Gandhi, N., Rose, R., Croxford, A., & Ward, C. (2021). Developing a high-fidelity knowledge base for improvements in the nondestructive testing of advanced composite material products. In *Procedia Manufacturing* (Vol. 51, pp. 345-352). (Procedia Manufacturing). Elsevier Limited. https://doi.org/10.1016/j.promfg.2020.10.049

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 51 (2020) 345–352

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

33th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)
15-18 June 2021, Athens, Greece.

Developing a high-fidelity knowledge base for improvements in the non-destructive testing of advanced composite material products

Nikita Gandhi [a,b]*, Rob Rose[b], Anthony Croxford[c], Carwyn Ward[a]

[a]Bristol Composites Institute (ACCIS), Queen's Building, University Walk, University of Bristol, Bristol, BS8 1TR, UK]
[b]National Composites Centre, Feynman Way Central, Bristol, BS16 7FS, UK
cUltrasonics and Non-destructive Testing (UNDT), Queen's Building, University Walk, University of Bristol, Bristol, BS8 1TR, UK

* Corresponding author. 44 (0)1174568469. *E-mail address:* Nikita.Gandhi@bristol.ac.uk

---

Abstract

With the application of composites driven by an industry need to replace conventional materials, products must be designed to a lightweight criterion with safety margins essential to guarantee consumer safety. Non-destructive testing is used to ensure that safety and confirm that a component is fit for purpose. To improve inspection processes, the National Composites Centre, UK, aims to address gaps in understanding the state-of-the-art of inspection methods in the composites industry.

This paper describes an opportunity to further inspection understanding through the development of a novel high-fidelity knowledge base mapping material, component, and defect configuration to capabilities and limitations of selected detection methods. Using the proposed methodology, component and method criteria are used to establish a capability matrix. This matrix captures the evaluation of first iteration experimental testing of reference components. Deployment is expected to provide validated applicability data to support knowledge-based decision making for a range of inspection applications.

Keywords: Composites; Non-destructive testing; Knowledge management; Six sigma

---

1. Introduction

The versatility of composite materials is attractive for applications across many industrial sectors, with the expected growth of the UK composite product market to reach £12bn by 2030 (previously valued at £2.3bn in 2016) [1]. Elastic tailoring of properties such as stiffness, strength and toughness, in addition to the ability to light-weight components, provide opportunities for improvements in efficiency and operating costs [2].

However, composite products are particularly susceptible to the appearance of defects, interpreted here as 'an irregularity in a material or structure that causes it to depart from its specification as defined during the design process'[3]. These defects can occur due to decisions made in design or manufacturing process limitations, and during the in-service life of the component. However it is difficult to state at what point exactly a consequence of variability of an input to the manufacturing process becomes a defect [3,4].

Defects that can be introduced into composite structures due to these factors include delamination/disbond defects, fibre misalignment and porosity (void content). These non-designed features can detrimentally affect the structural integrity of a product and lead to potential catastrophic failure [5]. Defect occurrence, size, and frequency depend on the design characteristics and process cycle of the structure [6]. Since properties of composites are strongly influenced by their constituent materials, their distribution, and the interaction

10.1016/j.promfg.2020.10.049

among them, defects may lead to stress concentrations with the potential to knock down mechanical performance [7]. Therefore, it is important to ensure defects are identified and parts are verified as fit-for-purpose before they are employed in-service.

Component verification can be described as the process of assessing the conformance of an as-manufactured component against an acceptance criteria. This is a set of requirements prescribed by designers and product stakeholders to dictate the maximum allowable deviation from the designed component, providing a threshold for inherent processing variability [8]. Non-conformance of a component to the acceptance criteria risks potential catastrophic failure if employed in service. This is particularly relevant in the transportation industries where verification could be the difference between life and death.

Non-destructive testing (NDT) encompasses a group of specialist methods within quality assurance or control processes. NDT involves the detection and characterisation of surface and sub-surface discontinuities without altering the original attributes or harming the component being tested [9]. NDT methods enable a cost-effective route to ensuring production quality control with the level of inspection required for any given feature dependent on the criticality and risk of non-conformance [10].

The inspection of composite materials poses a challenge. Since materials are often non-homogenous and anisotropic, many traditional types of NDT do not work or are inconclusive [11]. For a defect detection method to be suitable, the response for an area of non-conformity must be highly distinguishable from the response for an acceptable region [6]. Moreover, prior knowledge of the component configuration, including material composition and defect type to be detected, is necessary for obtaining optimal results [12]. For those methods that are acceptable, each has their own set of advantages and limitations. As a result, methods can be seen to be complementary. In order to gain all relevant information with regards to a defect both quickly and precisely, a combination of NDT methods should be considered [13].

