Mechanical Characterization of an Alternative Technique to Embed Sensors in Composite Structures: The Monitoring Patch

**Mauricio Torres Arellano · Laurent Crouzeix ·
Francis Collombet · Bernard Douchin ·
Yves-Henri Grunevald**

Abstract Sensor embedding is one of the main operations in dealing with composites in-core instrumentation. In this work, an alternative encapsulation technique called "monitoring patch" is proposed to achieve correct sensor embedding, to facilitate the industrialised instrumentation procedure and to adapt the sensors according to the geometry and material heterogeneities required of the composite structures. The monitoring patch is mainly developed with the aim to reduce the variability effects produced if the sensor alone is placed. In this initial study, a first patch's configuration is manufactured with CTMI pre-impregnate epoxy–woven glass, hosting two kinds of silicon prism sensors. The monitoring patch is then placed in the thick middle plane of an epoxy-carbon M21 T700GC quasi-isotropic plate. The plates are instrumented with strain gauges and tested using digital image correlation (DIC). The strain field maps are calculated to analyse the over-strain zones and to infer fracture paths. At the same time, a FEM model is developed to compare the numerical and the experimental observations. The results show that the mechanical strength of the instrumented plates is not significantly affected by the presence of the patch. The failure path of the instrumented plates with monitoring patch is found along the patch perimeter; therefore, the sensors can be recovered without damage even after the failure of the instrumented structure. The feasibility of the monitoring patch is discussed with other embedding techniques. In further studies, the monitoring patch will host a streaming sensor with an aim to carry out in-core strain measurements.

Keywords Monitoring patch · Silicon sensor · Embedding · Strain field · Digital image correlation

M. Torres Arellano (✉) · L. Crouzeix · F. Collombet · B. Douchin
Université de Toulouse, INSA, UPS, ICA (Institut Clément Ader), 133C Av. de Rangueil,
31077 Toulouse, France
e-mail: mauricio.torres@iut-tlse3.fr

Y.-H. Grunevald
Composites, Expertise & Solutions, 4 Rue Georges Vallerey, 31320 Castanet Tolosan, France

1 Introduction

Recently, several high risk industries, such as aeronautics, aerospace, maritime, oil-extraction, and railway transports, have been interested in applying integrity monitoring in their main structures [1–3]. The benefits of in-core instrumentation have not only been underlined in the structural point of view but also in the economical, safety, and operational aspects.

The employment of electronic ceramic sensors for in-core instrumentation of composite structures has been robustly developed during the past decades. For instance, improvements in this field deal with an achievement of a mutual compromise between the sensor's functionality and the mechanical performance of the monitored structure.

Piezoelectric actuators (PZT), silicon sensors (Sich), and, nowadays, Micro-Electro-Mechanical Systems (MEMS) have been used to capture the strain phenomena inside composite structures [4–6]. In the beginning, only a simple sensor was embedded in order to capture an electrical signal related to external stimulations. Nowadays, multiple sensor arrays are being integrated to follow the mechanical phenomena inside composite structures [7, 8]. The goal of these investigations is to have a robust continuous measuring to achieve an integral structural health monitoring capable of predicting damages and failures. However, there are still some issues to be addressed concerning the sensor embedding procedure in order to take a major advantage of the recorded measurements.

Usually, the sensor in-core implementation has been handled by placing the sensors directly in the composite layers. Numerous studies have compared the effect of placing the PZTs by three methods. The first one involves the insertion of the sensor between the plies [9–11]. The second one is by cutting a host area in the composite plies [12, 13]. The third technique for embedding electronic actuators is proposed by locating them as dispersed or interlaced plies [14]. Interlaced plies are made by inserting an extra hosting layer of the same composite material and making a small drop-off to reduce the created over-thickness. Even if all these researches conclude that there are no significant reductions in the mechanical strength associated with the insertion of electronic devices, malfunctions and interrupting measurements have been found when the composite structure is submitted to loads close to failure [15]. Sensor embedding between plies causes the formation of resin clusters and ply distortions at the area close to the sensor [16]. Moreover, debonding between the piezoceramic and the interconnections was also observed and, in some cases, sensor fracture [17]. On the other hand, sensor embedding by cutting a host area causes porosity and fibre-breaking in the composite material, which can lead to crack initiation or matrix degradation, either in static or dynamic loads [18, 19]. Finally, even if the interlaced embedding procedure reduces the size of the resin clusters and the distortions of ply laminates, these problems still remains in the composite plies and they can be related to a first damage appearance.

All these non-controlled variations, due to direct sensor-embedding techniques, may have an unknown and undesired impact in the mechanical strength of the instrumented structure. Moreover, these drawbacks can influence the mechanical and electrical performance of the embedded devices, significantly reducing their measurement capacities.

In order to reduce those random variations during the instrumentation procedure, the present work proposes the use of an alternative embedding technique called "monitoring patch". The ICA, together with the CES Company, has proposed the monitoring patch as a sensor embedding technique within the research program, Multi-sensor Instrumentation for Composite Materials (I2MC).

The monitoring patch is based on the concept of hosting the electronic device inside an independent and controlled composite laminate [20]. This technique follows an integration

philosophy named "ready to place", where the sensor, the connections, and the encapsulation layers form one package which will be placed inside the composite structure. The facts of pursuit are to facilitate sensor implementation, to adapt the sensor to the specific needs of the structure and to smooth the intrusive effect of the embedded devices on the parent composite components.

