coating is realized with a composite material based on aqueous latex dispersed with carbon black (CB) as filler. The heating element (comb electrodes and electro-conductive coating) can thus adopt the desired pattern. This is an important aspect of our heating element as it allows integration of the heating element in various fabrics designed for varied and diverse applications.

3.1 Materials and methods

Comb structure was made with stainless steel yarns (2 x 275 x 12 µm from Bekintex®). The average yarn count was 500 Tex, with a resistivity of 14 ohm/m. These yarns were either woven or sewn on an existing fabric. The common feature of all the configurations is that only one comb-teeth structure was used (Fig. 12). The textile fabric was woven on a hand loom (ARM loom equipped with Selectron command box). A plain weave was chosen. Cotton yarns were used in warp and weft having densities of 27 and 10 yarns/cm respectively. The stainless steel yarns were introduced manually during the weaving process according to the pattern (Fig. 12).

Samples with heating surface (*i.e.* L x l in Fig. 12) larger than 180 cm² were prepared. In typical samples, the dimension *L* was about 140 mm while *l* was about 150 mm. In this study, the distance between electrodes (*lp*) remained unchanged: i.e., 20 mm.

The coating was made using a conductive polymer composite (CPC) composed of carbon black (CB, Printex ® L6, Degussa), a synthetic rubber latex solution (Kraton® IR-401, Kraton Polymers) a dispersing agent (Disperbyk®-2010, SPCI) and water.

The preparation procedure is as follows: the dispersing agent is put into water and the CB particles are gradually added while mixing continuously. The polymer is finally added while mixing gently in order to avoid too strong shearing. The coating was then applied on the fabric with a magnetic coating table equipped with a magnetic bar as scraper. 12 samples were prepared with different CB content: 2.5, 5.0, 7.5, 10.0, 15.0, 20.0, 30.0, 35.0, 40.0, 45.0, 50.0 and 60.0 wt.-%. These contents were calculated from the total weight CB + Latex solution. After coating the woven fabric samples were dried at 50 °C for 12 hours. For all the samples, the thickness of the final coating layer was 450 ± 50 µm.

For each coating surface resistivity was measured using four-point probe (MR-1 Surface resistance meter, Schuetz Messtechnik). The aim of these measurements is to determine the percolation threshold and the minimum CB content which allows sufficient electrical conduction for our application.

