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"Geometric Parameter effects on the design of Yarn based Strain Sensor "

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Résumé :

Le contrôle de l'état structural et la détection des défauts géométriques en temps réel sont l'objectif principal du chercheur afin d'éviter une défaillance catastrophique et des coûts de réparation importants. Pour cela, plusieurs travaux de recherche ont été menées pour développer des capteurs in situ et des systèmes de surveillance adaptés et efficaces pour différentes applications. Dans cette étude, un capteur à base de fibre de nylon enrobée d'argent est étudié numériquement à l'aide du logiciel ABAQUS. Le comportement électromécanique du capteur a été étudié en utilisant l'analyse du champ couplée sous une contrainte de traction, tandis que la résistance électrique a été mesurée durant le chargement mécanique. Des critères d'endommagement du nylon et de l'argent sont mis en œuvre pour quantifier l'effet de la présence des dommages sur les performances électromécaniques de ce capteur. Après une corrélation MEF/essais et une validation du modèle numérique du comportement électromécanique d'une seule fibre, une étude paramétrique a été réalisée pour quantifier l'effet du nombre de fibres, du nombre de nœuds de torsion et de la longueur du fil sur le comportement électromécaniques du capteur. Les résultats donnent les paramètres optimaux pour la conception d'un détecteur à base de fibres de nylon enrobés d'argent. Ces détecteurs ont la particularité de suivre l'état de contrainte/déformation ainsi que l'initiation et la propagation des dommages dans les structures d'une façon générale et plus particulièrement les structures composites.

1. Introduction

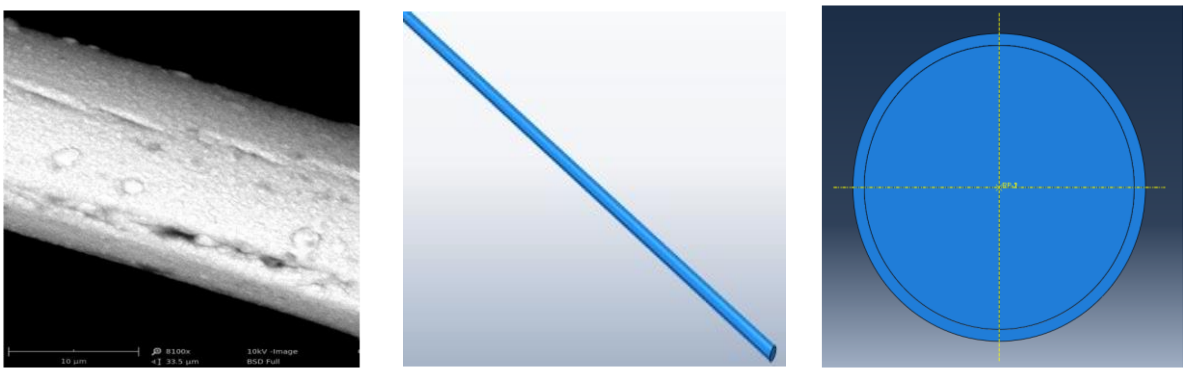
Structural health monitoring (SHM) is an evolving technique to examine and control the 'health' condition of composite materials and avoid catastrophic failure [1]. That is the reason why the need of SHM have been continuously increasing with the passage of time. The potential advantages of SHM consist of improving safety and reliability, helping in material design and dropping lifecycle costs. Vast research has been conducted in developing SHM sensors over the past decades which include strain gauges with strain resistance effect, fiber optic sensors which work on the principle of phase shift of relative optic waves, piezoelectric sensors which can be employed as both actuators and sensors, and microelectromechanical systems (MEMS) system which can sense the circumstances and do responses by the microcircuit control [2] [3] [4] [5]. But these sensors have limitations such as strain gauges can be viewed as inclusions and behave as a defect, fiber optic sensors require lot of instrumentation and data analysis, piezoelectric sensors are made of brittle material and manufacturing of MEMS is difficult [6] [7] [8].

