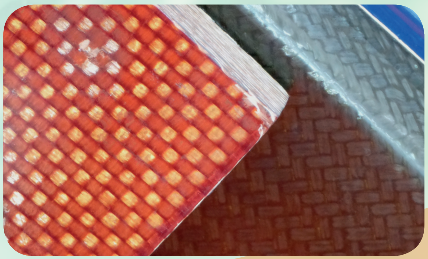
Aerospace Workshop

Report from the Workshop on NDT and SHM Requirements for Aerospace Composites

9-10 February 2016

National Composites Centre, Bristol, UK



BINDT THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

. . . engineering safety, integrity & reliability

Workshop on NDT and SHM Requirements for Aerospace Composites

Compiled by: Robert A Smith, BINDT President, University of Bristol, Bristol, BS8 1TR.

An ambitious British Institute of Non-Destructive Testing (BINDT) workshop, with the above title, brought the regulatory, design, manufacturing, structural integrity and NDT communities to the National Composites Centre (NCC) on 9-10 February 2016. The objective was to establish the opportunities and requirements for successful NDT solutions to current aerospace design and manufacturing constraints in the use of composite materials. An example would be the use of NDT to remove the requirement for back-up (safety) features, such as fasteners, in adhesive joints in the primary structure. The three main subject areas for the workshop were: adhesive-bonded joint inspection, 3D characterisation of composite materials and structural health monitoring (SHM). The stated objective of the workshop was:

*For the **regulation**, **design**, **manufacturing**, **structural integrity** and **materials** communities to tell those in **NDT** and **SHM** what we need to do, solve or prove in order to provide benefit through: lighter and more efficient composite designs, reduced production cost or reduced in-service cost of ownership.*

The workshop was aligned to the following BINDT objectives:

Relevant Aerospace Group objectives:

- To define NDT requirements to meet future aerospace industry goals.
- To develop roadmaps for NDT technologies to guide knowledge generators (for example universities and RTOs) towards aerospace industry goals.
- To change the perception of NDT into being a solution rather than a burden, by promoting the benefits of NDT methods within the design, production and maintenance communities.
- To promote and enable the introduction of new NDT technologies by identifying and tackling barriers, and through scientific evaluation, validation and education of manufacturing and maintenance supply chains.

Relevant Composites Group objectives:

- To capture present, and anticipate future, requirements for NDT of composites and enable a route to the solutions via roadmaps for new technologies.
- To work with the structural integrity, manufacturing and design communities to identify and define mechanisms through which NDT/CM can 'enable' optimised composite designs, lower-cost manufacturing and life extension.

A technical panel from academia and industry convened the workshop, comprising:

- Professor Robert Smith, University of Bristol (BINDT President and Chair of the Composites Group)
- Professor Peter Foote, Cranfield University (Chair of BINDT's new SHM Working Group)
- Professor Phil Irving, Cranfield University (CAA Damage Tolerance Chair)
- Dr Barbara Gordon, University of Bristol (ex-BAE Systems)
- Professor Ian Lane, Airbus
- Dr Martin Gaitonde, Airbus
- Dr Tim Barden, Rolls-Royce.

This technical panel was acknowledged and thanked by the BINDT President, Professor Smith, in his opening remarks, as were the UK Engineering and Physical Sciences Research Council (EPSRC), the NCC and BINDT for making the workshop possible through their support.

Key participants in the workshop represented airworthiness regulators EASA (Europe) and CAA (UK), constructors such as Airbus, BAE Systems and Fokker Aerospace (now GKN) and their aero-structure and aero-engine manufacturing suppliers such as Rolls-Royce and GKN Aerospace. Also represented were academia, High-Value Manufacturing (HVM) Catapult Centres (NCC and the Manufacturing Technology Centre, MTC) and aircraft operators such as British Airways and the Ministry of Defence (MoD), as well as several NDT equipment suppliers and service providers (see delegate list, Appendix A).

In addition to short, invited presentations, a key feature of the programme was the focused and facilitated discussion time, through two breakout sessions and four panel-led discussions. These were carefully recorded and documented. This paper provides a summary of those presentations and discussions.

Design, qualification and certification

Composite structures – basic principles and issues

Dr Barbara Gordon, University of Bristol

Dr Barbara Gordon drew on her extensive experience of military-aircraft composite structural design (for BAE Systems) to explain some of the complexities, constraints and strategies involved in designing a structure that meets the (often conflicting) requirements of performance, structural integrity, production cost and in-service maintenance costs (Figure 1). In terms of structural performance, composites offer great flexibility because stiffness can be tailored to the application using different 'lay-ups' – sequences of layered carbon-fibre orientations embedded in a resin 'matrix'. Stiffness links the failure stress (strength) to failure strain (the fractional change in a dimension of the component) and strain is the preferred design criterion for large areas of the structure, coupled with localised stress-based design for detailed structural features. Fundamental to this is an understanding of the important failure modes, such as matrix cracking, delamination or fibre breakage. In order to predict how the structure will perform, the local loading conditions need to be understood and finite element modelling is now used extensively to ensure that the strain at any location is within acceptable limits to avoid the relevant failure modes.

Figure 1. The wings, empennage and fuselage of modern aircraft, such as the Eurofighter Typhoon and Airbus A350, use large amounts of composite structure. Dr Gordon's presentation highlighted how different issues and principles dominate design for different parts of the structure

Photo courtesy BAE Systems

In-service accidental impact damage is a key design constraint for some components and Dr Gordon explained how such damage becomes a stress concentration, rather like a machined through-thickness hole. Both holes and impacts have to be accounted for in terms of residual strength but their relative importance differs, depending on whether the structure is primarily in tension (for example lower wing skin) or compression (upper wing skin). For some components, the designer can focus on stiffness but is still constrained by buckling (bending under compression) thresholds. From an NDT perspective, important global constraints are that the structural integrity must allow for the possibility that a 6 mm-diameter hole may be required anywhere (for example for a repair) and any damage that is undetectable visually must not grow under fatigue.

Certification of civil composite structures based on detectable damage thresholds – overview and critical NDT detectability thresholds

Dr Simon Waite, European Aviation Safety Agency (EASA)

One of the most progressive aspects of this workshop was that the regulators engaged directly with the NDT community regarding the mapping of future underpinning requirements. Dr Simon Waite from the European Aviation Safety Agency (EASA), the European airworthiness authority, presented the current position in terms of high-level certification of composite aerostructures and Dr Ted Blacklay, from the Civil Aviation Authority (CAA), was heavily involved in the discussions. Dr Waite explained that the basic high-level aviation regulations simply state that 'no aircraft shall be operated unless… inspections and tests demonstrate that the aircraft is in a condition for safe operation'. There is little further prescriptive guidance regarding specific inspection methods. Furthermore, other requirements, such as CS25.571, allow the use of 'inspections or other methods' to address damage tolerance. This allows, in part, the potential to use new NDE or SHM methods. However, as has always been the case for the use of existing established methods, such new methods must be substantiated and shown to be reliable with respect to damage tolerance (including residual strength requirements) and inspection philosophies to the satisfaction of the type certificate holders and the regulators. The new methods, and the potential to find more defect types at lower thresholds of detectability, may be of increasing importance as new materials and processes evolve and are applied to aviation applications, for example composites, additive manufacturing, etc, such that improved production control and more consistent design-allowable data become possible. However, the need also remains to maintain a safe and robust design philosophy at the aircraft level, which recognises practical operational needs and the realistic damage allowables that entails.

Dr Waite mentioned the potential for 3D non-destructive characterisation to provide an improved link between the mechanical test and analysis in the test/analysis 'pyramid' – see Figure 2. In terms of NDT challenges, he had several recommendations. He warned against making assumptions about damage modes and locations – NDT techniques that cover many damage modes and large areas are preferable because composites are complex and causes of damage are unpredictable. Dr Ilcewitz of the FAA had asked Dr Waite to include the challenges of heat damage detection and characterisation. NDT should aim to output residual strength, not just the sizes and locations of defects, because future requirements will be performance-based. There is a concern that many new techniques that work well in the laboratory are not practical or cost-effective for use in a realistic environment, particularly in-service where conditions are rarely ideal. In the following lively discussion, Dr Waite emphasised the need for NDT to provide more and better information for the type certificate holders, as this will enable them to benefit from novel NDT. Dr Blacklay added that a joined-up approach is needed where NDT Level 3s, who approve NDT techniques, should be working closely with the design organisation that understands design concepts and knows what defects need to be found, as required in CAA documentation.

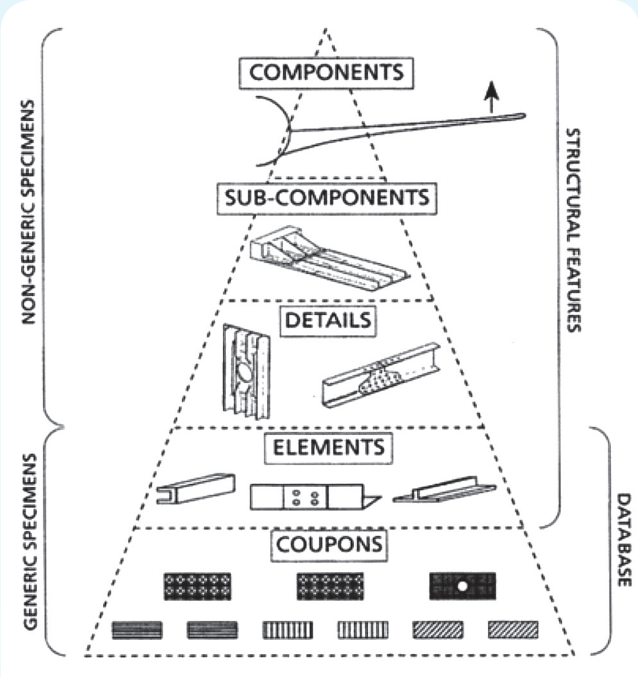


Figure 2. The test/analysis pyramid for composite components
Image courtesy of EASA

Damage tolerance and defect growth in composite aerostructures

Professor Phil Irving, Cranfield University

Professor Phil Irving began his presentation by comparing the behaviour of composites with more traditional and better understood metallic structures. NDT for damage tolerance of the structural integrity of metals assumes that defects such as cracks will grow slowly under the fatigue of the material, providing multiple opportunities for NDT detection of cracks. In some materials, such as high-strength metals under high stresses, cracks can grow very rapidly from a detectable size through to failure, allowing insufficient time for multiple inspections. In these cases, the damage tolerance philosophy is inappropriate and a safe-life certification is adopted, where the life of the component is predicted based on models and fatigue tests. In composites, in-service impacts cause delamination damage, which has no real equivalent in metals but significantly reduces the compression strength of the composite. Fatigue strength is much less affected by impact damage than static strength and, in the current generation of polymer composites and component designs, these defects do not grow significantly under fatigue at stresses less than 70% of the reduced compression strength (*ie* after impact). At fatigue stresses greater than 70%, delaminations can suddenly begin to grow rapidly with a very small window of opportunity for detection. Thus, the important thing is to detect any significant damage very early and visual inspection for surface dents is relied on for this, with appropriate consideration of the reliability of this method. The NDT and damage growth questions posed by Professor Irving were: how should inspection intervals for a zero damage growth scenario be set?; can NDT determine when damage begins to grow?; is there an alternative to visual inspection for damage?; do environmental factors influence when a defect begins to grow?; and can structural health monitoring play a role?

