eJNDT e-Journal of Nondestructive Testing - ISSN 1435-4934 - www.ndt.net

EWSHM 2024
11th European Workshop on Structural Health Monitoring

Development of Photonic Smart Veil for Structural Health Monitoring

Emanuele CASCIARO[1], Paolo BETTINI[2]
[1] Politecnico di Milano, Milan, Italy, emanuele.casciaro@polimi.it
[2] Politecnico di Milano, Milan, Italy, paolo.bettini@polimi.it

Abstract. The widespread adoption of fiber optics in structural health monitoring (SHM) systems is facilitated by the creation of individual Bragg grating sensors (FBGS) or sensor arrays. This technology offers advantages such as small size, durability, real-time monitoring capabilities and integration within composite structures. However, challenges arise in placing FBG sensors accurately during the composite component creation, particularly in maintaining their position during autoclave curing. To address these issues, improvements have been made to the commonly used configuration, the Quick Pack. Various materials and configurations were explored to enhance adhesion and flexibility. Peel tests confirmed performance improvements. Prototyping led to the development of the Photonic Smart Veil. This new transducer ensures that FBG sensors are accurately positioned and secured during composite component production, enhancing their performance.

Keywords: Structural Health Monitoring · Fiber optic · Quick Pack · Embedment · Composite materials

1. Introduction

In recent years, the aerospace industry has seen a growing demand for lightweight and highly efficient structures, resulting in extensive use of composite materials. This trend is in line with the global initiative to reduce maintenance costs, which is encouraging the development of Structural Health Monitoring (SHM) systems. SHM systems have proven to be highly effective in providing real-time insight into the performance and condition of structures. Among the various SHM techniques, Fiber Bragg Grating (FBG) sensors have garnered significant attention, also due to their immunity to electromagnetic fields. FBGS enable direct measurement of physical parameters such as deformations, vibrations, forces, pressures and temperatures. This multifaceted capability makes fiber optics (FO) a versatile and reliable option for sensing applications [1]. To fully leverage the potential of FBGS, it is necessary to incorporate them correctly without altering their performance. To achieve this goal, this work aims to develop a Photonic Smart Vail (PSV), a thin layer that incorporates optical fiber. In this way, sensors can be positioned along an arbitrary path, embedded without compromising the composite element and easily handled during the production process. This

Media and Publishing Partner
https://doi.org/10.58286/29861

would also enable easy incorporation of optical fibers into company processes without the need for specialized workers. The layer containing the optical fiber and sensors would be positioned within the lamination sequence. This paper presenting is organized as follows: section 2 elucidates the Quick Pack technology for embedding optical fibers in composites. Section 3 proposes alternatives in Quick Pack production to mitigate invasiveness. Section 4 examines various lamination sequences for the PSV. Section 5 introduces a system to increase membrane adhesion to the composite and reduce its invasiveness. Section 6 evaluates the efficacy of these systems in composite adhesion performance. Section 7 deals with conclusions and future developments.

2. State of the Art

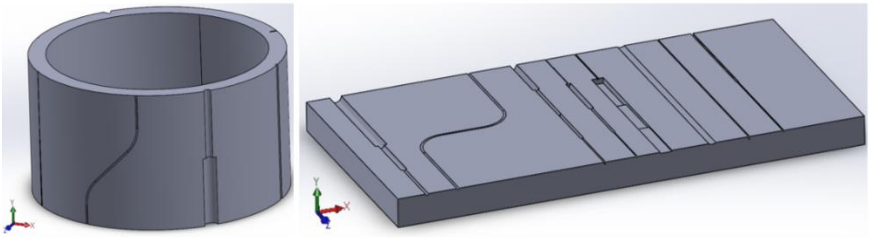
Fibers can be coupled to the structure via two distinct methods: complete embedment within the host material or bonding on the surface (through co-bonding or secondary bonding [2]). Complete embedding provides the opportunity for internal monitoring of components in typically inaccessible areas. Simultaneously, full embedment shields the FBG sensors from external factors. However, the challenge lies in installing them correctly during the manufacturing process to ensure the proper disposition and to preserve their integrity during the curing cycle. Fiber optics embedded within composites are often inserted parallel to the unidirectional (UD) reinforcing fibers. This allows the optical fibers to accommodate among the reinforcing fibers. In this way, the integrity of the fiber can be maintained, significantly reducing invasiveness. It is evident that this imposes significant limitations on the design. This study aims to eliminate this constraint by inserting optical fibers into a protective veil, as in the article [3]. Additionally, this veil would allow positioning the fibers between pre-impregnated layers of fabric and change the sensitivity of FBG sensors. The work presented continues the research conducted by D. Rigamonti et al. [4]. The proposed smart veil aimed to achieve several objectives: provide protection for fiber optics and ensure minimal invasiveness, reduce attenuation due to macro-/micro-bending, position fiber optics along complex paths, co-locate two sensors in the same point and embed the optical connector for a "plug and play" connection. The FO was enclosed between a thin film of structural adhesive (Scotch-Weld AF 163-2U Film, $0.139\,mm$ thickness) and a layer of a thin glass fabric prepreg (E glass, $48\ g/m^2$, $0.05\,mm$ thickness). The use of these two materials ensures compatibility with composite structures, as the resin closely resembles that used in prepregs. To ensure the possibility of positioning the fiber along a complex path, a mold with the engraved route was used. The steps of the production phase were:

- Applying a layer of structural resin onto the mold.
- Wrapping the optical fiber with a strip of UD glass fiber (CYCOM® 5216 by Solvay). This ensures fiber protection and leverages the adhesive properties of the prepreg.
- Carefully positioning the fiber within the groove.
- Shielding the fiber exit point with a small tube and depositing a small amount of two-component epoxy resin to prevent resin from entering the tube.
- Applying a layer of thin fiberglass fabric.

After curing, the fiber maintains its position. Notably, the component exhibits flexibility away from the fiber's trajectory but high rigidity along the groove. This rigidity is attributable to both the UD glass fibers and to the excess of resin. Moreover, significant bending of the component could generate cracks along the groove, primarily due to the brittle nature of the resin. In addition, the area near the tube represents a fracture risk zone. In the same article, several case studies were presented where the proposed solution was tested. The smart veils were inserted into a motorcycle fork, encapsulating the optical connector [5]. In other applications, fibers were overlapped, providing the opportunity to take two measurements at the same point. Finally, a case involving a series of FBGS inserted into a representative element of a helicopter tail rotor blade is reported. Sensors were inserted to measure loads. In particular, those related to torsion were arranged with a precise orientation angle. From the article, it is evident the usefulness and potential offered by this embedding method. The veil designed through previous research had been named Quick Pack. The aim of this study is to enhance this component by developing a new sensor, called PSV (Photonic Smart Veil), including the sensitive element, the optical fiber, and the protective structure.

3. Alternative Solutions for Molds

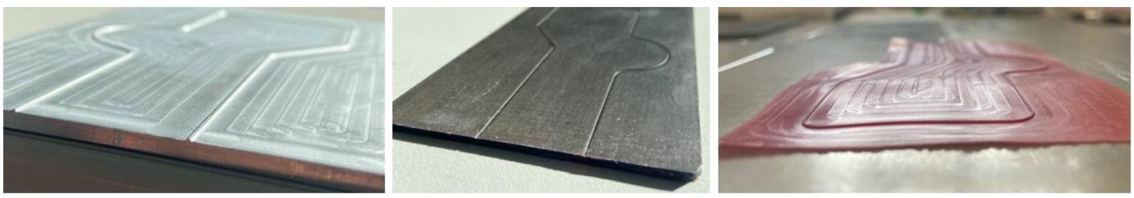
The mold previously utilized is made of aluminum and incorporates a groove, measuring $2\,mm$ in width and tens of millimeters in depth, formed along a complex trajectory. The geometric constraints in mold creation are linked to the numerical control milling machine. The groove is excessively large compared to the diameter of a standard fiber. During the curing process, the epoxy resin is facilitated to occupy the groove. Consequently, the resultant components exhibit a fiber path rich in resin, thus making it brittle and stiffer. Therefore, the groove can be reduced to minimize the invasiveness of the PSV. Two solutions were explored. The first one employed a 3D printer, the Stratasys Fortus 450, employing the smallest available nozzle, T12, with a diameter of $0.178\,mm$. ASA (acrylonitrile styrene acrylate) was the material selected for the tests. To assess the limitations of this technique, two molds were fabricated: one curved and one planar (figure 1).