In this study, a new SHM technology is developed and presented for the follow-up of the life cycle of a composite structure. The overall goal is to study different parameters which play vital role in designing a conductive wire that functions like resistance strain gauge. A FEM approach is presented to study the mechanical behavior of multifilament twisted flexible yarn sensor using ABAQUS CAE. The electromechanical analysis on single fiber is performed and then a parametric study based on number of fibers in yarn and number of twists in yarn has been conducted to analyze their effect on stress-strain relation of the yarn.

2. Modelling Strategy

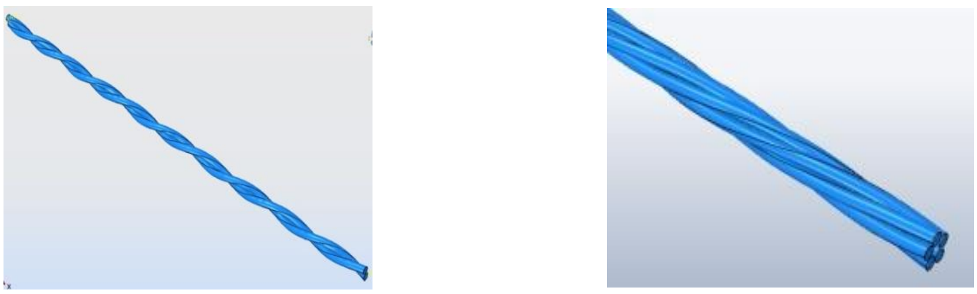
1. Geometry

Silver coated nylon-6 monofilament of 2mm in length was created first as shown in Figure 1 to design and study the numerical model in electrical-mechanical coupled field. Diameter of a single filament of nylon and silver coating was approximated from the SEM images of the prepared samples and literature as shown in Figure 1 (a). The diameter of nylon yarn is less than 24 µm and coating is approximated as almost 1-2% of nylon diameter. Then geometric variations were carried out to understand the effect on mechanical properties. Geometric parameters include number of twists, number of filaments and length have been shown in Figure 2. Figure 2a and Figure 2b show the yarn with five twists and five fibers respectively.



(a) Real geometry *(b) Modeled geometry*

Figure 1: Single Coated Filament (a) SEM image of single coated nylon filament with silver (b) CAD model of single filament



(a) Five Turns *(b) Five Filaments*

Figure 2: Geometric Parameter: Yarn with Number of Twists, Number of Filaments and Pitch Length

2 Material Properties

Literature studied was conducted for the material model of nylon and pure silver. Material model for both materials was divided into two categories i.e. Mechanical properties and Electrical properties. All the units were converted into SI unit system. These properties are taken from the study performed by Huang and Spaepen [9] for silver and by Wang and Naderikalali [10] for nylon 6.

Nylon 6 and silver both behave as ductile materials. Therefore, ductile damage criteria define in Abaqus CAE has been used for the failure of the monofilament sensor. The damage criterion is dependent on the experimental tensile procedure. Fracture strain, displacement at strain, strain rate and stress triaxiality are the important parameters required to define it for both materials.

Electrical conductance value for pure silver and nylon 6 were taken from the literature and are given in the table 1.

Table 1: Electrical Properties

Material	Electrical Conductance (S/mm)
Nylon 6	1x10-15
Silver	63x103

3. Boundary Conditions

For coupled mechanical-electrical field analysis, the geometry was fixed from one end in all direction and a displacement was applied on the other end in x-direction. For electrical behavior, and electrical potential i.e. voltage of 12V is applied on the both ends of the yarn and the variation in current density along was studied. Moreover, for more illustration the applied boundary conditions are displayed in Figure 3

