Integration of long-gage fiber-optic sensor into a fiber-reinforced composite sensing tape

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ABSTRACT

Thermoplastic and thermoset fiber-reinforced composite materials are well established in aerospace engineering, but also more and more used in the oil and gas industry as well as in civil engineering. In these applications they are mainly used to reinforce, repair or straighten existing structures, but recently full-composite structures have also been built. Independently from the domain of the use, there is a need for these composite structures to be monitored. Since the composite materials are usually applied in form of thin tapes or sheets, sensors have to be embedded within the structure, depending on structural layer that has to be monitored. Embedding the sensors may have as a consequence a significant decrease of the mechanical properties of the composite material due to the dimensions of the sensor. The solution presented in this paper is integration of a fiber optic sensor directly into the main composite component, i.e. into the composite tape. In this paper we present the development of a thermoplastic fiber-reinforced composite tape with integrated long-gage fiber-optic sensors. The fiber-optic sensors are selected due to small transversal dimension and good compatibility with the plastic materials. The tape with integrated optical fiber can be used for tape winding of a structural element, embedded between different layers, but also as a separate sensor – a sensing tape. The optical and mechanical properties of the tapes with sensor are tested. The sensing tape is then installed onto the rail along with standard long-gage fiber optic sensor, additional tests are performed and performance of both sensor compared. The integration of optical fiber into the composite tape, the results of the tests as well as the performances of the tape with integrated optical fiber are presented in this paper.

Keywords : Fiber-optic sensing tape, fiber-reinforced composites, long-gage interferometric sensors.

INTRODUCTION

The new domains of the use of thermoplastic and thermoset composite materials, notably in gas and oil industry[1] and civil engineering[2] created a need for appropriate monitoring systems. The aim the monitoring systems is to register in permanence the parameters important for proper functioning of structure and in-service condition. Collected data helps cost effective management[3] and increase safety[4].

The main components of a monitoring system are the sensors, accessory equipment (connection boxes, cabling, connectors, etc.), reading unit and software for data processing and post-processing (see Figure 1). While the reading units, accessory equipment and software of existing monitoring systems can be used in composite monitoring with practically no modifications, the sensor itself has to be modified and adapted to the host material. Fiber optic sensors are provided with good specification for this application. Their material compatibility with composites, and small transversal dimension (diameter of cross-section) make them less intrusive compared with traditional, electrical sensors. The composite materials are often applied in form of thin tapes or sheets. The sensors are to be embedded within the structure, depending on structural layer that is to be monitored. Improper embedding of the sensors may be a source of delaminating that has as a consequence a significant decrease of the mechanical properties of the composite material.

The sensor can also be installed onto the surface of the structure, and in this case the optical fiber has to be protected against environmental influences.

On the other hand, if the sensor is designed to monitor the strain or deformation, it is necessary to guaranty a good bonding of optical fiber with the composite, i.e. to guaranty good transfer of strain from the host material to the sensor. Hence, a natural solution is to first safely embed the optical fiber into the composite tape, and then to apply the tape itself as a construction material. Moreover, the tape gives to the optical fiber necessary protection against an accidental damaging during handling and installation. The fiber-reinforced composite tape with integrated optical fiber is called a sensing tape. Development, testing, application and performance of a sensing tape designed to be used with SOFO deformation monitoring system is presented in this paper.

INTRODUCTION TO SOFO SYSTEM

The monitoring system SOFO[5] (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) is based on low-coherence interferometry in optical fiber sensors. It consists of sensors, a reading unit and data acquisition and analysis software. The sensor consists of two optical fibers called the measurement fiber and the reference fiber, both contained in the same protection tube. The measurement fiber is coupled with the host structure and follows the deformations of the structure. In order to measure shortening as well as elongation, the measurement fiber is pre-strained to 0.5%. The reference fiber is loose and therefore independent of the structure's deformations; its purpose is to compensate thermal influences to the sensor. Typical sensor length (gage-length) ranges from 250 mm to 10 m, while the resolution reaches 2 μm independent of the gage-length and with an accuracy of 0.2%. The dynamic range of the standard sensors is 0.5% in compression and +1.0% in elongation.

