Real-Time Strain Monitoring and Damage Detection of Composites in different directions of the applied load using Microscale Flexible Nylon/Ag Strain Sensor.

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Abstract

Composites are prone to failure during operating conditions and that's why vast research had been carried out to develop in-situ sensors and monitoring systems to avoid their catastrophic failure and repairing cost. The aim of this research paper was to develop a flexible strain sensor wire for real-time monitoring and damage detection in the composites when subjected to operational loads. This flexible strain sensor wire was developed by depositing conductive silver (Ag) nanoparticles on the surface of nylon (Ny) yarn by electroless plating process to achieve smallest uniform coating film without jeopardizing the integrity of each material. The sensitivity of this Nylon/Ag strain sensor wire was calculated experimentally and gauge factor was found to be in the range of 21-25. Then, Nylon/Ag strain sensor wire was inserted in each composite specimen at different position intentionally during their fabrication depending upon the type of damage to detect. The specimens were subjected to tensile loading at a strain rate of 2mm/min. Overall mechanical response of composite specimens and electrical response signal of the Nylon/Ag strain sensor wire showed good reproducibility in results however, Nylon/Ag sensor showed a specific change in resistance in each direction because of their respective position. The strain sensor wire designed did not only monitor the change in the mechanical behavior of the specimen during the elongation and detected the strain deformation but also identified the type of damage whether it was compressive or tensile. This sensor wire showed good potential as a flexible reinforcement in composite materials for in-situ SHM applications and detect damage initiation before it can become fatal.

Keywords: *Structural composites; Mechanical Deformation; Nylon/Ag Strain sensor wire; Real-time monitoring; Damage detection*

Introduction

Composites had replaced traditional materials nearly in every industrial application because of their superior mechanical performance, structural durability, low density, cost-effectiveness and resistance to environmental factors [1,2]. However, even they were not exempt from limitations and their deformation and damage mechanisms were well established [3,4]. Therefore, it was essential to examine and control the performance of the structure during operation to avoid unexpected failure which could be initiated either because of the extreme loading conditions or by extreme environmental conditions such as creep, moisture, etc. Macroscopic damage was usually visible externally in composites, but microscopic damage or internal cracks were extremely challenging to detect and usually required inspection techniques [5–7].

Structural health monitoring (SHM) is a renowned and extensively used procedure to study and control the performance of composites to ensure more reliable and safer structures [8]. SHM sensors were developed gradually over the time form nondestructive testing methods to real-time monitoring of structures [9–12]. In-situ SHM had been often used for sensing different kinds of damages in materials such as thermal degradation, deformation, corrosion, fiber cracking, intralaminar cracking, debonding/delamination, etc. to confirm save and durable service life of the structures [13–18]. Likewise, many studies were available which investigated the strain and damage sensing of the composites structures using different SHM techniques but limited information was available in the literature regarding the effect of sensitivity and location of the sensor on damage detection [19,20]. Moreover, it was very important to study the behavior of sensing response in a different direction and to distinguish between the tensile and compressive damage during the test.

The electrical resistance (ER) measurement was one of the examples of in-situ SHM used for active damage monitoring in composites by measuring the change in resistance of the material [21–25]. This method was commonly applied to carbon fiber reinforced composites (CFRP) because of the high electrical conductivity of the carbon fibers. The change in the resistance was associated with the contact change between the carbon fibers and their rearrangement within the composite during the deformation process [26,27] For example, the ER response for unidirectional UD composites was directly proportional to the strain measurement while composites with random dispersion of fibers showed more complexed signal response especially with large deformation applications such as flexural displacement [28–31]. Moreover, this method was not applicable to composites with low conductivity such as glass fiber reinforced composites (GFRP) or cementitious composites. This limitation was overcome by increasing the electrical conductivity and self-sensing behavior of the structure using nanofillers such as nickel powder, carbon fibers/nanofibers, carbon nanotubes (CNT), graphene and carbon black [32,33]. But this couldn't be applicable on large scaled structures subjected to flexural loading because large weight percentage of nanofillers was required to achieve good conductivity which could result in high cost and dispersion problems [32,33].

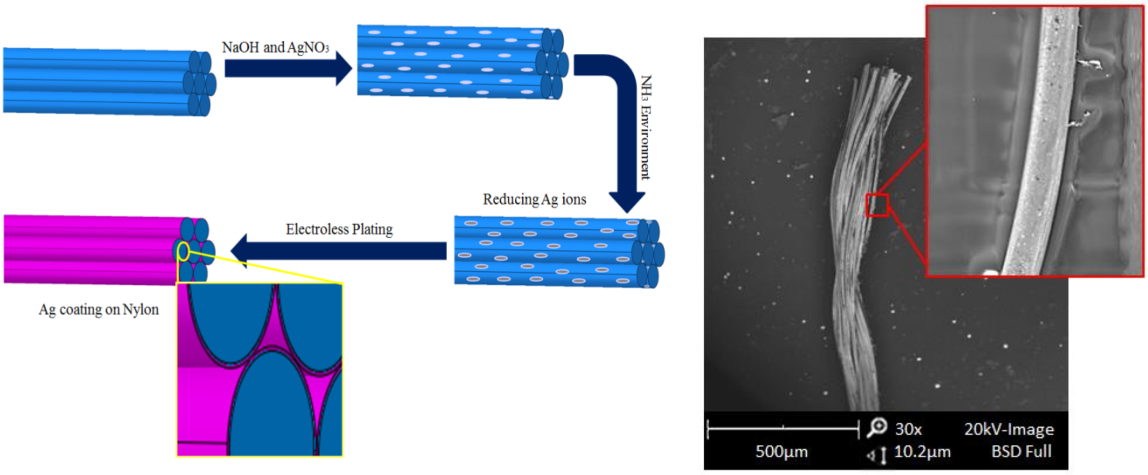
Flexible conductive wire sensors were considered to be a very promising solution for SHM of composite materials. After integration, they not only perform damage sensing but also act as reinforcement [34–37]. They operate on the working principle of traditional metal strain gauges [36]. These smart textiles, fabrics, and yarns were first developed by using conductive polymers for real-time damage detection in composite structures but they were unstable when exposed to the environment and had low conductivity in comparison to nanoparticles [38–41]. Similarly, Coating or inserting conductive nanoparticles such as carbon nanotubes (CNTs), graphene, etc. into the filaments were also considered as a possible solution of real-time SHM [42]. For example, CNTs based fibers, having high sensitivity, flexibility and outstanding impact resistance, were used in real-time damage monitoring of composites [43,44]. But their sensitivity was affected when inserted into the composite specimens because of the two reasons, one tunneling effect and other is the porous network of CNTs which is permeable to resin molecules [45–48]. Fibers coated with reduced graphene oxide (RGO) didn't have resin penetration because of their geometry and surface conformability and showed high sensitivity, flexibility, and stability in real-time monitoring of high strain applications [49]. These fibers were more suitable for early detection of damage in the structure with distinguished two-stage behavior from linear to nonlinear. However, even graphene had a stability issue when exposed to air and is toxic in nature [50,51]. Moreover, metal nanoparticles such as gold, nickel, aluminum, stainless steel, copper and silver were commonly used as coating materials for in-situ SHM applications [52–54]. Amongst all these metal nanoparticles, silver (Ag) showed great potential as a coating material on the flexible polymeric substrate because of its excellent conductivity, competitive price, stability in air and other mechanical properties [55]. Silver had already been used in anti-microbial activity and as wearable sensing clothes for medical monitoring and showed better stability, responsivity, repeatability and low drift in electrical signal in strain sensing application [56–58]. Although, the silver metal coated fabric was studied numerous times for antibacterial and medical activities its application regarding structural health monitoring purpose in composites is still underdeveloped. Y. Qureshi et al. [59] recently conducted a study to investigate the application of silver-coated nylon yarn as strain sensor under tensile loading. But, up to best knowledge of the author, no information in the literature is available regarding the use this flexible microscale sensor wire [59] to detect strain in a different direction of the applied load in composite structures and to distinguish between different stresses.

So, in this context, an experimental study was conducted to investigate the in-situ/real-time strain and damage sensing capabilities of the silver coated nylon (Nylon/Ag) sensor wire within composite structures under tensile loading in this research. The second objective was to study the ability of the sensor to distinguish between the tensile and compressive damage of the composite specimen during the test in addition to the sensitivity of the response signal. This flexible strain sensor was fabricated by depositing conductive silver (Ag) nanoparticles on the surface of nylon (Ny) yarn by electroless plating process and its electromechanical response and sensitivity were calculated experimentally. Then, the fabrication process of the specimen was carried out by inserting the strain sensor wire within the glass fiber plies of the GFRP composites. A mold was used for the fabrication of the specimens and sensor wires were placed between the plies in their respective directions depending upon the mode of failure to detect during the test. Then each specimen was tested on INSTRON-50 machine under tensile loading and its mechanical performance was correlated with the electrical signal response of each Nylon/Ag strain sensor wire. The results showed that the sensor not only detected the strain in each direction under tensile loading with good sensitivity but was also able to differentiate between tensile and compression stresses.

Fabrication Process

2.1.Fabrication of Nylon/Ag strain sensor wire

Sensors were developed by depositing silver (Ag) metal nanoparticles in the form of continuous and uniform thin film coating on the surface of each filament of nylon (Ny) yarn. Metal film coating was applied because even though, nylon yarn behaved well mechanically but was poor in electrical conductance. There were studies where nano fillers can be inserted inside the fiber but only up to a certain weight percentage because further increase can result in a decrease in mechanical performance [60]. But with the coating process, 100% uniform coating was formed without affecting the structural integrity or flexibility of core material. Electroless plating was used for the deposition of metallic nanoparticles because it's a simple and effective process and can be easily done on complex substrates/geometries. Nylon-6 yarn was cleaned with ethanol to remove any dust particles or surface impurities to ensure good adhesion for the nanoparticles of Ag metal. Then nylon was treated with silver nitrate ($AgNO_3$) and sodium hydroxide (NaOH) at 130 °C for 2 hours and after that, followed by a reduction process in ammonia (NH_3) environment for a period of 2 hours. The reduction process produced ethylene as a reducing agent which reduced the Ag(I) to Ag(0) ions. Finally, after post-treatment with ammonia, silver nanoparticles were deposited on the surface of nylon. The complete process is demonstrated in Figure 1 (a). Scanning electron microscopy (SEM) characterization confirmed that the coating consisted of Ag nanoparticles deposited on the surface each filament of the Ny yarn, Figure 1 (b). The fabricated sensor wire was 50cm in length, 225 μm in diameter with a coating thickness of approximately 1-2 % of the diameter of the individual filament of the yarn i.e. 1-2 μm. This thickness of Ag-coating was chosen because it was the best compromise between the good conductive flexible coating and minimum uniform thickness throughout the yarn. After the fabrication process, the sensor wire was cut into the specific length required for insertion in the composite specimen.



(a) *(b)*

Figure 1: (a) Fabrication process of the Nylon/Ag strain sensor wire, (b) Nylon/Ag strain sensor wire after fabrication

2.2.Fabrication of Specimens inserted with sensor wire

i. Star Specimen for strain monitoring

Specimens of the composite were prepared using fabric plies of chopped glass fibers as reinforcement because of their poor conductivity and to ensure isotropic mechanical behavior of the specimen. The fabric of chopped glass fibers was cut into sections and five plies were used. Nylon/Ag sensor wires were separated from each other by the ply for electrical isolation and were placed in their respective directions i.e. sensor A in 0°, sensor B in 45°, sensor C in 90° and sensor D in -45°. Then, resin mixed with a hardener with a ratio of 1:4 was poured into the mold and full integration of sensor in each specimen of the composite was achieved Figure 4. Now, sensor wire was visible in all specimens and afterward, specimens were cured at room temperature for 48 hours. Then, the specimen plate was machined using CNC in a star shape and each leg represented the direction and placement of the Nylon/Ag sensor wire moreover, the sample was marked with the DIC correspondence points, Figure 2a. Each leg of the star specimen was kept at standard dimension as 25 mm in width, length of each leg was approximately 200 mm and the thickness of the specimen was 5 mm, Figure 2b. Schematic representation of the composite star specimen with the embedded Nylon/Ag sensor wires demonstrated that sensors were represented by A, B, C, D and each leg of the star specimen represented the direction according to the loading axis, Figure 2c-2d.