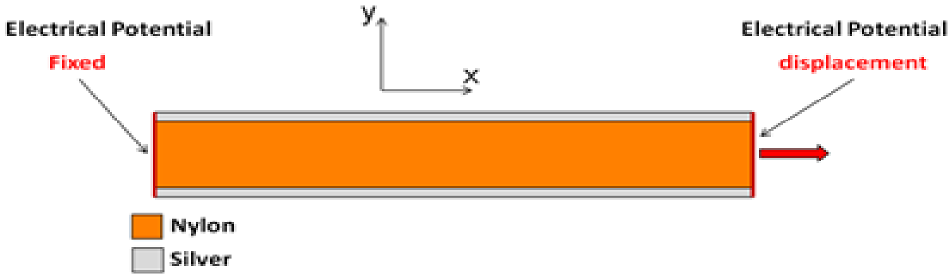
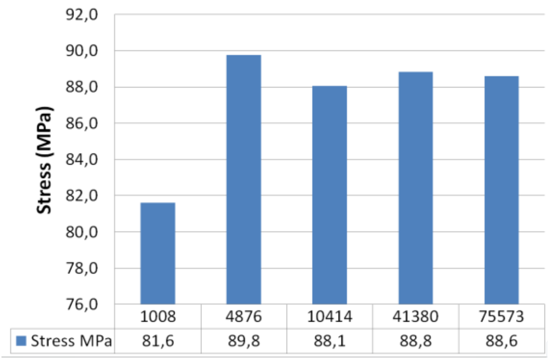


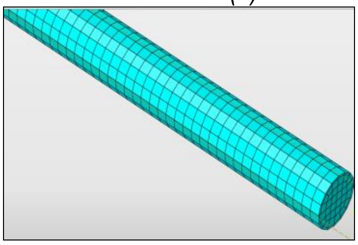
Figure 3: Illustration of Boundary Conditions

4. Mesh

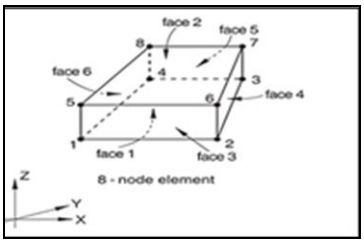
Mesh refinement was performed on the model to eliminate the dependency upon the mesh. Before launching finite element calculations to evaluate the mechanical and electrical behavior of the monofilament yarn sensor, it is important to ensure the convergence of the mesh. For this, 5 mesh sizes are considered and studied 0.05, 0.01, 0.008, 0.005 and 0.004mm. Mesh convergence study is performed on maximum stress so that the results become independent of the element size, Figure 4a. As it can be seen that mesh convergence is achieved at 0.008 but, for better accuracy mesh size-0.005 is used, Figure 4b. Q3D8 element type is used for the electromechanical behavior, Figure 4c.



(a) Mesh Convergence Study- Maximum Stress



(b) Mesh Size=0.005

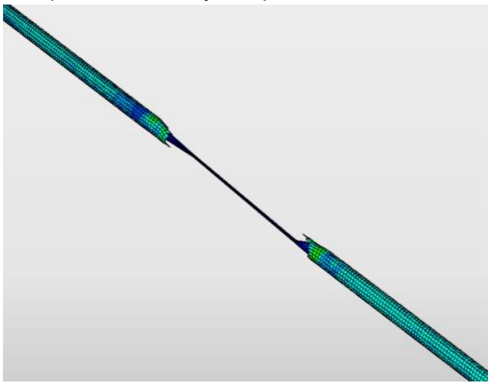


(c) Q3D8 Element type [9]

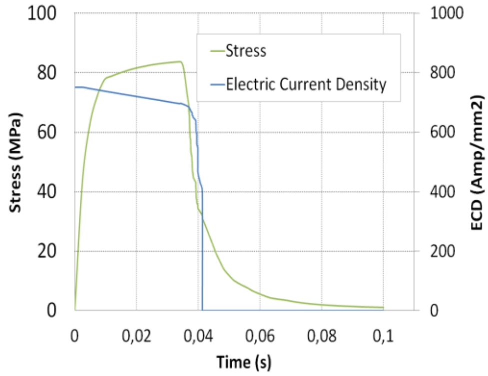
Figure 4: Mesh Convergence, Mesh Size with structured mesh and Element Type that are used for coupled field analysis

