Composites Workshop

Report from the Workshop on NDT Requirements for Automotive Composites

23 March 2017

The Manufacturing Technology Centre, Coventry, UK

BINDT
THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

. . . engineering safety, integrity & reliability

Workshop on NDT Requirements for Automotive Composites

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A British Institute of Non-Destructive Testing (BINDT) workshop, with the above title, brought the regulatory, insurance, materials, design, manufacturing and NDT communities to the Manufacturing Technology Centre (MTC) on 23 March 2017. The objective was to brief the NDT community on the ways in which NDT would be required to help in the anticipated increased use of composite materials in high-volume car manufacture.

Due to considerable environmental regulatory pressure on the automotive industry to reduce CO_2 emissions (see Figure 1), there is a new urgency in the drive to reduce the weight of cars. Composite materials can play a key role, but only if:

- *Manufacturing cycle times can be reduced from hours (for aerospace) to minutes*
- *Yield can be brought to nearly 100% – the 'right first time, every time' approach*
- *In-service assessment of damage to composites can be performed to the satisfaction of the insurance industry.*

Manufacturers are sure that NDT will play a crucial role and they want to engage with the NDT supply chain to help deliver their solutions.

The workshop was aligned to the following BINDT 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 Past President)
- Dr Paul Gallen, National Composites Centre
- Dr Hassan El-Dessouky, Advanced Manufacturing Research Centre
- T Gethin Davies, Jaguar Land Rover
- Andrew Elford, CCT
- Andrew Foreman, QinetiQ Ltd.

This technical panel was acknowledged and thanked by BINDT Past President, Professor Smith, in his opening remarks, as were the UK Engineering and Physical Sciences Research Council (EPSRC), the Manufacturing Technology Centre (MTC) and the British Institute of Non-Destructive Testing (BINDT) for making the workshop possible through their support.

Key participants in the workshop represented regulators (HORIBA MIRA), motor insurers (Thatcham Research), constructors (Jaguar Land Rover) and manufacturing suppliers (CCT). Also represented were academia, High-Value Manufacturing (HVM) Catapult Centres (MTC, the National Composites Centre (NCC) and the Advanced Manufacturing Research Centre (AMRC)), 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 focused and facilitated discussion time, through breakout sessions and panel-led discussion. These were carefully recorded and documented. This paper provides a summary of those presentations and discussions.

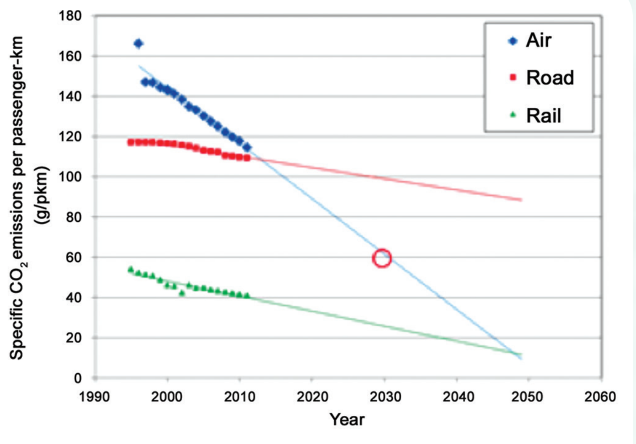

Figure 1. Historic CO_2 emissions for road, rail and air extrapolated, with the road target for 2030 highlighted with a red circle

Source: TREMOVE v3.3.1 (EU-27 + 3 countries)

NDT of composites

Overview of potential for NDT of automotive composites

Professor Robert Smith, University of Bristol

Professor Robert Smith summarised the state-of-the-art in non-destructive testing and characterisation of aerospace unidirectional composites, emphasising the wide range of material types, defect types and NDT methods used to detect and characterise them. In his experience, in over 95% of cases ultrasound and X-ray CT methods are up to the task of detection and characterisation. However, when their superior capabilities are unnecessary, other methods may be chosen for reasons of cost-effectiveness, such as the size of the component, total inspection time or access problems.

In the context of opportunities for use in the automotive sector, Professor Smith then considered recent work using 3D non-destructive characterisation of material properties to create finite element (FE) models of mechanical performance. 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 percentage 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 and in service, 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 2). Similarly, out-of-plane wrinkles can be tracked and the angle of the ply measured at each location[2]. Delaminations can be distinguished from resin layers between plies and from 'multiples' of the delamination signal. Woven composites are much more prevalent in the automotive sector than aerospace and some initial work has been carried out on the characterisation of woven composites using a 'ply fingerprinting' method, where different weaves have characteristic in-plane angular distributions[3].

Professor Smith then showed how the inverted maps of material properties can be used to create FE 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, has 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.

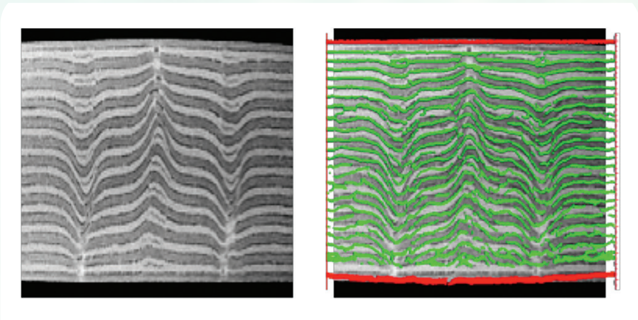

Figure 2. X-ray CT (left) with overlaid ultrasonic analytic-signal ply tracking (right) for a cross-ply specimen containing tape gaps and overlaps, with consequent wrinkling. The superimposed red lines are the front and back surfaces, while the green lines are the resin layers between plies, all determined automatically from the ultrasonic full-waveform data[1]

Motorsport, sports cars and supercars

30 years of composites and NDT in Formula One (F1)

Brian O'Rourke, Williams F1

For this presentation, Brian O'Rourke, who originally had an aerospace composites background, aimed to review 30 years of composites and NDT in Formula One (F1) motor racing. His work for the Williams F1 team for the past thirty-five years puts him in a unique position to talk about the changes in material use and testing techniques during that period.

Brian's presentation started with a description of the present F1 cars. He explained how the complicated assembly of composite components is built for a variety of functions (chassis, clutches and brakes, steering and suspension). Whilst there are some primary structural composite elements, others are used for decorative or aerodynamic 'clothing'; the composite components are very different to one another in their design criteria. As the primary aim of F1 cars is to be fast, safety regulations drive the designs and they must be subjected to rigorous load testing. In particular, the chassis assembly, which is made of composites, must meet the inertial and aerodynamic Federation Internationale de l'Automobile (FIA) regulations. The wide range of materials used in F1 cars includes: high-specification steels, titanium, aluminium alloys, magnesium, polymeric matrix composites, metal matrix composites and carbon/carbon composites (particularly used for brakes and clutches). There is, therefore, considerable interest in the NDT of adhesive joints between dissimilar materials.

