Local measurement of dynamic strain of impacted woven structure

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Abstract:

The dynamic behaviour of a woven fabric submitted to a ballistic impact is a complex phenomenon. The dynamic deformations of yarns over time are still unknown both from the experimental and modeling point of view. To overcome this lack of information, a sensor yarn has been developed to monitor the dynamic strain while based on the same raw material as adjacent and close yarns inside the woven structure. This PEDOT:PSS-coated sensor has been developed and characterized both in quasi-static and dynamic modes. The mechanical and electro-mechanical behaviours were characterized in a quasi-static regime and made it possible to access the gauge factor of the sensor yarn. An impact test, corresponding to the dynamic regime, has been performed and has proven the ability of the sensor yarn to detect the transmitted dynamic waves of elongation through the fabric.

Keywords:

Fibrous sensor yarn; PEDOT:PSS, In-situ measurement, Woven fabric

1. Introduction

Many studies have been focused on the description of the woven fabric behaviour subjected to a ballistic impact and have highlighted parameters that can influence its impact performance [1]. During this dynamic event, two damaged zones can be distinguished corresponding respectively to the primary yarns which are directly in contact with the projectile, and the secondary yarns which are linked to primary yarns without being in direct contact with the projectile [2]. These primary yarns are both warp and weft threads directly impacted by the contact surface of the projectile. Due to the weave diagram of the fabric, the secondary yarns absorb the transmitted energy by the primary yarns through the various interconnections between warp and weft yarns. When the projectile strikes the fabric, it generates longitudinal stress waves (in the plane of the fabric) and transverse stress waves (outside the plane of the fabric). Building an analytical model of an impacted woven fabric is complex because of the propagation of the stress wave, which is transmitted and reflected at the crosslinking points of the woven structure [3]. To simplify the impacted fabric model of behaviour, several assumptions can be formulated. The propagation of these stress waves leads to the deformation of primary and secondary yarns in a pyramid shape (also called a cone or tetrahedron) on the fabric surface. The primary yarns along the X and Y-axes (respectively warp and weft directions) are the most mechanically stressed ones. Hence, those primary yarns are the most likely to break during a ballistic impact. Many parameters influence the ability of a fabric to stop a ballistic impact [4]. The weaving pattern [5], the velocity of the impact [6], the angle between the projectile and the fabric surface [7], and the shape of the projectile [8] are some of these main parameters.

The mechanical behaviour of a woven fabric during an impact can also be explained thanks to the complex dynamic behaviour of yarns inside the woven structure. Various testing methods and devices have been developed to characterize a yarn submitted to dynamic stresses: Split Hopkinson Tension Bars [9], Transverse Firing Device [10], Split Flying Bar [11,12], and Yarn Pull-Out Test [13].

Nevertheless, all these experimental techniques allow approaching the dynamic characteristic values of a yarn (dynamic Young's modulus in particular). They also demonstrate the difficulties in carrying out a dynamic characterization, particularly due to the stress concentrations created by the yarn attachment systems.

There are few solutions for real-time measurement in the textile structure under dynamic load. The Fibre Bragg Grating (FBG) is an optical guide, in which modulations of the refractive index according to a specific step (Λ, grating period) come to form a Bragg grating. It has been shown that FBGs are suitable for measuring strain induced by a low-velocity impact in carbon-reinforced composite [14]. Another solution for real-time monitoring is a sensor yarn. Sensor yarns find multiple applications [15]. The measurements made using sensor yarns are based on variations in electrical resistance, induced by the deformation of the yarn. Piezo-resistive sensor yarns are the combination of a substrate (a thread) and a conductive polymer. This type of sensor yarn has been able to measure the dynamic stresses that warp yarns undergo during weaving [16]. This sensor wire is composed of an E-glass yarn coated with a PEDOT:PSS conductive polymer solution. Copper wires connect piezo-resistive coating to an acquisition system. These produced sensor yarns have a resistance of 100 kΩ for a K-gauge factor between 1 and 1.5 (at 1% elongation). The acquisition system receives a variation in electrical resistance from the sensor yarn and it then allows the monitoring within a composite structure [17]. The 3-points bending behaviour of a composite was tracked by the insertion of 2 piezo-resistive sensor yarns into the reinforcement [18].

