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Standardisation requirements for Ultrasonic C-scanning of Polymer Matrix Composites - An Initial Assessment

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ABSTRACT

As part of a wider programme aimed at new or improved test methods for quality control, qualification and design data purposes, an assessment has been undertaken on the "standardisation" requirements for the use of the ultrasonic C-scan technique for evaluating polymer matrix composites. This report is a compilation of that assessment, which covered current practices used by industry and requirements in terms of defect detection and measurement.

The report contains sections on calibration of the equipment, determination of porosity and detection and measurement of all types of defects. The requirements for standards have also been investigated. The principal needs identified are for standards for calibration of the equipment and defect detection. The large majority of participants do not measure porosity using the ultrasonic C-scan technique and there was not a strong requirement for standards in this area. Very few participants were aware of the requirements in the draft European standard, pr EN2565, to measure porosity using ultrasonic methods.

The results of the assessment will be used to guide a research programme to satisfy the identified needs.

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1. INTRODUCTION

Ultrasonic inspection techniques are widely used for the non-destructive testing (NDT) or evaluation, of polymer matrix composites. The principal forms of the technique require that the interrogating beam be aligned normal to the surface of the sample, where it is particularly sensitive to the detection of defects lying parallel to the surface, such as delaminations. The technique is also sensitive to the detection of porosity, which attenuates the beam. The received information may be displayed in point, cross-section (yz) or area (xy) form, termed A, B, or C-scans respectively. C-scan is the most common form, where the information displayed can be on a grey or more recently colour scale, which usually represents the received maximum peak amplitudes within a defined gate. Ultrasonic C-scan equipment normally uses water as the acoustic couplant, the sample either being immersed in a water bath or scanned using water jets. Modern ultrasonic C-scan equipment can be very sophisticated and in some cases, very large. This is especially the case in the aerospace industry, which has pioneered the use of automation and image processing techniques for investigating large components, involving considerable capital and manpower resources. More information on the technique can be found in ref 1.

Although used extensively for the detection of manufacturing and in-service defects in polymer matrix composites, there is currently no national standard practice available specifically aimed at the inspection of these materials. Nevertheless, the technique is in such widespread use that a recent draft European standard on the production of carbon fibre reinforced resin test panels for the aerospace industry, pr EN2565, included a clause which required the porosity of the panels to be determined using ultrasonic methods[2]. A recent review on standards development for advanced polymer matrix composites, conducted on behalf of the British Plastics Federation by the National Physical Laboratory (NPL) in 1990, also highlighted a need for reference materials for ultrasonic scanning of these materials for void content[3].

These factors prompted the NPL to take a wider look at the use of ultrasonic C-scanning of polymer matrix composites and the need for standard procedures and, if practical, reference materials. This initial investigation has involved an assessment of current practices used by industry and the requirements of industry for porosity measurement and defect detection. This report is a compilation of that assessment. A total of 62 assessment forms was sent out. Ten were sent to interested parties for information only, and 6 were sent to manufacturers of C-scan equipment. Thirteen forms from current users and three from manufacturers were completed and returned. This amounted to a response rate of around 30%. The manufacturers responses have not been included in the overall scores as it was felt that this might cloud issues, however their responses have been taken into account in the section on calibration of the equipment. Not surprisingly, users from the aerospace industry made up a sizeable proportion of the participants, however it should be noted that users across a range of industries and organisations were given the opportunity to participate.

In the following report the next four sections follow the original assessment form. Section 2 summarises the response to the initial assessment of a range of NDT techniques used for polymer matrix composites. Sections 3, 4 and 5 concern the ultrasonic C-scan technique. Section 3 summarises the response to the section on usage, calibration and operation procedures, whereas Sections 4 and 5 summarise the responses to the sections on porosity measurement and defect detection respectively. Section 6 gives a summary of the assessment.

Where applicable, the results of the questions in the assessment form have been complied into tables, which are given in the appendices. The majority of questions required more than a simple 'yes' or 'no' answer. The answers therefore had to be grouped in these cases and consequently are not literal representations of the answers given in the assessment form. A

score of one was attributed to each participant for each answer represented in the tables. Many questions required lengthy answers and the quality and quantity of information was felt to be high, for which NPL is grateful.