Civil composite aero-structure designs

Dr Martin Gaitonde, Airbus

Dr Martin Gaitonde explained that there has been a step-by-step increase in the utilisation of composites within Airbus aircraft since the A300 up to the current A350 XWB, for which more than 50% of the airframe is a composite structure. Regarding future NDT challenges associated with composite structures, four areas for potential improvements are:

- NDT during manufacture – reduce the amount of NDT and make it quicker, lower cost and more integrated;
- NDT in service – make it quicker, lower cost and 'remote' (data potentially analysed off-site);
- NDT for SMART engineering – use NDT to improve understanding of how best to use the material to enhance design and performance, and NDT modelling to optimise the design and inspection;
- NDT for bond-quality assessment.

Aero-engine composite designs

Dr Tim Barden, Rolls-Royce

Dr Tim Barden explained that the main design drivers are improved performance in terms of thrust, reduced through-life cost, safety, future environmental requirements on reduced CO_2 emissions and noise pollution and the increasing reliability and availability of engines. Reducing fuel burn becomes important for several of these drivers, as does the environment in which the engines fly, which vary between military and civil use. Weight is an issue in engines, primarily because of centrifugal loads, but aerodynamic loads on blades are also very important, so thinner blades are desirable and careful control of the blade shape is crucial in production. Due to the large numbers of blades in each engine, these are high-volume low-cost components, giving an opportunity for automation and the knock-on benefits of reliability and consistency in the product. There are currently only a few composite components in an aero-engine, around 5%, although future civil engines will have up to 65% of composite. This includes the main fan blades (Figure 3), allowing a higher bypass ratio, which increases efficiency by reducing the velocity of the bypass flow, reduces noise and also reduces the effects of fatigue on reliability and availability. Dr Barden identified the main NDT opportunities in three categories:

- design, through shape control, feeding data into models and confirming material quality;
- production, through process verification, product verification and new-process development;
- maintenance, through efficient life management and life extension.

Figure 3. Composite fan blades in an engine mounted on the Rolls-Royce flying test-bed *Photo courtesy of Rolls-Royce plc*

Opportunities for benefit from NDE

Opportunities for benefit from NDT

Dr Barbara Gordon, University of Bristol

Dr Barbara Gordon highlighted the ongoing challenges within the aerospace industry, both civil and military, particularly to reduce cost, weight and timescales throughout the whole lifecycle of the product. To address these, the approaches in design and manufacturing have changed fundamentally over the last 25 years, with the introduction of computer-aided design, 3D modelling, integration of the design/manufacturing interface and the introduction of automated manufacturing processes. For composites, this has included automated tape laying (ATL), fibre placement (FP), out-of-autoclave curing, resin infusion and an increased use of bonded structures. Automated processes and alternative techniques have been introduced for the NDT of composites, for example laser NDT, but the information generated and its overall role – principally production support and quality assurance – remains largely unchanged. However, new analysis capabilities for NDT data are developing and these offer the potential for increased resolution, the ability to identify defects not previously identifiable (Figure 4), to produce 3D images of the defects and possibly to move into new roles within the lifecycle of the product. Examples for such roles could include online NDT to identify and rectify defects as they occur during composite lay-up, active roles within the design/qualification phase of the product or integration with new structural analysis capability for sentencing individual defects. This talk then led into subsequent breakout sessions/panel discussions posing the question: Where would this technology be most valuable and where should efforts be targeted?

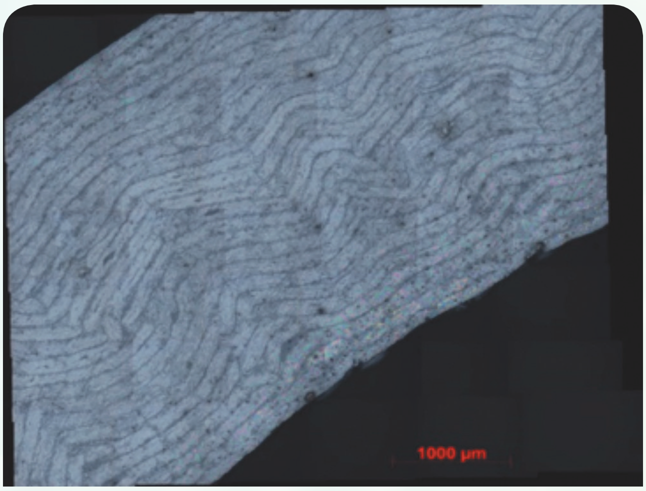


Figure 4. New NDT analysis methods offer the potential to find defects, such as this out-of-plane ply wrinkling in composite laminates *Photo courtesy of Professor Kevin Potter, University of Bristol*

Design for manufacture: advancing lamination technologies towards 'right first time, every time'

Professor Kevin Potter, University of Bristol and National Composites Centre

Professor Kevin Potter drew material from a 'Design for Manufacture' project within the Engineering and Physical Sciences Research Council (EPSRC) Centre for Innovative Manufacturing in Composites (CIMComp). He explained that the goal is to achieve easy and economic manufacture, but these aspects are set at the conceptual design stage and a detailed understanding of all the processes is required in order to determine where the different impacts on quality and cost occur. If the processes are controlled and reproducible then components will be made 'right first time, every time' and post-manufacture NDT will not be required on every component. In order to assist the control of processes, in-process inspection (IPI) could allow prediction of the final quality from a knowledge of the pre-cure state of a composite lay-up. However, current post-process NDT techniques are generally inapplicable to an uncured composite, which has to be treated very carefully and without contaminating any composite surfaces. Current work is focusing on a combination of image analysis and surface metrology to verify fibre direction during draping processes, the absence of wrinkling or bridging and correct locations of ply drops. Unfortunately, the often sticky and matt-black materials are not ideal for image analysis or surface metrology, so this is a challenging arena. Whatever IPI is eventually used, its ease of integration into the production flow is a key determinant of the plant efficiency and how costs build up through manufacturing. Integration must be seamless 'with the grain of manufacture', without causing significant delays in the manufacturing process.

Breakout session report

The overall challenge of the breakout session was to 'identify opportunities for benefit from new NDT or SHM'. Five breakout groups were each asked to consider two different lifecycle stages, chosen from: design, qualification, certification, production and in-service. They all considered the following potential benefit areas: conventional pre-pregs, dry-fibre preforms (RTM, RFI, etc), sandwich structures (to replace laminates where possible), new materials, adhesive joints (to remove the need for fasteners and allow co-bonding), SMART (joined-up) engineering, manufacturing cost and throughput, process control and yield, and better-informed concession/repair decisions at manufacture and in-service.

Design and qualification

The breakout group discussing design and qualification flagged a use for NDT in determining material properties, such as lay-up and cure state, and mechanical properties, such as strength, with the aim of understanding material variability and determining defect criticality at the design stage. Determining strength or other properties without failing the structure is important, not just for composite materials but also for additive layer manufacturing and adhesive-bonded joints. The group raised the issue of potential global defects, such as incomplete cure, pre-preg life or environmental degradation. For inspection during manufacture there is potential for improved process control, including during a repair process, to verify lay-up, correct cure temperature, etc. Finally, the group highlighted the many areas of complex geometry where inspection is still a problem.

Qualification and certification

The breakout group discussing qualification and certification explained that the context of NDT is crucial – the significance of a defect depends on its scale relative to the size and purpose of the structure it is in. Therefore, the benefit of an improvement in defect sensitivity also depends on the context. During processes and in relation to process control, improved NDT capability and information could be put into 'effects of defect' calculations to improve material strength models. The group also recognised the benefit of being able to determine the strength of adhesive joints non-destructively. On production, improved defect sensitivity would be a benefit, but we cannot 'inspect quality into a product' so the aim would be to use NDT within the process-control feedback loop.

In-service and certification

The breakout group discussing in-service and certification started on improving NDT outcomes, particularly in terms of training. Some NDT, such as visual inspection and tap testing, is very subjective – how can judgement be tested? Emphasis is still on metal inspection, resulting in a gap in training for composites inspection. There is a challenge in managing the training burden through the lifecycle of the aircraft. Some guidance was given to academics and technology developers: the implementation of emerging techniques should not just look at the physics of the method but should consider the end-to-end process, including how it will be certified, training, challenges for its use, etc. There is increasing evidence of technology gaps, for example in additive manufacturing processes. Another example is the detection of kissing disbonds in adhesive joints, where the issue is one of controlling the production process better. Often, development of the process is ahead of the NDT development. What are the certifiable steps in the process? Structural health monitoring (SHM) was discussed in terms of SHM-enabled design, such as by linking SHM to substantiation of bonded structures.

There was an acknowledgement of the importance of including all communities (for example design, production, inspection and continued airworthiness) in these discussions and learning, for example, from the lessons of previous failures of structures. Where have these failings occurred, how did the problem arise and what were the contributing issues?

Design and production

The breakout group discussing design and production felt that this should be a single requirement category, because both desire zero defects in a manufactured structure. A feature is only a defect if it has a greater effect on the performance of the part than the design criterion. The methodology should be able to link NDT, design and residual strength to features at manufacture. We are looking for more collaboration between design and production functions, potentially embedding inspection into a proper process failure mode effects analysis (PFMEA) that controls and describes the process parameters and capability.

