Structural Health Monitoring of Composites with Newly Developed Textile Sensors In Situ

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Abstract Smart textile structures are promising solution nowadays for in situ structural health monitoring of composite parts that have important place in transportation industry. Composites made from a polymeric matrix and a fibrous reinforcement have been increasingly studied during the last decade. Conductive yarns as textile sensors can be integrated in textile structures by diverse technologies and crucial issue is that sensors integration does not modify their general behavior. In this work interest is focused on the structural health monitoring of textile reinforced thermoplastic composites with newly developed textile sensors in situ based on the conductive polymer complex poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS).

Keywords—Smart Textile, Structural Health Monitoring, Textile Reinforced Composites, Textile Sensors

I. INTRODUCTION

SMART textile structures are promising solution nowadays for in situ structural health monitoring of composite parts that have important place in transportation industry [1]. Composites made from a polymeric matrix and a fibrous reinforcement have been increasingly studied during the last decade [1-3]. In composite applications, the low material density is of environmental interest because fuel consumption and CO2 emissions are directly related to vehicle weight [4], [5]. Conductive yarns as textile sensors can be integrated in textile structures by diverse technologies [6]. Textile sensors inside the textile reinforcements have to present all the characteristics of traditional textile materials: flexibility, lightweight and capability of adopting the geometry of the reinforcement. Therefore, it is important that sensors integration does not modify their general behavior [7], [8]. Textile materials are very flexible and easily deformable in all directions, and sensors used should be able to support, often all at the same time, tensile, shear, bending and even compression deformations [7], [9], [10]. Researches on electroconductive textiles and related up graded composites prepared from conductive polymers such as Polypyrrole (PPy), Polythiophene (PT), Polyaniline (PANI) and Poly(3,4-ethylenedioxythiophene) (PEDOT) are developing quickly in the recent years due to their optimal compromise among electrical conductivity, stability, processability and high potential applications in different fields [11-13].

In this work interest is focused on the structural health monitoring of textile reinforced thermoplastic composites with newly developed textile sensors in situ based on the conductive polymer complex poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS).

II. METHODS AND PROCEDURES

E-glass/polypropylene (GF/PP) and E-glass (GF) yarns by PD Fiberglass group (Glasseiden GmbH, Oschatz, Germany) were used for textile sensors production. Finess of GF/PP commingled yarn is 842 tex (with GF/PP mass content of 71%-29%), while fineness of GF yarn is 830 tex. Conductive coating for yarn treatment was defined according to the study of percolation threshold of the polymer complex PEDOT:PSS. The percolation threshold determination was based on conductive dry films’ electrical properties analysis to develop highly sensitive sensors [1]. A novel piece of laboratory equipment based on a conceptual design was taken to ensure effective and equally distributed coating of electroconductive polymer without destruction of textile properties [1]. Aluminum roll to roll device and plexiglass bath were used for textile sensors production needed for in situ structural health monitoring of composites during tensile loading [14]. GF/PP and GF textile sensors (Fig. 1) were integrated during weaving 2D fabric, 4-end satin (warp density, 4 ends/cm and weft density, 6 ends/cm), thickness ~2.660 x 10^{-3} m, in weft direction using computer controlled ARM hand weaving loom (Biglen, Switzerland).
Three-layered textile preforms with integrated textile sensors (Fig. 2) were consolidated at the Dolouets heating press (Soustons, France) under the pressure of 4-5 MPa and the temperature of 185 °C during 5 minutes followed by cooling at 100 °C in 2-3 minutes. The dimensions of developed composites were 21 cm x 8 cm x 0.15 cm.

The tensile measurements of composites were performed on the Instron 5900 (Norwood, USA) testing machine with a speed of 2 mm/min and 115 ±1 mm difference between clamps. Electrical resistance measurements were carried out simultaneously. Keithley® KUSB-3100 data acquisition digital I/O counter/timer and two resistance boxes were connected to a computer (QuickDAQ software) to record the electrical resistances of two textile sensors integrated in each composite specimen during tensile loading in situ.