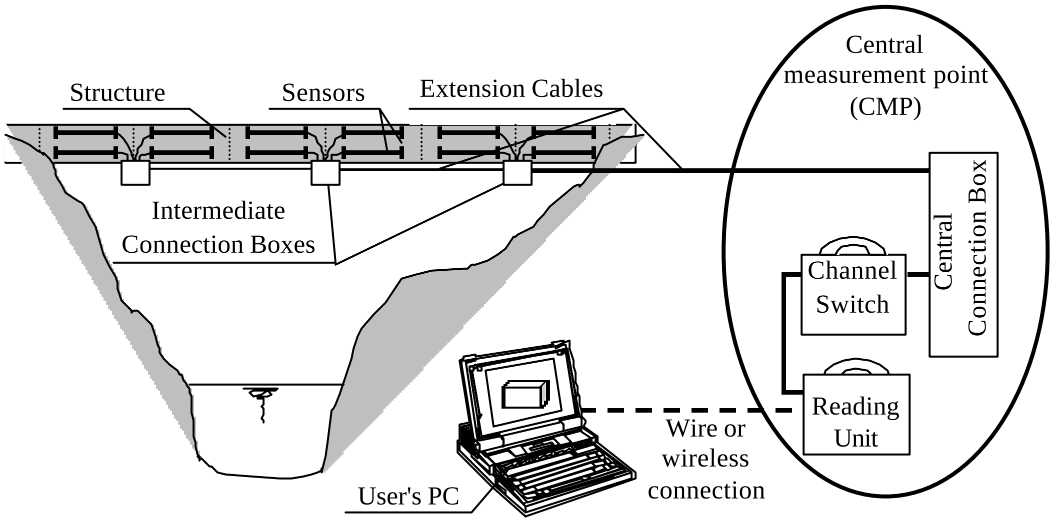

Figure 1: Components of the SOFO system

The SOFO system was developed in early 1990's and since 1995 it has been commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few[6]. The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift, making it ideal for both short- and long-term monitoring (estimated long-term stability is up to 20 years). The long gage-length makes the sensors more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by local defects in material such as cracks and air pockets. More information on the SOFO system and its applications can be found in references [5] and [6].

DESIGN CRITERIA FOR SENSING TAPE

The measurement fiber (optical fiber dedicated to average strain measurements) is to be in permanent mechanical contact with the host structure in way that straining of the last one will generate the straining of the former one. The transfer of strain is to be full, with no losses due to sliding. Therefore an excellent bonding between strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding it has been recommended to integrate the optical fiber within the tape in the similar manner as the reinforcing fibers are integrated. Since this involves heating to high temperature (in order to melt the matrix of composite material) it is necessary for fiber to withstand this temperature without damage. In addition the bonding between the optical fiber coating and the matrix is to be excellent. The polyimide coated optical fiber fits to presented requirements.

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing of composite structures in range of ten to twenty millimeters, and therefore is not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fiber, and there is a risk that the optical fiber will emerge from the tape. The schema of the sensing tape cross-section, with typical dimensions, is presented in Figure 2.
The use of the sensing tape is twofold: it can be used externally attached to the structure, or embedded between the composite laminates, having also a structural role. Regardless the use, the optical fiber is to be integrated into the composite tape in the same manner.

