Document Reference: RD2021-04_ES

Revision no.: v2

Executive summary

Subject	Technical note
Prime Contractor	Com&Sens
ESA contract no.	000136778/21/NL/AR
Framework	ESA-TDE-TECM-SOW-023514
Project Title	Space Composite Structures Life-Cycle Monitoring
Document reference	RD2021-04_Executive Summary

Action	Name	Function	Signature	Date
Approved by	Geert Luyckx	Project engineer (C&S)	GL	30/07/2024
Checked by	Steve Nardone	Project manager (Engie LBE)	SN	24/06/2024
Prepared by	Geert Luyckx	Project engineer (C&S)	GL	13/06/2024

Rev.	Date	Description	Prepared	Checked	Approved
1	13/06/24	Initial document	GL	SN	GL
2	30/07/2024	Typo check	GL	SN	GL

Executive Summary

The consortium Com&Sens (Prime), ENGIE LBE and SABCA joined forces to successfully finish the ESA life Cycle monitoring project. In this project, a benchmark structure (composite assembly) coming from the Themis project (Figure 1) for reusable launchers, is chosen. It considers the load bearing structure of the grid fins of the reusable launchers depicted in Figure 2. The Grid Fins are aerodynamic control surfaces folded during launch and deployed in flight to steer the direction of the launcher during re-entry.

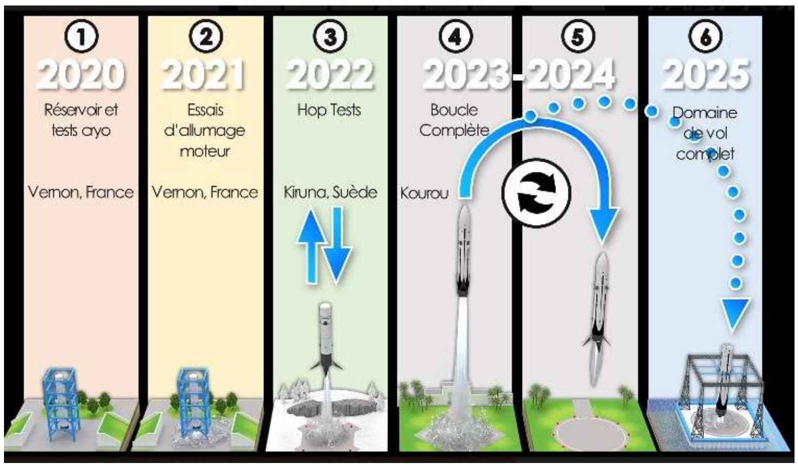


Figure 1 An overview of the Themis project with the different stages in the research and timing (https://spacewatch.global/2020/11/arianeworks-on-first-european-reusable-rocket-prototype-themis/)

Figure 2 is a simplified image of a part that SABCA predesigned for an ESA reusable rocket program. The depicted part is the Flight Control Bay (FCB) and contains the systems for the airbrake grid fins whose axes pass through the wall of the cylindrical section. To absorb the important operational loads a doubler is foreseen in that area as well as a bushing to support the axes. The flat manufactured benchmark is a simplification of the actual application which is curved. The manufacturing process used is automatic tape laying (ATL).