Ultrasonic testing (UT) is commonly used in the aerospace industry [6], and is based on the propagation of high frequency sound waves transmitted to the test object by a transducer and couplant [13]. Material properties can be ascertained through loss of original amplitude (or energy) in the response pulse. This pulse is dependent on how the ultrasonic wave propagates through the component, with beam incidence angle, wave velocity and material density, and how it interacts with any interfaces, grain discontinuities or defects affecting the response [9]. UT has been used to evaluate the effects of fatigue and damage tolerance testing on aircraft fuselage structures, detect cracks in components, and determine the presence of disbonds in wind turbine blades [14–16]. There are two techniques of UT that are typically employed; pulse-echo and through transmission UT. Choice of appropriate technique depends on the specific application; careful consideration must given to material and geometry specification, and process/quality control requirements [17].

The pulse-echo technique involves the detection of echoes produced when a contacted transducer/receiver unit introduces an ultrasonic pulse into the material and is reflected by a discontinuity within a component. The echoes provide information on flaw location, depth and size [18,19]. Conversely, through transmission uses separate transducer receiver units which are placed on either side of the part. Ultrasonic waves only travel once through the thickness and therefore do not provide depth information for discontinuities encountered along the wave path [20].

Process verification underpins design, structural integrity and manufacturing of composites, necessary for knowledge practices through the product development cycle. Additionally, verification is crucial for assessing the safety of components. However, it is evident that a lack of knowledge of inspection practices for composite manufacturing exists in a variety of industries. In the aerospace industry, defect criteria and failure constraints from decades ago are still used in acceptance criteria. Within the automotive and marine industries, a lack of experience and guidance have limited the use of NDT methods.

Outputs of cross-sector events such as the NDT Requirements in Composites workshop series hosted by The British Institute of Non-Destructive Testing and Composites UK’s event, Confidence in Composites, have identified that [21,22]:

- The state-of-the-art for NDT of composites is not completely clear.
- Knowledge sharing routes for the applicability of NDT are not established. The accessibility of understanding of what inspection methods can achieve is reported as an issue within NDT circles in addition to product development engineers/customer groups.
- Product development engineers do not have the justification for capital investment in NDT technologies.
- NDT has not been able to adapt to the requirements of different industries; for example, targeted NDT to cater for automotive rate requirements.

From this, event stakeholders identified two routes to bridge the existing knowledge gap in NDT for composites:

- Current state technology mapping, comparing NDT method capabilities and limitations against composite component and defect type.
- Integration of inspection data with defect criticality assessment as a route to bridge the existing knowledge gap in NDT for composites.

To support existing and future research and development programs and industry trends, National Composites Centre (NCC), Bristol, UK has identified a requirement for large scale automated NDT capabilities to be developed. The Composites Integrity Verification Cell (CIVC), Fig. 1is a novel multi-method, single platform system that will enable the combined scanning effort of UT and optical inspection. Inspection equipment is mounted upon an automation platform with twin robot repeatability of ±0.1mm.

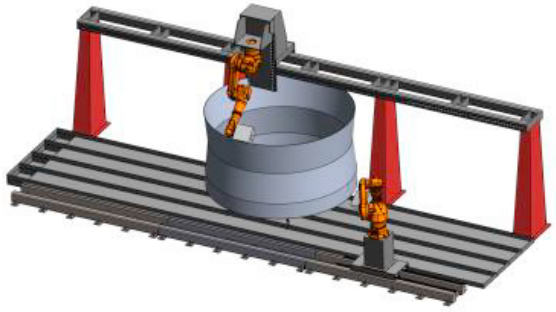

Fig. 1. Application of CIVC system on sample component at NCC [23]

This system ensures improved scan reproducibility and resolution over manual methods when inspecting large and complex components. To optimise the scan result, a combination of NDT methods and automated scan path generation can be used. The benefits of such a system include:

- Fast, repeatable, and accurate inspection.
- Inspection of large, complex geometry.
- Cater to industry development and demand.
- Provide a platform for development and scaling of new and existing inspection technologies.
- Opportunity for data fusion of inspection results from different NDT acquisition methods.

However, there are also risks associated with utilising this system technology:

- Novel technology requires a period of learning in order to effectively operate the equipment.
- Obtaining results from different methods requires an understanding of the appropriate application of NDT methods with respect to component/feature configuration.
- The knowledge of how best to operate the equipment for research and development programs to obtain an optimum inspection result has not been established and implemented into a robust process.