3. Result and Discussion

The monofilament sensor was subjected to tensile elongation until failure, Figure 5a. The ductile damage behavior can be seen in both materials however, the coating failed before the core material. This phenomenon is because coating in comparison to the core, has very small cross-sectional area. Electromechanical behavior of the monofilament can be observed in Figure 5b. Current flow in the filament is affected when it starts to fail. This not only confirms the sensing behavior in a coated yarn sensor numerically but also shows that electrical behavior only dominates at failure. So, to design a sensor with good mechanical properties, it is important to study the parameters which can affect the mechanical behavior of yarn sensor



(a) Monofilament sensor wire after failure



(b) Stress & ECD w.r.t time Curve

Figure 5: Monofilament Wire Sensor Model and Electromechanical Behavior of the Monofilament Wire

1. Parametric Study

The results of parametric study have shown some very interesting phenomena during the numerical analysis. Geometrical parameters have great effect on the behavior of yarn. The results are summarized as effect of number of twists, number of filaments and variation in pitch length on elastic-plastic behavior of yarn.

Number of Twists

The model with variation of number of twists ranging from 0 to 5 is a yarn of two coated filaments twisted together with 2mm pitch length. With same boundary conditions, this geometrical variation has shown some interesting results. Figure 6 shows the overall mechanical behavior of the yarn in terms of force-displacement curve. These curves have shown that yarn with zero turns show perfect elastic plastic behavior but as the number of twists increase the behavior of the curves changes to nonlinear. There is a linear increase in delay at the start of the analysis as the number of twists in the yarn increases. This showed that as the number of twists increases the interlocking between the filaments increases and hinders the elongation of the yarn.

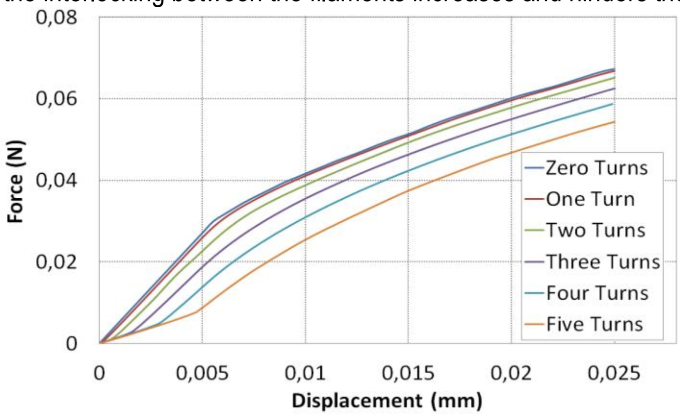


Figure 6: Overall Force-Displacement w.r.t Number of Twists

Number of Filaments

The model with variation of number of filaments ranging from 1 to 5 consists of two coated filaments, 2mm pitch length and two twists with applied displacement of 0.01mm. With same boundary conditions, this geometrical variation has shown some interesting results. The overall force displacement curves showed that by increasing the number of wires in the model the force displacement curve becomes steeper and the linear delay in the start of the curve increases, Figure 7.

