Development of an Additive Manufactured Fitting Sensorized with Optical Fibres for Load Recognition

A. Airoldi and P. Ballarin
Politecnico di Milano, Milan, 20156, Italy

S. Di Mauro
Politecnico di Milano, Milan, 20156, Italy

D. Rigamonti
Politecnico di Milano, Milan, 20156, Italy

F. Reinert
Protoshape 3D Printing AG, Neunegg, 3176, Switzerland

M. Dadras
Centre Suisse d'Electronique et de Microtechnique, Neuchatel, 2002, Switzerland

S. Zabihzadeh
Centre Suisse d'Electronique et de Microtechnique, Neuchatel, 2002, Switzerland

P. Bettini
Politecnico di Milano, Milan, 20156, Italy

L. Cartabia
Plyform Composites Srl, Varallo Pombia, 28040, Italy

I. Introduction

In the recent years the application of Structural Health Monitoring (SHM) systems was deeply studied in many fields, from aerospace engineering to civil engineering, with the aim to assess constantly the integrity of a structure. Optical fibre sensors were found to be particularly suitable for the application in aerospace structure because of their low weight and low required volume, combined with the immunity to electromagnetic disturbances. SHM systems are often proposed for damage growth detection, although dense sensor network is actually required to perform such task ([**1**-**3**]). However, another important application can be represented by load reconstruction [**4-5**]. Such application is particularly interesting for aircraft since it can provide important information about the actual loads acting on a structural component during the operational life, which can be exploited for maintenance on condition strategies. A fundamental obstacle for the installation of such Health and Usage Monitoring Systems based on optical fibre sensors is represented by the difficulties related to the integration of the sensors in the structural elements. The work presented is aimed to exploit the characteristics of additive manufactured technology to develop structural elements where sensors can be easily integrated. Indeed, additive manufacturing techniques allows the production of very complex shapes and are particularly interesting for the production of aerospace components, which are characterized by relatively low production volume with respect to other fields, such as automotive. Fibre optic sensors can be integrated inside metallic components produced by additive manufacturing by designing properly their geometry, for example preparing some channels inside which the sensorized optical fibre can be inserted. Consequently, fittings and connections elements that can perform primary structural role can be produced with the possibility to measure the load transmitted continuously during the operational life of the aircrafts. The activities presented are a part of the achievements of Eurostar project DIAManT (Direct Sensor Integration by Additive Manufacturing Technology) and makes available technologies and concepts for practical integration of optical fiber-based sensing systems in real-world structures.

II. Integration of fibre optical sensors in metallic components

In this work the integration of such fibre optic sensors inside a metallic component made of titanium alloy was investigated. Some specimens were produced with the aim to investigate the technological feasibility of the proposed integration strategies. Two types of sensors integration techniques were considered. A first option was based on internal channels hosting optical fibres, which were glued to the metallic element at sensor locations (gluing strategy). A second option was based on the positioning of fibres inside properly shaped groves carved on the fitting surfaces and the subsequent application of composite patches to fix and protect the optical fibre and to optimize the strain transfer between the metallic element and the sensors (composite patch strategy). These two techniques were compared by producing some specimens, which were tested in 3 point bending configuration; tests setup are shown in Figure 1. In the specimens the optical fibre carries three Fibre Bragg Sensors (FBG) to measure the strain on one of the surfaces. Then the fibres passes through an internal channel until to a cavity that is designed to host a connector integrated in the element.

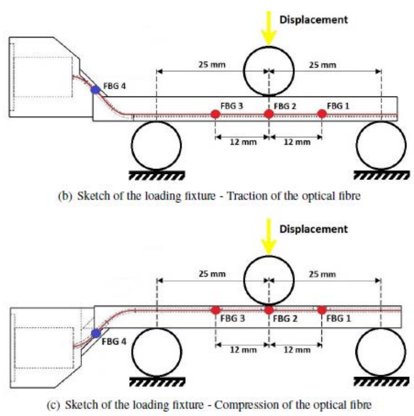


Figure 1: specimen test setup

Composite patch strategy is presented in Figure 2. The groove prepared at the centre of the component is visible in Figure 2-a. A layer of structural adhesive is placed over the surface leaving the groove still visible (Figure 2-b) and the optical fibre is placed in the groove over the adhesive with some prepreg unidirectional glass fibres, needed to reduce the risk of voids creation around the optical fibre. The patch of composite is applied over the adhesive and the optical fibre (Figure 2-c). Finally, Figure 1-d shows the mould assembly, which is cured to integrate the sensor in the element.