2. AN INITIAL ASSESSMENT OF NDT TECHNIQUES USED FOR POLYMER MATRIX COMPOSITES

This first section of the assessment was intended to give an overview of the use of the commonly known NDT techniques and the use of standards with these techniques. The scores are given in Appendix 1.

Given that the assessment as a whole was aimed at users of the ultrasonic C-scan technique, it is not surprising that this technique scored highly in the 'in use' column. However it is interesting to note the extent of the use of other techniques by the participants, indicating to some degree the limitations of the C-scan technique. After C-scan, the most commonly used techniques are (in order): film based X-radiography, ultrasonic A-scan, followed by mechanical impedance and the coin tap method. The purpose of the latter technique is in general described as being an informal or rough guide, whereas the mechanical impedance technique is predominantly used for the inspection of thin skinned honeycomb structures. From comments made, film-based X-radiography, ultrasonic A and C-scan techniques are all used for production and in-service inspection. Film based X-radiography and ultrasonic C-scanning are also used for defect characterisation/analysis. Usage of the C-scan technique is covered in Section 3. Less common but other notable techniques included penetrant enhanced X-radiography (PEXR), eddy current, the Fokker bond tester and the acoustic emission technique. Other techniques used includes liquid state nuclear magnetic resonance (NMR) to monitor cure, a water leak test to detect porosity through skins of honeycomb sandwich panels and some additional techniques currently being developed, including D-sight, an optical surface inspection technique.

The most important point to note from a standards point of view is that a high proportion of the participants use some form of standard procedure or reference material, demonstrating their importance in the NDT of polymer matrix composites. The requirements for standards with the ultrasonic C-scan technique will be looked at in more detail in the following sections.

3. USAGE, CALIBRATION AND OPERATION PROCEDURES

Where applicable, the answers to the questions in this part of the assessment have been compiled into tables and are given in Appendix 2.

3.1 USAGE

Table 2.1 shows the current most common usage of the C-scan technique by the participants. The technique is principally used to inspect test panels. However, component and known (simulated) damage assessment also scored highly. Assessing components for unknown service damage may be less common due to the problem of removing components in order to carry out the inspection. Recent developments in portable C-scan equipment may change this situation in the future. Other uses stated included quality control of production panels, damage development monitoring and technique development.

Overall, the information given regarding equipment details was insufficient to attempt any tabulation. However, it can be said that the range of C-scan equipment used by the participants is very wide, and was supplied by only a very few manufacturers. Equipment in use ranges from small immersion tanks to large multi-axis jet squirter systems, individual

organisations frequently employing a range of equipment for development and production purposes. Jet systems are often custom-built to scan large areas (say 10m x 5m). Both plain and focused transducers are used, operating at frequencies in the range from 0.5 MHz to 80 MHz.

3.2 EQUIPMENT CALIBRATION

The answers to the questions on equipment calibration varied enormously. In some cases, references were simply made to customer and/or company procedures, or the use of 'reference specimens' of some kind. In a few cases, however, more detailed answers were given, allowing more of an insight into individual calibration procedures. Nevertheless, it is difficult to generalize about calibration procedures overall. However, from the answers given, the calibration of the equipment may be divided into two types; instrument/electronics calibration and system calibration. The incidence and frequencies of these two types of calibration are given in Table 2.2. Only 39% of participants carry out instrument/electronics calibrations and these are done either annually or biannually. System calibrations are more frequent, the majority (62%) being carried out immediately prior to each scan.

Instrument/electronics calibrations are either carried out by the manufacturer or by the organisations themselves using electrical attenuators. Two out of the three manufactures who replied to this assessment recommended annual or biannual instrument/electronics calibrations. Details concerning calibration were not given. Table 2.3 shows that the participants have varying amounts of information regarding their system characteristics. This may indicate that calibration procedures and to some extent requirements, may vary between participants.