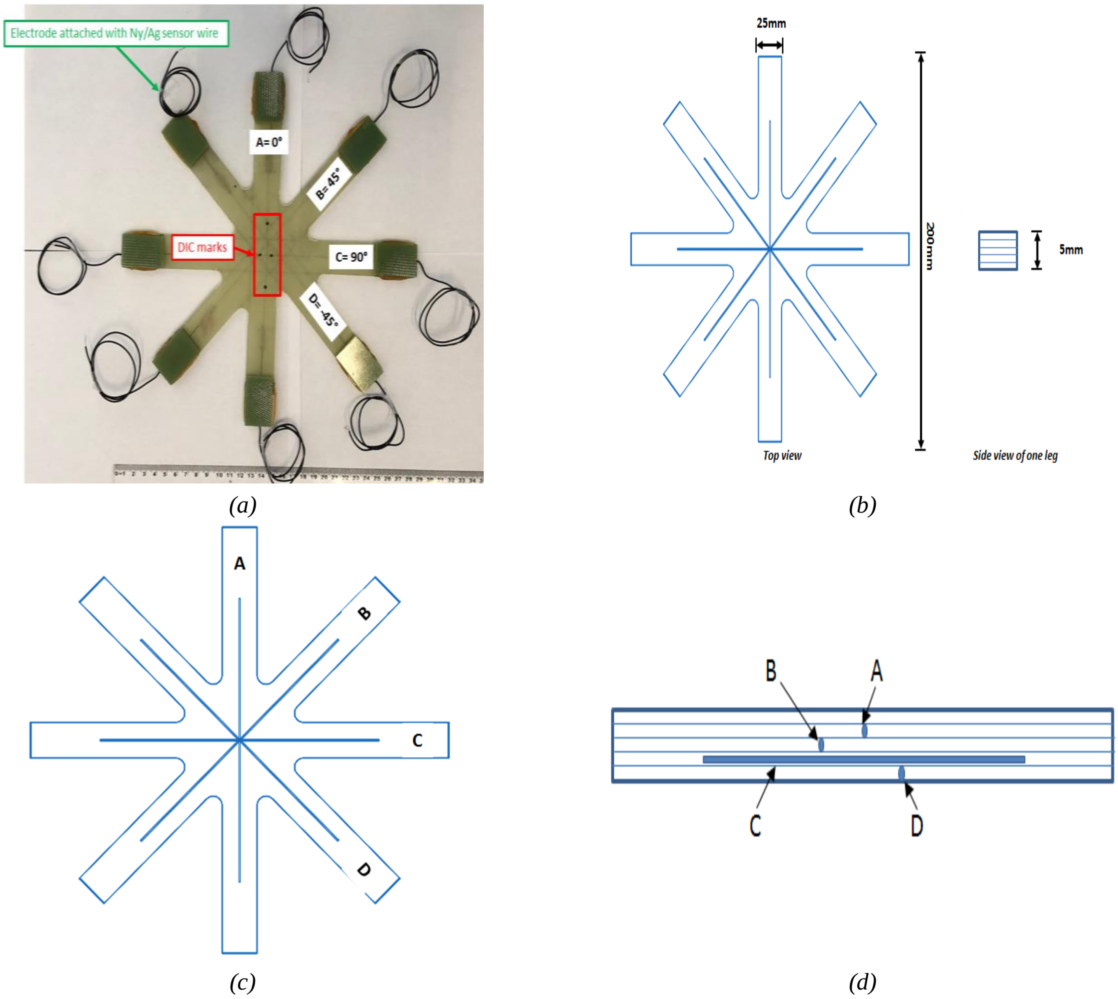
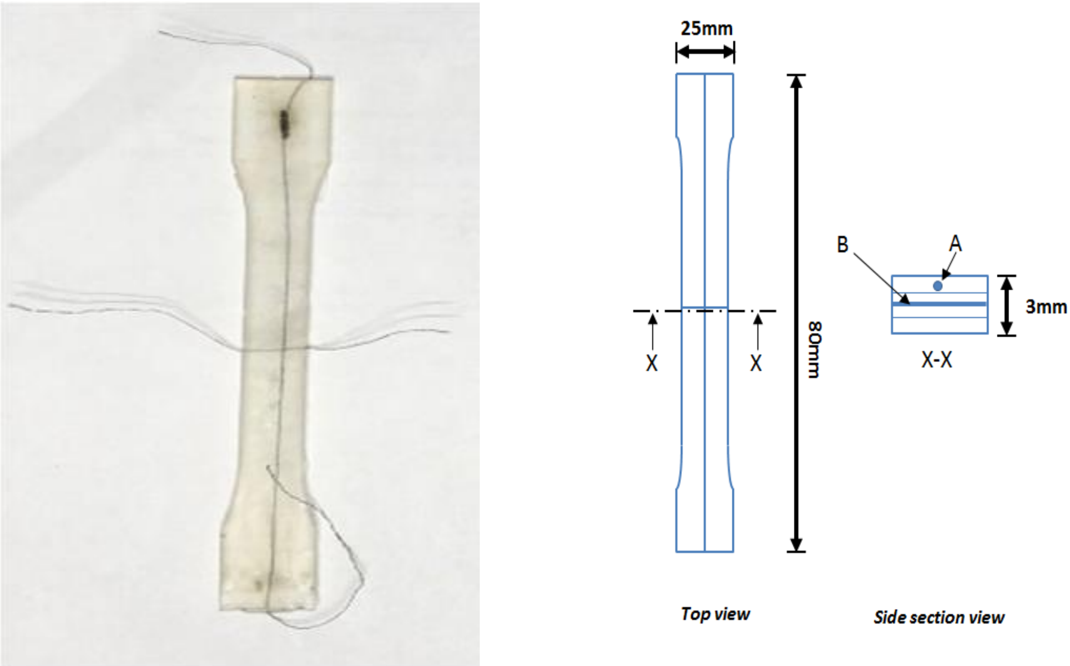


Figure 2: (a) Example of a composite specimen embedded with Nylon/Ag sensor wires after the fabrication process. The specimen became transparent after the curing process and the sensor wire is visible. (b) Geometric characteristics of the star specimen. (c)-(d) Schematic representation of the position of Nylon/Ag strain sensor wire in each direction and between each ply (section view) respectively

ii. Standard Specimen for overall damage detection

Standard specimens of the composite were prepared using similar materials which were used for the star specimen however, three plies were used and both sensor wires were intentionally for electrical isolation. Then, resin mixed with a hardener with a ratio of 1:4 was poured into the mold and full integration of sensor in each specimen of the composite was achieved. Once the molds were filled the samples were completely transparent and the chopped glass fiber fabric was not visible, Figure 3a. Now, sensor wires in longitudinal and transverse direction were visible in both samples and afterward, specimens were cured at room temperature for 48 hours. The specimen was characterized as 25 mm in width, 80 mm in length and 3 mm in thickness, Figure 3b. Schematic representation of the composite star specimen with the demonstrated placement of embedded Nylon/Ag sensor wires according to the loading axis.



(a) *(b)*

Figure 3: (a) Example of a standard composite specimen embedded with Nylon/Ag sensor wires after the fabrication process. (b) Geometric characteristics of the specimen and schematic representation of the position of Nylon/Ag strain sensor wire in 0° and 90° direction.

Experimental Procedure

3.1. Experimental testing of the electromechanical response of Nylon/Ag strain sensor wire

Standalone Nylon/Ag sensor wire was tested under tensile strain to calculate the gauge factor. This test was conducted using INSTRON-50 apparatus to record the mechanical behavior while oscilloscope was used to record the electrical signal of the sensor wire, Figure 4. Many experimental challenges were encountered, such as difficulties in gripping the samples inside the fixtures of machine because of its size and it was critical to making sure that the sensor wire was not in contact with any metallic portion of the machine. All the necessary parts of the machine were insolated by covering with the insulation tape so the electrical response of the sensor could not be affected. Paper frame was used to provide support to such a small specimen in the tensile machine, however; it was cut from the sides before conducting the test so it could not affect the mechanical response of the Nylon/Ag strain sensor wire during the test. Besides this, electrode wires were attached at both ends of the specimen to provide a better connection with an oscilloscope by reducing any chance of perturbation in the signal during the test and then, the specimen was placed in the tensile machine. The tensile test was performed at low strain rate i.e. 2 mm/min. Three successful tensile tests were conducted to determine the reproducibility of results. The Nylon/Ag sensor wire samples were loaded and unloaded respectively within the elastic limit and electromechanical response of the sensor wire was plotted as the change of resistance with respect to the strain.

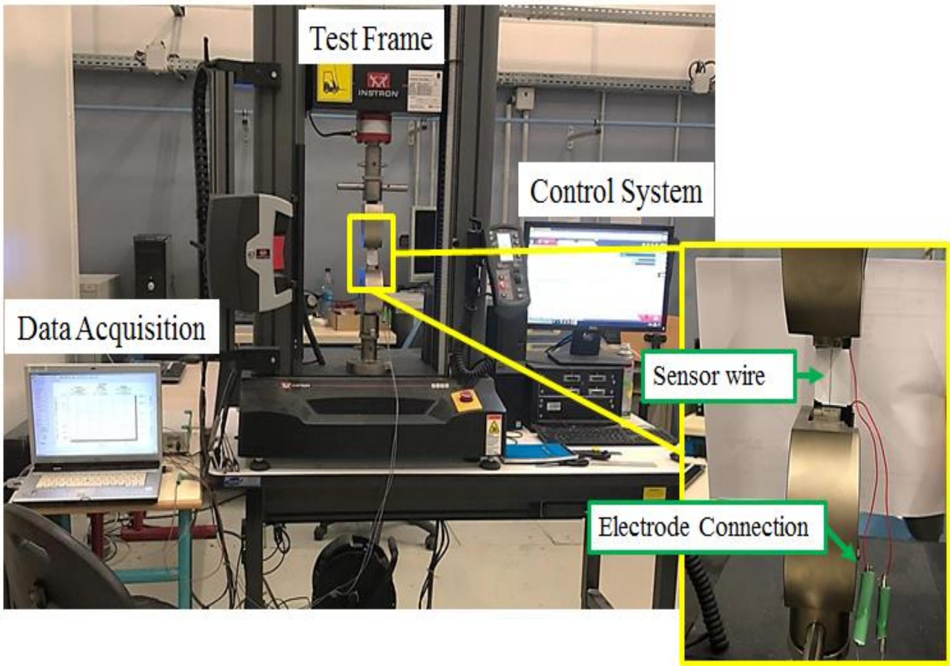


Figure 4: Experimental setup to test the sensitivity of the designed strain sensor wire.

3.2. An experimental test of composite specimen containing Nylon/Ag sensor wire

i. Star Specimen for strain monitoring

A cured composite specimen consisting of sensor wires was tested using INSTRON-50 and data acquisition system (Spider 8 manufactured by HBM) with the LabVIEW program was connected to the electrodes attached with the Nylon/Ag sensor wires for real-time monitoring of specimen deformation, Figure 5. INSTRON-50 was used to study the mechanical behavior of the composite specimen and electrical system was used to record the signal from the sensor wires simultaneously. It was important not only to ensure that the specimen was placed properly between the fixtures but, also that the electrical connections were not in contact with any metallic part of the machine because it could have influenced the electrical response of the sensor. Then, the specimen was placed in the machine and test was performed at low strain rate i.e. 2 mm/min up to 15 kN to avoid permanent damage and the mechanical behavior of composite specimen with resistance profile of the Nylon/ag strain sensor wire was obtained. Furthermore, strain deformation behavior of each specimen was also confirmed by the DIC (digital image correlation) camera and DIC marks were calibrated with the camera before conducting the test. Each test showed the Nylon/Ag sensor wire in each direction showed different resistance profile according to their placement which will be discussed in detail in next section.

