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STRAIN GAGES FULL BRIDGE INSIDE COMPOSITE LAYERS TARGETING WING SHAPE FEEDBACK FOR FLIGHT CONTROL LAWS

Angelo A. Verri[1 2], Jason de Barros[1], Flávio L. S. Bussamra[2], Flávio J. Silvestre[2], Fernando J. O. Moreira[1], Antônio B. Guimarães Neto[2], Carlos E. S. Cesnik[3], Jéssica S. Martins[2]
[1] Brazilian Aeronautical Company - EMBRAER
[2] Technological Institute of Aeronautics – ITA
[3] University of Michigan - UniMich

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Abstract

This article presents the development of a real-time flight load measurement system convertible to real-time flight geometry measurement. It uses already known full bridge strains gages in a different manufacturing possibility: inside composite layers before resin cure. The manufacturing process is validated using a composite bar prototype. The prototype is submitted to a four points structural test in order to validate the measurements and influences of the manufacturing process. The whole process is applied to X-HALE aircraft disclosing a composite built-in measurement system for real-time flight load and flight geometry.

1 Introduction

The increasing recent developments on HALE (High Altitude Long Endurance) aircrafts are leading to important improvements in high flexibility knowledge for flight controls and aeroelasticity. It is influencing even the design of conventional aircrafts. The aircraft prototype Helios, after mishap during flight, brought a big challenge for the scientific community [4] and different researches are studding the design of highly flexible aircrafts. Among many aircrafts under development, some are intended to use the benefits of a HALE aircraft type and others are created as platform for high flexibility studies.

As part of the recent developments, the X-HALE aircraft was created at University of Michigan (UniMich) and it has been used as a platform for high flexibility studies in flight dynamics, which is highly influenced by the flight shape geometry [2].

The X-HALE aircraft is also being manufactured by Technological Institute of Aeronautics (ITA) in the Laboratory of New Concepts in Aeronautics (LNCA) in partnership with UniMich [3], for research purposes in flight dynamics and aeroelasticity of higher aspect-ratio aircrafts.

Part of the challenge of the LNCA research is to manufacture the X-HALE with a built-in system of strain-gages and use it for a real-time flight shape measuring for flight control laws, in both open and closed loops, as an alternative to the image system used by Cesnik [2].

This paper presents part of the development of a real-time flight geometry measurement system in the X-HALE aircraft. It uses the well-known full bridge strain gages [5] [1] in a different manufacturing possibility: inside composite layers before resin cure.

2 Aircraft

The under study X-HALE has 6 meters (m) span with a chord of 0.2 m resulting in an aspect ratio of 30. The wing has no sweep angle but the tips have dihedral. The propulsion system is fully electrical with 5 engines/propellers. The control surfaces are 2 ailerons for the wing tips and 4 elevons in the outboard tails. The center tail surface is responsible for reducing intentionally the lateral stability after take-off by rotating from vertical position to horizontal position.

Fig. 1 presents the 6 meters X-HALE. The light color parts are made of fiber glass composite material and the dark color parts are carbon fiber composite material. The aircraft was hanging on the building ceiling for exposition purpose but only the electrical installation and control boards were missing.

The aircraft is modular. The wing is made of two modules: center ones and tip ones, both with 1.0m span. They differ by having the aileron on the tip ones. Both types of modules have the same geometry main-box that is 1.0m span by ~30 millimeters (mm) chord by ~20mm height. The upper and lower surfaces of the main-box follow the airfoil curvature.

In the manufacturing process of each wing module the main-box and the loft layer are assembled in a mold and cured together. This is why any internal instrumentation is challenging in this case. As more complex composite aeronautical structures are developed this challenge tends to be more frequent.

3 Real-time flight shape

This paper contains part of the development of an aircraft real time flight shape measurement system. The system concept, hardware and manufacturing process are presented. Further steps includes hardware integration with aircraft systems including integration with flight control laws.

The under development concept for real time flight shape feedback for control laws is presented in Fig. 2. The aircraft needs to have deformation sensors along the span. The sensors are connected to the analogic input of the Board Computer. The digital information is sent to the central processor. Without any calculation the simple sensors voltage readings are usable. Calculations are made using the strain in order to build aircraft flight shape information for each time reading step. The loads in the structure are also possible calculated information based on strain. The flight control laws receive all the generated information that may also have fixed limitations for the received variable, even rate limitations, even target values. The flight control laws uses the control surfaces in order to change the aircraft shape or to avoid any incursion in the limits set up for the variables.

The proposed sensors in this study are common strain gages full bridge with the novelty of having it embedded in the aircraft composite layers. A bridge set has bending, torsion and shear full bridges. The initial challenge is to have one bridge set for every center module main-box.

The development of the hardware system for the real-time flight shape measurement is presented starting from a bar prototype used as an equivalent main box for concept testing. The challenges for the hardware are: hardware definition, process feasibility, process influence, engines electromagnetic field interference, thermal stability.