This paper demonstrates the development of a knowledge base (KB) mapping material, component and defect to capabilities and limitations NDT methods. A Six Sigma methodology is employed to construct the foundation of the knowledge tool, with population using only selected NDT methods and component configurations. A comprehensive KB can be used to support knowledge-based decision making for the selection of appropriate detection methods on CIVC and industrial applications to guarantee safety of components.

2. Development of a knowledge base

2.1. Research framework

The project utilises a waterfall project management system with a process flow based on the Six Sigma DMAIC (Define, Measure, Analyse, Improve, Control) framework [24].

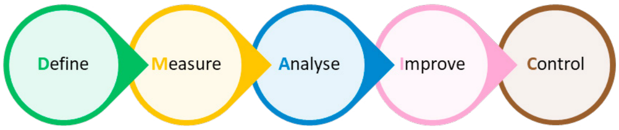

Fig. 2. Six Sigma DMAIC framework

Lean/Six Sigma tools are chosen in preference to other process improvement tools, such as Total Quality Management and Toyota Production System, due to the flexibility offered by the systems [25]. The Six Sigma DMAIC framework is preferred to the 5S Lean methodology for mapping the current state and identifying risks in NDT. However, utilising Lean Six Sigma frameworks can provide an opportunity to employ a variety of tools from both methodologies. Tools then can be tailored to requirements within the DMAIC framework.

Demonstration of the tools and outputs from the first three phases of the framework, shown in Fig. 2, are presented in this section, with the final two phases discussed as future work.

2.2.1. Define

The define phase of the DMAIC framework presents an opportunity to identify, prioritise and plot key aims and deliverables for the project.

Problem statement: A gap in understanding the current state capabilities and limitation of industry-standard NDT processes has been identified by NCC and industry. This is evident in all stages of the product development and manufacturing value stream. Additionally, lack of appreciation or misconceptions concerning the benefits of NDT (for example, quality assurance and process verification) have led to improper use of technologies.

Project objective statement: The objective of this project is to address the NDT knowledge deficit by introducing knowledge management (KM) practices. Explicit and tacit knowledge is captured in a high-fidelity KB through documentation of inspection results and technical 'know-how'. In the absence of single definition, KM encompasses [26]:

- The leveraging of knowledge towards an attainment of organisational goals and objectives.
- The management of knowledge artefacts, human sources of knowledge and processes of how knowledge is generated and applied.
- A resulting organisational culture that fosters knowledge of discovery sharing and learning.
- The involvement of knowledge, people, processes and technology.

By mapping composite material, component and defect configurations to selected NDT methods in a database, a comprehensive understanding of the state-of-the-art capabilities and limitations of detection methods can be determined. Once populated with the capabilities and limitations of a range of NDT methods, this expansive database can be exploited in inspection operations. Deployment will

Table 1. SIPOC diagram mapping an inspection process

Suppliers	Inputs	Process	Outputs	Customers
Manufacturers of inspection equipment	Equipment setup	Inspection of component	Characterisation of component (scan/image data)	Component suppliers
Inspection process theory	Scan settings		Data for process/design related issues	Design teams
Customer	Inspection requirements		Quality assurance	Manufacturers
	Component to be inspected		Pass/fail component	

enable informed decisions to be made on usage of the most appropriate inspection technology for an application.

The five elements of the SIPOC tool (Suppliers, Inputs, Process, Outputs, Customers) in Table 1 have been used to evaluate inputs and deliverables required for effective NDT to be implemented [27]. By focusing primarily on the inputs, process and outputs to the system, identification the key enablers/inputs that provide maximum output for customers can occur.

The key system enablers for the inspection process can be identified as the independent variables, or key performance variables (KPVs), that an operator is required to input in either physical or equipment setup to maximise valuable output. In the SIPOC tool, these inputs are found under two groups. 'Equipment setup' refers the choice of technical instrument or apparatus used, and 'scan settings' defines the instrument parameter choices the operator makes when conducting an inspection. Optimal characterisation of a component is obtained, with details of quality of the material and the inclusion of any non-designed features.

Key system enablers for an inspected component include the component design choices (for example, geometry and material characteristics) and manufacturing processing parameters.

Examples of these variables are discussed in the analyse phase.

2.2.2. Measure

KPVs defined from the SIPOC tool in the previous phase are used to construct a capability matrix. The applicability and suitability of NDT methods for composite configurations are then evaluated through a series of inspections with results entered into the matrix.

