Assessment and Criticality of Defects and Damage in Material Systems

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Abstract:

A defect criticality framework and assessment procedure for composite material systems has been proposed, based on the multi-level assessment philosophy contained within API (American Petroleum Industry) 579 - Recommended Practice for Fitness-For-Service and Continued Operation of Equipment. The basis for the framework detailed in this guide is a 3 Level approach which involves increasing levels of sophistication in the assessment approach, from operator to expert. For each level, guidance and recommendations have been provided as to the degree of knowledge and complexity required for non-destructive evaluation (NDE), defect classification, defect criticality assessment and materials characterisation.

Four industrial case studies have been undertaken in order to demonstrate various aspects of the framework and to validate the approach proposed.
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- INSYS Ltd.
- LOT-Oriel Ltd.
- LTI
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- NetComposites
- Qinetiq
- Rolls-Royce Plc.
- RAF St. Athan
- SP Systems Ltd.
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Assessment and Criticality of Defects and Damage in Material Systems

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Nomenclature

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>PMC</td>
<td>Polymer matrix composite</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon-fibre reinforced plastic</td>
</tr>
<tr>
<td>GRP</td>
<td>Glass-fibre reinforced plastic</td>
</tr>
<tr>
<td>UD</td>
<td>Unidirectional</td>
</tr>
<tr>
<td>CSM</td>
<td>Chopped strand mat</td>
</tr>
<tr>
<td>SMC</td>
<td>Sheet moulding compound</td>
</tr>
<tr>
<td>BMC</td>
<td>Bulk moulding compound</td>
</tr>
<tr>
<td>DMC</td>
<td>Dough moulding compound</td>
</tr>
<tr>
<td>GMT</td>
<td>Glass mat thermoplastic</td>
</tr>
<tr>
<td>UHM</td>
<td>Ultra high modulus</td>
</tr>
</tbody>
</table>

Test Methods

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCB</td>
<td>Double cantilever beam</td>
</tr>
<tr>
<td>CBT</td>
<td>Corrected beam theory</td>
</tr>
<tr>
<td>MCC</td>
<td>Modified compliance correction</td>
</tr>
<tr>
<td>4ENF</td>
<td>Four-point end notch flexure</td>
</tr>
<tr>
<td>ELS</td>
<td>End-loaded shear</td>
</tr>
<tr>
<td>CAI</td>
<td>Compression-after-impact</td>
</tr>
</tbody>
</table>

Standards Organisations

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECMA</td>
<td>European Association of Aerospace Industries</td>
</tr>
<tr>
<td>AITM</td>
<td>Airbus Industries Test Method</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials (produce ASTM standards)</td>
</tr>
<tr>
<td>BSI</td>
<td>British Standards Institution (produce BS standards)</td>
</tr>
<tr>
<td>CEN</td>
<td>Comité Européen de Normalisation / European Committee for Standardisation (produce EN standards)</td>
</tr>
<tr>
<td>CENELEC</td>
<td>European Committee for Electrotechnical Standardisation</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organisation for Standardisation (produce ISO standards)</td>
</tr>
<tr>
<td>SACMA</td>
<td>Suppliers of Advanced Composite Materials Association (closed)</td>
</tr>
<tr>
<td>VAMAS</td>
<td>Versailles Project on Advanced Materials and Standards</td>
</tr>
</tbody>
</table>
Glossary of Material Property Symbols

**Ply Level; UD Laminate**

- **E\(_{11}\)**: Young’s modulus in 1-direction
- **E\(_{22}\)**: Young’s modulus in 2-direction
- **E\(_{33}\)**: Young’s modulus in 3-direction
- **G\(_{12}\)**: In-plane shear modulus (1-2 plane)
- **G\(_{13}\)**: Shear modulus in the 1-3 plane
- **G\(_{23}\)**: Shear modulus in the 2-3 plane
- **ν\(_{12}\)**: In-plane (major) Poisson’s ratio

- **ε\(_{\text{matcrack}}\)**: Strain at onset of matrix micro-cracking

**Laminate Level**

- **E\(_{xx}\)**: Young’s modulus in x-direction
- **E\(_{yy}\)**: Young’s modulus in y-direction
- **E\(_{\text{min}}\)**: Minimum value of in-plane Young’s modulus for laminate (thickness averaged)
- **G\(_{xy}\)**: In-plane shear modulus
- **ν\(_{xy}\)**: In-plane (major) Poisson’s ratio
- **S\(_{xxt}\)**: Tensile strength in x-direction
- **S\(_{yyt}\)**: Tensile strength in y-direction
- **S\(_{zzt}\)**: Tensile strength in z-direction
- **S\(_{xxc}\)**: Compressive strength in x-direction
- **S\(_{yye}\)**: Compressive strength in y-direction
- **S\(_{zzc}\)**: Compressive strength in z-direction
- **S\(_{xy}\)**: In-plane shear strength (1-2 plane)
- **S\(_{xz}\)**: Shear strength in the 1-3 plane
- **S\(_{yz}\)**: Shear strength in the 2-3 plane

**Fracture Energy Properties**

- **ΔG\(_{Ith}\)**: Mode I crack growth threshold strain energy release rate
- **ΔG\(_{IIth}\)**: Mode II crack growth threshold strain energy release rate
- **G\(_{IC}\)**: Mode I critical strain energy release rate
- **G\(_{IIIC}\)**: Mode II critical strain energy release rate
- **G\(_{TOT}\)**: Total strain energy release rate

N.B. Ply (or fully unidirectional laminate) properties are denoted using numeric suffixes, whilst laminate properties are denoted using alphabetic suffixes
1 Scope

The use of materials systems such as composites, coatings and adhesively bonded structures can provide manufacturers with a number of advantages including higher performance and reduced costs. However, the current lack of design methodologies, reliable test methods and useable data for such systems has meant that their use is still far less than their potential and that of traditional materials. Defects and damage, which reduce the strength and stiffness, and determine the safe working life of composite structures, are complex and intricately related to a variety of service conditions and failure modes under many different circumstances.

An important issue with composite technology and across a range of sectors e.g. aerospace, automotive, marine, pipes/vessels etc., lies in:

- identifying the most suitable techniques for determining the extent of defects,
- understanding the effects of defects and damage on composite structures,
- understanding the significance and practical usefulness of various toughness parameters for materials selection and engineering design.

Defect tolerance and toughness are important properties in many applications. A variety of intuitive qualitative and quantitative measurement techniques exist. The evaluation of defect tolerance is a particularly challenging area as it involves different threats, materials and structural situations, varying strengths and fracture modes, and varying end-use criteria. Defects and stress concentrations may be introduced during manufacture, accidentally in-service or perhaps unavoidably in design because of the requirement to introduce discontinuities such as cut-outs, ply drops or structural connections. Considerable work has been undertaken to investigate the significance and assessment of defects and damage in materials systems, including composite materials, over the past three decades. This has covered fundamental level test coupon fracture samples (e.g. compression-after-impact, CAI), through to failure analysis of full-scale components. The type of defect or flaw produced when composite materials are damaged in-service depends on the structural design and the conditions of damage such as the energy and momentum of an impact event. In general terms, damage tolerance is used in the context of the ability of a material system containing damage, i.e. a severe stress concentration, to continue to bear load and hence continue to operate safely.