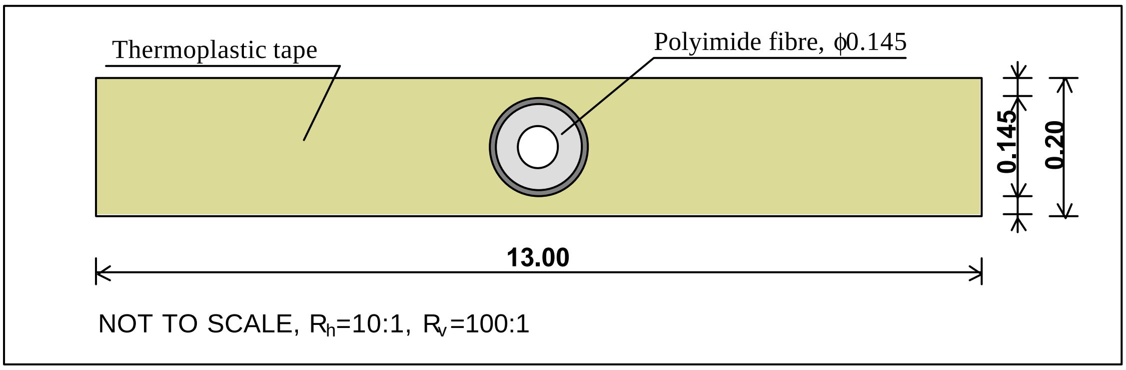

Figure 2: Cross-section of the sensing tape

MANUFACTURING OF THE SENSING TAPE

A bench of the sensing tape prototype was produced in order to perform necessary tests on interaction of optical fiber and tape, and to determine mechanical and optical performance. It was produced using the "sandwich" technique: two half-thickness (~0.10 mm) glass fibers reinforced thermoplastic tapes were produced first, then the optical fiber was placed between them, and finally tapes and optical fiber were assembled under high pressure and temperature. The unidirectional glass fibers (type G2) reinforced thermoplastic tape with PPS matrix was used. The schema of production is presented in Figure 3.

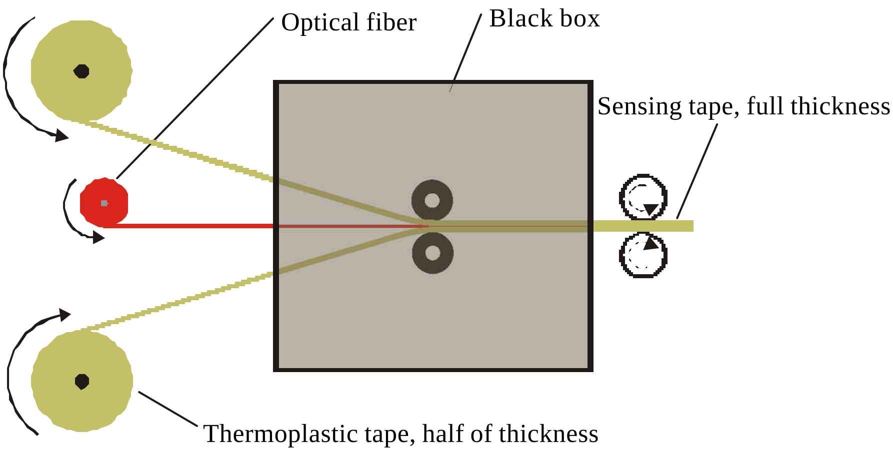

Figure 3: Production of the sensing tapes using the "sandwich" technique

This procedure was selected in order to keep the optical fiber in the center of the sensing tape cross-section, i.e. to prevent eccentricity of the optical fiber with respect to both horizontal and vertical axis (see Figure 2). The first bench of was tested optically, microscopically and mechanically.

TESTING OF THE SENSING TAPE

Optical tests

The aim of the optical test was to evaluate for the sensing tape the suitability to be used as a sensor. The optical losses are not critical for functioning of the sensor, since based on interferometry, but it is important that the fiber is not damaged or broken and that no excessive attenuation occurred.
In order to perform optical tests, the optical fiber was extracted from the tape and connectorized. Red visible light was inserted at one and observed at the other end of the tape, as shown in Figure 4.

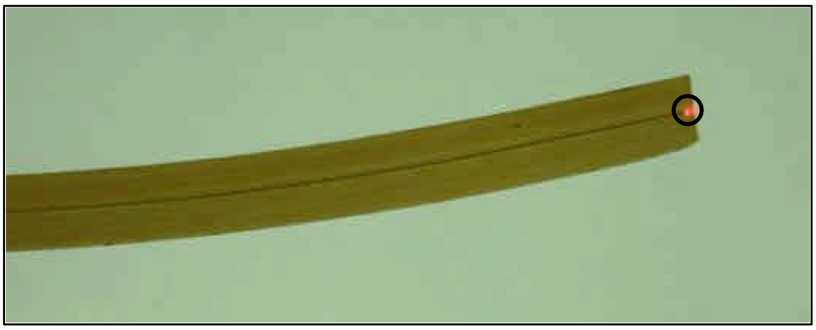

Figure 4: Sensing tape with inserted visible light (encircled)

When the test with visible light confirmed that the optical fiber was not broken, the other end was also connectorised. Both ends were connected to the backreflection meter and the optical losses of the light used for sensing purposes (1300nm) are evaluated. This test demonstrated extremely high attenuation of light. The attenuation was so high that the optical signal was practically not measurable at the end of 100m long tape. The following reasons could be in origin of attenuation:

1. Ovalisation of optical fibre cross-section (less probable);
2. Microbending due to crossing with reinforcing glass fibres;
3. Microbending due to shrinkage of matrix.