The move to composite materials was pioneered by the McLaren MP4/1 around 1981. The idea was to use a monocoque design with external 'clothing'. The first Williams monocoque (FW10) was introduced later, in 1985, with the objective of making its external surfaces form both the aerodynamic shape and the main working structure. Figure 3 shows how composites are now used in an F1 car.

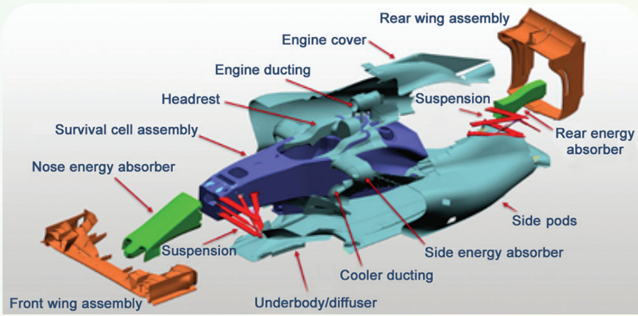

Figure 3. Use of composites in an F1 car

After a review and brief description of the different types of Williams composite monocoques since the 1980s, Brian O'Rourke showed some recent photographs of the strength-critical bonded joints. An early NDT technique used for composites was known as audiosonic (a test system for non-destructive identification of defects using acoustics). Today, ultrasonic phased array and real-time radiography are the main methods used to test the F1 composite parts. Brian ended his talk by showing output resulting from modelling and testing of a roll-over hoop and a practical example for using OmniScan phased array ultrasound to detect anomalies within an inboard joint.

Composite NDT requirements in sports cars

Jan Olav Endrerud, DolphiTech

In this presentation, Jan Olav Endrerud was able to summarise the current capability in automotive composite inspection of three European manufacturers that use equipment from his company, DolphiTech, which specialises in ultrasound imaging solutions, based on its patented ultrasound 2D array transducer technology. Its main product, the DolphiCam, is optimised for carbon-fibre composite structure inspections and is capable of detecting delaminations resulting from impact damage, machining or drilling of holes and bonding defects as well as laminate-to-core disbonds in sandwich structures (see Figure 4).

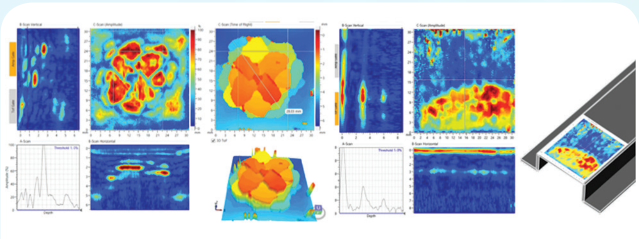

Figure 4. Impact damage imaged by the DolphiCam (left) and a manufacturing defect (right) in a complex part (far right)

Based on DolphiTech's experience, car manufacturers such as Lambourghini, Volkswagon and Audi have developed procedures to detect defects in different composite materials, as well as joints in multi-material structures, including:

- Carbon fibre-reinforced plastic (CFRP);
- CFRP bonded to CFRP, metals or core materials (foam or honeycomb);
- Hybrid materials, for example CFRP and glass fibre-reinforced plastic (GFRP) mixes; and
- Thin metal adhesive joints.

Many automotive structures include some composite materials, normally 2 mm to 4 mm thick. DolphiCam uses a 3.8 MHz transducer, giving sufficient penetration combined with high resolutions in these materials.

Challenging areas include:

- Attenuative materials, for example CFRP/GFRP hybrids or materials with high porosity levels;
- Highly attenuative adhesive materials, for example incorporating glass beads for thickness control;
- Inspecting defects in multi-layer sandwich structures; and
- Structures with limited geometric access where the camera/probe cannot be put in contact with the surface.

Furthermore, having a good understanding of the car structure is imperative to interpret the results correctly. Hidden structural features might lead to wrong interpretations of the ultrasound images and indications.

German car maker Audi has implemented the DolphiCam in final part inspection and for structural part inspection after an accident involving the Audi R8. The system is also used by Lamborghini for the Huracán model. Some challenges for future inspection solutions include:

- The need to inspect multi-fibre (for example carbon/glass) materials, both layered and integral;
- Inspection of fibre-reinforced plastic (FRP) parts covered by metallic paints; and
- Inspection of CFRP parts with foam cores.

DolphiTech is developing its second-generation system, to be released towards the end of 2017, which will address the need for multi-material inspection solutions in the automotive industry.

Regulation, insurance and repair

Regulatory NDT requirements for composites on public roads

Richard Whiting, HORIBA MIRA

Richard Whiting looked at aspects of legislation required for road vehicles, pointing out that composite materials themselves did not invoke any specific requirements for road vehicles and that the legislative elements were performance-based for the vehicle, as opposed to the specific material construction. He covered how vehicle legislation varies across the globe but essentially deals with the whole vehicle type approval. It does not have any traditional NDT requirements and instead focuses on the environmental, active safety (avoiding accidents), passive safety (protecting in the event of an accident), lighting equipment and other directives such as electromagnetic compatibility (see Figure 5).

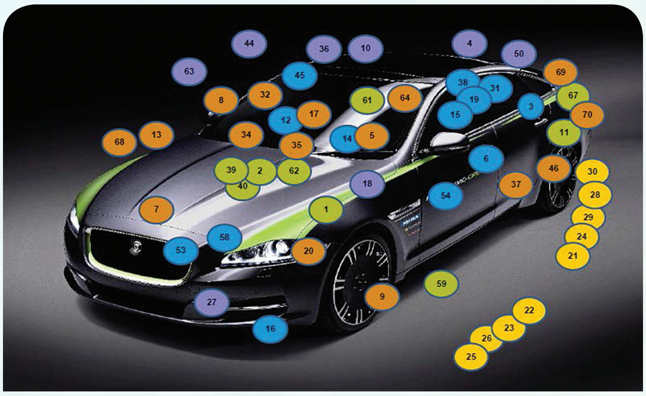

Figure 5. Key legislative areas on a vehicle relevant to each part of the whole vehicle type approval legislation

Although the process is traditionally understood to involve crash testing of vehicles, Richard highlighted the role of tests that are not destructive, such as emissions and drive-by noise, and how these aspects are checked as part of the conformity of production audits and checks of production vehicles.