This guide details a general procedure for the assessment and criticality of defects and damage in composite material systems. Guidance is provided on defect characterisation, non-destructive evaluation (NDE) techniques, defect criticality and test methods for materials characterisation data. The guide is primarily concerned with carbon and glass fibre-reinforced polymer composite material systems, and focuses on “crack-like” defects such as delamination and matrix micro-cracking.
2 Defect Assessment Framework

Initially a review [1] was undertaken of the current status of industrial guidelines, codes of practice and available design information [2-13] for determining the presence, identification, size, location and criticality of defects in material systems, with particular reference to residual performance and component life. The purpose of carrying out the review was to identify suitable analysis approaches for the assessment of defect detail and criticality in composite material systems, and also to determine where additional work may be needed, i.e. where existing methods do not currently offer possible assessment routes for specific material systems or defect types. Most of the industrial guidelines and documents reviewed are available in the public domain. These included information from Det Norske Veritas (DNV), the European Committee for Standardisation CEN, the British Standards Institute (BSI), the American Society for Mechanical Engineers (ASME), the International Standards Organisation (ISO), the Norwegian Standards body for the offshore sector (NORSOK), the European Space Agency (ESA) and various aerospace sources, including Boeing and Airbus. Specifically, the review determined:

- the types of material systems/structures/component/industries to which they are applicable
- coverage of manufacturing and/or in-service defects
- the bases for the criteria defined
- how the criteria are related to a fitness for service approach
- conflicts between different guidelines and why they exist
- gaps in existing guidelines

From the findings of the review, a defect criticality framework and assessment procedure for composite material systems has been proposed, based on the multi-level assessment philosophy contained within API (American Petroleum Industry) 579 - Recommended Practice for Fitness-For-Service and Continued Operation of Equipment [13]. The basis for the framework detailed in this guide is a 3 Level approach which involves increasing levels of sophistication in the assessment procedure, from operator level to expert. For each level, recommendations have been made as to the degree of knowledge required for non-destructive evaluation (NDE), defect classification, defect criticality assessment and materials characterisation. A schematic of the framework detailed within this guide is shown in Figure 1.

From the starting point of a defect having been found or suspected in a component or structure, the first stage in the assessment procedure is to gather further information about the defect by inspection and consideration of design and materials aspects in addition to operational issues.
The next stage is to assess the criticality of the defect and this can be done at either of three levels. The Level 1 assessment has been defined so as to require the operator to undertake only a relatively simple analysis involving basic calculations and retaining a high degree of conservatism. The Level 2 approach allows for a reduction in some of the conservatism associated with Level 1, but is based on more detailed analysis reliant on fewer simplifying assumptions. A Level 3 assessment is the most complex and involved, with fewer simplifying equations and will typically involve a finite element analysis (FEA). Moving from Level 1 to Level 3, the assessment involves an increasingly detailed knowledge of inspection techniques to accurately locate, identify and size the defect(s) and also material data needed for the recommended modelling approaches. The degrees of conservatism associated with each assessment level are summarised in Table 1 for inspection/NDE, material properties and stress analysis.

Figure 1 - Framework for assessment and criticality of defects in composite material systems

The next stage is to assess the criticality of the defect and this can be done at either of three levels. The Level 1 assessment has been defined so as to require the operator to undertake only a relatively simple analysis involving basic calculations and retaining a high degree of conservatism. The Level 2 approach allows for a reduction in some of the conservatism associated with Level 1, but is based on more detailed analysis reliant on fewer simplifying assumptions. A Level 3 assessment is the most complex and involved, with fewer simplifying equations and will typically involve a finite element analysis (FEA). Moving from Level 1 to Level 3, the assessment involves an increasingly detailed knowledge of inspection techniques to accurately locate, identify and size the defect(s) and also material data needed for the recommended modelling approaches. The degrees of conservatism associated with each assessment level are summarised in Table 1 for inspection/NDE, material properties and stress analysis.
Table 1 - Degrees of Conservatism in 3 Level Approach to Assessment of Defect Criticality

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Level 1 - Operator</th>
<th>Level 2 - Engineering</th>
<th>Level 3 - Specialist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection/ NDE - defect geometry</td>
<td>Simple visual inspection to provide sufficient information on defect parameters</td>
<td>Rely on visual inspection where possible, but acknowledge benefit of using more advanced NDE techniques</td>
<td>Advanced inspection is more readily justified in giving precision in defect parameters consistent with the enhanced accuracy of analysis</td>
</tr>
<tr>
<td>Comment</td>
<td>Can be used but not always - many situations require a more detailed analysis as information from visual inspection is limited (e.g. barely-visible impact damage (BVID))</td>
<td>Specify suitable additional techniques where visual inspection is not adequate</td>
<td>Enhanced information allows reduction in conservatism of assumptions and assists in justification for acceptability</td>
</tr>
<tr>
<td>Material properties</td>
<td>If measured material data are not available then conservative, valid and justifiable assumptions can be made to estimate values (e.g. use of software such as CoDA)</td>
<td>Lower bound generic properties can be used, but give credit for more accurate/reliable knowledge</td>
<td>Greater dependence on measured material properties and perhaps further testing in support of analysis</td>
</tr>
<tr>
<td>Comment</td>
<td>Lower bound values can be used without impacting on analysis criteria utility</td>
<td>Lower bound values can be used without impacting on utility, but accurate properties may reduce conservatism</td>
<td>At this assessment level additional materials information is usually warranted</td>
</tr>
<tr>
<td>Stress analysis/ defect criticality</td>
<td>Use of simple geometric criteria, (e.g. direct definition of maximum allowable dimensions, or established by simple calculation with respect to geometric parameters). Seek to use existing “as-manufactured” acceptability criteria as a basis where possible</td>
<td>Definition of relatively simple analytically established criteria (can be implemented in fairly straightforward software)</td>
<td>Allow use of best available (but validated) approaches to analysis - this may require specialist skills and sophisticated software</td>
</tr>
<tr>
<td>Comment</td>
<td>Not always possible to implement with the desired level of simplicity. More complex stress analysis than would normally be associated with a Level 1 assessment. Limited scope for this approach as it may result in overly conservative results in many situations</td>
<td>Suitable for delaminations, however, the parameters in the criteria for matrix micro-cracking are less easily established</td>
<td>Most defect types can be assessed by using FEA and linear elastic fracture mechanics (LEFM) in tandem</td>
</tr>
</tbody>
</table>
3 Defect Characterisation

3.1 Introduction

The first part of the assessment of the criticality of defects on the in-service performance of a component or structure, as shown by the simplified flow diagram in Figure 2, is the determination of the presence, identity, location, size, morphology etc., of defects. This assessment should be based on a sound understanding of the nature of defects that are typically found in different composite material formats and at what stage of the component life they occur. In the context of this guide, the term ‘defect’ includes defects introduced during manufacturing/processing, machining operations and damage incurred during the service life of the component. The wide range of manufacturing/processing techniques, machining operations and in-service conditions that can give rise to some or all of the defect types listed, and examples of these, are given in Table 2.

This guide provides information on the range and types of defects commonly found in a variety of polymer matrix composites (PMC) and illustrates their appearance using a range of techniques, including visual observation, optical microscopy, thermography and X-radiography. Qualitative guidance on the probability of occurrence and effect on residual life for various defects is provided later in this chapter (Table 5). Input has been taken from

![Figure 2 - Characterisation of defects](image-url)
several available codes of practice and standards [2-8] that provide descriptions of typical defect types and acceptance criteria. These documents cover a range of industries, material types and formats, and were reviewed in [1].

