The aim of the STRAINMON project was to develop methodology procedures needed for the implementation of an SHM system, based on FOBG sensors and/or standard strain gauges (SGs), onto/into a CFRP fuselage stiffened panel as well as to implement the system. The role of the FOBG sensor system is to monitor the structural integrity of impacted and fatigued panels under compression loading. The FOBG and/or SG sensors were placed (embedded or bonded) at various locations into and/or onto the structure.

A methodology for integration (embedding) of the selected sensors (FOBGs) in the structure, relat-ed to the selected manufacturing process (autoclave process), was developed by HAI. In this procedure, special attention was given to the ingress/egress points as well as to the definition of appropriate interfaces (connectors) of the testing equipment. An appropriate testing plan (static & fatigue loading scheme) for demonstrators of a typical fuselage panel was defined in order to fully capture the structural integrity of the panel. Associated test rigs/jigs/tools, necessary for the correct application of loading of the panels, were designed and built. Two panels were impacted by low velocity impact with various energies corresponding to BVID (Barely Visible Impact Damage) and VID (Visible Impact Damage) by UNIPatras. The extent of impact damage progression under fatigue and compression loading was evaluated during the panels mechanical testing. The static and fatigue tests including data measurement and evaluation were conducted at VZLU. The NDI was conducted before the mechanical testing by UNIPatras and HAI and during and after mechanical testing by VZLU. Both ultrasonic and laser shearography method for NDI were used.

The comparison between the predicted and actual behaviour of panels were performed. The strength of reference panel without any defects was highest in comparison with other results. The lowest strength was obtained for panel containing the manufacturing defects and BVID. The FOBG data is in good agreement with the SG and optical measurements.

Aim of the STRAINMON project was to develop methodology procedures for the implementation of a SHM system, based on FOBG sensors and/or standard strain gauges (SGs), onto/into a CFRP fuselage stiffened panel as well as to implement the system. The role of the FOBG sensor system was monitored the structural integrity of impacted and fatigued panels under static compression. The FOBG and/or SG sensors were placed (embedded or bonded) at various locations into and/or onto the structure.

A methodology for integration (embedding) of the selected sensors (FOBGs) in the structure, related to the manufacturing process selected (autoclave process), were developed. In this procedure, special attention was given on the ingress/egress points as well as to the definition of appropriate interfaces (connectors) to the testing equipment. An appropriate testing plan (static & fatigue loading scheme), representative of typical fuselage panels loading was defined in order to fully capture the structural integrity of the panel. Associated test rigs/jigs/tools, necessary for the correct application, of loading in the panels were designed and manufactured. Non-destructive inspections (Ultrasonic B & C-Scan) of the panels were conducted before and after tests, mainly for panel with BVID and manufacturing defects.

The above described work was performed within STRAINMON project through WPs 1 to 2. This was accompanied by WP3 devoted to dissemination and exploitation of the gained knowledge and WP4 devoted to management.

WP1 was set the requirements and specifications of the proposed FOBG system with respect to the loading conditions, decide on the equipment (hardware and software) that was used, describe the methodology for integration of the sensors, design and fabricate the test-rig (antibuckling devices) and determine the test plan.

In WP2, the panels were tested according to the test plan decided in WP1.

WP3 was deal with all aspects of dissemination and exploitation of project's results, such as journal publications, conference presentations and possibly others.

WP4 was related to all management aspects of STRAINMON project.

Three panel tests with FOBG sensors have been performed within STRAINMON project. The first panel was manufactured as a reference without any defects. The other panels contained various artificial damage of BVID and VID type (low velocity impacts) and artificial delamination. Both static and fatigue tests were conducted. The aim of these tests was to examine the effectiveness and accuracy of the proposed FOBG sensor-based system in monitoring health of composite stiffened panels. The second aim was to determine potential damage or delamination growth during the fatigue test by means of NDT tests (Ultrasonic B- and C-scans and Laser Shearography). Strain measurement using traditional strain gauges and FOBG sensors embedded in panels and deformation measurement using optical system PONTOS (Digital Image Correlation system) were performed and documented.

All panels were manufactured by HAI, impact damages were done by UNIPatras and all other work had been provided by VZLU.

In order to properly design the fiber sensors' so as to effectively measure strains, which are representative of the critical damage that will develop during compression of the panel, a finite element analysis (FEA) of the panel has been performed. Numerical results from FEA will also assist the design of mechanical testing since it will give a correlation between applied load and damage progression which is very useful in the definition of loading sequence.