III. RESULTS

A. Electrical Resistance of Textile Sensors After Production and Insertion in 2D Fabrics

Electrical resistance of textile sensors (Table 1 and 2) after production is in range between 350 Ω - 500 Ω for GF/PP textile sensors while 330 Ω - 880 Ω for GF textile sensors. Electrical resistance of textile sensors after insertion in 2D fabrics is slightly higher compared to results after their production. It is in range between 390 Ω - 550 Ω for GF/PP textile sensors while 380 Ω - 1000 Ω for GF textile sensors.
### Table I

| Textile sensor                  | Electrical resistance of textile sensor after production (Ω) | Electrical resistance of textile sensor after insertion in 2D fabric (Ω) |
|--------------------------------|-------------------------------------------------------------|---------------------------------------------------------------------|
| GF/PP-Sy08sp03-1               | 490                                                         | 550                                                                 |
| GF/PP-Sy08sp03-2               | 500                                                         | 550                                                                 |
| GF/PP-Sy08sp03-3               | 370                                                         | 410                                                                 |
| GF/PP-Sy08sp03-4               | 350                                                         | 390                                                                 |
| GF/PP-Sy08sp03-5               | 440                                                         | 510                                                                 |
| GF/PP-Sy08sp03-6               | 390                                                         | 450                                                                 |
| Mean                           | 423                                                         | 477                                                                 |
| Standard deviation             | 63                                                          | 70                                                                  |

### Table II

| Textile sensor                  | Electrical resistance of textile sensor after production (Ω) | Electrical resistance of textile sensor after insertion in 2D fabric (Ω) |
|--------------------------------|-------------------------------------------------------------|---------------------------------------------------------------------|
| GF-Sy08sp03-1                   | 790                                                         | 920                                                                 |
| GF-Sy08sp03-2                   | 730                                                         | 870                                                                 |
| GF-Sy08sp03-3                   | 550                                                         | 700                                                                 |
| GF-Sy08sp03-4                   | 580                                                         | 740                                                                 |
| GF-Sy08sp03-5                   | 330                                                         | 380                                                                 |
| GF-Sy08sp03-6                   | 880                                                         | 1000                                                                |
| Mean                           | 643                                                         | 768                                                                 |
| Standard deviation             | 198                                                         | 221                                                                 |

### B. Electrical Resistance of Textile Sensors in Consolidated GF/PP Textile Preforms – Textile Reinforced Composites

Electrical resistance of GF/PP textile sensors after consolidation of GF/PP textile preforms prepared from related 2D fabric and right before electromechanical tests is in range between 16 kΩ - 240 kΩ (Table 3). Higher difference in electrical resistance values between two GF/PP sensors was observed in the first GF/PP composites. Low electrical resistances of GF/PP textile sensors were detected for the second GF/PP composite.

### Table III

| Textile sensor                  | Electrical resistance of textile sensor after consolidation of 2D textile preform in composite (kΩ) | Electrical resistance of textile sensor before electromechanical test of composite (kΩ) | Mean (kΩ) | Standard deviation (kΩ) |
|--------------------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------|------------------------|
| GF/PP-Sy08sp03-1               | 30                                                                                                | 26                                                                                     | 28        | 2                      |
| GF/PP-Sy08sp03-2               | 240                                                                | 190                                                                                   | 215       | 35                     |
| GF/PP-Sy08sp03-3               | 19                                                                                               | 16                                                                                     | 17        | 2                      |
| GF/PP-Sy08sp03-4               | 20                                                                                               | 18                                                                                     | 19        | 1                      |
| GF/PP-Sy08sp03-5               | 130                                                                | 117                                                                                   | 124       | 9                      |
| GF/PP-Sy08sp03-6               | 87                                                                                               | 92                                                                                     | 90        | 4                      |

Electrical resistance of GF textile sensors after consolidation of GF/PP textile preforms prepared from related 2D fabric and right before electromechanical tests is in range between 3 kΩ - 67 kΩ (Table 4). Higher difference in electrical resistance values between two GF sensors integrated was observed in the third GF/PP composite.