Table 2 - Examples of Manufacturing/Processing Techniques, Machining Operations and In-Service Phenomenon for Composite Material Systems

<table>
<thead>
<tr>
<th>Manufacturing Processes</th>
<th>Machining Processes</th>
<th>In-Service Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin film transfer</td>
<td>Cutting</td>
<td>Loading regime:</td>
</tr>
<tr>
<td>Filament winding</td>
<td>Slitting</td>
<td>• Static</td>
</tr>
<tr>
<td>Pultrusion moulding</td>
<td>Routing</td>
<td>• Impact/shock/high rate</td>
</tr>
<tr>
<td>Wet compression moulding (hand lay-up)</td>
<td>Drilling</td>
<td>• Vibration</td>
</tr>
<tr>
<td>Preimpregnate moulding</td>
<td>Milling</td>
<td>• Fatigue</td>
</tr>
<tr>
<td>Resin transfer moulding</td>
<td>Notching</td>
<td>• Creep</td>
</tr>
<tr>
<td>Resin film infusion</td>
<td></td>
<td>Thermal cycling</td>
</tr>
<tr>
<td>Hot-press moulding of sheet and bulk moulding compounds (SMC/BMC)</td>
<td>(N.B. [14] provides information on processing routes listed above)</td>
<td>Lightning strike</td>
</tr>
<tr>
<td>Hot-press moulding of glass mat thermoplastics (GMT)</td>
<td>(N.B. Guidance on machining good practice is given in [15])</td>
<td>Environmental cycling</td>
</tr>
</tbody>
</table>

3.2 Method of Characterisation

A detailed list of defects is provided in Table 3 identifying the types of defects that can be present in, or introduced into a material, at various stages throughout the material’s life cycle. To rationalise the large number of individual defect types, they have been categorised as follows:-

- Process control - these are defects related to lack of process control, which in some cases will give rise directly to cracks. In other cases criteria need to be developed, for example for fibre waviness, that are associated with production quality assurance,

- Cracks - these are the most important defects that directly influence the component’s remnant capability,
<table>
<thead>
<tr>
<th>Occurrence</th>
<th>Defect</th>
<th>Generic Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing/processing</td>
<td>- inclusions</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- fibre fracture - tension</td>
<td>Dispersed damage</td>
</tr>
<tr>
<td></td>
<td>- delaminations/de-bonds</td>
<td>Cracks</td>
</tr>
<tr>
<td></td>
<td>- improper fibre splicing/abutment</td>
<td>Process control/Cracks</td>
</tr>
<tr>
<td></td>
<td>- fibre wrinkling/kinking</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- fibre misalignment/knots/whorls</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- incorrect stacking sequence (warpage)</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- voidage/porosity/resin starvation/resin rich areas</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- partial/local cure of material</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- damage due to tooling installation/removal</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- residual stresses/thermal cracking</td>
<td>Process control/Cracks</td>
</tr>
<tr>
<td></td>
<td>- crushed sandwich core</td>
<td>Stability</td>
</tr>
<tr>
<td></td>
<td>- sandwich skin-to-core de-bonding</td>
<td>Cracks/Stability</td>
</tr>
<tr>
<td></td>
<td>- contamination (e.g. solvents)</td>
<td>Process control</td>
</tr>
<tr>
<td>Machining</td>
<td>- fibre fracture - tensile</td>
<td>Dispersed</td>
</tr>
<tr>
<td></td>
<td>- delaminations/de-bonds</td>
<td>Cracks</td>
</tr>
<tr>
<td></td>
<td>- matrix micro-cracking</td>
<td>Cracks</td>
</tr>
<tr>
<td></td>
<td>- sandwich skin-to-core de-bonding</td>
<td>Cracks</td>
</tr>
<tr>
<td></td>
<td>- crushed sandwich core</td>
<td>Stability</td>
</tr>
<tr>
<td></td>
<td>- contamination (e.g. solvents, lubricants)</td>
<td>Process control</td>
</tr>
<tr>
<td></td>
<td>- damage due to tooling installation/removal</td>
<td>Process control</td>
</tr>
<tr>
<td>In-service</td>
<td>- fibre fracture - tension (compression)</td>
<td>Dispersed/Cracks</td>
</tr>
<tr>
<td></td>
<td>- delaminations/de-bonds</td>
<td>Cracks</td>
</tr>
<tr>
<td></td>
<td>- fibre pull-out</td>
<td>Dispersed (cracks)</td>
</tr>
<tr>
<td></td>
<td>- matrix micro-cracking</td>
<td>Cracks/Dispersed</td>
</tr>
<tr>
<td></td>
<td>- sandwich skin-to-core de-bonding</td>
<td>Cracks/Stability</td>
</tr>
<tr>
<td></td>
<td>- crushed sandwich core</td>
<td>Stability</td>
</tr>
<tr>
<td></td>
<td>- moisture/chemical ingress</td>
<td>Dispersed</td>
</tr>
<tr>
<td></td>
<td>- damage due to maintenance e.g. tool drop</td>
<td>Stability/Cracks</td>
</tr>
<tr>
<td></td>
<td>- corrosion, erosion (material thinning)</td>
<td>Wear out</td>
</tr>
<tr>
<td></td>
<td>- thermal damage, lightning strike</td>
<td>Dispersed/Cracks</td>
</tr>
</tbody>
</table>
• Dispersed - where the damage is not represented by a crack, but is over an area, such as many individual tensile fibre fractures or transverse cracks in cross-ply laminates,

• Stability - these are cases whereby, while not constituting a crack, result in reduced stability, particularly under compression loads e.g. an area of crushed core in a sandwich construction,

• Wear out - represents damage where material bulk is lost due to the long-term actions of wear/friction, erosion, corrosion etc.

These categories simplify assessment procedures and techniques for detection and identification, and also aid the understanding and prediction of their behaviour and criticality to the service life. The focus of work detailed in this guide is the “crack-like” defects (i.e. delamination and matrix micro-cracking) that while perhaps differing in detail, will in general retain broadly similar morphology and effect on material behaviour. Identification of the location of where defects are likely to occur (e.g. on or near the material surface, internal, throughout bulk) and description of their morphology (e.g. shape, size) is essential prior to attempting to assess whether the defect is critical.

In addition to factors already mentioned, a number of other issues must be considered when determining the criticality of defects. These include: component dimensions, relative dimensions (i.e. local radii), type of fibre reinforcement, fibre orientation, type of matrix, stress state/loading regime, support conditions and environment. Establishing the criticality of defects may involve one or a combination of: (i) reference to appropriate standards, (ii) predictive modelling [19-21] and (iii) experimental determination.

3.3 Defect Observation Techniques

Techniques used in the analysis of defects in composite material systems include:

• **Optical microscopy** - this technique has proved to be a critical tool for defect analysis. Cross sections, produced by mounting and polishing regions of material of interest, provide an insight into the detailed microstructural features related to construction, defects and defect propagation. Fractographic evidence of defects is of paramount importance to the determination of the cause and sequence of failure.

• **Scanning electron microscopy (SEM)** - because SEM uses electrons rather than light, images of 3 dimensional surfaces can be captured due to the excellent depth of field capability of the technique. The large depth of focus is particularly useful for looking at fracture surfaces, which are often very irregular and with fibres widely dispersed. The resolution that can be obtained with SEM is approximately 100 times greater than with optical microscopy, and thus far more detailed analyses can be performed, which is often extremely useful for defect and failure analysis. Composite
specimen preparation for SEM analysis is straightforward; a conductive carbon-loaded adhesive is used to bond samples, such as carbon fibre-reinforced plastics (CFRP), onto an aluminium stub which sits in a holder in the chamber of the microscope. If the sample being analysed is non-conductive e.g. glass reinforced plastic (GRP), a conductive coating needs to be applied to the surface of the specimen to prevent charging by the electron beam. For most cases an anti-static spray is satisfactory for preventing charge build-up, but a more effective gold-palladium coating can be used if the spray is not sufficient.