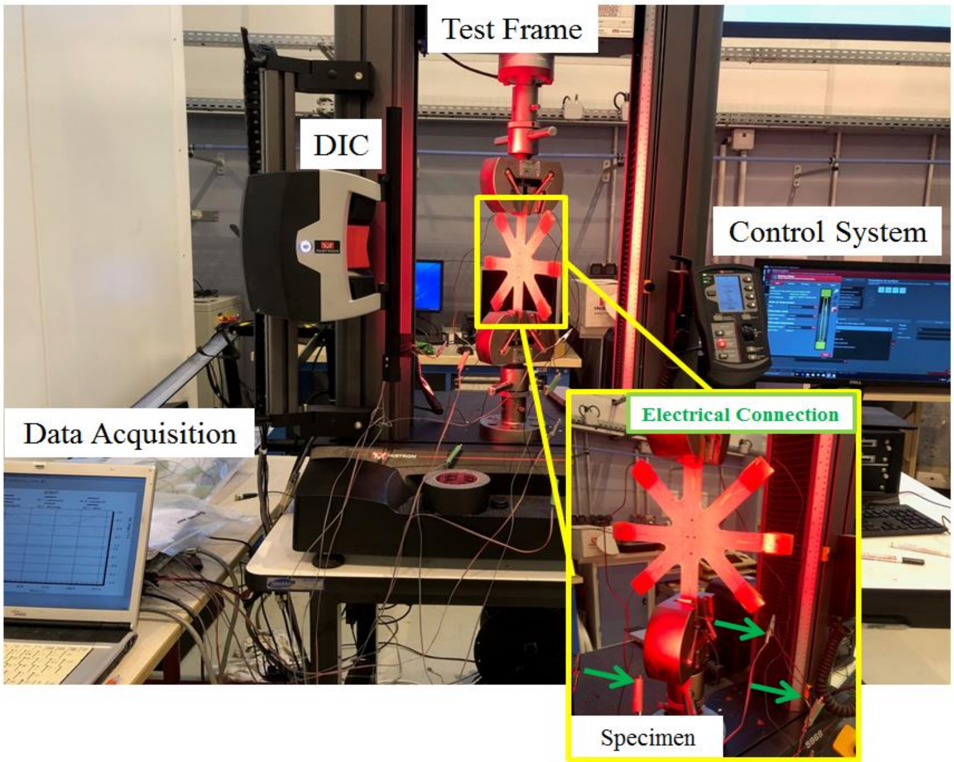


Figure 5: Experimental setup to test the real-time damage detection of the Nylon/Ag strain sensor wire in composite star specimen. Electrical connections are highlighted with green arrows.

ii. Standard Specimen for overall damage detection

Standard composited specimen consisting of sensor wires in two directions i.e. 0° and 90° was also tested using INSTRON-50 and data acquisition system (Spider 8 manufactured by HBM) like star specimens, Figure 6. INSTRON-50 demonstrated the overall mechanical behavior of the composite specimen while the electrical recorded the signal from the sensor wires until fracture. It was ensured again that the specimen was placed properly between the fixtures and none of the electrical connections were not in contact with any metallic part of the machine. The test was performed at low strain rate i.e. 2 mm/min up to final fracture and the mechanical behavior of composite specimen with the resistance profile of each sensor wire was obtained. Both tests showed that Nylon/Ag sensor wire detected the strain deformation and final damage in each direction according to their position.

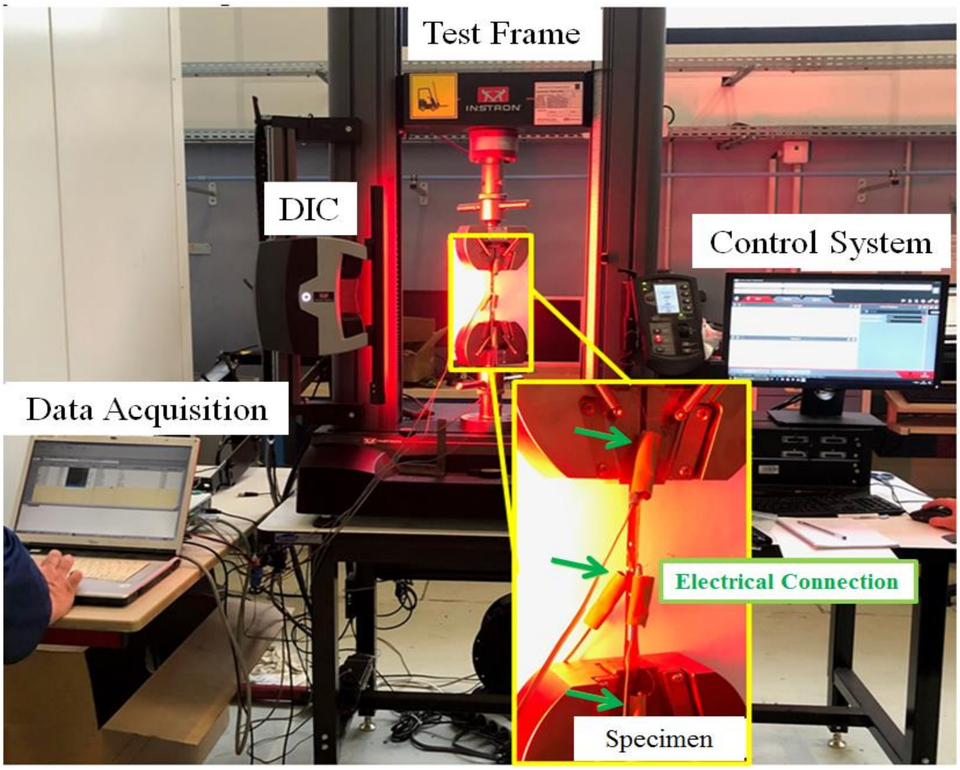
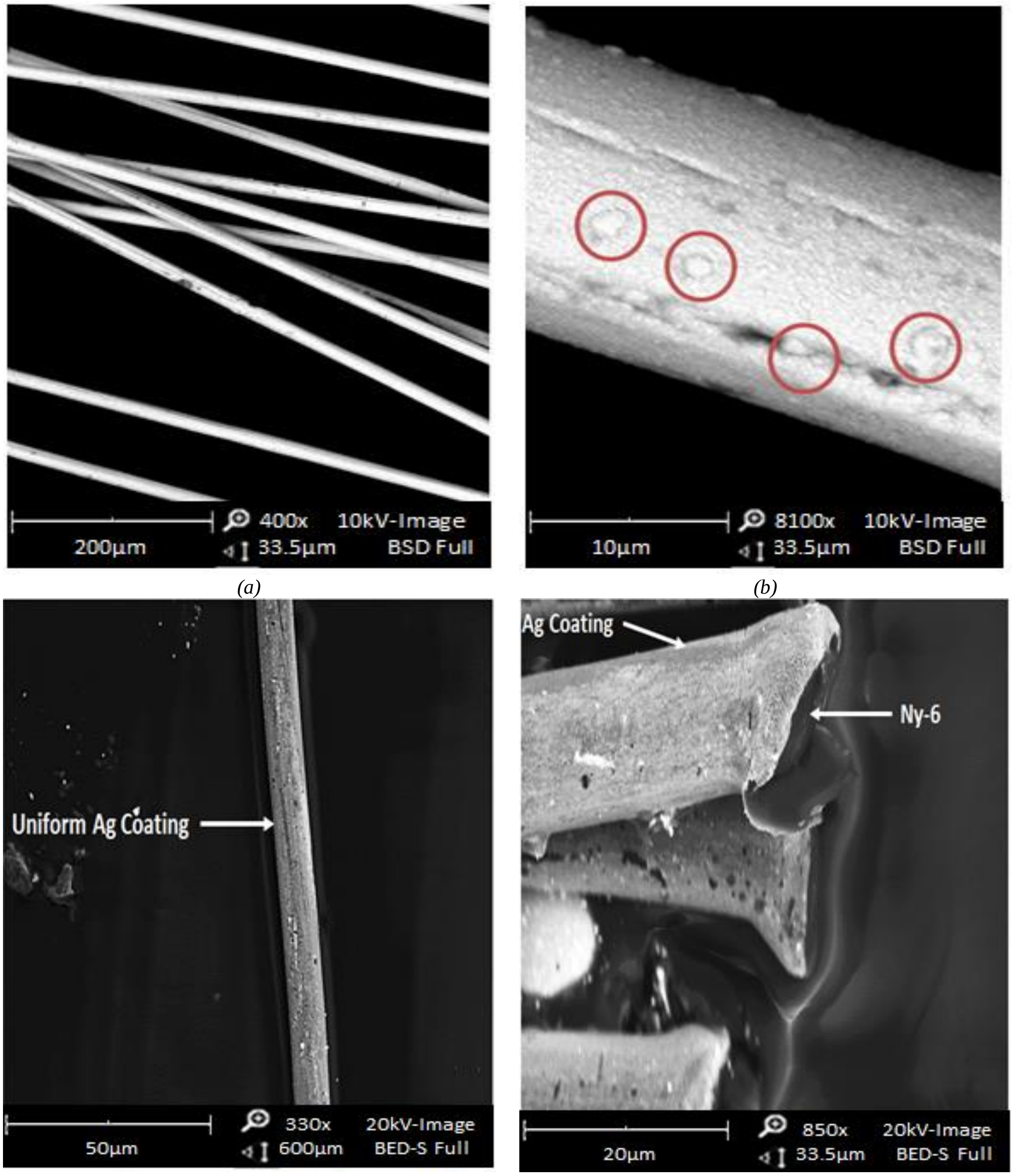


Figure 6: Experimental setup to test the overall real-time damage detection of the Nylon/Ag strain sensor wire in the standard composite specimen. Electrical connections are highlighted with green arrows.

Results and discussions

4.1.SEM Characterization of Nylon/Ag strain sensor wire

SEM characterization revealed that Nylon-6 yarn consisted of numerous filaments and all the filaments were homogeneously coated, Fig. 7a-c. Nylon-6 fibers and yarn showed good adhesion bonding because of their surface roughness. These small cavities acted as anchoring points for deposited metallic particles and thus showed better adhesion as compared to polyester and polypropylene polymeric materials [61]. Furthermore, SEM confirmed that the Ag coating was formed by the continuous deposition of Ag nanoparticles on the surface of Nylon-6 yarn, Figure 7b. In addition, large magnification showed that some filaments exhibited minute gaps (of nanoscale) regardless of which the electrical current flow through the yarn was almost 100 % because these minute imperfections were found in very few filaments in comparison to the whole yarn and their presence did not affect the overall path of current flow. Furthermore, SEM distinguished the nylon core by the Ag coating, Figure 7d.



(a) *(b)* *(c)* *(d)*

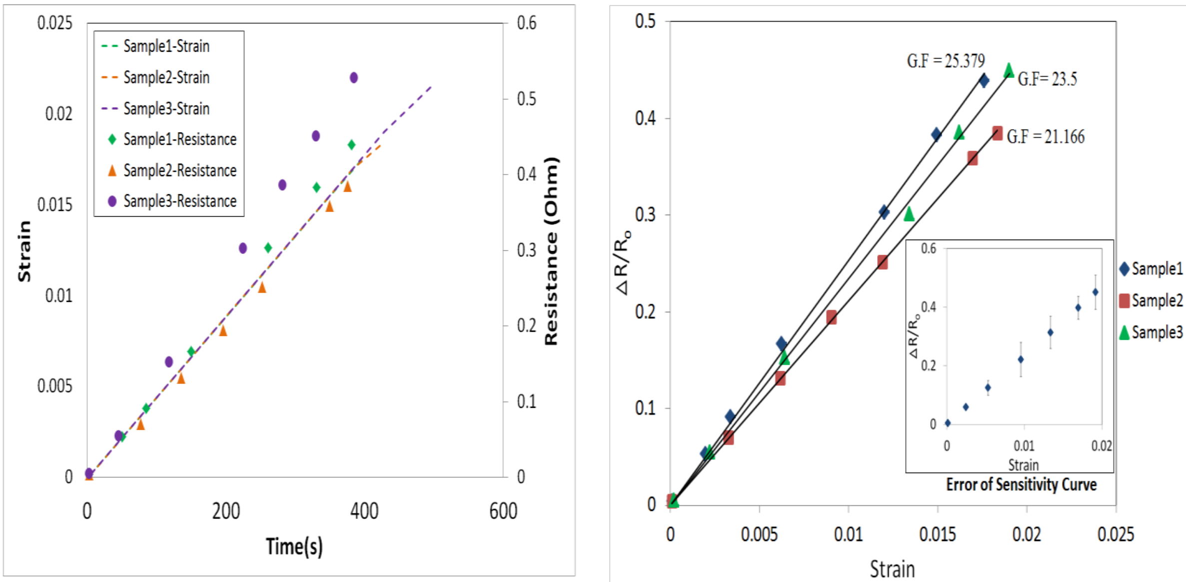
Figure 7: SEM Characterization of the Nylon/Ag strain sensor wire. (a) shows the uniform coating of all filaments of the yarn with some minute discontinuities (b) confirms that the Ag thin film coating on the Ny-6 surface consisted of deposition of nanoparticles of silver. (c) Uniform Ag coating on single filament of the Ny-6 yarn (d) Cross-sectional view of a coated filament to differentiate between the core Ny-6 and Ag coating

4.2. Electromechanical response and sensitivity of strain sensor wire

The resistance was changed gradually as the strain was applied to the sensor wire. This progressive behavior of the sensor wire validated the good correlation between the electrical and mechanical responses of the sensor, Figure 8a. The results were very encouraging and tracking the resistance change of this conductive yarn as a function of increasing load seemed to be correlating very well. The sensitivity of the sensor wire was demonstrated by calculating the gauge factor (G.F). Gauge factor defines the sensitivity of the sensor by comparing the change in resistance of the sensor with respect to the applied strain and equation (1) was used to calculate it.

$$G.F = \frac{\Delta R/Ro}{\varepsilon} \quad (1)$$

The gauge factor of this flexible strain sensor wire was found to be in the range of 21-25 with error of sensitivity of 1.72 within the elastic limit, Figure 8b. This showed that the Nylon/Ag sensor wire had good sensitivity and could be used for real-time damage detection applications.