Composites encompass a large variety of materials with choice of constituents and fabrication method influencing the resulting product quality. Therefore, the range of different component configurations becomes too expansive for initial testing and matrix population. Carbon fibre specimen configurations are down-selected and categorised by geometry, source materials, specimen structure (monolithic or sandwich), and defect type (delamination/void and inclusions defects). These configurations are used to determine designs for reference standards, with consideration of components typically found in industrial applications.

For the first iteration population of the capability matrix, components are fabricated from simplified, well characterised material systems under laboratory conditions (between 18°C at 63% humidity and 24°C at 43% humidity [28]). Seeded defects are positioned in accessible locations, designed to test the limitations of an NDT technique across several component configuration criteria. Details of inputs and processing methods of an example reference standard and the number of matrix component configuration identifiers are summarised in Table 2. The design of this part is shown in Fig. 3.

Demonstrator F1 has been designed with step thicknesses varying between 5mm and 30mm. Artificial delamination defects are simulated as flat bottom holes at the near, mid and far surface of each step. This demonstrator part is typical of NDT reference standards used to calibrate an equipment setup and ensure the method is suitable for a component to be inspected. The series of 6mm diameter flat bottom holes are used as the indicator of method capability; aerospace acceptance criteria typically state that a 6x6mm discontinuity is the limit of acceptance [23]. Therefore, this condition is applied to all capability tests.

Reference components are inspected using the selected NDT methods and their sub-techniques. UT is one of the most universally applied methods in a variety of industries for detection of defects in composites [29], therefore UT is used to baseline the population of the capability matrix. Baselining against this well-researched method will enable a frame of reference to established. Other inspection methods then can be normalised against this set of results.

KPVs are adjusted for each inspection procedure to produce an optimum inspection result. The term 'optimum' is recognised as being dependent on diligence of method operator, where a degree of human error is assumed [10]. In order to account for operator variation, inspections of components are repeated with variable data logged for further analysis.

Variables are captured within the matrix and analysed. Techniques within the UT method bracket, such as pulse echo and through transmission, are treated as individual inspection processes. An example UT pulse echo inspection result for

Table 2. Reference component configuration, holes and steps machined to ±0.1mm tolerance

Part	Material type	Form	Thickness	Defect type	Processing route	Matrix Identifiers
F1	CFRP prepreg	Flat	Stepped at thickness (t) 5mm, 10mm, 15mm, 20mm, 25mm, 30mm	Artificial delamination defects simulated by flat bottom holes (FBHs). Near, mid, far surface defects in each step.	Hand prepreg lay-up, autoclave (180°C)	F1.1: t≤5mm F1.2: 5mm<t≤10mm F1.3: 10mm<t≤20mm F1.4: t<20mm