The monitoring patch is being developed based on an industrialised procedure to implement any type of sensor inside complex composite structures, where the classic embedding techniques are not achievable. The monitoring patch creates a reproducible host cavity for the sensor regardless of its volume and assures industrial manipulation of the sensor and its connections. It is conceived with the same principle of interlaced embedding; however, the possible distortions will only be related to the patch and not to the structure layers.

In addition, the patch improves the environment between the sensor and the structure by reducing the risk of porosities near the sensor and controlling the local misalignment of the plies around the electronic device. Finally, the patch allows an electrical isolation against the electromagnetic interferences between the sensor and the composite structure, as well as it permits the possibility of repairing the instrumented zone in case of damage.

Nonetheless, the insertion of the monitoring patch might have an influence over the mechanical behaviour of the instrumented structure. For this reason, the potential effects of the monitoring patch insertion must be known to minimise the risk of an interior damage initiation. With the exposed advantages and the possible disadvantages that the monitoring patch could offer as embedding technique, it is necessary to compare it with the other embedded procedures in order to underline its benefits and improve its limitations.

For these reasons and with the aim of knowing the mechanical performance of a composite plate instrumented with a monitoring patch, an experimental multi-instrumented study coupled with numerical analysis is presented here. In this first approach, the validation of the embedding procedure is pursued by means of an experimental-numerical work on elementary specimens. Therefore, the main goal is to present the reliability of the monitoring patch as an alternative embedding technique for composites in-core instrumentation, towards its application in more representative scenarios such as structural panels or composites assemblies such as the Multi-Instrumented Technological Evaluators (MITE) developed by the ICA [21, 22].

For a better understanding of the goals of this research, this paper is organised as follows. The first part explains the patch configuration and the experimental set up. The second one discusses the first results from mechanical tests using digital image correlation (DIC) and numerical simulations by FEM. After that, a fractographic examination is made in order to infer if the fracture path and failure mechanisms are related to the embedding technique. Then, the paper highlights the different aspects of the monitoring patch compared with the classic embedding techniques. Finally, the paper concludes with remarks citing further work.

2 Experimental Procedures

2.1 Fabrication of Composite Plates with Monitoring Patch

The first configuration of monitoring patch is carried out in host silicon sensors (Sich) developed by the Laboratory for Analysis and Architecture of Systems (LAAS) at Toulouse, France. The Sich consists of a mono-crystalline silicon prism with a sensitive electronic layer which transmits an electrical variation due to an external stimulation. Two sensors are used in this work, having nominal dimensions of $2 \times 2 \times 0.525$ mm^3 and $5 \times 5 \times 0.525$ mm^3.

The mechanical properties of the silicon sensors are indicated in Table 1. In this study, only the mechanical aspect of the sensor is considered. The sensor operation will be discussed in subsequent work of this research.

The monitoring patch is fabricated with 5192–1808S epoxy-woven glass pre-impregnates provided by CTMI™. The choice of a glass environment is to reduce the electrical interference that carbon fibres might induce on the sensor function. This pre-impregnated taffeta is used for aeronautic applications and its mechanical properties are summarised in Table 2.

The monitoring patch is fabricated with four woven plies described as follows. The first ply, called the "base ply", is of 25 mm per side and it is where the sensor is placed on. The next two plies, called the "hosting plies", are of sides 35 mm and 45 mm. In the hosting plies, a square with the same dimensions as of the sensor is cut out in order to allocate the Sich sensor. At last, the "covering ply", of side 55 mm, is placed to encapsulate the sensor inside the monitoring patch. As it can be observed, the patch ply drop-off distance is set on 5 mm, making a drop-off slope of 1/30 as recommended in previous studies [23–27]. Once again, it is underlined that the monitoring patch forms an integration package where the sensor is embedded. For a better visualization of the patch configuration, a scheme is shown in Fig. 1.

The monitoring patch is placed in the middle plane of a HEXCEL™ M21 T700GC carbon—epoxy quasi-isotropic plate as shown in Fig. 2. Therefore, the ply sequence of the plate remains as follows: [0/45/90/-45/patch/-45/90/45/0]. The mechanical properties of the carbon—epoxy material are indicated in Table 3.

The instrumented plates are polymerised in autoclave. The temperature cycle is defined by a 2°C/min heating slope until a temperature of 180°C is reached. The curing process lasts 2 h and then a cool-down slope of −2°C/min is applied. During all the autoclave cycles, the pressure is set at 7 bar at a vacuum of 0.85 bar.

2.2 Mechanical Tests Using Digital Image Correlation (DIC)

The mechanical characterization of composites plates with monitoring patch is carried out by tensile tests using digital image correlation (DIC) as described in previous works [28, 29].

The plate's nominal dimensions are $200 \times 80 \times 2.5$ mm^3. First, two strain gauges are glued in the patch zone to acquire strain data at these points. Then, the plates are painted with a white/black random speckled blueprint. For the DIC, a CCD camera is placed and calibrated for image acquisition without optical distortion. The CCD camera has a lens of 2.4 mm diameter and 55 mm focal distance. The pixel resolution for all images is set at 3888×2592 px^2. The plate is aligned to the camera set, selecting the zone where the monitoring patch is embedded as the region of interest (ROI). Then, the tensile tests are carried out at a displacement rate of 2 mm/min until the plate failure is reached. Each time a picture is taken, the corresponding load is registered. The plate preset and the experimental setup are illustrated in Fig. 3.