(a) *(b)*

Figure 8: Experimental calculation of the sensitivity of the Nylon/Ag strain sensor wire. (a) shows the change of resistance for all three Nylon/Ag sensor wires with the applied strain. This also shows a good correlation between the mechanical and electrical response of the sensor wire. (b) shows the calculation of GF. Three tests were conducted to show the reproducibility and GF was found to be in the range of 21-25 and error of sensitivity curve for all three tests is also presented in this figure

In addition, the electrical resistance of Nylon/Ag sensor wire was recorded and compared with neat nylon yarn experimentally to record the change in resistance of the nylon yarn with the addition of Ag nanoparticles, Figure 9. This experimental study showed that initially, nylon yarn had very high resistance i.e. poor conductivity thus; it could not be used for SHM application. However, with the deposition of Ag nanoparticle by electroless plating drastically reduce the resistance of the nylon yarn and made it a good conductor of electrical current. Moreover, Nylon/Ag sensor wire was compared with other similar Nylon-Ag SHM systems to further understand the performance of our sensor wire. In comparison with other SHM systems, it was concluded that Nylon/Ag sensor wire produced by electroless plating showed better conductivity than nylon fibers inserted with Ag nanofillers [62] and nylon fibers coated with Ag nanoparticles using iodine method [63]. In addition, it was previously discussed that nanofillers could be inserted inside the fiber but, up to a certain weight percentage because further increase can result in a decrease in their mechanical performance. Moreover, even though Ny/Ag sensor wires produced by depositing the nanowires of Ag [58] and nano-crystalline thin film of Ag [55] showed better conductivity than our Nylon/Ag sensor wire but their fabrication processes are complexed and expensive additionally, Ag nanowires health and environmental effects should be considered for Ag nanowire including their impact during fabrication and disposal

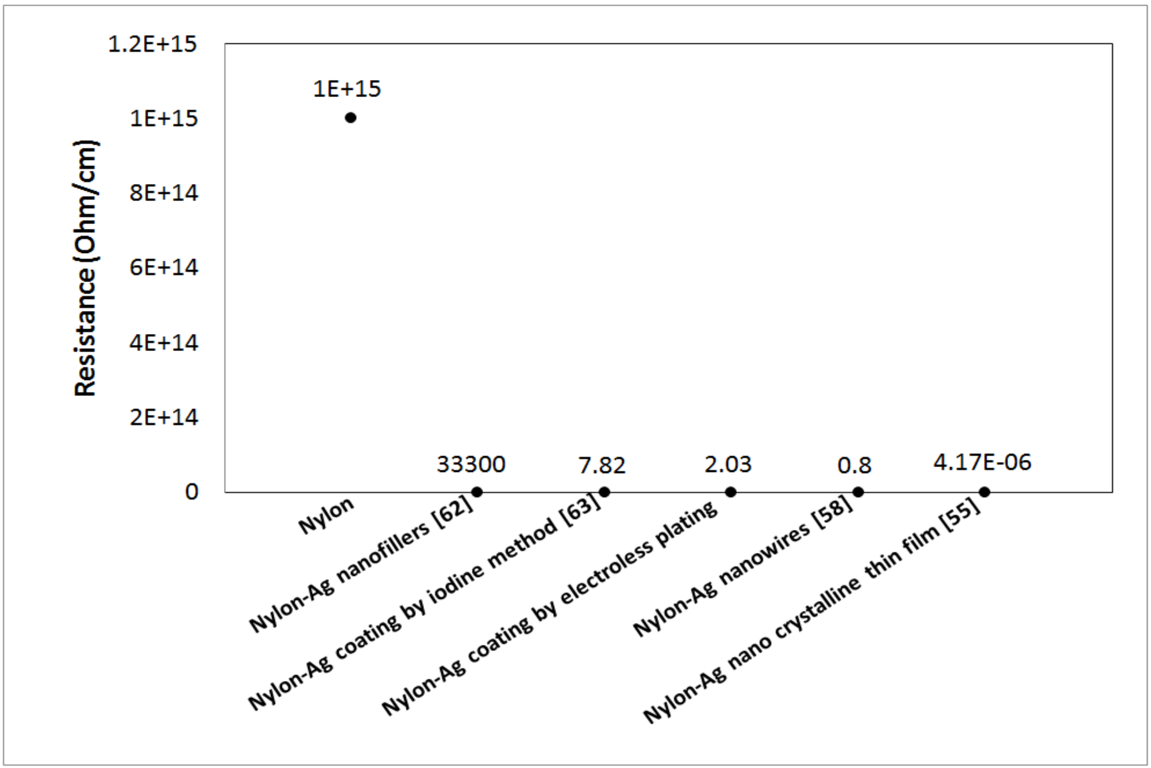


Figure 9: the change of electrical resistance of Nylon yarn with the addition of Ag nanoparticles and comparison of this change of resistance with other similar Nylon-Ag SHM systems [55], [58], [62], [63].

4.3.Mechanical characterization and deformation behavior of the composite

i. Star Specimen for strain monitoring

It was vital to apprehend the deformation behavior of the composite star specimen subjected to tensile loading to understand the deformation detection response of the Nylon/Ag strain sensor wire, Figure 10. Star specimens were fixed at one leg and the tensile load was applied on the opposite leg and all other legs were free. When specimens were subjected to tensile load, the deformation caused tensile stress along the loading axis i.e. 0° because of the elongation and compression stresses along the leg of the star specimen in the transverse direction of the loading axis i.e. 90°. Moreover, it was understood that the combination of these two stresses, compressive and tensile, were generated at the oblique direction i.e. ±45°.
Three successful tests were performed, and data were plotted as stress-strain behavior, Figure 11. However, for sample 1 and 2, sensor A was in the loading axis i.e. in 0° but for the third test, sample was rotated such that sensor C was in the loading axis i.e. 0°, sensor A was in the 90° and sensor B and D also interchanged their position, Figure 12 . This step was carried out to test the sensitivity of the Nylon/Ag sensor wire with respect to the axis of the applied load and it did not affect the mechanical behavior showed good reproducibility in results. Moreover, during the test, the applied load was kept constant as 15kN so it was important to study the strain deformation behavior of all three samples. The total strain deformation of all three samples also showed good reproducibility in results and the strain deformation of each sample was further confirmed by the DIC camera, Figure 13. This comparison showed that the deformation behavior of each star specimen was similar to the other two specimens, irrespective of the loaded leg. This also confirmed the isotropic characteristic of the

composite structure and that the presence of Nylon/Ag sensor wire at different locations and directions did not affect the integrity of the structure.

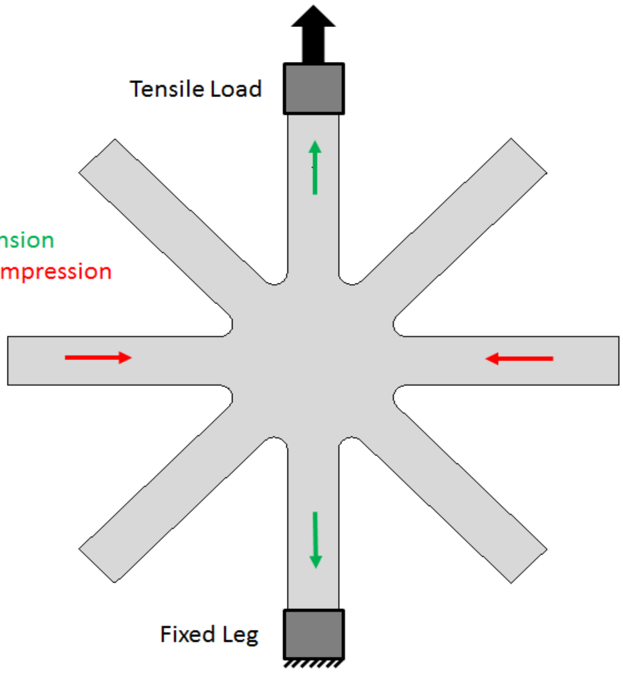
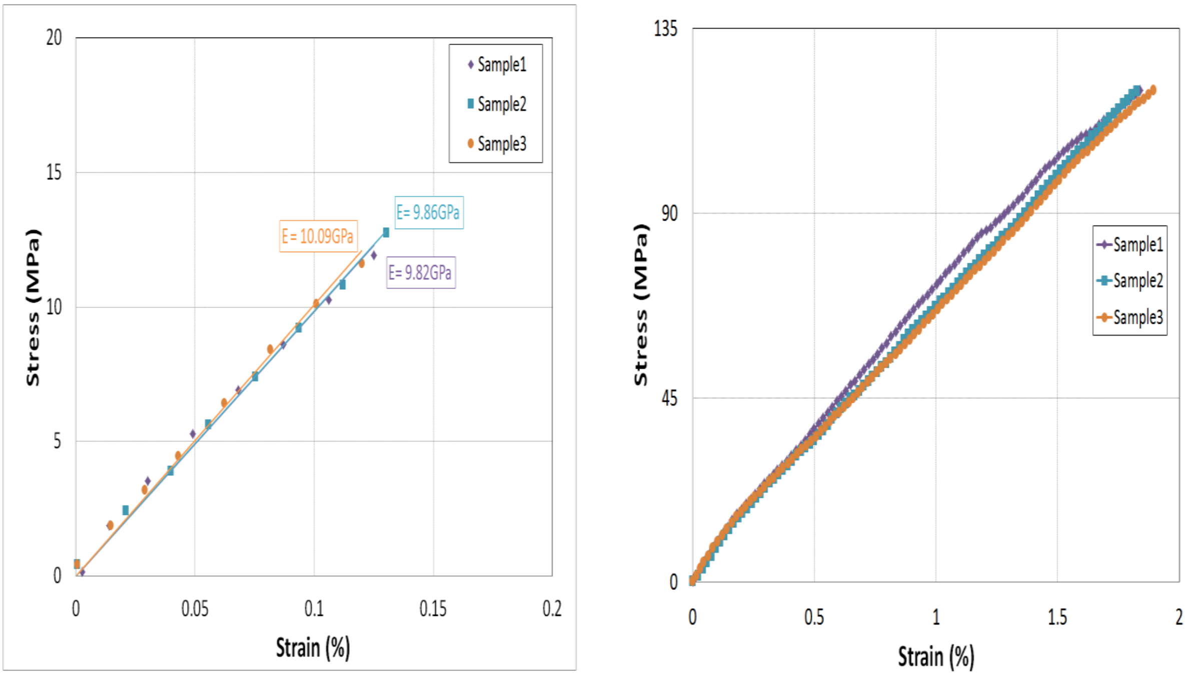
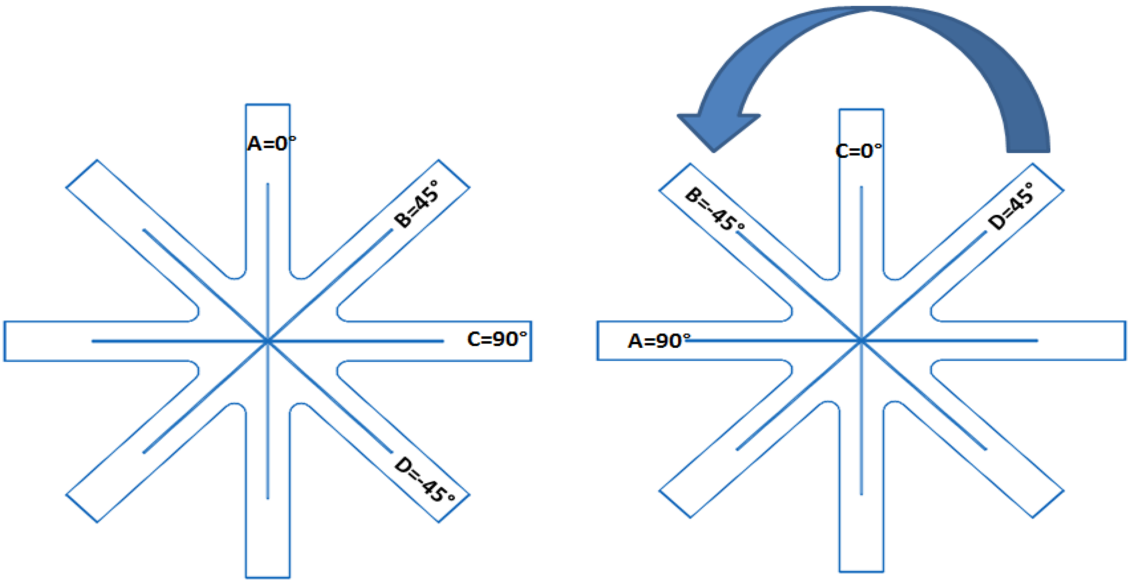


Figure 10: Deformation behavior of star specimen during tensile loading.