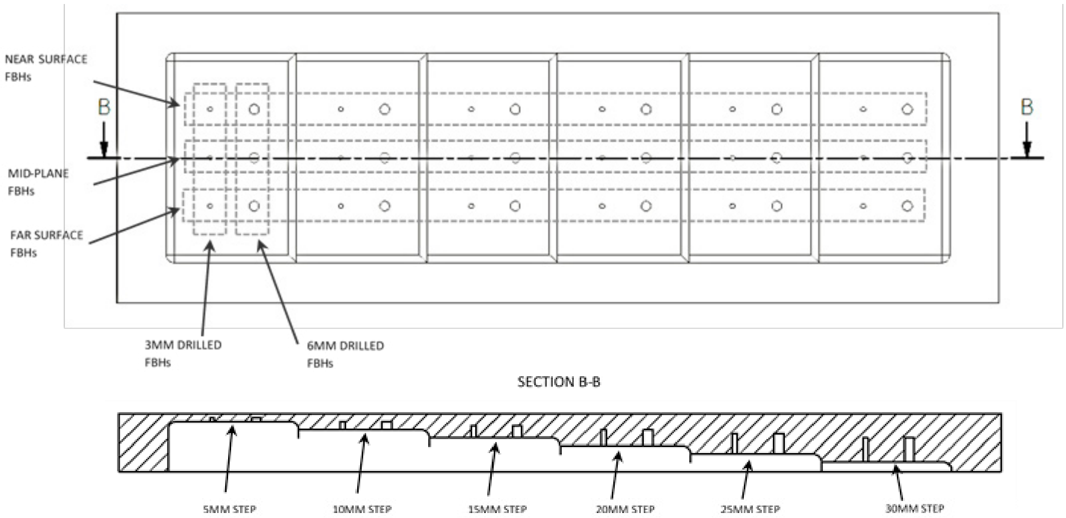

Fig. 3. Drawing of reference standard F1, first angle projection

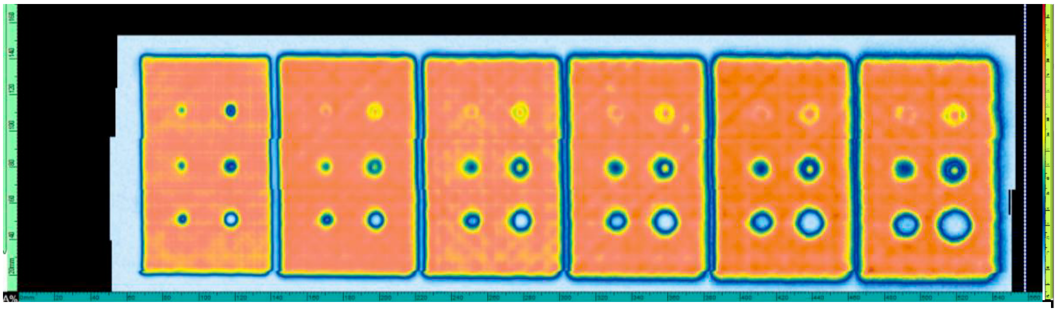

Fig. 4. Ultrasonic inspection scan image of reference standard F1 with 6mm defects identified, as scanned from flat surface

component ID F1 is given in Fig. 4, with further details on inspection analysis given in the next section.

2.2.3. Analyse

KPV data captured from inspections is analysed to evaluate the effectiveness of the inspection technique with respect to component configuration through the assignment of a red-amber-green (RAG) rating criteria.

RAG rating criteria have been formulated from interviews with two NCC NDT specialists and three external NDT specialists concerning the 'success' of inspection processes. All interviewed participants were aware of the project and have been involved in the development of NDT techniques. The semi-structured interviews comprised of investigations into operator experience and information priorities when interrogating a structure for defects. Presented with an example assessment criteria, they were asked if the criteria descriptions provided an adequate evaluation of NDT technique capabilities.

In the rating assignment, there are two parts against which effectiveness of an inspection process is assessed:

- Detection: where an anomaly is identified as being present in a structure. This could be an indication on the scan data that non-uniformity exists in the specimen and requires additional analysis to confirm a defect is present.
- Characterisation: where features of the anomaly are identified. This may be defect size or depth, details of which are confirmed against specimen drawings. Defect type is not considered in characterisation; it is a function of the specimen tested.

Table 3 provides a management-level perspective where a simplified description of capabilities would be beneficial to high-level engineering operations. Table 4 introduces an expanded set of definitions from a technical-user perspective.

In the scan result shown in Fig. 4, it is evident that all 6mm defects are detected in the material. Certain defect characteristics can cause defect visibility, and hence ability to analyse, as in the representation in Fig. 4, to vary considerably.

Table 3. Rating definitions from a management perspective

Rating	Definition
Red	Technique not capable of detection and characterisation
Amber	Technique capable of limited detection or characterisation
Green	Technique capable of detection and characterisation

Table 4. Rating definitions from a technical user perspective

Rating	Definition
Red	Technique not capable of detection and characterisation
Orange	Technique capable of characterisation only
Amber	Technique capable of detection only
Yellow	Technique capable of detection and part of characterisation
Green	Technique capable of detection and characterisation

Defects of ~1mm from the surface (bottom row) are clearly observed with no difference in visibility from the thinnest step to the thickest. For defects situated at the mid-plane depth of each step (middle line), visibility is less than for those near surface. This is due to the increased ultrasonic penetration depth, but defects are still identified with confidence. However, far-surface defects are observed with some uncertainty. This is due to the placement of ~1mm from the back surface as opposed to the relative depth; compensated signal strength remains fairly consistent over depth range. The resolution of the equipment is such that it is difficult to differentiate between the ultrasonic reflection signals from the defects and the back-wall surface. Careful analysis is required for this type of defect occurrence to ensure it is not missed. This is determined to be limitation for UT.

From further analysis, size and depth characteristics of the discontinuities are determined, which are then validated against drawings. Therefore, for all matrix identifiers of component F1, capability ratings are green. The assignment of these matrix ratings and inspection settings used are shown in Table 5. KPVs and setups used have been optimised such that a true positive or negative result is achieved. This highlights the importance of ensuring the correct setting are used; a single non-optimised setting could invalidate matrix entries with false positive or negative errors.