The presentation also mentioned the use of simulation work, particularly for more expensive scenarios such as crash testing and also relevant for composite constructions. Richard explained that simulation is becoming increasingly important in vehicle development.

Further coverage was given for new challenges to the automotive sector such as autonomous vehicles and cyber security, both of which are looking to simulation aspects to act as a means of conducting failure mode effects analysis (FMEA) for complex logic circuits as a pragmatic risk management strategy is adopted throughout the industry. Richard cited examples such as ISO 26262 as a means of providing an auditable route to ensuring adequate compliance for control system development. FMEA methods determine the potential failure paths following the failure of a component and the potential effects of that failure. The potential-effects element is critical for the electronic logic circuit process to clarify if the system fails and what safety elements must be implemented to counter the potential failure.

Richard explained that NDT, in the classical sense, is not really used in type approval. Type approval focuses on performance functionality of the item/system/component as opposed to the traditional NDT monitoring of structural integrity. As such, there are tests conducted that are non-destructive to ensure the vehicle is performing correctly and meets the range of characteristics detailed within the appropriate legislation. NDT is certainly used in the development and monitoring of vehicle construction, for example for engine wear monitoring, and simulation is now significantly used for crash test development. However, it is also used in non-legislated areas such as aerodynamic profile development or even cooling requirements for the engine bay.

When asked where NDT could provide benefit in the future and for composites, Richard explained that NDT feeds into the simulation process, which is then further proved through field trials where NDT is used to monitor component performance, for example in body structures or suspension systems to fine tune any simulation work. With composites, this is particularly useful due to the time needed to form new components and in determining the most effective weave characteristics for the particular application.

Insurance and repair requirements for NDT of composites

Andrew Hooker, Thatcham Research

Andrew Hooker of Thatcham Research, the motor insurers' automotive research centre, gave a reality check with regard to the issues to be faced if mass-produced cars contain significant amounts of composite materials.

Automotive accident insurance claims could grow in costs and need to be resolved swiftly and efficiently. Hire car costs, claim handling, legal costs and other incidentals can quickly inflate a repair cost. UK insurers take their duty of care to their customers very seriously and, as such, have strongly supported the use of defined standards in repair. The current repair standards relate to 'man' (skilled and qualified), 'methods' (a defined model-specific technical procedure), 'machine' (calibrated and maintained to a defined schedule) and 'materials' (identifying the material properties for the correct repair procedure).

The automotive industry requires an NDT procedure that is equally safe and accurately defines (to the vehicle manufacturer's specification for each model) the requirement to ignore, repair, replace or declare total loss as unsafe. This needs to be relatively time efficient but, above all, safe. The owner/driver needs to be reassured and he/she and the insurance/lease company quickly needs clarity as to the structural integrity and actions needed to restore this, to maintain their confidence in the product and those involved in managing the repair.

Responsibility for managing good design for the complexity of a car body, with trims and components not restricting access for NDT and practical and cost-effective repairability, reinstating the integrity of the car body, remains solely with the vehicle manufacturer. A replace-only strategy is unlikely to be successful as the resultant high repair cost is likely to be statistically recognised and the model underwritten accordingly; manufacturers need to be aware of global repair practices and design their vehicles to enable safe repair. Thatcham Research welcomes and supports good diagnostic and repair strategies and is already exploring NDT procedures, cutting-edge repair techniques and strategies and evaluating their relative merits. Thatcham works with a number of vehicle manufacturers to improve repair in the UK and other global markets and is open to further engagement on this.

Figure 6. A two-dimensional array 'ultrasonic camera' used by Thatcham Research to inspect a complex composite component

High-volume challenges

The move to lightweight designs – NDT challenges

T Gethin Davies, JLR

Since the very beginning, automotive structures have been dominated by metallic parts and components – firstly with steel and then, more recently, aluminium. The move to use aluminium was not easy, but the dividends of using this material were such that vehicles were lighter. This meant cars could go faster and further and could also be more efficient. Efficiency has become something that all automotive manufacturers seek to improve upon so that the environmental impact of their vehicles is as low as possible; a fleet-wide average CO_2 emission of 99 g/km is a lofty target set by legislative bodies and needs to be achieved by 2020. Customers are also more conscious of their choice of vehicle and a more efficient car is usually more attractive to buy than one that is more polluting.

In order to ensure that future vehicles continue to be as lightweight as possible and help improve their efficiency, the natural progression would be to adopt composite materials. These paradigm-shifting materials will probably not be used on their own in the vehicle, but would be part of a mixed-material design approach: using the right material in the right place to maximise its effectiveness.

One of the main issues surrounding the use of composite materials, however, is the lack of experience that the automotive industry has in their use. Damage in these materials can be extremely subtle, with little or no visible sign on the material surface; the best analogy would be an iceberg, with only a small amount visible above the waterline and the vast bulk of it hidden below, out of sight. As a result, NDT methods will be vital in ensuring the integrity of any parts built using these materials, in both the manufacturing and after-market environments.

The use of structural composites in the automotive industry is still very much in its infancy, with many questions on the effective use of NDT remaining unanswered. Systems currently exist that already fulfil the requirements that the automotive industry is likely to have. However, the effective deployment, use and management of these technologies, along with the nature of the data that they provide and how this is used, still needs development. As such, the question that many automotive manufacturers will likely ask is: "Lightweighting means incorporating composites – how do we effectively find damage?"

Figure 7. Jaguar F-type Project 7 soft top

The challenge for NDT of affordable composites

Paul Gallen, NCC

Paul Gallen, from the National Composites Centre (NCC), gave a talk focused on the work by the Affordable Composites Group (ACG), a High Value Manufacturing Catapult project. The presentation mainly showed how this group works to establish a viable supply chain in the UK.

Paul briefly presented the benefits for using composites in general and in the automotive sector in particular. He showed a graph that predicted both global and UK increases in the demand for composite components over the next ten years in the automotive sector (see Figure 8). Besides the lightweighting benefit, the use of composites was explained to be helpful in achieving better component integration, reducing part count and improving car performance. There are lots of other opportunities for using composites in a car besides on the 'body in white' structure. The chassis sub-structures, steering, suspension and interior components are some of the possibilities investigated by the ACG in the Tier 1 (sourced) part of the supply chain. Within the next ten to 20 years, the use of composites and multi-materials is expected to have a positive effect on the powertrain and the gas tank for hybrid models. Jaguar Land Rover (JLR) and Ricardo, for example, were reported to have started to use multi-materials in novel ways. All of these opportunities suggest interesting challenges to the NDT community as every new material that is considered for use will have its own potential and challenges.

