PATCHBOND

Publishable Synthesis Report

EDA Cat B project : PATCHBOND

Project No. : B1324 GEM1 GP

Project duration : 1 November 2014 until 1 April 2019 (52 month)

Project budget : 7 M€

Responsible partner : NLR

Dissemination level : Public

Testing of the PATCHBOND demonstrator panel

Revision table

Issue	Date	Modifications
V1	8 May 2019	First issue
Final	22 May 2019	Partner comments implemented

Glossary

AU	Acoustic
BRC	Bonded Repair Coupon
cMS	Contributing Member States
DoW	Document of Work
EDA	European Defence Agency
FE(M)	Finite Element (Method)
FBG	Fibre Bragg Grating
LL	Limit Load
NDI(T)	Non Destructive Inspection (Technology)
UL	Ultimate Load
MoC	Means of Compliance
OHC	Open Hole Compression
PJAT	PATCHBOND Joint Analysis Tool
PZT	Lead Zirconate Titanate
SHM	Structural Health Monitoring

Summary and conclusions

The PATCHBOND main target was to develop boltless repair methods for restoring the operational capabilities of damaged primary composite aerospace structures that are compliant with the airworthiness requirements.

The certification approach as agreed upon in the PATCHBOND project consists of 1) the use of so-called Bonded Repair Coupons (BRC's) to substantiate the initial strength of the bonded repair, and 2) a Structural Health Monitoring (SHM) system to monitor the unexpected, in-service behavior of the repair patch.

At the beginning of the project it was decided to concentrate on the NH90 materials and repair methods, as all countries participating in the project are operating this platform. More specific, the horizontal stabilizer was selected as the demonstration structure.

An analytical method for fast assessment of the remaining strength of a damaged structure was developed and a Microsoft Excel® based tool was developed for a quick assessment of the repaired structure. Different commercially available software tools for finite element (FE) analysis were considered and applied; the obtained results were compared for quality assurance.

Research into SHM methods was a substantial part of the project as a proper installation off SHM systems contributes to the certification of bolt free repairs. Moreover, SHM systems will be relevant for efficient maintenance of the repaired and also the pristine part of the composite helicopter structure.

Finally, it was decided to manufacture and test a demonstration repair on a sandwich panel representing the NH90 stabilizer structure. Impact damage was applied to the patch, followed by two fatigue test campaigns and a dedicated test to substantiate the ability of the SHM system to monitor damage propagation. The latter test was needed due to the fact that, despite 1.5 M cycles at 45% failure load, no sign of damage propagation was observed. In the final test, the damage was stepwise manually increased towards the center line of the panel. The strain increase at the crack tip was clearly indicated by the SHM system showing the ability of the system to detect crack propagation.

The demonstrator repair patch was equipped with Fibre Bragg Grating (FBG) sensors. Within the framework of the PATCHBOND project, an alternative system using Piezo type (PZT) sensors was also evaluated, and it was proven that size and location of in-service damages can be determined by a SHM system consisting of a number of PZT sensors surrounding the patch.

The final certification of a bonded repair has to be done by the airworthiness authorities of the countries participating in the PATCHBOND project. Based on the results of the PATCHBOND project the conclusion can be drawn that with the BRC/SHM certification approach, as applied to the demonstrator panel, it is possible to substantiate the initial quality of the repair and monitor in-service damage propagation. However damage tolerance is not ensured into the PATCHBOND approach and in-service damages can still propagate to a fatal size. Application of the PATCHBOND technology is therefore limited to structures that still can take Limit Load with a completely failed adhesive bonded repair joint.
For this reason the PATCHBOND consortium will continue the research into repair methods ensuring the damage tolerance design philosophy.

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1 Project consortium

The EDA project **PATCHBOND – "Bolt free battle and operational damage repairs of metal and composite primary aircraft structures"** started in November 2014 and ended in April 2019. Five nations and 15 partners have been involved in the project; National Aerospace Laboratory – NLR (The Netherlands), KVE Composites Repair (The Netherlands), Fokker Services B.V. (The Netherlands), Aalto-korkeakoulusäätiö *(Finland), Patria Aviation (Finland), VTT Technical Research Centre of Finland (Finland), Bundeswehr Research Institute for Materials, Fuels and Lubricants – WIWeB (Germany), Airbus Defence and Space (Germany), Spanish Institute for Aerospace Research – INTA (Spain), Norwegian Defence Research Establishment – FFI (Norway), Norwegian Defence Material Agency – NDMA (Norway; former NDLO), DolphiTech (Norway), FiReCo (Norway) and Light Structures (Norway).

* The Aalto University withdraws from the project in 2017; responsibilities were taken over by Patria.

2 Introduction

The PATCHBOND main target was to develop boltless repair methods for restoring the operational capabilities of damaged primary composite aerospace structures that are compliant with the airworthiness requirements. The project concentrated on repair of composite structures. Limited work has been done on the repair of metal structures.