(a) (b)

Fig. 1. Model of the curved mold (a), model of the flat mold (b)

The cavities exhibited variations in section shape, size, and encompassed either straight or highly curved trajectories. The filament failed to adequately occupy the cavities, and the resolution achievable made this technology unsuitable for our applications. The second explored solution involves surface replication to create a mold in composite material. An aluminum mold was fabricated and the relief section had a width of $0.3\,mm$ and a height of $0.2\,mm$. These dimensions were selected to accommodate a $0.125\,mm$ fiber wrapped with UD glass fibers. The chosen path features straight segments and curvatures, aimed at assessing the fiber's ability to maintain its position. The composite mold was laminated onto the aluminum panel. The materials employed include: three glass fabric prepreg ($0.05\,mm$ in thickness) as initial plies due to their drapability to the raised path, a UD carbon ($0.3\,mm$ in thickness) prepreg, ensuring alignment of the fibers with the direction of the path, and six carbon fabric ($0.3\,mm$ in thickness) plies to impart thickness to the laminate. The curing cycle in autoclave with high pressures ($3\,bar$) imprints the path onto the composite.



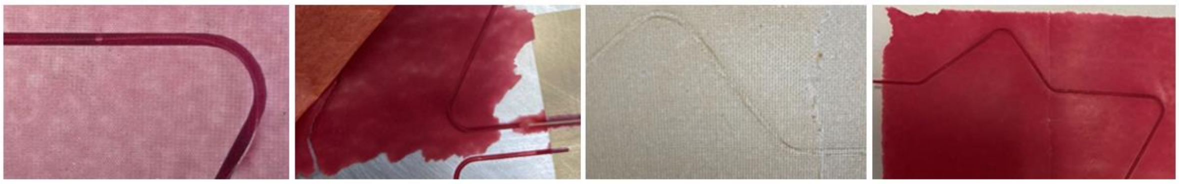
(a) (b) (c)

Fig. 2. Aluminum mold (a), composite replication (b) and veil with minimized fiber path cross-section (c)

The composite mold meets the specified requirements and enables the production of highly flexible PSV (figure 2). It is noteworthy that upon flexing, the component exhibits no indications of brittleness along the designated path. Furthermore, the optical fiber remained positioned in the path throughout the entire process. However, the technique is applicable in limited scenarios and not suitable for large-scale production of molds. Other manufacturing techniques, such as laser engraving and chemical etching will be evaluated in future works.

4. New Quick Pack Configurations

The compatibility of epoxy resin with pre-impregnated composites justifies preserving this material. However, exploring various lamination sequences for the PSV is possible. In figure 3(a), a veil made from the same materials as a standard Quick Pack but without UD glass fibers is shown. Optical fiber positioning was achieved by using the adhesiveness of the thin glass fabric as the first layer, followed by inserting the optical fiber and adding the unsupported epoxy resin film layer. The resulting veil is more flexible but may experience small breaks in the fiber path due to the high resin content. However, the fiber generally remains in place for most of the route, exiting near critical bends. Figure 3(b) shows a prototype with the fiber, wrapped in UD glass fibers, between two layers of unsupported epoxy resin. Removing the cured piece from the mold and the peel-ply proved to be challenging due to the veil's fragility, and that demonstrates its infeasibility. Figure 3(c) aimed to evaluate the possibility of inserting the optical fiber, without UD fibers, between two layers of thin glass fabric using its adhesive properties. Positioning was complex, but the resulting veil exhibited significant flexibility, showing no fragility along the groove. The optical fiber remained in position, yielding excellent results. Figure 3(d) depicts the test using a single layer of supported epoxy resin structural adhesive film (Scotch-Weld AF-2K) in place of the two materials used previously. The structure is stiffer due to the greater thickness of the supported resin film and the component is more fragile, especially along the groove.



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

Fig. 3. Alternative configurations of the veil: glass fabric and epoxy resin without glass UD fibers (a), two layers of epoxy resin (b), two layers of glass fabric (c), glass UD fibers and supported epoxy resin (d)

The analysis of the standard Quick Pack reveals a critical area near the tube, which protects the final section of the optical fiber. This region is susceptible to cracks and breakage during PSV handling due to localized stiffness. To address this, UD glass fiber elements can be inserted at the discontinuity point, providing stiffness and safeguarding the optical fiber. While this solution increases thickness in the area, it improves component handling.