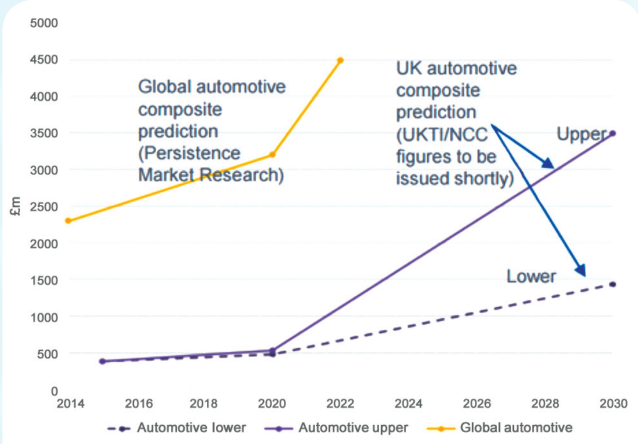

Figure 8. Prediction growth in UK production requirement for composite components alongside global automotive composites

So, the ACG aims to contribute considerably in building the supply chain for the UK through lots of activities described in both short- and long-term programmes. To achieve this, the ACG constantly needs to address important questions such as how to share data to create standards or how to create industrial outputs from any activity or project. This also requires lots of work on training, education, data, knowledge and best practice. The activities of the ACG were summarised under the need to aggregate the opportunities, standardise the offers and commoditise the knowledge. As part of the aggregation process, opportunities are defined in very simple blocks. This makes it easy for the non-composite specialists to understand the work. The main target of the ACG was to be globally competitive in comparison to the American (IACMI) and German (MAI carbon) groups. The American group aims to target the cost of composites in the USA, while the German group has made itself known for building a supply chain in Germany and achieving some of the above targets. Therefore, the challenges break down to the need to be comparable to other processes, to reduce the cycle (takt) time to far more acceptable levels, to reduce the material cost in finished carbon-fibre parts, to reduce the carbon fibre-reinforced plastic (CFRP) embodied energy and to address the issue of sustainability. Besides these challenges, there is an industry agenda (Industry 4.0) to address, which aims to connect intelligent manufacturing systems to assure a good process in control, mainly regarding rapid sensing, multiple criteria and decision making.

HVM Catapult: 'High-Efficiency Preforming' project

Paul Gallen, NCC and Redland Sanders, MTC

Paul Gallen presented an overview of the 'High-Efficiency Preforming' project, a composites large-scale project within the High Value Manufacturing (HVM) Catapult involving the Advanced Manufacturing Research Centre (AMRC), National Composites Centre (NCC), Manufacturing Technology Centre (MTC) and the Warwick Manufacturing Group (WMG). The aim of the project is to identify and develop high-efficiency composite preforming processes suitable for automotive applications from 2020 onwards and capture process data, including cost, rate, repeatability and sustainability. Preforming (prior to consolidation and cure) is a future requirement across the range of composites manufacturing, although the method chosen will be highly dependent on the production volume and rate requirements of the industry. It offers manufacturing benefits through increased rate, repeatability and yield by allowing inspection for deviations and defects prior to consolidation, potentially reducing scrap at the post-cure inspection stage. The non-destructive evaluation aspects are being led by the MTC and were presented by Redland Sanders. The MTC is examining a range of inspection technologies relevant to different stages of the manufacturing process chain, spanning surface and through-thickness inspection. A video was shown of a complex-shaped dry-fibre preform being scanned by a robot-mounted high-frequency eddy current sensor during a technology trial conducted at Fraunhofer IKTS (Dresden, Germany).

HVM Catapult: 3D woven preforms for automotive

Dr Hassan El-Dessouky, AMRC

The Composites Manufacturing Forum (CMF) within the UK's High Value Manufacturing (HVM) Catapult is a cross-catapult forum in the area of composites manufacturing. It was formed in 2015, after an initial study was conducted in which it was identified that there is significant risk to the automotive sector due to the upcoming CO_2 emissions regulations. The tighter emissions regulations will drive a greater emphasis on vehicle weight, so integrating lightweighting materials into vehicle construction is a necessity. Whilst there is a risk to the industry, this set of conditions also provides an opportunity, which the UK's automotive sector is well positioned to support.

'Large-Scale Project – Composites' (LSP-C) is a collaborative project between the following four Catapult centres to develop the composite manufacturing supply chain for the automotive industry:

- Advanced Manufacturing Research Centre (AMRC) with Boeing – 3D woven preforms;
- National Composites Centre (NCC) – Preform and multi-materials joining;
- Warwick Manufacturing Group (WMG) – Preforming and high-pressure resin transfer moulding (HP-RTM); and
- Manufacturing Technology Centre (MTC) – Cost analysis.

3D weaving for preform generation is a very efficient way of depositing fibre with minimal labour associations. Weaving is already used in the composites industry, though mostly to produce 2D woven architectures (see Figure 9). AMRC with Boeing is developing 3D woven-blank technology for preforming applications to accelerate the current weaving technology, whilst reducing the need for further lay-up and thus reducing the associated labour costs. The output of the 3D weaving machine can be tailored to be the exact architecture necessary for the component in question, with minimal or no need for further manual lay-up. Both 2D and 3D weaves are described below.

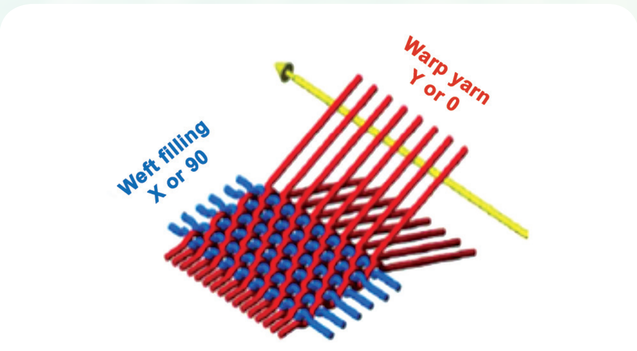

Figure 9. 2D weave process

2D weaving

XY (0, 90), or 2D, woven fabric (see Figure 9) is produced by weaving fibres from the warp (X = 'end') and weft (Y = 'fill') directions. Different weave styles can be manufactured; the most common patterns used in composites are plain, twill and satin. 2D woven structures exhibit good in-plane mechanical properties but not out-of-plane (through-thickness).