At the beginning of the project a selection was made on the materials and processes to be investigated for the repair. As all countries participating in the project are operating the NH90 helicopter it was decided to concentrate on the NH90 relevant/specified materials and repair methods. More specific, the horizontal stabilizer was selected as demonstrator structure.

After a thorough literature review to define the state of the art related to composite repairs, a demonstrating repair was developed for the stabilizer.

To support the design of this repair, material tests were performed on the included materials (composites and adhesives) and elements representing the repair.

Non-destructive inspection (NDI) methods, such as ultrasound, have been evaluated and employed for inspection of the repaired composites.

Numerical methods for assessment of the remaining strength of a damaged structure and the strength of the restored (repaired) structure were investigated and established. Different commercially available software tools for finite element analysis were considered and applied, the obtained results were compared for quality assurance. Some software tools for analysis and a quick assessment were also developed by the consortium.

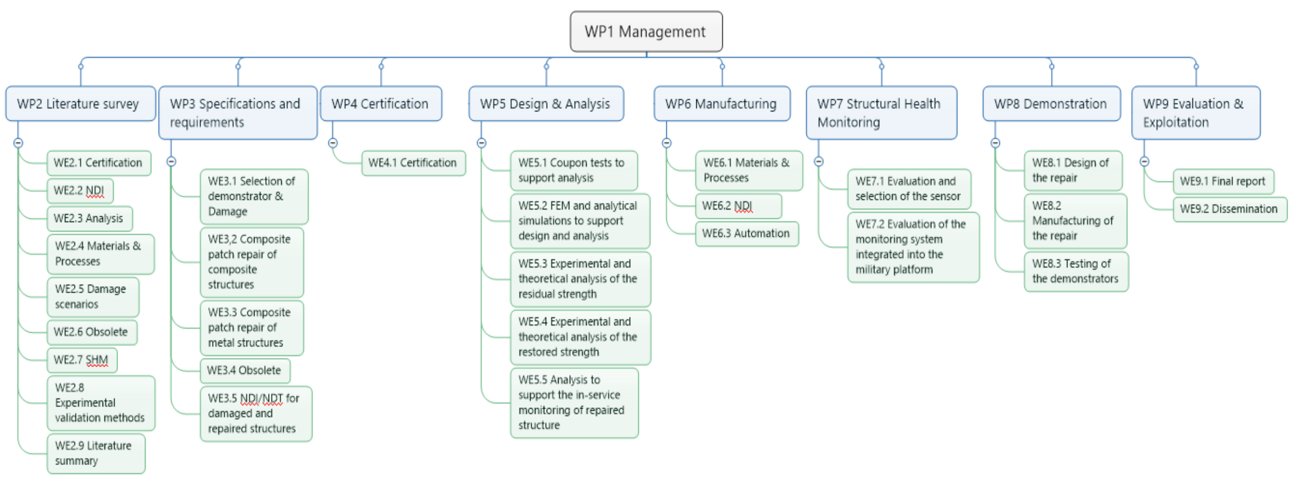
Research into Structural Health Monitoring (SHM) methods was a substantial part of the project. SHM systems may be a possible way for certification of the bolt free repair. Moreover, SHM systems will be relevant for efficient maintenance of the repaired helicopter structure – but also the pristine/undamaged part of the composite structure. Different sensors, i.e. PZT and FBG, were tested in the project on representative test panels for aircraft structures.

One of the main obstacles for using bonded repairs on primary aircraft structures is the certification of the repair. The certification approach as agreed upon in the project for bolt free composite repairs of primary structures consists of 1) the use of so-called Bonded Repair Coupons (BRC's) to substantiate the initial strength of the bonded repair, and 2) a SHM system to monitor the unexpected, in-service behavior of the repair patch.

Finally, it was decided to manufacture and test a demonstration repair on a sandwich panel representing the stabilizer structure. The demonstrator was tested (static and fatigue) to demonstrate/validate the design and manufacturing procedures including the certification approach.

3 Work performed

The project was structured into 9 work packages as shown in the figure below:



The responsibility of each partner is indicated in the list of deliverables (Appendix A)

3.1 WP1 Management.

Progress (Milestone) meetings were organized half-yearly where all partners presented and discussed the project work and progress. Two weekly a work package leader WebEx was organized to discuss in detail the project progress and actions to be taken. The status of the project was presented in every EDA Materials Captech meeting.

3.2 WP2 Literature survey

In this WP the state of the art with respect to the PATCHBOND research topics was defined and guidance was given to the work performed in the work packages 3 to 8.

3.3 WP3 Specifications and requirements

The horizontal stabilizer of the NH90 helicopter (see Figure 1) was selected as this composite part is manufactured by partner Fokker and material properties were available to the consortium. A stabilizer was available for repair and testing but for budget reasons it was decided to demonstrate the PATCHBOND work on a representative flat sandwich panel.