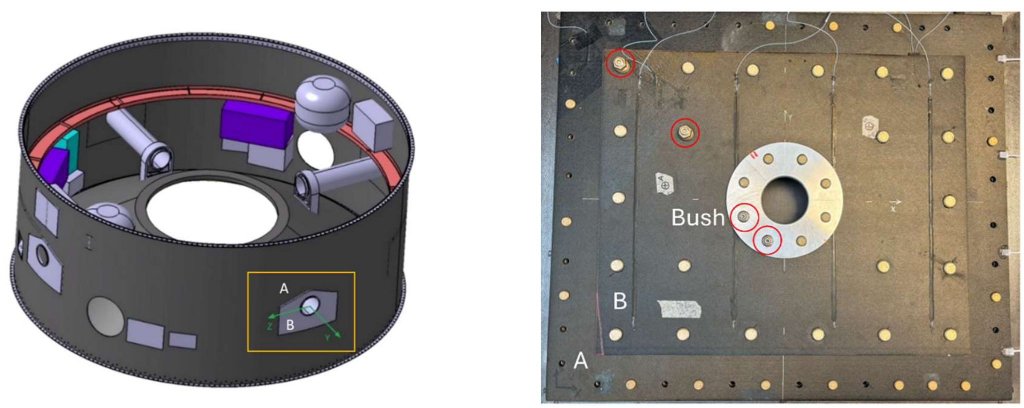


Figure 2: Left, grid Fin schematic with doubler panel and its local coordinate systems, right the benchmark structure.

The different loads contributors of such a grid fin are considered (such as aerodynamic, general, thermal, pressure and local loads). The life cycle of this structure and more in general of the control bay consists of the following phases:

- **Manufacturing phase** mainly comprises the production (lay-up and curing) of the different components and their pre-assembly.
- **Storage/Transport phase** includes phases and events like transport on street, transport on boat, transport by airplane, storage.
- **Integration / Handling phase** refers to phases like handling during integration, transfer from integration and final assembly buildings to launch pad, transfer from horizontal position to vertical position, etc.
- **Use phase**
    - o **Ground phase** covers all the events occurring when the launcher is on the launch pad or test bench.
    - o **Ascent phase**. From engine start-up until first flip-over manoeuvre
    - o **Re-entry phase** use phase of the fin grid

The main parameters to be monitored that will be used to assess the carbon fiber reinforced composite component performance during its life-cycle are strain distribution, temperature distribution, humidity sensors. The position of the strain, temperature and humidity sensors are shown in Figure 3. For both panels, the position of the temperature sensors (Fiber Bragg Gratings, i.e. FBG technology, embedded in a capillary) are integrated in the middle layer of the composite. The strain sensors (FBG technology) are integrated for the Base Panel in between layer 33/34, along the 0 degree direction (x-axis) and for the Doubler Panel in between layer 25/26, along the 90 degree direction (y-axis) (Figure 3). The humidity sensors are surface mounted (HYT271) and have an integrated temperature probe

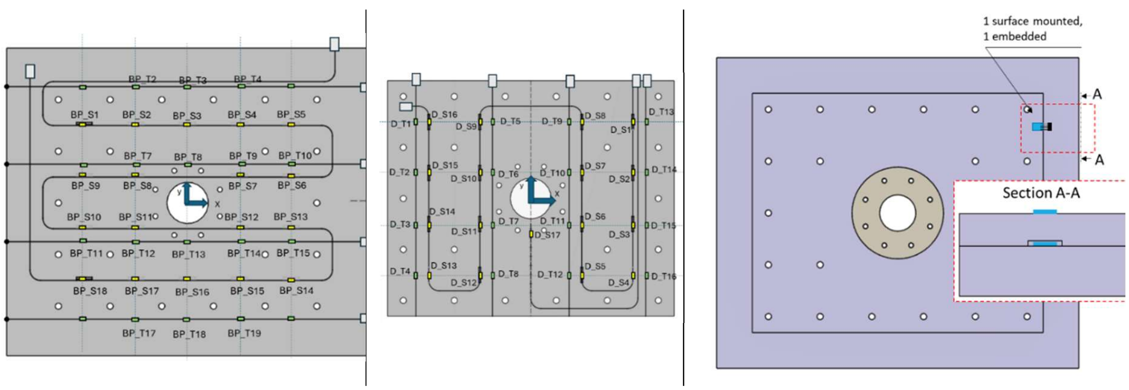


Figure 3: Final sensor set-up, left Base panel, middle Doubler panel, right location humidity probes

To demonstrate the integrated sensor technology for life cycle monitoring of composite structures (benchmark) within laboratory conditions (TRL 4), a building block approach is suggested. As depicted in Figure 4 (left), a classical building block approach consists of 4 levels ranging from coupon testing towards the full component testing. In this project, the aim of the pyramid of test was to prove the functionality of sensors towards life-cycle monitoring and not in qualifying a composite design.