3D weaving

The 3D woven materials are fabrics that could be formed to near-net shape with considerable thickness. There is no need for layering to create a part because a single piece of fabric provides the full component thickness with full 3D reinforcement. 3D weaving is a variant of the 2D weaving process, an extension of the well-known technique of creating double- and triple-layer woven cloth. 3D weaving allows the production of fabrics up to 10 cm in thickness or more. Fibres, 'yarns' or 'tows' placed in the through-thickness (Z) direction are usually called the 'Z-yarn', 'warp weaver' or 'binder yarn'. More than one layer of fabric is woven at the same time, and Z-yarn interlaces warp (Y-) and weft (X-) yarns of different layers during the weaving process (see Figure 10). At the end of this process, an integrated 3D woven structure of a specific thickness is produced in a chosen weave architecture, such as 'orthogonal', 'angle-interlock' and 'multi-layer'. The Z-yarns provide a desirable level of out-of-plane strength, preventing the layers of woven warp and weft yarns from separating; consequently, improved mechanical properties will be achieved.

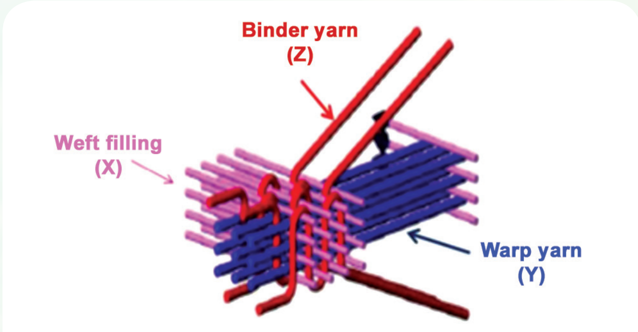

Figure 10. 3D weaving process showing 'orthogonal' weave

Floor-panel demonstrator

In LSP-C, a generic automotive component that offers a selection of manufacturing challenges was required on which the efforts of the consortium could be focused. The floor panel was selected and condensed in size to remove the larger featureless areas of the component, leaving the more challenging aspects of the component in one sub-scale piece.

Traditionally, the floor panel (see Figure 11) is made of discrete 2D fabric preforms, such as non-crimp fabric (NCF), with the following disadvantages:

- Preform overlap
- Thickness non-uniformity
- Fibre discontinuity
- Interlaminar delamination
- Labour (layering is time consuming).

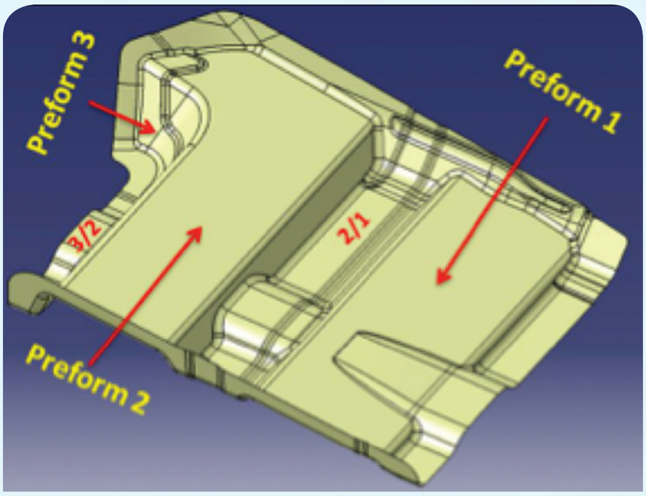

Figure 11. Floor-panel demonstrator with flat uniform areas reduced in size

As an alternative, AMRC with Boeing developed 3D woven fabric (see Figure 12) to be used in a single-piece preform, leading to the following advantages:

- Unitised/integrated preform
- Thickness uniformity
- Fibre continuity
- Improved interlaminar shear
- Less time consumed.

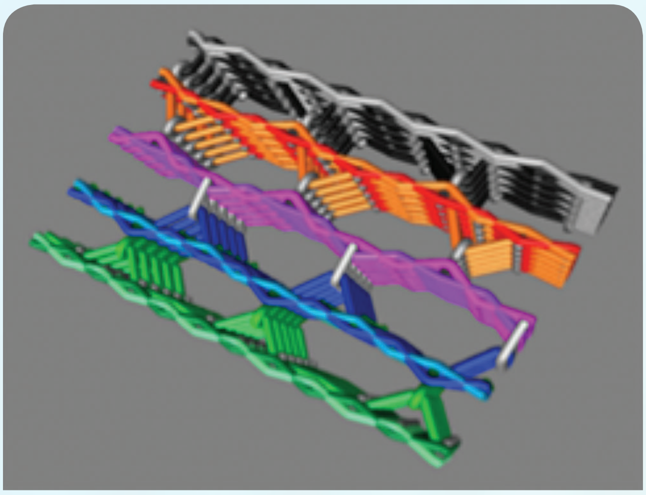

Figure 12. AMRC's 3D-weave single-piece preform for the floor panel

Figure 13 shows the most recent composite part manufactured as a demonstrator for the LSP project.

In general, 3D woven composites can offer:

- A supply chain for dry-fibre preforms for the composite industry;
- A high volume and serial manufacturing solution for the automotive industry;
- Single-piece blank fabric ready for composite preforming;
- A solution for complex geometries and structures;
- Built-in through-thickness reinforcement;
- Balanced mechanical properties in in-plane and out-of-plane directions; and
- Less 'takt time' for manufacturing composites.

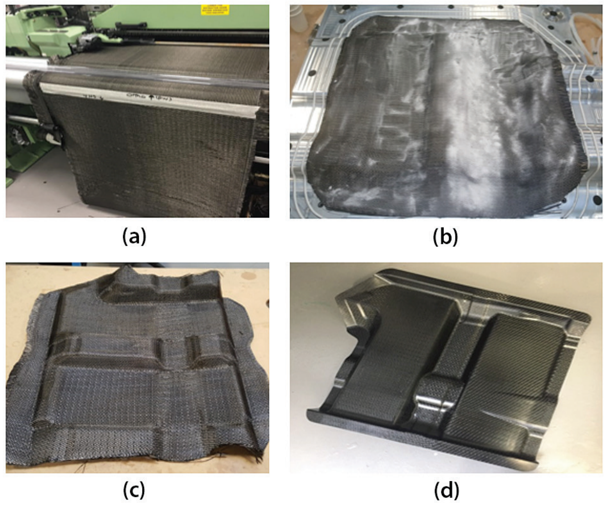

Figure 13. The most recent composite part, manufactured as a demonstrator for the LSP project, showing: (a) weaving of 3D fabric blanks; (b) preforming trial; (c) dry-fibre preform; and (d) resin-transfer moulded (RTM) cured part

3D non-destructive characterisation of preformed composites

Professor Robert Smith and Dr Rostand Tayong, University of Bristol

Professor Robert Smith explained the use of the analytic signal formulation to analyse ultrasonic responses of composite materials[1] in terms of instantaneous amplitude, phase and frequency. He showed examples of previous work to decompose the in-plane responses into an angular distribution or 'ply fingerprint', which varies according to weave and any draping distortions in the ply[3].