An in-situ measurement could be a solution to fill the information gaps about the dynamic behaviour of impacted woven fabrics. This measurement must be performed by a sensor yarn to disturb as little as possible the local behaviour of the woven structure. The main objective of the present work is to develop a sensor yarn with the same properties as a thread used in a ballistic structure so that the dynamic strain can be detected during an impact.

2. Materials and Methods

2.1 Sensor yarn materials

A para-aramid yarn (Twaron©) of linear density 930 dTex has been chosen as the structural yarn due to its use in existing ballistic protection solutions. A twisting value of 25 twists/meter has been fixed to give cohesion to the multifilament, without altering its mechanical properties. This yarn twisting allows making easier to manipulate and attempts to be more cohesive. The conductive coating part of the piezo-resistive sensor yarn has been designed to perfectly transfer the mechanical load from the filament to the yarn without any slippage or delamination. Thus, to ensure the best adhesion from the multi-filaments yarn to the coating, a process of impregnation has been done with the Polyvinyl alcohol polymer from Sigma-Aldrich (Saint-Louis, Missouri, USA). Polyvinyl alcohol (PVA) is used to form a regular film and fill the pores of the yarn structure. The connections are the junction between the sensor and the acquisition system that performs the measurement. A copper multi-filament wire has been selected to perform this function thanks to its excellent electrical conductivity. The use of a copper multi-filament instead of a monofilament allows maximizing the surface of contact with the conductive coating. The electrical resistance at 20°C of the copper multi-filament used is equal to 6.046 $\Omega.m^{-1}$ [19]. The conductive coating is Clevios F020 from HeraeusTM (Hanau, Germany) and was based on an intrinsically conductive polymer PEDOT:PSS. A uniform thin layer of 4 µm thickness provides a surface resistance that does not exceed 2500 $\Omega.m^{-2}$. Its drying temperature is between 80°C and 120°C during 3 to 5 minutes process [20].

2.2 Production method of sensor yarn

To produce the sensor yarn, the structural yarns have been stretched during the pre-coating and coating phases on dedicated frames designed to accommodate several threads together, corresponding to one batch. During the first step, the PVA solution is applied to each yarn over 20 mm long. It can be noticed that since the PVA is largely absorbed by capillarity, the final length of the pre-coating is 45 mm. The frames are placed in an oven (Memmert UF 110 plus) for 60 minutes at 80°C to evaporate the water from the PVA solution. The second step is to set up the connections on each pre-coated yarn. The aim is to ensure the most complete contact surface possible with the conductive coating to allow the optimal electrical measurement. Six spires are formed on one end of the copper multi-filaments, from right to left. The distance between the two connectors is set at 25 mm and corresponds to the sensor length. The final step is to apply the conductive coating (Clevios F020) on the PVA impregnated yarn. The conductive coating is deposited in 3 layers using a fine brush. Each layer is applied on and between the connectors as homogeneously as possible. Between each layer, the deposited Clevios F020 is dried in the oven. The drying temperature was set at 120°C for 3 minutes and 30 seconds for the first two layers, and 130°C for 5 minutes for the last layer. The produced sensor yarns are dried for 24 hours on their frame. Figure 1 presents the arrangement of all the elements of the sensor yarn.

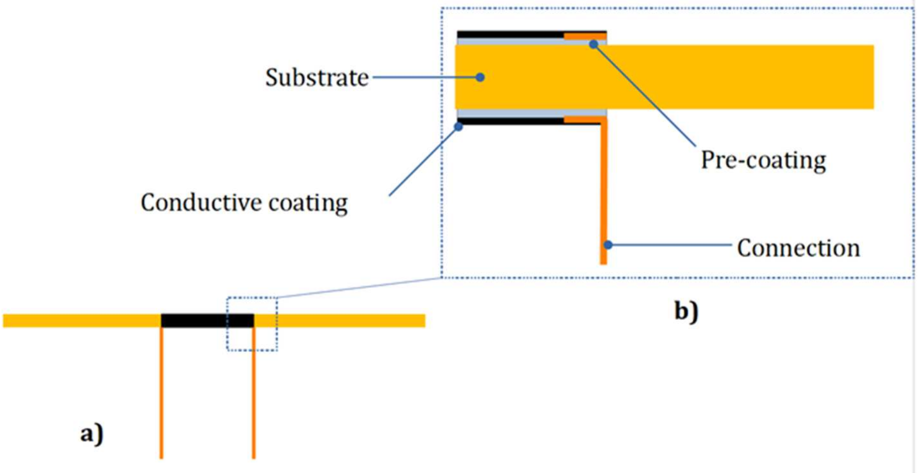

Figure 1. Schematic arrangement of the constituent elements of the sensor yarn a) global view b) longitudinal sectional view