4 Bar prototype

A rectangular cross-section bar was the prototype selected for hardware testing in order to demonstrate the concept feasibility. The target was to overcome the above mentioned challenges using an easy manufacturing geometry. A rectangular cross-section, instead of the original curved section of the main-box, simplifies any structural test boundary condition in addition to a simpler mold for curing process.

The bar prototype with 5 composite layers have the sensors inside the last layer before the material curing process. The bar prototype passed on vacuum inside the mold, constant elevated temperature for material cure and electrical wiring for further testing. Exactly the process required to manufacture the aircraft with sensors.

Fig. 3 shows the manufacturing process of the bar prototype of ~1m by 31 millimeters (mm) and by 25.5mm height. In Fig. 3 (a) the first 4 layers of uncured material are rolled in the internal mold. In Fig. 3 (b) the last uncured layer is rolled in the mold already with the sensors inside. The thin wires are pulled outside the last layer for further electrical lead-wire soldering. The aircraft will have the wiring inside the loft. Fig. 3 (c) shows the bar prototype already cured with the sensors embedded in the composite structure and the wires free for installation.

The embedded sensors are part of the whole instrumentation of the bar prototype for concept validation. The sensors are strain gages and they are wired as four-active strain gage bridges. There are two full bridges in bending configuration embedded in the structure (BFB1 and BFB2) and an additional external bending full bridge is installed after the cure process using standard industry gluing procedures (BFB3). In addition, one more full bridge for shear (SFB) and another one for torsion (TFB) are installed also using standard industry gluing procedures after cure. The bending bridges uses gages CEA 06-250-UW-350 and the shear and torsion bridges differs by positioning and the gages are CEA 06-187-UV-350.

Fig. 4 shows the middle of the bar prototype fully instrumented. The figure shows only the upper gages for the bending bridges but there are equivalent one in the lower side of the bar. Note the visible misalignment for the immersed gages as result of the manufacturing process.

5 Four points test

A four points test was executed in order to evaluate the instrumented bar prototype strain results. The usual four points test was inverted by having the reaction in the middle and the forces applied in the tips. The concept behind the four points test was kept: constant moment in the center of the structure. All full bending bridges are submitted to the same bending moment, this is why the span positions of the bending bridges are not relevant. Fig. 5 shows the inverted four points test in the bar prototype. Hanging weight loads are discretely applied equally on both tips. The gages are acquired using Vishay Model D4 Data Acquisition Conditioner. The deflection of the center of the bar prototype was measured using a Digimatic Indicator 543-260B from Mitutoyo.

The tests are made with increasing load followed by decreasing load in order to expose any sensor issue. The main part of the test is made with hanging weights aligned with the bar prototype center line generating no torsion. This is sufficient to evaluate the differences from BFB1 and BFB2 to BFB3. There are test conditions with additional torsion generated by misaligning the load from bar center line. These tests are intended to evaluate the SFB and TFB sensitivity to the applied torsion and also, at same set up, verify the engine interference in the SFB and TFB together with bending full bridges. The constant moment in the middle of the bar prototype does not occur when torsion is applied.

Before the loading tests, the bridges were electrically tested by shunting one high accurate calibrated resistor through one bridge arm to simulate a strain deformation on the bridge. A 9820 Ohms Shunt resistor was manually connected to one of the bridge gages while the acquisition system was measuring the corresponding reading. When the strain result is very close to the expected one, the measurement system is proved to work properly and to delivery confident results. The difference between expected result and measurement quantifies the wiring or excitation errors, or even voltage drop on long excitation cables.

Second test was intended to show the correct response of the full bending bridges due to different loads. The deflection results are used to adjust the FEM model. Because of the same moment in all three full bridges they should have only offsets due to manufacturing process influence and layer positioning. The weight load sequence on each tip was zero, 1.5kgf, 3kgf, 1.5kgd and finally zero again.

Third test was intended to show electromagnetic interference in the strain measurements. This may happen because the electrical wires of the gages will pass close to the aircraft electrical engines. The test is emulated by turning on the engine close to the wires of the gages during test. There are two engine situation: engine on without torque and engine on with torque where the electromagnetic field is higher. The load amplitude is not important but the strain oscillation around the average.

The last test was intended to show any tendency for heating accumulation on immersed gages compared to standard ones. Composite materials are in general poor thermal conductor, which could lead to measurement instability due to the gage self-heating. Evaluating the sensors along time may show any tendency for changing the results. The bridge was powered with 5Volts for 6.5 minutes.

6 Bar model

A Finite Elements Method (FEM) model of the bar prototype was used as an additional reference for bending results. The same geometry was represented using plate elements with composite material. The Elasticity Module is initially set at a reference and later it is adjusted using experimental deflection results.

Fig. 6 shows the bar prototype FEM model. The same boundary condition and loads of the inverted four points test are added to the FEM model. The strain results at the same position of the bending bridges are taken from Nastran® structural static linear analysis in order to estimate the bending full bridge results. The center of the bar deflection was also taken from the same Nastran® analysis.