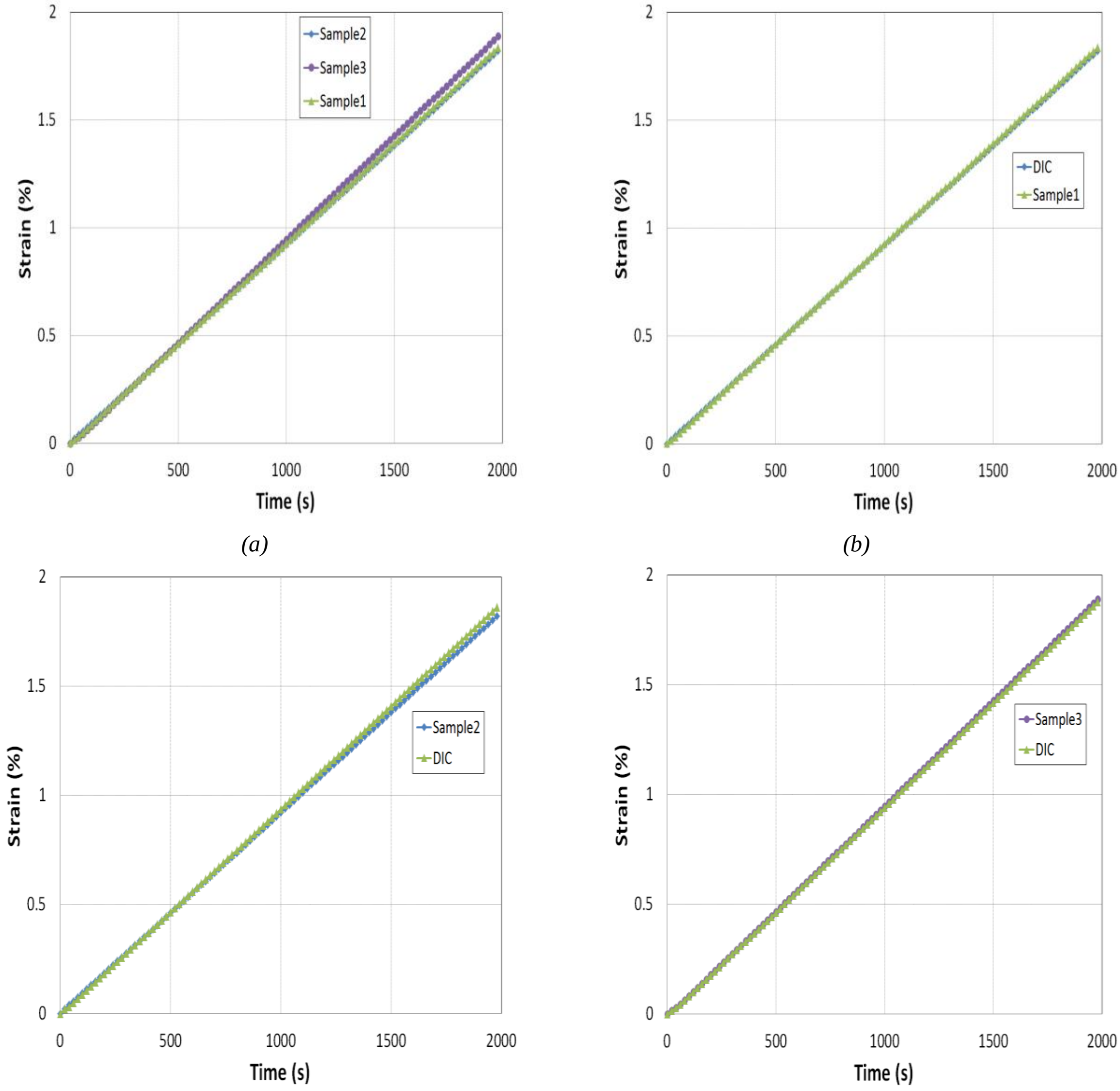
(a) *(b)*

Figure 11: Comparison of the experimental stress-strain behavior of all specimens



(a) *(b)*

Figure 12: Placement of the composite star specimen in the tensile machine (a) Sample 1 and 2 and (b) Sample 3

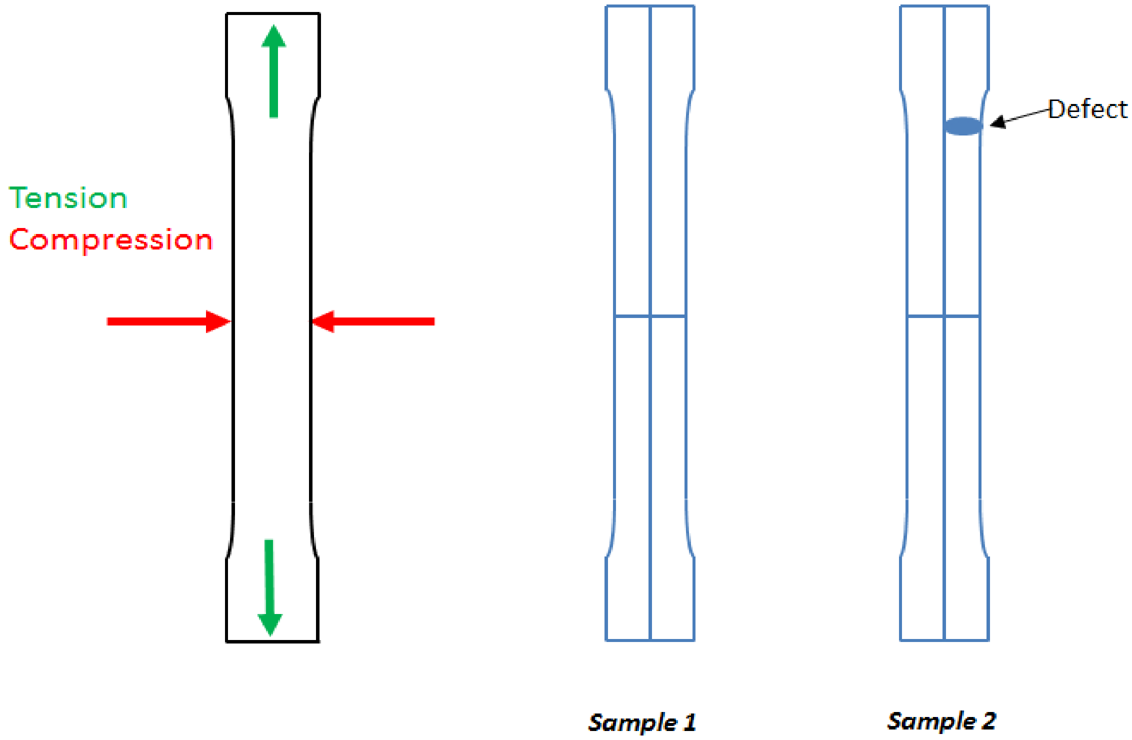


(d)

Figure 13: (a) Total strain deformation of all three specimens. (b)-(d) Comparison of the total strain of each specimen with the DIC respectively.

ii. Standard tensile specimen for overall damage detection

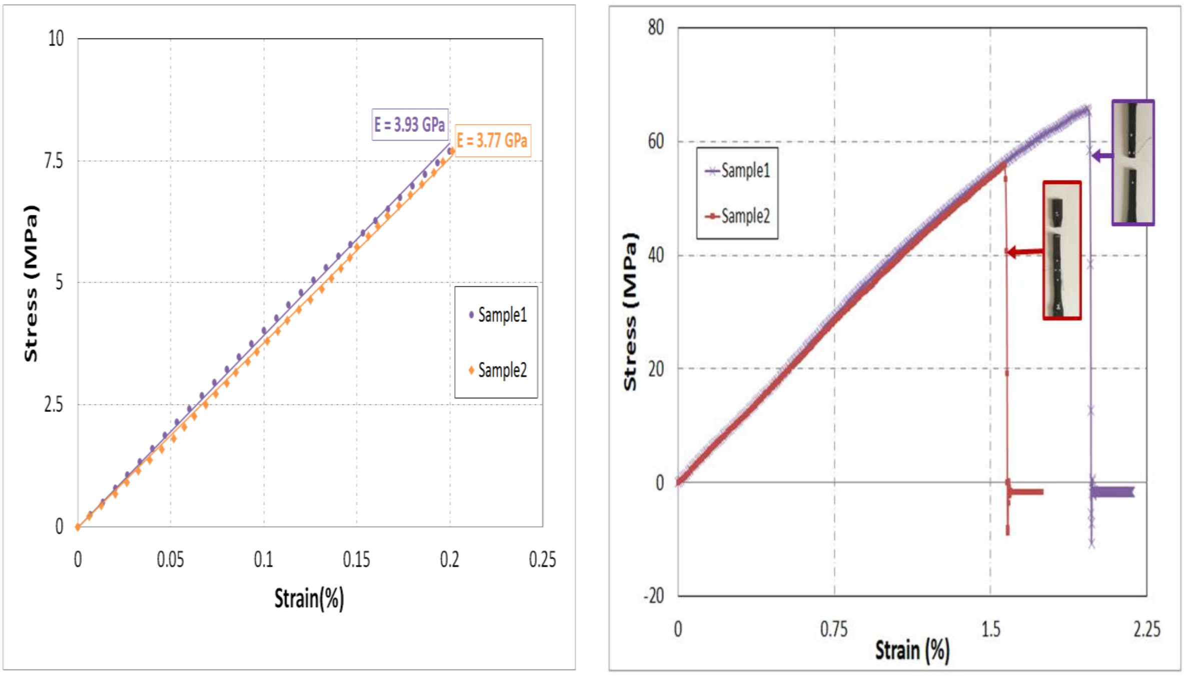
The deformation behavior of the standard composite specimen was identical to the star specimen because it was also subjected to the tensile loading however; the only difference was that these specimens were studied up to final fracture, Figure 14. Two composite specimens with sensor wire in 0° and 90° direction in each specimen were studied for overall deformation behavior. Sensor wires in each specimen were placed in the middle of both directions however in sample 2; a defect was intentionally introduced near the fixture, Figure 14. This step was carried out to observe the difference in the damage detection behavior of the sensor wires especially the sensors placed in the transverse direction in both specimens because it was vital to understand the deformation detection response of the Nylon/Ag strain sensor wire whether the damage occurs near or far from its position. When specimens were subjected to tensile load, the deformation caused tensile stress along the loading axis i.e. 0° because of the elongation and compression stresses in the transverse direction of the loading axis i.e. 90°.