### Table IV

| Textile sensor                  | Electrical resistance of textile sensor after consolidation of 2D textile preform in composite (kΩ) | Electrical resistance of textile sensor before electromechanical test of composite (kΩ) | Mean (kΩ) | Standard deviation (kΩ) |
|--------------------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------|------------------------|
| GF-Sy08sp03-1                   | 19                                                                                                | 14                                                                                     | 17        | 3                      |
| GF-Sy08sp03-2                   | 59                                                                                                | 18                                                                                     | 38        | 29                     |
| GF-Sy08sp03-3                   | 48                                                                                                | 38                                                                                     | 43        | 7                      |
| GF-Sy08sp03-4                   | 27                                                                                                | 22                                                                                     | 24        | 4                      |
| GF-Sy08sp03-5                   | 3                                                                                                | 4                                                                                      | 3         | 0.2                    |
| GF-Sy08sp03-6                   | 67                                                                                                | 46                                                                                     | 57        | 15                     |
C. Electromechanical Results of Textile Reinforced Composites with Integrated Textile Sensors

According to electromechanical results, gauge factor for all composites was determined from a polynomial equation of degree 2. The first GF/PP composite (Fig. 3) showed similar electrical resistance-elongation curves of GF/PP textile sensors. For the second GF/PP composite, curves of electrical resistance variation of GF/PP textile sensors versus elongation showed several interruptions in the second part due to beginning of the delamination and cracks inside the composite. Breakage of one GF/PP sensor was occurred during in situ structural health monitoring of the third GF/PP composite.

Fig. 3. Results of electromechanical measurements of GF/PP composites with integrated GF/PP textile sensors - stress of composite (σ) and electrical resistance variation of textile sensors (Δ$R/R_0$) versus elongation (Δ$L/L_0$): (a) GF/PPcmp-GF/PP-Sy08sp03-1_2, (b) GF/PPcmp-GF/PP-Sy08sp03-3_4, (c) GF/PPcmp-GF/PP-Sy08sp03-5_6

Fig. 4. GF/PP composites with integrated GF/PP sensors in weft direction after electromechanical test - front side: (a) GF/PPcmp-GF/PP-Sy08sp03-1_2, (b) GF/PPcmp-GF/PP-Sy08sp03-3_4, (c) GF/PPcmp-GF/PP-Sy08sp03-5_6
Maximum peaks of GF/PP textile sensors curves appeared before the maximum stresses achieved for the composite specimens. Stress at break of GF/PP composites with integrated GF/PP textile sensors was in range between 207 MPa and 217 MPa while elongation at break between 4.40 % and 4.45 %. Composite breakage “in a line” (Fig. 4) can be seen after electromechanical test between clamps for the first GF/PP composite with integrated GF/PP textile sensors what is not in case for the other two composite specimens.

The first GF/PP composite with integrated GF textile sensors (Fig. 5) showed also similar electrical resistance-elongation curves, what is not in case for the other two composites.

![Graphs showing stress and electrical resistance variation](a) and (b)

![GF/PP composites after electromechanical test](c)

Fig. 5. Results of electromechanical measurement of GF/PP composites with integrated GF textile sensors - stress of composite (σ) and electrical resistance variation of textile sensors (ΔR/R0) versus elongation (ΔL/L0): (a) GF/PPcmp-GF-Sy08sp03-1_2, (b) GF/PPcmp-GF-Sy08sp03-3_4, (c) GF/PPcmp-GF-Sy08sp03-5_6

![GF/PP composites in weft direction](a) and (b)

![GF/PP composites after electromechanical test](c)

Fig. 6. GF/PP composites with integrated GF sensors in weft direction after electromechanical test - front side: (a) GF/PPcmp-GF-Sy08sp03-1_2, (b) GF/PPcmp-GF-Sy08sp03-3_4, (c) GF/PPcmp-GF-Sy08sp03-5_6

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For the second GF/PP composite, breakage of one GF sensor was occurred during in situ structural health monitoring. In case of the third GF/PP composite, due to interruptions occurred inside the composite at the beginning of electromechanical test, breakage of one GF textile sensor was detected as well.

Maximum peaks of GF textile sensors curves appeared before or at the maximum stresses achieved for the GF/PP composites. Stress at break of GF/PP composites with integrated GF textile sensors was in range between 235 MPa and 269 MPa while elongation at break between 4.97 % and 5.34 %. GF/PP composites with integrated GF sensors were not displayed breakage “in a line” between clamps after electromechanical tests (only partially the last specimen) (Fig. 6).

IV. CONCLUSION

Textile sensors showed resistance to high temperature and pressure as given electrical resistance values after consolidation of textile preforms as a part of these structures what is important in order to obtain in situ structural health monitoring of composites during tensile loading. Textile sensors showed also possibility to follow the tensile loading and to detect damages in the composites in situ. Earlier fractures inside the structures were noticed for some composites. Several interruptions due to beginning of the delamination and cracks inside were detected as well.

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