PATCHBOND II - Certification of adhesive bonded repairs for Primary Aerospace composite structures

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Abstract

The European Defence Agency (EDA) project PATCHBOND II (June 2020 – June 2025) was established for studying adhesively bonded repairs of primary composite structures. This multinational project is based on collaboration between several aerospace companies, governmental institutions, research institutes and universities. The main targets are to study damage tolerance and monitoring of the bonded repairs of primary aircraft structures. The project is divided into four technical work packages, for which motivations and developments are presented. The on-going project work has already provided valuable results in the field of adhesively bonded repairs.

Keywords: bonded repair, primary structure, damage tolerance, structural health monitoring

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1. Introduction

Aerospace composites structures are widely repaired using adhesively bonded patches. The bonded repairs have several advantages, but challenges still exist. The main challenges are related to adhesively bonded repair damages and undetected manufacturing defects for primary aerospace composite structures. For that reason, the certification of such repairs has still some limits. The main limitation is that the repaired structure needs to sustain limit loads if the patch is lost, which significantly restricts the repaired damage size.

The European Defence Agency (EDA) project "Certification of adhesive bonded repairs for primary aerospace composite structures" (EDA B.PRJ.RT.670;PATCHBOND II), funded by the involved nations, was started in 2020 with a four-year duration, but recently got extended one year to complete all the activities. The multinational project involves participants from six different countries (Netherlands, Czech Republic, Germany, Finland, Norway and Italy). In total, 15 different companies, governmental institutions, research institutes and universities are participating. The project consortium is led by Netherlands Aerospace Center (NLR). The project is a continuation for the EDA project "Bolt free battle and operational damage repairs of metal and composite primary aircraft structures" (EDA B-2324-GEM1-GP; 2014-2019; PATCHBOND).

The PATCHBOND II project has two main goals. Firstly, the project aims to study damage no-growth/slow growth assumption validity – both experimentally and by numerical simulations, and to develop adhesively bonded repairs damage tolerant design. Secondly, the project goal is to establish a structural health monitoring (SHM) system for bonded repair patches, for early indication of bond line damage.

The project covers different fields related to adhesive bonded repairs and monitoring. The technical work has been divided into four work strands, being materials and processes, design and analysis, testing and SHM. The objectives of these research strands are presented in the following sections.

2. Materials and process

Within the materials and process strand, first the materials were selected for the programme, in close cooperation with the MoDs (Ministry of Defence). The materials were selected based on the different aerial platforms operated in the participating countries. Repair materials were selected based on repair manuals from international organizations, like CACRC. With the selected materials, processes for bonded repairs were investigated. Different mechanical surface pre-treatments were investigated, including cutting processes (end milling) and parameters, see Figure 1. Surfaces were characterized and correlated to the final bond strength. Different repair methods were investigated. Pre-manufactured secondary repair patches were developed for fast in-field temporary repairs, including printed tools, see Figure 2.

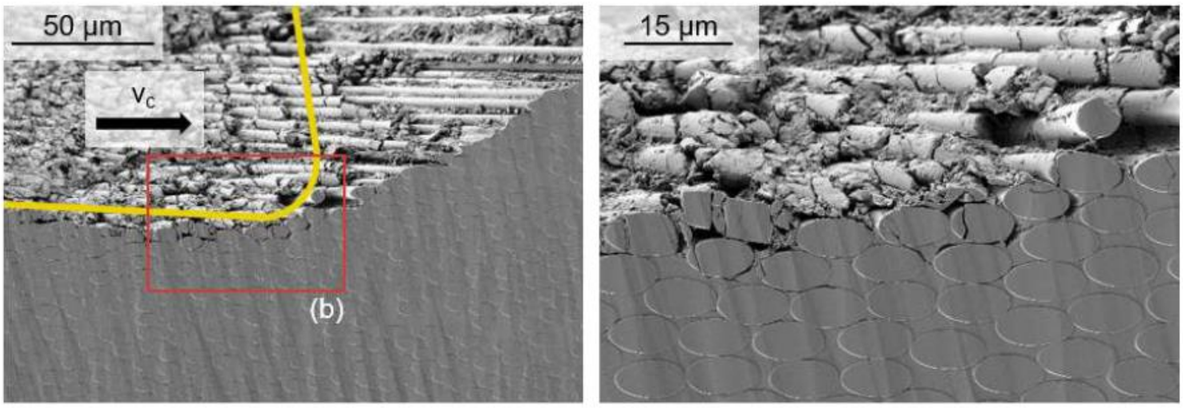

Figure 1. SEM-image of chip root of an end milled CFRP surface.