2.3 Mechanical and electromechanical characterisation methods

A 1906 Multimeter Computing from Aim-TTI (Cambridgeshire, United Kingdom) was used to measure the electrical resistance of sensor yarns batches. These measurements were made with grip-wire clamps directly on the connectors (copper multifilament) of the sensor yarn. R0 is the initial electrical resistance measured 24h after the production. All the results presented in the present work were produced following this method. A Criterion Model 43 MTS (Eden Prairie, Minnesota, USA) bench has been used to perform tensile tests. The bench is controlled by the MTSElite software, which allows to set up testing and data acquisition. The frequency of data acquisition was set to 100 Hz for all trials.

A USB-6003 from National InstrumentsTM (Austin, Texas, USA) acquisition system was used to measure and record electrical data for electro-mechanical testing. This system is controlled by the DAQExpress software. However, this acquisition system is not able to directly measure the electrical resistance variations of the sensor yarn. Then, a voltage divider bridge has been set up to continuously measure the voltage at the sensor terminals. The complete electrical data acquisition system includes the in/out acquisition system and associated software, a resistance box, and a trigger. The function of the resistance box is to balance the voltage divider bridge, *i.e.* to obtain a Vs output voltage at the terminals of the sensor yarn equals to 2.5 V (the Ve input voltage being

5.0 V). The layout of the voltage divider bridge is represented by R_1 the resistance box and R_2 the electrical resistance of the sensor yarn. The trigger synchronizes the acquisition of electrical data with mechanical data. The DAQExpress software allows starting an acquisition with a "StartTrigger" command. The physical quantity measured by the acquisition system during the electromechanical testing is an electrical voltage. To access electrical resistance, the divider bridge formula is used. Each Vs value collected during an electromechanical test is converted to an R_2 value. These resistance values are then smoothed using an R-order moving average statistical method. The objective of this moving average (over 20 consecutive values) is to reduce noise, smooth the data and observe the electrical resistance variations of the sensor yarn more easily. Once the voltage data is processed, the ratio of the R_2 resistance (R_2 - R_0) to the initial R_0 resistance is calculated for each R_2 value as given in Equation 1:

$$R_2 = \frac{Vs}{(Ve - Vs) \times R_1}, \quad (1)$$

where Vs is the output voltage measured at the sensor yarn terminals, Ve is the input voltage (5.0 V), R_1 is the electrical resistance of the resistance box, and R_2 is the electrical resistance of the sensor yarn.

3. Results

3.1. Production and calibration of sensor yarn

3.1.1. Mechanical characterization of sensor

Table 1 shows the statistical results concerning the strain and the strength at the break for the substrate and the produced sensor yarn. These measurements have been made on 10 samples each.

Table 1. Statistical results concerning the strain and the strength at break of the substrate and the produced sensor yarn

	Substrate (Twaron© 930 dTex)	**Sensor yarn**
	Strain at break (%)	
Average	4.92	5.59
Standard deviation	0.22	0.31
CV%	4.47	5.49
	Strength at break (N)	
Average	200.00	175.78
Standard deviation	4.01	4.85
CV%	2.00	2.76

3.1.2. Electromechanical characterization in static regime

Electromechanical characterization provides access to the sensor's gauge factor, measurement range, and resolution. The initial resistance R_0 of the sensor is important data to calculate the gauge factor. On average, the initial resistance of the sensor yarn in the present work is 0.72 ± 0.15 kΩ (over 66 sensor yarns). The gauge factor k is the coefficient of proportionality that exists between strain and variation in electrical resistance governed by Equation 2:

$$k = \frac{\Delta R/R_0}{\varepsilon} \qquad (2)$$

where ε is the strain, ΔR is the resistance variations, and R_0 is the initial resistance. It has been calculated by linear regression. The measurement range refers to the extreme values that can be measured by the sensor. The resolution is the smallest variation in magnitude that can measure the sensor (the strain in this case). A batch of 11 sensors was produced for electromechanical testing. A test is considered as failed if the sensor slips from the clamp or if it breaks too far from the sensitive coating. Only five sensors were able to obtain useful electromechanical data.