7 Results

The Shunt calibration test result is presented in Fig. 7. There are two results for each full bridge. The manual connection of the resistor occurs first on one gage and sequentially in another one, in the same way it could be made for the other two. The expected Shunt calibration strain is also plotted showing how close the results are from expectation. The use of different gage types for bending and shear/torsion also changes the gage factors, this is why the expected strain is different for SFB and TFB. The difference from expected strain to measured strain was below 0.5% for BFB1, BFB2 and BFB3. For SFB and TFB the difference from expected strain to measured strain was below 1.3%. The results are considered inside the expected variation.

The inverted four points test is presented in Fig. 8. The results for all bending full bridges along time were parallel showing an expected behavior for the immersed gages compared to the external ones. All three bending full bridges had less than 7 micro-strain difference from zero load in the beginning to the zero load in the end, showing they are well attached to the structure and the structure is free from hysteresis. The FEM analysis result was following the test tendency but both strain and deflection measurements were offset from test due to its initial material property. Also the strain offset due to layer positioning was much higher for test than FEM analysis indicating necessary corrections.

The material Elasticity Modulus in both directions was changed from 21.0GPa to 18.6GPa in order to reach the test deflection. For the internal layer gages the FEM result was also adjusted in order to consider 18 degrees alignment error. Using the angle correction is equivalent to a linear calibration factor of 0.9511. Fig. 9 shows again the same inverted four points test, after FEM adjust. Then, FEM model is presented as very correlated to the test result. The test difference in strain due to layer position in the 3kgf load step was between 178 (BFB1 to BFB3) to 232 (BFB2 to BFB3) micro-strain and FEM analysis difference was first 31 micro-strain and later with angle correction it was 188 micro-strain. There is also the possibility to have different angle correction for each internal full bridge. The FEM structural analysis strain result differs less than 1.3% from test in all bending full bridges while the deflection difference was less than 0.6%. The bar prototype results demonstrated there is a calibration procedure using linear factor for considering all manufacturing and installation influences generated during immersion of the gages. The resultant built-in hardware is fully functional.

Fig. 9b shows load versus strain for the same inverted four points test result of Fig. 9a. The plot evidences the system linearity and negligible hysteresis.

Fig. 10 shows results for the inverted four points test with additional torsion in order to excite also the SFB and TSB. In the first 300 seconds the full bridges signals were clean. After 300 seconds, the results for the same setup but approaching one engine of the X-HALE aircraft to the wires of the bar prototype are presented. It shows the electromagnetic interference in the full bridges measurements. Fig. 11 shows details of the engine interference for all bending full bridges. The interference amplitude was below 1.5% for BFB1, BFB2 and BFB3. For SFB and TFB the interference amplitude was below 1.8%.

Fig. 12 shows the strain results along time for thermal stability in the inverted four points test. For both intermediate and higher load steps there were 0.26% average change in built-in bending bridges and there were 0.41% average change for the BFB3 for the same period of time. The time at the lower force step was 4 minutes and in the higher load step the time was 1.5 minutes. In this case the BFB1 and BFB2 didn’t have any indication for reduced thermal stability compared to usual gage installation. This is why no longer time was evaluated during test.

After the presented results, the proposed built-in hardware for in-flight real-time geometry measurement was made available for aircraft use.

8 Aircraft manufacturing process

After hardware and manufacturing process validation for the bar prototype there was sufficient confidence to develop a manufacturing process for the whole X-HALE aircraft using the disclosed knowledge.

This chapter presents the resultant hardware and manufacturing process for the X-HALE of six meters. Each module of 1m span will have a set of built-in full bridges. The same procedure is applicable to all modules or to additional sets on the same module. The whole aircraft with built-in gages is the deliverable for this paper and further development to integrate the hardware to the aircraft systems are part of next publications.

Fig. 13(a) shows the main box of the aircraft central module before cure with the gages positioned. Half of the bending full bridge is visible and both torsion and shear full bridges are visible. The wiring was pushed to the trailing edge where there was space for the cables bundle routing. The gages are the same type selected for the bar prototype. Fig. 13(b) shows the main box being positioned in the module loft with one layer below and a hanging layer that later will be the upper loft surface.

Fig. 13(c) presents the module completely assembled before cure. The loft composite layer of the module is over the bending and torsion instrumentation. The upper mold closes the module in order to proceed for curing process. Fig. 13(d) presents the final module already cured. The gages are visible through the loft layer.

X-HALE aircraft of Fig. 1 is already assembled using four instrumented modules. The aircraft is fully available for built-in measurement hardware integration with aircraft systems and testing, in ground and in flight.

9 Conclusions

The full bridges made of gages embedded in the aircraft structure performed equally to usual strain gages externally glued.