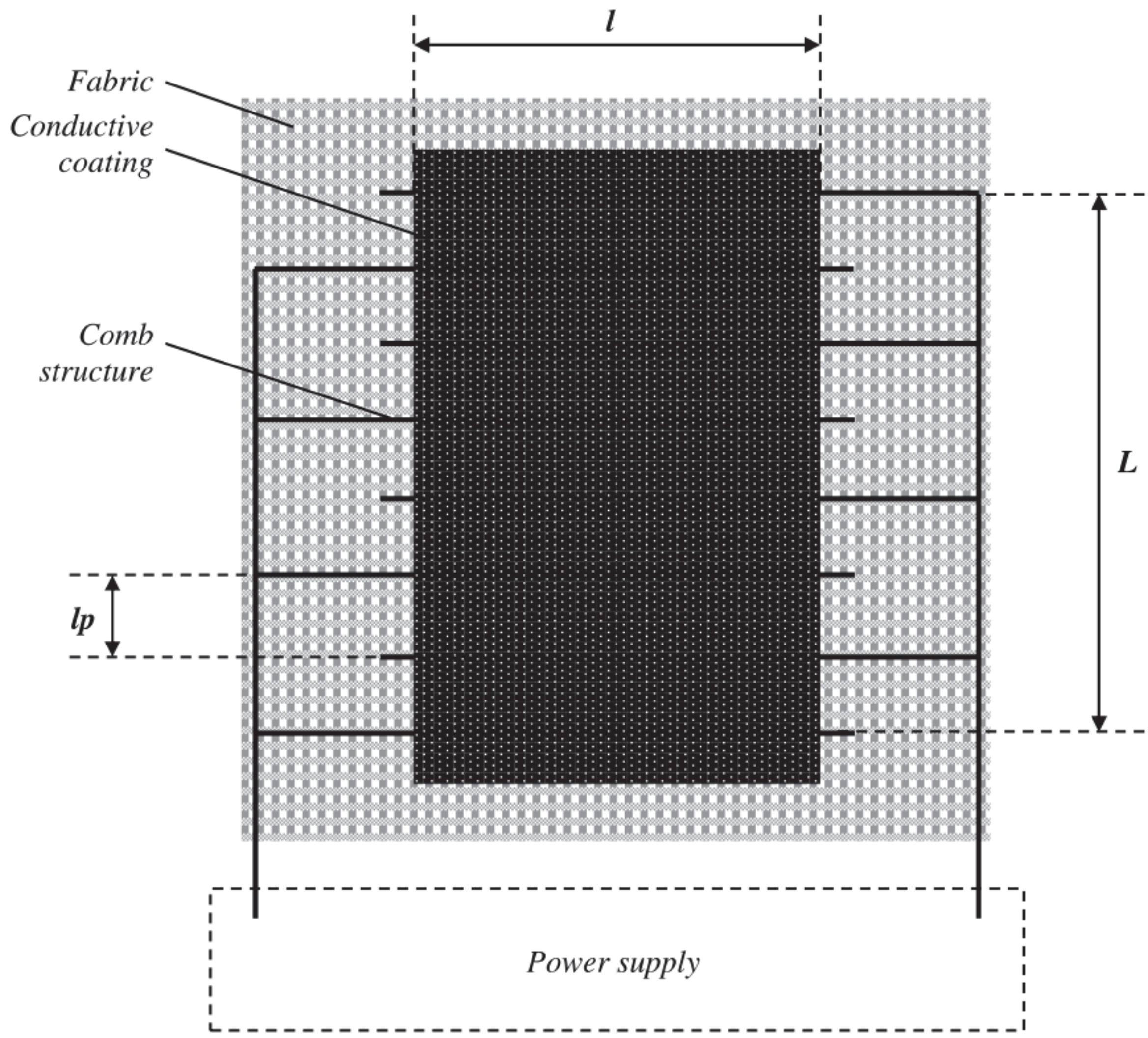


Fig. 12. General structure (comb-teeth pattern and conductive coating) of heating textile element

To characterize heating effect of the samples, 2 processes were used:

- Feeding of the heating element with variable voltage supply (10, 15, 20 and 24 V). The surface temperature was recorded using thermocouple at 15 minute intervals at 5 different locations of the fabric. The average temperature was calculated from 5 measurements. Ammeter was used to determine the power consumption (W) of the heating element. This consumption is expressed in mW/cm^2 (taking into consideration the surface area of each sample),
- Feeding of the heating element with constant voltage supply (15 V) in conjunction with an IR camera (Agema ThermoVision 900). This camera took an IR image every 20 seconds.

3.2 Results

Fig. 13 shows electrical resistivity of coatings plotted against filler (CB) content in the latex solution. As expected, it is possible to identify the percolation threshold from this plot, which lies at 12 ±1 wt.-%. The form of the plot is in accordance with the typical behaviour of systems consisting of percolation networks (Kirkpatrick, 1973).