3.3 SYSTEM CALIBRATION

System calibration was generally described as involving the use of reference standards of some sort, as specified in Table 2.4. The majority of participants (62%) employed a reference specimen containing simulated flaws, four of which were described as being representative of the component under test. Where quoted, the defect simulators consisted of polytetrafluoroethylene (PTFE) or aluminium inserts. The defect simulators are generally laminated into the test piece at given depths through the thickness. Some participants indicated that the reference specimen design was dictated by the customer. In addition, some participants indicated that the reference specimens used for calibration were the same as those used for checking the system for defect detection (see Table 4.3, Appendix 4). Overall, the reference specimens used for calibrating the equipment would appear to be similar if not the same as those used for checking the system.

In some cases system calibration was described as setting up the equipment to the manufacturers instructions and then adjusting the 'scanning sensitivity' to detect the flaws in the reference specimen. Reference specimens may be scanned alongside large samples as a check on the calibration of the system. Comments made by manufacturers suggest that the electronics would be unlikely to drift over such short durations.

Table 2.5 clearly shows that the majority of participants feel there is a need for a reference material to calibrate their equipment, demonstrating the need for uniform standards for calibration. A high proportion (69%) of participants currently have some form of written procedure for the calibration and operation of their equipment, as shown in Table 2.6. However, the widespread use of such procedures by inexperienced personnel are in some instances prevented by customer enforced requirements for training.

4. DETERMINATION OF POROSITY

Answers from the questions in this part of the assessment have, wherever applicable, been compiled into tables and are given in Appendix 3.

Out of a total of 13 participants in this study, only three measure porosity using the ultrasonic C-scan technique (see Table 3.1). One of these uses an unspecified customer method, whilst the other two use empirical formulae linking percentage void volume (%Vv) to attenuation, based on the work carried out at RAE, Farnborough, in the mid-seventies[4]. These authors linked %Vv to attenuation for a particular laminate. The composites were manufactured with varying levels of porosity and the surfaces were ground prior to scanning.

Low levels of porosity (ie < 1.5%) are determined by these participants using the same methods. However, one participant made the comment that their organisation was, in general, not interested in measuring low levels of porosity (ie < 1.5%). Similar comments have been made informally, with references to the more recent work carried out at RAE, on the criticality of defects[5,6]. These authors have shown that design criteria are more important limiters to the performance of composites than low levels of porosity, and have suggested that 5% Vv is acceptable for composites under tensile stress[5]. However, even porosity levels < 1% have been shown to affect interlaminar shear strength[4].

The reference standards used by those participants measuring porosity using ultrasonic C-scanning can be broadly described as samples containing a range of porosity. The stated use of correction factors to calculate attenuation values may suggest that not all these reference standards are made of the same material as the sample under test. No reference was made to surface condition.

Overall it would appear that the ultrasonic C-scan technique is not used routinely to establish % Vv levels, indeed only six participants indicated an ability to distinguish between porosity and 'other defects' using C-scanning (see Table 3.2). The 'other defects', where quoted were delaminations, disbonds and inclusions, distinguished by the appearance of the C-scan, attenuation levels and reference to the A-scan. However, one participant made the comment that it was not possible to distinguish porosity from other flaws using the through-transmission technique alone, though this is possible using the pulse-echo technique. Some participants indicated that other NDT techniques are also used to characterise porosity, including visual examination and X-radiography. Comments made here and informally elsewhere, suggest that porosity in general is not considered to be a major problem in polymer matrix composites. However, one participant indicated that their organisation do determine porosity qualitatively using the ultrasonic C-scan technique, by comparison with a low porosity laminate. This may well be the norm. More information regarding defect detection is given in Section 5. Other participants indicated that porosity was only determined quantitatively on the start up of production runs and/or on production control pieces using destructive methods such as chemical digestion or microscopic cross section.

Those participants who do measure porosity using the ultrasonic C-scan technique, estimated the errors to be ± 0.5% and the minimum level of porosity measurable at between 0.5 and 1%. However, surface effects, geometry, resolution and the errors involved in destructive determination of porosity, were all indicated as being limiters to accuracy.