(a) *(b)*

Figure 14: (a) Deformation behavior of star specimen during tensile loading. (b) Schematic representation of Sample 1 with no initial defect and Sample 2 with initial defect

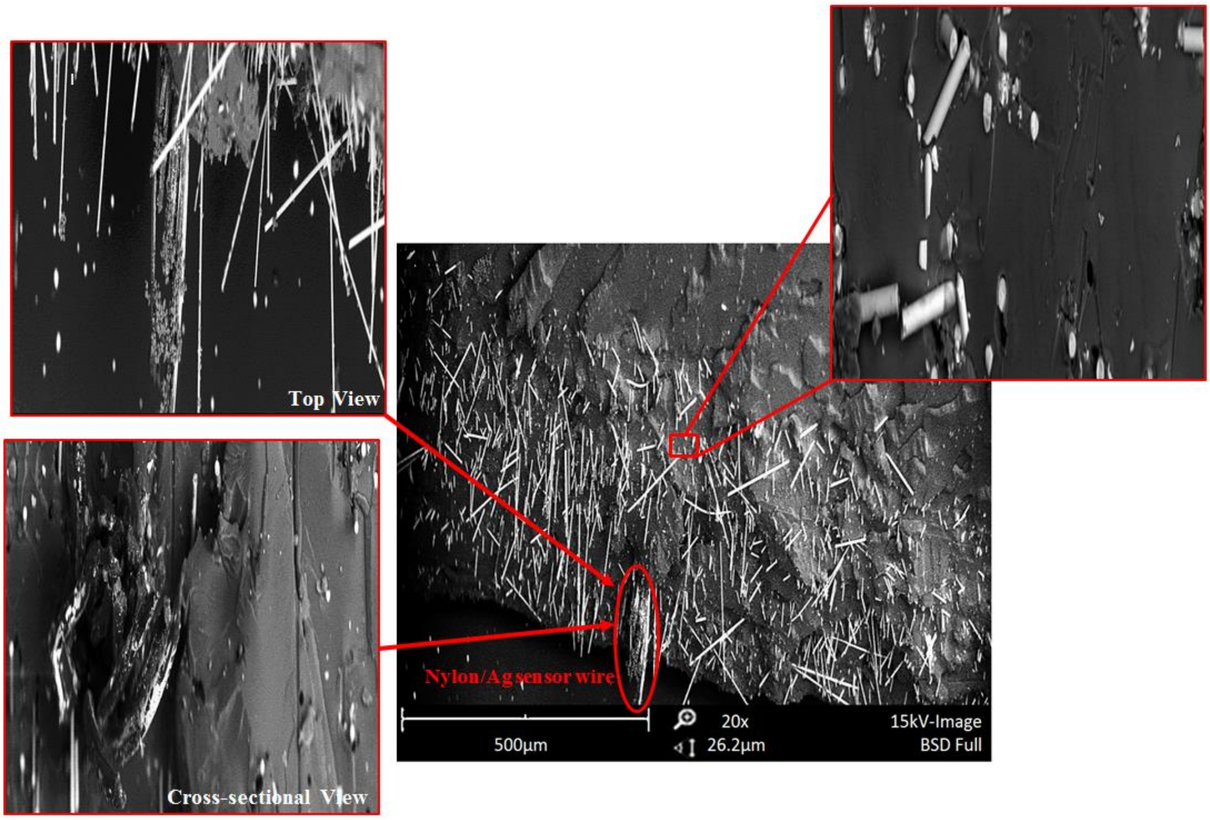
The mechanical response of both samples showed good reproducibility during the elastic deformation and elastic modulus was found out to be in the range of 3.7-3.95 GPa, Figure 15a. Overall mechanical behavior of both specimens showed good reproducibility during elastic deformation, however, the difference observed in the damage and final fracture was because of irregular stress distribution and damage propagation because of the introduction of an intentional defect in sample 2, Figure 15b. The objective of this study was to examine the sensitivity and real-time damage detection response of the designed sensor wire incorporated into the composite specimens that could be subjected to variable damage behavior.



(a) *(b)*

Figure 15: Experimental stress-strain behavior of standard composite specimen with and without initial defect. (a) Calculation of Elastic Modulus of each specimen during elastic deformation which showed reproducible behavior. (b) Overall mechanical behavior of both specimens showed good reproducibility during elastic deformation. The difference in the damage and final fracture was because of irregular stress distribution and damage propagation because of the introduction of an intentional defect in sample 2.

Furthermore, SEM of the fractured surface of each specimen not only showed fractured fibers and matrix but also indicated the position of the Ny/Ag sensor wire (broken), Figure 16a. Then, on further zoom, fractured Nylon/Ag sensor wire was also studied and two distinct morphologies were observed. Almost every filament of the Nylon/Ag conductive fiber showed a clean ductile fracture with both coating and core material, Figure 16b. In addition, some filaments also showed a pullout or breakage of the coating during the tensile strain. This breakage of the coating was because of the strain deformation of the core material during elongation and it was more prominent near the ductile failure of the filaments. The breaking of coating could result in the change of resistance of the sensor wire which would be discussed in detail next section. SEM characterization further confirmed that Nylon/Ag sensor wire was completely integrated within the matrix and between the random orientation of the fibers as a reinforcement with good contact.



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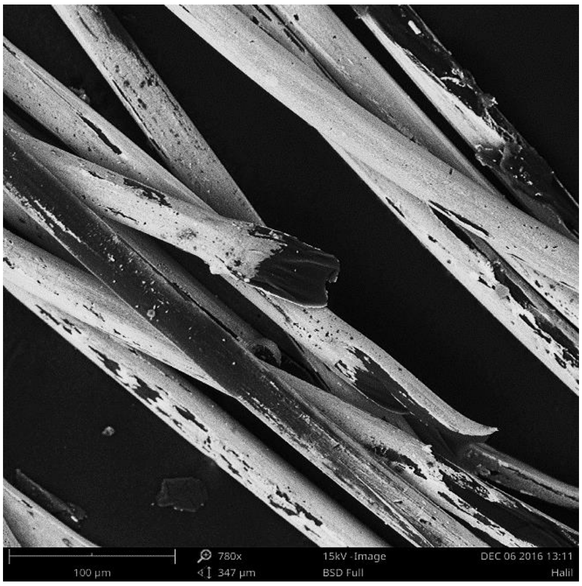

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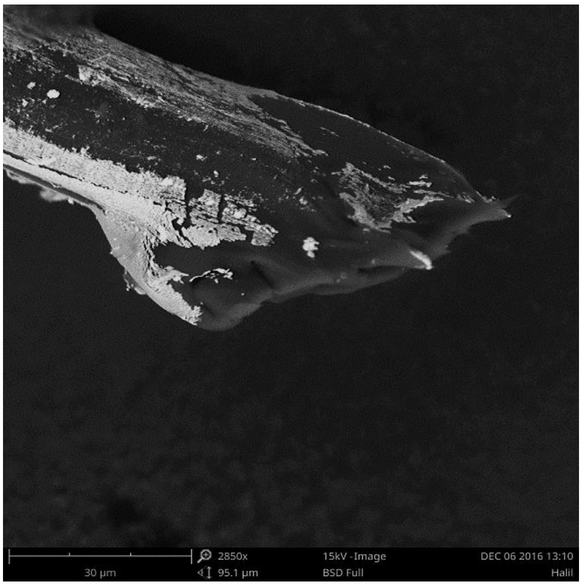

(c)

Figure 16: SEM characterization of the fractured composite specimen integrated with Nylon/Ag sensor. (a) Fractured surface of the composite specimen showed random orientation of fibers in epoxy matrix. It also showed the placement of Nylon/Ag sensor (after fracture) wire from both top and cross-sectional view. (b) shows fracture of Nylon/Ag sensor wire after the failure of composite specimen at 100 µm and 786x zoom (c) shows single fractured filament of the coated yarn at 30 µm and 2850x zoom presenting both ductile fracture and breakage of coating due to elongation.

4.4. Real-time strain monitoring by Nylon/Ag sensor wire in different directions within Composites

i. Strain monitoring behavior of Nylon/Ag sensor and reproducibility of results

Nylon/Ag strain sensor wire showed good electrical signal response during all three mechanical tests of the composite star specimen. The resistance was changing in each case with the gradual increase of the load and sensor wire in all three samples showed a similar response in all 4 directions i.e. 0°, ±45°, and 90°. Electrical response of each Nylon/Ag sensor wire showed change of resistance with increase of strain in the specimen, however, during deformation the strain sensor wire within the specimen showed different behavior because of its position and direction with respect to the loading axis. This showed that it not only monitored the deformation but, also identified it as to whether it was compressive, tensile or both. Test 1 and test 2 were performed by placing the specimen in such a way that sensor A was in the loading direction and sensor C was in the transverse direction while in test 3, the specimen was placed in such a way that sensor C was in the loading direction and sensor A was in the transverse direction.

- Test 1 and Test 2 confirmed the reproducibility of electrical response and the real-time strain monitoring behavior of the Nylon/Ag sensor wire. All sensors A, B, C, and D showed changed in resistance during the deformation and correlated perfectly in both tests, Figure 17. Moreover, it was observed that the maximum increase in resistance was recorded by sensor A which confirmed maximum tensile deformation occurred in the loading direction. However, sensor C showed a decrease in resistance and this negative behavior confirmed the presence of compressive stress and deformation which established the poisson effect during the deformation of the structure. The minimum change in resistance was recorded by sensor B and D and both sensors showed identical response. This identical response of sensor B and D was because of the fact that in isotropic material, these two directions are a mirror of each other with respect to the loading axis.
- Test 3 was performed and compared with Test 1 to check the sensitivity of the Nylon/Ag sensor wire with respect to the loading axis, Figure 18. This comparison was carried out to not only confirm the strain detection response of the Nylon/Ag sensor wire but also showed its sensitivity to the applied load or loading direction. Sensor C recorded the maximum increase in resistance in test 3 because it was placed in the loading direction while sensor A showed a decrease in resistance because it was in a transverse direction with respect to the loading axis. However, sensor B and D showed similar behavior in both tests because of their identical response in both directions i.e. ±45°. In addition, it was observed that the change in resistance was the same in each direction in both tests irrespective of the sensor. For example sensor, A in test 1 and sensor C in test 3 showed a similar change in resistance because both placed along the loading axis. This confirmed that the sensitivity of the sensor was dependent on its position and direction of the applied load otherwise the response of each sensor A, B, C and D can be similar and in every case, the strongest signal was recorded along the loading direction, Figure 19.

In each specimen, the sensor did not only detected the deformation but also distinguished between the type of deformation whether it was tensile or compression.

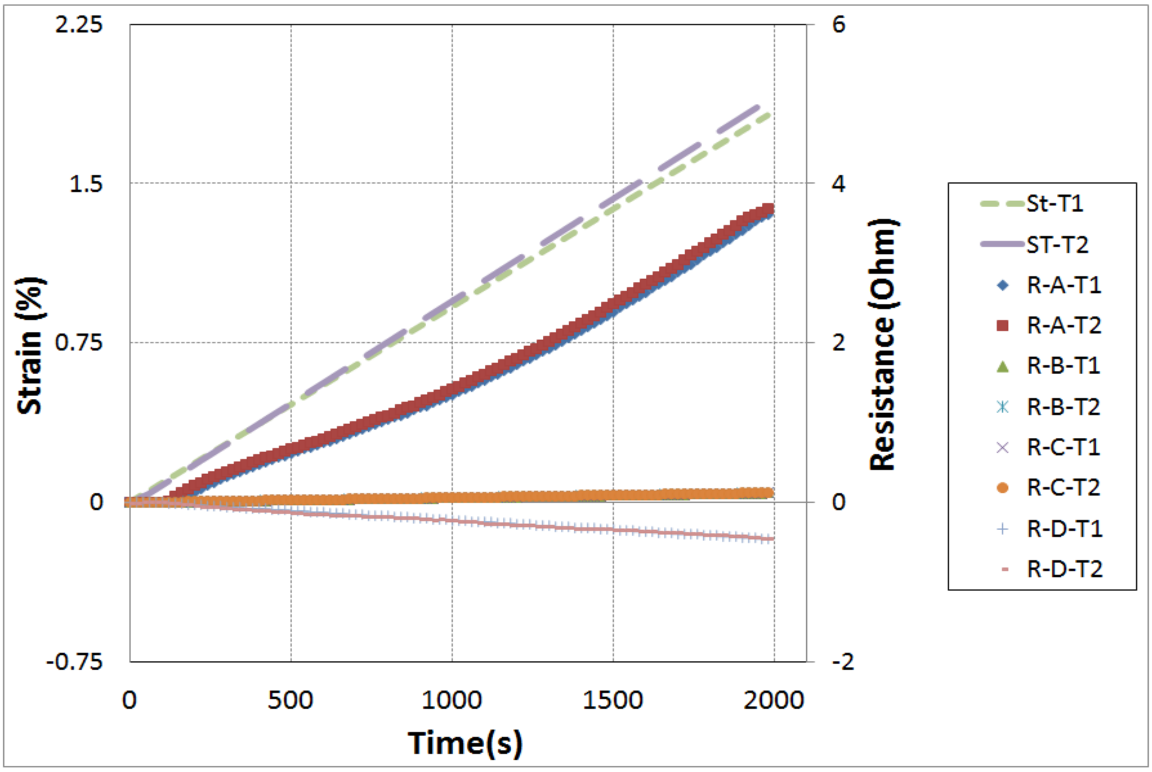

Figure 17: Real-time strain monitoring by Nylon/Ag strain sensor wire in composite Star specimen.