He then presented some results obtained on 2D and 3D woven automotive composites as part of an EPSRC-funded proof-of-principle 'Impact Acceleration' project aimed at engaging with the automotive composites sector. In a development of the ply-fingerprint principle, a new two-dimensional fingerprint has been proposed, which is sensitive to the spacing of features as well as angle. For 3D woven composites, such as those shown in Figure 14, instantaneous frequency was shown to be sensitive to some aspects of the weave, such as the binding yarn's presence in the stack. Finally, Dr Rostand Tayong presented initial results from a finite element simulator of the ultrasonic response from woven composites, developed under another short EPSRC pump-priming and feasibility-study project. This simulator will allow a systematic parametric study of the ultrasonic response to woven composites, including optimisation of both acquisition and analysis. Whilst this kind of detailed acquisition and analysis is currently too time-consuming for automotive production rates, its main benefit will be in the design and test, process design and process verification stages. A further research programme has been proposed to EPSRC as part of an extension to Professor Smith's EPSRC Fellowship in manufacturing.

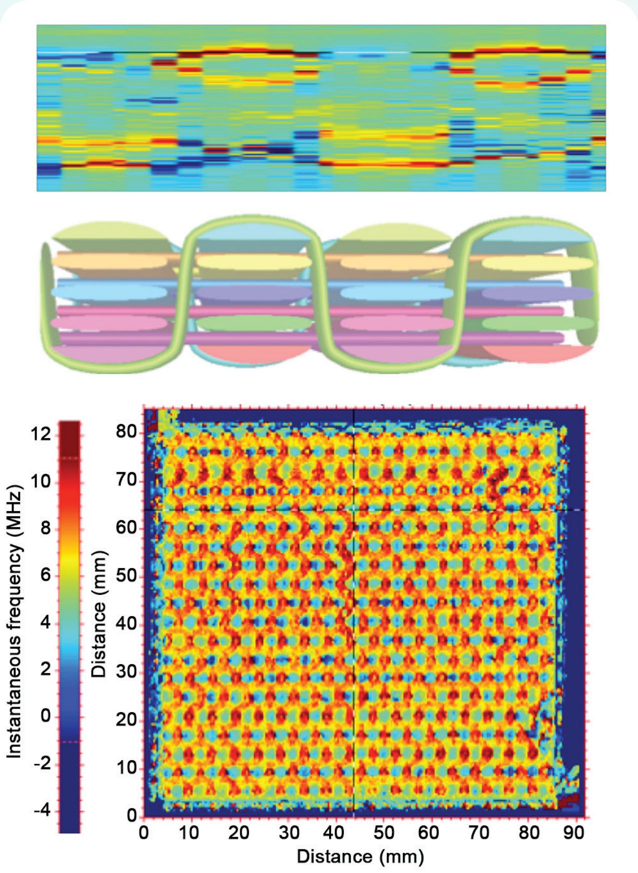

Figure 14. Cross-sections through the instantaneous frequency data calculated from the analytic signal response of a 3D woven composite (middle)

Breakout session report

For the breakout session, the delegates formed four groups that spent 10 minutes considering each of the following four topics: skills demand, production-line rapid inspection, offline NDT cell detailed inspection and in-service inspection and repair. Their comments and suggestions were recorded and reported back in a subsequent feedback session.

Skills demand

Lead: Brian Thornton, NCC

Brian categorised comments into three topics based on the following questions: What level of NDT skills will be required? How do we implement them? How many will we need?

What level of skills will be required?

It was proposed that there could be different skill levels for the acquisition and analysis of NDT data on automotive composites and these should be mandated in regulations. NDT operators carrying out acquisition may only need NDT Level 1 or NDT Level 1 (limited) as in the aerospace industry, whilst analysis could be completed remotely or centrally by an NDT Level 2 or 3 technician. People in design and people involved in repair should have knowledge of NDT. Special training and qualifications will be needed for automotive composites. BINDT should create a syllabus, requirements and training content and advise on appropriate levels. Certification should be a legal requirement.

How do we implement NDT skills?

Delegates wondered how current composite car manufacturers are covering the skills requirements and questioned whether the NDT requirement should be undertaken by original equipment manufacturers (OEMs). At manufacture, the NDT requirement may be placed on their supply chain (as in aerospace), with checks made at construction. In-service requirements may also be delegated to repair centres but overseen and audited by OEMs. BINDT has established three Trailblazer apprenticeship schemes and there is work to do to ensure that we map this to meet automotive composites requirements.

How many will we need?

There are 2000 (authorised) repair centres and at least one NDT specialist would be required in each centre. OEMs, suppliers and material manufacturers will all need NDT people. The requirement will ramp up over maybe the next three to five years. However, remote NDT, where NDT data is sent to an NDT analyst/expert at a remote location, may assist with the skills shortage.

There will be an NDT hardware requirement meaning increased numbers of composite-skilled people in equipment suppliers.

Additional skills

In design and repair, an understanding of NDT of composites will be required in order to design inspectable vehicles.

One question posed was: if the acquired NDT data is not suitable for analysis, who is responsible? A technique for data acquisition will need to include suitable checks on the quality of the data to ensure an acceptable resolution and signal-to-noise ratio at the very least, using reference test samples, as in most NDT techniques. This will be the responsibility of the NDT Level 3 in the OEM, who signs off the technique.

Production-line rapid inspection

Lead: T Gethin Davies, JLR

NDT will need to be rapid, with less than 20 seconds to apply it, potentially analysed by remote experts or by automated analysis software. It will be needed at various stages in the production process, performed not just by suppliers, but when a component is applied on a vehicle, later in production and maybe at the first service by the manufacturer's service centre (10,000 miles). So we need consistent tolerances throughout and continuity of measurement systems. Pass/fail criteria will be required with no ambiguity. We will need to know the structure, how the NDT signal interacts and what is the acceptable defect size in each case.

Bonded joints need to be inspected: how do we know they are good? We will need to design for inspection as well as manufacture and may need to avoid exotic designs. Curved structures are difficult for some ultrasonic variants due to the need to maintain coupling and normal incidence.

Why not use passive methods, for example structural health monitoring (SHM) such as embedded optical fibres in the structure or bruising paint/laminate, which could also be usable in service?

We need to engage with manufacturers of parts and NDT equipment manufacturers and get tests planned and designed by the equipment manufacturers and NDT experts. Inspection needs to be designed in and measurement tolerances need to be consistent with manufacturing tolerances.

Offline NDT cell detailed inspection

Lead: Paul Gallen, NCC

Offline NDT would have applications in development, manufacturing (within a quality plan) and in-service repair.