3. Discussion

3.1. Method Evaluation

The adoption of a Six Sigma DMAIC framework provides a process-orientated approach to addressing the NDT knowledge gap. Systematically arranged measurement tools have enabled the prioritisation of key issues and development of effective solutions. The flexibility of the DMAIC framework allows tailoring of the most beneficial tools to be used at each stage of current state mapping of capabilities and limitations of inspection techniques. Conversely, statistical process control frameworks were not considered to be applicable for process improvement in this project. The project does not exist within a production environment or impact on the improvement of an aspect of the inspection process.

The experimental method for inspection is based on documented NCC procedure. KPVs were altered to allow for inspection of matrix specimens with scan data analysed using industry standard data evaluation software as documented.

Experienced NDT specialists with relevant qualifications conducted all scans using the same equipment with a calibrated setup. However, standardised operating instructions tend to be generic and so a degree of operator freedom is required for each inspection setup. Individual method is a function of learning and past experience, hence no two operators will end up with the exact same variables from an optimised scan. Repeated inspections will assist in identifying relationships between KPVs and any outliers in inspection data. It is recognised that confounding variables exist, such as human error and environmental factors, however these have been disregarded and considered outside the scope of the project.

To date, approximately 70 tests have been conducted with UT techniques, populating the capability matrix and validating results. This provides the first steps towards recording undocumented capabilities and limitations of NDT techniques in a novel format. The experimental method detailed has evolved from initial tests following the development of tacit understanding of the process of inspecting components.

The use of composite reference samples fabricated under laboratory conditions with purposefully implanted seeded defects provides ‘best-case scenario’ results. However, it is a possibility that ‘real-life’ industry components could have more variability due to geometry, material, and processing differences. As a result, these components will be more susceptible to variability in NDT results which have the potential to nullify the capability matrix value in certain situations. To counter this, matrix values will be validated using example components with the required configuration that have not been fabricated as part of this project. This validation process discussed as further work.

3.2. RAG rating system

The assignment of capabilities using a RAG rating system aims to remove some ambiguity from NDT processes such that they become more accessible to project teams who are not versed in the technical details of NDT. The set of definitions held in Table 3 and Table 4 provide base values for an assessment criteria. Obtaining additional perspectives from different backgrounds will improve the applicability of definitions. Encouraging user engagement from focus group participants at NCC during the early stages of KB development and dissemination will assist in reinforcing these definitions.

Table 5. Population of KPVs and assignment of matrix ratings for inspection of reference standard F1

Pulser-Receiver Configuration		Probe Configuration		Matrix Rating	
KPV	Value	KPV	Value	Matrix ID	Rating
Energy	80V	Frequency	5MHz	F.1.1	Green
Gain	11.17dB	Number of elements	64	F1.2	Green
Pulse width	100.00ns	Manipulator type	Semi-auto	F1.3	Green
Element aperture	8	Coupling method to part	Water, contact	F1.4	Green

It is evident that variations in individuals' definitions stem from experience and the environment in which they anticipate the matrix will be used. For users with a technical viewpoint, deploying the matrix as a decision tool on project tasks require an increase in distinct definitions. This may be for ease of use with more detail where criteria boundary conditions are too vague. The terminology 'with limitations', used to describe the amber category, could indicate a multitude of result variations. It is therefore considered to be where the most definition uncertainty lies. Despite this uncertainty, the amber category or the orange-amber-yellow bracket both encompass the notion that there is limited confidence in the inspection result. This is an important statement as it indicates that there is possibly poor reliability or a lack of experience in this area and requires more focus. When coupled with industry trends and requirements, it provides an initiation point for research and development.

3.3. Impact of the knowledge base

By creating a central repository of knowledge, the KB enables furthering of NDT knowledge through the capture of the current state of inspection technique capabilities and limitations. This organised information can be used to underpin the effectiveness of an NDT system, providing the rationale to support the application of a certain method during inspection. This is crucial when utilising a system such as NCC's CIVC, where knowledge-based decision making should be employed to determine the most effective detection method for a feature of a component. It is also expected to be necessary when looking to produce a compound optimum inspection result.

The KB additionally provides a key enabler in the introduction of KM practices in NDT. It is anticipated that integration into a knowledge management system (KMS) will follow the development of the KB, given the deployment on CIVC. Incorporating a KMS enables a feedback loop from inspection into design and manufacturing activities, augmenting decisions made through design for inspection methodologies. Additionally, the validation data can provide assurance for optimising components, with the confidence that the controls to detect anomalies will be effective. Currently the status of how CIVC will work as a system is undetermined, therefore determining how the KB will best merge with CIVC processes as a KMS will require further work.