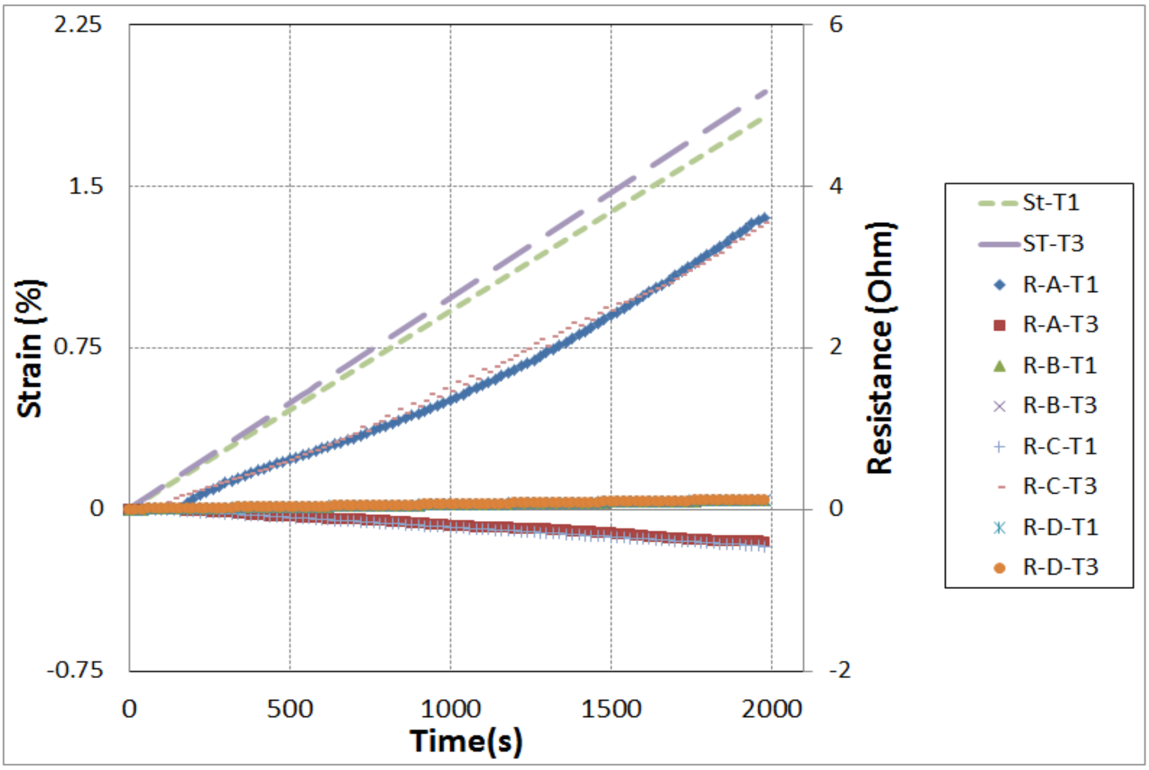

Figure 18: Real-time strain monitoring by Nylon/Ag strain sensor wire. In test-1, sensor A was along the loading axis, sensor B at 45, sensor C at 90° and sensor D in -45° while in test-2 the specimen was placed transversely with respect to the specimen 1 and sensor C was along the loading axis, sensor D at 45, sensor A at 90° and sensor B in -45°.

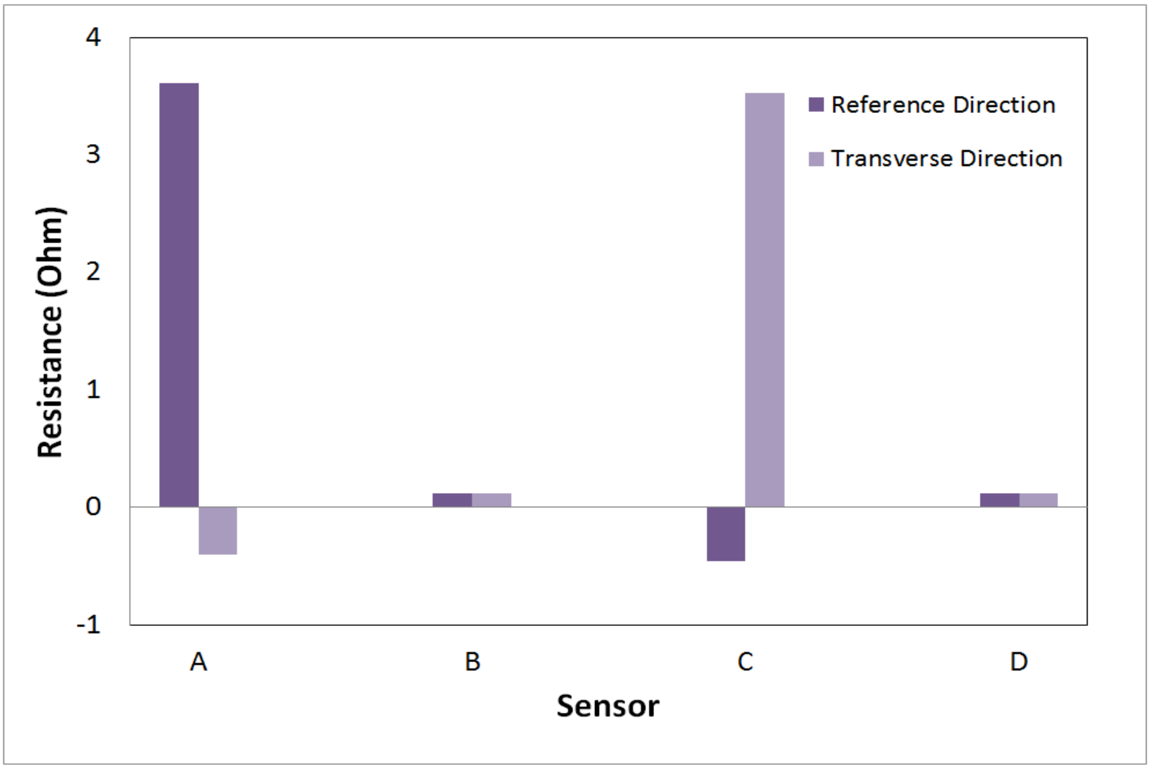

Figure 19: Sensitivity of the Nylon/Ag strain sensor wire with respect to the loading axis

ii. Strain monitoring behavior of Nylon/Ag sensor in Composites under cyclic tensile loading

The cyclic tensile test further confirmed the reproducibility of electrical response and the real-time strain monitoring behavior of the Nylon/Ag sensor wire under the 20 cycles of tensile load. All sensors A, B, C, and D showed changed in resistance during the deformation and correlated perfectly with the applied strain in each cycle, Figure 20. This showed that the Nylon/Ag sensor wire also had stability in the detection response and long-term response cycle. This also verified that this strain sensor wire can be reused unless it is fractured even then; the divided part of the sensor wire could be used as a sensor for damage detection. Moreover, it was observed that the maximum increase in resistance was recorded by sensor A and sensor C showed a decrease in resistance, even during the cyclic loading which confirmed maximum tensile deformation occurred in the loading direction and negative behavior of sensor C confirmed the presence of compressive stress because of the poisson effect. The minimum change in resistance was recorded by sensor B and D as recorded in the previous test and their behavior was also identical during cyclic loading. Moreover, it could be seen that even up to the applied cyclic strain as high as between 1-2% and for 20 cycles the Nylon/Ag sensor wire perfectly correlated with the applied strain in each cycle. This confirmed the durability and stability of the sensor. However, slight diminution with less than 1 % was recorded for the sensor A in comparison with the sensor B, C and D. This reduction was negligible in comparison to the overall behavior during the cyclic loading. Nevertheless, the reason behind this behavior of sensor A was because of the fact that sensor A was placed in the loading direction and was experiencing the maximum effect of the applied strain.

Moreover, the applied cyclic strain was applied between 1-2% which is within the plastic deformation regime. Sensor A might experience minute permanent deformation during cyclic tensile and compressive strain because of the poisson effect during the loading and unloading of the cyclic load.

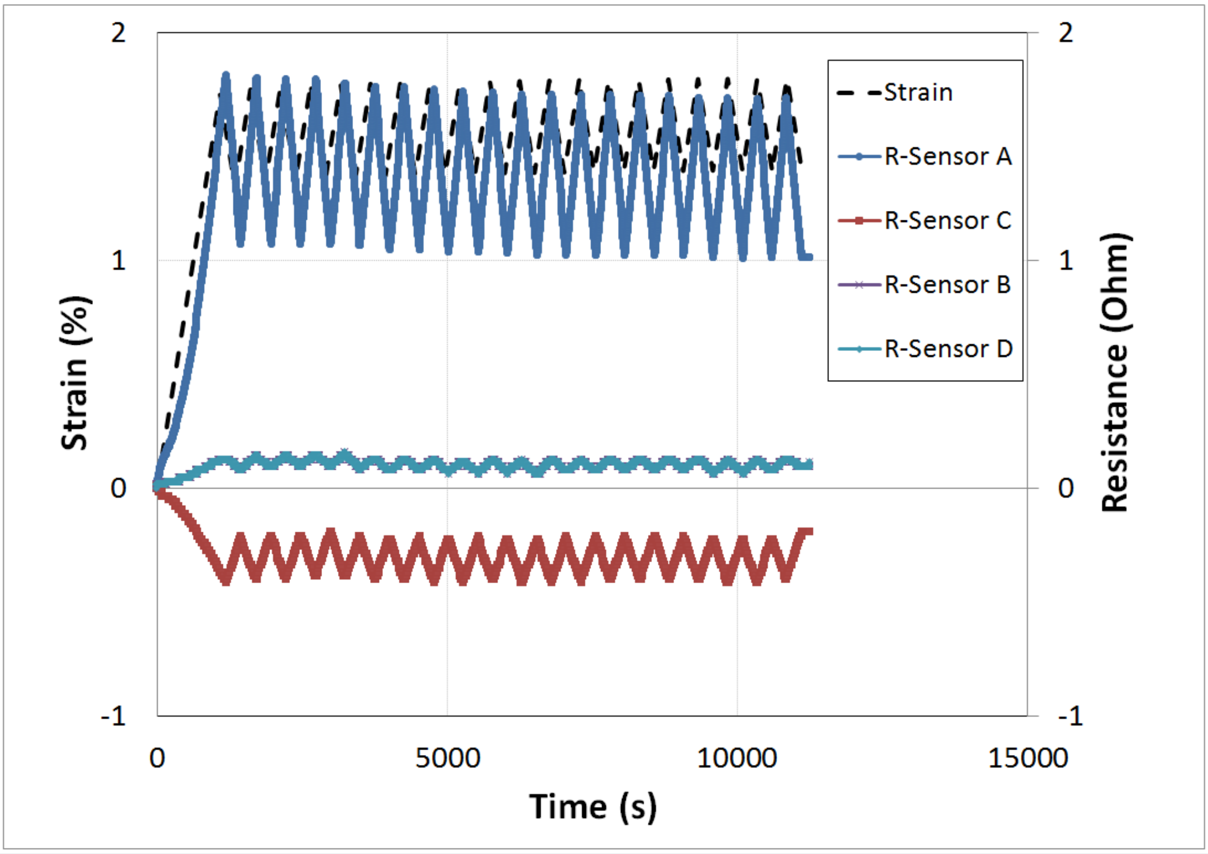

Figure 20: Real-time strain monitoring by Nylon/Ag strain sensor wire in composite Star specimen when subjected to cyclic tensile loading.