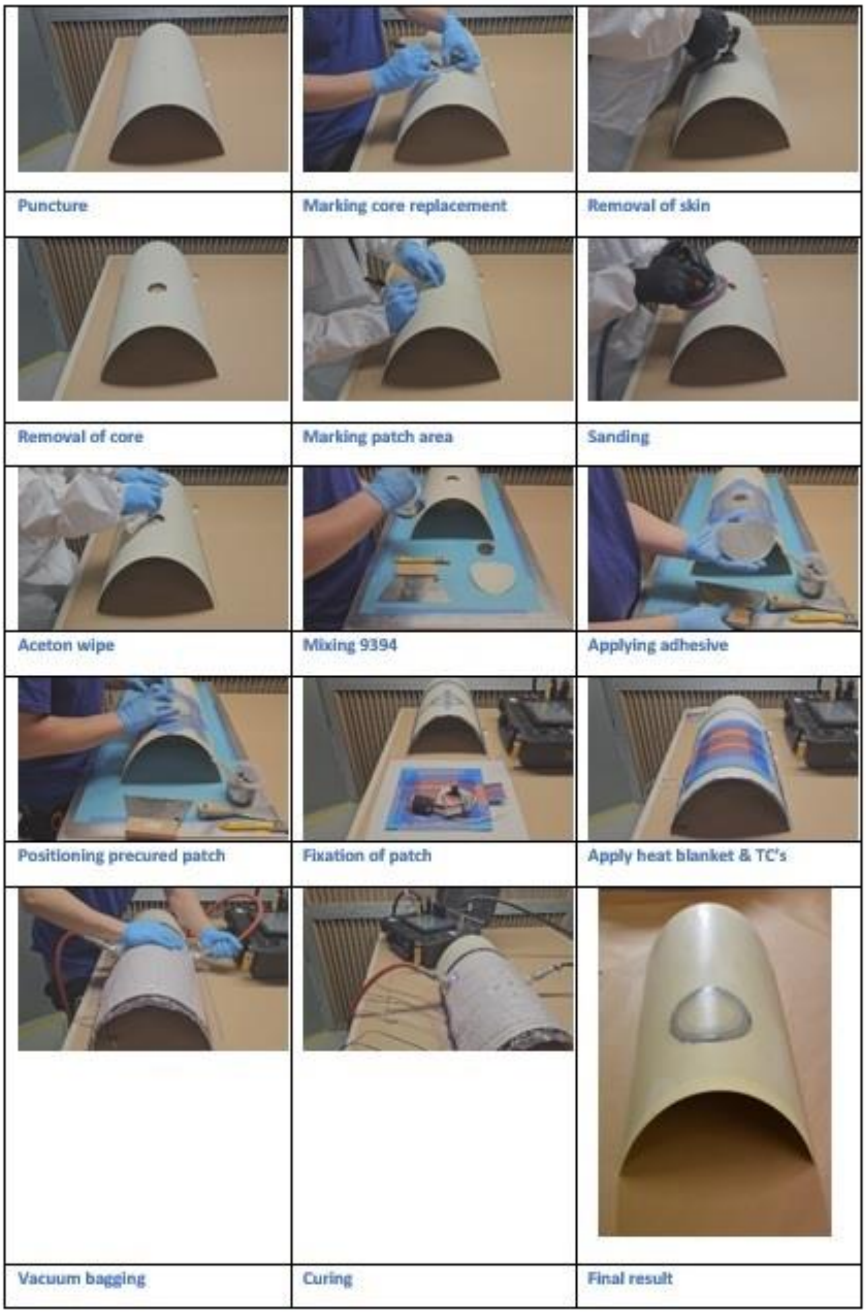

Figure 2. Repair of a puncture using a precured patch.

The effect of aging of bonded repairs has also been investigated. Scarfed co-bonded repair specimens were tested after thermal cycling or after exposure to humidity. For the certification of larger bonded repairs, the use of bonded repair coupons was investigated. Analyses were done to compare the stresses in a scarf repair and in a bonded repair; see Figures 3 and 4.