5. Analysis of Partial Polymerizations

One of the enhancements is provided by the ability to increase the adhesion between the Quick Pack and the composite through partial polymerizations. This would allow for a co-curing bond between the veil and the composite, as in the T. Noble's work [6], that increases the load transfer capacity and reduces the invasiveness of the sensors [7]. The investigation of these material states was conducted using Differential Scanning Calorimetry (DSC). Samples were prepared for all three materials involved in the standard Quick Pack. The degree of cure represents the difference between the total heat released by an uncured resin and the residual heat released by the partially cured material. The samples underwent a thermal treatment in oven and were subsequently analyzed following the reported cycle:

1. Cooling the instrument to -20 ℃ and maintaining this temperature for $1\ min$.
2. Heating at a rate of $10\ ℃/min$ until 230 ℃, followed by a $1\ min$ isotherm.
3. Cooling at a rate of $20\ ℃/min$ down to 30 ℃ and maintaining 30 ℃ for $1\ min$.
4. Repeating the heating and cooling steps described above.

The first heating ramp assessed the enthalpy required to complete polymerization, while the second cycle identified any residual peaks attributed to incomplete transformations. The dependence of the degree of polymerization on both the temperature of the thermal treatment and the holding time necessitated the investigation of the phenomenon at constant temperatures (120 ℃, 110 ℃, 100 ℃, 80 ℃) for various holding times ($55\ min$, $40\ min$, $25\ min$, $10\ min$). Below are presented two images. Figure 4 illustrates the results specifically for the epoxy resin, serving as an example. Meanwhile, figure 5 showcases the polymerization percentage graphs with respect to time and temperature for all three materials.

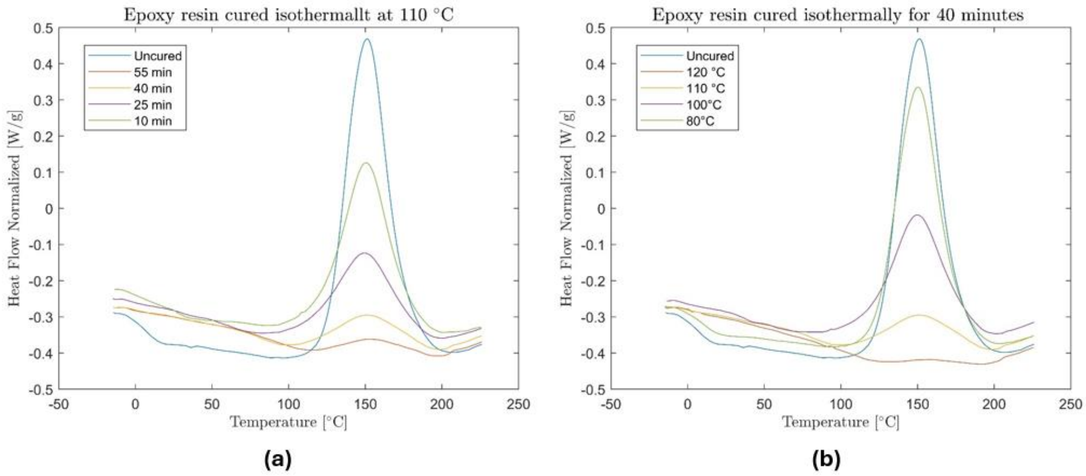


Fig. 4. DSC of epoxy resin at different holding times (a) and different temperatures (b)