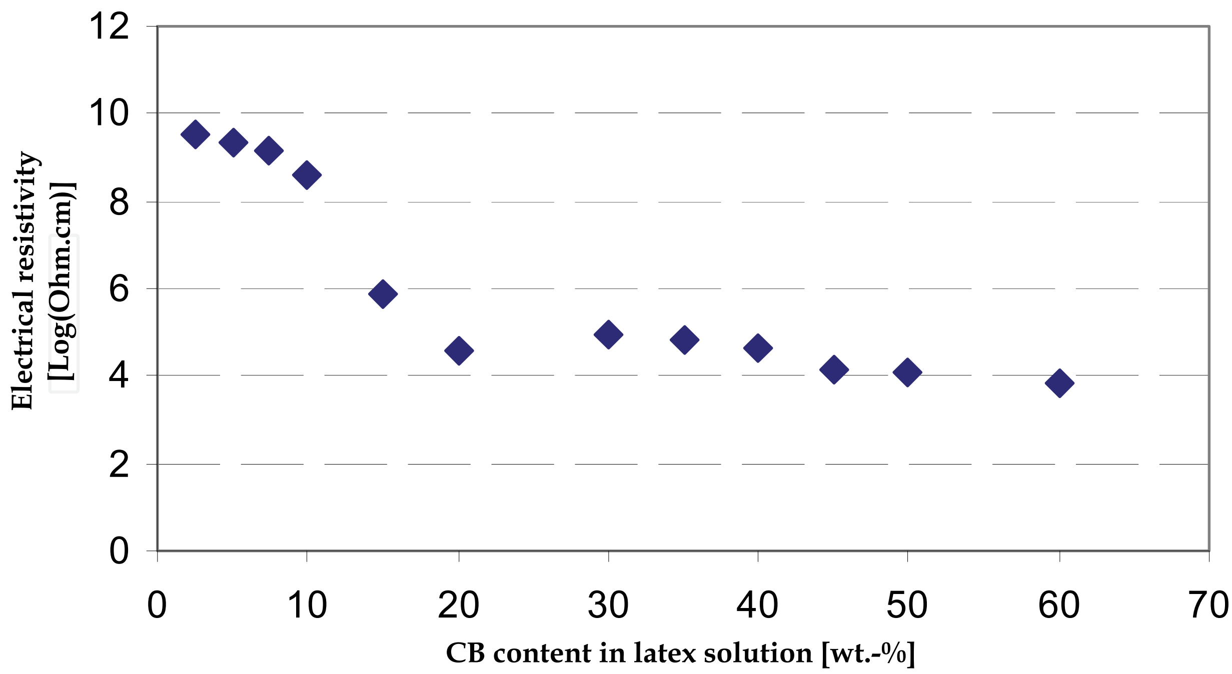


Fig. 13. Electrical resistivity of the coating vs. CB content in the latex solution

This threshold value in wt.-% is expressed for liquid latex solution. Liquid latex contains approximately 63 % of dry material by weight. Thus, the corrected value of percolation threshold is near 18 wt.-%. This value is relatively higher than the value reported in literature for similar systems, (Grunlan et al. 1999, 2001). In our study, process of dispersion (including rupture of CB aggregate) and coating on fabric is not yet optimized. Obtained results show that 15 wt.-% of CB is necessary to obtain à conductive coating. Nevertheless, Fig. 13 shows that between 15 and 40 wt.-% resistivity is not optimal: therefore it is necessary to fill the composite at least by 45 wt.-% to obtain lower resistivity.

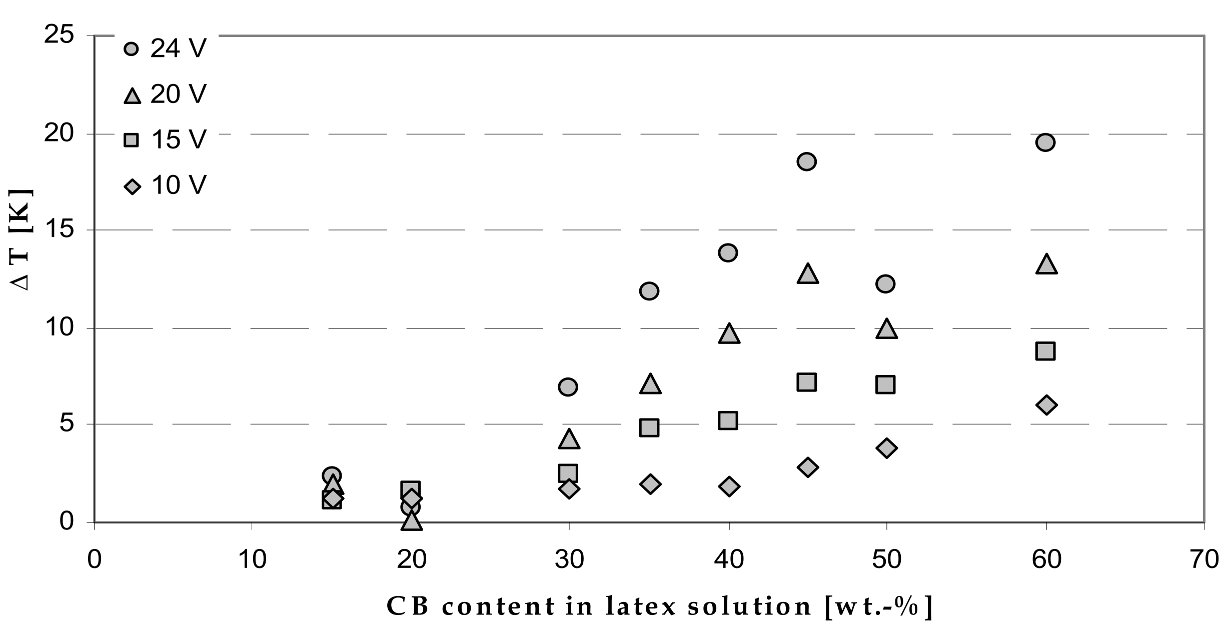


Fig. 14. Surface temperature vs. CB content for feeding voltage of 10, 15, 20 and 24 V