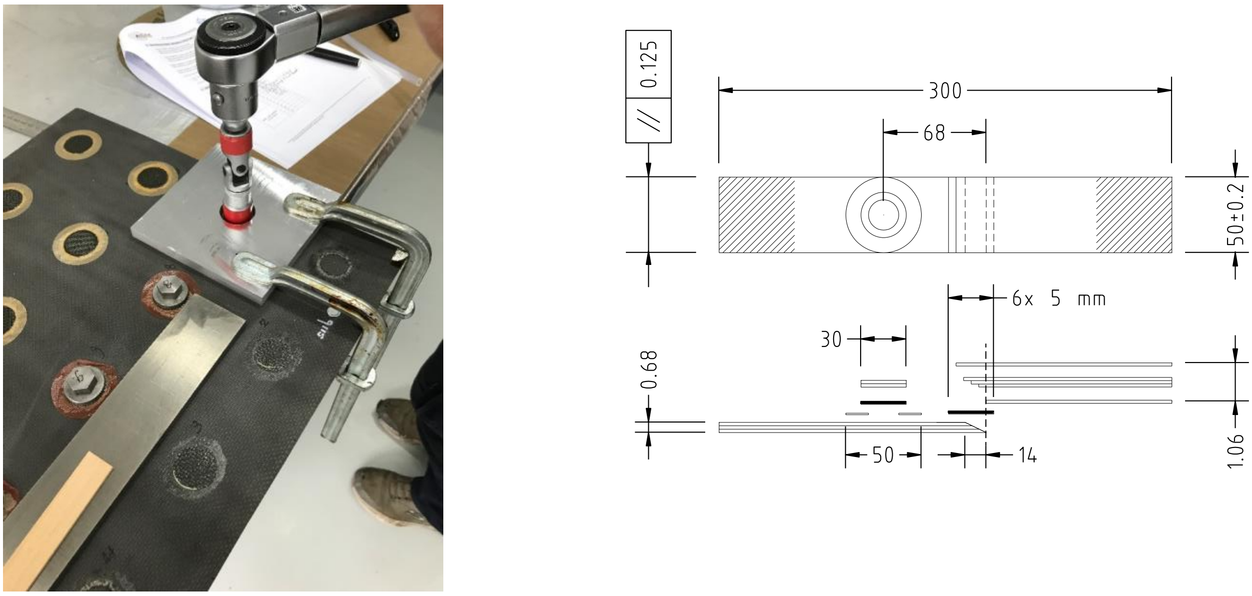

Figure 3. Bonded repair coupon testing on flat panels and on scarfed specimens after ageing.