- **Non-destructive evaluation (NDE)** - guidance on the use of a variety of NDE techniques for detecting and observing defects is discussed in Section 4. In the defect characterisation work detailed in this section, visual observation, thermography and X-radiography techniques have been used.

- **Edge replication** - in this technique acetone is spread over the region of material under investigation and a thin film of acetate is then placed over the acetone and held firmly for two or three minutes. The acetone softens the acetate sheet and under pressure the softened acetate assumes the near surface profile of the material, i.e. fills in any voids or delaminations exposed on the surface of the material. The acetate is left to harden before separation from the specimen. The film is then visually inspected with the naked eye or under magnification.

### 3.4 Defect Appearances

The following sections describe the defect types listed in Table 3. Where possible the appearance of defects are provided through a series of images using visual observation, optical microscopy, thermography and X-radiography. These are given in Appendix A.

#### 3.4.1 Fibre Related Defects

**Misalignment/Knots/Whorls**

Fibre misalignment, knots and whorls are typically caused by poor manufacturing and processing practices. Some of the more common reasons for misalignment are; (i) poor incoming material quality (will normally be marked on cloth or pre-impregnated material), (ii) poor alignment of fibre pre-forms during hand and automated lay-up operations, (iii) incorrect tension in fibres during processes such as filament winding, pultruding and production of unidirectional, woven or stitched fibre formats and (iv) poor machining practice, i.e. cutting of coupons and components at an incorrect angle. For composite material formats such as chopped strand mats (CSM), sheet, bulk and dough moulding compounds (SMC/BMC/DMC), and glass mat thermoplastics (GMT), fibre misalignment is
usually not an issue as the fibre direction is inherently random. However, some grades include additional unidirectional material in specified directions.

For aligned fibre systems (unidirectional, multidirectional etc.), fibre misalignment, knots and whorls are major causes for concern and can be extremely detrimental to material performance. Figure 3 shows the effect of fibre angle on the tensile longitudinal and transverse, and shear moduli and strengths of a fully unidirectional CFRP laminate. It is clear that a 5° or 10° misalignment of the fibres from the true zero direction has a significant effect on the laminate stiffness and even more so on the strength. For multidirectional laminates (e.g. quasi-isotropic lay-ups) this effect will be less pronounced. Fibre misalignment can be measured by cutting the material under analysis at an angle of less than or equal to 15° to the direction of the expected longitudinal axis of the fibre (Figure 4a), as this is the region in which the change in the major to minor fibre axes ratio is most sensitive (Figure 4b). Material sections are then mounted in a potting compound, polished and viewed under an optical microscope. The approximate fibre direction can then be calculated from the ratio of the major to minor axes. Table 4 shows the appearance of fibres sectioned at various angles, the major/minor axes ratio and the calculated approximate fibre angle (N.B. (i) the fibres shown in Table 4 are carbon (nominal diameter ~7 µm) and (ii) a 90° fibre will have a major/minor axes ratio of 1).

**Wrinkling/Kinking**

Fibre wrinkling and kinking are examples of ‘out-of plane’ fibre misalignment and are again caused by poor manufacturing and processing practices. Wrapping of fibre formats over or around pre-forms of complex and/or irregular profile containing small inner radii at curved sections, can result in this type of defect.

![Figure 3 - Effect of fibre angle on stiffness and strength of a unidirectional laminate](image-url)
Table 4 - Appearance of Fibre as a Function of Angle of Misalignment

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Major/minor axes ratio</th>
<th>Approximate cut angle (°)</th>
<th>Appearance</th>
<th>Major/minor axes ratio</th>
<th>Approximate cut angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td>20</td>
<td>3</td>
<td><img src="image2" alt="Image" /></td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td><img src="image3" alt="Image" /></td>
<td>12</td>
<td>5</td>
<td><img src="image4" alt="Image" /></td>
<td>1.7</td>
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<td><img src="image5" alt="Image" /></td>
<td>7</td>
<td>10</td>
<td><img src="image6" alt="Image" /></td>
<td>1.1</td>
<td>65</td>
</tr>
<tr>
<td><img src="image7" alt="Image" /></td>
<td>3</td>
<td>20</td>
<td><img src="image8" alt="Image" /></td>
<td>~1</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 4 - (a) schematic to show cutting angle for measurement of fibre misalignment and (b) variation of the ratio of major to minor fibre axes with fibre angle
Fracture

Fibre fracture can occur due to manufacturing/processing and machining operations, and damage sustained in-service. It can occur in practically any fibre-reinforced composite regardless of format. During manufacture, fibre fracture can be present at the inner radii of corners and poor machining practice can result in fibre breakage and fraying at the edges of holes or cut outs. This is to be avoided as such areas of damaged material can act as failure initiation sites and potential channels for moisture ingress. Excessive loading (tension or compression) during service is also a cause of fibre fracture. In the case of continuous fibre composites, fracture will occur when the stress build up in the fibre exceeds the fibre strength. For short fibre systems, fibre fracture will only occur when the length of fibres is greater than the critical value. For the case where the fibre length is shorter than this critical value, fibre pull-out will occur instead. Fibre fracture can occur in all types of PMCs. Figure A1, Appendix A shows an example of fibre fracture in a multidirectional CFRP laminate.

Pull-Out

Fibre pull-out (Figure A2) is predominantly a defect sustained during the in-service lifetime of a component. It typically occurs due to excessive loading in short fibre composite systems or continuous fibre systems that have sustained a significant degree of fibre fracture. If the length of fibres is less than the critical fibre length, or the length of fibre from a matrix crack, then the stress build-up in the fibre is not sufficient for fracture and pull-out from the surrounding matrix will occur.

Improper Splicing/Abutment

Improper splicing of fibres and/or poor abutment of fibre performs such as pre-impregnated tapes can result in gaps (resin rich areas) or overlaps (steps or ramps). This can occur during manufacturing and/or processing and can effect any PMCs involving ply lay-up or filament wound structures.

3.4.2 Matrix Related Defects

Micro-cracking

Micro-cracks are caused by stresses which can be generated by either mechanical and/or thermal loading. Thermal stresses result from differences in coefficients of thermal expansion between adjacent plies, exothermic chemical reactions and resin cure shrinkage. High temperature curing fibre/matrix systems are most prone to micro-cracking, especially in combination with low failure strain resin systems. In addition, cross-ply or generally multidirectional material systems are susceptible to micro-cracking due to the anisotropy of the thermal expansion of 0° and 90° plies, resulting from the low thermal expansion of the fibre compared to the resin. Examples of matrix micro-cracking are shown in Figure A3.
**Voidage/Porosity/Resin Starvation/Resin Rich Areas**

Voids and/or porosity may result from trapped air between fibres, the presence of solvents/moisture or other volatiles, or incorporation of air in the resin during mixing. These defects occur in all of PMC materials and are of considerable concern as they can act as local weaknesses. Voids/porosity can cause a reduction in structural performance (i.e. lower transverse and through-thickness tensile, flexural, shear and compression strengths, corrosion resistance and electrical properties), particularly when exposed to service environment (e.g. hot/wet) conditions for long periods. Large voids may be of sufficient size to act as delaminations, resulting in premature failure of the component. It is generally accepted that the void or porosity content of a component should not exceed 1-2% for high performance laminates. Figure A4 shows examples of voidage in unidirectional pre-preg and filament wound CFRP materials.