FEA has been performed using the LS-DYNA commercial FE code. To this end, a 2D FE model of the panel has been created by importing into the ANSYS pre-processor a CATIA drawing. The ANSYS SHELL163 element has been used to represent the entire panel. This is a 4-node element with both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has 12 degrees of freedom at each node: translations, accelerations, and velocities in the nodal x, y, and z directions and rotations about the nodal

x, y, and z-axes. This element is used in explicit dynamic analyses only. SHELL63 has also composite layered mode, which has been used for the composite skin and the stringers of the panel. Through the thickness of the skin four elements have been used while through the thickness of the stringer one element. This leads to the consideration of four layers per element in order to model the 16 layers of the skin and 12 layers per element for the stringer. The boundary conditions applied to solve the model are identical to the ones that will be applied by the loading frame and the anti-buckling device during mechanical loading.

Predicted initial local buckling occurs in the bays at the moment when the load achieved 75kN in force. The behaviour of the panel is almost linear with a small non-linearity at the 250kN which is due to the change of the local buckling modes in the bays. Final failure of the panel is predicted at 473kN due to the buckling of the middle stringer at the area close to the loaded side. Fig. 1 shows the contour of normal displacement (in mm) of the panel at 473 kN.
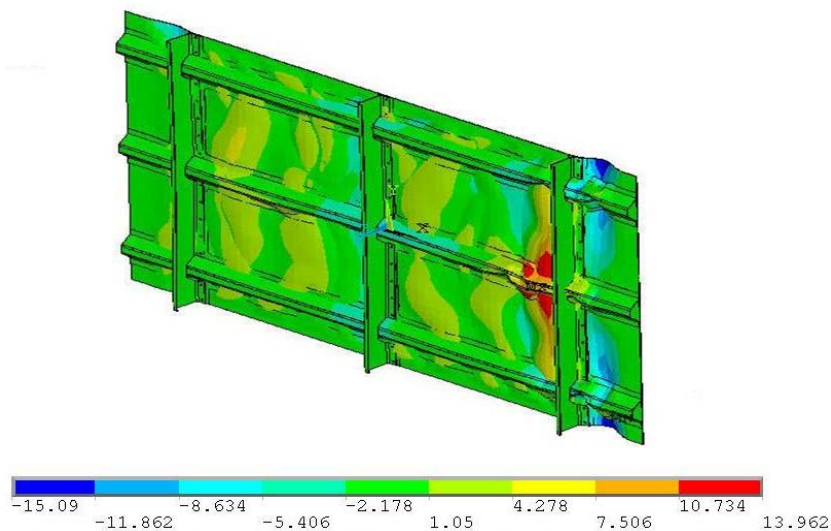

Fig.1: Contour of normal displacement (in mm) of the panel at 473kN.

From the load-displacement curve and the observed buckling modes of the panel, it is concluded that the FOBGs should be placed at the middle of the bays in order to capture early bulking as well as the change in the buckling modes. Special attention should be given at the bays close to the loading side.

The methodology for integration (embedding or bonding) of the selected sensors (FOBGs) in the structure related to the autoclave manufacturing process is very crucial work for the success of the project since the effective integration of sensors in the panel during manufacturing is the first and most important step towards the fulfilment of project objective which is the establishment of a reliable measuring system for monitoring the structural health of the panel. Ineffective integration of sensors may lead to failure of sensors during manufacturing which is a highly undesired phenomenon.

Standard aerospace grade pre-preg materials have been used for the manufacturing of the panels. More specific HexPly 8552 (by Hexcel) pre-preg in UD configuration has been used. This is a high performance tough epoxy matrix pre-preg for use in primary aerospace

structures. It exhibits good impact resistance and damage tolerance for a wide range of applications. The CPT of the pre-preg is 0.125mm.

The configuration of 300 mm role width dimension was chosen. Therefore, the panels were manufactured by collating (butted along the fiber length) role widths of 300mm in order to create the appropriate full plies. The panels were modelled in CATIA CPD, which was used for this purpose in order to obtain the flat patterns required.

The curing cycle was defined by the manufacturer. A co-curing process was used for the manufacturing of the panels, so the panels and "omega" stringers were cured in "one-shot" creating a "monocoque" structure. An appropriately machined large flat aluminium plate was used as the mould base. Especially designed aluminium mandrels of appropriate shape were used for shaping the "omega" stringers. Standard manual hand lay-up process was followed for the manufacturing of the panels. Standard vacuum bagging process was followed. De-bulking process during the lay-up process was followed every four consecutive plies. The whole assembly was cured in the autoclave following the cure cycle as described by the pre-preg manufacturer.