Production and in-service

The breakout group discussing production and in-service opportunities for NDT talked about in-line inspection, which would enable the detection of problems higher up the manufacturing chain, before too much value has been added into the component. Automation of NDT and of composite repairs is relevant to both production and in-service supportability and this led to a discussion on reducing the human element in an inspection. The group proposed that NDT is actually a good link between design and production because, during development of the manufacturing process, NDT can evaluate the capability of the process for consistently producing a reliable product. Characterisation of material properties for new manufacturing, for example measurement of waviness and wrinkling, should be advantageous, but these have to be both rate- and cost-effective. SHM has opportunities within in-service maintenance and repair. It is desirable to have better, faster approval processes for demonstrating the reliability of new NDT methods, in order to reduce the burden of introducing novel techniques. There is also an opportunity for NDT to make a significant difference in adhesive joint usage for primary structure.

Panel discussion report

The panel for the subsequent discussions comprised Dr Tim Barden (Rolls-Royce), Dr Martin Gaitonde (Airbus), Professor Phil Irving, (CAA Chair in Damage Tolerance), Dr Simon Waite (EASA), Dr Barbara Gordon (University of Bristol and ex-BAE Systems) and Professor Kevin Potter (University of Bristol). Taking the 'opportunities' from the talks and the breakout groups, the panel were asked to consider three questions:

- What will provide most benefit?
- What is the highest priority?
- What does success look like in each of the areas proposed?

What will provide the most benefit?

There are concerns about knowing whether defects matter; a lot of defects are actually concessed (allowed to remain in the unrepaired structure). Many of the global acceptance criteria were determined over 30 years ago and those methods have now been superseded. Knowledge was limited then, but the acceptance limits were cast in stone. Structural engineers are naturally conservative and people are reluctant to change. Could they relax some acceptance criteria based on location on the aircraft, for example? Sometimes it is worth NDT engineers challenging this, but zone-based acceptance criteria and concession decisions ultimately rely on better modelling. Even in the absence of a model, sufficient test data may sometimes already exist, depending on the location and defect type. Many structures are much more capable than expected and many concessions are allowed for defects at manufacture and in-service, but these are not captured in quality standards, they are on a case-by-case basis. The significance of a given defect size will increase as the thickness reduces, so any route to a lighter structure will rely on increased stress analysis to maintain safety levels. However, it is not clear that we are able to design composite aircraft according to composite experience and composite safety levels; we are still applying metallic experience.

At present, the design criterion is that defects should not grow under fatigue. Suppose it were possible to produce a material or structure where slow growth is possible, giving time for defect detection – would it help? Yes, but not if we lose the other benefits of composites. We need more predictable damage growth characteristics. The EPSRC programme grant 'High-Performance Ductile Composite Technology (HiPerDuCT)' at the University of Bristol is aimed at achieving a paradigm shift, by realising a new generation of high-performance composites that overcome the key limitation of conventional composites: their inherent lack of ductility. They will have the ability to fail gradually, undergoing large deformations whilst still carrying load, but it is still very early days. There will be hierarchical levels within the laminate plies. With this kind of ability to manipulate material properties, as with additive manufacturing, we need to think ahead to inspectability and monitoring of the structure. Also, there is a danger that we manipulate composite materials to behave like metals because our current design rules are based on metallic behaviour; should we modify the design rules to suit composites instead?

What is the highest priority?

The panel members were asked where the priorities lie. The regulators' driver is that safety is the top priority – whatever we do, we must not reduce the level of safety – but measuring and ensuring that is difficult. It comes down to forensics to determine the causes of failures and ensuring that we are asking the right questions and solving the right problems. This requires an understanding of failure modes and how NDT is related to design, so that we are clear about the relevance of what we are measuring and detecting. Particularly in composites, we need to be sure we are detecting the right kind of defect or failure mode.

It was pointed out that within the list of opportunities for NDT, some are more important than others because they could threaten the long-term safety of an aircraft and are currently only poorly understood, whilst others may be 'nice to have' but are less critical. When assessing priorities in NDT, one strategy used in industry is based on cost/productivity, sensitivity and reliability.

Commercial opportunities for NDT benefit exist in production and operation: can better NDT reduce production costs and operational costs? For example, there is a danger that components are scrapped unnecessarily; do false-positive indications figure in the assessment of NDT? It was acknowledged that NDT technique validation should always include an assessment of the probability of false positives (PFP) as well as the probability of detection (POD). An example was given of failures at the final NDT stage being mainly known about during the production process. The process could capture such failures prior to NDT if the control systems are in place and then the inspection of every component may be unnecessary.

What does success look like in each of the areas proposed?

When the panel discussed success criteria, a productivity increase in rate and a reduction in cost was proposed. A target of 10 times faster production was suggested, which would require a very high yield – 100% 'right first time' – so that NDT is not required on all components. NDT needs to be fast, even on more complex geometries, where NDT is difficult.

Integrated SHM offers a benefit for finding the location of a defect on a large structure where NDT is expensive. Inspection intervals can be very short. When we are not sure about failure modes or degradation with age, we tend to over-design. We could use SHM as an integral part of the lifecycle.

NDT could become part of the design process to take out time and cost. It can tell us when defects appear in the production process. For example, X-ray CT can show when the in-process state has changed. It could help reduce the amount of mechanical testing within the test/analysis pyramid for composite components (Figure 2), particularly by improved characterisation for larger components at the top of the pyramid, but also for linking the different levels of the pyramid by using NDT to prove that the properties of larger components match those of the smaller coupons. In this way, time can be taken out of the design process and thus reduce the time to the first flight. The final point was a reiteration of the need to understand the loads in order to direct the NDT requirements.

Adhesive-bonded joint inspection

Introduction – Successful NDT of adhesive joints?

Professor Robert Smith, University of Bristol

Professor Robert Smith introduced a session dedicated to determining 'what adhesive-bonded joint NDT success looks like'. For decades, we have heard that NDT is not delivering the required confidence in adhesive bonding and that the 'Holy Grail' of NDT is to detect kissing disbonds. Several phases of research funding have not solved the problem, although emerging methods may have, but how would we know when we have not defined success? A significant question is whether we need to actually measure and map bond strength or is it sufficient to provide confidence that there is no evidence of any kissing disbonds? Or would an ultrasonic 'proof-test' be adequate, as proposed by some in the USA at present? And finally, what do we need to do or prove in order to satisfy regulators that adhesive joints and co-bonds are safe without secondary fasteners?

The kissing disbond – avoidance and detection

Jeff Kapp, 3M

Mr Jeff Kapp, from 3M, gave a useful presentation, entitled: 'The kissing disbond – avoidance and detection', which challenged us to question what a kissing disbond actually is and how NDT can play a role in ensuring it never occurs. He defined a kissing disbond as an adhesive joint with dramatically lower than expected strength, where cohesive (adhesive-layer) mechanical properties are retained and there is no volume of air in the disbond, *ie* 'the bond looks OK but does not meet our expected performance requirements'. In terms of aerospace risk, he described this as 'a reduction in the load-carrying capability of the joint, sufficient to cause unexpected or unpredicted failure, without any prior indication of there being a problem'. Mr Kapp noted that these definitions were receiving nods of approval from the audience. He had concluded that, unlike other defects such as volumetric disbonds or porosity or cracking in the adhesive, current NDT techniques do not at present provide sufficient assurance demanded by aerospace engineers of the absence of such a kissing disbond and this limitation is one of the factors preventing widespread use of adhesive-bonded joints for joining aerospace composites. An interesting proposal was the use of the risk priority number (RPN), a numeric parameter used in failure modes and effects analysis science for assessing the risk assigned to a process, or steps in a process, based on the likelihood of occurrence, the likelihood of detection and the severity of the defect on performance:

$$RPN = \frac{Likelihood\ of\ occurrence}{Likelihood\ of\ detection} \cdot Severity\ of\ the\ defect$$

Thus, if a kissing disbond has a severe impact on the strength and the likelihood of detection of the kissing disbond is very low, the RPN is extremely large and it becomes a critical defect, which leads to the requirement for limit-load protection fasteners and a non-optimum joint. In discussing potential definitions of kissing disbonds, he summarised these by saying that a 'practical' view is that the kissing disbond is a failure of the adhesive to form a structural connection with the adherend. As an adhesives engineer, he would say that 'this defect should rarely, if ever, occur with a correctly specified adhesive system'. It could, therefore, be considered a theoretical defect, but even theoretical defects need to be addressed and minimised if it concerns the end-user and hence influences design. In considering the theoretical risk, it was proposed that there are two broad areas that need to be considered: surface incompatibility and gross contamination of the bond-line. Much of this can be addressed at the design stage, but it will also be necessary to prove robustness to potential variation and/or deviation with the process. NDT methods will have a role to play in both demonstrating robustness and increasing the probability of defect detection.

As an initial action, it is necessary to create test samples reliably containing kissing disbonds. Adhesive manufacturers have an understanding of how to produce defects because this is a fundamental part of avoiding them. A programme at the NCC has created some reference defect artefacts (RDAs) and these are currently being mechanically tested, along with similar specimens with disbonds created using a different contamination process at the National Physical Laboratory (NPL).