Using an instrumented bar prototype in a four points test was sufficient for validation of the bending full bridges inside composite layer with easy manufacturing, simple setup and fast results.

The loading tests also showed that the strain gage sensors respond linearly with respect to load, exhibiting negligible hysteresis, important characteristics for loads calibration purposes.

Immersing the gages in the structure composite layers before cure is feasible. The missing control of gages positioning inside the curing mold generated misalignment. The misalignment was corrected using linear factor of 95.11% (~5% correction). The alignment linear factor is suggested to be incorporated in the final calibration of the full bridges. The manufacturing process worked for the bar prototype and also for the X-HALE aircraft.

Any expected electromagnetic field interference from X-HALE engine to the strain gages measurements is negligible. There was no indication of thermal stability degradation for the gages inside one composite layer using 5Volts input.

In-flight shape measurement using built-in gages in the aircraft composite structure is feasible.

The under development concept of in-flight shape measurement and feedback for control laws was disclosed for the X-HALE. Sequential studies are expected in future publications.

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Contact Author Email Address

Angelo A. Verri
e-mail: angelo.verri@embraer.com.br
Flávio L. S. Bussamra
e-mail: flaviobu@ita.br

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Figures

Fig. 1 – X-HALE aircraft hanging in the ceiling for concept demonstration. It was manufactured with built-in strain gages.

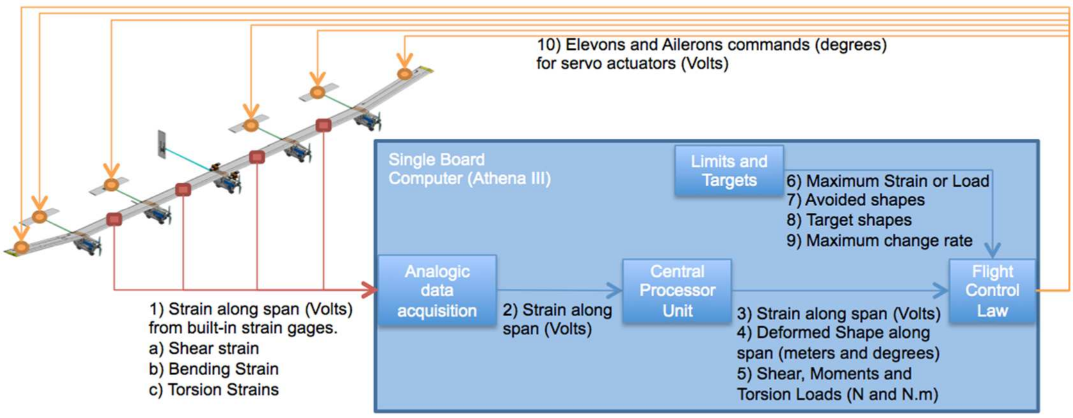
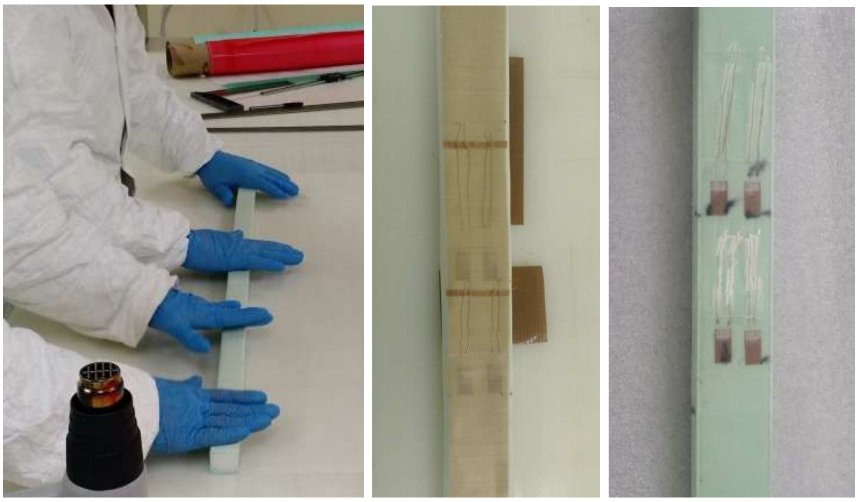


Fig. 2 – Integration of in-flight shape measuring with Flight Control Law



(a) (b) (c)

Fig. 3 – Bar prototype manufacturing process. a) Four layers of composite are rolled in the mold. b) Last layer of composite is rolled in the mold with strain-gages between layers. c) Bar after resin cure process.