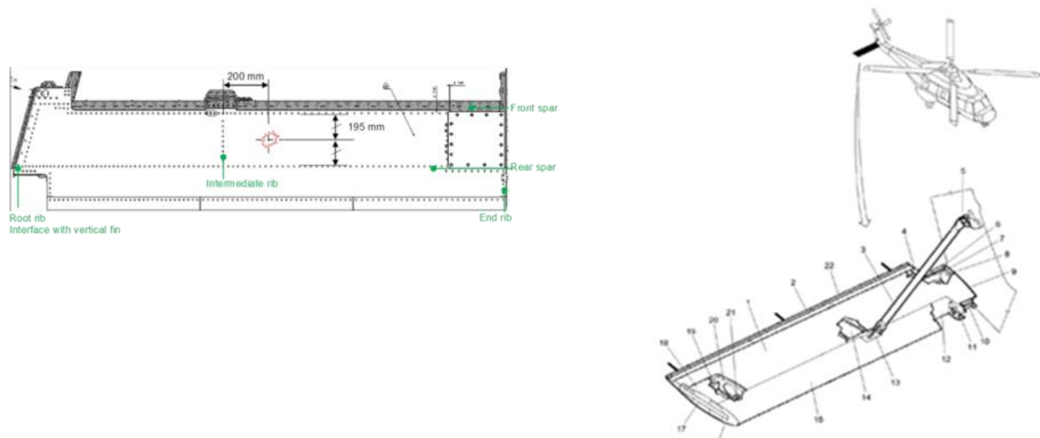


Figure 1 NH90 stabilizer and location of the demonstration repair (left)

Repair materials and processes were selected from the NH90 repair manual. Some work was performed on composite patch repair of metal structures (see Figure 2).

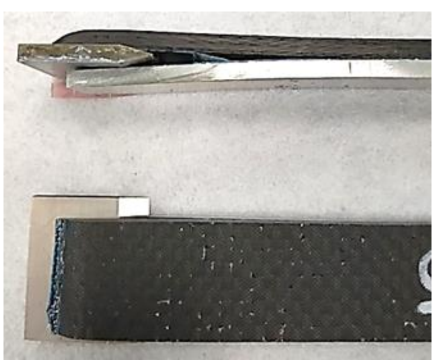


Figure 2 wedge test on composite patch repair of an Aluminium structure

3.4 **WP4 Certification**

A bonded repair must meet the same performance requirements as the original aircraft structure; a bonded repair is simply a special case of any normal bonded joint. All relevant airworthiness requirements (AMC20-29, CS23.573, FAA AC20-107B ...) were evaluated within WP4 and as a general guideline the following guidance can be taken:

"*For any bonded joint, the failure of which would result in catastrophic loss of the aeroplane, the limit load capacity must be substantiated by one of the following methods:*

(i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or

(ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or

(iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint."

None of these three so-called Means of Compliance (MoC's) are suitable for use within the PATCHBOND project. The use of design features requires an extensive knowledge of crack propagation, proof testing is not practical and NDI methods for weak bond detection are not available.

Therefore it was decided to develop an alternative certification approach by a using the Bonded Repair Coupon (BRC) method developed by the Australian ARC-ACS organisation. The BRC's are manufactured within the same process cycle as the inner- and outer skin repairs. The BRC's are subjected to shear loading that is applied mechanically using a torque wrench through an adaptor and the aim is to establish a lower bound proof load for standard (un-degraded) patch/parent/adhesive, thus validating the initial strength of the BRC and skin repairs. The in-service performance of the repair will be monitored by integrated sensors that are capable of measuring any deformation of the repair patch during the life cycle of the aircraft (see Figure 3).

