# Final Publishable JRP Summary Report for ENG57 VITCEA
# Validated inspection techniques for composites in energy applications

## Overview

The excellent mechanical properties of fibre reinforced plastic (FRP) composites gives them considerable advantages for use in renewable energy (wind, wave and tidal), oil and gas, and transport applications. The low weight, strength, fatigue and corrosion resistance mean that FRP composites have the potential to reduce fossil fuel reliance, energy consumption and greenhouse gas emissions. However, FRP composites can contain a diverse range of defects and damage mechanisms that can reduce the strength, stiffness and life of a structure. These can be difficult to detect, but reliable non-destructive evaluation (NDE) would aid characterisation of FRP material quality and encourage their full exploitation.

Defects can be detected and sized using a range of NDE techniques, which has been done quite widely for high performance composites in the aerospace industry. However there is less evidence of the suitability, applicability and limits of detection for NDE for FRP products in energy applications, e.g. wind and marine turbine blades, nacelles, and oil and gas flexible risers, where different materials and varying thicknesses are used. This project looked at several NDE techniques to determine the relative applicability and suitability for defect detection in FRP, in a range of energy applications, as well as the development of operational procedures for each technique, so that users can have confidence in component performance and working life of FRP composites.

## Need for the project

Despite many innovations in the development of NDE for the assessment of defects and damage, relatively few methods are commonly used. This is mainly because standardised operational procedures are not available, and there are perceptions that NDE is too unproven, costly or complex. There are currently no ISO standards for NDE in existence that are specific to defect detection in FRP composites. Several American Society for Testing Materials (ASTM) composite NDE specific standards are available, but these tend to be focused on the aerospace sector and do not provide enough detail and validated data on issues such as probability of detection (POD), defect size and location sensitivity. Therefore new NDE techniques to enable the increased use of FRPs for energy applications are needed.

This project assessed five relatively novel NDE techniques in order to check how applicable they were for defect detection in FRP products post fabrication and their subsequent in-service assessments. The five NDE techniques had contrasting detection capabilities and were: (1) microwave, (2) active thermography, (3) laser shearography, (4) phased array ultrasonics and (5) air-coupled ultrasonics.

One of the challenges facing accurate and repeatable defect detection in FRP composites is the multitude of defect types that exist, each with characteristics that may be more easily detected with one technique over another. Therefore, in order for a particular NDE technique to achieve broad acceptance by industry, it is desirable for the technique to be able to detect a range of defect types with a high level of confidence. This is referred to as the probability of detection (POD and is usually a graphical representation which reflects a low probability of detecting a small defect to a high probability for larger defects. It then typically requires many measurements to create the POD ‘curves’.

The applicability and suitability of NDE techniques can be evaluated using Reference Defect Artefacts (RDAs) and Natural Defect Artefacts (NDAs). RDAs are manufactured to have known artificially created defects, with well-defined sizes and in known positions, and NDAs are samples which have been loaded to introduce damage that is representative of what will actually occur in service. This project aimed to create RDAs and NDAs which could then be used to develop and validate traceable procedures for the 5 novel NDE techniques under test. In order to underpin the increased use of FRP composites in energy related applications.



EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

## Scientific and technical objectives

The project's objectives are:

1. To design and manufacture suitable NDAs and RDAs that are representative of the materials and defects typically found in, and of concern to, the renewable energy (wind, wave, and tidal), oil and gas and transport sectors;
2. To develop operational procedures, drafted in the style of CEN and ISO standards, for: microwave; active thermography; laser shearography, phased array ultrasonics and air-coupled ultrasonics. The metrology objectives are to:
   i) Establish the limits of detection for each NDE technique;
   ii) Develop analytical techniques for accurately sizing defects for the five different NDE techniques;
   iii) Compare the NDE techniques for different defect type using an objective POD benchmarking framework;
   iv) Advance the theoretical simulation of the inspection techniques;
3. To evaluate the POD methodology, based on modelling simulations with the aim of reducing the cost and time requirements of intensive experimental POD trials;
4. To validate and refine operational procedures via intercomparison exercises and field trials in collaboration with organisations from the renewable energy (wind, wave and tidal), oil and gas and transport sector supply chains. Defect artefacts will be inspected using the developed operational procedures.

## Results

1. *Design and manufacture of suitable NDAs and RDAs*

A survey of composite product designers, manufacturers and end-users, as well as NDT service and equipment suppliers, regulators and material suppliers was undertaken to establish the material systems, components/structural elements and defect types (including size and location) that are most routinely required to be inspected, and those that present significant challenges to NDE inspection. The outcome of this survey resulted in a total of 13 designs for RDAs and 2 NDAs covering marine and automotive transport, renewable energy and oil and gas sector applications. The RDAs and NDAs were designed and manufactured, and circulated to all project partners for further characterisation and assessment. The defects reflected issues in material consistency, processing-related issues, and damage that may be encountered in service. The materials included FRP composites based on thermoset and thermoplastic matrix systems reinforced with glass and carbon unidirectional and multi-directional tape and fabric formats.