Regions of resin starvation are areas of material where the fibre preform is still bare and dry. It may be caused by inadequate wetting of fibres, poor consolidation during laying-up or problems with resin delivery. Resin starved regions may be difficult to detect and often occur at inner radii of curved components. Figure A5 shows regions of resin starvation in a woven GRP laminate. The opposite effect also occurs, whereby there are resin rich areas caused by the displacement of fibres or fibre preforms during processing. This tends to occur in structures with sharp bends (i.e. small radii), steps and chamfered edges as fibre reinforcement tends to pull around corners leaving a resin rich area near the outer radius. It can also occur locally as shown in Figure A6 for a filament wound material. This type of defect is of concern as it can be a potential location for the initiation of failure. Resin starved and rich areas can occur in all forms of PMC material, but they are not found so much in injected short fibre systems, where variable orientation of the short fibre lengths is of more concern.

**Partial/Local Cure**

Partial cure may occur if the recommended cure cycle for the material is not followed (including post-cure) and can result in a reduction of material properties (particularly those dominated by the matrix). Local pre-cure may also occur, typically in pre-impregnated materials, where regions of material have been subjected to elevated temperatures during storage or handling prior to manufacture. Non-uniform cure may result in poor consolidation, leading to undesirable volume fraction gradients and entrapped volatiles or voids. Both types of defective cure are causes for concern, but can be avoided if appropriate quality and operational procedures are adhered to. Partial/local curing occurs in thermosetting PMC materials, but not in thermoplastic systems.
3.4.3 Laminate Related Defects

Inclusions

Typically introduced during the manufacturing/processing stage of laminated structures, inclusions occur basically as a result of poor operational practice. Inclusions can range from release films used in pre-impregnated materials that are not fully removed prior to consolidation, to artefacts such as scalpel blades, staples etc., that are accidentally introduced during lay-up procedures. Inclusions are of great concern as they act as artificial delaminations within the material and potential sites of failure.

Delaminations/De-Bonds

Delaminations or de-bonds are one of the principal defects that can occur in manufacture, machining and in-service. They are caused by contamination at ply interfaces, insufficient cure or out of life material, inclusions (e.g. backing film), certain loading conditions such as impact and poor machining practice. This type of defect has a severe detrimental affect on mechanical strength, particularly under compressive loads, and on the life expectancy of composite components. The occurrence of production/handling induced delaminations should be avoidable with good practice. Delaminations are mainly found in laminated PMC structures and can occur throughout a component including central, edge and radial (i.e. at radii of curved profiles) positions.

Figures A7-A11 show a range of images of delaminations viewed using digital photography, optical microscopy and X-radiography. Figure A7, clearly shows multi-level delaminations (plan view and visible to the naked eye, note presence of surface crack) within the top GRP skin of a Nomex® cored sandwich construction that has been subjected to impact. Figure A8 is a digital photograph showing the back face of an impacted CFRP panel with large scale damage including delaminations and fibre fracture clearly visible. For carbon fibre systems, internal delaminations are not visible with the naked eye. Instead, techniques such as ultrasonic C-scan and X-radiography can be used to give plan views of such defects. Figures A9 and A10 are X-ray images of delaminations due to impact in a panel and poor machining of a drilled hole respectively. Figure A11 is a through-the-thickness optical micrograph of an edge delamination in a CFRP laminate.

Incorrect Stacking Sequence

Errors in the lay-up of a material during processing will result in incorrect mechanical properties and possibly warpage depending on the coupling between plies and the balance and symmetry of the lay-up. Defects of this type should be avoidable through the use of good operational procedures as given in Part 4 of ISO 1268 [14], which sets out a standard designation code for lay-up of plies.
Contamination

Contamination (dust, release agents, cleaning fluid, grit etc) within PMC materials can be extremely detrimental to material properties as it can cause regions of poor interfacial or interlaminar adhesion, and voidage. Contamination is not limited to any one specific location within a component or structure and can spread during processing causing widespread degradation. It can effect all types of PMC materials, but should be avoidable through effective processing procedures.

Residual Stresses/Thermal Cracking

Residual stresses are strongly influenced by processing history and can have a significant effect on the properties of laminated structures inducing warpage, fibre buckling, matrix micro-cracking and delaminations. These types of stresses arise from resin chemical shrinkage, as a result of curing, and differences in thermal contraction between adjacent plies, set at different orientations, on cooling the laminate from the cure temperature. Complex thermal and degree of cure gradients may develop within thick sections and curved structures during the cure process. These gradients may induce a non-uniform state of cure through the laminate thickness.

Excessive Heating/Lightning Strike

The risk of material degradation due to exothermic chemical reaction of the matrix exists when dissipation of liberated heat through thermal conduction is slow. The internal temperature may be elevated to levels that induce irreversible thermal damage. This problem is particularly associated with thick sections. Extreme forms of thermal damage can be caused by phenomenon such as fire and lightning strike. In such severe cases the resin can be burned-off from around the fibres.

Tooling Installation/Removal and Maintenance

Several of the defects described in prior sections of this report can be introduced to a component or structure through operations such as tooling installation/removal and routine maintenance. Incorrect installation of tooling (e.g. moulds, inserts etc.) can distort fibre preforms and cause fibre misalignment. In addition, it may result in local increases in fibre volume fraction and restrictions of resin delivery routes causing regions of resin starvation. To aid removal of a cured part, release agent/film is often applied to the surfaces of the tooling. If this is not applied evenly then areas of the cured material may be bonded to the tooling, thus resulting in damage (e.g. matrix micro-cracking, fibre fracture, delaminations, etc.) on removal. Superficial damage such as chips, gouges and crazing may also be caused with careless handling. Damage is often introduced to a component when it is undergoing maintenance and tool drops, chemical spills, and machining operations, for example, can all introduce potentially critical levels of damage if the operator does not take sufficient care.
3.4.4 Sandwich Laminate Related Defects

Sandwich constructions, as applied to PMCs, consist of thin facing sheets of structural laminated materials bonded to and separated by a relatively thick, lightweight core. They provide a method of obtaining high bending stiffness at low areal weight in comparison to monolithic laminate constructions. This advantage must be weighed against the risk of increased processing difficulty that can increase production costs over monolithic construction. Damage tolerance and ease of repair should also be considered when selecting sandwich panel or monolithic laminate construction. Good structural design practice requires selection of skin, core and adhesive materials to be strategically based on overall part quality. As well as the fibre, matrix and laminate defects that have been detailed in previous sections (Figure A12), sandwich constructions also have other inherent defect types.

Skin-to-Core De-Bonding

De-bonding of the skin and core in a sandwich construction is one of the principal defects that can occur in manufacture, during machining and in-service, and is analogous to a delamination in a monolithic laminate. Manufacturing de-bonds can occur due to inadequate bonding or coverage of adhesive between the skin and core and also from inclusions such as backing paper or release film. De-bonds can also occur as a result of poor machining practice (e.g. drilling of holes in sandwich constructions for installation of inserts may cause de-bonding of the skin from the core as well as delamination in the skin). De-bonds are of high concern, lead to a loss of structural integrity in the sandwich construction and are potential failure sites. However, the risk of de-bonds occurring during processing and machining should be minimised with good operational practice. Those de-bonds occurring in-service will often be unavoidable as a result of impact (e.g. tool drop, stone/bird strike, etc.), lightning strike and pressure build-up in closed cells of the core (e.g. in Nomex® honeycomb cores) as a result of water ingress. Figure A13 shows a sandwich construction that has suffered a skin-to-core de-bond due to excessive in-plane compression loading.