Assessment and criticality of defects and damage in adhesively-bonded composite structures

Dr Bill Broughton, NPL

Dr Bill Broughton presented on behalf of the National Physical Laboratory (NPL). Currently, there is a shortage of design methodologies, reliable NDE techniques and useable data for assessing defect criticality and damage in adhesively-bonded composites, as well as metallic structures/systems. This includes both bonded laminated systems and sandwich constructions. Acceptance of adhesive bonding for safety-critical loading in aerospace applications is dependent on a determination of the presence, identity, location, size and morphology of defects and their effect on the strength, stiffness and life-expectancy of the structural components. Defects may arise in manufacturing, processing and machining operations, as well as from in-service damage. There is a requirement for *in-situ* real-time SHM techniques, supported by an infrastructure of NDE techniques, for accurate and reliable monitoring and quantification of deformation and damage. The drivers are the improved probability of detection (POD) of safety-critical defects and remanant life determination of bonded composite and hybrid engineering structures for in-service performance assessment. Improved predictive modelling of failure mechanisms (*ie* damage initiation and growth) under complex loading conditions (including static, cyclic fatigue and hostile environments) is reliant on accurate and traceable standardised NDE techniques. These will depend on methods for simulating safety-critical defects in reference defect artefacts (RDAs). As well as the defects encountered within the composite adherends, additional defects need consideration in adhesively-bonded composite structures, such as kissing disbonds, partial or localised cure of the adhesive, non-uniform adhesive distribution, thermally-induced cracking in the adhesive due to a thermal expansion mismatch between adherends and adhesive, sandwich skin-to-core debonds and crushed-core damage, etc. These defects have a pronounced effect when located at the bond ends – a region of high peel and shear stresses. Current NDE techniques struggle to detect many of these defects in bonded composite structures. The National Physical Laboratory (NPL) has been actively involved in an ESA-funded collaborative research project with partners Psi-tran Ltd and Theta Technologies, focused on developing non-linear elastic wave spectroscopy (NEWS) as a possible alternative method to conventional NDE techniques, such as ultrasonic C-scan, active thermography and X-radiography, for detecting defects/damage (including kissing disbonds) in these structures. In addition, NPL has been involved in a European Metrology Research Programme (EMRP) – EURAMET/NMS funded project EMRP JRP ENG57 'Validated Inspection Techniques for Composites in Energy Applications (VITCEA)' – with the objectives of practical application and experimental optimisation of scanning techniques (*ie* phased array and air-coupled ultrasonics, and microwave), full-field techniques (*ie* active thermography and laser shearography) and simulation/modelling capability development (excluding shearography). This project, involving other national measurement institutes (BAM, PTB, CMI and CEA) and a wide range of industrial, standards and academic organisations and institutions, includes the design, manufacture and characterisation of RDAs and natural defect artefacts (NDAs), and inter-comparison exercises and field trials with the final aim of producing written inspection procedures.

Analysis of kissing disbonds in metallic joints

Professor Felicity Guild, Imperial College London

Professor Felicity Guild, from Imperial College London, gave a presentation entitled: 'Analysis of kissing disbonds in metallic joints', based on work carried out at Queen Mary University of London. This presentation included both experimental results and finite element simulations of double-lap joints containing kissing bonds. The kissing bonds were prepared using surface contamination and ElectRelease™ adhesive. The contaminants used were PTFE film and spray, Frekote mould release, sweat and cutting oil lubricant, covering 25% of the bond area. Examination of the cross-section of the joints using scanning electron microscopy revealed that the PTFE spray, sweat and cutting oil all penetrated the adhesive, while the Frekote remained at the interface. These observations were confirmed by the strength results, which showed identically reduced values for the Frekote and PTFE film. The three-dimensional finite element models used uncoupled surfaces for the contaminant and cohesive elements for the adhered surfaces. The properties of the cohesive elements were measured independently using fixed arm peel tests (Mode I) and four-point bend end notch flexure tests (Mode II); the values gained from these tests were used for the cohesive properties. Very good agreement was found between the experimental and predicted strength values for the control and contaminated joints. Good agreement was also found between the experimental and predicted values of strain, both local values at the joint and more global values across the joint. The finite element strain results were then examined along an axial profile across the whole joint; both axial (applied) and lateral (Poisson's ratio contractions) were extracted. Significant differences between the profiles of the control and contaminated joints were found for the lateral strains. Professor Guild postulated that monitoring of lateral strain may form the basis of a future detection method for kissing joints. Such strain differences could also be detectable using digital image correlation (DIC).

Bonded joints in military composite aircraft

Dr Barbara Gordon, University of Bristol

Dr Barbara Gordon explained that bonded joints have been used successfully within military aircraft since the mid 1980s. However, the next generation of aircraft offers a different set of challenges to those currently in-service, many of which were part of large multinational projects with long, expensive development programmes and large production runs (1000+ aircraft). Future aircraft programmes will involve small batch numbers (for example 30-off), with multiple customers each requiring their own configuration. Development times must be short and costs low. This requires a completely different approach to the design and manufacture of the aircraft. Historically, the use of bonded joints has required complex, expensive tooling to achieve the required level of dimensional control and produce good quality bonding, using thin-film adhesives. The introduction of high-strength paste adhesives offers the potential for gap-filling capability, giving design flexibility and allowing the use of cheap tooling and methods for bonded structures. However, this involves the use of secondary bonding of pre-cured structures, with all the inherent problems of surface cleaning, potential contamination and determining the integrity of the bondline. Methodologies are being developed involving automated cleaning and surface inspection prior to bonding. After bonding, technologies are then required to inspect the bond, whether by advanced NDT and/or SHM. Paste adhesives are subject to more porosity/voids than film adhesives, limiting the ability of NDT, and the thicker bondlines are more liable to crack. However, the biggest issues remain associated with the surface, where there can be low-strength bonds or kissing bonds (zero volume disbonds), as well as more conventional disbonds. Because of this, proof loading is currently required to guarantee the integrity of the structure, with all its inherent problems/costs. The industry therefore requires new NDT techniques that can address these issues.

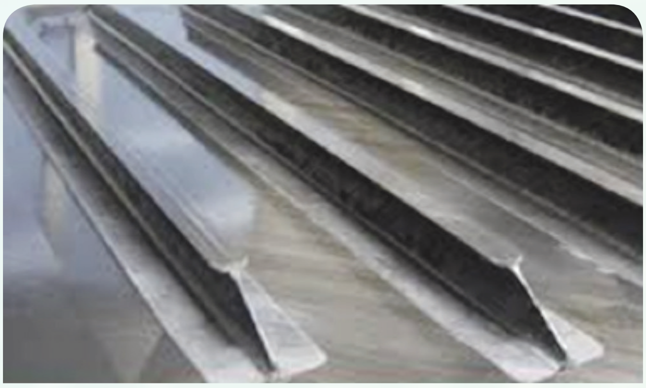


Figure 5. Typical I-section bonded stringers on a composite panel

Panel discussion report

The panel for the subsequent discussions comprised Dr Tim Barden (Rolls-Royce), Dr Simon Waite (EASA), Dr Bill Broughton (NPL), Jeff Kapp (3M), Professor Felicity Guild (Imperial College) and Dr Barbara Gordon (University of Bristol). We are seeing an upsurge in funding for NDT of adhesive joints, but how will we know when we have succeeded? The questions posed to the panel were:

- On which failure mechanism(s) should we focus?
- What do we need to achieve in order to demonstrate that adhesive-bonded joints (ABJ) are acceptable and remove the need for back-up features (for example rivets) to carry limit load?
- Should we be trying to: (a) measure a strength-related parameter; or (b) find defects?

On which failure mechanism(s) should we focus?

The panel was clear that the kissing disbond is the front-runner requiring an NDT solution and discussions ranged around specimens and potential NDT methods. NCC-manufactured kissing-bond 'DCB' specimens are being tested at NPL to determine knock-down in strength and measure the energy loss across the fracture plane, but there is a potential large scatter in fracture toughness due to mixed failure modes. Other panels are being manufactured with the same geometry but using a different contaminant to create the weak adhesion, based on some trials at NPL.

There followed a discussion about an NDT solution for kissing disbonds proposed in the USA: the local proof-test LAser Shock-wave Adhesion Test (LASAT)[1-3]. This uses a high-power laser pulse to generate a really intense plasma, which results in a compressive pressure load on the material, leading to a shock wave formation. A tensile pressure is also generated and this can open up a weak bond. It can also cause delaminations in otherwise good composite if the laser power is too high, so the laser parameters have to be tuned to prevent damage to the composite adherends[4] and to ensure that only very weak bonds are actually proof-loaded and opened, while good bonds remain intact. The discussion was around whether local proof-loading would be an acceptable penalty for the detection of kissing disbonds. A parallel was drawn to non-linear methods and vibro-thermography, which also stress the joint with high-amplitude ultrasound. If this test does locally open up a joint that may have had 10% strength, is that a problem? It would make this a semi-destructive technique. There is a danger that defects could be created where there were none before and a limit would have to be controllable on the strength of joint that could be opened. Other proposed methods use much lower loads, but stress will need to be applied in some way to see the difference between a kissing disbond and a good bond. If this LASAT method could be applied and makes a kissing disbond detectable, then measurements could be made to create a model that could determine strength without having to apply a proof stress.

The lateral strain measurement idea, which had been presented by Professor Guild, was discussed in terms of whether strain could be imaged perpendicular to the load direction, for example digital image correlation (DIC) under a shear load. How could we measure strain in other ways? Linked to the through-life requirement, sensors embedded in a bond could measure strain actually in the bond. The problem is that a sensor is effectively a defect in the bondline, so it is a trade-off. It was noted that Raman spectroscopy works well for CFRP.

There was a subsequent conversation regarding sandwich structures. Problems with understanding failure modes and linking with detection and characterisation of different defect types, have led to a move to monolithic structures, but solving these problems could lead to a renewed usage of sandwich structures.

What do we need to achieve in order to demonstrate adhesive-bonded joints (ABJ) are acceptable and remove the need for back-up features (for example rivets) to carry limit load?

The discussion revolved around the importance of process verification for manufacture of bonded components; ideally, NDT would not be required to inspect every adhesive joint (although it is at present), but it could be instrumental in proving that an adhesive-bonding production process consistently produces high-strength bonds. Fundamental to this is the importance of maintaining a controlled environment when bonding, both at manufacture and for in-service repair, and quantifying that environment so that it can be reproduced. Back-up limit-load features are only required because of the uncertainty in the process.

Another line of discussion was around the potential for getting smarter with bonded areas by, for example, designing-in crack growth arresters. Is a continuous adhesive area the best way to go, or is it best to have crack-arrester regions or other geometrical methods for stopping cracks? These have similar benefits to back-up features such as rivets, but they do not necessarily have the weight penalty. The design must be demonstrated to carry limit load.

In-service inspection of bonded joints is the most challenging scenario. If a bonded area is large, then finding a defective area is the first problem. However, bonded repairs are known locations and they require verification that they can carry limit load. Monitoring with SHM sensors could prove useful here. This raised the question of whether monitoring could be by a surface-strain measurement under loading; Professor Guild had just presented results showing that lateral strain, perpendicular to the load due to Poisson's ratio, is different for a weak bond. Could this lend itself to SHM, for example fibre-optic continuous strain measurement? This again would be best for a repaired structure rather than the baseline as-manufactured structure.

3D characterisation of composite material properties

This session was focused on full 3D mapping of composite material properties with application to as-manufactured components or test coupons. This included the potential for NDT-based performance modelling to determine residual strength and the use of finite element analysis modelling to determine which metrics about materials and their defects are most important for NDT to measure.

NDT requirements, or what is needed to define them?