However the attenuation was not of importance on the shorter lengths of tape and therefore, from the optical point of view, the tape with length in range of meters could be used for the sensing purposes.

Microscopic tests

The microscopic tests were performed in order to verify the vertical position of the optical fiber in the cross-section (1), to detect possible delamination caused by integration of optical fiber (2) and to find out if the source of the losses in geometry of the optical fiber (3). The microscopic analysis was performed on 14 samples of the cross-section along the 15 meters long sample. The most important results are presented in Figures 5 and 6.
The position of optical fiber was not in the middle of the cross-section and up-and-down variations were observed (see Figures 5 and 6). The optical fiber was mainly surrounded with the composite material, as shown in Figure 5, and this arrangement characterized 13 samples (out of 14). No delamination was noted but, different amount of glass-reinforcing fibers surrounds the optical fiber and in 3 cases only very thin layer of composites protects the optical fiber (~0.01 mm).

The emerging of the optical fiber, as well as delamination of composite, was perceived on only one sample. Therefore, this anomaly is considered as local, and can be improved using better control of manufacturing process. This cross-section with the anomaly is presented in Figure 6.

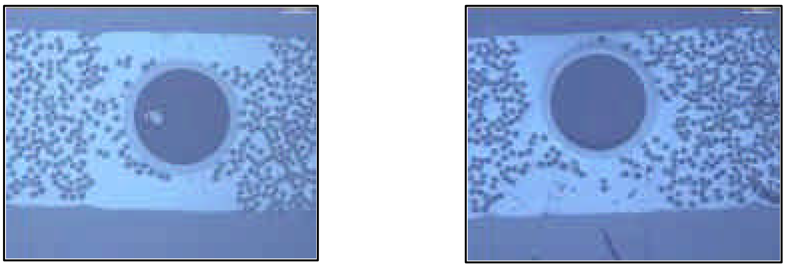

Figure 5: Cross-section in limits of tolerance – no emerging of optical fiber from tapes

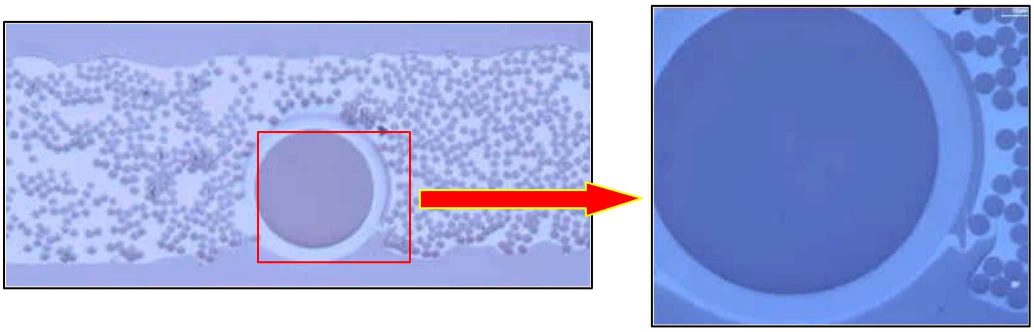

Figure 6: Optical fiber emerges from the tape at bottom of the cross-section; delamination is observed in close up.

The ovalization of optical fiber was not detected and therefore it is not the cause of the attenuation of the light. Also, neither horizontal microbending nor intersection with reinforcing fibers was observed. Therefore the possible source of attenuation is microbending in vertical direction due to shrinkage of the matrix after the cooling. This microbending can probably be avoided by pre-straining the optical fiber during the manufacturing process.

Mechanical tests

Three 17 cm long samples of the sensing tape were connectorized and provided with mirrors, in order to be transformed in sensors. The samples were put in traction using the testing device and deformations of the samples were registered using both, SOFO system and traditional micrometer measurements. The aims of mechanical tests were to compare measurements performed with the SOFO with these performed with micrometer in order to detect the sliding of the optical fiber (1), to determine the range of the sensing tape (2) and to verify mechanical properties of the tape (3). The samples were tested to linearity, repeatability, relaxation (creep) and maximal elongation. The samples before the tests and the testing device are presented in Figure 7.