After completion of the curing process the aluminium mandrels (figure 1) where removed by sliding along their length, thus leaving the hollow shape of the "omega" stringers profile, co-cured on top of the flat composite plate representing the fuselage skin.

FC/APC Connectors were placed on the fiber optic cables by standard splicing process FOBG sensors arrays where placed on the skin and on the stringers on selected locations. In both cases (skin & stringer) the FOBG sensors where placed in the middle of the laminate thickness between two consecutive 0 degree layers.

The experimental campaign is divided into three main parts:

  1) Compression testing of undamaged panel

In order to characterize the compressive behaviour of the reference panel, compression tests to failure were conducted on undamaged panel. The stiffness and strength in compression of the panel was evaluated. NDT inspection of the failed panel was performed in order to detect the type and extent of damage. This first stage of the testing efforts covers the work described in task T2.1 of Strainmon project.

  2) Static and fatigue compression test of BVID damaged panel

Low velocity impact tests were conducted by UNIPatras on selected critical locations of the panel in order to create impact damage. The damage definition/location and means of application were defined by HAI. NDT inspection of the BVID damaged panel was performed in VZLU in order to detect the type, extent and location of impact damage induced. Fatigue of the impacted panel up to predefined number of cycles was conducted in order to create additional fatigue damage. Compression fatigue and static test to failure were conducted at VZLU to evaluate the residual stiffness and strength of the BVID panel. This second stage of the testing efforts covers the work described in task T2.2 and T2.3 of Strainmon project:

  3) Static compression tests of VID damaged panel

Low velocity impact tests were conducted by UNIPatras on selected critical locations of the panel in order to create impact damage. The damage definition/location and means of application were defined by HAI. Compression static test to failure were conducted at VZLU to evaluate the residual stiffness and strength of VID panel. This third stage of the testing efforts covers the work described in task T2.2 and T2.3 of Strainmon project:

During the test campaign, HAI wireless communication device was verified on selected strain gauges.

The panel dimensions are 1650 mm (length) x 900 mm (width). Overall panel dimensions including potting plates are 1750 mm (length) x 1000 mm (width) x 150 mm (depth). The panel consists of a 2 mm thick skin, three omega profiles/stringers (both made of a carbon fibre composite material) and three metallic ribs screwed to the skin by 14 bolts each.