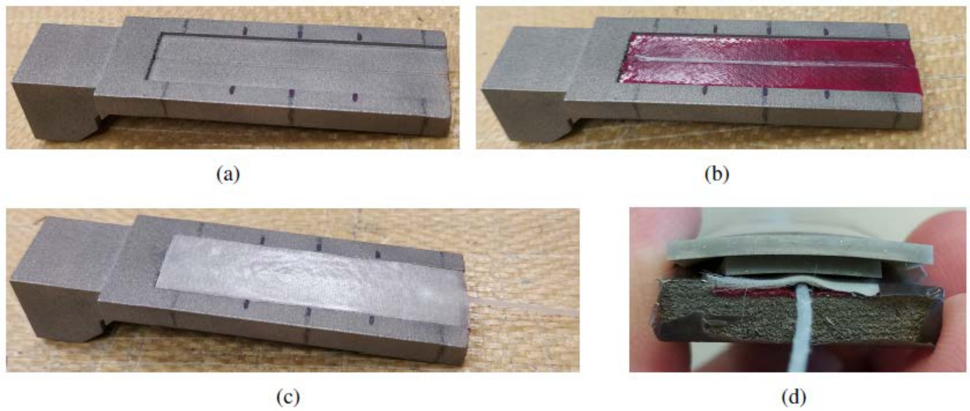


Figure 2: specimens produced with composite patch strategy to investigate the optical fibre embedment

After the co-curing of adhesive and composite layers, the specimens were tested in a 3 point bending test, first making the optical fibre subjected to tensile loads and then loading the fibre to compression loads; the test was carried out statically and the test setup was already shown in Figure 1.

The results show that composite patch strategy is more reliable and easily applicable to measure the strain in the vicinity of the sensors, while gluing strategy resulted more critical. The strain transfer capability was analyzed by means of detailed FE models, evaluating the role of resin, composite layer and glue properties in the different techniques.

III. Application case: flap track rear support and load identification algorithm

Once the embedment technique of the optical fibre in the additive manufactured element was assessed by a technological point of view, an application case was considered. In particular, a metallic fitting was taken into account, made of titanium alloy and produced by Protoshape, which represents the rearward flap track support of a business jet. The component, modelled with the Finite Element software Simulia/Abaqus, is shown in Figure 3.

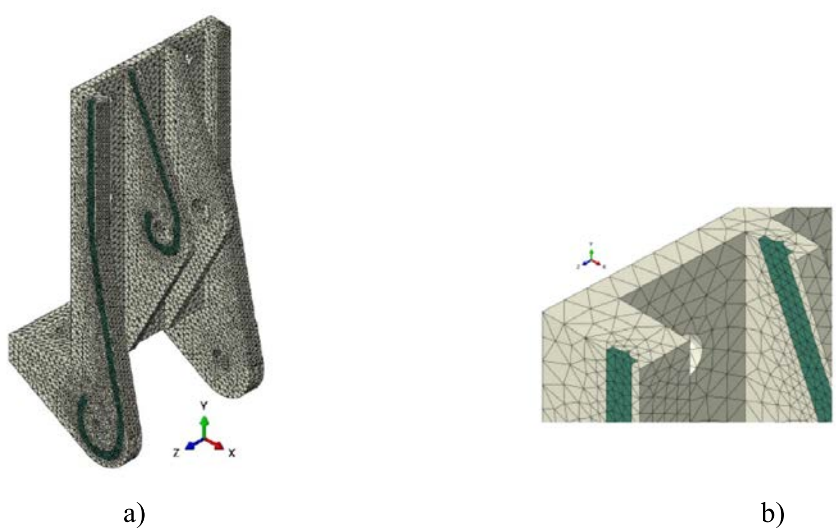


Figure 3: a) Rearward flap track support modelled with finite elements; b) detail of the component