Professor Robert Smith, University of Bristol

Professor Robert Smith introduced the session by giving examples of specific requirements for NDT that would be useful for researchers and developers of new 3D characterisation technologies in the areas of fibre wrinkles, porosity and impact damage:

- Which metrics (for example angle, volume, shape)?
- With what accuracy (for example +/– 1 degree)?
- With what 3D spatial resolution (for example a scan pitch of 0.5 mm)?
- How fast (for example process whole wing spar in 24 hours)?
- On what components (curvature, thickness, etc)?
- Under what constraints (without removing paint, in the dark, on the ramp, from the external surfaces only, etc)?
- At what stage in the lifecycle (maintenance intervals, between flights, at manufacture, on repairs, etc)?
- Is there a need to feed NDT data directly into FE models (for example only at design stage, at manufacture or in-service)?

Current status of modelling of defects and failure in composites

Professor Stephen Hallett, University of Bristol

Professor Stephen Hallett proposed that, as the modelling capability for composite structures advances, so there is an increased drive to include more numerical simulation as part of component certification. A risk in using data from small-scale coupons for structural scale simulations is that the as-manufactured condition of the material may not be captured. Additional empirical knock-down factors thus need to be included, potentially leading to less efficient designs and significant testing still being required. Hi-fidelity finite element analysis is now well developed and is capable of being used as a virtual test to replace physical experimentation for understanding of the effect of defects on mechanical performance. This talk presented a range of case studies in which state-of-the-art modelling techniques have been used to predict the failure resulting from defects, such as wrinkles, automated fibre placement (AFP) gaps and overlaps, embedded delaminations and low-velocity impact.

Current 3D characterisation and the importance of metrics

Professor Robert Smith, University of Bristol

Professor Robert Smith then presented on 'Current 3D characterisation and the importance of metrics'. His team is developing methods for inverting the ultrasonic response of a composite laminate to measure and map in 3D various material properties, such as the 3D orientation of fibre tows, local % porosity, ply-drop locations and delaminations from impact damage. In this way, serious defects, such as out-of-plane ply wrinkling, can be detected, mapped and quantified in a way that will allow better-informed concession decisions at manufacture, in-service and prior to repair. The technique uses the ultrasonic analytic signal response of the laminate, which has been shown to contain amplitude, phase and instantaneous frequency information that is clearly well 'locked' to the plies in the structure[1]. Ply drops show characteristic changes in these parameters, enabling them to be mapped through the structure (see Figure 6). Similarly, out-of-plane wrinkles can be tracked and the angle of the ply measured at each location[6]. Delaminations can be distinguished from resin layers between plies and from 'multiples' of the delamination signal. Professor Smith then showed how the inverted maps of material properties can be used to create finite element models in order to determine residual strength. These models can also be used to determine which metrics are most indicative of residual strength. Miss Ningbo Xie, Professor Smith's PhD student, had exercised the model to determine that the maximum ply angle is the key metric for a given volume of wrinkled composite. For a particular maximum wrinkle angle, the strength depends on the size of the affected volume. The knock-down in strength is greater for a larger cross-sectional area (perpendicular to the load direction) and for a smaller wrinkled region in the load direction, due to an increased stress concentration. This information has not been published previously.

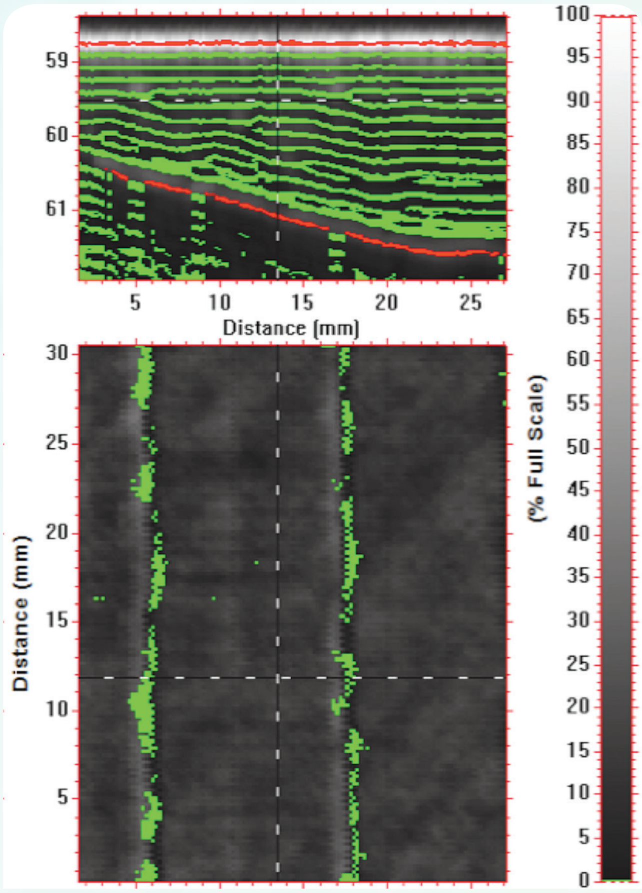


Figure 6. Ultrasonic analytic signal imaging for a wedge specimen containing ply drops. B-scan slice at 11.8 mm (top) and C-scan slice at depth 0.8 mm (bottom). The greyscale represents instantaneous amplitude and the superimposed red lines are the front and back surfaces, whilst the green lines are the resin layers between plies, all determined automatically from the ultrasonic full-waveform data[5]

Breakout session report

Characterising manufacturing defects

This breakout group started by discussing the required resolution. One ply in depth resolution would be desirable, but speed of inspection is probably more important than ultimate accuracy. There is an issue of what will be done with the data of any higher resolution. Questions were raised around the definition of acceptance criteria and specification of OEM requirements for suppliers. For example, if we can make a per-ply porosity measurement but only have a through-thickness average porosity criterion, then we have a mismatch. An evolution of the whole system is needed to account for the fidelity of data before that data becomes useful. In terms of wrinkles, sub-laminate fidelity is required – a measure of the percentage of plies that are wrinkled and distinguishing between this and multiple wrinkles.

Regarding the link between FE models and concessions, there is a relationship between part value, the value in doing NDT and the time it takes. For low-value, high-volume parts it is possible to build a good database of knowledge based on affordable tests of lots of components, so FE modelling is less valuable because a good track record has been established. But for high-value, low-volume parts, there is more benefit in using FE modelling because there is a smaller historical database of defect characterisation and few full parts are tested. Such parts can also stand a longer timescale for defect concessions. So, we can use FE to build a database or for concessions on a part-by-part basis. This raises the question: what level of fidelity is required to resolve a concession?

Maximising long-term availability

This group started by discussing 3D modelling of the NDT process. If we could model ultrasound and better understand the inspection, then we can use this to validate NDT techniques. In terms of the sensitivity required for 3D characterisation, this needs a good understanding of the use of the data.

What information is required from NDT and what do we need to do to be able to use the output of NDT? For this we need a good understanding of the behaviour of composites under load and of the failure modes. If we could do this then it might improve aircraft/engine availability, because we could measure damage, fly on and schedule corrective action later, resulting in better fleet management.

Training of NDT inspectors will also be important when moving to a defect measurement-based maintenance regime as opposed to a testing regime.

More efficient civil designs

This breakout group focused on future high production-rate single-aisle aircraft, where there will be a need for rapid concession decisions on the shop floor. Whatever the outputs of our advanced NDT methods, they should be interpretable by non-expert decision makers, so must contain exactly the form of information required. Such information also underpins automation in the production process. High throughput and high profit will be very important, so stockpiles of components awaiting repair must be avoided. This needs a more systems-engineering approach with the production-process engineers working closely with NDT engineers. The functional requirements in the process should be established first and this leads to more realistic NDT requirements. Regarding NDT resolution, a low resolution obtained rapidly may be more appropriate than a high resolution obtained slowly, so NDT outputs should be 'adequately accurate'. It may be impossible to give generic requirements for NDT at the early design stage so the multi-functional team is crucial.

Realistic NDT capability at manufacture

It was suggested that many commercial ultrasonic systems used for routine NDT of composites are still not capable of capturing full-waveform (3D) data. *[This was disputed during the de-brief – many phased array and automated systems are capable of full-waveform capture, which is a requirement for the scanning of much of the composite structure on Boeing 787s]*. There would be a cost associated with updating hardware, which would still need to be able to do the routine NDT. Full matrix capture (FMC) may help to fulfil the requirements for 3D data capture (although FMC is not a requirement). As most ultrasonic instruments already digitise the waveform and a software upgrade would be more economical, it is important to engage with manufacturers to enable storage of full-waveform data and reading of file formats. Other methods are used in production, such as single through-transmission ultrasound scanning, which are not capable of providing 3D information. And others, such as laser shearography, may measure parameters that are more directly related to models, such as strain.

More physical data is needed for validating NDT-based material models. There may be such data locked away in companies but it will be proprietary and specific. 3D properties in thermoplastic materials would be of interest and 3D NDT would be useful at the start of the process of using a new material. Optical fibres and other SHM sensors in composites were discussed and there is still concern over their structural effects.

The military design picture

An obvious issue for the military is whether 3D characterisation can be (or needs to be) carried out in all environments, such as in-theatre to determine whether a battlefield repair is required. Speed requirements depend on the environment; sometimes slow analysis is fine, such as in production, though in-theatre the NDT needs to be fast. So, the questions are: can the data capture be fast enough and would the interpretation be carried out on-site or would it need to be carried out remotely (which would involve data communication issues)? An FE model for the entire aircraft would be great (the aircraft are small). Models of entire aircraft are currently too coarse, but the boundary conditions from these are already used to generate finer models of particular components, or even finer detailed models of features on components in a multi-scale methodology (see Figure 7). The challenge is to get the NDT output to be communicated to these models.