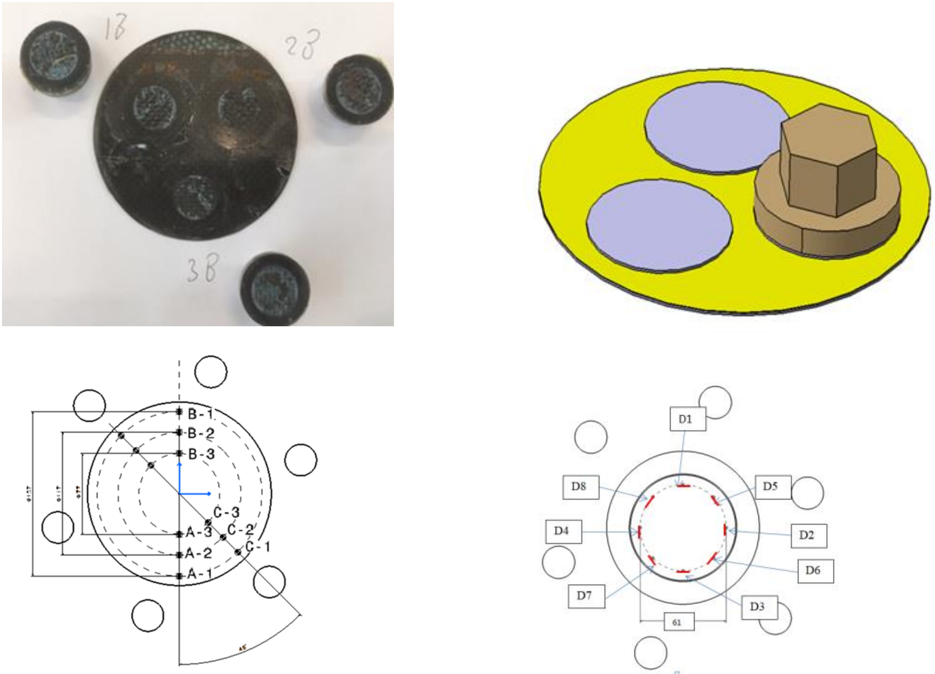


Figure 3 BRC after test of the inner patch (upper left), BRC with adapter bonded to the top surface (upper right), FBG sensors off the outer patch repair (lower left) and FBG sensors in the inner repair patch (lower right)

3.5 WP5 Design and analysis

A large number of coupon/element tests were performed to obtain the material properties of the materials and to validate the analytical and Finite Element analysis methods.

An analytical method was developed to calculate the remaining strength of a damaged structure by comparing the damage to an equivalent open hole. The method was validated by testing a number of Open Hole Compression (OHC) samples (see Figure 4).

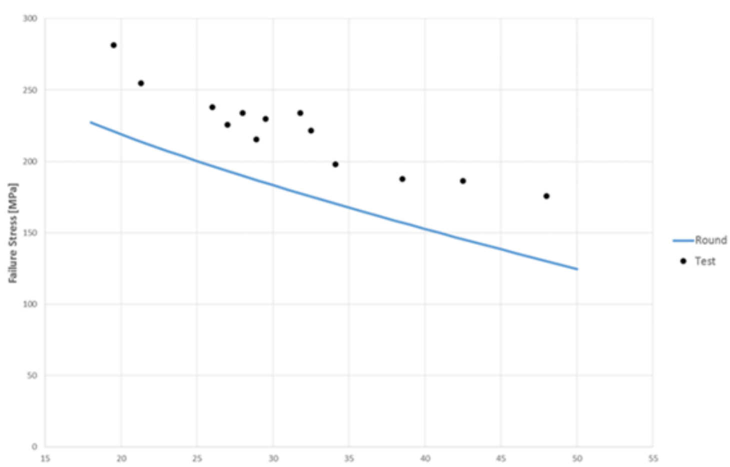


Figure 4 open hole method for residual stress calculation (Aalto)

The PATCHBOND Joint Analysis Tool (PJAT) was developed as an Excel based tool for a fast analysis of the bonded joint strength. Based on the material parameters and joint geometry the joint strength is calculated. In Figure 5 the strength of a scarf joint is calculated for different scarf angles.

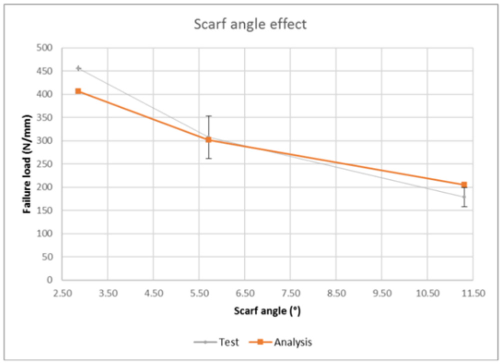


Figure 5 results of a PJAT calculation on the scarf angle influence

Impact damages were simulated for pristine and repaired sandwich using dedicated FEM methods (see Figure 6). For the pristine panel at lower impact levels (≈4 kJ) the results matches well with the test results. Impact simulations could not sufficiently validated due to the problematic inspection of the wet lay-up patch.

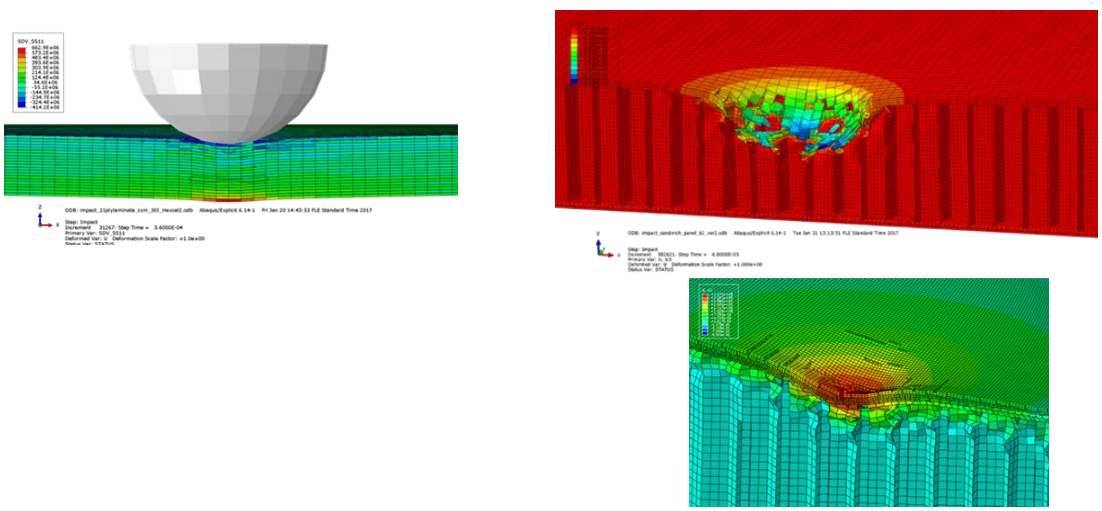


Figure 6 impact simulations on the base material (upper) and patch (lower)