Crushed Core

Core crushing is caused as a result of impact, local indentation and/or excessive through-the-thickness loading of a sandwich construction. This type of defect can effect all types of core material and should be avoided as it can result in localised de-bonding and a lack of support to the sandwich skin laminates, leading to potential failure of the component. Figure A14 shows two examples of core crushing due to impact in Nomex® honeycomb sandwich laminates.
3.5 Summary

Table 5 provides a summary of the defects considered, typical causes and qualitative guidance on the probability of occurrence and effect on residual life. Defects of greatest concern are those scoring a ‘high’ on probability and ‘severe’ on effect such as fibre fracture. Effective understanding and assessment of the criticality of defects is partly reliant on a full appreciation of the nature of defects; how they arise, where they occur, their appearance, size shape etc and in what material systems they can be found in. However, it is not practical to consider and/or assess criticality on an individual defect basis, and therefore a system for categorisation has been outlined in this guide that simplifies the analysis procedures proposed. In addition, not all of the defects that have been detailed in this guide represent a serious threat to residual life reduction (i.e. resin rich areas). Hence, the focus of the analysis procedure is on the “crack-like” defects such as matrix micro-cracking and delamination that give real cause for concern over remnant performance.
<table>
<thead>
<tr>
<th>Defect</th>
<th>Material type</th>
<th>Cause</th>
<th>Probability of occurrence</th>
<th>Effect on residual life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Manufacturing/Processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Machining</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Contamination</td>
<td>All PMCs</td>
<td>Any processing route solvents, volatiles, grit, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Through use of solvents, volatiles, lubricants etc.</td>
<td>Moisture or chemical ingress during life</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion/Erosion</td>
<td>n/a</td>
<td>Galvanic corrosion due to aluminium-carbon contact, wear, friction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crushed sandwich core</td>
<td>Sandwich laminates - all types of core</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delaminations/ de-bonds</td>
<td>Laminated PMCs</td>
<td>Poor practice - all machining operations</td>
<td>Impact, local indentation, excessive through thickness loading, etc.</td>
</tr>
<tr>
<td></td>
<td>Fibre fracture</td>
<td>All PMCs, possible in regions of tight curvature</td>
<td>Poor practice - all machining operations</td>
<td>Excessive loading, impact, lightning strike, fatigue, etc.</td>
</tr>
<tr>
<td></td>
<td>Fibre misalignment</td>
<td>Aligned fibre systems</td>
<td>Cutting of material at wrong angle</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Fibre wrinkling/kinking</td>
<td>All PMCs, present in regions of tight curvature</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Improper fibre splicing/abutment</td>
<td>PMCs fabricated using process routes listed</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Inclusions</td>
<td>All PMCs - pre-pregs</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Defect</td>
<td>Material type</td>
<td>Cause</td>
<td>Probability of occurrence</td>
<td>Effect on residual life</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Incorrect stacking sequence</td>
<td>Laminated PMCs, sandwich constructions</td>
<td>Incorrect, ply lay-up, filament winding, pultrusion moulding</td>
<td>High</td>
<td>Severe</td>
</tr>
<tr>
<td>Matrix micro-cracking</td>
<td>All PMCs</td>
<td>All processes that involve significant temperature changes or resin shrinkage</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Partial/local cure</td>
<td>Thermoset resin based PMCs</td>
<td>All processes that involve curing of a resin system</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Residual stresses/thermal cracking</td>
<td>Thermoset resin based PMCs</td>
<td>All processes that involve significant temperature changes or resin shrinkage</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Resin starvation</td>
<td>All PMCs</td>
<td>Possible in all process routes</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Resin rich areas</td>
<td>All PMCs</td>
<td>Possible in all process routes</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Sandwich skin-to-core de-bonding</td>
<td>Sandwich laminates</td>
<td>Lack of consolidation/poor adhesion during lay-up</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Excessive heating/lightning strike</td>
<td>All PMCs</td>
<td>Excessive exothermic heating</td>
<td>Low</td>
<td>Minima</td>
</tr>
<tr>
<td>Voidage/porosity</td>
<td>All PMCs</td>
<td>Trapped air, volatiles, solvents during cure</td>
<td>Low</td>
<td>Minima</td>
</tr>
</tbody>
</table>
Non-Destructive Evaluation (NDE) Assessment

There is an extensive and growing research base in non-destructive testing (NDT) or non-destructive evaluation (NDE) of composites and materials systems. The term NDE is more appropriate in this context as non-destructive testing may be used to characterise the material condition as well as detecting damage or defects.

Despite many innovations in the development of NDE techniques for the assessment of defects and damage, relatively few NDE methods are commonly used. These include visual inspection, ultrasonics, thermography, laser shearography, tap testing, radiography, and acoustic emission. Indeed, outside aerospace it is more common to proof test or rely on simple visual inspection than to carry out more involved NDE. This is due to a perception that NDE is too untried, costly or complex, that procedures may not be available and that interpretation of NDE data is difficult.

The most widespread use of NDE has been in the aerospace industry, where higher performance materials systems are favoured based on carbon fibre-reinforced plastics (CFRP) and use of metallic sandwich structures. Unfortunately, the issues and the practical use of NDE for composites in other industries such as the chemical, marine, transport and offshore industries is not so straightforward: components are often thicker, more complex and variable in material quality. Where procedures exist, these are often proprietary, or may be too complex to be practical to use, requiring a detailed knowledge of physics rather than the practical implementation of a technique. Conversely, they may be too simple making the procedures unreliable to apply. Specialist knowledge may be required to interpret or use the data, for example in assessment of defects. The damage and defect types may be quite different to those prevalent in aerospace. For all these reasons procedures developed in high technology aerospace applications are not simply applied to other industries.

The last few years has seen a significant uptake in the use of NDE methods across industry. This is due to a number of reasons. First, as composites are used in more structural applications there is a greater need for assessing the quality of manufacture. Second, the activation barriers to the use of NDE have been partly overcome by recent DTI funded programmes, for example Composites Performance and Design (CPD) projects CPD4A and CPD4D which developed practical procedures for NDE and funded practical case studies in specific areas such as composite repairs. Second, technological advances have transformed the ease and cost of application of what were considered more specialised techniques. One example of this is laser shearography driven by the availability of portable lasers and improved methods of data analysis and presentation. Similarly, transient thermography has seen increased application due to the development of portable integrated systems and improved data analysis software and methods. Finally, application of more specialised techniques has been facilitated by the funding of practical trials by industry groupings, such as the offshore composite repair group.
4.1 NDE Methods

The most common inspection techniques currently applied for inspection of materials systems including GRP and CFRP composites are:

- Visual inspection
- Ultrasonics
- Laser shearography
- Tap testing
- Thermography
- Radiography
- Acoustic emission
- Dye penetrant
- Eddy-current (Metallic, CFRP only)
- Magnetic (metallic only)

For composites, suitable characterisation methods may be used to assess the quality of the fabrication. These include Barcol hardness and differential scanning calorimetry (DSC) as indirect measures of cure, and pressure-fill proof testing (for pressure pipes or vessels).

There are a significant number of more specialised techniques which find application for specific defect types or in particular applications, notably in the aerospace industry. These include ultrasonic lamb-waves, x-ray backscatter, ultrasonic phased array, polar back-scatter and many others. However, it must be emphasised that there is considerably less worldwide experience of these, and consequently, direct evidence of detection limits is scarce. The judgement on what is common and what is considered specialised is not clear-cut and will depend on the industry concerned. For example, laser shearography is now very widely used across industry. Ultrasonic lamb-waves and phased arrays are increasingly used in aerospace applications. There are many more which should be considered developmental as they are rarely applied in non-research applications. The NDE methods discussed in this guide are those concerned with the external inspection of a materials system.