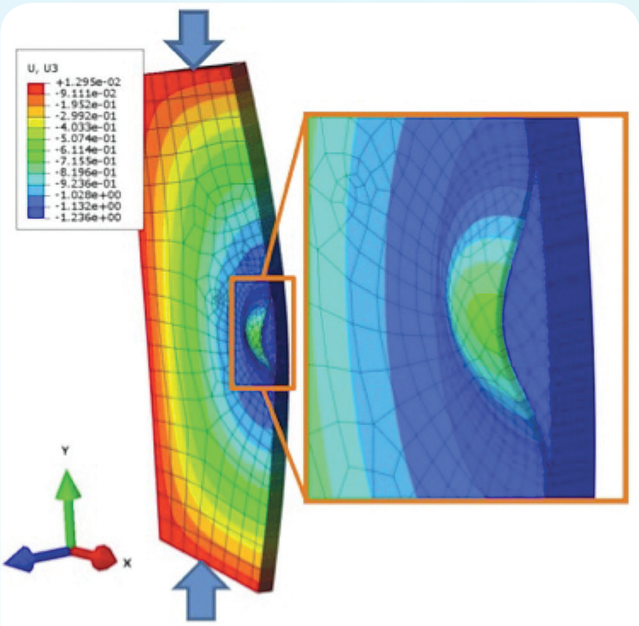


Figure 7. Example of an FE model of a particular feature on a component, used to determine stresses and displacements under load *Image courtesy of BAE Systems*

Currently, we inspect a part to pass or fail a criterion, but in the future we may need to carry out NDT in order to generate a dataset that will then be used to populate an FE model. The question is whether we can scale up from laboratory test conditions to non-ideal inspection scenarios, in-theatre, with complex shapes, tight curvatures, etc. Regarding the resolution requirement, the group could not imagine needing sub-ply resolution in the near future.

Panel discussion report

The panel comprised Professor Robert Smith (University of Bristol), Professor Stephen Hallett (University of Bristol), Dr Barbara Gordon (University of Bristol), Professor Ian Lane (Airbus) and Dr Richard Freemantle (Wavelength NDT). The questions presented to the panel for discussion were:

- What range of material properties will cover all possible failure mechanisms?
- What does 3D non-destructive characterisation success look like?
- Is 'better-informed concessions' a suitable target for early adoption?

What range of material properties will cover all possible failure mechanisms?

Certification by 'analysis supported by test' is allowed, but there is concern about understanding the pyramid (Figure 2) integration, boundaries between test and analysis and between development and certification. Could the future be certification by analysis only? Simulations can now create virtual test models with low- and high-resolution sections where any number of load cases can be tested. All future aircraft will have a non-linear model of that complexity. Failure modes can be built-in but are still conservative and testing is still required to determine the relevant failure modes to model in each location. Thus, most test work is mid-pyramid in order to determine failure modes. NDT detectability constraints and requirements could be part of this modelling work; the structure could be tuned so that it can be inspected and interpreted quickly. High production throughputs of high-value components means no scrapping and ideally every feature needs to be able to be concessed. This is possible because the ability to withstand large amounts of damage has to be built into the structure. Process control by NDT is also important.

If analysis of NDE data and integration into models were quick enough, then consideration of concessions against design intent could be conducted. But the missing link is knowing what the residual life of the part is: the prognostics. The regulators apply a no-growth requirement and that is sufficient. Any bonded component has to have limit-load back-up features in case the bond fails.

What does 3D non-destructive characterisation success look like?

Progression of NDT methods up the test/analysis pyramid can be quite difficult – unknown or unpredicted problems affect the rate at which this could be achieved. Programme timescales limit what can be implemented and it is difficult to keep ahead of the development and production rate. We need to predict all possible failure modes and defect types early on in the NDT development cycle. We do not need to go all the way to NDT-based modelling before 3D characterisation becomes useful; simple tools giving some 3D capability would lessen the burden on NDT operators and be a big step forward for manufacturing, helping to communicate data through to stress engineers and provide quicker answers for concession decisions.

There is a risk in showing up features where a need has not been defined; a part may have passed all certification requirements and a new NDT method providing more data, where interpretation of the significance of the data could be difficult, causes problems. If new features are discovered that we have lived with before, what do we do with that information? Those features could be the cause of some unexplained variability that we have never understood in the past but have had to live with. From an academic viewpoint, in order to apply new NDT effectively, the whole system needs to be aligned to needing that data. For example: mechanical tests have shown that wrinkles in composites are an issue where more NDT information is required; we have demonstrated that we can measure relevant parameters about wrinkles; we have now modelled wrinkled structures based on NDT measurements; and, finally, we have used the models to prove which are the significant parameters about a wrinkle to measure and to place acceptance criteria on. This is an example where mechanical test data exists that can be used to validate future automated NDT methods.

An anomaly discovered might not be a defect in the current design but could be in a future design, so we need to understand the effect of discovered features on the properties of the component. We need to feed that back into the design process. More information is always coming into the design process, but it is a large task to understand that data and reach conclusions. It takes time and effort to analyse data and reconcile how it affects design strategies and, if this does not add knowledge, then it might not be worth doing. Having the right information is more important.

Current defect testing is conservative and a lot of impact damage may well be insignificant. Current designs can absorb a large amount of damage without it threatening the integrity of the aircraft due to multiple load paths and the design being limited by the need to withstand limit load after relatively large damage.

Improved inspection resolution may not be required *per se* in each component and the loading context of the feature is of great importance too. Also, the significance of defects can change over time; what is not significant at the moment could become significant in future designs as loading environments change. There is still a requirement for academia to improve defect detection and characterisation (and also to increase resolution) for future designs, because we will not get to the next generation of designs until we can understand the effects of small features on failure loads, etc. For example, triggers to failure modes derived from NDE could be used in virtual test platforms. We need to look for the non-intuitive design features and we need to integrate NDE into the design process rather than just the production process. The effects of defects need to be understood as composite aircraft are required to have an equivalent safety level to metallic aircraft, or better. The detail matters, but regulators are looking for consistent failure modes at a statistically credible level and robust design concepts so that the 'adequately accurate' level of NDT can be determined. Understanding the effect of defects is critical in getting the design right rather than later in the production process, so manufacturers want post-production NDT to be just a quality check, thus moving the benefit of 3D characterisation into the design stage rather than the production process.

Are 'better-informed concessions' a suitable target for early adoption?

One opinion was that the easiest way to introduce new NDT is with a new platform whilst developing new technologies – as part of the design pyramid (Figure 2). At this stage, we are mechanically testing designs with defects and features, carrying out modelling to understand the accuracy of solutions and building confidence. But going straight for better-informed concessions could require full confidence in the accuracy of the measurement technique. Regulators agree that, for new aircraft, starting to use new NDT during the development process is important, rather than leaving it to the certification stage. However, better-informed concessions would be an easy way to introduce and validate new NDT from a regulatory point of view, particularly by running the new path in parallel with the current airworthiness path. This would allow us to answer the questions:

- Is there something we are missing in the current process?
- Is there something which we missed but still is not important?
- Is the data we can generate required or not?

Structural health monitoring (SHM)

Introduction – Successful SHM for composites?

Professor Peter Foote, Cranfield University

The requirements of SHM for aerospace composites were discussed in a dedicated session. Professor Peter Foote (Cranfield University and Chair of BINDT's SHM Working Group) introduced the session and gave a presentation describing recent activities and developments regarding the implementation of SHM in commercial aviation. The issues surrounding the introduction of SHM into aircraft maintenance programmes are generic to both metallic and composite structural inspection tasks. Many of the technologies involved are capable of detecting defects in composites as well as cracks in metals using fixed and permanently-installed sensors.

A key remaining challenge for SHM is a demonstration of the reliability of these techniques to the same or equivalent standards as current NDT techniques. There are, however, key differences between NDT and SHM, such as the lack of human factors in the latter. NDT is a manual process and the viability of the techniques must account for the variability in human performance. Reliability assessment is based on the statistics of trials and uses probabilistic metrics. On the other hand, SHM systems could be configured to give simple, appropriate binary indicators of the presence of defects, sufficient to trigger maintenance actions. If SHM installations are characterised by the largest defect capable of being missed under all operating conditions (plus a suitable margin), then systems that give close to deterministic behaviour (*ie* equivalent probabilities of detection close to unity) are possible. A challenge for SHM technology providers was proposed to characterise their systems in this manner. The challenge for the maintainers is then how to use these SHM system capabilities to achieve maintenance credits and benefits. A recent and crucial operational installation of SHM (the first to be used in service) was also mentioned. This is the trial of SHM crack-gauge technology in the Delta Airlines fleet of ageing 737s. The SHM is being used instead of manual inspection called up in a Boeing Service Bulletin and is allowed because it is not a safety-related inspection. Use of SHM removes the need for expensive and time-consuming disassembly to allow access for manual inspection.

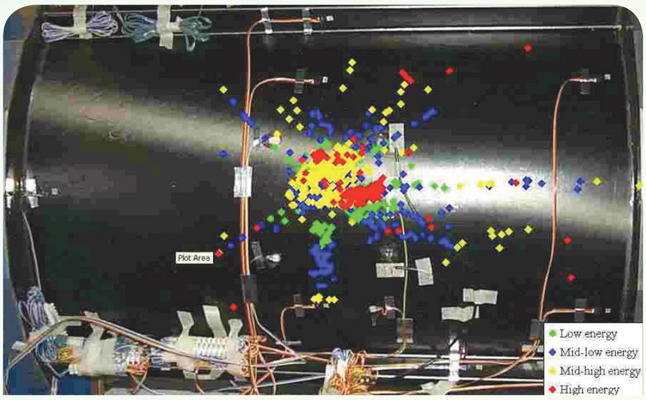


Figure 8. Individual acoustic emission sources for a carbon-fibre composite structure during compression after an impact causing barely visible impact damage (BVID)

Image courtesy of BAE Systems and QinetiQ Ltd

Certification requirements for SHM

Dr Hesham Azzam, HAHN Spring Ltd

Dr Hesham Azzam, of HAHN Spring Ltd, presented an overview of the regulatory and certification framework for military and commercial aircraft with which SHM must comply as an aircraft system and as a maintenance aid. The presentation reviewed the differences in design methodology for commercial and military aircraft and noted that, although military aircraft structures (at least in the UK) are designed to safe-life principles in contrast to damage-tolerant designs for commercial fleets, the routes to product development and insertion, including SHM technologies, are broadly similar in both cases from an airworthiness and certification perspective. As an aid to maintenance, SHM would still be required to undergo the same rigours of reliability assessment, verification and validation. The eventual specification for these systems would be driven by the intended function and operational requirements (for example as a substitute for an existing NDT task or an enabler for condition-based maintenance). Some key differences between military and commercial applications were, however, highlighted, especially regarding the intended function of SHM for new and emerging aircraft. The trend for military aircraft is increasingly towards unmanned (remotely-piloted and autonomous) vehicles. SHM could not only play a role in maintenance but, in complete contrast to NDT, could also form an integral part of mission systems. The new MASAAG Paper 123[7] on the implementation of SHM for military aircraft applications was also described in the talk.