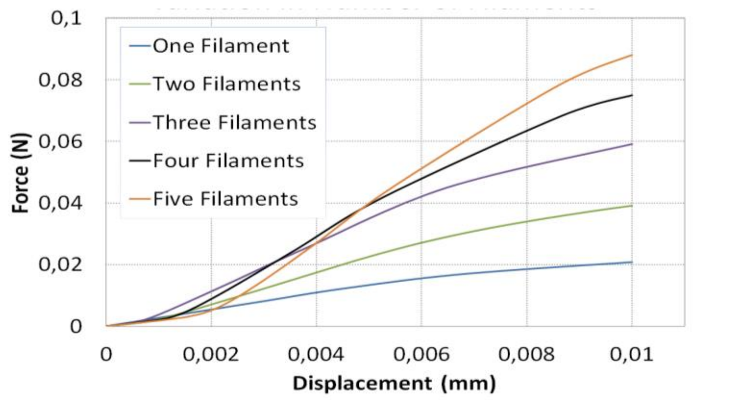


Figure 7: Overall Force-Displacement behavior w.r.t Number of Filaments

4. Conclusion

In this study, the electromechanical behavior of a coated yarn is studied numerically in coupled field analysis using CAD/CAE. The electromechanical behavior is verified using a monofilament of nylon6 with silver coating using ductile failure criterial under tensile loading. Variation of ECD with Stress has shown promising results. Furthermore, it has been shown that geometric parameters play vital role in the designing of yarn sensor. Geometric parameters such as number of twists and number of filaments affect the mechanical behavior of the yarn. This therefore, shows that these nonconductive but cost affective polymeric nylon yarns can be used as sensors for structural health monitoring in different applications with conductive coating. Also, by altering the geometry of the yarn, one can design a yarn sensor with better mechanical properties with further reduction in the cost.

5. Bibliography

[1] IHN, Jeong-Beom; CHANG, Fu-Kuo. *Pitch-catch Active Sensing Methods in Structural Health Monitoring for Aircraft Structures*, Structural Health Monitoring, 2008, vol. 7, nº 1, pp. 5-19.

[2] LOAYSSA Alayn, *Optical Fiber Sensors for Structural Health Monitoring*, in New Developments in Sensing Technology for Structural Health Monitoring, MUKHOPADHYAY, Subhas Chandra, Ed., Heidelberg, Springer, Berlin, Heidelberg, pp. 335-358, 2011.

[3] LIN Bin and GIURGIUTIU Victor, *Modeling and testing of PZT and PVDF piezoelectric wafer active sensors*, Smart Materials and Structures, 2006, vol. 15, n° 4, pp. 1085-1093.

[4] RAGHAVAN Ajay; CESNIK Carlos E. S. *Review of Guided-wave Structural Health Monitoring*, The Shock and Vibration Digest, vol. 39, no. 2, pp. 91-114, 2007.

[5] ZILBERSTEIN Vladimir; WALRATH Karen; DAVE Grundy; SCHLICKER Darrell; GOLDFINE Neil; ABRAMOVICI Eugen; YENTZER Tom, *MWM Eddy-Current Arrays for Crack Initiation and Growth Monitoring*, International Journal of Fatigue, vol. 25, no. 9-11, pp. 1147-1155, 2003.

[6] SPECKMANN H., HENRICH R. *Structural Health Monitoring (SHM) - Overview on Technologies under Development*, in 16th WCNDT 2004 - World Conference on NDT, Montreal, Canada, Aug 30 - Sep 3, 2004.

[7] CHRISTIAN Boller, *Next Generation Structural Health Monitoring and its integration into Aircraft Design*, International Journal of Systems Science, vol. 31, no. 11, pp. 1333-1349, 2000.

[8] VARADAN Vijay K.; VARADAN Vasundara, *Microsensors, Microelectromechanical Systems (MEMS), and Electronics for Smart Structures and Systems*, Smart Materials and Structures, vol. 9, no. 6, pp. 953-972, 2000.

[9] HUANG Haibo and SPAEPEN F., *Tensile Testing of Free-Standing Cu, Ag and Al Thin Films and Ag/Cu Multilayers*, Acta Materialia, vol. 48, pp. 3261-3269, 2000.

[10] WANG Xin, KALALI E. Naderi, WANG De-Yi, *An in-situ polymerization approach for functionalized MoS2/nylon-6 nanocomposites with enhanced mechanical properties and thermal stability*, Journal of Materials Chemistry A, no. 48, 2015.