Table 1 Mechanical properties of mono-crystalline silicon

Young modulus	E_{Si} (GPa)	140
Poisson ratio	ν_{Si}	0.27
Ultimate strength to compression	σ_{Si} (MPa)	1300
Density	ρ_{Si} (kg/m^3)	2330
Thermal dilatation coefficient	α_{Si} (°K^{-1})	2.6 E-6

Table 2 Mechanical properties of CTMI 5192-1808S

Young modulus	E_{lp} (GPa)	21
Poisson ratio	ν_{ltp}	0.23
Shear modulus	G_p (GPa)	4
Ultimate strength	σ_p (MPa)	500
Interlaminar shear strength	τ_p (MPa)	45

Once the assembly of images is captured, the DIC code CORRELI™ [30, 31] developed in MATLAB™ is used for the image post-treatment. First, an unloaded initial image is designed as reference image. Then, the correlation algorithm is performed with a subset of S=256 px and a step of p=84 px. The image resolution g is calculated as 0.012 mm/px, with a spatial resolution *(S·g)* of 3.072 mm.

A longitudinal strain mapping at the patch zone is obtained with the DIC algorithm for having a direct qualitative detail of the monitoring patch strain field. Accurate measurements from the strain gauges are taken to make a quantitative comparison with the image correlation results.

2.3 Numerical Simulation for Composite Plates with Monitoring Patch

With a goal to complete an experimental-computational study for the insertion of a monitoring patch in composite layered structures, a numerical 2D model is performed using the finite element method (FEM) by means of the SAMCEF™ software. This model will aid in the study of the influence of each geometrical and material parameter as well as in the test of multiple patch configurations in further works.

The model is created with 16640 linear multilayer shell elements and 50177 nodes. The assigned offset-transfinite mesh allows the composite layering to be numerically stable. The domains concerning the sensor, the patch, and the composite plate respect the ply-sequence and material properties. The boundary conditions are imposed to represent the tensile test.
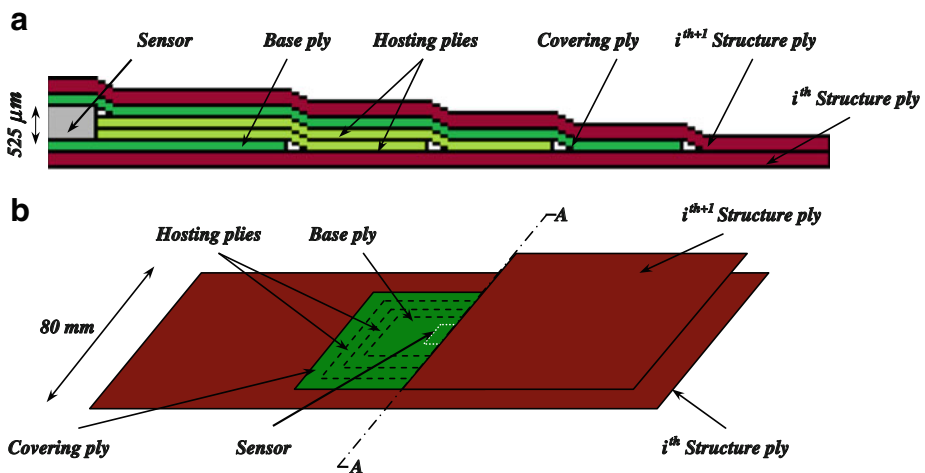

Fig. 1 Scheme of the principle of monitoring patch during the embedding procedure in a composite plate (**a**) transverse view (**b**) perspective view
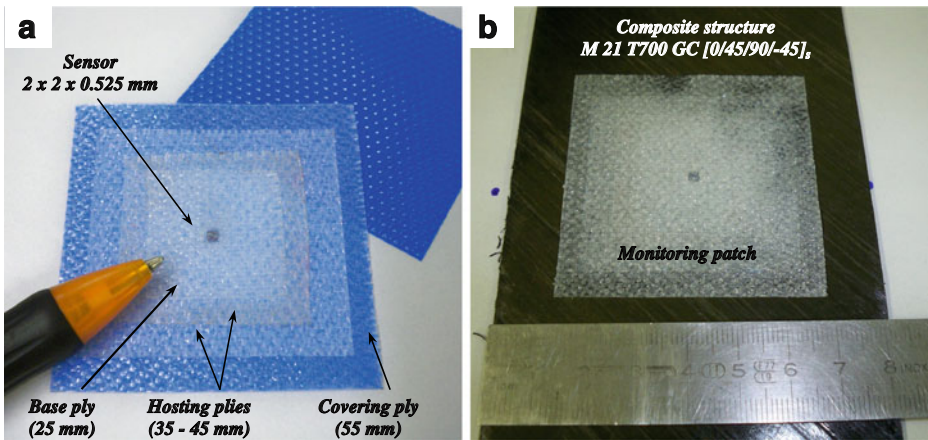
Fig. 2 Monitoring patch for embedding silicon sensors (**a**) patch initial configuration (**b**) location of monitoring patch in the thick middle plane of a carbon-epoxy quasi-isotropic plate

The model is clamped at the bottom by means of the fixations along the X, Y, and Z axes and rotation is along the X axis. At the top, the fixations are set along the Y, Z axes and rotation is along the Z axis. The machine displacement is imposed via the X direction. The FEM model can be visualised in Fig. 4.