Technique validation for SHM

Dr Matthieu Gresil, University of Manchester

Dr Matthieu Gresil, from the i-Composites Lab, School of Materials, University of Manchester, presented on 'Technique validation for structural health monitoring'. Advances in the development of fibre-reinforced polymer composites and their manufacturing techniques have led to the increased use of these materials in structural engineering applications. They offer corrosion resistance and high specific strength and stiffness, when compared to metallic materials. Anisotropy can provide weight reductions when carefully designed; however, there is uncertainty associated with understanding the consequences of damage in composites. Non-destructive evaluation techniques are adopted in many cases, but represent significant down-time and labour costs. The introduction of embedded structural health monitoring (SHM) systems has shown promise in improving the reliability and safety of composite materials, while reducing lifetime costs, informing the optimisation of design and manufacture processes. SHM is a process of diagnosis of the state of the constituent materials to predict the remaining life of the structure using permanently-attached sensors. This paper presented two different techniques that can be used in a complementary way to achieve more information on the state of the structure. A distributed optical fibre sensor is embedded through the thickness and along the length of a six-ply composite laminate during fabrication, such that there are three sensing regions near the top, middle and bottom surface of the laminate. The development of temperature and strain in the panel, in each of these regions, is monitored *in-situ* and in real-time during the resin infusion and curing processes. Data acquired from the embedded optical sensor led to tracking and characterising the strain profile at every stage of the manufacture process (vacuum bagging, infusion, curing and cooling). Moreover, the residual strain is slightly higher close to the edge of the structure. The recorded data reveals a correlation between the infusion strain and residual strain following manufacture[8].

It is a big challenge to relate acoustic emission (AE) signal events to specific damage modes developed in composites under hygro-thermo-mechanical loading. This study provides further insight into the AE monitoring of a 3D angle interlock (AI) glass fibre composite and has revealed the complex nature of the relationship between the principal characteristics of recorded AE events on the one hand and the mechanical behaviour of the material on the other. A transverse crack in the warp yarn was detected and quantified in a 3D AI woven glass composite plate during a tensile test using piezoelectric wafer active sensors bonded on the surface of the sample. Preliminary results show that the amplitude of the AE signal depends on the distance between the crack and the sensor (affected by damping). A complete study on the guided wave propagation and the attenuation effect has to be carried out in order to increase the accuracy of the results. Moreover, for this material the amplitude of the AE signal from this transverse crack is between 60 dB and 100 dB[9]. The frequency component with the highest amplitude is between 100 kHz to 200 kHz. Although some good progress has been demonstrated, there are still some outstanding questions that need to be answered. A complete experimental research programme and a finite element method need to be performed in order to better understand the damage evolution (that includes delamination and fibre breakage) and ultimate failure of these 3D AI glass composite plates. This paper concluded with some actual SHM implementation in aerospace and civil engineering. Finally, it needs to be emphasised that the SHM field has a lot of potential for composite materials in aerospace, energy and civil engineering.

Future military aircraft requirements for SHM

Steve Massam, BAE Systems

Steve Massam, from BAE Systems, presented on 'Future military aircraft requirements for SHM', where SHM is seen as part of the wider subject of integrated vehicle health management (IVHM). He highlighted the modelling, simulation and analysis that is carried out in systems health management and the benefits of using a similar approach for structural health monitoring (SHM). In terms of 10- to 15-year future requirements, few regulatory environment changes are anticipated at the higher levels.

For future unmanned air vehicles (UAVs), designs will be more customised, production runs smaller and service lives extended, with the majority of this time in storage. Timescales will be shorter and budgets lower. To achieve this, technology solutions from other domains will be used and test article requirements reduced. But overall, safety and compliance must be maintained, so simulation and modelling will become increasingly important in order to achieve this.

The biggest driver will be fleet maintenance management in UAVs around fatigue, corrosion and damage, although the detailed regulatory environment still remains to be defined. Access points into airframes are fewer, while aircraft will spend long periods in storage and skilled service personnel will be less available. All these combine to mean that conventional NDT will be harder to implement, so automation and robotics for inspection and maintenance will be increasingly important.

Events may occur during a mission, for example a birdstrike, which will require a sensory/SHM system to replace the pilot during the flight and potentially make decisions about the strategy for the rest of the flight. On-aircraft data processing has become more possible but also remote analysis is becoming increasingly attractive.

The move to UAVs will require a reduction in time-based inspections towards condition-based maintenance and require systems such as SHM to monitor the environment and integrity. The structure is part of a larger system and there will be more integration of management of the system as a whole. Technology needs to mature across a broad front to achieve this. A specific challenge for SHM is the connections between the sensors and to the data collectors within the aircraft.

Panel discussion report

The panel comprised Dr Hesham Azzam from HAHN Spring Ltd, Steve Massam from BAE Systems and Dr Matthieu Gresil from the University of Manchester and was chaired by Professor Peter Foote from Cranfield University. The title of the discussion was: 'What does SHM success look like?', but in the context of the meeting requirements. Other questions to be addressed were:

- What are the differences between NDT and SHM and how does this influence the meeting of requirements?
- What are the biggest hurdles to SHM implementation?
- What is the way forward?

What does SHM success look like?

The discussion began with a system viewpoint: SHM success is when an SHM system is in place that gives information in-service to effectively manage a platform throughout its life and feeds back information to designers about how the platform is used. Another view of success involved automation, lightweight sensors, better integration of sensors on the surface or embedded and that the durability of the whole system must be more than the life of the component. Technology developments in systems, processing and sensors will help SHM success.

What are the differences between NDT and SHM and how does this influence the meeting of requirements?

In NDT the sensor moves and measurements are occasional, so NDT looks for changes with position. In SHM the sensor does not move and measurements could be continuous, so SHM looks for changes with time. SHM can have variability in time to deal with, whilst NDT may not.

SHM automation may have less onerous validation than NDT if there are fewer variables in the inspection (but this will not necessarily be the case), because it would be less probabilistic and uncertainties should be smaller. Deterministic SHM would be ideal, but we need to understand uncertainty and the probabilistic approach.

What are the biggest hurdles?

The perceived implementation barriers to SHM are: weight, power, integration and cost. A crucial challenge is the speed at which information can be moved. Also, the choice of SHM has to last the life of the component, so it is difficult to get to a stage where this decision can be made confidently. Much work has been carried out on simple structures but very little on complex structures, such as military aircraft. What is the interaction of other components (structural or system) on the SHM system? A major challenge in the future will be that as soon as an airframe is in use, people will want to modify it. This is tricky with composites, but it will be even harder with SHM because the change to the structure could also change the interpretation and analysis of the SHM data.

Data storage is now only a challenge because there is too much data being stored; what is the SHM community required to do with it? The regulatory view is that an 'acceptable level of safety' is the bottom line. There is a level of defect that matters. Data is only useful if it can affect or change decision-making. We do not want to be a slave to data. There is a trade-off between data size and fidelity of information. For example, the policy for metallic aircraft has been that we cannot fly with a known crack, but on composites we can fly with known, managed damage that is less than a predefined size. Hence, SHM should identify damage that matters. The model is that substantiated damage limits are 'allowed', but the decision will always depend on the method of determining defect size and the rationale for the continued airworthiness.

There are lots of regulatory and functional requirements and the issue of how to demonstrate and quantify the reliability of an SHM system is crucial to the certification of SHM-enabled structures. The building blocks for certification already exist and will assist technology maturation. Committees are looking at how to determine the capability of SHM systems. SHM developers need to understand requirements from regulators. The regulator view is that visual and NDT POD curves for determining inspection intervals and maintenance schedules will not significantly change for SHM. The reliability of the whole process, including electronics and electrical wiring, may need assessing using sensor-intervention methods. Some content in EASA's acceptable means of compliance (AMC) to CS25.302 (see also CS-25 Appendix K), which currently addresses system/structure interaction from a design load management perspective, could offer the potential to be adapted and used to support the development of such activity. One or two new SHM methods will need to be characterised where the NDT reliability method cannot be read across. We need to determine a sensor's uncertainty as usual if it is making a measurement. If it gives a hit/miss answer then we need a probabilistic approach, such as POD for NDT. It is debatable whether human factors are relevant if an automated decision in the process can potentially limit the amount of data an operator is presented with and therefore bias the operator's decision, and a human will have coded the automated process.

What is the way forward?

Aircraft safety depends on lots of other (avionics) sensors, so can the SHM community learn from how they are assessed? With those sensors there is in-built redundancy, allowing a choice of sensor when readings differ. But it is very difficult to get this right and there have been accidents due to incorrect decisions by computers about which sensor to believe. There are lots of mature requirements already in place for those avionics sensors. It is necessary to determine the accuracy and range of a sensor or system, as well as the dependence of its accuracy on environmental factors. A sensor may compensate for variations in temperature and pressure, for example in order to maintain accuracy, and this is similar to SHM. If variability in environment can change the system response, then this has to be dealt with by tolerances. The reference point is the worst case within the tolerance. If the number of variables can be reduced then the system can be made more deterministic.

A challenge to the SHM community could be: what is the maximum size of defect that the SHM system could miss under the whole spectrum of variabilities? The regulator view is that we should not design in a dependence on these variabilities in SHM measurements.

Is there a requirements specification that could be posed as a challenge to the SHM community? How accurately can an SHM system measure a defined damage level in a composite? How accurately can it define when the limits are approached? Multiple failure modes need to be handled. There is a risk of an undeclared large defect and SHM could help with this.

A regulator suggestion is that SHM suppliers should submit a proposal to the regulator for a system that can be run in parallel with the current airworthiness system in order to build confidence. This establishes SHM as a viable technique, for example in the case of the Delta trial. How can this experience be migrated into more complex technologies?

Conclusions

The workshop was widely praised by the attendees for several reasons. It brought together several communities for the first time to work out what is needed in order for NDT to make a difference for aerospace composites. The benefits of a more joined-up approach were clear to those present. Many NDT community attendees had never really seen presentations or heard discussions about how their NDT underpins design, structural integrity and manufacturing of composites.

The key messages from the regulators were that: safety levels must not be reduced; all possible failure modes and defect types should be taken into account by NDT methods; process verification is crucial and NDT can help; and increasing the amount of information fed back from NDT to the type certificate holders will result in increased confidence in their designs.

During the workshop, future requirements were defined for the NDT research and development communities to use as their targets. These are summarised as follows.