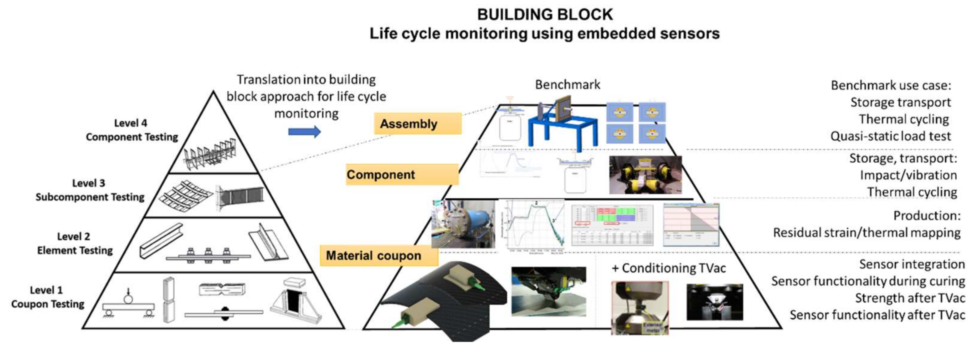


Figure 4: Left, Test and analysis pyramid (Credit: Dan Adams, www.compositesworld.com), right translation to life-cycle monitoring of composite structures for space applications

The first level of the building block is working on the material coupon level. A robust sensor integration method (with clear procedure) is developed. The results of the embedding during ATL machining is described. After embedding and production the plates are ultrasonically C-scanned . This scan of the inside of both panels did not reveal any damage around the embedded optical fibers nor around the embedded capillary. After cutting the plate into coupons, the coupons are conditioned in a combined temperature vacuum chamber for 10 temperature cycles. The side of the conditioned and non-conditioned (compression and inter laminar shear strength, ILSS) coupons are polished and the effect of TVac is qualitatively examined. No significant difference is noticed when comparing the embedded structures (fiber and capillary) with and without TVac conditioning.

After microscopic inspection functionality and mechanical strength tests were conducted: From the functionality test (tensile test), we could conclude that there is no decrease of accuracy or precision because of the TVac conditioning. The mechanical strength testing consisted of the tensile test on the samples for which no difference in tensile strength between coupons with and without embedded optical fiber after TVAC was found. Also for the compression test (without sensors, with sensors, with capillary and with capillary but not conditioned) no difference in strength is observed between the different tests. As last ILSS tests are executed, which are short beam bending tests on small coupons (10mm x 20mm). A small decrease in interlaminar shear strength of about ± 8 % was noted for the capillary and fiber coupons compared to the reference material. No significant extra decrease in interlaminar shear strength is noticed after TVac conditioning of the coupons and even slightly higher values are observed.

At component level, after production of the Base panel and doubler, impact/ vibration and thermal cycling are performed to simulate the storage and transport phase of the life cycle. In the last block, the components are monitored while being assembled, again storage and transport is simulated and finally the assembly is loaded in a quasi-static loading set-up. The removal or untightening of one or different bolts will simulate a controlled damage pattern of the assembly which can be measured with the integrated sensor grid.

To better visualize life cycle effects, a GUI is developed to capture and plot the obtained sensor data. First the strain and temperature data (optical fiber sensors) are compiled in csv format every minute at a sampling rate depending on the life cycle from 10 to 1000 Hz. Secondly, the humidity and temperature data coming from humidity/temperature probe, is compiled in an ASCII format in a continuous file with a sample rate of 1Hz. All data streams are combined/synchronized in the CS Data object also containing the sensor ID, type, position,….. The data flow is shown in Figure 5.