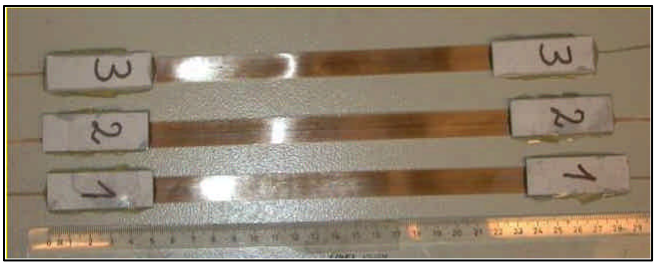

Figure 7: Sensing tape samples before the test (left) and set-up for traction (right).

As an example, the stress-strain diagram obtained from both, micrometer and sensing tape measurements on a sample #1 is presented in Figure 8. The gage lengths of the sensing tape and the micrometer were 186 mm and 130 mm respectively. Therefore the average strain given by each instrument is calculated as measured deformation divided with gage length and transformed in micro-strain [με]. The average strain is calculated as a measured force divided by the area of the cross-section of the sensing tape.

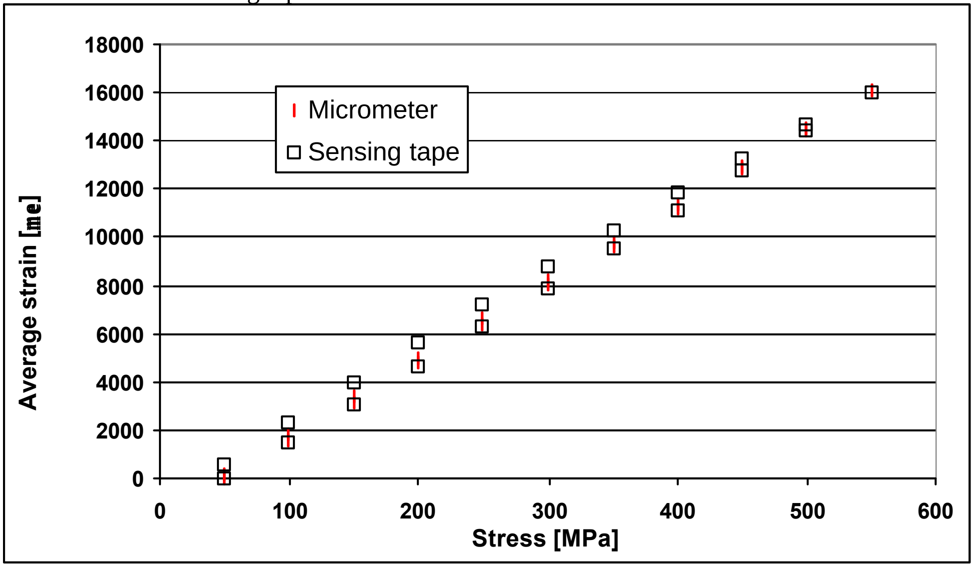

Figure 8: Strain-stress diagram of the sensing tape obtained using both, micrometer and sensing tape as a SOFO sensor

Hysteretic behavior of the sensing tape is noted, and is consequence of plastic properties of the composite materials. Since the tape, when used as a sensor, will be in permanent contact with the monitored structure, and the strain will be imposed from the structure to the tape, this hysteric behavior will not affect the measurement.
Maximal dynamic range was better than 3%. At approximately 3% the sensing tape was broken, which corresponds to specifications of the tape without optical fiber. The linear correlation coefficient between the tape and the micrometer during the force rising (straight part of the diagram in Figure 8) was 1.003 and the degree of correlation was R^2=0.99992. The linearity between the micrometer and sensing tape measurements is presented in Figure 9.