4.1 EUROPEAN STANDARD ON TEST PANEL MANUFACTURE

As mentioned in the Introduction, part of the reason this study has been conducted is to determine whether the requirements in the draft European standard, pr EN2565[2] regarding porosity determination, may be realised. Only three participants in this study were aware of the existence of this standard and only two were aware of the requirements to determine

porosity using ultrasonic methods (see Table 3.3). Briefly, the draft standard, circulated for public comment in 1988, describes two methods for the preparation of carbon fibre reinforced resin panels, methods for determining the quality of the panel and information to be included in the report on preparation. The clauses on porosity are clause 5.3.4 and clause 6.8. Clause 5.3.4, in the section on quality determination, states "determine the porosity by means of an ultrasonic inspection method using the procedure agreed between the parties concerned". Clause 6.8, in the report section, requires the "porosity level shown by ultrasonic scan picture" to be stated. Neither of the two participants who were aware of the above clauses outlined a method for fulfilling these clauses or described what reference standard could be used.

When questioned on the need for a reference material for determining porosity using the ultrasonic C-scan technique, less than 50% of participants gave a clear "yes" in answer (see Table 3.4). The difficulty in producing a relevant reference standard was cited by some participants as a problem, whereas others indicated that their organisation would only need a reference standard if customer requirements necessitated its use. The application of prEN2565, if published in the current draft, would fulfil such a requirement. The stated requirements for a reference material for determining porosity using the ultrasonic C-scan technique, where given, are summarised below:-

variable porosity, between 0 and 6%
attenuation/unit thickness representative of component under test
same surface finish as component under test.

The acceptance levels given for porosity in test panels and production panels were, in general, considered to be the same. The actual value of porosity for a component was generally described as being dependent on the size of component, design and application and could be as much as 5% or less than 0.5%.

Overall, only those participants measuring porosity using the ultrasonic C-scan technique have procedures for acceptance/rejection based on ultrasonic data regarding porosity levels (see Table 3.5). These were described as being company confidential and were not detailed. However, some participants indicated that material would be rejected if the attenuation exceeded a critical value for whatever reason. Acceptance/rejection criteria for defects in general are covered in the next section on defect detection.

5. DEFECT DETECTION

Where applicable, the answers from the questions in this part of the assessment have been compiled into tables and are given in Appendix 4.

Table 4.1 shows the defects that the participants indicated they can detect using ultrasonic inspection methods. The scores indicate the number of times each type of defect was quoted. Delaminations scored highly, as did disbonds, foreign inclusions and voids. Voids and porosity tended to be quoted separately. The distinction may have been made on the basis of size, voids tending to be considered larger.

In general, defects were described as being detected by changes in received signal amplitudes as represented on the C-scan. In some cases, references were made to set procedures and the use of reference test pieces for comparison. Some participants also indicated the use of a range of techniques to detect defects, including visual methods, X-radiography and mechanical impedance, as well as ultrasonic methods (see Section 2). Most participants distinguish between different types of defect on the basis of experience. This often involves reference to the A-scan and if necessary, other NDT techniques or destructive analysis for confirmation. Delaminations and inclusions were generally described as being distinguished

by the received signal amplitudes, their size and shape on the C-scan. Porosity was generally described as being distinguished by an increase in attenuation of diffuse nature or a reduction in backwall echo strength on the A-scan in pulse-echo mode.

Table 4.2 shows the defects the participants indicated that they need to detect. In general, they are the same as those quoted as being detectable using ultrasonic methods. The scores do not give the complete picture however, as some participants gave no definite answer or else made references to customers acceptance criteria.

The accuracy to which the participants can measure the size of a defect is given in Table 4.3. The wide range of accuracies (between ± 0.3 and ± 5 mm) is indicative of the wide range of equipment in use. The acceptable accuracy for defect size measurement also shows a wide range, implying a commensurately wide range of acceptance criteria for defect size.

The reference standards used for defect detection by the participants have been tabulated in Table 4.4. The majority use some form of reference specimen containing known defects. In some cases these were described as being representative of the component under test, implying the same material and geometry. It is not clear, from the answers given, whether those simply described as reference specimens are made from the same material as the sample under test. Some participants did indicate that the reference materials used for defect detection are the same as those used for equipment calibration. This may suggest that the equipment is set up to detect only those defects that are represented in the 'defect standard', ie the reference specimen containing artificial defects. Where quoted, reference defects were described as being made from PTFE, aluminium or backing tape of known dimensions. In two cases, reference defects were described as real defects, though maintenance of real defect size was stated by one participant as being a problem. Informal discussions elsewhere have indicated that this may also be a problem with PTFE inserts.