The element is connected from one side (the backside of Figure 3-a) to a wing rib. Two pairs of lugs provide the attachment for the flap actuator (internal upper holes in Figure 3-a) and to the flap track (lower external holes in Figure 3-a). The component was modified to be sensorized with four optical fibres surrounding the holes, with the possibility of carrying several FBG's. The monitoring system and the associated data elaboration algorithm has the goal to identify the value and the direction of the force transmitted through the fitting by the actuator and the track support. The path of the optical fibre to be introduced around an external hole is shown in Figure 4. The V-groove that host the fibre, filled with the composite patch, is shown in Figure 3-a and in the detail of Figure 3-b, coloured in green. The potential positions of the FBG's along the path are also shown in Figure 4.

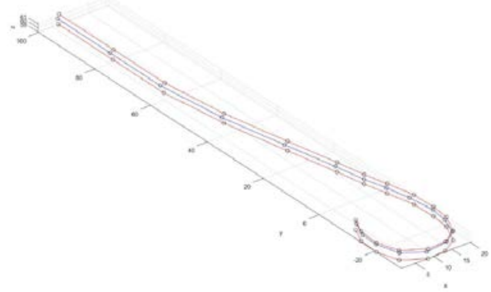


Figure 4: optical fibre path and sensors distribution

The choice of the number of sensors and their location was made based on the quality of load identification. Initially 18 FBG potential positions were selected on the predefined path shown in Figure 4. The load identification strategy was based on linearity assumptions between the forces transmitted and the strain measured by FBG's. The finite element model was used to define a series of influence functions, capable to provide for each sensor the strain along the fibre path as a function of the magnitude, F, and the orientation, theta, of the applied loads. A Least Square Technique was devised to minimize an objective function, which minimizes the errors between the strain measured in an experiments and the prediction of the influence coefficient. Such minimization is potentially capable to identify the value of F and theta, thus reconstructing the load condition. The objective function is given in Eq. 1

$$y = \ min \frac{1}{M} \sqrt{\sum_{i=1}^{M} \left(\eta_i - F f_i(\vartheta) \right)^2} \qquad \text{Eq. 1}$$

where M is the number of sensors, η_i is the strain measure of the i-th sensor, F and θ are the load magnitude and direction to be identified.

Virtual experiments were performed in different load conditions by developing another FEM model, with uncertainties in material properties and sensor position, moreover, Gaussian noise was introduced. Such experiments led to define a more limited number of sensors for the monitoring system, which was eventually designed with 6 and 5 FBG's around the external and internal holes, respectively. Moreover, the studies pointed out the need of a correction procedure for the influence functions defined through the nominal FE model, which has to be performed on the real elements to allow for the discrepancies between the model and the physical element produced by additive manufacturing.

IV. Algorithm calibration

A high sensitivity to the sensors position, material properties and strain transfer was found comparing the identified loads given by the nominal FE model used for the definition of influence functions and the refined model, where the composite patch was modelled. A calibration procedure was devised to correct the load identification algorithm once the sensorized element is produced, by performing a N tests in known load conditions, where N is a limited number in the range 2÷5.

The procedure introduced three corrective factors in the influence functions defined for each sensor, namely, an amplification factor α_i, a phase correction for load orientation φ_i, and a Gauss function, defined by two additional parameters. A minimization procedure is set-up to minimize an objective function that considers the results of the N calibration tests and is given by Eq. 2.

$$\begin{cases} F_j, \theta_j, \alpha_i, \varphi_i, G_i \quad \xrightarrow{s.t.} \quad Y = \sum_{j=1}^{N} y_j \\ y_j = \frac{1}{M} \sqrt{\sum_{i=1}^{M} \left[\eta_{ij} - F_j \left(\alpha_i f_i (\theta_j + \varphi_i) + G_i \right) \right]^2} \qquad j = 1:N \\ G_i = a_i e^{-\frac{(\theta - b_i)^2}{c_i^2}} \qquad i = 1:M \end{cases} \qquad \text{Eq. 2}$$

The sum of the quadratic errors related to the j-th calibration experiments has to be minimized under the equality constraints that impose to obtain a force amplitude and an orientation equal to the ones actually applied in the calibration experiment. The correction procedure was assessed with a series of virtual experiments that proved its effectiveness in the reduction of errors induced by the potential discrepancy between the nominal model and the physical experiments. An example of the effect of the correction procedure on an influence function is presented in Figure 5.