Table 2. Statistical results on electromechanical behaviour of sensor yarns

	Strain at break (%)	**$\Delta R/R_0$ (%) at break**	**Minimum strain (%)**	**Gauge factor *k***
Average	5.35	11.27	0.78	3.31
Standard dev.	0.07	2.38	0.08	0.34
CV%	1.35	21.13	10.17	10.37

Table 2 presents statistical results on the electromechanical behaviour of sensor yarns. The gauge factor was calculated by linear regression. The sensor yarns in this batch have an average gauge factor k of 3.31 ± 0.34 and represent the coefficient of proportionality between electrical resistance and deformation. The higher the k factor, the more sensitive the sensor is.

3.2 Dynamic characterization

To perform an impact test, a drop tower bench equipped with a normalized knife has been used. The total mass of 1,5 kg with the knife falls from a height of 30 cm and strikes the tested woven fabric at a speed of 1 $m.s^{-1}$ measured by two magnetic sensors. The tested fabric has been extracted from a 3D warp interlock fabric with 5 layers (O-L 3 4-2 {Twill 5 Weft effect}) and made with para-aramid yarns. A sensor yarn has been manually inserted in the weft direction in the last layer of the 3D warp interlock fabric. The 3D fabric coupon equipped with the sensor yarn has been located under 6 plies of 3D fabric to avoid any perforation. Thus, the last layer of 3D fabric equipped with the sensor yarn can be suddenly deformed. The electrical resistance of the sensor has been measured using the setup described above. The data frequency acquisition has been set up at 1 kHz.

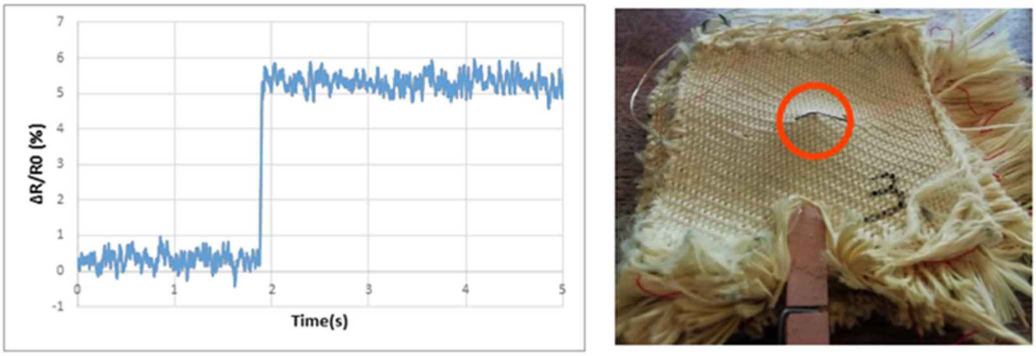

Figure 2. Variation of the electrical resistance of a sensor impacted on its conductive coating (on left). In the orange circle, the location of the impact (on right).

Figure 2 shows the variations of electrical resistance and the impact location of a sensor inserted into 3D fabrics. Before the impact of the knife, the sensor has a stable variation of electrical resistance near 0%. When the sensor yarn is impacted directly, the electrical resistance varies from 0% to 5% (Figure 2). As the conductive coating of the sensor yarn is deformed, the electrical resistance stays stable after the impact.

3.3 Multi measurements tests

Sensor yarns have been woven in the weft direction in a Twill 2-2 weave. The Twill 2-2 has been selected because of its crimp and its high number of crosslinking points of the woven structure. To keep the initial properties of the sensor yarn safe, the warp threads on the loom have been loosened (between 50 cN and 80 cN). The fabric equipped with a sensor yarn is woven with Twaron© 930 dTex threads with a twisting value of 25 twists/meter. The warp density of the equipped fabric is 8 yarn/cm. The equipped fabric is tested with the same drop tower bench used for the dynamic characterization of the sensor yarn.

3.3.1 Case 1: parallel sensor yarns located in the fabric plane

The first multi-measurement test has been carried out with fabric equipped with two sensors. Those two sensors have been inserted as weft threads and separated from a distance a. Three values of the distance a (Figure 3) have been set up: 1 cm, 2 cm, and 4 cm.