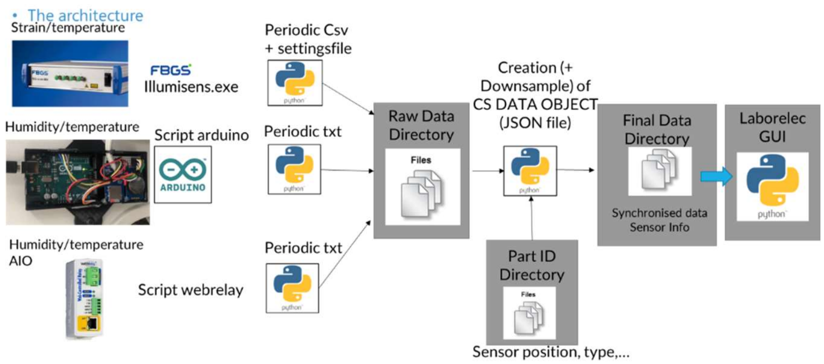


Figure 5: Project architecture and dataflow diagram

The GUI has been designed so that by looking at the overview of all the collected data on the right of the screen, the user can interpret the important events (Figure 6).

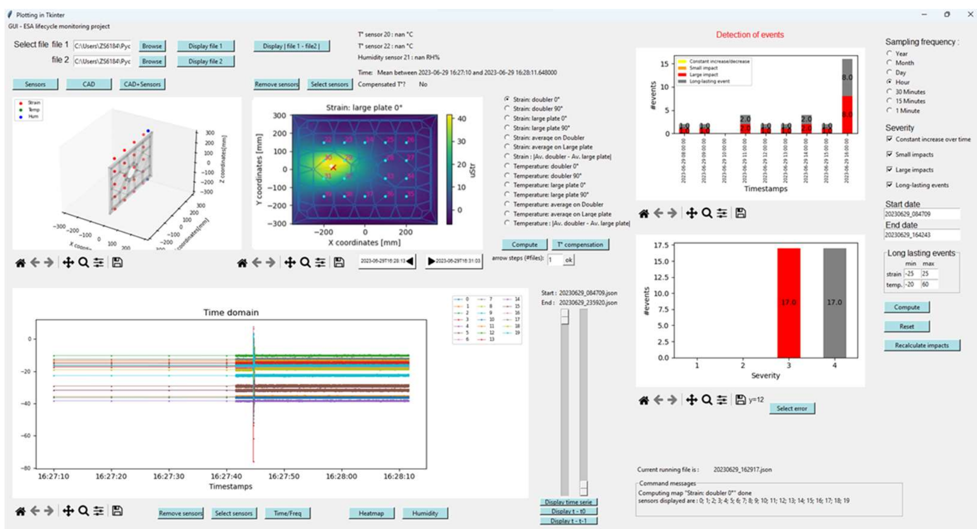


Figure 6 GUI with Strain heatmap with the impact location shown with a white dot and the calculated position with a red cross.

The following life cycle phases and thus specific test phases are executed:

- **Manufacturing phase.** This phase deals with the production (lay-up, curing, demoulding and NDT) of the different components (Base and doubler composite panel). After demoulding, edge trimming and surface mounting of extra capillaries on top of the doubler still 100% of the strain sensors and 89% of the temperature probes are operational. Even after all the life cycle tests the same set of sensors are still operational. During manufacturing, small residual strains could be measured with small differences between sensor locations. The mean residual strain for all sensors and the standard deviation is given in Table 1.

Table 1 Residual strains of the strain sensors of the Base panel and Doubler

Panel	Name	Sensor Type	Residual strain [µstrain]
Base panel	BP_S1	Strain	-480±11
Doubler	D_S1 – D_S16	Strain	-536 ±26

- **Storage and transport phase** at component level.

  The storage is subdivided in tests within the climate chamber and tests in storage with events using an impact hammer. The sensor system is able to detect impacts during transportation and during storage. Impacts at the side of the panel (in-plane) are difficult to detect for the Base panel as the sensors are more inwards compared to the doubler.

  To limit the amount of data during monitoring of the whole phase, the data is down sampled when no event occurs. The climate chamber test demonstrated the working of the humidity sensors and showed for most of the T-probes a one on one relation with the measured temperature of the climate chamber.