To support the application of SHM sensors in the patch analysis were performed on sandwich panel patch repairs with different artificial defect/damages. The stress distribution in the patch was analyzed and validated by testing dedicated repair samples. Advice was given to the sensor positioning of the demonstrator repair panel.

3.6 WP6 Manufacturing

In this work package manufacturing trials were performed to obtain the optimal processing parameters and several manufacturing trials were performed including the manufacturing of test panels to include the SHM sensors and BRC’s (see Figure 7). In WP6 all test specimens were manufactured and the final repair method for the demonstrator was selected. It was assumed that the repair area is only one-sided accessible and therefore a flexible foil was bonded to the inner side to create an airtight surface allowing for vacuum bagging (see Figure 7).

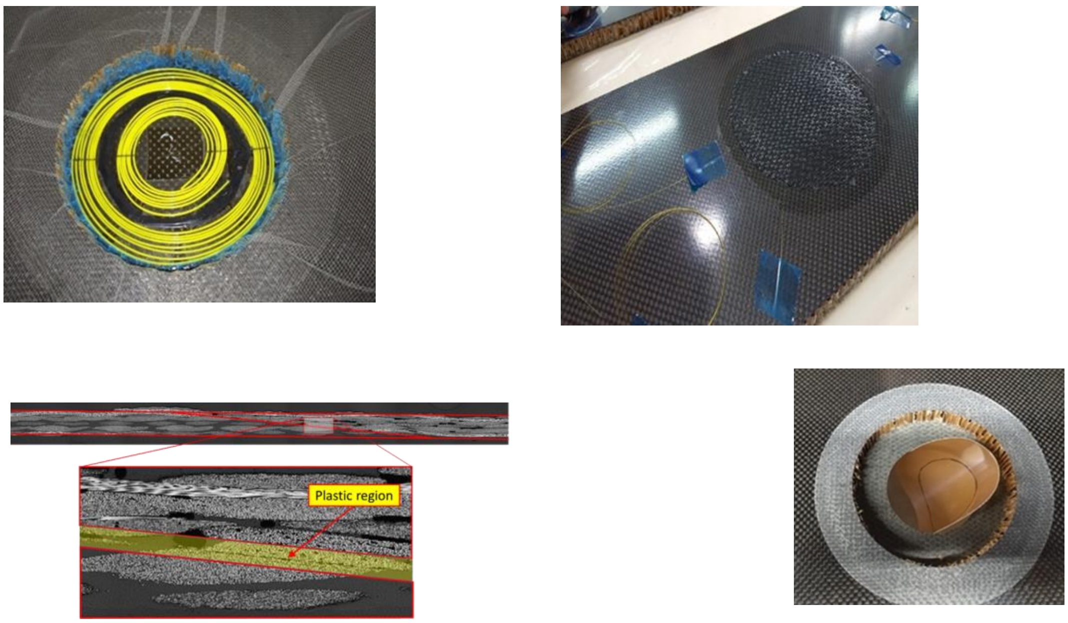


Figure 7 FBG sensors for the inner patch (upper right), FBG's integrated in the outer patch (upper right), micro section of a wet lay-up patch (lower left) and application of a flexible foil (lower right)

Evaluation of automated repair methods was also part of the WP6 work. The automated milling robot MobileBlock® manufactured by the German DMGMORI company was evaluated and used to manufacture test samples.

Lightning strike tests were performed on repaired composite panels. Additional damage occurred at the edges of the patch due to sparking between the base material and edge of the patch (see Figure 8)