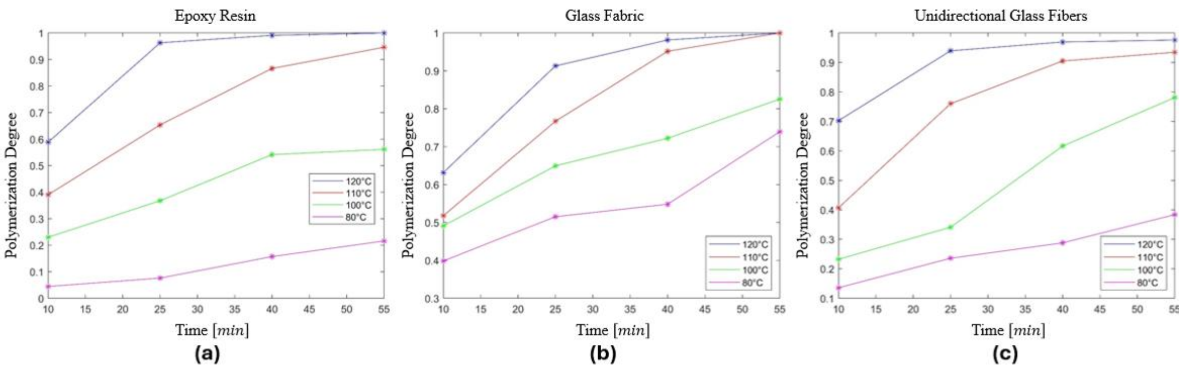


Fig. 5. Degree of polymerization as a function of holding time and temperature for epoxy resin (a), glass fabric (b), and glass UD fibers (c)

From these graphs, it is possible to select the production process based on the desired degree of polymerization. It was decided to produce the PSV and to test the developed methodology. Various degrees of polymerization were chosen, with the polymerization degree of the epoxy resin being used as a reference. Tests were conducted initially in the oven and subsequently in the autoclave (controlling the heating and cooling ramps). The results are reported in table 1. At lower temperatures, achieving the desired polymerization state is easier due to a manageable induction phase with a slow rate of reaction. As temperatures increase, polymerization accelerates, making precise control more challenging. Discrepancies between expected and obtained degrees of cure are minimal but may be influenced by factors like mold heating and cooling rates. Varying holding times to achieve desired cure degrees is difficult due to thermal inertias and instrument limitations. So, altering holding temperature is preferable over time adjustments. The tests in autoclave are limited and do not allow us to determine whether there is actual improvement and its cause (better controlled temperature ramps or applied pressure). However, it is evident that achieving precise high degrees of polymerization is more challenging than lower ones.

Table 1. Followed process in oven and in autoclave, expected degree of polymerization, and obtained one

	Time $[min]$	**Temp.** [℃]	**Desired Curing Degree (%)**	**Actual Curing Degree (%)**
Oven	28	110	70	85
Oven	17	110	50	66
Oven	25	105	55	76
Oven	15	105	40	62
Oven	37	100	50	63
Oven	20	100	30	47
Oven	20	95	25	43
Oven	50	80	20	19
Oven	30	80	10	12
Autoclave	25	110	70	88
Autoclave	35	100	50	52
Autoclave	50	80	20	21.5

6. Peeling test

Peel tests are essential for validating the effectiveness of partial polymerizations and the efficacy of the bond, as done by J. Renart [8]. The ASTM D 3167 standard, adapted to composite materials, was followed. An example of the application of this test is described in this article [9]. The materials used to produce the specimen were UD glass fibers and the adhesive film was replaced with the PSV. Five specimens for each configuration were tested. It was decided not to use the UD glass fibers and optical fibers, as the objective was to evaluate solely the adhesion achieved. The configurations analyzed are:

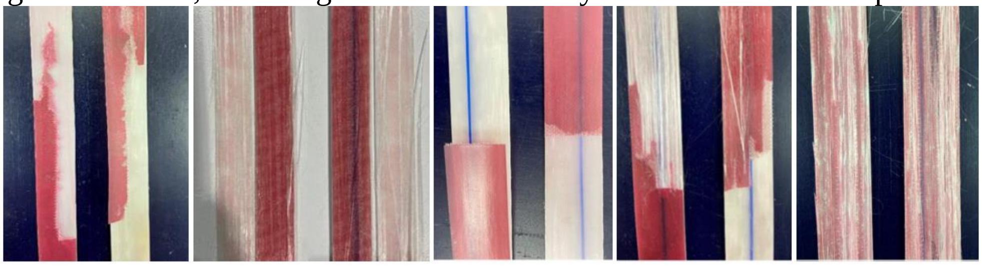
- Sample without PSV for comparison with the samples containing PSV.
- PSV polymerized at 100%, with a cycle of 120 ℃ for $60\ min$.
- Same PSV but with peel-ply applied on both sides (to increase roughness).
- PSV polymerized at 82%, with a cycle of 110 ℃ for $20\ min$.
- PSV polymerized at 62%, with a cycle of 100 ℃ for $35\ min$.
- PSV polymerized at 21%, with a cycle of 80 ℃ for $50\ min$.