Fig. 14 shows surface temperature of coating plotted against the filler content (in liquid latex) for several feed voltages (10, 15, 20 and 24 V). Temperature on the graph (ΔT) is expressed as difference between measured temperature and room temperature (between 20 and 22 °C). No elevation of temperature was recorded for sample under 30 wt.-% of CB. For CB content between 30 wt.-% and 45 wt.-%, ΔT increases with the CB content. Above 45 wt.-% of CB, ΔT does not increase significantly with filler addition. These results are in agreement with the previous remarks concerning resistivity vs. CB content.
These results show that the best content of CB was, in our case, 45 wt.-%. Under this value heating effect was non optimal. Above this value addition of CB does not increase heating ability.
Maximum value of ΔT (near 20 K) was registered for sample voltages of 24 V and CB content of 45 wt.-% and 60 wt.-%. Fig. 15 shows that for these heating elements, electrical input power was close to 250 mW/cm².

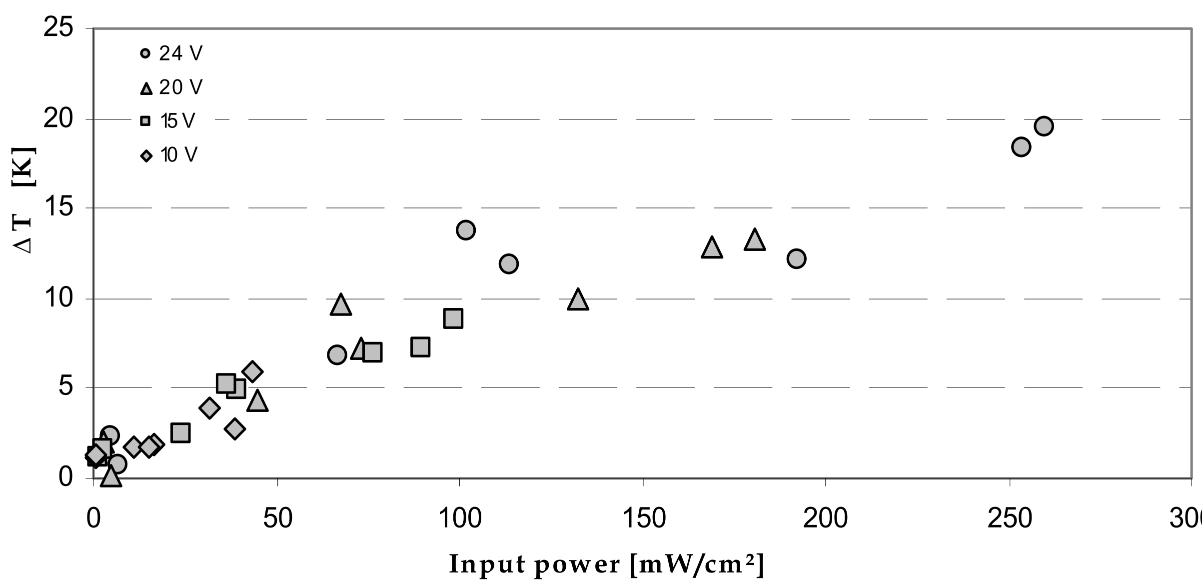


Fig. 15. Increase of surface temperature (ΔT) vs. power consumption of heating element

Infrared images show the distribution of heat in the structure (comb electrodes and conductive coating) vs. time. Fig. 16 shows temperature of sample with 60 wt.-% of CB from t = 0 s (Fig. 16-a) to t = 180 s (Fig. 16-f). Feeding voltage was constant and was equal to 15 V.
Fig. 16 shows that comb structure (stainless steel yarn) heats first after switching on. The maximum temperature of this yarn was about 70 °C. This temperature is achieved after 120 s. CB coating heats relatively slowly but it can be conjectured that after 120 s the temperature of all the surface area exceeds 35 °C while it exceeds 40 °C after 180s. This behaviour is expected since stainless steel yarns have better thermal conductivity than carbon based composite.