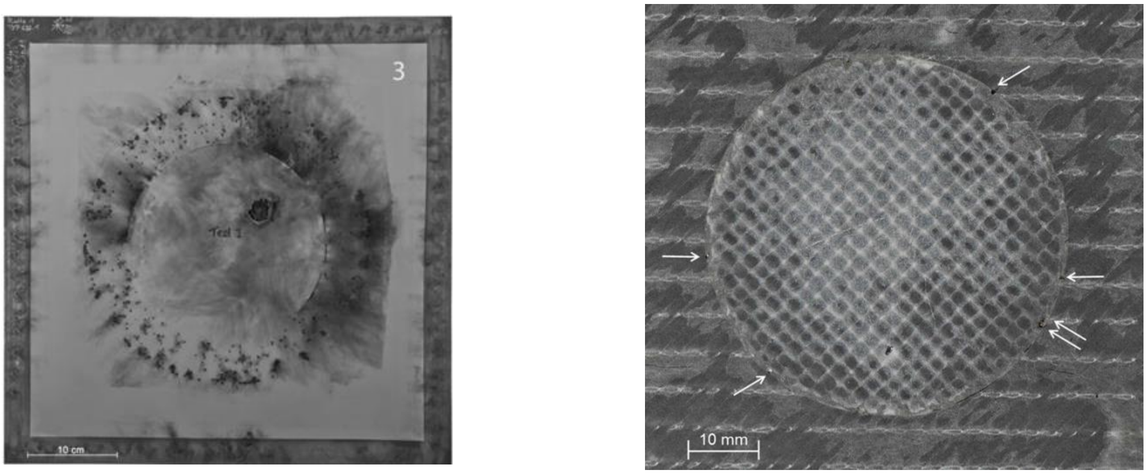


Figure 8 Lightning strike damage

Inspection methods were evaluated and trials on the test panels and repairs were performed. Thermographic imaging proved to be a good method to inspect the repair patches (see Figure 9) and localize disbonds.

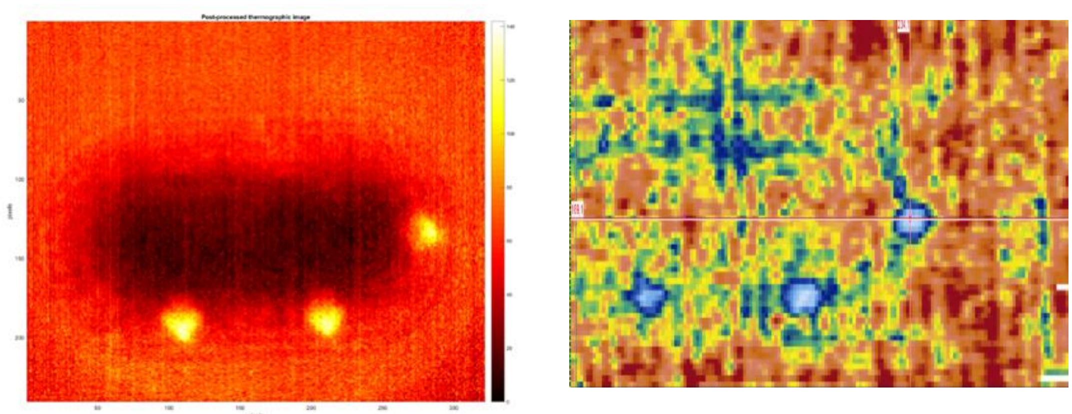


Figure 9 Thermographic image (left) and US recording (right) of a patch with disbonds

3.7 WP7 Structural Health Monitoring (SHM)

Part of the work was the investigation of the Acousto Ultrasonic SHM method for composite bonded repair monitoring. Different sensors were tested to investigate their resistance to fatigue loading. Test panels were designed and equipped with AU sensors. The instrumented panels were fatigue loaded and impacts were applied during the test campaign. The ability of the AU system to detect the location and size of the impacts was evaluated including effects of temperature variations and ageing of the sensors.

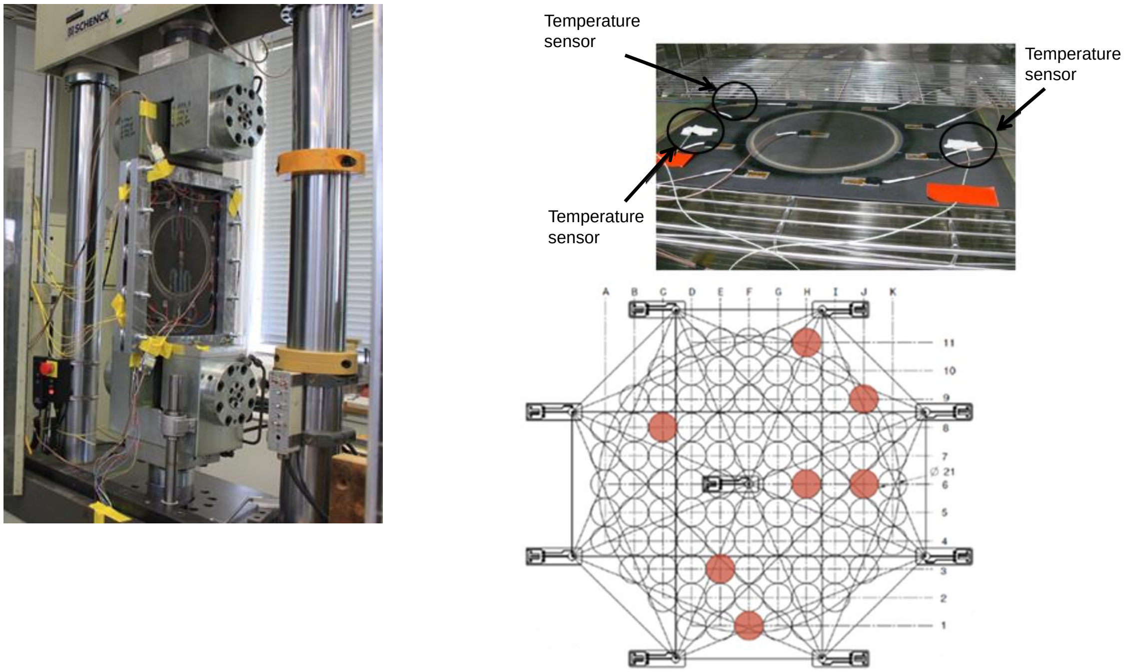


Figure 10 testing of the panel with AU sensors (upper left), detail of the panel (upper right) and location of the impacts (lower)

The system was capable of detecting the impacts (size and location) as indicated in Figure 10. Temperature compensation methods are needed to improve the results.