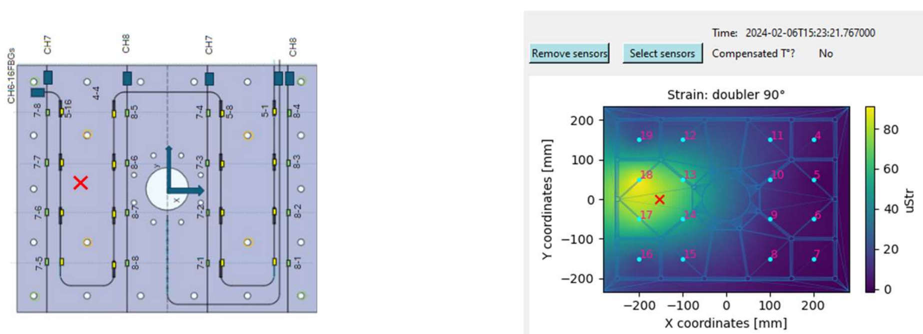


Figure 7 Impact detection, left real impact position, right calculated using the sensor grid

- **Assembly phase.** This phase deals with the assembly of the 3 components: base and doubler panel along with the metallic bushing.

  Different steps were successfully measured using the grid of FBG sensors. Low residual strains changes are noted proving a qualitative assembly.

- **Storage and transport phase** of the assembly.

  Similar results as on component level are seen. Out-of plane impacts (simulating tool drops) are easily seen within the data. In-plane impacts are more difficult.

- **Use phase:**
  - Sinusoidal Loading on Assembly (SLA)

  By this sinusoidal vibration testing, the ability of the equipment (assembly and integrated sensor system) to withstand to low frequency excitations of the launcher is demonstrated. In this case, a chirp signal sweeping from 5 Hz to 100 Hz is used. During the test 2 FBG channel lines (one for the doubler and one for the base plate) were constantly monitored with a frequency of 1000 Hz. Variation on the strain excursions was less than 150 µstrain peak-to-peak.

- Random Vibration

This test could not be executed because of the 12mm limit in displacement of the shaker.

- Operating Temperature

This test demonstrated the resistance of the equipment (assembly and embedded sensor lines) to the range of temperatures representative of a space mission in LEO (A maximum temperature when non-operating of 125°C +10°C = 135°C and a minimum of -30°C -10°C = -40°C is considered)

- Resonance of Assembly Test (RAT) and Damage Simulation Resonance Test (DSRT)

A chirped signal sweeping from 1Hz to 1000Hz is used. The amplification gain for the shaker is set to a value that limits the displacement of the shaker to 12mm. During the test 2 FBG channel lines (one for the doubler panel and one for the large base plate) are constantly monitored with a frequency of 619Hz. Therefore, a frequency analysis up to about 300Hz is valid (Nyquist limit). The with the FBGs reported eigenfrequencies are similar to the ones measured by the accelerometer. When untighten one or two bolts of the bushing, changes in the eigenfrequency above 300Hz are seen by the accelerometers which are invisible for the current strain measurements.

- Quasi static test (LC1 - Vertical load and LC2 – Horizontal load) (Figure 8)

Five different damage scenarios were tested. Scenario 0 is considered as the baseline scenario with no visible damage present. For Scenario 1 to 4, every time a different bolt is untightened which can be considered as a failure of the assembly in this specific zone. The results (strain/load sensitivity and residual strain change) show a clear difference in the region where the bolt is untightened.