A standard Non Destructive Inspection procedure (C-Scan) has been performed after the end of
the manufacturing process for each panel so as to access the quality of manufacturing. The type of inspection was immersion Pulse / Receive on the entire part with A-Scan and C-Scan data acquisition and presentation. Inspection after manufacturing was performed by a UT-Level 1 Inspector. Tools and equipment used:
 - UT equipment (Bridge type, 3 axis immersion tank)
 - Pulser/Receiver PR-90
 - Analog/Digital AD-IPR-1210
 - UT Probe Mateval 5Mhz (focus) – 20mm diameter
 - Ultrasonic couplant Water
 - Post Processing Software UTIA 4.1 Professional by Mistras Group Hellas
The example of NDI results for reference panel 1 without defects is shown in Fig.2.
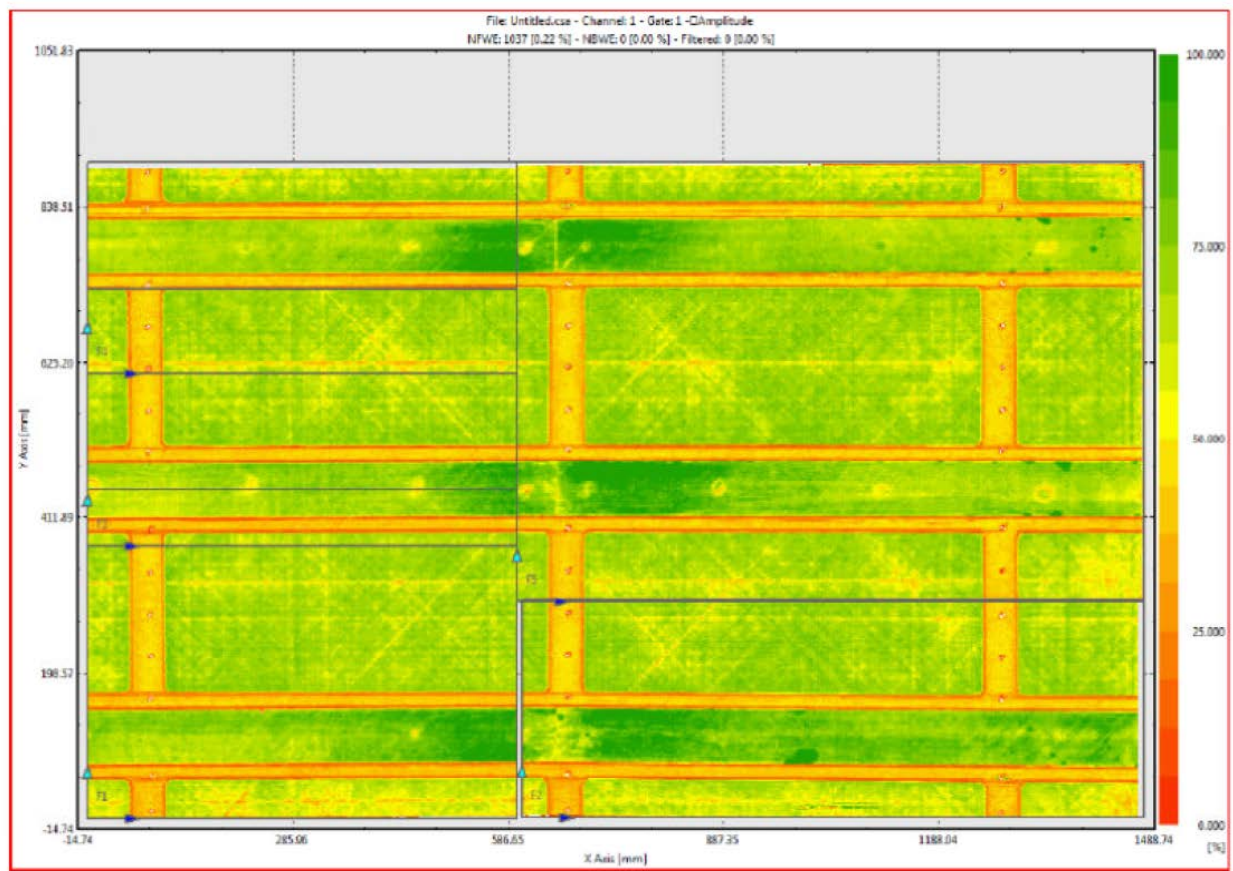

Fig. 2: C-scan image of reference panel 1.