More than 50% of the participants feel that their reference standards successfully represent real defects (see Table 4.5). In some cases the reference design was described as being dictated by the customer. Only one participant felt their reference standard was unrepresentative. However, almost 70% of the participants feel there is a need for reference standards for defect detection (see Table 4.6), demonstrating the need for standards in this area. The stated requirements for such a standard are summarised below:-

representative of component as regards material, geometry and surface finish
representative defects, encompassing as many defect variables as possible
standard means of including defects
defects at different depths, of known size
simple to produce and reproducible

Further requirements regarding the use and application of such standards are given below:-

standard means of assessing porosity
standard procedure for identifying and sizing flaws against known references

A high proportion of participants (77%) currently have procedures for acceptance/rejection based on ultrasonic data regarding defect size (see Table 4.7). These are predominantly customers criteria and vary according to the customer. In some cases examples were given and these basically involve the following:-

limit on maximum length of defect in major dimension
limit on number of defects in a specified area
limit on spacing between defects
limit on proximity of a defect to an edge
limit on area of a single defect

limit on defect area as a percentage of component area

To some extent the variation in what is considered an acceptable defect may be due to the variability of application, but must also be due in part to the fact that the significance of defects in primary load bearing components of polymer matrix composites has not yet been established. However, many organisations are working in this area to establish the criticality of defects.

6. SUMMARY

Some form of standard procedures and/or reference materials are currently widely used with non-destructive testing of polymer matrix composites. In this study, a high proportion of participants use ultrasonic A-scanning and X-radiography as well as ultrasonic C-scanning, to characterise defects. The ultrasonic C-scan technique in particular, is currently used to detect, characterise and size a wide range of manufacturing and in-service defects in polymer matrix composites. However, currently the principal uses are for test panel and component assessment and known (simulated laboratory) damage assessment.

In general, the methods of detecting and characterising defects would appear to rely heavily on experience and training. However, reference specimens containing known defects play an important part in both the characterisation of defects and the calibration of the equipment. Reference specimens would appear to be used to establish scanning sensitivity and/or for characterising and sizing of defects and may be manufactured to company and/or customer specifications. Although the majority of participants feel their reference specimens for defect detection are representative of real defects, almost 70% feel there is a need for reference standards for defect detection.

The majority of participants in this study use some form of written company and/or customer calibration and operation procedures. However, this assessment has also highlighted a need for standards for calibration of the equipment.

The vast majority of participants do not currently measure porosity using the ultrasonic C-scan technique. Less than 50% of participants gave a clear "yes" answer to the need for a reference material to determine porosity using C-scanning. This may indicate that the participants have reservations regarding either the use of the C-scan technique for void level measurements or the need to make quantitative porosity measurements non-destructively. From comments made it would appear that porosity is, in general, determined destructively at the start up of production runs or from production control test specimens. It is clear that current requirements regarding porosity measurements in pr EN2565 cannot be readily realised.

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APPENDIX 1

TABLE OF ANSWERS FROM AN INITIAL ASSESSMENT OF NDT TECHNIQUES USED FOR POLYMER COMPOSITES

Method	In Use	Standard Procedures, Reference Materials (including in-house)	
		Existing	Needed
Ultrasonic:			
A-scan	10	9	2
B-scan	3	3	2
C-scan	13	11	5
X-Radiography:			
PEXR	4	4	
real time	2	2	1
film base	11	8	1
CAT	0		
Compton tomography	0		
Thermography:			
IR	1		2
SPATE	2	2	
Optical:			
holography	1	1	1
moire interferometry	1	1	
Eddy current	4	2	1
Acoustic emission	3	1	1
Stress wave factor	2		
Mechanical impedance	7	7	2
"Coin tap"	7	6	1
Fokker bond test	4	4	

Scores out of 13

APPENDIX 2

TABLES OF ANSWERS FROM USAGE, CALIBRATION AND OPERATION PROCEDURES SECTION

Table 2.1
Current Usage of Ultrasonic C-scanning Equipment

Use	Score*
Test panel assessment	11
Component assessment	9
Known (simulated laboratory) damage assessment	9
Repair assessment	7
Unknown service damage assessment	5

Table 2.2
Current type of calibration employed

Type of Calibration	Frequency	Score
Instrument/Electronics	annual/biannual	5
System	prior to each scan	8
System	weekly	1
System	daily	1
System	each time switched on	

Table 2.3
Which of the following characteristics of your system do you know: transmitted frequency, beam width, pulse length?