4.5. Overall in-situ strain monitoring and damage detection by Nylon/Ag sensor wire within Composites

Both standard specimens with sensor wires in longitudinal and transverse direction showed good electrical signal response during the mechanical loading. The resistance of sensor wire along loading (0°) was changing in each case with the gradual increase of the load, however, the response of sensor wires placed in the transverse direction in both specimens showed a dissimilar response, Figure 21-22. Global electrical response of the sensor wire in each specimen showed a change of resistance with the increase of strain in the specimen and resistance reached maximum value during the crack propagation and final fracture. Each position detected different response and it not only monitored the deformation but also identified it as to whether it was compressive or tensile.

In both specimens, the detection of deformation and final fracture by sensor A placed in 0° was identical. The resistance of the sensor A increased gradually in both cases with the increase of strain and reached maximum resistance upon fracture. Moreover, the increase of resistance of sensor A confirmed the presence of tensile stresses along the loading axis in both specimens.

However, sensor B placed in 90° direction in both specimens showed different overall electrical response. Sensor B in specimen 1 showed a decrease in resistance with the gradual increase of the applied strain which indicated the presence of compressive stresses because of the poisson effect during the tensile loading and then, resistance reached maximum value upon the damage initiation and final fracture because of breakage, Figure 21-22. Sensor B in specimen 2 showed no prominent change in electrical response during the deformation and even upon fracture, a slight increase in the resistance was observed with good sensitivity, Figure 21-22. This change of behavior of sensor B in specimen 2 was because of the fact that damage did not occur in the middle of the specimen where sensor B was placed but occurred near the position of the defect which was introduced during the fabrication. This showed that the placement of the sensor plays a vital role in the monitoring of damage detection. Moreover, the slight increase in the resistance of the sensor B indicated the presence of tensile deformation which confirmed the occurrence of poisson effect near the area of the initial defect before final damage. This also verified that even though sensor B did not detect the damage initiation in transverse direction during deformation of the composite specimen but, it indicated the presence of tensile stresses near its position which could be used as a signal to predict that the sample would not fracture ideally because of the presence of imperfection or defect during the fabrication process.

Moreover, it was observed that the resistance increased progressively during the large plastic deformation or damage initiation and propagation just before the final failure of the specimen which was caused by the breaking off of the conductive layer of Ag during the strain deformation of Nylon yarn (as discussed in the previous section). This phenomenon was the actual concept behind the real-time strain monitoring and damage detection performance of the Nylon/Ag sensor wire. In addition, the SEM images shard in the previous section showed that Nylon/Ag sensor wire was completely inserted within the fibers and matrix of the composite specimen with good contact and it was deforming simultaneously with the composite specimen that is why there was no loss of contact between the sensor wire and the mechanical response of the sensor.

Thus, in each specimen, the sensor did not only detect and identify the failure but it also demonstrated the importance of the damage initiation with respect to the position of the sensor wire in damage detection and prediction. This study can be further continued in the future to study the behavior of the sensor wire during the fabrication process of composites and to detect any imperfection or defect in the sample prior to structural performance.

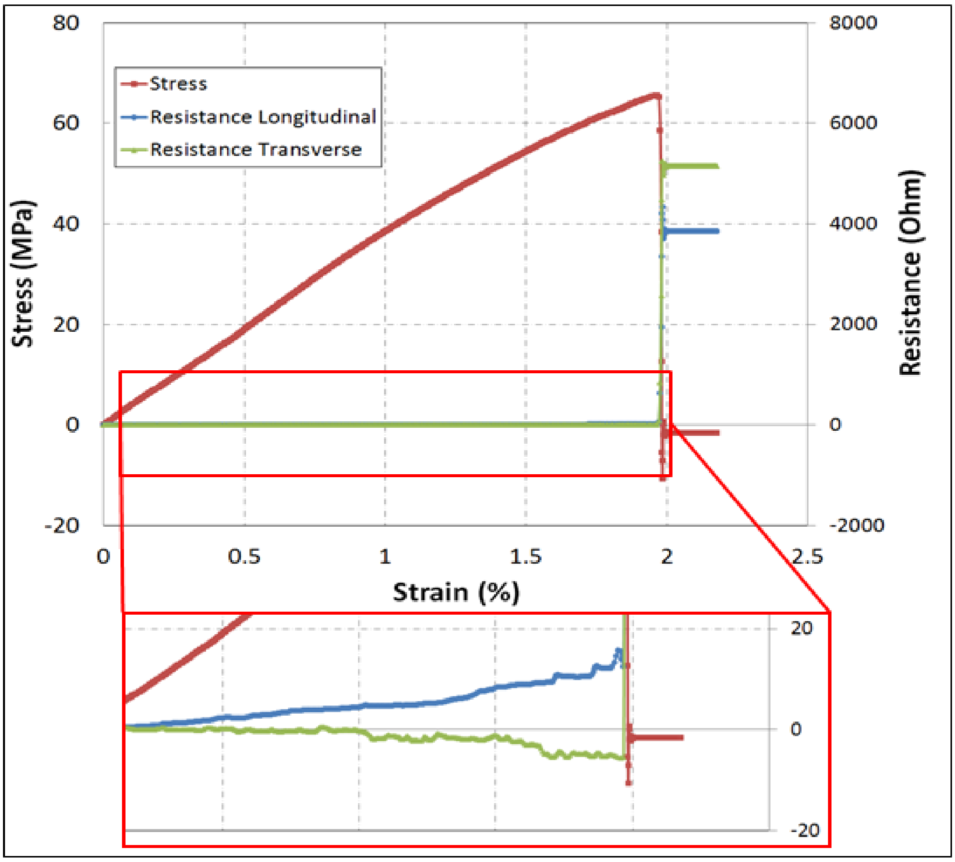

Figure 21: Real-time strain monitoring and damage detection by Ny/Ag strain sensor wire in standard composite specimen 1

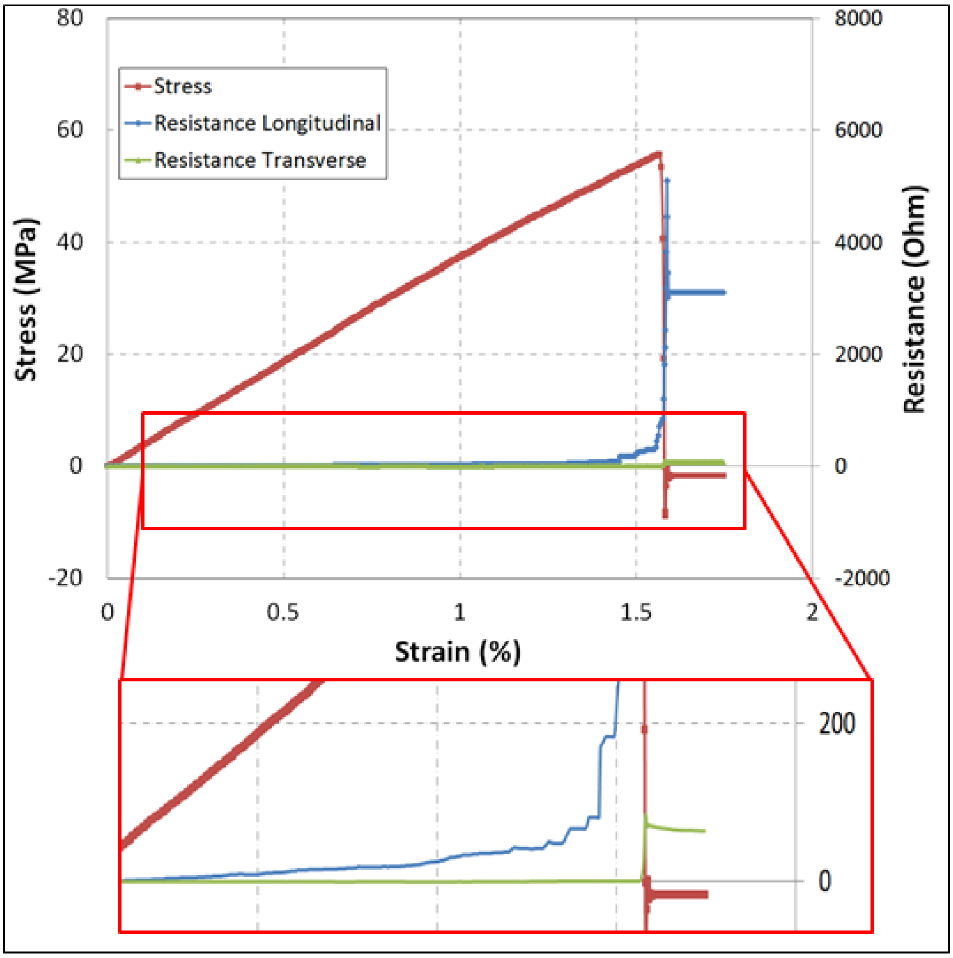

Figure 22: Real-time strain monitoring and damage detection by Ny/Ag strain sensor wire in standard composite specimen 2

Conclusion

In this work, an experimental investigation was carried out to develop a microscale strain sensor wire by depositing nanoparticles of Ag conductive metal on the surface of flexible nylon yarn and to examine its application in real-time monitoring and identification of deformation in composites subjected to tensile load. First, standalone strain sensor wire was tested experimentally showed good sensitivity to applied strain and gauge factor was calculated to be in the range of 21-25. The sensor wire was then inserted in the individual composite specimens at four different locations and directions with respect to the loading axis intentionally depending upon the type of damage to be detected. The experimental results showed good reproducibility in the overall mechanical response of the composite structures and electrical signal of the Nylon/Ag sensor wire in the monitoring of the deformation. Following conclusions were drawn from this study:

- It confirmed the novel concept of using flexible strain sensor wires based on nylon yarn with nanoscale conductive metal coating for in-situ and real-time structural health monitoring.
- The fabrication process was simple, cost-effective and applicable to complex structures such as yarn and SEM images of the Nylon/Ag sensor wire showed a uniform and continuous thin film metal coating of Ag nanoscale particles on the surface of each filament of the Nylon-yarn which confirmed the good conductivity response of the sensor.

- Four Nylon/Ag sensor wires were embedded in 0°, ±45°, and 90° direction with respect to the loading axis in each star specimen subjected to tensile loading which did not only show reproducibility in mechanical response but also showed reproducibility in the electrical signal of the sensor wire in the monitoring of the deformation.
- All four sensor wires placed in each specimen showed variation in the resistance response of the sensor wire because of its different position and direction according to the loading axis and maximum increase in resistance was recording along the loading axis which not only confirmed the detection of tensile load but also predicted that the specimen will most likely fail in this direction.
- The decrease in resistance in transverse direction confirmed the presence of compressive stresses because of the poisson effect during the tensile deformation and this behavior was similar in each test. Moreover, Sensor B and D showed that identical response because of their mirror position with respect to the loading axis, however, their minute change in resistance showed detection of less deformation in the oblique direction during the tensile test.
- Moreover, It could be seen through the experimental results that even up to the applied cyclic strain as high as between 1-2% and for 20 cycles the Nylon/Ag sensor wire perfectly correlated with the applied strain in each cycle. This confirmed the durability and stability of the sensor.
- The overall in-situ damage detection of Nylon-Ag sensor wire in standard composite specimen showed that the placement of the sensor plays a vital role in the monitoring of damage detection. Moreover, this study also verified that even though sensor did not detect the damage initiation in transverse direction of specimen with initial defect during deformation but its signal indicated the presence of tensile stresses near its position which could be used to predict the presence of imperfection or defect during the fabrication process which led to the imperfect fracture.
- The strain sensor wire designed did not only monitor the change in the mechanical behavior of the specimen during tensile deformation but, also identified the type of damage whether it was tensile or compressive.
- Moreover, the results of sensitivity data of the sensor wire with respect to the loading axis confirmed that response of the signal is dependent on the position and the direction in which a sensor is a place for monitoring the damage.
- In addition, Nylon-Ag sensor did not only detected and identified the failure but it also demonstrated the importance of the damage initiation with respect to the position of the sensor wire in damage detection and prediction. This study can be further continued in the future to study the behavior of the sensor wire during the fabrication process of composites and to detect any imperfection or defect in the sample prior to structural performance.

This Nylon/Ag strain sensor wire showed good potential as a flexible reinforcement in composite materials for real-time monitoring, detection, and identification of damage. Moreover, this study also showed that it is possible to detect the damage whether it is within the direction of applied load or not by studying the response of the Nylon/Ag sensor wire.

This study was performed using chopped fiber fabric to ensure isotropic behavior of the composite but can be extended to directional composites to understand the damage detection response of the strain sensor wire under more complex deformation.

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