The main NDE methods are briefly described in the following sections. More detailed descriptions of these techniques and others may be found in [22]. Additional data and case studies using current NDE systems are detailed in [23].
4.1.1 Visual Inspection

Visual inspection is the most common form of inspection for composites and other material systems. This may be termed enhanced or close visual inspection if assisted by magnifying glasses, lighting or other tools. Increasingly closed circuit television (CCTV) or video cameras are used either for monitoring or to provide a permanent record of the inspection. Limited guidance on the type of defects detectable and what is acceptable can be found in design standards such as ISO 14692 [3] for pipes, GRP pressure vessel standards [2], [57] and industry specific guidelines such as NORSOK [6].

The best quality visual inspection for transparent/translucent composite materials (i.e. GRP) is where access is possible from both sides with backlighting. In this case internal defects such as delaminations, fabrication defects and cracking may be seen. The effectiveness will depend on wall thickness, resin type and coating. It is increasingly common practice to paint GRP vessels and pipes for aesthetic reasons, which makes backlit inspection impracticable. If access is limited to one side then only surface apparent or obvious defects will be seen. Users often have great confidence in visual inspection, which belies the limited data available on actual reliability. Enhanced visual inspection is widely used in airframe components as for this case large areas need to be inspected. Identifiable defects include, delamination, cracks, localised (thickness) deformation, impact damage, poor wetting of fibres, inclusion, air entrapments, excessive adhesive in joints (reducing internal diameter), environmental effects (e.g. UV, erosion) and wear damage. However, for applications using CFRPs, through visual inspection is not possible.

4.1.2 Ultrasonics

Ultrasonics is the main NDE technique used to find defects in composite material systems. Ultrasound is introduced into the component using a transducer and reflections from defect interfaces, attenuation or diffraction signals are recorded. Difficulties arise due to the need to calibrate equipment for different lay-ups, coupling and requirements for different probe types. The method can be used for measuring the thickness of composite components. The thickness that can be inspected is limited in materials such as GRP due to the high attenuation, requiring lower frequencies which tend to reduce the resolution possible. The method is sensitive to surface roughness. Identifiable defects are generally in-plane perpendicular to the beam direction, including regions of delamination, de-bonding, voids, lack of adhesive in bonded joints and general joint defects.

The main methods are manual ultrasonics (Figure 5), typically monitoring using an A-scan presentation of signal versus time or using a conventional ultrasonic thickness tester, and ultrasonic C-scan which produces a planar image map by measuring the attenuation (Figure 6). An X-Y scanning system is required to produce C-scan images and is often used for manufactured components and test panels. Ultrasonic C-scanning is often mandatory for many aerospace components. For general composite applications, ultrasonic C-scanning is
often performed under water immersion or via water-jets, using a scanning frame either in transmission or by reflection, to ensure good coupling.

Significant recent trends include the use of ultrasonic linear scanning methods (B-scan) for measuring erosion in pressure vessels including Time of Flight Diffraction (TOFD) [24] (Figure 7), the use of ultrasonic lamb-wave or guided wave methods, air coupled ultrason [25] and ultrasonic phased arrays. A phased array comprises an array of miniaturised probes, often produced by etching a flexible polyvinylidene fluoride (PVDF) film. If 0° probes are used this can be used to produce real time C-scan images. Alternatively, a range of beam angles can be produced by altering the firing sequence of individual cells using the software. Procedures for ultrasonic B-scan were developed in the Composite Performance and Design programme within project 4D [26]. Within the same programme, NPL and Qinetiq (Farnborough) developed and evaluated procedures for ultrasonic C-scan inspection of PMCs. The following three draft procedures were submitted to the technical committee BSI ACE 56 (NDT) for consideration as a new work item for AECMA standardisation:

- Operational procedures for ultrasonic C-scan equipment,
- Ultrasonic transducer calibration procedure,
- Procedure for the preparation of reference panels with simulated defects [27].

Round-robin validation exercises have been undertaken by NPL in conjunction with industry at both national (UK) and international (USA) levels in order to evaluate the operational procedures and generate precision data [28-29].
4.1.3 Laser Shearography

In recent years, laser shearography [30-32] has become a serious contender with ultrasonics, for detection of delaminations, de-bonding, poor adhesion and other flaws in materials systems. This is due to the advent of portable lasers and innovation in data processing, including phase analysis. There are two major suppliers of field inspection services in the UK: Laser Optical UK Ltd, a spin-off from Loughborough University, and Laser Testing UK Ltd a subsidiary of Laser Testing Inc. in the USA. The former is one of the main centres of excellence in the UK and a leader in development of the method. The advantages of the technique are that it is fast, global and non-contact with a high sensitivity and requires no immersion or complex scanning equipment. The method can also indicate areas of reduced or increased adhesion, not simply the presence of a delamination. The main limitation of the technique is accessibility and that it provides an indirect surface measurement.

Laser shearography determines the surface strain fields from the difference in displacements between unloaded and loaded states using a scanning laser system. Surface condition is not critical, rough or smooth surfaces will return a result, but translucent or shiny specular surfaces degrade the image and should be toned or painted to promote optimum speckle on the surface. For laser shearography to work, a load has to be applied to the sample; this may be produced by a number of methods including mechanical loading, vacuum loading,
heating, and internal pressurisation. Simple integrated systems are available for inspection of components such as lifeboat hulls and airframes. Although the method measures a surface effect, the technique has been applied to thicker materials systems, for example measuring 1-2 cm delaminations on the far GRP skin of an 80 cm thick boat hull sandwich structure with an internal foam core.

Shearography employs a single expanded beam of laser light, which is reflected back from the specimen. The camera includes an image-shearing device. The effect of shearing is to bring two separate areas on the object surface to meet in the image plane. The two overlapped areas of the sheared images interfere and produce a speckle pattern. When the surface of the object is deformed, the speckle pattern is modified. Comparing the two speckle patterns (stressed and unstressed) produces a fringe pattern, which depicts the relative displacement of the surface. Since the magnitude of shearing is small, the fringe pattern approximately represents the derivative of displacement, i.e. the surface strain. Practical procedures for shearography were produced in the CPD4D programme [33].

4.1.4 Thermography

Thermography refers to the detection of defects by measuring differences in thermal response, usually by monitoring infrared emissions using a thermal imaging camera. The term is often used to simply refer to thermal imaging, correctly termed as passive thermography. A hot source (or sink) may be applied to one side of the component. Passive thermography has specific applications such as detection of process variations, major erosion, water ingress into insulation and short circuits in electrical circuits. Only major defects are likely to be found in this way.

To detect and image real defects with any reasonable sensitivity it is necessary to put a pulse of heat (or cooling) into the component and monitor the changes with time. This is referred to as pulsed or transient thermography. The rate at which temperature changes take place is often more important than the amplitude of the temperature change which is usually only a few degrees centigrade. Heating methods include excitation, a hot air gun, flash tubes, electromagnetic induction, hot and cold water, or acoustic. The most suitable will depend on the thermal response and thickness of the material. Thermography can be successfully applied to a variety of material systems including composites, sandwich structures, ceramics and metallic systems. The technique is particularly widely used in aerospace and marine applications.

There have been significant recent advances in the technology, which is now a very fast, global and practical technique. Much development was undertaken in the UK National NDT Centre [34], in the US ageing aircraft programmes and by Thermal Wave inc. in the USA [35-37]. These include development of fully integrated systems such as the ThermoScope system, which combine a flash tube for heating and integrated thermal camera and analysis.
software. Practical procedures have been developed in CPD4D, by the American Society for Non-Destructive Testing (ASNT), by NORSOK and also for marine and lifeboat applications. Automated scanning systems are available for large airframe components. A major advance has come from the development of improved data processing methods such as synthetic signal processing: these significantly enhance the image quality and signal/noise ratio, allow large volumes of data to be handled, give better defect characterisation and enable images to be produced at specific depths or combined.