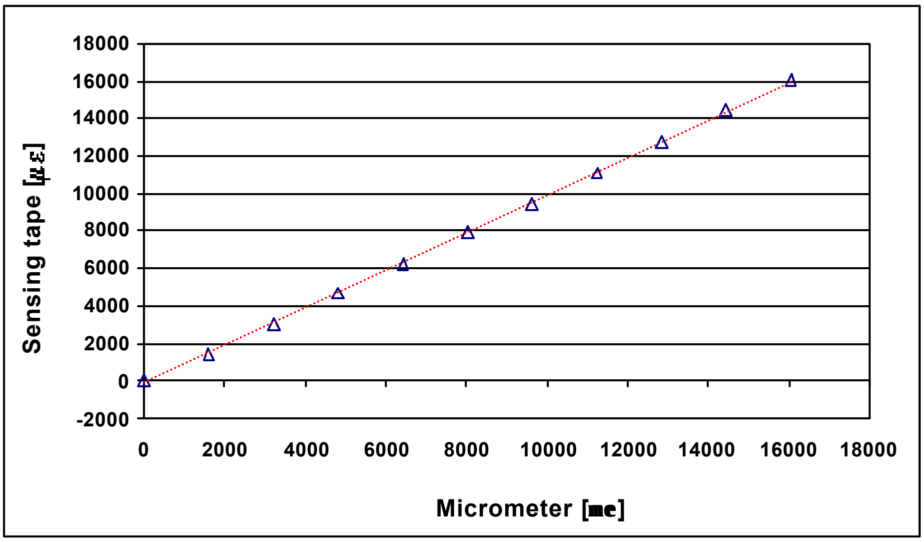

Figure 9: Linearity between micrometer and sensing tape measurement (for rising load only)

The main conclusion of the tests is that the sensing tape can be used as a deformation (average strain) sensor. However, the improvements are required in manufacturing procedure in order to decrease the optical losses, avoid the local delamination and emerging of optical fiber.

ON-SITE TEST OF SENSING TAPES

On site test was performed on rails with aim to compare the results obtained using sensing tapes and SOFO standard sensor. For this purpose, two one-meter long sensing tapes were installed on rails in parallel with a SOFO standard sensor, as shown in Figure 10.

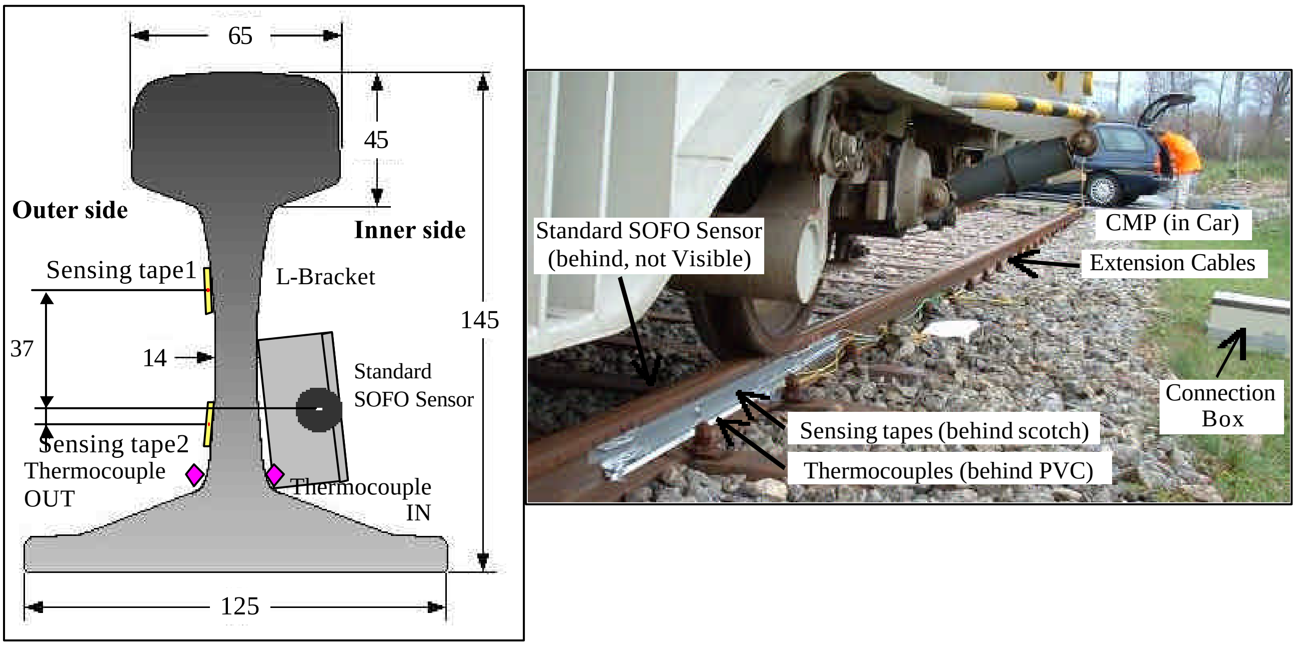

Figure 10: Position of sensing tapes and standard SOFO sensor installed on rails, and photo taken during the test