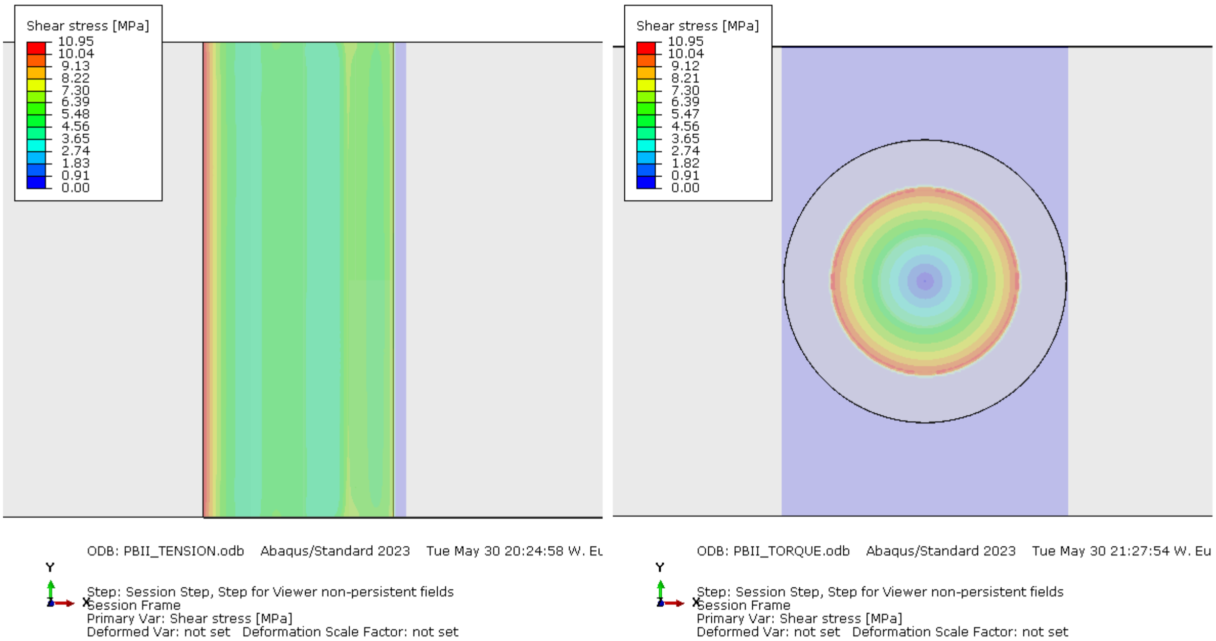

Figure 4. Comparison of shear stresses in a scarfed repair under tension loading (left) and in a bonded repair coupon under torsion loading (right).

3. Testing

The testing strand was performed to understand the behaviour of adhesive bonded panels in the event of damage. For this purpose, a modified specimen based on the EN 6066 standard was used (WEN6066) as the scarf has been explored as a design feature to suppress crack growth of a damage when exposed to fatigue. One of the targets of the test program was to analyse the overlapping length in a scarfed joint, to investigate whether it is of significant influence on the bonding strength. Another factor of the panels was the scarfing ratio of such panels; two ratios, 1:20 and 1:40, were investigated. Furthermore, a sample configuration with a disbond instead of a barely visible impact damage (BVID) was tested. The aim here was to test the extent to which the previously used impact can be replaced by a release film in the repair to achieve more uniform damage to the components.

A drop-weight tower was used to perform impact damage on selected panels targeted to the edge of the joint or to the centre of the joint, alternatively. The panels were partly subjected to static and partly to fatigue loading. If the dynamically tested specimens survived the required number of cycles, a static residual strength analysis was performed. Strain gauges were applied to selected panels to monitor the actual strain of the specimen during fatigue. The strain gage measurement was used also before fatigue to design the loading levels based on permissible loads. The failure process during the strength test was documented using a high-speed camera recording and by aftermath picture documentation. Typical failure modes were identified for each type of panel.

Non-destructive analyses using ultrasound were performed before, during and after the uniaxial tensile testing to find the actual crack growth rate and direction. Moreover, ultrasonic guided waves as a sophisticated SHM method were used for crack growth detection for one panel. A set of 14 PZT sensors was installed, designed to generate and detect ultrasonic guided waves (UGW). In this method, ultrasonic guided waves (Lamb waves) are involved, which place high demands on the signal analysis, mainly due to their dispersive nature. RAPID (Reconstruction Algorithm for Probabilistic Inspection of Damage) was successfully used as the probabilistic imaging algorithm (Figure 5). Additional means of analyses by deformation measurement using digital image correlation and high-speed camera were used to assess the damage initiation and means of fracture of the tested panels.