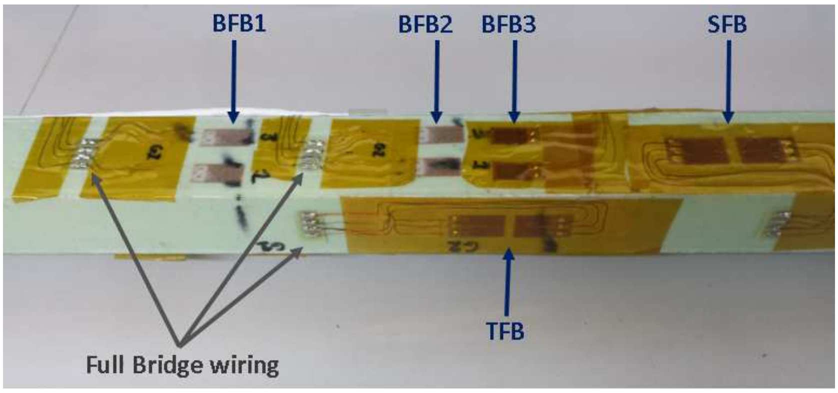


Fig. 4 – Center of the bar prototype fully instrumented and wired in five full bridges. BFB1: Bending Full Bridge 1 inside layers. BFB2: Bending Full Bridge 2 inside layers. BFB3: Bending Full Bridge 3 external with standard gluing procedure. SFB: Shear Full Bridge external with standard gluing procedure. TFB: Torsion Full Bridge external with standard gluing procedure.

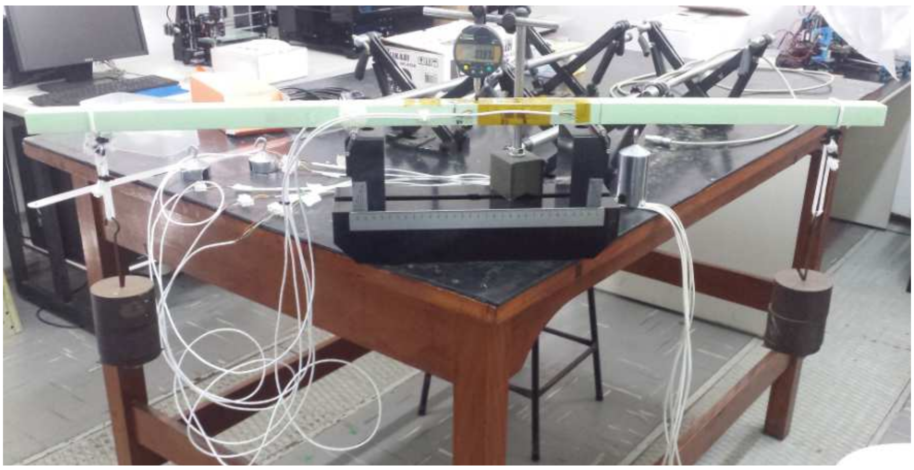


Fig. 5 – Bar submitted to inverted four points test, with weight loads applied in both tips.

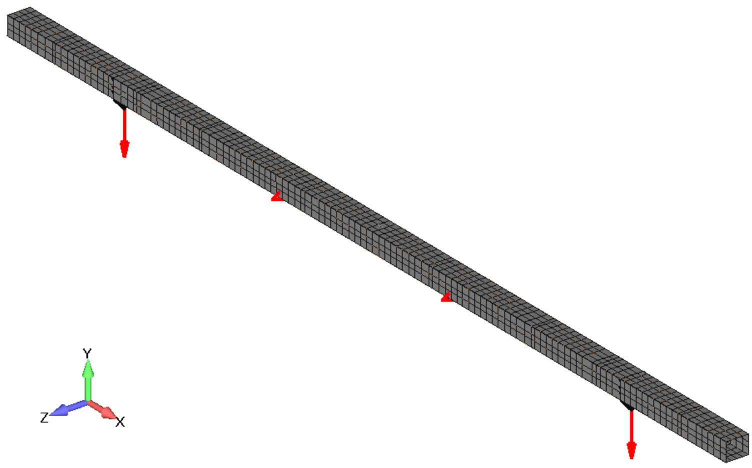


Fig. 6 – Isometric view of the bar prototype FEM model.
Triangles are constrains in Y direction and arrows are equal forces at the same magnitude and position of the test hanging weights.