4. Conclusion

The sensor based on conductive polymer composite, developed for in situ measurements on carbon fibre based woven fabric composite, is capable of detecting strain in the structure. The electrical resistance variation in the sensor follows the deformation pattern of the composite, mainly due to its sensitivity to its environment and because of the fact that it is

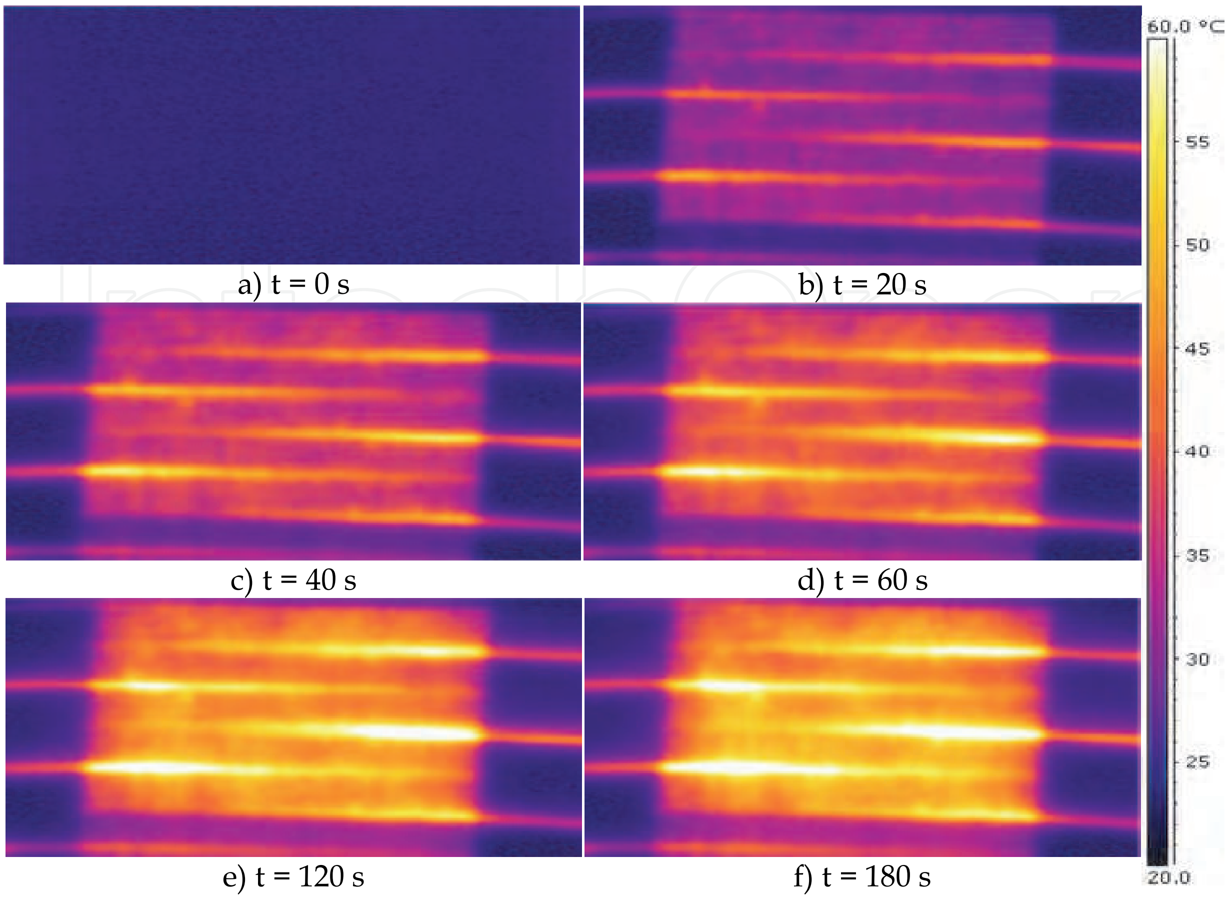


Fig. 16. IR image of 60 wt.-% CB heating element from a) t = 0 s to f) t = 180 s, voltage = 15V