Before the start of the static and fatigue tests the impact damages with different energy were created. The scope of impact testing was to generate impact damage of different severity at different locations in the panels. This was imposed by the general scope of the project which is to develop a fiber Bragg grating optical system capable to monitor the integrity of composite panels subjected to compression after impact and compression after impact and fatigue. C-scans planned at unloaded panels and after impact will give information about the quality of manufacturing process which includes the egression of the sensors in the composite material.
Low velocity impact tests have been performed using the mass-drop method. To this end, the INSTRON DYNATUP 9250HV drop tower has been used. Impact tests have been performed using a semi-circular impactor with a radius of 16mm. Fig. 3 shows the example of impact test results and NDT inspection results after impact.
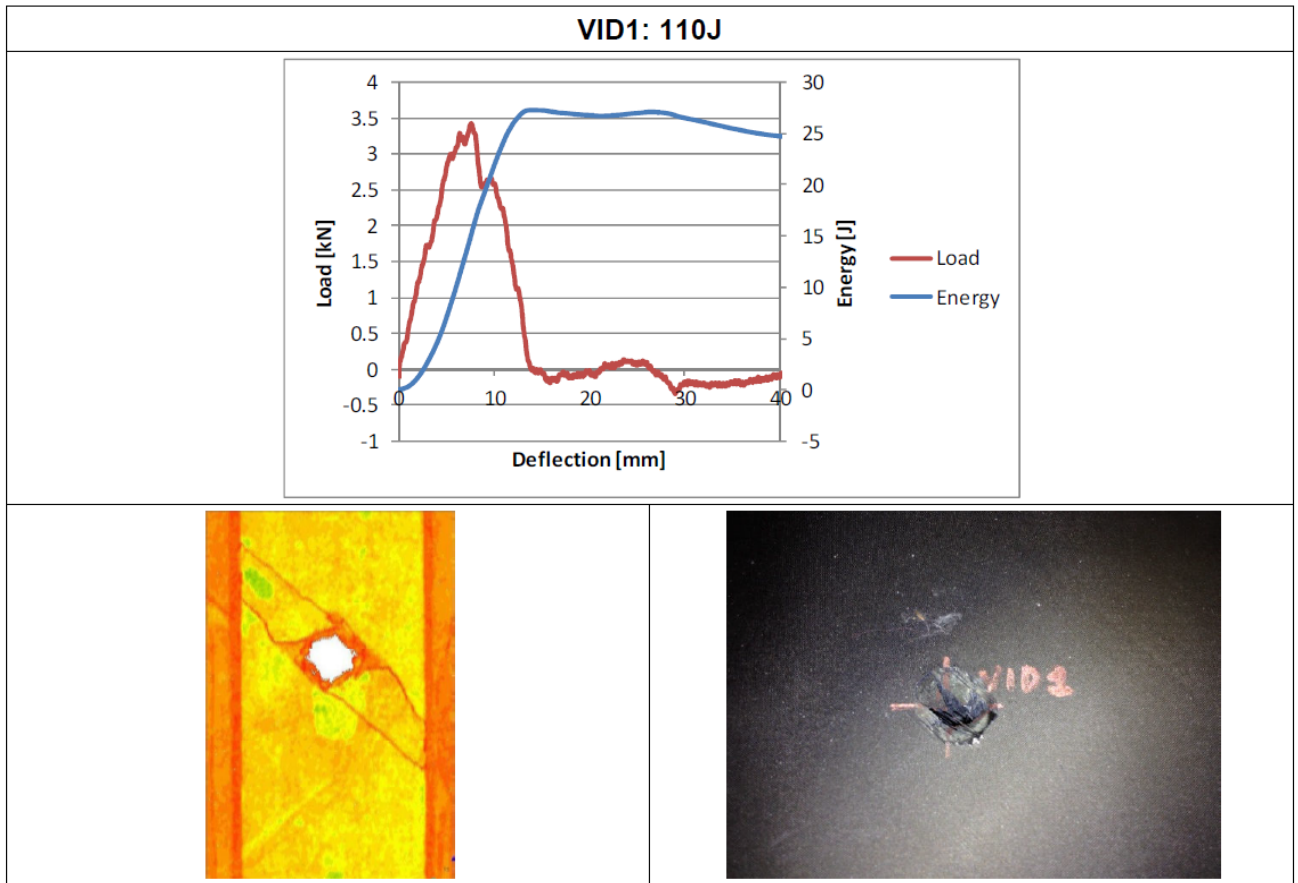
Fig. 3: Example of impact damage and NDT results for 110 J energy

The MTS four column load frame model 311.31 with capacity of 1 000 kN equipped with a cross head mounted actuator was used for mechanical testing. The load frame is designed for dynamic loading with range of ±1 000 kN, for static loading with range of ±1 200 kN. Test space is 711 mm wide, 406 mm deep and 2800 mm high (between load cell and actuator) not including fixtures.The MTS FlexTest40 control system was used for easy-to-use servo-controller for general testing applications. It provides real-time closed loop control with transducer conditioning and function generation to drive various types of servo-actuators.

Special antibuckling devices were designed and manufactured. The following requirements were fulfilled. The test article was provided with

- An anti-buckling device along both sides in "x" direction to simulate a simply supported constraint conditions
- Dummy frames at the location as reported in the related drawings to constraint the out of plane displacements
- Flexible plates (joined to dummy frames through rigid plates) which allow the skin stringers to be compressed in the x-direction.
- Potted aluminium frames in order to introduce compression loads uniformly and orthogonally to the skin stringers section.

The antibuckling system was designed and manufactured by VZLU on the basis of above mentioned requirements. Relevant information for correct design of an antibuckling system

location in the test frame was positioning of the neutral axis of bending. The antibuckling device configuration with the panel and all used sensors (FOBG, SG, and points for optical measurements) is shown in Fig. 4.

Fig. 4: Panel test configuration

Used data acquisition system consisted of the following parts:
- Displacement measurement system
- Strain gage measurement system
- FOBG measurement system
- Non-destructive inspection ultrasonic and laser shearography systems.

PONTOS system was used for displacement measurement. In contrast to conventional displacement measuring systems, the PONTOS system reduces the measuring procedure to a fraction of the time. In addition, the understanding of the measuring results is visually supported by an animated representation. PONTOS fully replaces conventional displacement measuring systems and accelerometers. Independent of the structures to be measured, displacements and deformations are captured rapidly in a non-contact manner. All measured data ensure 3D displacement information. As an indicator (sensor) is used the special point marker which is bonded directly to the investigated structure. PONTOS system allows analysis, computes and documents rigid body movements in discrete points.