In addition static/dynamic tests were performed for evaluation of the Acousto Ultrasonic (AU) based SHM system concentrating on monitoring damage propagation. Samples were tested in a 4-point bending test fixture (see Figure 11). Due to the brittle nature of the repair a sudden failure occurred during the cyclic loading and controlled damage propagation was not observed.

Figure 11 4-point bending test of a sandwich panel with AU sensors

FBG sensors were tested on a number of repaired sandwich panels with different artificial damage sizes to validate the WP5 analysis methods. An analyzing method based on a damage index was developed for a quick interpretation of the results (see Figure 12).

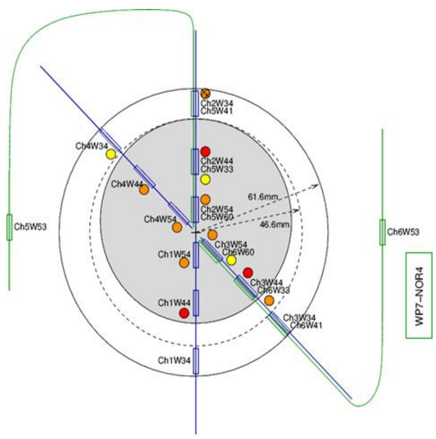


Figure 12 FBG sensor distribution for a patch repair

3.8 WP8 Demonstration

The demonstrator panel was designed and analyzed based on the WP5 and WP6 results. The outer layer of the sandwich panel was repaired using a wet lay-up repair patch, the inner layer was repaired by applying a secondary bonded cured patch. Both repairs were equipped with BRC's that were manufactured together with the actual repair. Outer patch and inner patch were both instrumented with FBG sensors.

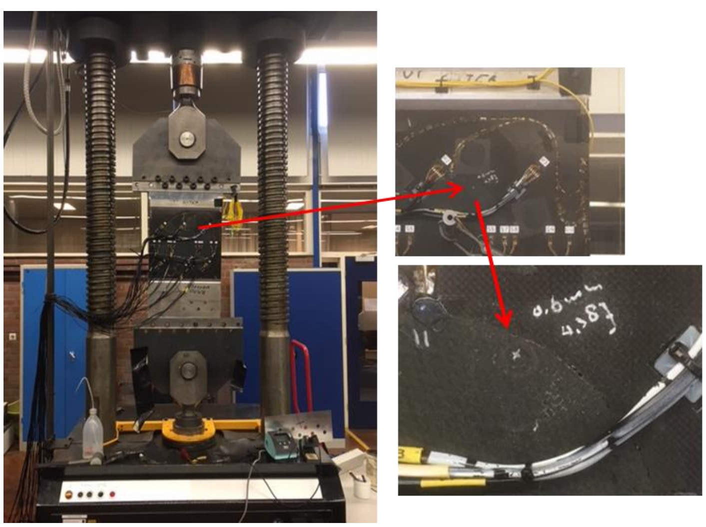


Figure 13 demonstrator panel and impact damage location

Around 1.500.000 loading cycles were applied at 45% failure load without any damage propagation. To demonstrate that the SHM system is capable to detect damage propagation, the damage was manually propagated (see Figure 14).