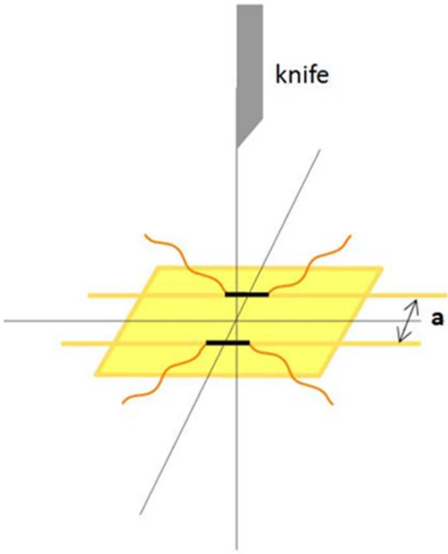

Figure 3. Woven fabric equipped with two sensor yarns separated from a distance a, and location of the knife used during the test

Figure 3 shows the location of the impact and the distance a. Three equipped fabrics have been woven and tested for each distance a. The tests carried out on fabrics with distance a fixed at 1cm gave no satisfying results. This is because the sensors were too close to the impact location. Moreover, the drop tower bench does not allow to precisely target the impact location. Consequently, some sensors were not deformed by the stress waves but deteriorated. Figure 4 and Figure 5 show the variations of the electrical resistance of impacted parallel sensors with the distance a respectively equals to 2 and 4 cm. The tests carried with a distance between the sensor yarns equal to a = 2 cm gave average values of electrical variation equal to 9.27 ± 0.23% after the impact. The tests carried with a distance between the sensor yarns equal to a = 4 cm gave a value of the variation of electrical resistance equals to 3.21 ± 0.71% after the impact.

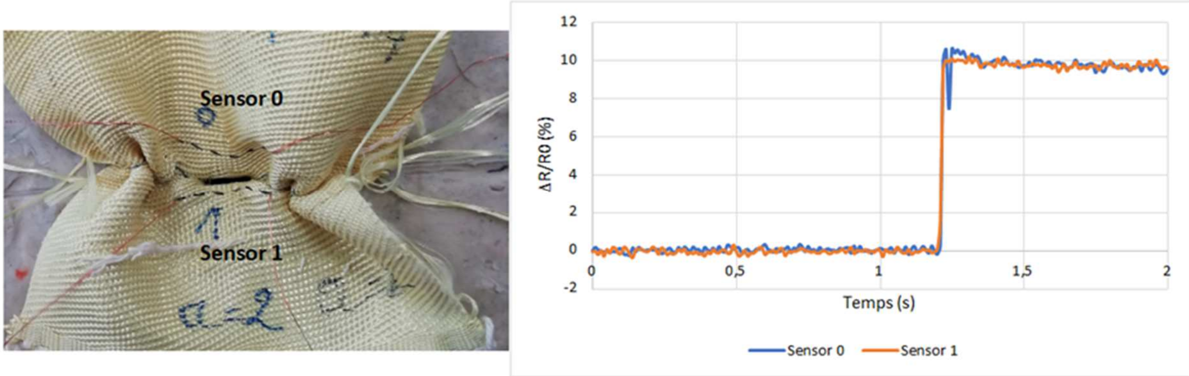

Figure 4. On the left, the location of the impact on the equipped fabric. On the right, variations of the electrical resistance of impacted parallel sensors (a = 2 cm)