3 Results and Discussion

3.1 Mechanical Response of Composite Plates Instrumented with Monitoring Patch

The mechanical performance of composite plates with monitoring patch is described by means of the load-strain curves. Three types of strain measurements are presented, strain gauges, digital image correlation, and finite element simulations, in order to have convergence of results. The measurements are taken from the zone where the sensor is placed. Figure 5 presents the strain measurements related to a patch hosting a $2\times2\times0.525$ mm^3 sensor, while Fig. 6 shows the mechanical behaviour of the patch with a $5\times5\times0.525$ mm^3 sensor.

For both sensors, the instrumented plates with monitoring patch show a double stiffness change, located between 2000 and 4000 $\mu\varepsilon$. The first change shows an augmentation on the

Table 3 Mechanical properties of M21T700 GC

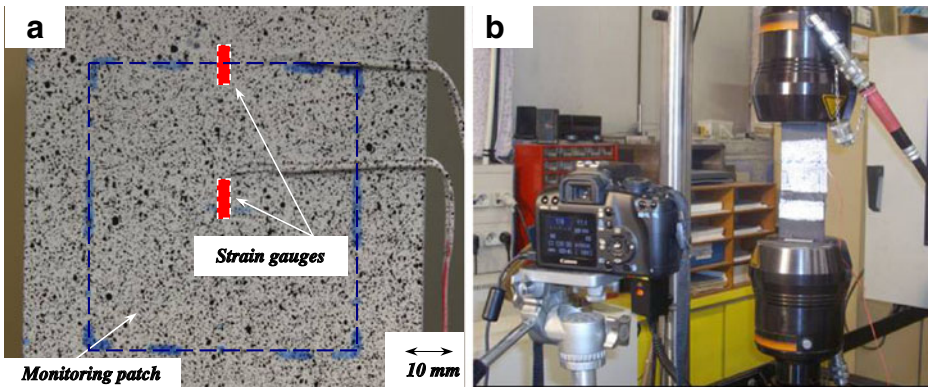| Longitudinal Young modulus	E_{ls} (GPa)	142
Transversal Young modulus	E_{ts} (GPa)	8.4
Longitudinal Poisson ratio	ν_{lts}	0.32
Transverse Poisson ratio	ν_{tls}	0.023
Shear modulus	G_s (GPa)	4.6
Longitudinal ultimate strength	σ_{ls} (MPa)	2282
Transverse ultimate strength	σ_{ts} (MPa)	65
Interlaminar shear strength	τ_s (MPa)	105

Fig. 3 Set up of mechanical characterization (**a**) plates preparation (**b**) tensile test using digital image correlation

plate stiffness. The second change indicates an increment in the strain rate until failure is reached. This second stiffness change is presumably related to damage initiation. However, the ultimate strength remains at the same level, despite the different sizes of the hosted sensors.

Numerous strain values at different load stages, obtained by strain gauges and by DIC, describe a non-linear behaviour. Nonetheless, the FEM model shows a linear behaviour very close in magnitude to the values recorded experimentally. Even if the experimental values show a small change in the load-strain relationship, this behaviour does not significantly affect the average mechanical performance observed in non-instrumented plates in previous studies [20].

With the aim to have a global vision of the mechanical behaviour of carbon-epoxy plates instrumented with a monitoring patch, the strain cartographies are calculated from the DIC measurements. Figure 7 shows the axial strain field (ε_{xx}) obtained at different load stages. The first cartography concerns a load level where the stiffness change occurred. The second cartography corresponds to a high load level near the plate's failure.

As visualised in Fig. 7, the axial strain field is heterogeneous and it shows distinct zones. The central zone of the patch exhibits the lowest strain values in non-uniformed
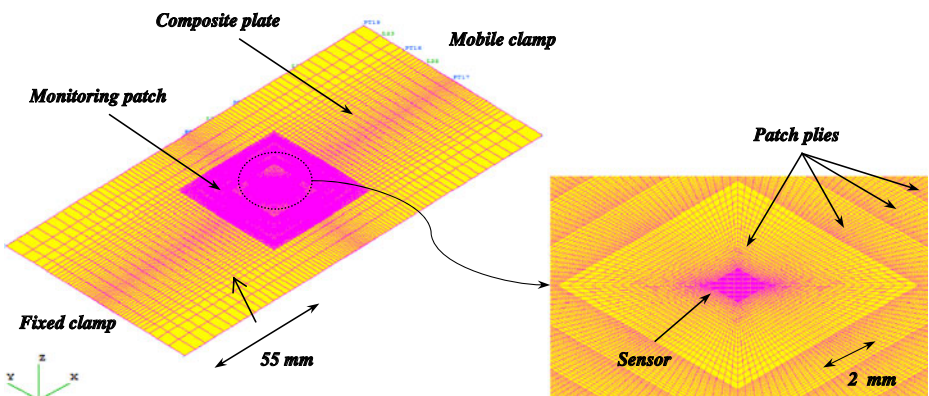