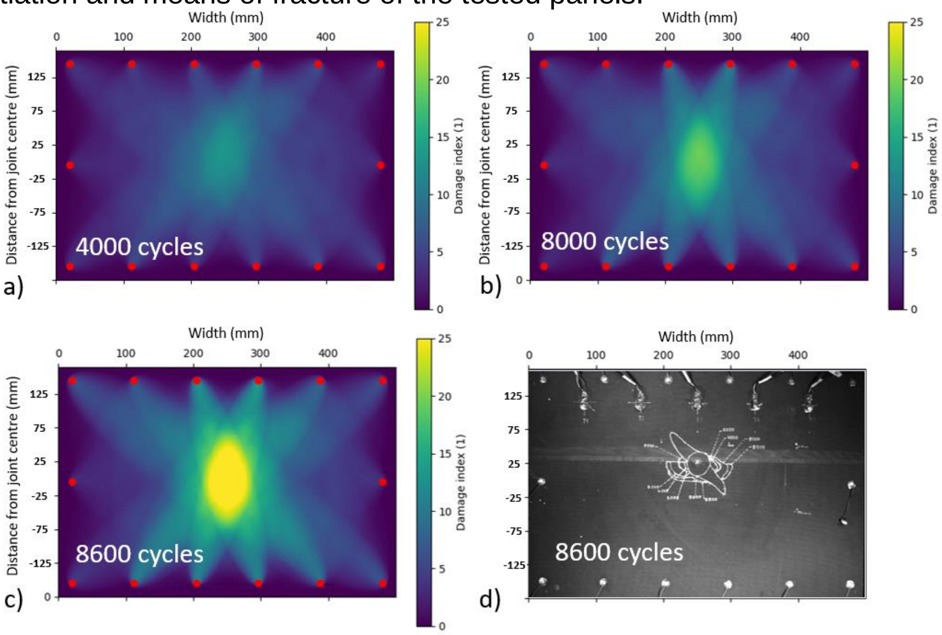

Figure 5. UGW detection of crack growth using RAPID algorithm. Evaluation of damage using a damage index at a) 4,000 cycles, b) 8,000 cycles, c) 8,600 cycles and d) actual damage detected by ultrasonic A-scan.

In addition to the tests described above, coupon test programs linked to design and analysis and SHM strand have also be conducted; see Section 4 and Section 5.

4. Design and analysis

The design and analysis strand performs analysis of experimentally tested bonded repair joints and further develops analysis methods. The method development is focused on the damage assessment of the repair joints, especially under consideration of bond line defects. Damage growth will be studied under both static and fatigue loadings. The design and analysis strand is divided into four work elements (WEs), which (i) defines damage scenarios, (ii) studies crack arresting features of bonded joints, (iii) develop methods applied for analysis, (iv) defines element test to be performed in testing strand.

The methods and applied material properties will be validated using coupon level testing results. The tests are initiated from basic fracture coupons such as double cantilever beam (DCB) and end notched flexure (ENF) specimens, aiming towards specimens representing bonded repairs. Static analyses methods have been focused on virtual crack closure technique (VCCT), continuum damage model (CDM) and cohesive zone model (CZM) based approaches. An example of the comparison between experiments and analysis is shown in Figure 6. Figure 6 compares VCCT analysis results to performed DCB experiments. The development of CDM for adhesive damage in mode II has been developed [1].

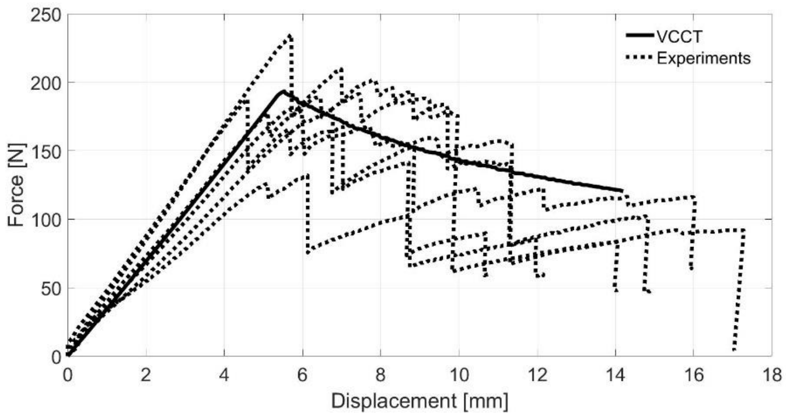

Figure 6. The comparison of VCCT analysis and experiments of bonded composite DCBs.

Fatigue analysis methods have been developed to predict the crack growth rate in an implicit loading step using a user defined field. The crack growth rate prediction utilizes an approach developed by Sachse et al. [2] for the calculation of the expected progression. The approach was developed to allow a fast first assessment of the severity of a pre-existing damage. In order to validate the results, the predicted crack growth rate was compared at different crack length against DCB, ENF and cracked lap shear (CLS) specimens to evaluate the accuracy across different mixed mode ratios. Figure 7 shows the results of the explicit crack propagation simulation against the test results, as well as the predicted crack growth rates for both simulation approaches.