Opportunities for benefit from NDT

Three generic opportunities were identified where progress in NDT of composites could provide significant additional benefit for aerospace composites:

- at the design stage;
- in process verification; and
- in better-informed concession decisions.

Composites are still designed against defect criteria and failure constraints determined decades ago. Whilst mechanical testing at the design stage is being gradually replaced by more model-based analysis, detailed 3D-NDT linked to materials models could help to reduce the testing burden and increase confidence in new designs. 3D non-destructive characterisation could provide an improved link between mechanical test and analysis in the test/analysis 'pyramid'. The significance of a given defect usually increases with decreasing thickness, so the route to making lighter structures must include improved NDT at some stage in the lifecycle in order to maintain safety levels.

Commercial opportunities for benefit from NDT also exist in both production and operation. Instead of just quality control inspections at the end of the process, online NDT could verify that processes are not producing defects, detect early signs of process changes, or even detect potential defect sites before components are cured. Reducing false-positive NDT calls by improving the discrimination of NDT techniques would reduce scrap rates.

When features (deviations from design) are discovered, the concession process is faster and has a more beneficial outcome if high-quality information is provided to the stress engineers. Future requirements are likely to be performance-based, so it is important that future NDT can predict the strength and life of a component. It may be possible to use 3D profiles of material properties and create a model to determine the remanent strength of the structure, thus reinforcing the concession decision with an actual assessment of whether the component will still carry the required load.

Adhesive-bonded joints

The main benefit areas for NDT of adhesive-bonded joints are in process verification, both for original manufacture and for repair-patch bonding. The key to the regulators allowing adhesive joints without limit-load back-up features is to verify that the production process will always produce a bond that will carry limit load and will never create a kissing disbond. Proposed proof-test methods, such as the laser ultrasound shock-wave method, were not regarded as suitable solutions by workshop attendees. Kissing disbond specimens are being produced by a collaboration of NCC, NPL, 3M and the University of Bristol. These will be used to test and evaluate current and future NDT methods for kissing disbond detection. The BINDT Aerospace and Composites Groups are monitoring this activity.

3D characterisation of composites

During the workshop, opportunities were identified for 3D characterisation to provide benefit at all stages of the product lifecycle: design, test/analysis pyramid, production process verification, process control, post-manufacture inspection, as well as in-service damage assessment and repair verification. It will be most beneficial for high-value low-volume parts where it makes commercial sense to spend the time on justifying a concession. Better-informed concessions would be an easy way to introduce and validate new NDT from a regulatory point of view, provided the new path is run in parallel with the current airworthiness path. However, for new aircraft, starting to use new NDT during the development process is important, rather than leaving it to the certification stage.

In civil aircraft operation, continuing to fly with a known defect until the next maintenance opportunity may eventually be facilitated if NDT, with modelling, can determine the residual life of the part (prognostics). For military aircraft, 3D characterisation and NDT-based modelling would be useful in both production and design stages, where analysis can be slow, but for in-theatre use the NDT data acquisition and analysis need to be fast. NDT detectability constraints and requirements could be included in the modelling at the design stage; the structure could be tuned so that it can be inspected quickly.

The output of 3D characterisations should be in a form that directly informs the prognostic and concession/repair decisions – the right parameters for stress engineers, removing the need for expert NDT interpretation. NDT outputs should be 'adequately accurate' – the right resolution and sensitivity for the purpose and no more, and this depends on how the data will be used. The important thing is that any information provided can be used beneficially. An evolution of the whole design methodology is needed to account for the fidelity of data before that data becomes useful. There will be a significant requirement for validated test data on known physical components.

We do not need NDT-based modelling before 3D characterisation becomes useful; simple tools giving some 3D capability would be an advantage for manufacturing, help communication with stress engineers and provide quicker answers for concession decisions. In the case of wrinkling features, per-ply depth resolution would be beneficial provided it can be achieved fast enough. As well as the maximum wrinkle angle and amplitude, measurements are required of the extent of the wrinkle in the load direction and the wrinkle cross-sectional area (perpendicular to the load direction). This is an example of where mechanical test data exists that can be used to validate future automated wrinkle-measurement methods.

There is still a requirement for academia to improve defect detection and characterisation (and also to increase resolution) for future designs. We need to integrate NDE into the design process rather than just the production process. Understanding the effect of defects is critical in getting the design right. Manufacturers want post-production NDT to be just a quality check, thus moving the benefit of 3D characterisation into the design stage rather than the production process. Process control by NDT and pre-process NDT could ensure a 'right first time, every time' manufacturing process.

Structural health monitoring

The use of installed sensors, either embedded or surface-mounted, would provide information about changes in the structure over time, in the areas being monitored. Benefits include regular assurance of structural integrity and early detection of damage, but NDT will nearly always be required to determine the size and severity of any damage. A few systems have been implemented on a trial basis on operational aircraft, but there are significant challenges with implementation, validation, verification and certification. A view of what success will look like for SHM could provoke more activity targeted to achieving this. The proposed whole-system viewpoint is that success is when an SHM system is in place that gives information in-service to effectively manage a platform throughout its life and feedback information to designers about how the platform is used. Key elements of this are: automation, lightweight sensors, integration of sensors on the surface or embedded and the durability of the whole system must be more than the life of the component. Technology developments in systems, processing and sensors will all help with SHM success.

SHM should only identify damage that matters based on substantiated 'allowed' damage limits, but the decision will always depend on the method of determining defect size and the rationale for the continued airworthiness. A regulator suggestion is that SHM suppliers should submit a proposal to the regulator for a system that can be run in parallel with the current airworthiness system in order to build confidence. This establishes SHM as a viable technique.

Demonstration and quantification of the reliability of an SHM system is crucial to the certification of SHM-enabled structures. The building blocks for certification already exist and committees are looking at how to determine the capability of SHM systems. The regulator view is that current methods for determining inspection intervals and maintenance schedules will not significantly change for SHM. The reliability of the whole process, including electronics and electrical wiring, will need to be assessed.

The perceived implementation barriers to SHM are: weight, power and cost. A crucial technical challenge is the speed at which information can be moved. The choice of SHM method has to last the life of the component, so this decision must be made confidently. Most work has been carried out on simple structures and very little on complex structures, such as military aircraft. An additional challenge in the future will be in-service modifications for the interpretation and analysis of the SHM data for composites.

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References

1. M Perton, A Blouin and J-P Monchalin, 'Adhesive bond testing of carbon-epoxy composites by laser shockwave', Journal of Physics D: Applied Physics, Vol 44, 034012, 2011.
2. R Ecault, M Boustie, L Berthe, F Touchard, H Voillaume, B Campagne and D Loison, 'Development of a laser shock wave adhesion test for the detection of weak composite bonds', Proceedings of the 5th International Symposium on NDT in Aerospace, Singapore, November 2013.
3. B Ehrhart, R Ecault, F Touchard, M Boustie, L Berthe, C Bockenheimer and B Valeske, 'Development of a laser shock adhesion test for the assessment of weak adhesive-bonded CFRP structures', International Journal of Adhesion & Adhesives, Vol 52, pp 57-65, 2014.
4. R Ecault, M Boustie, F Touchard, F Pons, L Berthe, L Chocinski-Arnault, B Ehrhart and C Bockenheimer, 'A study of composite material damage induced by laser shock waves', Composites: Part A, Vol 53, pp 54-64, 2013.
5. R A Smith, L J Nelson, M J Mienczakowski and P D Wilcox, 'Ultrasonic tracking of ply drops in composite laminates', Proceedings of the 42nd Annual Review of Progress in Quantitative Nondestructive Evaluation, Minneapolis, July 2015. Published in AIP Conference Proceedings 1706, 050006, 2016. DOI: 10.1063/1.4940505, 2016.
6. R A Smith, L J Nelson, N Xie, C Fraij and S R Hallett, 'Progress in 3D characterisation and modelling of monolithic carbon-fibre composites', Insight – Journal of the British Institute of NDT, Vol 57, No 3, pp 131-139, March 2015.
7. H Azzam and J McFeat, 'Development, validation, verification and certification of structural health monitoring systems for military aircraft', MASAAG Paper 123, Issue 2, Ministry of Defence, UK, 2015.
8. D M Sánchez, M Gresil and C Soutis, 'Distributed internal strain measurement during composite manufacturing using optical fibre sensors', Composites Science and Technology, Vol 120, pp 49-57, 12 April 2015.
9. M Gresil, M Saleh, M Arshad and C Soutis, 'Acoustic emission of 3D angle interlock glass fibre composites', 10th International Workshop on Structural Health Monitoring, Stanford, USA, 2015.

Appendix A. Delegate List

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Nick Bradley	3M, UK
Bill Broughton	NPL, UK
Allan Coley	Aerotech Inspection & NDT Ltd, UK
Eduardo Colin	University of Bristol, UK
Jane Dawson	GE Digital Solutions, UK
Jeff Dobson	University of Strathclyde, UK
Maria Felice	MTC Ltd, UK
Peter Foote	Cranfield University, UK
Cailean Forrester	Inspectahire Instrument Company Ltd, UK
Ben Forshaw	Civil Aviation Authority, UK
Richard Freemantle	Wavelength NDT Ltd, UK
Iryna Gagauz	University of Bristol, UK
Martin Gaitonde	Airbus UK Ltd, UK
Barbara Gordon	University of Bristol, UK
Dan Graham	GKN Aerospace, UK
Matthieu Gresil	University of Manchester, UK
Felicity Guild	Imperial College London, UK
David Hallam	DSTL Porton Down, UK
Stephen Hallett	University of Bristol, UK
John Hewitt	J Hewitt NDT Ltd, UK
Gary Holden	BAE Systems, UK
Phil Irving	Cranfield University, UK
Richard Jones	Composite Inspection Ltd, UK
Jeff Kapp	3M, UK
James Kirkpatrick	University of Bristol, UK
Thierry Laffont	GE Digital Solutions, UK
Ian Lane	Airbus UK Ltd, UK
Gary Lowton	Sonatest Ltd, UK
Steve Massam	BAE Systems, UK
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Ben Payne	British Airways, UK
Michael Phillips	Sonatest Ltd, UK
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Jonathan Pugh	Exova Ltd, UK
Rob Rose	Testia Ltd, UK
Carl Sheppard	British Airways, UK
Cameron Sinclair	BINDT, UK
Robert Smith	University of Bristol/President of BINDT, UK
Jaap Speijer	GKN Aerospace, Netherlands
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