BMCM data acquisition system with NextView 4.2 data acquisition software was used as a strain gauge measurement system. BMCM is a modular system assembled in-situ of the test. The actual configuration of BMCM system made use of 64 channels. Six selected strain gauges were measured using Wireless Logger Box developed by HAI. This system was

delivered to VZLU from HAI for the time of project. The number of SGs applied to the panels varies from 32 up to 46 (50 channels).

FBGuard (Safibra producer) 4-channel high accuracy FOBG static and dynamic measuring device was used for FOBG data measurement. The main wavelength bulk was set at 1550 nm ± 20 nm. Data acquisition was performed by an embedded device PC and data transfer was available via SSH protocol(s). The system evaluates a wavelength-intensity FOBG sensor peak position via the centre of gravity method and computes strain from it using known sensor length (alternatively Gauss approximation is available to get the peak position, but for this purpose is irrelevant). FBGuard measuring device does not save raw spectrum of wavelength-intensity data from light spectrometer.

OmniScan MX and MasterScan 340 devices with Phased Array 5 MHz and single element 5MHz SONATEST probes were used for ultrasonic non-destructive inspection at VZLU. Q-800 system was used laser shearography inspection at VZLU.

The stiffeners deflection increases during loading monotonous. Maximum deflection of the stiffeners before failure was observed in the upper section of the middle stiffener and reached 4 mm. The panel failure occurred in this upper section. The buckling wave occurred under static load of 70% of the predicted failure load. Other panel results seem to be very similar from point of view measured data. The typical failure mode initiation was delamination development between the skin and stringer (panel with manufacturing defects and BVID). The final failure of panel occurred after the stringer failure.

Comparison of BVID C-scans before and after fatigue test of the panel with manufacturing and BVID defects shows that no delamination growing was detected after fatigue loading. The same conclusion was stated also for artificial manufacturing delamination.

The force vs. displacement curve is the basic result measured by means of MTS 1MN test facilities. Comparison between maximum forces and displacement values achieved at failure for the tested panels were carried out and analysed.

The ultimate strength of panel 1 (reference) without any defects and impact damages is the highest in comparison with the other tested panels, as expected. On the contrary, panel 2 with BVID and manufacturing defects has lower ultimate strength than the panel No. 3 with VID.

The actual maximum failure load of the reference panel 1 is about 20% lower than the predicted failure load by HAI. The predicted stiffness of this panel is also higher than actual value. The rate of the actual and predicted displacement compared at the same force differs about 20%. Fig. 5 shows the buckling mode at 70% of predicted failure mode.

Fig. 5: Panel 1 reference – skin side view to the panel with buckling waves
(70% of predicted failure load).

Different buckling behaviour was noticed during loading for different static sessions of individual panels. Various buckling waves initiation was observed during the preload up to 20% and following unload to zero with comparison of the subsequent loading up to 70% with following unloading to zero and finally up to failure. Three subsequent static loadings in the scale up to 20% predicted failure load of the reference panel No. 1 were conduct with the aim of deformation evaluation. No differences and permanent deformation between the static phases occurred. On the contrary some of strain gauges behaviour is totally different in the phase of the first loading up to 70% of predicted failure load with comparison of the second loading up to 70% of predicted failure load. Several changes in buckling modes have been identified during loading of the panels using the optical deflection measurements of PONTOS. A significant damage occurred in panel 1 during a buckling at 49% of the predicted strength by the first static loading. It influenced the buckling state of the second static loading to failure. Comparison of all SGs with FOBG sensors data of reference panel 1 is shown in Fig. 6.