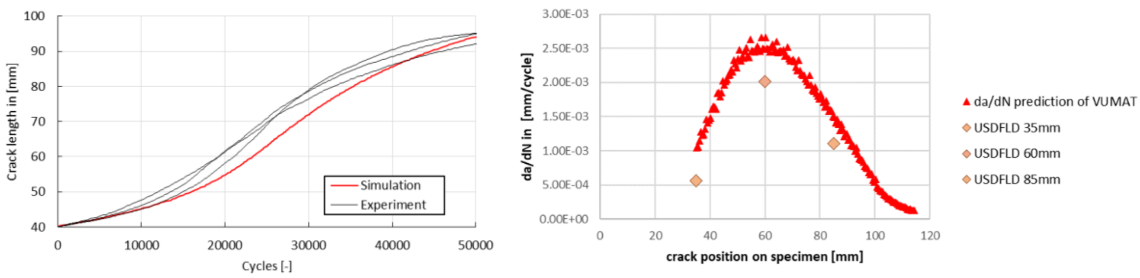

Figure 7. (left) comparison of ENF test results with an explicit crack propagation simulation. (right) comparison of the predicted crack growth rates of the explicit and implicit simulations.

A novel analysis approach for predicting the arrested state of a crack under fatigue loading has been developed. The approach is based on cohesive zone elements (CZE) representing the adhesive layer and on only one quasi-static FE analysis run up to the maximum fatigue load. By an additional pre-processing step, the traction-separation law is manipulated in a way to reduce the critical energy release rate based on the Power law for a pre-defined no-growth limit of crack growth rate. Upon convergence of the implicit analysis run at maximum fatigue load, the damage state output of the CZE allows to determine the position of the arrested crack front in good agreement with experimental test results (see Figure 8).

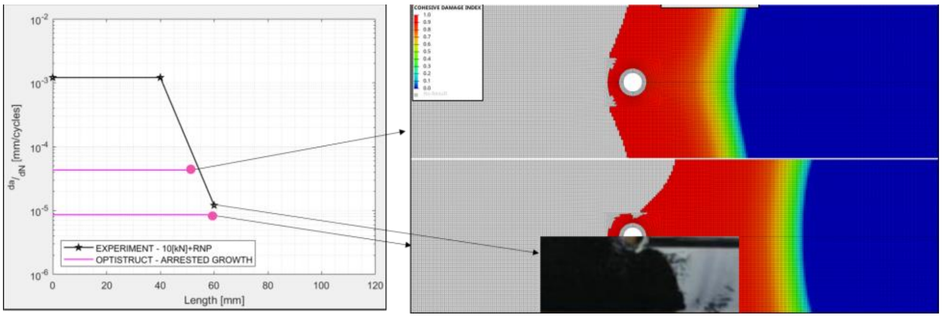

Figure 8. Crack arrest predictions for a CLS specimen including crack arrest feature.

5. Structural health monitoring

The monitoring strand considers SHM systems and how to integrate and utilize such systems to meet the certification requirements for a bolt free primary structure composite repair. A first bonded repair certification strategy approach for SHM was developed as part of the project PATCHBOND. The PATCHBOND certification approach used SHM for detection of an unsystematic problem of the bonding process (local disbond) leading to a damage growth, as well as the detection of discrete source damages that may occur during operation or maintenance. Damage categories relevant for SHM for monitoring of a composite bonded repair were defined. As an example, a local (slowly) growing disbond may not directly be visible to the aircraft crew during walk around inspection, but limit load capability of the composite bonded repair may be affected (requiring immediate repair after recognition).

To utilise an SHM system for composite bonded repair monitoring, the system has to demonstrate the capability to detect (and also evaluate) defects before the defect size becomes critical. To prove the damage detection capabilities of an SHM system, a method/procedure that helps the decision makers in their analysis and evaluation, has to be developed to accurately identify the probability of detection (POD) for prediction of the performance of the SHM system, utilized for composite repair integrity monitoring.

In PATCHBOND II, the work for developing and demonstrating such an SHM system has been organized in five work elements (WEs). These WEs cover 1) the definition of relevant damage scenarios, relevant SHM systems, certification requirements and available standards and procedures for the certification, 2) design of an SHM system for a given damage case for preliminary testing in laboratory environment and subsequent implementation on an NH90, 3) numerical models and simulation tool development for damage identification and prediction of damage growth, 4) laboratory tests on coupon and test panel/component level, and 5) in-flight testing on a Dutch NH90.