Can we define a failure mode for a given location? Different criticality, levels of NDT and levels of understanding may be required in different locations. Could we design in a (ductile) failure mode so we know what to look for? Or maybe break things down to smaller problems – it is easier to look for a specific failure mode in a particular zone, possibly even with an SHM sensor for particular damage.

Modelling of the composite components will be essential, possibly the 'digital twin' concept. Defect types will need to be studied to determine failure modes and what defines a flaw that must be detected for a given material and application. This will need to be backed up with experimental test data.

The NDT process needs to be understandable, cost-effective and simple. NDT must be deployable and robust. Accessibility may be difficult.

At the repair stage, how much fidelity is needed? We may just need to know that something has changed, without requiring the whole picture. Can we combine simplified NDT with, for example, bruising paint, brittle lacquers, on-board printed sensors, etc?

We should provide guidance based on an established body of knowledge, disseminate good practice and develop standards. Will this be OEM driven and then shared with the supply chain? Sharing of information is a difficult problem; can we share across supply chains?

We need a shared programme of linked projects involving academia, research and technology organisations (RTOs) and industry but how will it be funded? Industry 4 – SMART manufacturing – may have a role.

In-service inspection and repair

Lead: Richard Freemantle, WNDT

The breakout group discussing in-service inspection and repair started by considering the link to structural integrity with the need to define primary, secondary and tertiary structure, as in aerospace.

Inspection needs to be low cost with low training requirements. This could involve, for example, a basic thickness check and referring the results to an expert after the initial check or the potential for relaying results to a remote expert. A geometric survey could decide go/no-go based on distortion relative to a 'fingerprint' or key measurement points.

A discussion on how to assess damage to inaccessible parts of a vehicle led to a potential solution in embedding structural health monitoring (SHM) sensors to monitor the structure and direct more detailed inspection. It is not clear how to implement sensors; radio frequency identification (RFI) tags could help. Robotic manufacturing could allow sensors to be woven in. New car assessment programme (NCAP) crash tests could be used to collect sensor data. Engine management experience suggests there may be a trust issue with the risk of sensor failure.

If there is a lack of confidence in composite repair then it is likely that a component will be scrapped and replaced rather than repaired. Thermoplastics may have a role for repairing or self-healing by reheating. There may be a distinction between repair at manufacture and in-service repair. Write-off of the whole vehicle may still be the norm because repair may not be cost-effective or trusted.

There are various 'smart car' possibilities, including the use of smart coatings to indicate impact damage: the 'badger imprint'. It is important to design for inspection; a disposable or removable outer shell could allow deeper access for inspection. A modular design may be beneficial, similar to the F1 monocoque with bolt-on functional components, crash energy absorbers and a cosmetic skin. Does this translate to high-volume designs?

NDT requirements panel session

Chair: Professor Robert Smith
Scribe: Dr Richard Freemantle
Panel: Paul Gallen, Brian Thornton, Andrew Hooker, Brian O'Rourke, Gethin Davies and Jan Olav Endrerud

The panel session had the objective of identifying approximately ten of the top priority NDT requirements and then highlighting the three with the highest priority. Professor Smith asked each panel member to identify their top priority requirement and then this discussion was extended to the rest of the workshop participants.

*Brian Thornton (NCC): **Training***

There is a small window of opportunity to address the need for training enough qualified people in NDT techniques for the predicted increased use of automotive composites. It is, therefore, essential that the experts in this area agree and create a comprehensive training syllabus and qualification system as well as an apprenticeship scheme mapped to the automotive composites sector. Several participants are already involved in apprenticeship schemes in topics such as composites, NDT and engineering welding, etc. BINDT would be the best suited organisation to take this forward as part of the Composites Certification Working Group, currently chaired by Dr Richard Freemantle.

*Paul Gallen (NCC): **Stakeholder map and state-of-the-art report on NDT in automotive***

NDT in automotive is a complex landscape that needs a stakeholder map in order to increase the existing knowledge and understanding of this sector, as well as finding alignments between original equipment manufacturers (OEMs) and other supply chain members. A state-of-the-art report is also required on where the NDT techniques are in relation to automotive composites, in order to prompt discussions on how to move forward. A programme of work that looks into benchmarking current capability would definitely have lasting value. The HVM Catapult centres are well positioned to explore and exploit the current knowledge and build up this state-of-the-art report.

*Gethin Davies (JLR): **Improved knowledge of composite materials in the automotive sector and industry engagement***

Only with a better understanding of the characteristics of the composite materials will there be a more informed decision on which NDT techniques can be used. This knowledge will give us an indication of the depth of the required training, what sort of rate of testing is needed and how often (*ie* every MOT, every service, etc). In order to answer these questions, automotive manufacturers need to engage more with the NDT community and stakeholders.

*Brian O'Rourke (Williams F1): **State-of-the-art in NDT methods***

The state-of-the-art of the methods is not totally clear. We need to identify all of the NDT methods applicable to NDT in automotive because ultrasound testing (UT) or X-ray computed tomography

(CT) might not be adequate for the automotive sector due to speed and resolution requirements. More research on different techniques is required to understand the current state-of-the-art in all appropriate methods. This activity (determining the state-of-the-art) could be carried out at the HVM Catapult centres and some realistic specimens are going to be needed.

Jan Olav Endredud (DolphiTech): ***Improved understanding of the materials***

At the moment, ultrasonic testing can help to identify 80% of the defects and problems but, with better understanding of the materials and better training of the operators, this could be pushed up to 90%. Equally, incorporation of other methods that help identify the remaining 10% is required. Composites are a broad collection of materials and techniques; a better understanding of how those materials are joined is essential.

Andrew Hooker (Thatcham Research): ***Global project approach***

Cars are globally produced for a global market. Therefore, a global framework on NDT for automotive is needed, otherwise different approaches are going to be developed and this will create confusion in terms of different training and verification systems. This requires involving as many manufacturers as possible as all of them currently have some kind of strategy on high-value manufacturing of composites that can feed into a global programme

This requirement could be taken forward in two different ways: through the International Committee for Non-Destructive Testing (ICNDT), which has sector-specific working groups, or as a UK-specific activity that feeds into an international NDT standards committee. ICNDT Special Interest Groups (SIGs) are led by national NDT societies that have their own national groups. If BINDT started leading a working group on NDT for automotive composites within ICNDT, the UK could be well positioned as the main driver of any new standards and regulations in this area.

Whatever the approach, it is essential that all the manufacturers are on board and agree on technical standards for NDT in automotive. Also essential is to think about this approach as a long-term programme of work: composites is an industry that will have a big role in the future of manufacturing.

Once the panel members finished their contributions, the Chair asked the audience for further comments and suggestions.