Testing was conducted using the MTS 858 Mini Bionix II. The specimens were peeled at a bond separation rate of $152\ mm/min$. The peel tests yield two key results: peel strength and the failure mechanism. For each scenario, the maximum and minimum peeling loads (PL) were assessed, with the average PL for unit of width (table 2). Regarding specimens with the 82% polymerization veil, no available data exists as the veil of each specimen ruptured shortly after the test began. In the case of specimens with PSV polymerized at 62%, the samples broke after a certain peeling period. Only the data preceding the rupture were used.

Table 2. Peel test results: peeling load (PL), peeling load per unit width, and types of failures

	Max PL $[N]$	**Min PL** $[N]$	**Avg. PL** $[N]$	**Avg. PL** $[N/mm]$	**Type of Failure**
UD samples	14.05	9.66	11.97	0.92	ILFC
100%	8.43	2.39	5.79	0.44	AF
Double Peel Ply	16.06	10.37	13.95	1.07	ILFC, CF
82%	-	-	-	-	AF
62%	22.51	10.33	17.57	1.35	AF, ILFC, CF
21%	43.02	25.27	34.87	2.68	CF, ILFC

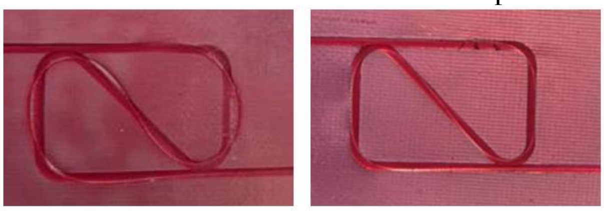
Fully polymerized PSV leads to decreased adhesion, posing risks of delamination or imperfect bonding. Inserts with double peel-ply show similar adhesion to samples without PSV (increasing the rough surfaces increased the adhesion). Lower polymerization levels (62% and 21%) significantly improved adhesion, with the 21% polymerization PSV achieving approximately three times higher PL. The failure modes were determined by visually estimating the area of failure (figure 6). Three distinct failure mechanisms were identified: adhesive failure (AF), cohesive failure in the adhesive (CF), and intra-laminar composite failure (ILFC). Adhesive failure indicates poor adhesion occurring at the interface between the insert and the adherent. Cohesive failure and intra-laminar composite failure suggest good adhesion, occurring within the insert layer and within the composite adherent.



(a) (b) (c) (d) (e)

Fig. 6. Inspection of tested samples: 100% polymerization with one rough surface (a), 100% polymerization with two rough surfaces (b), 82% polymerization (c), 62% polymerization (d), and 21% polymerization (e)

The specimens with a 100% polymerized insert show detachment primarily from the side in contact with the glass fabric (AF). Those with 100% polymerized inserts, with double peel-ply, showed dual failure modes: ILFC in the UD glass adherent and CF in the epoxy resin layer, indicating good adhesion. In specimens with an 82% polymerization veil, the insert broke shortly after the test began probably due to the discontinuities caused by the higher degree of polymerization of glass fabric compared to the epoxy resin used as reference. However, AF was observed at the interface between the glass fabric and the rigid adherent. Specimens with a 62% polymerized insert exhibited CF in the epoxy resin layer and AF at the interface between the glass fabric and the rigid adherent, suggesting varying degrees of adhesion along the specimen. Specimens with a 21% polymerization insert showed ILFC of the flexible adherent and CF in the insert, indicating excellent adhesion. These findings highlight the effectiveness of adhesion through co-curing with partially polymerized inserts. The best result was obtained with the 21% veil. For future developments, it is necessary to consider the degree of polymerization of the glass fabric as reference. However, reducing the degree of polymerization as much as possible is not the optimal choice because the PSV must be able to maintain the fiber in the desired position. Therefore, it was chosen to produce PSV polymerized at 20% and 60% arranging the fiber along a path with small radii of curvature. This allows to verify that the degree of polymerization achieved is sufficient to maintain the fiber in position.