The elastic, dielectric, thermal and optical properties for each material used in the RDA and NDA designs were characterised by the partners. These material properties are important as they are the input data to the modelling techniques for the phased array ultrasonics, microwave and active thermographic NDE techniques, respectively. CMI measured thermal conductivity, specific heat capacity, thermal diffusivity and thermal penetration in all directions for each of the RDA and NDA materials.

In addition to the RDAs and NDAs, partners NPL, BAM and CEA designed and manufactured two additional RDAs specifically for use in the POD and intercomparison exercises in objectives 2 and 4. These POD-RDAs, were made from CFRP (carbon fibre-reinforced plastic) and GFRP (glass fibre-reinforced plastic) materials and featured 13 different sizes of artificial delaminations and back-face drilled holes that had diameters ranging from 1 mm to 40 mm.

On completion of the trials using all 5 NDE inspection techniques for damage detection in the NDAs, selected samples for both impact and tensile milled-notch NDAs were destructively characterised (i.e. the NDAs were destroyed as part of the testing) using a range of techniques, e.g. optical microscopy and 2-D X-ray inspection. The actual extent of defects created in the NDAs was compared to measurements made with the five NDE techniques being used in the project. The level of agreement between results was dependent on the NDE technique used and the type of defect but in general was good.

13 RDAs and 2 NDAs were designed and manufactured. The RDAs are now available for loan, although the NDAs are not available as they were destructively characterised at the end of the project.

2. *Development of operational procedures for microwave, active thermography, laser shearography and phased array and air-coupled ultrasonic NDE techniques*

The RDAs and NDAs developed in objective 1 were used to evaluate the detection limits and sizing capabilities of phased array and air-coupled ultrasonic, laser shearography, microwave and active thermography NDE methods. The defect types included: delamination, porosity, bonding, fibre misalignment, pipe wall thinning (back-face drilled holes), core damage, impact delaminations and matrix cracking. Draft operational procedures were produced for each NDE technique, which were evaluated via a series of POD assessments and an intercomparison exercises using the POD-RDAs and involving a number of stakeholder organisations.

For each of the materials used in the construction of the RDAs, NDAs and POD-RDAs, material property data (elastic, dielectric (excluding carbon FRP), optical and thermal) was measured in order to optimise practical application of the phased array and active thermography NDE techniques and, where the capability and fidelity of various modelling approaches allowed, the theoretical simulation of NDE techniques.

In the microwave NDE technique, modelling development activity focused on the application of electromagnetic modelling techniques to simulate microwave inspection of FRP composites. The results showed that there was good agreement between simulated and experimental results, and the simulations also indicated potential improvements that could be made to further optimise microwave transducer design. Additional modelling work resulted in a Researcher Excellence Grant (REG) from CEA modifying their CIVA ultrasonic software to take into account the true profile of delamination in curved laminates. BAM also developed the numerical models of anisotropic heat diffusion for active thermography including flash heating, step heating and lock-in excitation for the RDAs. These numerical models and solutions were then validated using experimental results.

3. *Evaluation of the POD methodology, based on modelling simulations*

Experimental and, where available, simulated data were used for POD modelling. The data was based on the signal response of the inspection results for microwave, ultrasonic and thermographic NDE techniques, and the hit/miss approach for the laser shearography technique. The outcomes of the POD assessments indicated the relative performance of each NDE technique for detecting certain defects, which is important as this will reduce the cost and time of carrying out extensive experimental POD trials.

4. *Validation and refinement of operational procedures via intercomparison exercises and field trials*

An intercomparison and POD exercise for all five NDE techniques focused on the inspection of two POD-RDAs. The intercomparison included stakeholders such as equipment suppliers, end users and academia within Europe and the USA. In addition, a number of real components selected from different energy sector applications were inspected as part of a series field trials. These real components included sections of wind turbine blade and composite overwrap repairs typically used in the oil and gas sector. The outcome of the intercomparison, POD assessment and field trial exercises has enabled the validation and refinement of the draft operational procedures for NDE techniques for FRPs. These draft operational procedures have now been finalised as pre-cursors for future standardisation and have provided input to the draft standards: VDI GMA FA 8.16 Temperature measurement with infrared camera (thermal imaging) and NA 062-08-27 AA Visual and thermographic examination.

## Actual and potential impact

*Dissemination*

The project was represented on the Composites Group committee of the British Institute of Non-Destructive Testing (BINDT), the General Technical Committee for Composites of the BINDT and the Millimetre-wave and THz Users Group of the BINDT as well as by attendance at an industrial engagement meeting of the UK National Composites Centre's NDE Defect Library initiative.

Presentations were made by partner BAM at the InnoTesting Conference (Germany) at the International Symposium of Fatigue (Italy, Sept 17) and at the 19th International Conference of Photothermal Phenomena (Spain, July 17). PTB, BAM and CMI also presented the project's results at Temperatur 17. Overall the project has delivered 26 conference presentations and has had 13 conference proceedings published. Six journal publications were submitted, with one of these now published. A further eight journal publications are in preparation.