Integrating NDT into the manufacturing process

It is important to understand the requirements for the potential application of NDT at the manufacturing stage, *ie* having better understanding of manufacturing times and constraints, to assess whether NDT methods can be applied during the manufacturing process and, if so, which ones are the most capable. Because typical manufacturing dwell times in automotive are so short, it might not be possible to perform all of an inspection on every component but, instead, a different part of the inspection could be performed on successive components in order to build a picture of the production quality. Emerging standards for the Industrial Internet of Things (IIoT) and Industry 4.0 allow high data-rate communication between sensors and storage/analysis and may allow for the creation of interoperability between NDT and automotive manufacturing processes. The providers of NDT equipment need to engage with the automotive manufacturers.

NDT for process design, process verification and process control

There is a role for NDT in process verification that will increase the confidence in the manufacturing process leading to manufacturing systems that are 'right first time, every time', reducing the need for NDT of every component. A stable production process, which should be possible for high-volume production, may still need to use NDT to diagnose deviations from a statistically-controlled process. NDT could be used as part of the process-control loop during production or may be able to detect deviations from design at a pre-cure stage or before resin infusion in order to allow rework or rejection to be carried out prior to escalating the value of the component. Equally, NDT can also be incorporated into the process-design stage in order to avoid defects, resulting in a more efficient and cost-effective manufacturing process. This will also result in automotive components being better prepared and more accessible for any potential NDT inspection.

NDT in repair facilities

Questions must be addressed regarding discussions about the use of remote experts to analyse data. Is there a liability issue if someone remotely analyses data sent by an 'inexperienced' damage assessor? Would insurers accept this remote-expert methodology and where would liability rest in the event that the repair did not fully address the damaged area? Unless we can increase confidence in the composite damage assessment and repair process, insurers will opt for replacement rather than repair and may feel they need to write off whole vehicles.

Conclusions

The workshop was widely praised by the attendees, as it brought together several communities for the first time to work out what is needed in order for NDT to make a difference for automotive composites. The benefits of a more joined-up approach were clear to those present and a Working Group on NDT for Automotive Composites will be established as a result, probably within BINDT's committee structure, chaired by Professor Robert Smith in the first instance.

A summary of the main requirements for NDT of automotive composites is as follows:

- Skills: Specific NDT skills for automotive composites are required, including a training syllabus and qualifications so that these can be mandated. It must be ensured that the new BINDT apprenticeship standards can be mapped to meet automotive composites requirements.
- Stakeholders: A stakeholder map is required to better understand the automotive composites landscape for NDT purposes.
- NDT technology: The state-of-the-art in NDT must be captured with direct application to automotive composites, including differentiation between off-the-shelf technologies (TRL6+), novel technologies (TRL 4-6) and future technologies (TRL 1-3). Realistic specimens will be needed and HVM Catapult centres could bid for funding for this.
- Coordinated global engagement between the NDT communities (researchers, equipment manufacturers, end-users, etc) and the automotive stakeholders via a new BINDT Automotive Composites Working Group, which should be proposed as an international (ICNDT) special interest group.
- Research to gain an increased understanding of the interaction between NDT methods and automotive composite structures, as well as the effect of defects.

- A technology map is needed of NDT methods (current and future) against component and defect type. Ultrasonic testing may meet 90% of defect detection and characterisation requirements but may be prohibitively slow in some cases, requiring other NDT technologies to be considered;
- A plan is required for the different options for integrating NDT into design, test, production and in-service cycles;
- The insurance sector needs to be engaged on the issues of damage assessment and repair and liability with regard to skill levels and use of remote-expert assessment; and
- Following the study of the state-of-the-art, research is required into NDT techniques for the gaps in capability, which will probably be:
  - Understanding the ultrasonic response of automotive composite materials;
  - Offline high-fidelity 3D characterisation methods for 2D and 3D woven composites at the design, test and process verification stages;
  - The link between defect characteristics and the effect of defects on performance;
  - Rapid-pass in-process quality check on the production line;
  - NDT for design of repairs and post-repair quality inspection;
  - Easy-to-use go/no-go NDT system for post-accident maintenance and repair; and
  - Use of installed-sensor monitoring systems for assurance of structural health.

Acknowledgements

Professor Smith would like to acknowledge the help of Dr Rostand Tayong and Miss Maria Arias in preparing this report on the workshop, and of the technical panel and all the presenters for providing summaries of their presentations for this document and for considerable assistance with convening the workshop. The workshop was organised by the Conferences Department of BINDT and this publication was made possible by the Publications Department of BINDT, to whom we are all very grateful.

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Appendix A. Delegate List

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Alastair Beaman	GKN Wheels & Structures, UK
Martyn Bills	Exova Ltd, UK
Darren Boakes	Resolution NDT Ltd, UK
Nick Brierley	Manufacturing Technology Centre, UK
Harry Brittin	Sonatest Ltd, UK
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Robert Crow	Jaguar Land Rover, UK
Annabel Dance	MTD Ltd, UK
T Gethin Davies	Jaguar Land Rover, UK
Hassan El-Dessouky	AMRC/University of Sheffield, UK
Andrew Elford	CCT/Hexion, UK
Andrew Feeney	University of Warwick, UK
Daniel Fish	Resolution NDT Ltd, UK
Richard Freemantle	Wavelength NDT, UK
Paul Gallen	National Composites Centre, UK
Gary Grubb	GE Power, UK
Neil Harrap	TWI Ltd, UK
Dee Harris	Jaguar Land Rover, UK
Laura Hayday	Babcock International, UK
Greg Hodge	Renishaw plc, UK
Andrew Hooker	Thatcham Research, UK
Vicki James	TWI Technology Centre (Wales), UK
Paul Jones	Lavender International NDT, UK
Andrew Kelly	National Composites Centre, UK
Gary Lowton	Sonatest Ltd, UK
Don Mann	Exova Ltd, UK
Laura Maybury	University of the West of England, UK
Tony Mays	Maycast-Nokes Precision Engineering Ltd, UK
Chris Minton	MTD Ltd, UK
Ben Morgan	Nikon, UK
Barry Morris	MISTRAS Group Ltd, UK
Michael Mullins	IMechE Engineering Training Solutions, UK
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Brian O'Rourke	Williams Formula One, UK
Sofia Pavlopoulou	Jaguar Land Rover, UK
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Published by:
The British Institute of Non-Destructive Testing
Midsummer House, Riverside Way
Bedford Road
Northampton
NN1 5NX, UK
Tel: +44 (0)1604 438300
Email: info@bindt.org
www.bindt.org

ISBN: 978 0 903132 67 2
DOI: 10.1784/book.2017.001

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