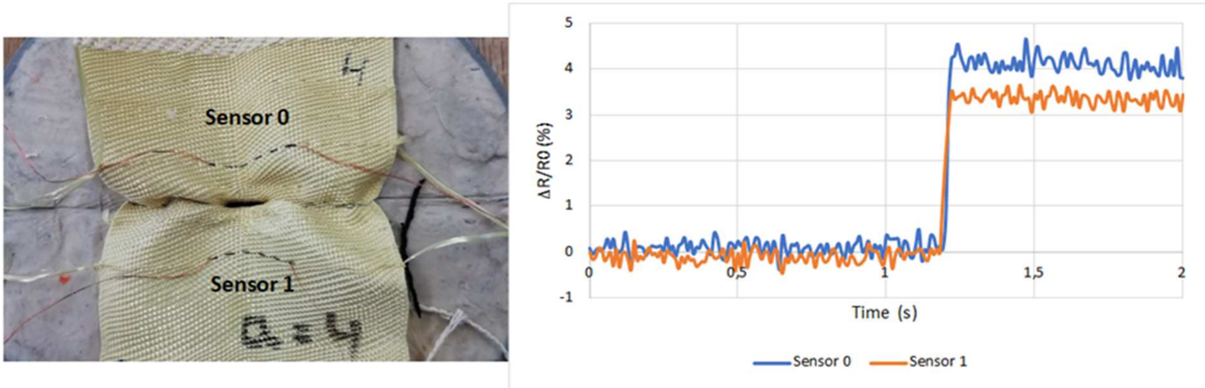

Figure 5. On the left, the location of the impact on the equipped fabric. On the right, variations of the electrical resistance of impacted parallel sensors (a = 4 cm)

3.3.2 Case 2: sensor yarns located in the fabric thickness

The second multi-measurement test has been carried out with two woven fabrics equipped each with one sensor yarn. The equipped fabrics are separated by 10 layers of fabric. The fabric used is a plain weave made with 3300 dTex para-aramid yarns from Twaron©.

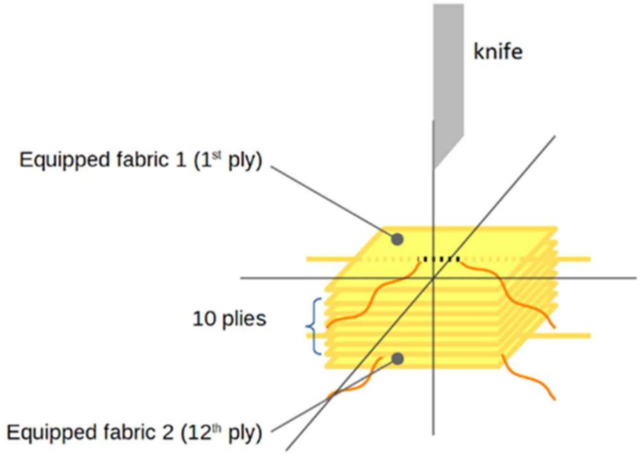

Figure 6. Location of the equipped fabrics

Figure 6 illustrates the location of the plies and equipped fabrics. The knife has been dropped at 1 cm from the upper sensor yarn. The thickness of 10 layers of Twaron© is equal to 6.49 ± 0.11 cm. The data frequency acquisition has been set up at 10 kHz. Three tests have been realized. Figure 7 illustrates the obtained results for one test.

The slopes of each test have been calculated by linear regression.

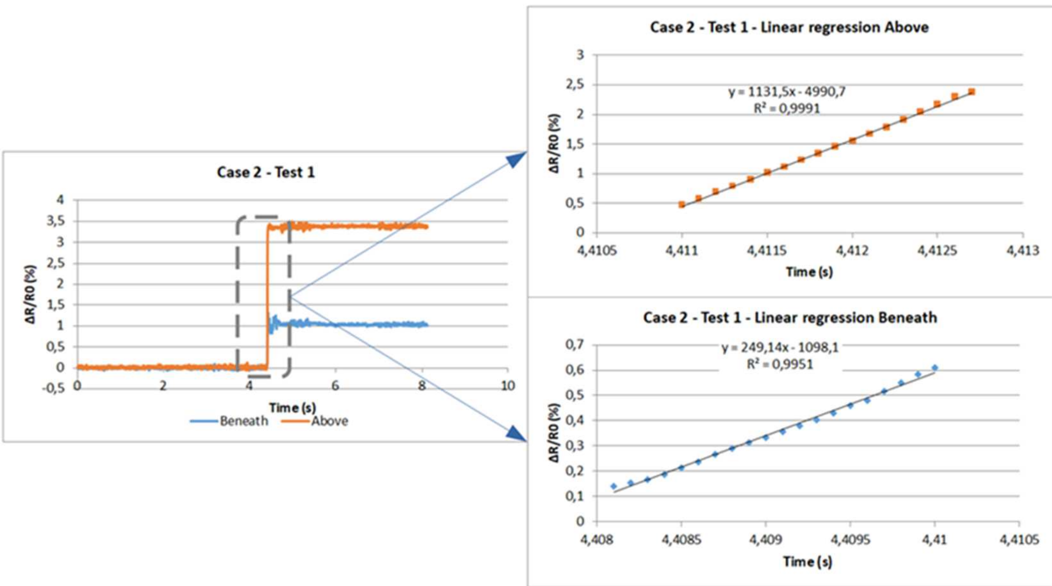

Figure 7. Variation of the electrical resistance during a test (left) and linear regressions (right)