Answer	Score
All	6
Transmitted frequency and pulse length only	2
Transmitted frequency only	5

Table 2.4
Reference standards used to calibrate equipment

Standard	Score
Reference blocks	2
Attenuator	3
Reference specimen containing known flaws	4
As above, representative of sample under test	4

Table 2.5
Do you feel there is a need for a reference material to calibrate your equipment?

Answer	Score
Yes	9
If same/similar material to item under test	2
No	2

* scores out of 13

Table 2.6

Do you have a written procedure for the calibration and operation of your equipment?

Answer	Score
Yes	7
For some, not all	2
No	4

Could an inexperienced operator carry out a meaningful C-scan using your procedure?

Answer	Score
Yes	4
Some, not all	1
Possibly	1
No	7

APPENDIX 3

TABLES OF ANSWERS FROM DETERMINATION OF POROSITY SECTION

Table 3.1
Do you measure porosity using C-scanning?

Answer	Score*
Yes	3
Not generally	2
No	7
Comparison with low porosity composite only	1

Table 3.2
Can you distinguish between porosity and other flaws/physical anomalies using C-scanning?

Answer	Score
Yes	6
No/No answer	5
Other	2

Table 3.3
Are you aware of the new draft European standard for the production of carbon fibre reinforced resin test panels for the aerospace industry pr EN2565?

Answer	Score
Yes	3
No	10

Are you aware of the requirement in this standard to use ultrasonic methods to determine the level of porosity in the panels?

Answer	Score
Yes	2
No	11

Table 3.4
Do you feel there is a need for a reference material for determining porosity using C-scanning?

Answer	Score
Yes	6
No	1
Other	6

Table 3.5
Do you have a procedure for acceptance/rejection based on ultrasonic data regarding porosity levels?

Answer	Score
No/No answer	10
Yes	3

* Scores out of 13

APPENDIX 4

TABLES OF ANSWERS FROM DEFECT DETECTION SECTION

Table 4.1
What defects can you detect using ultrasonic inspection?

Answer	Score
Delaminations	13
Inclusions	8
Disbonds	9
Voids/large voids	6
Honeycomb abnormalities	5
Porosity	4
Volume fraction differences	4
Gross errors in fibre alignment/stacking	2
Broken fibres	1
Thermal cracking	1
Lack of adhesive fillet	1
Poor compaction	1

Table 4.2
What defects do you need to detect?

Answer	Score
Delaminations	9
Inclusions	8
Disbonds	8
Voids/large voids	4
Porosity	4
Volume fraction differences	2
Honeycomb abnormalities	2
Stacking errors	1
Lack of adhesive fillet	1
Poor compaction	1

Table 4.3
To what accuracy can you measure the size of a defect?
range of answers: ± 0.3 mm → ± 5.0 mm
What accuracy is acceptable?
range of answers: ± 0.6 mm → ± 5.0 mm

Table 4.4
Reference standards used for defect detection

Standard	Score
Reference specimens containing known defects	6
As above, described as being fully representative of sample under test	4
Step wedges containing known defects	1
Reference blocks	1
Flat bottomed holes in panels	1
Scrap items	1

Table 4.5
Do your reference standards successfully represent real defects?

Answer	Score
Yes	7
Some, not all	3
Reference design dictated by customer	2
No	1

Table 4.6
Do you feel there is a need for reference standards for defect detection?

Answer	Score
Yes	9
Possibly	2
No/no answer	2

Table 4.7
Do you have a procedure for acceptance/rejection of panels or products based on ultrasonic data regarding defect size?

Answer	Score
Yes	8
No answer	2
No	3

LIST OF ABBREVIATIONS

CAT	computer aided tomography
IR	infra-red
NDT	non destructive testing
NPL	National Physical Laboratory
NMR	nuclear magnetic resonance
PEXR	penetrant enhanced X-radiography
PTFE	polytetrafluoroethylene
SPATE	stress pattern analysis from thermal emissions