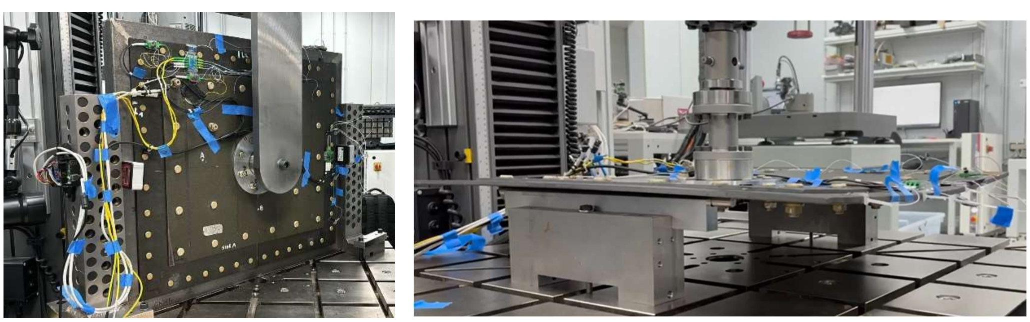


Figure 8 Component level - quasi static test set up , two load cases

The strain results of one of the sensor lines and an extract of the GUI are shown in Figure 9, a strain hot spot is detected which is also seen for the FE calculations done during the project.

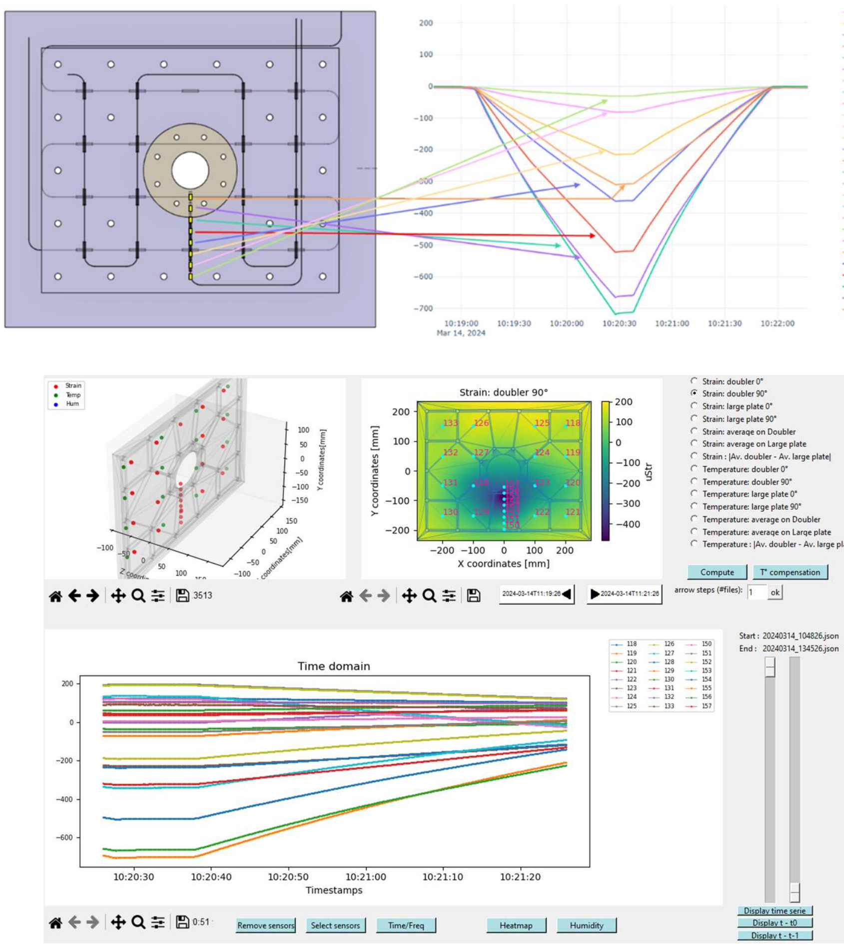
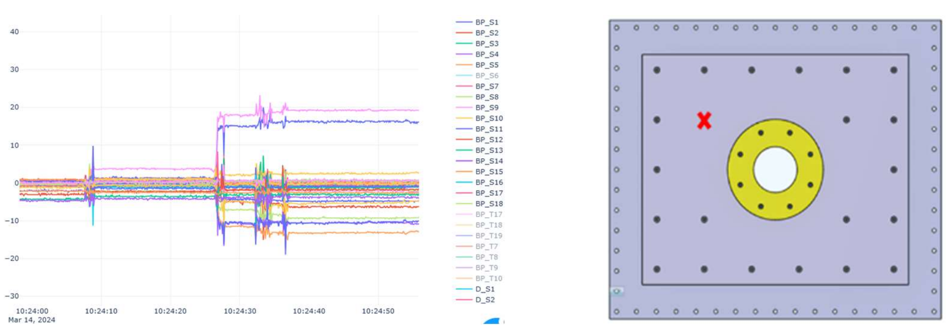