Fig. 4 FEM model of a composite plate instrumented with a monitoring patch for embedding silicon sensors
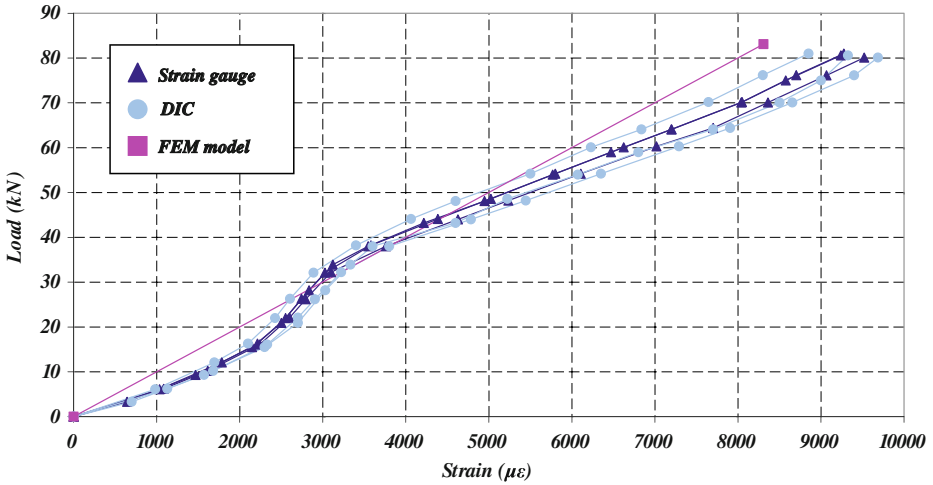
Fig. 5 Strain-load curves from different measure techniques for the composite plates with a monitoring patch hosting a 2×2×0.525 mm³ silicon sensor

bands which extend themselves through the width of the specimen. The strain increases gradually to the zones near the border of the patch and at the edge of the plate. These over-strain zones are responsible for the first internal damages which end up in the plate's failure.

It has to be underlined that the embedded sensor creates an over-thickness in the centre of the patch, which locally modifies the plate's geometry as well as its stress and strain field. This hump promotes a local strain value lower than the average strain value of the plate. Because the patch-plate boundary has a smaller thickness, the strain value raises at this zone and the risk of a possible cracking becomes higher. Even if the slope of the patch
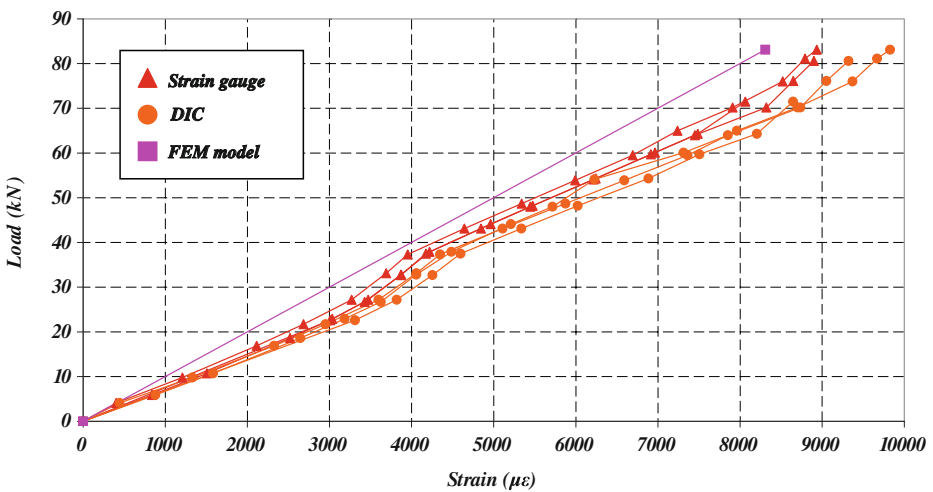

Fig. 6 Strain-load curves from different measure techniques for the composite plates with a monitoring patch hosting a 5×5×0.525 mm³ silicon sensor

drop-off reduces the sensor's abrupt intrusive effect, the patch-structure boundary seems like the weakest place, aiding crack initiation. However, it has to be remarked that this statement is restricted to narrow coupons and it should not be generalised to larger structures.

As the final failure occurs near the lateral sides of the plate, a possible influence related to end effects should not be discarded. It has to be remarked that the patch-plate width ratio reaches a value of 0.6 because of the use of a smooth drop-off slope. The end effect could increase the strain concentration in the zone between the patch border and the plate edge. In a larger structure, the patch-plate width ratio will diminish and in

Fig. 7 DIC strain fields (ε_{xx}) for composites plates with monitoring patch at different load stages at (a) 35 kN and (b) 70 kN
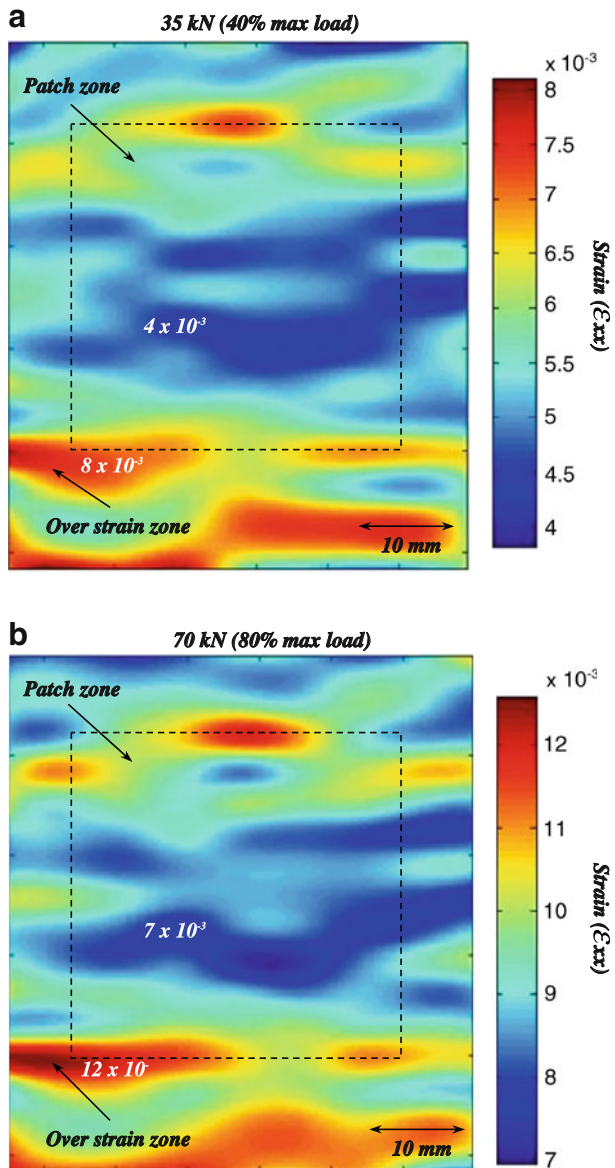
consequence the effect of the patch insertion should not be as deleterious as in the case of a narrow specimen.