(a) (b)

Fig. 7. PSV with critical radius of curvature: 20% polymerization (a), 60% polymerization (b)

Upon extraction from the mold, both the 20% and 60% cases showed the optical fiber nearly in the desired position. The 20% case demonstrated high flexibility and drapability. However, one day later, the fiber in the 20% case had shifted from its initial position. In contrast, the PSV with 60% partial polymerization maintained the fiber's position (figure 7).

7. Conclusions and Future Developments

In response to challenges encountered in embedding fiber optic sensors into structures, the Photonic Smart Veil (PSV) was developed. It's a thin composite membrane with an embedded fiber, aiming to reduce invasiveness and enhance adherence. Different mold production methods were evaluated to minimize invasiveness by reducing the groove section. Various lamination sequences of the PSV were also tested, with only the one using two layers of glass providing good results. Partial polymerizations of PSV materials were tested to improve flexibility and adherence. Achieving low polymerization degrees was found to be simpler and more controllable. Testing the adhesion of PSV at different curing degrees revealed increased peel strength with decreasing polymerization. However, excessively low polymerization degrees did not ensure optical fiber fixation. In future research, it's essential to conduct a thorough investigation to determine the optimal degree of polymerization needed to ensure fiber positioning. Alternative mold-making methods must also be validated to enable mass production of molds with the required dimensions.

Acknowledgements

This work has been undertaken in collaboration with Dott.ssa G. Alchieri.

References

[1] G. Sala, L. Di Landro, A. Airoldi, and P. Bettini, "Fibre optics health monitoring for aeronautical applications", *Meccanica*, vol. 50, no. 10, pp. 2547–2567, Oct. 2015, doi: 10.1007/s11012-015-0200-6.

[2] M. Ciminello, P. Bettini, S. Ameduri, E. Guerreschi, A. Concilio, and G. Sala, "Monito-Ring: An original fiber optic system for morphing application", *J Intell Mater Syst Struct*, vol. 26, no. 18, pp. 2463–2476, Dec. 2015, doi: 10.1177/1045389X14568818.

[3] P. Charlaftis, C. Koimtzoglou, P. Charlaftis, T. H. Loutas, C. Koimtzoglou, and V. Kostopoulos, "Structural Health Monitoring of Aerospace Components with Optical Fibre Ribbon-Tapes", 6th International Symposium on NDT in Aerospace, November 2014, Madrid, Spain, doi: 10.13140/RG.2.1.2842.5682, date of access: 2024-05-17.

[4] D. Rigamonti and P. Bettini, "Enabling FO-Based HUMS Applications Through an Innovative Integration Technique: Application to a Rotor Blade Mockup", in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2023, pp. 921–932. doi: 10.1007/978-3-031-07322-9_93, date of access: 2024-05-17.

[5] G. Sciamé, D. Rigamonti, P. Bettini, P. Tagliabue, and G. Sala, "An Integrated Fiber Optic Based SHM System for Structural Composite Components: Application to a Racing Motorbike Fork", in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2023, pp. 933–942. doi: 10.1007/978-3-031-07322-9_94, date of access: 2024-05-17.

[6] T. Noble *et al.*, "Powder epoxy for one-shot cure, out-of-autoclave applications: Lap shear strength and z-pinning study", *Journal of Composites Science*, vol. 5, no. 9, Sep. 2021, doi: 10.3390/jcs5090225.

[7] L. Moretti, P. Olivier, B. Castanié, and G. Bernhart, "Experimental study and in-situ FBG monitoring of process-induced strains during autoclave co-curing, co-bonding and secondary bonding of composite laminates", *Compos Part A Appl Sci Manuf*, vol. 142, Mar. 2021, doi: 10.1016/j.compositesa.2020.106224.

[8] J. Renart, J. Costa, C. Sarrado, S. Budhe, A. Turon, and A. Rodríguez-Bellido, "Mode I fatigue behaviour and fracture of adhesively-bonded fibre-reinforced polymer (FRP) composite joints for structural repairs", in *Fatigue and Fracture of Adhesively-Bonded Composite Joints*, Elsevier Inc., 2015, pp. 121–147. doi: 10.1016/B978-0-85709-806-1.00005-7.

[9] S. T. de Freitas and J. Sinke, "Test method to assess interface adhesion in composite bonding", *Applied Adhesion Science*, vol. 3, no. 1, Dec. 2015, doi: 10.1186/s40563-015-0033-5.