Similar behaviour of panel 2 BVID selected strain gauges relating to buckling waves initiationwas observed. The first buckling waves initiated approximately at 45 kN force during the first load application. The first buckling waves occurrence can be shown below 40 kN in case of load application up to failure. The initial zero values of strain gauges return to zero values in each load phase. Overall buckling initiation and development is different in comparison to reference panel 1.
The first nonlinearity during the static sessions of panel no. 3 with VID was recorded approximately at 38 kN. The strain gauges record is repeatable in each phase of the static session. Fig. 7 shows the comparison between the FOBG and SG data placed in the stringers area of panel 3 with VID.
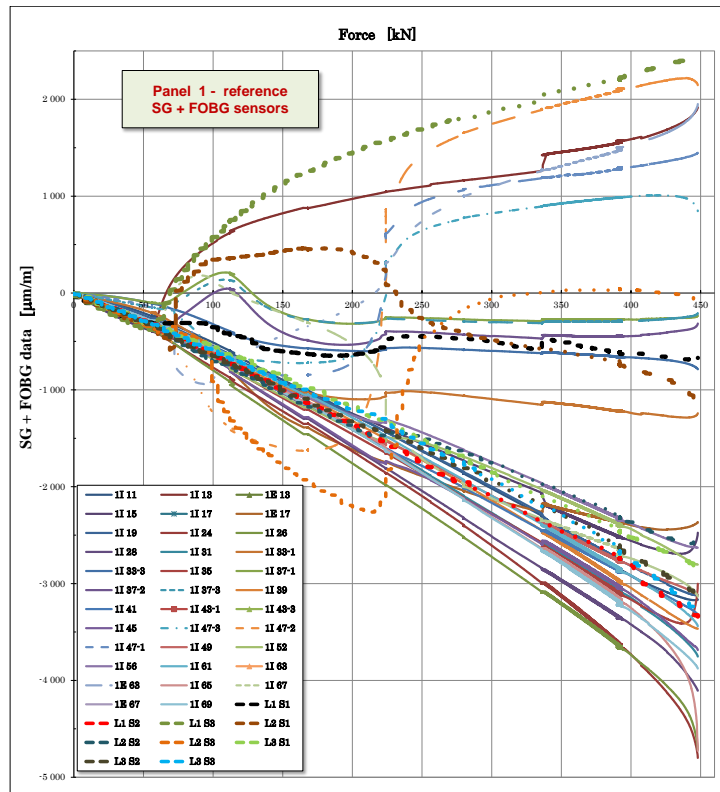
Fig. 6: Panel 1: comparison of FOBG and SGs vs. force data
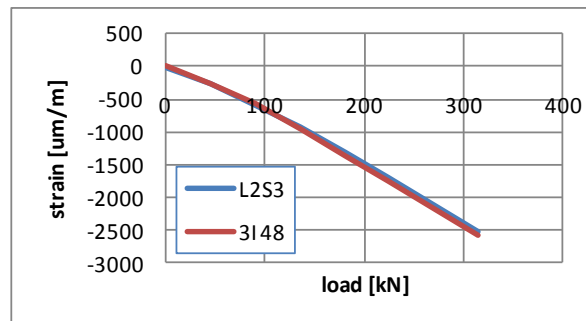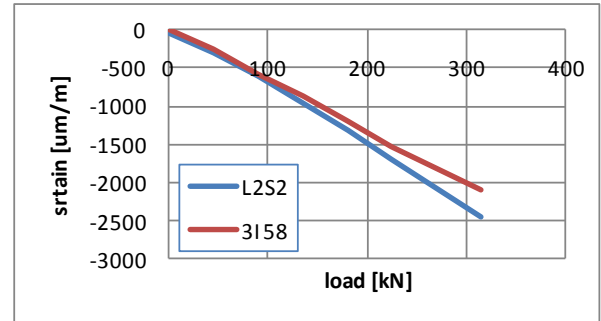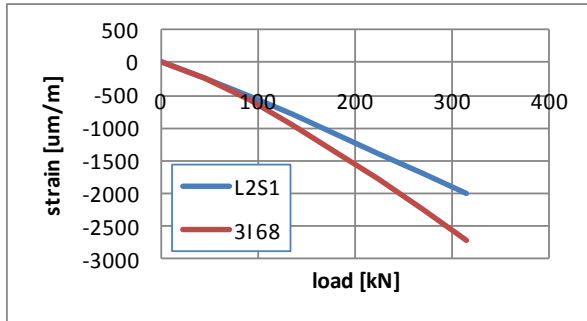*(up to failure load application).*

Fig. 7: Panel 3 VID: a) FOBG L2S1 vs. SG 3I 68; b) FOBG L2S2 vs. SG 3I 58; c) FOBG
L2S3 vs. SG 3I 48; strain comparison for up to failure test phase
(all sensors are placed on the stringer).

SG's and FOBG's sensor pairs were chosen according to their matching location to compare whether they correspond in measured strain values. The ability of FOBG sensors to copy an SG strain trend is shown in the following chapters. FOBG data corresponds to SG's data trend for the sensors positioned on/in a stringer. However, the values do not correspond for the sensors positioned on/in the skin in general. Some of these differences are discussed in the following chapters. But it is surprising that almost all FOBG sensor placed on the skin analysed very low strain values.