integrated in the structure and follows the fibre architecture of the reinforcement. It has been shown that the integrated textile sensors inside the reinforcement can be used as in situ strain gages for the composite materials. Moreover, if the placement of these sensors inside the reinforcement is carefully chosen, they can be used to follow the local deformation pattern so as to better understand the deformation mechanisms and predict life time of the composite parts. At present the sensors have been tested for tensile loading. Tensile strength tests were chosen to demonstrate the basic features of this novel SHM approach. In the future these sensors will be used for bending and fatigue tests on similar 3D carbon fibre woven reinforcement based composites. However optimisation of sensors needs to carried out in order to prepare finer sensors having negligible affect on reinforcement geometrical and mechanical properties. For carbon fibre based reinforcements which require an insulation coating on the sensor surface, a better and finer coating needs to be applied. In view of the test results presented, it can be concluded that these sensors can be used for in situ health monitoring of various types of composites for industrial applications (aeronautics, automotive etc).

We have also developed a heating element based on original comb-teeth structure (stainless steel electrode) and electro-conductive coating composed of latex and carbon black. Comb structure can be either woven or sewn into the fabric. Final product is flexible and lightweight. This study has show that ideal carbon content of the coating was 45 wt.-% in a latex solution. Our heating elements (about 200 cm^2) allow increasing the temperature (ΔT) by 20 K with low voltages (between 15 and 24 V). Temperature homogeneity of heating

elements is better than those of heating elements made with only stainless steel yarns because in the later case, heat is only produced and localized at conductive yarns. Moreover, our system is cost efficient because we used a few stainless steel yarns.
The next step of this study would allow, in the first place, the optimization of composite preparation (liquid Latex + CB) and secondly the realization of larger heating elements (> 0.5 m²). Potential applications of these heating elements can be found in garments (to improve thermal comfort), in transportation where heating is required for passenger comfort and in certain industrial systems (antifreeze).

5. Acknowledgements

This research was partially financed by Interreg IV via TRITEX (Transfer of Research and Innovations in TEXtiles) program (FLV1.1.1). Special acknowledgments to Textile Department Laboratory from UGENT (Belgium) for electrical measurements (part 3.) and use of IR camera.

6. References

Black, S. (2009). Structural health monitoring: Composites get smart, Composites World, http://www.compositesworld.com/articles/structural-health-monitoring-composites-get-smart

Cochrane, C., Koncar, V., Lewandowski, M., & Dufour, C. (2007). Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. Sensors, Vol. 7, pp. 473-492.

Cochrane, C., Lewandowski, M., & Koncar, V. (2010). A Flexible Strain Sensor Based on a Conductive Polymer Composite for in situ Measurement of Parachute Canopy Deformation. Sensors, Vol. 10, pp. 8291-8303.

Dharap, P., Zhiling L., Nagarajaiah, S. & Barrera, E.V. (2004). Nanotube film based on single-wall carbon nanotubes for strain sensing, Nanotechnology, vol. 15, pp. 379-382.

Droval, G., Glouannec, P., Feller, J.F., & Salagnac, P. (2005). Simulation of electrical and thermal behavior of conductive polymer composites heating elements. Journal of Thermophysics, Vol. 19, No. 3, pp. 375-381.

El-Tantawy, F., Kamada, K., & Ohnabe, H. (2002). In situ network structure, electrical and thermal properties of conductive epoxy resin–carbon black composites for electrical heater applications. Materials Letters, Vol. 56, pp. 112-126.

European Standard NF EN ISO 527-4 (1997), Plastiques - Détermination des propriétés en traction, Partie 4 : Conditions d´essai pour les composites plastiques renforcés de fibres isotropes et orthotropes.

Fiedler, B., Gojny, F. H., Wichmann, M. H. G, Bauhofer, W. & Schulte, K. (2004). Can carbon nanotubes be used to sense damage in composites?, Annales de chimie, 29, p. 81-94.

Gettinger, C.L., Heeger, A.J., Pine, D.J. & Cao, Y. (1995). Solution characterization of surfactant solubilized polyaniline. Synth. Met., 74, pp. 81-88.

Grunlan, J., Gerberich, W., & Francis, L. (2001). Lowering the percolation threshold of conductive composites using particulate polymer microstructure. Journal of applied polymer science, Vol. 80, No. 4, pp. 692-705.