The ratio of the slopes "above" and "beneath" was then calculated. This ratio tends to explain the variation in speed of the electrical resistance between the sensor yarn located on the top compared to the sensor yarn located at the bottom. Table 3 shows the values of the different coefficients for each test.

Table 3. Values of the slopes for each test with sensors located through the thickness

Test	**Slope "above"**	**Slope "beneath"**	**Ratio (%)**
Test 1	1131.50	249.14	-77.98
Test 2	1183.70	358.29	-69.73
Test 3	134.1	29.86	-77.73

The values of the slopes for Test 3 are less important than Test 1 and Test 2 because the knife has been dropped further away from the sensor yarns.

4. Discussion

The sensor yarn designed in the present work has been characterized as the static range. The static gauge factor of the sensor yarn has been determined at 3.31 ± 0.34 and its resolution is 0.78 ± 0.08% of strain. In the work of Trifigny *et al.*, the static gauge factor was ascertained between 1 and 1.5 at 1% of strain [16]. Thus, the characteristics of the sensor yarn produced in the present work are closed to those from Trifigny *et al.* [16]. The gauge factor is comparable with that found in studies about similar sensing materials [21] or on textile substrate [22]. The used para-aramid yarn sees its mechanical behaviour changes slightly (Table 1). The strength at break of the sensor yarn decreases by 12.11% whereas its strain at break increases by 13.61%. This is mainly due to the pre-coating because PVA has a tensile strength of 48.4 MPa and strain at the break of 220.7% [23].

For the multi measurements tests, the sensor yarn has been woven into a structure. As the tests gave useful data, the designed sensor yarn is still able to detect after the weaving process.

The multi measurements tests carried in Case 1 (two sensors in parallel) gave results on the ability of the sensor to detect the stress wave in the impacted fabric plane. The parallel sensor yarns were woven as secondary yarns. For the secondary yarn, the closer to the impact location is, the more stressed these yarns are [2]. This was observed at two distances from the impact location. The closest sensor yarn from the impact location (a

= 2 cm) had average values of electrical variation equal to 9.27 ± 0.23% after the impact whereas the farthest (a = 4 cm) had an average electrical variation equal to 3.21 ± 0.71%. Moreover, the pair of sensor yarn, for the same distance value of a, has detected similar deformation.

The multi measurements tests carried in Case 2 (two sensors located through the thickness) gave results on the ability of the sensor to detect transverse stress waves (outside the plane of the impacted fabric). The calculated slopes show that the sensor yarn located on the top is deformed more quickly than the one located on the bottom. This result seems to make sense since the sensor on the top is impacted by the blade at 1 $m.s^{-1}$ (maximum blade speed). Then the blade strikes the 11^{th} ply after puncturing 10 plies of woven fabric. Consequently, the blade is slowed down, and the velocity of the impact on the 11^{th} ply (equipped with a sensor yarn) has changed [6]. As a result, the slope of the bottom sensor yarn is smaller than the slope of the top one. The ratio of the slopes is between -69.73% and -77.98% and shows the decreasing of the variation in speed of the electrical resistance. Other tests should be carried out with different distances (*i.e.*: different fabric plies) between the sensors both located on the top and bottom.

Concerning the future research directions, there are several axes envisaged. First, the impact speed should be increased. Indeed, the purpose of this sensor yarn is to detect the stress generated by a ballistic impact. Moreover, the dynamic gauge factor must be established to describe the deformation at stake during an impact. The batches of sensor yarn presented in the present work were fully made by hand. This is a long and quite laborious process that could be easy. As an example, the connections could be produced with a hollow spindle machine.