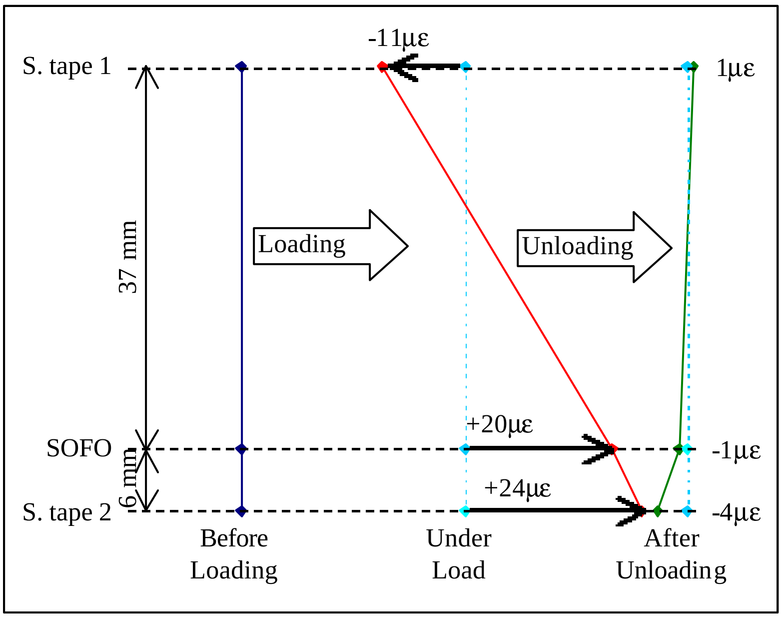

Figure 11: Results of the rail test using the sensing tapes and standard SOFO sensor

The measurements were performed before the arrival of the train, and then repeated when the wagon was parked with the wheel exactly on the sensor location (see Figure 10). One more measurement was performed after the wagon was moved. The results are shown in Figure 11.

Since the location of the tapes and standard sensor with respect to the height of the cross-section was not the same (see Figure 10), and the rail was subject to bending, the comparison was only possible if the three measurements are collinear, which was the case (see Figure 11). The results of test have shown very high level (order of magnitude of resolution) of comparability between the standard SOFO sensor and sensing tapes.

The test on rails continues in order to evaluate long-term performance of the sensing tape exposed to different environmental influences such as wind, rain, snow, temperature variations and mechanical actions (shocks, vibrations, straining etc.).

CONCLUSIONS

The development of polyimide-coated optical fiber into the fiber reinforced thermoplastic composite tape for the sensing purposes is presented in this paper. The tape with integrated optical fiber is called sensing tape. The integration procedure was developed and the prototype of the sensing tape produced and tested. Optical, microscopic and mechanical tests have confirmed good performance of the sensing tape, but also indicated necessary improvements in manufacturing procedures in order to avoid delamination, better control of the position of the optical fiber within the tape's cross-section and decrease the optical losses generated by shrinkage of matrix after the cooling. On-site test is finally carried out, and it confirmed good sensing performance of the tape and its applicability in real conditions.

ACKNOWLEDGEMENTS

The Authors are indebted to Dr. Gustav Jannerfeldt and Dr. Albert Maria Vodermayer from GURIT SUPREM, Flurlingen, Switzerland, for collaboration and fabrication of the sensing tape, Mr. Daniel Rickenbach, Mr. Thierry Luthy and Prof. Dr. P. Ermanni from Laboratory for Mechanical Systems (IMES) of Swiss Federal Institute of Technolgy, Zurich (ETHZ) for their advises, availability and work they performed to test sensing tapes, the Post Center of Manno, Switzerland for availability of rails for the tests, Mrs. Claire Nan from RouteAero Tech.&Eng., Taipei, Taiwan for availability of the data, and to Mr. Marco Cerulli and Mr. Marzio Rossi for their precious help during the whole project.

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