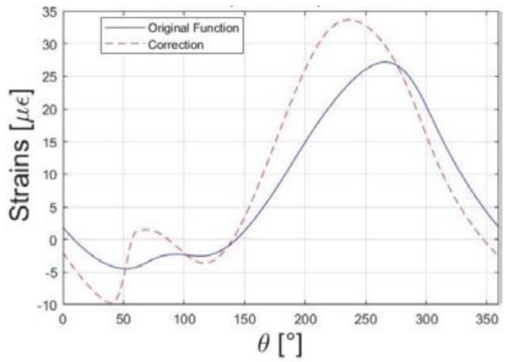
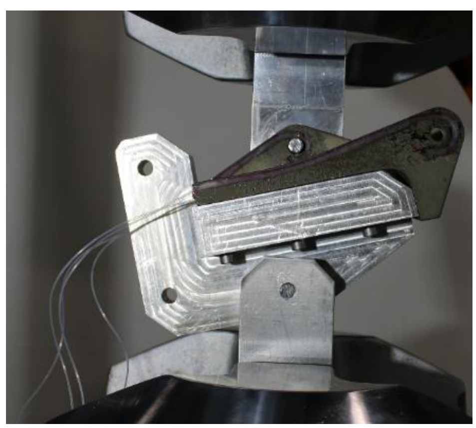


Figure 5: Example of original and corrected influence function

V. Experimental activity

The fitting elements were realized in Titanium Ti6Al4V alloy, by applying Selective Laser Melting Technology and a subsequent heat treated to improve material properties. Two elements have been sensorized by applying the composite patch strategy and the gluing strategy. A step of the application of the sensor is shown in Figure 6-a. Preliminary results have been performed with a fixture designed to apply loads representative of flap track and actuator, in the configurations shown in Figure 6-b and Figure 6-c.

a)



b)

c)

Figure 6: a) Composite patch version of the sensorized flap track rear support; b, c) flap track rear support subjected to testing

The sensors installed resulted to be fully functional. However, the preliminary results indicate the need to control accurately the test conditions and the applied constraints to fulfil the linearity assumptions involved in the algorithm. Further tests are scheduled to assess the validity of the load identification method.

VI. Conclusion

The activity explored the possibility to apply additive manufacturing technology to develop fittings with load monitoring capabilities, provided by an optical fibre-based sensing system integrated in the element. Different strategies for the integration of the sensors have been assessed and an element representative of a real-world aeronautical application has been designed and produced. The algorithms for the identification of loads applied to the fitting have been proposed, including a correction procedure to deal with the uncertainties in the properties of the physical element. Such algorithms are going to be assessed with a series of tests performed on fitting.

References

[1] Sala, G., Di Landro, L., Airoldi, A., & Bettini, P. (2015). Fibre optics health monitoring for aeronautical applications. *Meccanica*, *50*(10), 2547-2567.
[2] Rocha, H., Lafont, U., & Nunes, J. P. (2021). Optimisation of Through-Thickness Embedding Location of Fibre Bragg Grating Sensor in CFRP for Impact Damage Detection. *Polymers*, *13*(18), 3078.
[3] Di Sante, R. (2015). Fibre optic sensors for structural health monitoring of aircraft composite structures: Recent advances and applications. *Sensors*, *15*(8), 18666-18713.
[4] Airoldi, A., Marelli, L., Bettini, P., Sala, G., & Apicella, A. (2017, April). Strain field reconstruction on composite spars based on the identification of equivalent load conditions. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2017* (Vol. 10168, pp. 207-226). SPIE
[5] Li, J., Yan, J., Zhu, J., & Qing, X. (2022). K-BP neural network-based strain field inversion and load identification for CFRP. *Measurement*, *187*, 110227.