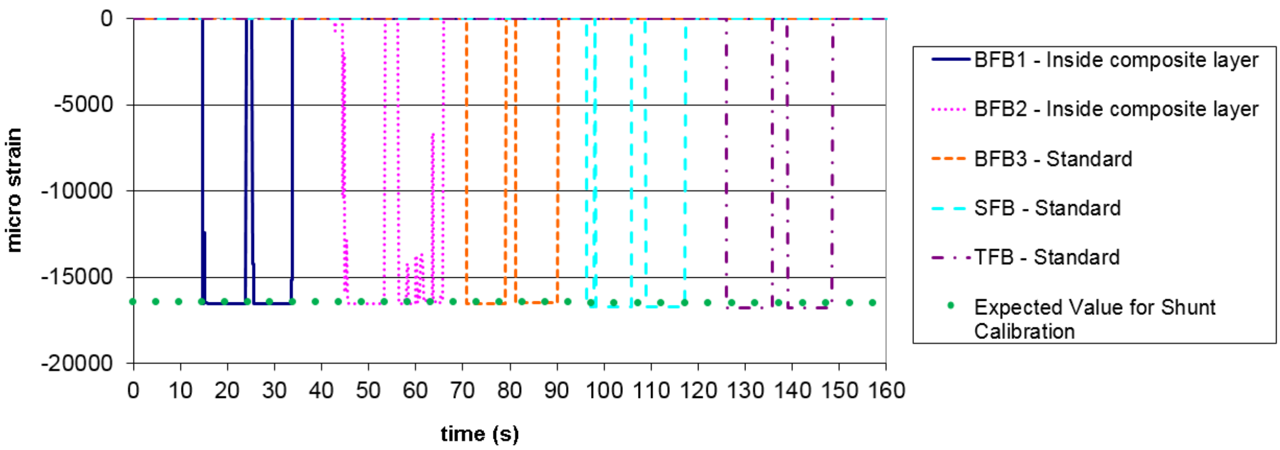


Fig. 7 – Expected and measured Shunt Calibration data.

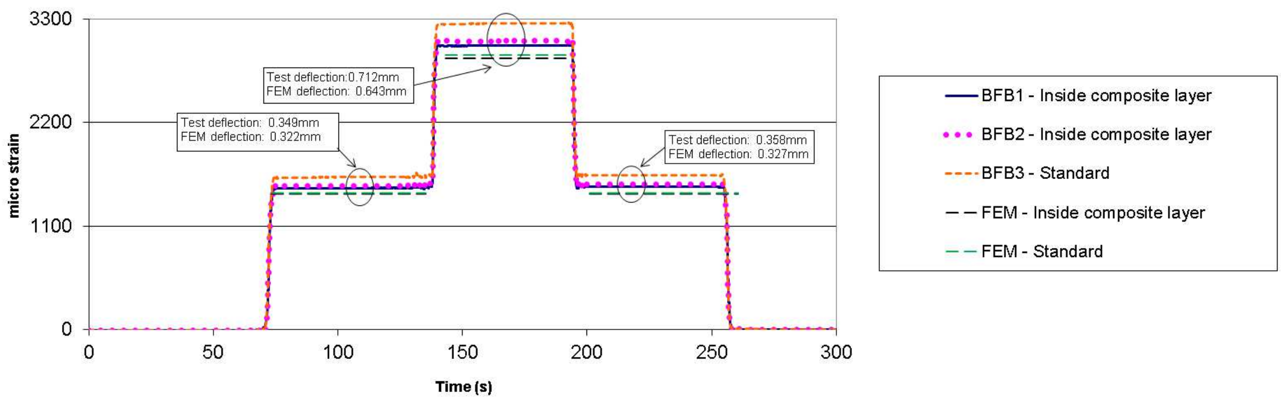


Fig. 8a - Four points test results compared to FEM model without adjust.

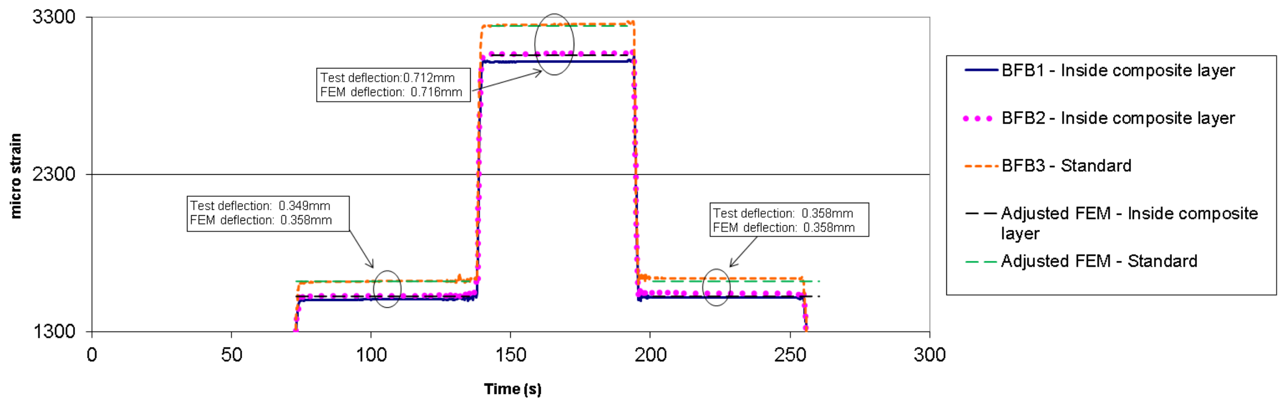


Fig. 9a - Four points test results compared to FEM model with adjust.