The comparison between the FOBG and SG data placed in the stringers area of panel 3 with VID shows some differences between data of FOBG and SG placed on the stringers areas. The differences between SG and FOBG can be caused by the different positioning of particular sensors through to thickness and correct positioning of sensors. FOBG sensors are placed inside in composite skin on the other hand the SG are place on the surface of skin. Moreover the actual location of FOBG sensor is not so easy to define. Based on the results analysis can be deduced that the FOBG sensor is embedded near the outer skin surface.

The following conclusions can be stated on the basis of data listed above

- The ultimate strength of panel 1 (reference) without any defects and impact damages is the highest in comparison with the other tested panels, as expected. On the contrary, panel 2 with BVID and manufacturing defects has lower ultimate strength than the panel 3 with VID. The actual maximum failure load of the reference panel 1 is about 20% lower than the predicted failure load by HAI. The predicted stiffness of this panel is also higher than actual value. The rate of the actual and predicted displacement compared at the same force differs about 20%.

- The high FPS video recording shows that at first, the waviness initiates a delamination of a skin/stringer interface and then, the weakened stringer fails by translaminar fracture. For panel 1, the final fracture occurred in the upper part of the panel in the vicinity of the upper rib. All three stringers were fractured in translaminar mode. Extensive delamination of stringer/skin interface was apparent between the upper and the middle rib for the middle and the right stringer. Two translaminar cracks were visible in the skin. Panel 2 was delaminated between the skin and the middle stringer. Skin translaminar failure in the vicinity of the BVID defect is evident. Extensive delamination of stringer/skin interface was apparent for the middle and the left stringer. Panel 3 was delaminated between the skin and the middle stringer. Skin translaminar failure in the vicinity of an artificial VID defect is also evident.

- FOBG's sensor testing after panel's arrival proved their bad durability during composite panel's production process. This result is proved by a comparison of reference panel 1 with FOBG sensors placed on the skin (not embedded) where the sensor intensity and quality of repelled laser rays was best of all (amount of intensity and distortion of sensor wavelength peaks). This is probably caused by careful handling with FOBG's sensors on panel 1.

- FOBG measurement data generally corresponded to SG's measured data trend. Remarkable buckling modes and theirs beginning has been evaluated to similar point of load. Absolute strain values between FOBG's and SG's method could not be compared strictly for some sensors, because of SG's sensors were positioned on panels skin and FOBG sensors were embedded or placed on different positions of skin. Good agreement between the SGs and FOBG sensors was achieved for all sensors placed on the stringers in general. In several cases good agreement for sensors located on the skin was achieved, but on the contrary some unpredicted differences were evaluated too. It can be deduced that the buckling wave initiation in

- surrounding of FOBG sensors induces the increasing difference between the SGs and FOBG data.
- Several changes in buckling modes have been identified during loading of the panels using both the optical deflection and SGs measurements. Different buckling modes occurred in panel 1 during the first and second static loading up to 70% of predicted failure load. Several sudden buckling mode changes occurred also for the BVID panel 2. The VID Panel 3 did not show sudden buckling changes and the deflection evolution was rather monotonous, same for both the 1st and 2nd loading. The stiffeners of all the panels buckled monotonously during loading. The failure of all the panels was apparently determined by the skin/stiffener interface delamination failure due to the high skin deflections.
- SGs data measured using wireless equipment contains a noticeable signal noise. Therefore, it was not possible to process them directly. The data smoothing using moving average was performed with the aim to clean the data and enable to evaluate the data trend.
- Laser shearography method for detection of the artificial BVID flaws in panel 2 was used. All the impact damage was detected and its size was measured. The interface manufacturing flaws marked A and B were not detected. An artificial delamination of the skin was clearly visible. Some secondary non-marked flaws were found.
- The ultrasonic inspection of BVID panel 2 was performed before, during, and after the fatigue test (0, 30 000, 60 000, 90 000 cycles). The ultrasonic C-scan mode of the phase array system detected all the flaws clearly. Unfortunately, access to the areas with artificial delamination in skin and skin-stringer interface was difficult because of installed strain gauges. Therefore, standard single element probe was used in these areas. Sizes measured by ultrasonic NDT were mostly a little larger in comparison with sizes measured by laser shearography.
- Ultrasonic non-destructive inspections did not detect any propagation (growing) of BVIDs and artificial delaminations during fatigue test.