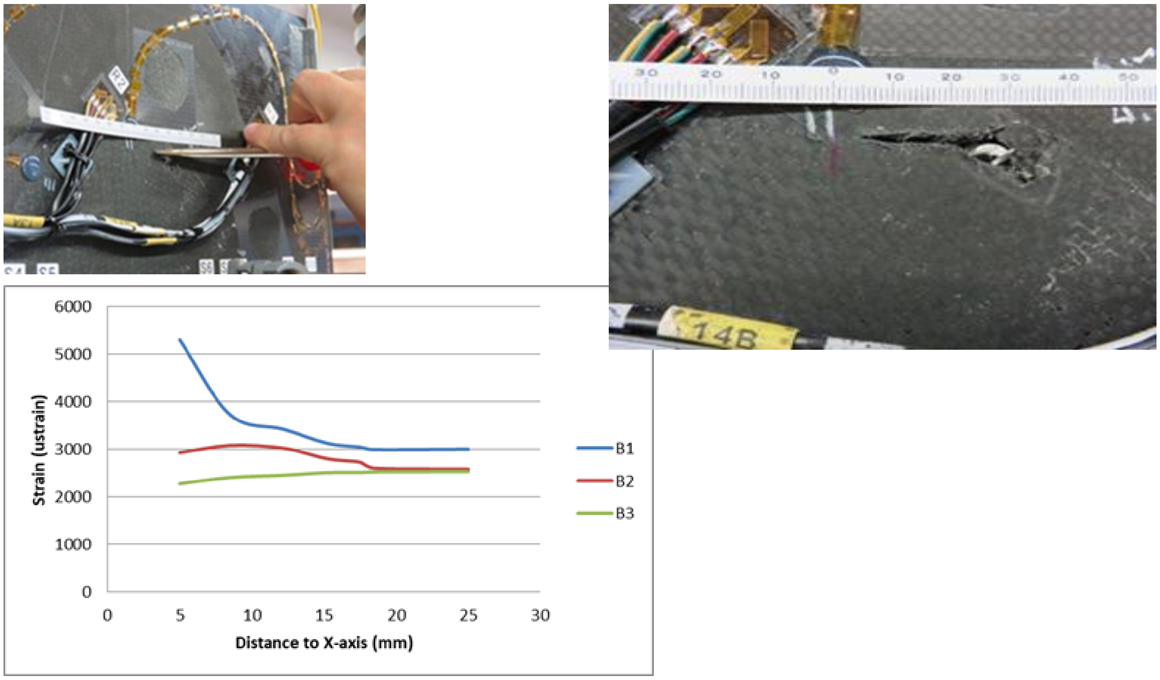


Figure 14 manual damage propagation (upper) and resulting FBG measurement (lower)

As shown in Figure 14 the sensor near to the crack tip (B1) clearly shows a stress increase due to the crack propagation.

Appendix A Deliverables list

ID	Deliverable title	Partner
D2.1	Certification and Means of Compliance	NLR
D2.2	NDI technology	VTT
D2.3	Analysis	Patria
D2.4	Materials & Processes	KVE
D2.5	Damage scenarios	NLR
D2.6	Battle damage repair methods	--
D2.7	State of the art SHM technology	Airbus DS
D2.8	Experimental validation methods	NLR
D2.9	Integration of WP2 the deliverables	VTT
D3.1	Selection of demonstrators and damage scenarios	NLR
D3.2	S&R for composite patch repair of composite structures	NLR
D3.3	S&R for composite patch repair of metal structures	INTA
D3.5	NDT/SHM for undamaged and repaired structures	FiReCo
D4.1	Strategy to comply with airworthiness regulations	NLR
D5.1.1	Coupon Tests to Support Analysis - Residual Strength	Patria
D5.1.2	Coupon tests to support analysis	INTA
D5.2	FEM and analytical simulations to support design and analysis	FFI
D5.3	Experimental and theoretical analysis of the residual strength	Aalto/Patria
D5.4.1	Experimental and theoretical analysis of the restored strength	Patria
D5.4.2	PATCHBOND joint analysis tool for analyzing bonded repairs	Patria
D5.4.3	Modelling of scarf joints	FiReCo/FFI
D5.4.4	FE analysis of an impact on the bondline of a repaired composite sandwich structure	NLR
D5.4.5	Low-velocity impact FE-simulations for damage tolerance analyses	VTT
D5.5	Analysis to support the in-service monitoring of the repaired structure	FFI/FiReCo
D6.1.1	Materials and Processes (KVE)	KVE
D6.1.2	Lightning strike protection concepts	WIWeB
D6.2.1	Evaluation of Conventional Ultrasonic and Thermographic NDI for Carbon Fibre Reinforced Plastics	VTT
D6.2.2	Evaluation and Selection of NDI Methods	WIWeB
D6.3	Automation	WIWeB
D7.1	Evaluation and selection of sensors	Airbus DS
D7.2.1	Evaluation of monitoring systems integrated on the	Light

	Norwegian sandwich test specimens	Structures/FFI/FiRe Co
D7.2.2	Acousto Ultrasonic Structural Health Monitoring method for composite bonded repair monitoring (WIWeB and Airbus DS)	Airbus DS/WIWeB
D7.2.3	Evaluation of monitoring systems integrated on the Spanish sandwich testing on metal and composite specimens	INTA
D7.2.4	SHM-system testing for repaired sandwich panels including artificial flaws	VTT
D8.1.1	Design and Analysis of the Repair for the Different Demonstrators	Patria
D8.1.2	Installation of BRC's on PATCHBOND Demonstrator	NLR
D8.1.3	Installation of FBG Sensors on PATCHBOND Demonstrator Inner Face Sheet Repair	INTA
D8.1.4	Installation of FBG Sensors on PATCHBOND Demonstrator Outer Face Sheet Repair	Light Structures
D8.2	Manufacturing of the repair	KVE
D8.3	Demonstrator test	NLR
D9.1	Final report	NLR
Discussion paper	Implementation of the Certification Strategy into the repair demonstrator	NLR
	Publishable Synthesis report	NLR