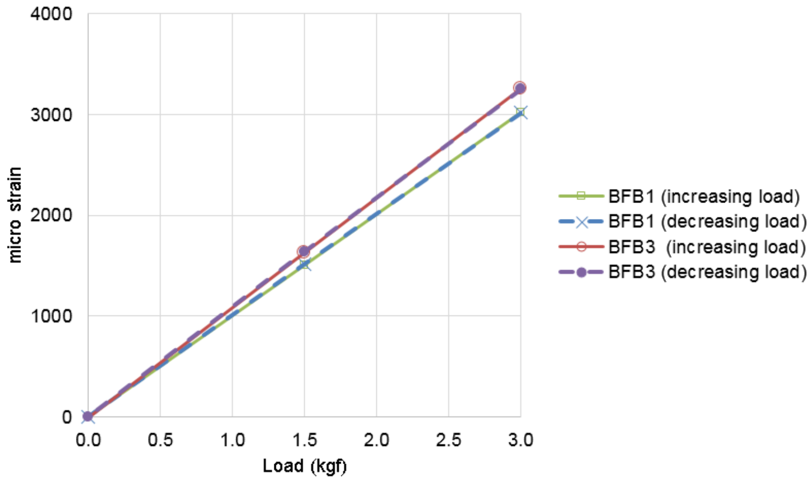


Fig. 9b - Four points test result - hysteresis evaluation

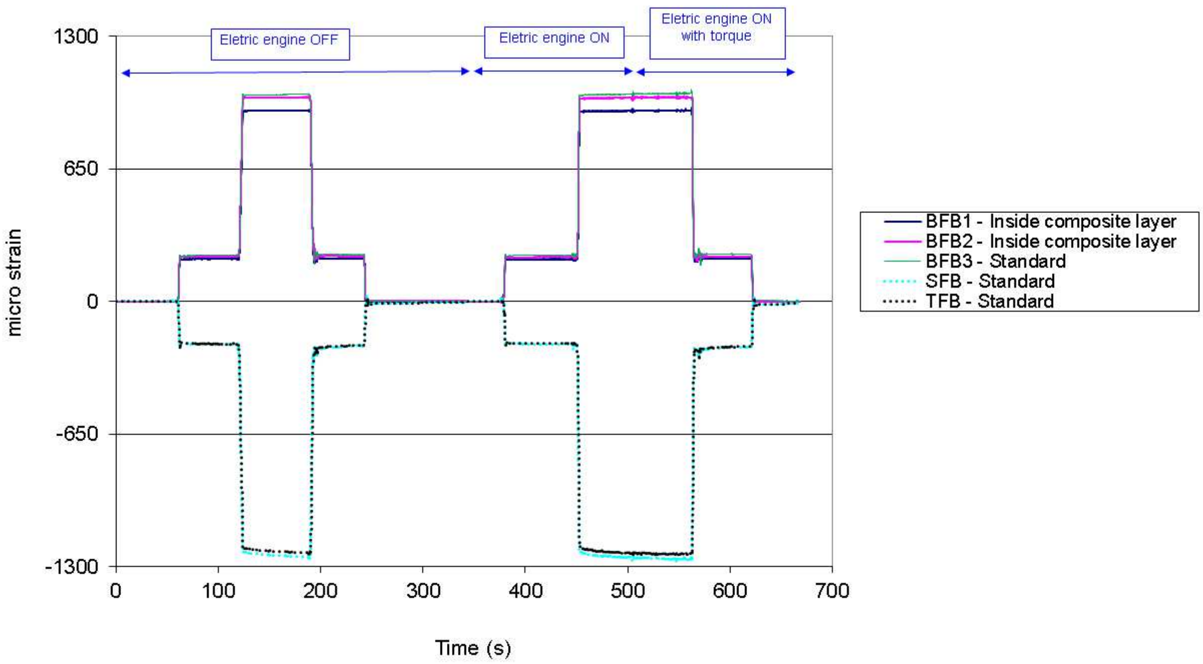


Fig. 10 - Torsion and bending test first without and sequentially with interference.