As described in parallel works [21], the final goal is to use the monitoring patch in the instrumentation process of a MITE. With the analysis of the present results, it can be considered that the use of the monitoring patch does not alter the strength of the parent structure. However, a series of tests must be carried out once the first MITE is ready to perform, in order to minimise the non-intrusive side of the monitoring patch.

3.2 FEM Simulations of Monitoring Patch

The FEM simulations are carried out for having a numerical approach of the mechanical response of an instrumented composite plate by monitoring patch. The strain field (ε_{xx}), at the surface ply, is plotted in Fig. 8. The main interest is to have a qualitative comparison between the strain field obtained by the DIC technique and the one obtained by the FEM model.

FEM strain cartographies for two load stages are illustrated in Fig. 9. As observed in the DIC strain fields, the lowest strain values are located nearby the sensor. For both sensor sizes, a gradual variation in the strain field can be observed in the composite plate zone. The over-strain zone is confined outside the patch domain where the thickness plate becomes smaller. With the FEM results, it is confirmed that the patch perimeter is the most vulnerable zone for a crack initiation and propagation, due to the reduction in thickness as well as material heterogeneity.

3.3 Fracture Path Examination

The main fracture zone is commonly located in the patch perimeter zone. The main crack runs throughout the composite plies causing interlaminar fracture. Plies at ±45° and 90°
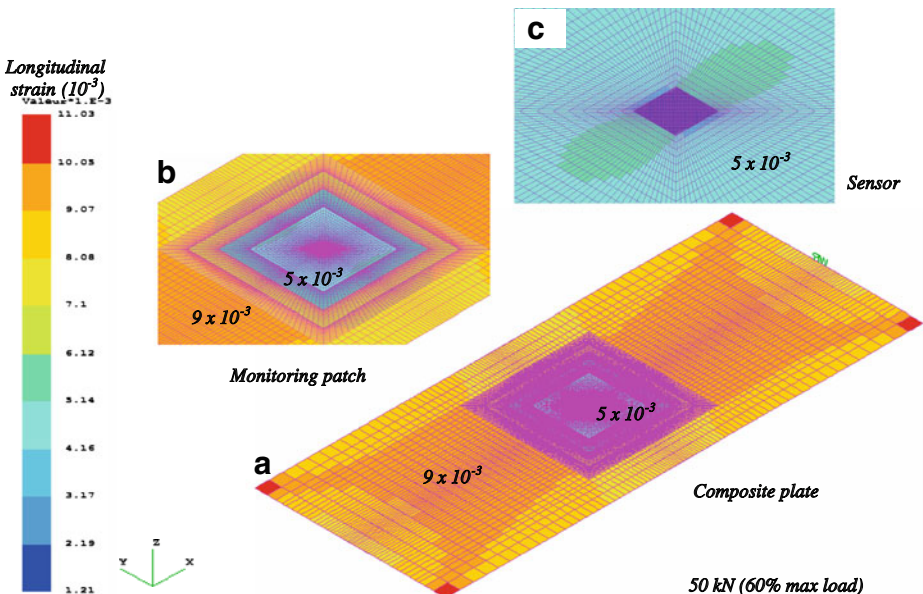

Fig. 8 FEM strain field (ε_{xx}) for the (**a**) composite plate, (**b**) monitoring patch and (**c**) sensor's neighborhood

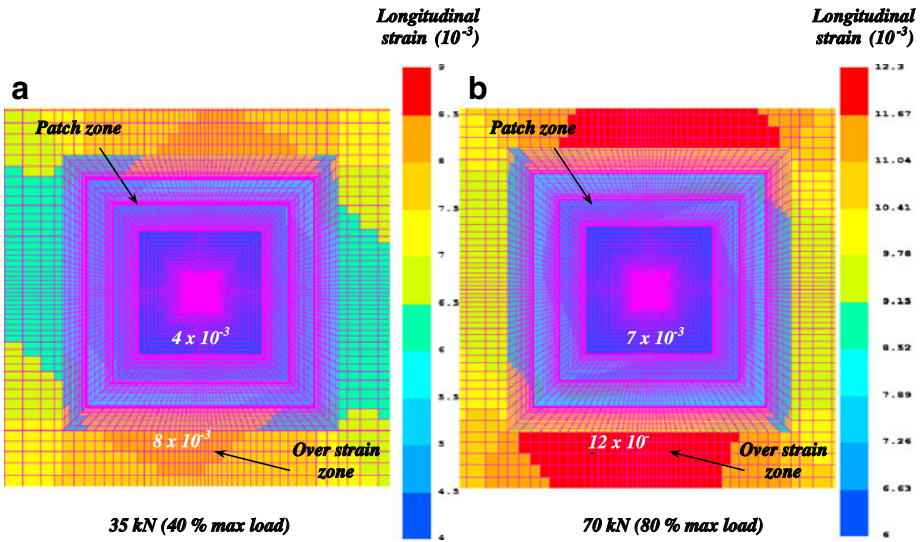**Fig. 9** FEM strain fields (ε_{xx}) for composites plates with monitoring patch at different load stages at (**a**) 35 kN and (**b**) 70 kN