From this study, it is understood that NDT of composites is representative of a complex system. KPV tailoring is required for each component, therefore a KMS will not provide a prescriptive solution for the inspection of components. Despite this, the data contained within the KMS will become a benchmark for inspections on CIVC through the generation of informed best-practice guidelines.

4. Conclusions

4.1 *Conclusions*

To date, the work within this project has focussed on the demonstration of a Six Sigma DMAIC framework to show the development of a KB mapping composite material, component and defect configuration to NDT method.

Establishing a KB provides the first step in moving towards the introduction of KM initiatives that will aim to address the gap in the understanding of capabilities and limitations of NDT techniques for inspection of composite components. This is an issue currently identified by industry.

A capability matrix is constructed to evaluate selected NDT techniques against reference samples representative of typical industry components. KPVs and scan data are recorded and analysed to assess the ability of the inspection technique to detect and characterise defects within the component configuration. This 'effectiveness' value is assigned a red-amber-green rating, with selected population of the capability matrix reported in this paper.

As the KB acts as a repository of knowledge, holding information pertaining to the capabilities of NDT techniques with respect to component configuration, it can be deployed as a decision tool for inspection activities. An improved inspection process is facilitated by the knowledge of the suitability of an NDT technique for a known part feature. Lessons learnt from each inspection can be fed back into understanding and developing the applicability of a technique. Furthermore, inspection results can be incorporated into the product lifecycle and design practices through integration of the KB into a KMS.

4.1. Future work

The remainder of this project will involve a continued effort to manufacture and inspect reference components for the iterative population of the capability matrix. In addition, investigations into the remaining phases of the DMAIC framework for the development of KMSs will commence.

4.1.1. Improve

Inspection processes will be further evaluated using a failure mode, effects and criticality analysis tool. An evaluation of inspections that resulted in a red or amber rating within the capability matrix will provide an opportunity to explore the factors why a green rating was not achieved. By highlighting the critical risks, it may be possible to provide development routes for the improvement of inspection processes and design of components for ease of NDT.

4.1.2. Control

Repeated testing of components will be necessary to verify the data captured in the capability matrix and to account for measurement and equipment variability. Additionally, components that have not been fabricated under this project will be tested to ensure applicability of the matrix to industrial components. Integration of the KB with NCC operations will be necessary for active deployment on project tasks and into CIVC systems. After effectiveness of the KB as a decision tool is demonstrated within NCC, it is expected the KB will be disseminated to the wider NDT community for improvement and expansion. Once baselined with UT, it will be possible to expand the KB to include and inform other NDT methods.

Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Composites Manufacture (grant: EP/L015102/1) and The Future Composites Manufacturing Hub (grant: EP/P006701/1). The authors acknowledge the National Composites Centre for their support of this research. All data necessary to reproduce the results and support the conclusions are included in this paper.

References

[1] Composites UK., 2016. The 2016 UK Composites Strategy. Hemel Hempstead.

[2] Clyne, T.W., Hull, D., 2019. An Introduction to Composite Materials. Cambridge University Press.

[3] Potter, K.D., Khan, B., Wisnom, M.R., Bell, T., Stevens, J., 2008. Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures. Composites Part A: Applied Science and Manufacturing 39(9): 1343–54, Doi: 10.1016/j.compositesa.2008.04.016.

[4] Potter, K.D., 2009. Understanding the origins of defects and variability in composites manufacture. 17 th International Conference on Composite Materials, Edinburgh, UK p. 27–31.

[5] Cong, J., Zhang, B., 2012. Methodology for evaluating manufacturability of composite materials. Applied Composite Materials 19(3–4): 189–201, Doi: 10.1007/s10443-011-9195-x.

[6] Smith, R.A., 2009. Composite defects and their detection. Materials Science and Engineering III: 103–43.

[7] Agarwal, B.D., Broutman, L.J., Chandrashekhara, K., 2006. Analysis and Performance of Fiber Composites. John Wiley & Sons.

[8] Crowley, D.M., Ward, C., Potter, K.D., 2013. A Status of Acceptance Criteria and Process Requirements in Advanced Composites Manufacturing, and Whether They are Fit for Purpose. SAE Technical Paper 2013-01-2144: 10, Doi: 10.4271/2013-01-2144.

[9] Gholizadeh, S., 2016. A review of non-destructive testing methods of composite materials. Procedia Structural Integrity 1: 50–7, Doi: 10.1016/j.prostr.2016.02.008.