Figure 9 Strain sensor readings for the extra OF sensor line installed in the Doubler panel, assembly orientation 90°. Schematic view on top left and GUI view on the bottom.

In Figure 10 the effect of untightening a bolt on the residual strain deformation versus time is given in more detail. The residual strain effects seem very logic in terms of the location where the bolt is untightened.

Scenario 1



16.4	-6.3	0.0	-0.9	0.6
19.4	-9.0		-0.5	0.6
-4.9	-4.9		-0.2	0.1
-0.8	0.1	-0.4	0.3	0.1

-10.8	-11.1		-1.2	-0.3
-5.2	-13.3		-1.0	-0.5
-2.4	-1.3		-1.2	-0.4
-1.7	-0.6		-0.7	-0.5

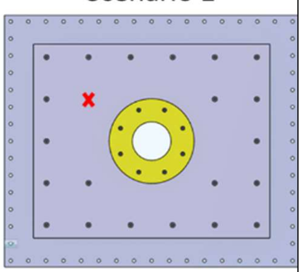
-2.6
-4.2
-3.9
-2.3
-1.4
-0.6
-0.2
1.1

Figure 10: Top, Sensor strain response untighten bolt scenario 1. Bottom, strain change for the different sensors during untightening of the bolt for scenario 1, left large panel, middle doubler right, extra OF doubler.

As can be seen in Figure 11 this also has an effect on the strain to load sensitivity on that location.

	BASE Panel 0°	**Doubler 90°**	**90° - Extra**

Scenario 1



BASE Panel 0°:

-0.175	0.155	0.055	0.027	-0.007
-0.155	0.171		0.012	-0.005
-0.016	0.073		-0.016	0.020
0.000	-0.001	0.008	-0.002	0.005

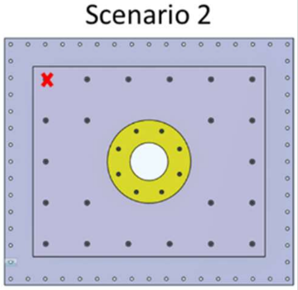
Doubler 90°:

-0.088	0.001		0.027	-0.007
-0.041	-0.005		-0.005	-0.006
-0.011	-0.125		-0.072	-0.010
-0.032	-0.036		0.017	0.003

90° - Extra:

0,06
0,16
0,13
0,08
0,05
0,05
0,03
0,01

Scenario 2



BASE Panel 0°:

0.087	0.013	0.015	0.029	0.003
0.035	-0.042		0.024	-0.017
0.012	0.027		0.006	0.025
0.000	-0.012	0.007	0.005	0.007

Doubler 90°:

-0.074	0.069		0.009	-0.018
-0.081	0.002		-0.022	-0.024
-0.061	-0.131		-0.081	-0.007
-0.048	-0.046		0.043	0.003

90° - Extra:

0,15
0,27
0,19
0,12
0,09
0,07
0,05
0,02

Figure 11: Difference of the 'strain to load sensitivity' [µ ε/kN] for the damage scenario 1 and 2 compared to the baseline scenario.

In conclusion, the application of smart composites makes integrity monitoring possible within all the critical phases of assembly integration and testing of a reusable spacecraft. The consortium's strategic choice of monitoring the life cycle of a lock bolted benchmark assembly represents the complexity of real-world applications. The monitoring results of all the different phases of the life cycle of smart composites are shown by extensive testing.