Figure 9 shows results of an SHM system based on distributed fibre optic sensors, specifically an Optical Backscatter Reflectometry (OBR) fibre, which provides an almost continuous strain measurement along the whole fibre length. A novel, truly load and material independent approach is adopted to infer the debonding entity from strain measurements in adhesive-bonded joints: the inverse Finite Element Method (iFEM) [3,4]. It allowed to quantitively evaluate the debonding entity independently of the applied loads, such as misalignmentinduced torsion, which otherwise would act as confounding influences for diagnosis. iFEM is used as a shape sensing technique to reconstruct the full-field strain as a function of a limited number of strain measures as input (Figure 10.a). Bayesian inference is then used in order to identify the most likely (and structurally compatible) damage configuration among a set of readily available models in a database, through strain comparison at some specific test locations [5] (Figure 10.b).

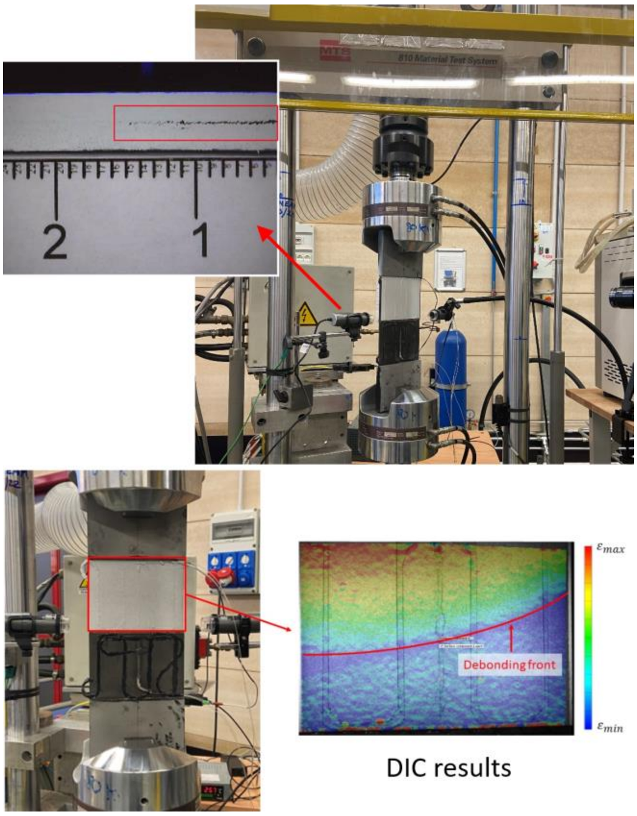

Figure 9. Laboratory tests at Politecnico di Milano facilities for SHM system testing on a large scale CLS specimen subject to fatigue load cycles.

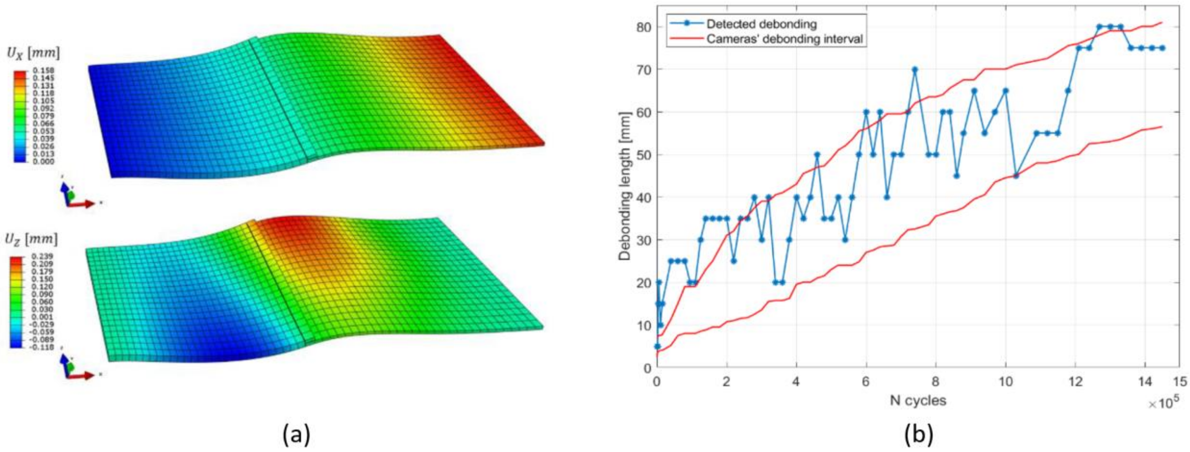

Figure 10. (a) iFEM shape sensing results (displacement field) for the tested specimen in the undamaged configuration. Deformed shape with a scale factor of 50. (b) Debonding length detected by Bayesian inference: uncontrolled torsion in the specimen provoked different debonding lengths to be measured at two sides of the specimen (red curves) while the predicted debonding size lies in between the two curves with sufficient robustness.