Grunlan, J., Gerberich, W., & Francis, L. (1999). Electrical and mechanical property transitions in carbon-filled poly(vinylpyrrolidone). Journal of materials research, Vol. 14, No. 11, pp. 4132-4135.

Haba, Y., Segal, E., Narkis, M., Titelman, G.I. & Siegmann, A. (1999). Polymerization of aniline in the presence of DBSA in an aqueous dispersion. Synth. Met., 106, 59-66.

Heeger, A.J. (2002). Semiconducting and metallic polymers: the fourth generation of polymeric materials. Synth. Met. No. 125, pp. 23-42.

Kamiya, R., Cheeseman, B. A., Popper, P. & Chou, T.-W. (2000). Some recent advances in the fabrication and design of three-dimensional textile preforms: a review. Composites Science and Technology, Vol. 60, pp. 33-47.

Kirkpatrick, S. (1973). Percolation and conduction. Reviews of Modern Physics, Vol. 45, No. 4, pp. 574-588.

Ko, F. (2007). 3-D textile reinforcements in composite materials, 3-D Textile Reinforcements In Composite Materials. vol. null: Woodhead Publishing Limited.

Krupa, I. & Chodak, I. (2001). Physical properties of thermoplastic/graphite composites. Europ Polym J., 37, pp. 2159-2168.

Kumar, D., & Sharma, R.C. (1998). Advances in conductive polymers. Eur. Polym. J. No. 34, pp. 1053-1060.

Li, C., Thostenson, E. T. & Chou, T. W. (2008). Sensors and actuators based on carbon nanotubes and their composites: A review, Composites Science and Technology, vol. 68, pp. 1227-1249.

Lorussi, F., Scilingo, E. P., Tesconi, M., Tognetti, A. & De Dossi, D. (2005). Strain sensing fabric for hand posture and gesture monitoring, IEEE Transactions On Information Technology In Biomedicine, vol. 9, pp. 372-381.

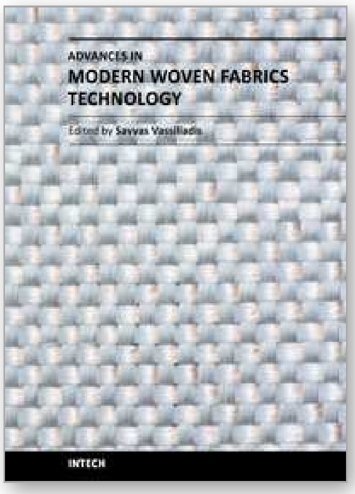
Novak, I., Krupa, I. & Chodak, I. (2002). Investigation of the correlation between electrical conductivity and elongation at break in polyurethane-based adhesives. Synth. Met., 131, 93–98.

Scilingo, E. P., Lorussi, F., Mazzoldi, A. & De Rossi, D. (2003). Strain-sensing fabrics for wearable kinaesthetic-like systems, IEEE sensors journal, vol. 3, pp. 460-467.

Wilson, J. (2004). Sensor signal conditioning, Sensor Technology Handbook. vol. null: Newnes Publishing Limited.

www.nottingham.ac.uk/~emxmns/texgen.htm, consulted on 10/01/2011

www.datasheetdir.com/INA101-Instrumentation-Amplifiers, consulted on 06/05/2010.



Advances in Modern Woven Fabrics Technology
Edited by Dr. Savvas Vassiliadis

ISBN 978-953-307-337-8
Hard cover, 240 pages
Publisher InTech
Published online 27, July, 2011
Published in print edition July, 2011

The importance of woven fabrics increases constantly. Starting from traditional uses mainly in clothing applications, woven fabrics today are key materials for structural, electronic, telecommunications, medical, aerospace and other technical application fields. The new application fields of the woven fabrics is directly reflected in the contents of the book. A selected collection of papers in the technological state-of-the-art builds the book â€œAdvances in Modern Woven Fabrics Technologyâ€. It is written by internationally recognized specialists and pioneers of the particular fields. The chapters embrace technological areas with major importance, while maintaining a high scientific level. This interdisciplinary book will be useful for the textile family member as well as for the experts of the related engineering fields. The open access character of the book will allow a worldwide and direct access to its contents, supporting the members of the academic and industrial community.