The project carried out three training workshops on specific NDE techniques, as well as one-to-one training sessions. It also developed an e-learning package *Microwave NDT for Composites Explained* which is available on the NPL website.

*Impact on standards*

There are no established standards in the area of NDE testing of FRP as standards have developed either around composite testing or NDE of materials for the aerospace sector, as in the ASTM standards. Information from the project has been passed to relevant committees such as ISO/TC135/SC08 'Infrared thermography for non-destructive testing', ISO/TC135/SC03 'Ultrasonic testing', ISO/TC135/SC9/WG2 'Composite Materials' and ISO/TC61/SC13 'Composites and reinforcement fibres' on international standards development on NDE, materials testing and polymer composites. There has also been input to the draft standards: VDI GMA FA 8.16 Temperature measurement with infrared camera (thermal imaging) and NA 062-08-27 AA Visual and thermographic examination.

*Actual impact*

The outputs of the project are already being used and include:

- Reference material sector specific RDAs and POD-RDAs, including operational procedures for ultrasonic (phased array, air-coupled), microwave, active thermography, and laser shearography NDE techniques. These are freely available via NPL or from the other project partners.
- Additional measurement services of the thermal properties of composite materials are now available from NPL and CMI.
- Improved optical property measurement services have been developed by PTB; emissivity of anisotropic composites under vacuum can now be measured with an uncertainty of 0.005.
- Development of new modelling capabilities at BAM, PTB and REG(CEA) for ultrasonic phased array, microwave and active thermography NDE techniques, enabling theoretical POD assessments to be undertaken.
- A UK based engineering consultancy company has used the microwave inspection facility developed in objective 2 to inspect GFRP-balsa and GFRP-balsa-metal reference samples. The company were impressed by the facility and wish to evaluate it further on additional samples.
- As a result of the project, a manufacturer of microwave inspection equipment, is planning potential modifications to its microwave transducers to eliminate/reduce unwanted standing wave formations. The company has acquired the same modelling software that was used in the project for simulation of microwave inspection as a tool to improve their equipment design.
- The modelling work done by REG(CEA) in objective 2 has extended the capability of the CIVA ultrasonic software, and therefore enhanced their services

The outputs of the project will benefit end-users, designers and NDE communities involved with the use of FRPs in energy applications. They will also enable integration of novel NDE techniques, allowing improved design, manufacturing and assembly of FRPs with NDE inspection being facilitated throughout the life cycle of FRPs.

*Potential impact*

This project has developed operational procedures for NDE techniques which will provide industry with increased confidence in the application of the NDE techniques used for defect detection in a range of FRP composite applications. The project has also increased industry's understanding of how to use NDE techniques, how to interpret their results and what sorts of defects can be detected in a range of different materials.

The project's optimised NDE techniques, operational procedures and modelling capability will lead to improvements in safety, life expectancy, energy efficiency and sustainability; and can contribute to reductions in fossil fuel reliance, greenhouse gas emissions and maintenance costs for FRP assets in the energy sector.

## List of publications


[1]. **Defect characterisation of tensile loaded CFRP and GFRP laminates used in energy applications by means of infrared thermography**, *Krankenhagen, Maierhofer et al*, QIRT Journal, http://dx.doi.org/10.1080/17686733.2017.1334312

[2]. **Hybrid Ray-FDTD Model for the Simulation of the Ultrasonic Inspection of CFRP Parts**, *Karim JEZZINE, Damien SEGUR, Romain Ecault, Nicolas Dominguez,* Proceedings of QNDE16, Atlanta , USA, 17-22nd July 2016, https://doi.org/10.1063/1.4974660

[3]. **Characterisation of artificial defects in CFRP and GFRP sheets designed for energy applications using active thermography**, *C. Maierhofer, R. Krankenhagen, M. Röllig, B. Rehmer, M. Gower, G. Baker, M. Lodeiro, A. Aktas, L. Knazovická, A. Blahut, C. Monte, A. Adibekyan, B. Gutschwager,* Proceedings of Conference QIRT 2016, http://dx.doi.org/10.21611/qirt.2016.076


| | |
|---|---|
| JRP start date and duration: | 1st July 2014, 36 months |
| JRP-Coordinator:<br>Michael Gower, NPL  Tel: +44 20 8943 8625  E-mail: michael.gower@npl.co.uk<br>JRP website address: http://projects.npl.co.uk/vitcea/ | |
| JRP-Partners:<br>JRP-Partner 1: NPL, United Kingdom<br>JRP-Partner 2: BAM, Germany | <br>JRP-Partner 3: CMI, Czech Republic<br>JRP-Partner 4: PTB, Germany |
| REG1-Researcher<br>(associated Home Organisation): | Damien Segur<br>CEA, France |

***The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union***