At the current state of the project, the first four WEs have been almost completed. This work has prepared for the final step, which is doing the in-flight testing on a Dutch NH90. The PATCHBOND II project will piggyback on a Dutch national program on SHM, using the same type of sensors and data acquisition system.

For the PATCHBOND II part of the in-flight test program, a test rig has been designed and established, see Figure 11. This test rig will be implemented on the Dutch NH90. The test rig set-up includes two cracked lap shear (CLS) type specimens (both pristine and damaged) in tension, as well as a scarf repaired NH90 panel. Fibre Bragg grating (FBG) sensors are in this case mounted on both the CLS specimens and on the front plate. The specimens and the front panel will be exposed to environmental loads during flights, as well as the mechanical loads from the (rest of the) helicopter, i.e. vibrations, G forces etc. Strains will be logged by the FBGs during the whole flight, and the data will be applied in the numerical models for prediction of damage growth. The in-flight data will also be compared to the laboratory tests performed in the project.

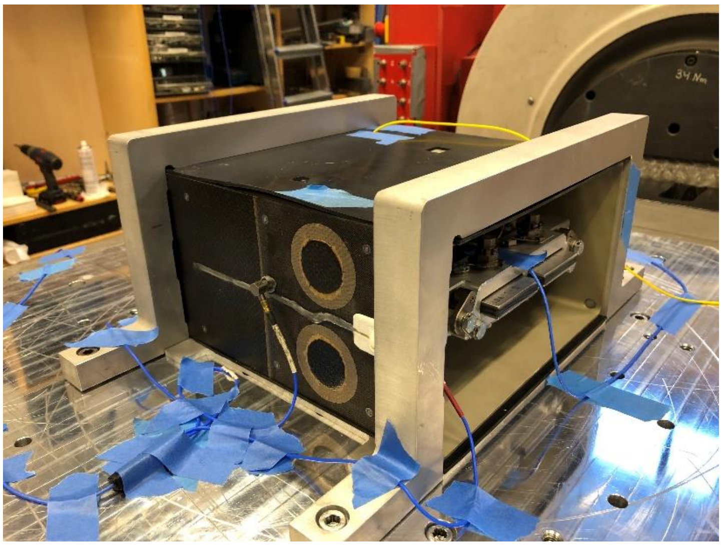

Figure 11. In-flight test box with CLS specimen and front panel with bonded repair coupons (BRCs). All specimens with FBGs.

The final output from this work strand is the development and demonstration of an SHM system that can be used as a mean of compliance for the certification of adhesively bonded repairs on primary composite aerospace structures.

6. Discussion and conclusion

The on-going project has already provided valuable results about adhesively bonded repairs behaviour, design, and structural health monitoring. A continuation of the project work could be to establish repair procedures for battle damage repairs (BDRs) of primary aerospace composite structures, supported by a SHM system.

7. Acknowledgement

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References

[1] O. Rodera, N. Pournoori, P. Hakala, M. Kanerva and J. Jokinen, Multi-layer continuum model for adhesive FM 300-2 in end-notched flexure carbon laminate, submitted for acceptance.

[2] R. Sachse, A. Pickett, M. Käß and P. Middendorf, “Numerical Simulation of Fatigue crack growth in the Adhesive Bondline of hybrid CFRP Joints,” in COMPOSITES, Bristol, 2015.

[3] A. Tessler, J. Spangler, Inverse FEM for Full-Field Reconstruction of Elastic Deformations in Shear Deformable Plates and Shells, 2nd European Workshop on Structural Health Monitoring, Munich, 2004.

[4] D. Oboe, L. Colombo, C. Sbarufatti, M. Giglio, Shape Sensing of a Complex Aeronautical Structure with Inverse Finite Element Method, Sensors. 21 1388, 2021.

[5] D. Poloni, D. Oboe, C. Sbarufatti, M. Giglio, Debonding quantification in adhesive bonded joints by the inverse finite element method, Smart Materials and Structures, 32 (4), art. no. 044002, 2023.