[10] Bertovic, M., 2016. Human Factors in Non-Destructive Testing (NDT): Risks and Challenges of Mechanised NDT. BAM, Berlin, Germany, 2016.

[11] Khattak, M.A., Mukhtar, A., Shahid, I.S., Sufian, M.S.M., 2016. Akademia Baru A Review on Application of Non Destructive Techniques on Composites Akademia Baru. Journal of Advanced Research in Applied Mechanics 20(1): 12–21.

[12] Bates, D., Smith, G., Lu, D., Hewitt, J., 2000. Rapid thermal non-destructive testing of aircraft components. Composites Part B: Engineering 31(3): 175–85, Doi: 10.1016/S1359-8368(00)00005-6.

[13] Garnier, C., Pastor, M.L., Eyma, F., Lorrain, B., 2011. The detection of aeronautical defects in situ on composite structures using non destructive testing. Composite Structures 93(5): 1328–36, Doi: 10.1016/j.compstruct.2010.10.017.

[14] Lee, W.J., Seo, B.H., Hong, S.C., Won, M.S., Lee, J.R., 2019. Real world application of angular scan pulse-echo ultrasonic propagation imager for damage tolerance evaluation of full-scale composite fuselage. Structural Health Monitoring, Doi: 10.1177/1475921719831370.

[15] Ibrahim, M.E., Smith, R.A., Wang, C.H., 2017. Ultrasonic detection and sizing of compressed cracks in glass- and carbon-fibre reinforced plastic composites. NDT and E International 92(August): 111–21, Doi: 10.1016/j.ndteint.2017.08.004.

[16] Kumar, S., Anand, R.B., 2019. A case study on damage detection of wind turbine composite blade. FME Transactions 47(1): 135–41, Doi: 10.5937/fmet1901135s.

[17] Wróbel, G., Pawlak, S., 2007. A comparison study of the pulse-echo and through-transmission ultrasonics in glass / epoxy composites. Journal of Achievements in Materials and Manufacturing Engineering 22(2): 51–4.

[18] Hasiotis, T., Badogiannis, E., Tsouvalis, N.G., 2011. Application of ultrasonic C-scan techniques for tracing defects in laminated composite materials. Strojniski Vestnik/Journal of Mechanical Engineering 57(3): 192–203, Doi: 10.5545/sv-jme.2010.170.

[19] Shen, Q., Omar, M., Dongri, S., 2011. Ultrasonic NDE Techniques for Impact Damage Inspection on CFRP Laminates. Journal of Materials Science Research 1(1): 1–16, Doi: 10.5539/jmsr.v1n1p2.

[20] Meyendorf, N., Nagy, P., Rokhlin, S., 2004. Nondestructive Materials Characterization: With Applications to Aerospace Materials. vol. 67.

[21] BINDT., 2017. Report from the Workshop on NDT Requirements for Automotive Composites. Workshop on NDT Requirements for Automotive Composites, Coventry.

[22] BINDT., 2018. Report from the Workshop on NDT Requirements for Marine Composites. Workshop on NDT Requirements for Marine Composites,.

[23] Limmack, A., 2017. Automated Composites Integrity & Verification Cell Specification. Internal National Composites Centre Report: Unpublished.

[24] Kumar, S., Sosnoski, M., 2009. Using DMAIC Six Sigma to systematically improve shopfloor production quality and costs. International Journal of Productivity and Performance Management 58(3): 254–73, Doi: 10.1108/17410400910938850.

[25] Hailu, H., Mengstu, S., Hailu, T., 2018. An integrated continuous improvement model of TPM, TPS and TQM for boosting profitability of manufacturing industries: An innovative model & guideline. Management Science Letters 8(1): 33–50, Doi: 10.5267/j.msl.2017.11.002.

[26] Desouza, K.C., Pacquette, S., 2011. Knowledge management: An introduction. Neal-Schuman Publishers.

[27] Pyzdek, T., Keller, P., 2009. The Six Sigma Handbook, Third Edition. McGraw-Hill Education.

[28] AC 21-26A., 2010. Quality Control for the Manufacture of Composite Structures. U.S. Department of Transportation, Federal Aviation Administration: 1–20.

[29] Broughton, W.R., Lodeiro, M.J., Sims, G.D., Zeqiri, B., Hodnett, M., Smith, R.A., et al., 1999. Standardised procedures for ultrasonic inspection of polymer matrix composites. ICCM 12th Conf. Composite Mater.,.