5. Conclusions

The main goal of the present work was to develop a sensor yarn for in situ and local measurements during an impact. The sensor yarn is designed to have mechanical properties close to a thread used in a ballistic structure and to detect the dynamic strain. The developed sensor yarn is made with several components like a 930 dTex para-aramid yarn for the substrate, a PVA polymer for the pre-coating, a copper multifilament for the electrical connections, and PEDOT:PSS for the conductive coating. The static gauge factor (k) of the sensor yarn has been determined at 3.31 ± 0.34. The resolution of this sensor yarn has been ascertained at 0.78% of strain. A test with a low speed of impact (1 m.s^{-1}) has been set up to test the sensor yarn into impacted 3D fabric. The developed sensor yarn can monitor accurately at this speed range. In future work, strain rates must be increased to determine the dynamic gauge factor so that sensor wire measurements can describe the strains involved in impacted woven fabric. Our wish is to gradually increase the speeds (for the calculation of the gauge factor and the impact) to verify the capacity of the sensor yarn developed to detect the stress generated by a ballistic impact.

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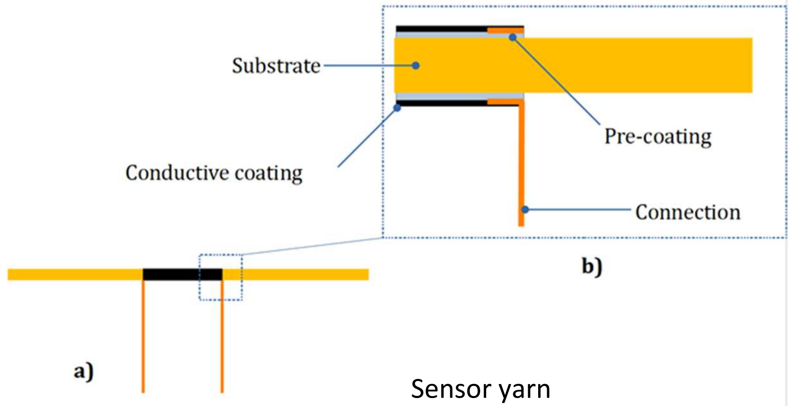
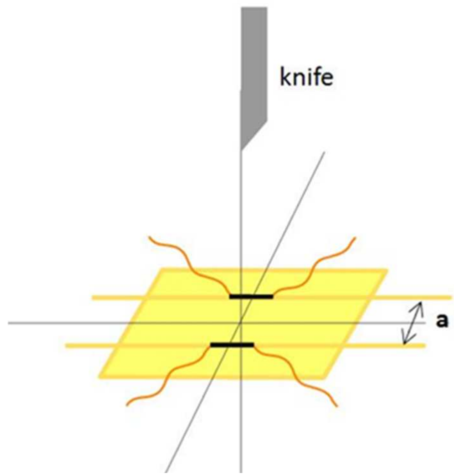
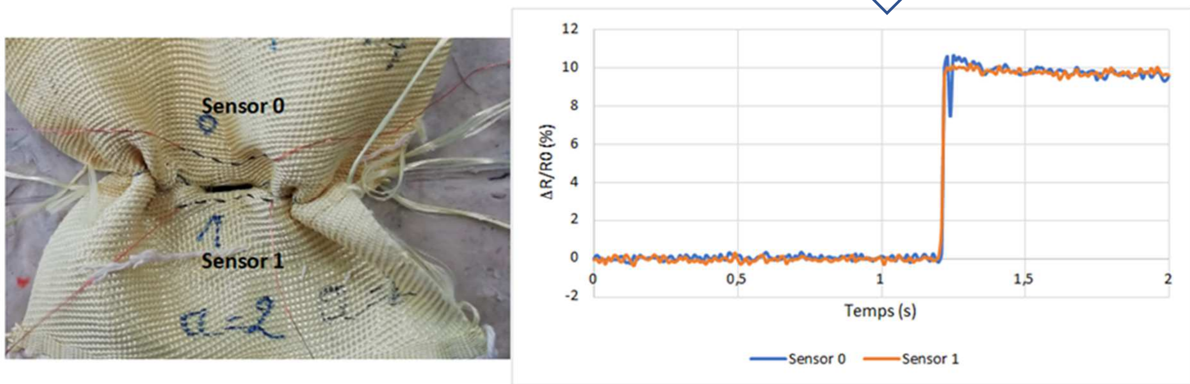


Sensor yarn



Inclusion of sensors in woven fabric for knife impact test



Result of knife impact test