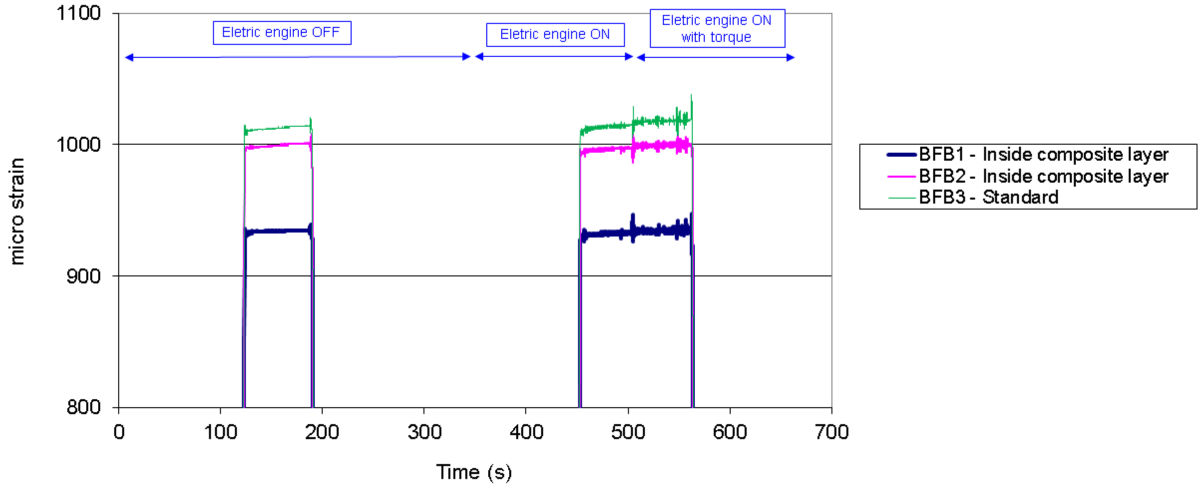


Fig. 11 - Torsion and bending test first without and sequentially with interference.

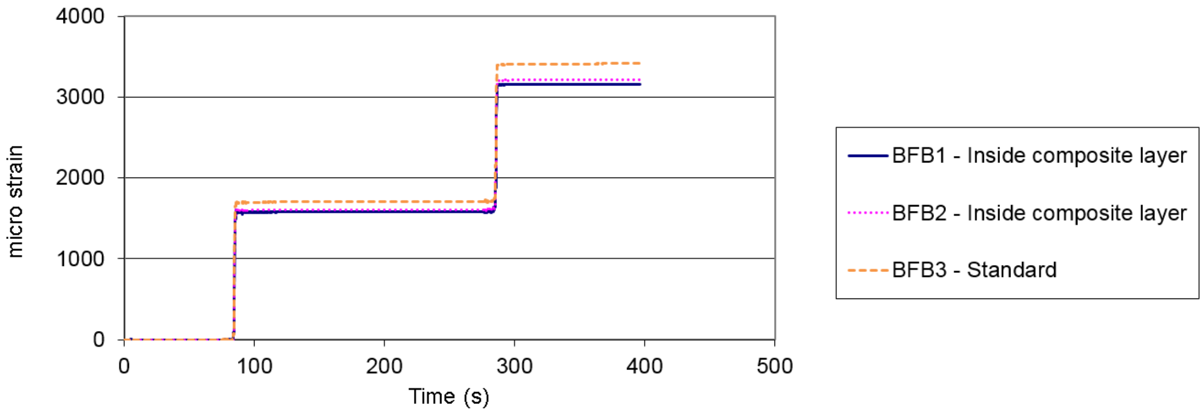
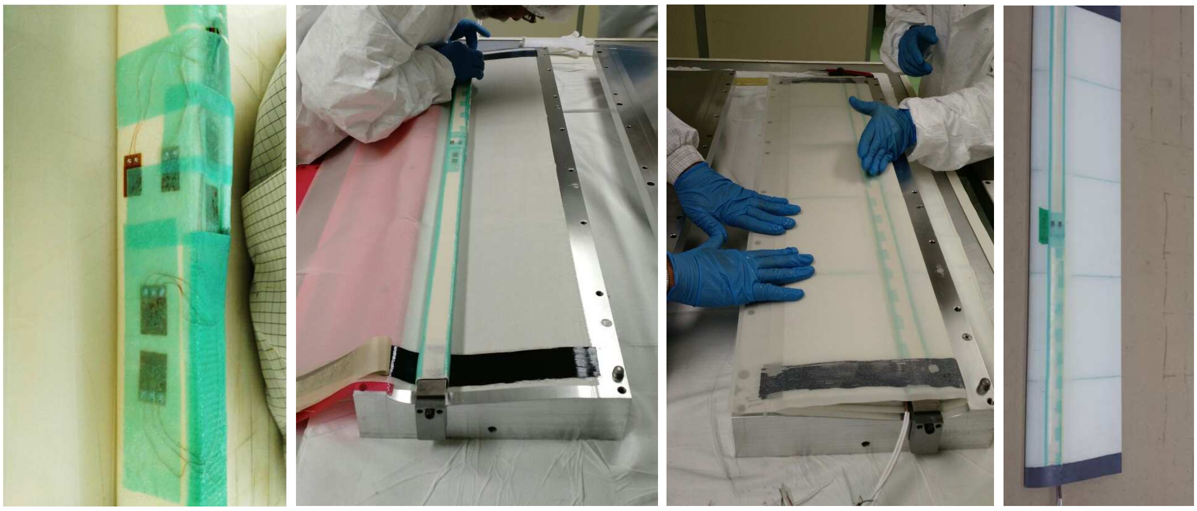


Fig. 12 - Strain gages stability measurement for a period.



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

Fig. 13 – Wing module manufacturing process with embed gages. a) Main box of the X-HALE center module with positioned strain gages. b) Wing center module being assembled before placing the upper skin. c) Wing center module ready for curing process. d) Final center module with built-in gages.