show interface break-up and fibre separation, while plies at 0° exhibit fibre breaking. It is remarkable that the sensor was recovered apparently without damage. The illustrations of the fracture zone and its characteristics are provided in Fig. 10a.

The micrograph of Fig. 10b shows an accurate insertion of the monitoring patch inside the composite plate. The embedded sensor can be distinguished as well as each constituting ply of the monitoring patch. It can also be seen that sensor integration inside the patch layers diminishes the resin clusters and the ply distortions within the composite structure. With these SEM observations, it is confirmed that the sensor remains without damage after loading, so the utilization of the monitoring patch as embedding technique for silicon sensors is reliable.
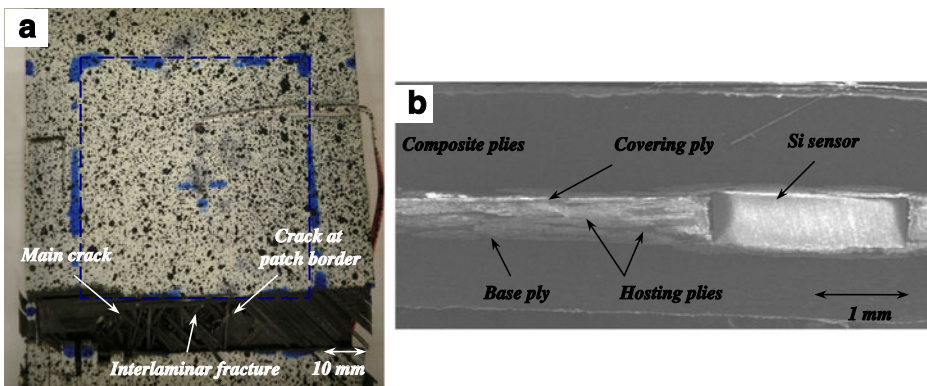

Fig. 10 Fractographic examination of an instrumented plate with monitoring patch (**a**) Photograph showing the main crack path (**b**) SEM micrograph illustrating the good insertion of a monitoring patch hosting a silicon sensor

4 Conclusions

In the present work, a monitoring patch is proposed as an alternative technique for embedding silicon sensors inside composite structures. The mechanical characterization of carbon-epoxy plates with this type of in-core instrumentation is carried out by tensile tests employing digital image correlation.

The monitoring patch causes a small stiffness in the instrumented plates due to the over-thickness zone created by the embedded sensor; however, it does not reduce the load-carrying capacity of the composite specimen or the general mechanical performance of the parent composite plate.

The failure path of the instrumented plates with monitoring patch is found along the patch perimeter. The main crack runs through the patch-plate interface causing delamination and fibre breaking. Even if the main crack causes a patch fracture, the embedded silicon sensor does not present any damage after loading. Hence, the monitoring patch as encapsulation technique has resulted into a benefit for avoiding a possible fracture in the sensor.

The axial strain fields, obtained by DIC and FEM, confirm that the over-strain zones are confined in the patch perimeter. These over-strain zones, due to the patch drop-off end, make this region more vulnerable to stress concentrations because the thickness is smaller in comparison to the patch zone. Also, the influence of the end effect of the plate cannot be denied and it could increase the strain concentration in the patch perimeter.

Even if the monitoring patch aids to reduce some of the drawbacks in classic embedded techniques (simple insertion and host cutting), the existence of small distortions cannot be denied and they need to be studied inside the patch configuration.

Further work is in course in order to implement the monitoring patch with a streaming sensor. Developments are being carried out in order to recover the processed signal during the load stages and to compare it with external measurements as presented here. In the near future, it is expected to introduce the monitoring patch into a larger composite structure, such as the MITE, to assure its reliability in industrial applications.

References

1. Baker, W., McKenzie, I., Jones, R.: Development of life extension strategies for Australian military aircrafts, using structural health monitoring of composite repair joints. Compos. Struct. **66**, 133–143 (2004)
2. Kudela, P., Ostachowicz, W., Zak, A.: Damage detection in composite plates with embedded PZT tranducers. Mech. Syst. Sig. Process. **22**, 1327–1335 (2008)
3. Cheng, J., Wu, X., Li, G., Taheri, F., Pang, S.S.: Development of a smart composite pipe joint integrated with piezoelectric layers under tensile loading. Int. J. Solids Struct. **43**, 5370–5385 (2006)
4. Zhou, G., Sim, L.M.: Evaluating damage in a smart composite laminates using embedded EFPI strain sensors. Opt. Lasers Eng. **47**, 1063–1068 (2009)
5. Leng, J., Asundi, A.: Structural health monitoring of smart composites materials by using EFPI and FBG sensors. Sens. Actuators A **103**, 330–340 (2003)

6. Hautamaki, C., Zurn, S., Mantell, S.C., Polla, D.L.: Experimental evaluation of MEMS strain sensors embedded in composites. J. Microelectromechanical Syst. **8**, 272–279 (1999)
7. Park, J., Ha, S., Chang, F.K.: Monitoring impacts events using a system identification method. Am. Inst. Aeronaut. Astronaut. J. **47**, 2011–2021 (2009)
8. Mueller, I., Chang, F.K., Roy, S., Mittal, M., Lonkar, K., Larrosa, C.: A robust structural health monitoring technique for airframe structures. Proceedings of the "7th International Workshop on Structural Health Monitoring" (2009)
9. Gaudenzi, P., Olivier, M., Sala, G.: Development of an active composite with embedded piezoelectric sensors and actuators for structure actuation and control. Proceedings of the "54th International Astronautical Congress" (2003)
10. Sala, G., Olivier, M.: Embedded piezoelectric sensors and actuators for control of active composite structures. www.naca.central.cranfield.ac.uk (2004)
11. Warketin, D.J., Crawley, E.F., Senturia, S.D.: The feasibility of embedded electronics for intelligent structures. Intell. Mater. Syst. Struct. **3**, 462–482 (1992)
12. Mall, S., Coleman, J.M.: Monotonic and fatigue loading behavior of a quasi-isotropic graphite/epoxy laminate embedded with piezoelectric sensors. Smart Mater. Struct. **7**, 822–832 (1998)
13. Mall, S.: Integrity of graphite/epoxy laminate embedded with piezoelectric sensor/actuator under monotonic and fatigue loads. Smart Mater. Struct. **11**, 527–533 (2002)
14. Hansen, J.P., Vizzini, A.J.: Fatigue response of a host structure with interlaced embedded devices. Intell. Mater. Syst. Struct. **11**, 902–909 (2000)
15. Huang, Y., Nemat-Nasser, S.: Structural integrity of composite laminates with embedded micro-sensors. Sens. Syst. Netw. **65**, 1–5 (2002)
16. Schaff, K., Rye, P., Nemat-Nasser, S.: Optimization of sensor introduction into laminated composites. Proceedings of the "SEM Conference and Exposition on Experimental and Applied Mechanics" (2007)
17. Paget, C.A., Levin, K.: Structural integrity of composites with embedded piezoelectric ceramic transducer. Proceedings of the "Conference on Smart Structures and Integrated Systems" (1999)
18. Mall, S., Hsu, T.L.: Electromechanical fatigue behavior of graphite/epoxy laminate embedded with piezoelectric actuator. Smart Mater. Struct. **9**, 78–84 (2000)
19. Yocum, M., Abramovich, H., Grunwald, A.: Fully reversed electromechanical behavior of composite laminate with embedded piezoelectric actuator/sensor. Smart Mater. Struct. **12**, 556–564 (2003)
20. Torres, M., Crouzeix, L., Collombet, F., Douchin, B., Grunevald, Y.H.: Mechanical performance of composite structures with embedded silica sensors: concept of monitoring patch. Proceedings of the "14th European Conference on Composites Materials" (2010)
21. Collombet, F., Grunevald, Y.H., Zitoune, R., Mulle, M.: Economical value added of Multi Instrumented Technological Evaluators for the development of composite civil aircraft. Proceedings of the "16th National Journeys on Composites" (2009), hal-00430585–version 1
22. Mulle, M., Zitoune, R., Collombet, F., Grunevald, Y.H.: Embedded FBGs and 3D-DIC for the stress analysis of a structural specimen subjected to bending. Compos. Struct. **91**, 48–55 (2009)
23. Mukherjee, A., Varughese, B.: Design guidelines for ply drop-off in laminated composite structures. Compos. B **32**, 153–164 (2001)
24. Mukherjee, A., Varughese, B.: A ply drop-off element for analysis of tapered laminated composites. Compos. Struct. **39**, 123–144 (1997)
25. Mukherjee, A., Varughese, B.: Development of a specialized finite element for the analysis of composites structures with ply drop-off. Compos. Struct. **46**, 1–16 (1999)
26. Mukherjee, A., Varughese, B.: A ply drop-off element for inclusion of drop-off in the global analysis of layered composite structures. Comput. Struct. **54**, 865–870 (1995)
27. Her, S.C.: Stress analysis of ply drop-off in composite structures. Compos. Struct. **57**, 235–244 (2002)
28. Torres, M., Crouzeix, L., Collombet, F., Douchin, B., Hernandez, H., Gonzalez, J.L.: Strain field measurement of filament-wound composites at ±55° using digital image correlation: an approach for unit cells employing flat specimens. Compos. Struct. **94**, 2457–2464 (2010)
29. Périé, J.N., Calloch, S., Cluzel, C., Hild, F.: Analysis of a multiaxial test on a C/C composite by using digital image correlation and a damage model. Exp. Mech. **42**, 318–328 (2002)
30. Crouzeix, L., Périé, J.N., Collombet, F., Douchin, B.: An orthotropic variant of the equilibrium GAP method applied to the analysis of a biaxial test on a composite material. Composites A **40**, 1732–1740 (2009)
31. Crouzeix, L., Périé, J.N., Torres, M., Douchin, B., Collombet, F., Hernandez, H.: On the use of digital image correlation and equilibrium GAP method for mechanical characterization of filament winding pipes. Proceedings of the 16th National Journeys on Composites (JNC) (2009), hal-00429798–version 1