The method is well suited to defects such as impact damage, voids, delaminations, water ingress, adhesive de-bonds, inclusions, corrosion and changes in wall thicknesses. Conditions that make defects more difficult to detect include well-matched thermal interfaces, inclusions of similar material, optical non-absorbing materials (mirror finish), kissing de-bonds and vertical cracks. It is important to use a high quality thermal imaging camera.

4.1.5 Impact Testing/Coin-Tap Testing

At it’s simplest; this involves tapping the composite component with a metallic object (Figure 8). Impact testing is a method which has been used for many years and covers a vast range including "coin tapping", the traditional method of testing aircraft flying surfaces, railway wheel tapping, to concrete testing using a hammer and vibration sensors. In its traditional form, the hammer is applied to the part by the tester, who also then listens to the 'ringing' sounds generated. Anomalies in the part are then recognised by an experienced tester, based on the differences in the characteristic ringing sound obtained. A trained operative will be able to assess the state of the material and thereby identify regions of de-bonding, delamination, poor cure not necessarily identifiable by visual inspection. Identifiable defects include regions of poor cure, regions of delamination, coating de-bonding or thickness variations. The method is not well suited to thick components. Applied manually the method is very subjective and limitations include the possibility of impact.
damage and the difficulty in applying in real structures, where the material is constrained and acoustic response will differ. For these reasons, shearography and thermography are increasingly favoured as alternatives. Tap testing is a relatively low cost option. The hearing ability of the operator is a key factor affecting reliability.

In the last few years, there have been rapid developments in this field, with the emergence of automated computer based systems (e.g. Woodpecker®), which are now in use for the production line testing of a variety of components. C-scan images can be produced similar to those produced by ultrasound. Inspection times can be less than 10 seconds per part. The vibrations can be excited by use of a local impact (e.g. "tapping" with a striker or instrumented hammer) or the method can be non-contacting, using an air operated acoustic transducer to supply the necessary transient energy in the form of an acoustic pulse (so called resonance methods).

### 4.1.6 Radiography

Radiography [38] uses localised differences in attenuation under X-ray illumination to provide a cross-sectional picture of the density of a material system. Images are typically recorded on film. Increasingly, digital or real-time recording systems are used. The method is well suited to volumetric defects and to complex components, which might be difficult to inspect by other methods. The method is not popular because of health and safety requirements. Increasingly portable low intensity systems are available, such as those used in the offshore industry, which reduce the associated hazards.

Radiography is sensitive to major changes in density so it is good at checking adhesive joint assembly but the nature of equipment limits the practical usage. Identifiable defects include voids, delaminations, cracks (dependant upon geometry), excesses of adhesive in joints. To improve definition, penetrants may be used which are less transparent to X-rays. Detection of cracks and tight delaminations requires the defects to be aligned along the X-ray beam as in tangential X-radiography. Three dimensional images can be obtained by integrating the equipment with a computerised tomography (CT) scanner and using appropriate tomographic software. This technique is known as X-ray tomography.

### 4.1.7 Acoustic Emission

Formation, growth or loading of defects may produce an acoustic response. Acoustic emission (AE) involves the use of sensors to monitor such emissions and determine medium to large-scale effects in composites, which would generally have structural integrity and/or strength implications. AE can be used on whole systems and works by picking up stress waves generated by inelastic deformation. The method generally identifies changes in systems by comparison rather than from absolute values. Identifiable defects include
delamination growth, leakage, crack growth, fibre fracture and matrix micro-cracking. AE was one of the techniques evaluated in the recently DTI funded CPD4A project on composite repairs.

AE historically has had difficulty in application to large structures and in generating false calls. Use of the technique has increased in recent years because of improved data interpretation methods. In refineries, the method has gained acceptance as a screening method for condition assessment of storage tanks and vessels.

4.1.8 Penetrant

Dye penetrant methods are widely used in examination of metallic components for inspection for surface-breaking cracks and defects, and can also be used for PMCs. Essentially it is a method of enhanced visual inspection. Detectability may be increased by use of fluorescent dyes. For magnetic components, a variant is magnetic particle inspection (MPI) in which the component is magnetised using a yoke and sprayed with a special paint containing iron filings.

4.1.9 Eddy Current

Eddy current inspection is one of the most widely employed methods for airframe inspection, used for example for the inspection of rivet holes in aluminium airframes. Typically an electromagnetic coil or arrays of coils are passed over the surface of the component under inspection. This induces local currents or eddy currents, below the coil(s), which are sensed by detection coils. The presence of a defect will affect the flow of eddy currents. By adjusting the frequency, it is possible to move from a surface specific technique to a lower frequency method with good depth penetration that allows inspection of sandwich structures and more complex components and materials systems, such as flexible risers in the offshore industry and concrete structures. The method cannot be deployed on GRP as it this material does not conduct, but it can be used for the inspection of CFRP components. Additional information on the use of eddy current methods for CFRP structures can be found in [39]. Eddy current arrays developed for crack inspections in the offshore industry are increasingly used in other applications such as rail inspection and pressure vessels. By using an array, these have sensitivity to both the depth and length of defect. As a non-contact method, which can allow standoff from the surface, eddy current inspection is possible through thick coatings, such as fire protection, or with minimal surface preparation. Eddy currents are also used for inspection for rebars in concrete as far as the first reinforcement layer.
4.2 NDE Techniques Comparative Performance

The performance of an NDE method in service may differ significantly to the theoretical sensitivity limits given by a manufacturer, sometimes referred to as the capability. The performance of an NDE method is considered in terms of key factors:

- Sensitivity
- Coverage
- Speed
- Reliability - i.e. Probability of Detection (POD), false calls, etc.

Sensitivity is the size of defect that can be detected by the technique and may be given with reference to a reliability or probability. Coverage is the fraction of the component that is actually inspected by the technique. There is a distinction between geometric coverage, the volume the NDE method can actually see, and statistical sampling where a decision has been made to only look at some of the component. Speed will affect the cost of the inspection or the coverage that it is practical within the time available for inspection. Other factors may affect the capability of a particular NDE technique include sizing and location accuracy and traceability to specific standards and codes of practice. The reliability is the probability that a defect will actually be detected, usually quantified in terms of the Probability of Detection (POD) and the number of spurious indications or false-calls (i.e. number of false indications NFI or probability of false indications PFI). False calls, where an inspection system flags up an indication where no defect is present is a key issue in many automated inspections, and may restrict the reliability that can be achieved in practice.

Quantitative performance measures such as POD are now routinely specified for inspections in the chemical, aerospace and other industries. The reliability usually increases with increasing defect size. For this reason, it is common to plot a POD curve against defect size, the size parameter chosen dependent on the application and the NDE technique. The curves compare techniques and also give an indication of effects that can arise from human reliability.

A growing database of information has evolved from trials in the nuclear, aerospace and offshore industries and there are accepted guidelines and software for analysis of NDE reliability such as MIL Handbook 1823 [40] and NORDTEST [41]. POD data has usually been obtained by trials. Theoretical models and simulators for estimating POD have been developed by the UK National NDT Centre (NNDTC) and also at IOWA State University in the USA. An NDE capabilities handbook has been produced by the the Nondestructive Testing Information Analysis Centre (NTIAC) in the USA, bringing together much of the data from the Ageing Aircraft programmes [42]. There have been a number of recent European-American exchange workshops on inspection reliability, that have brought together expertise on POD, most recently in Berlin in October 2002 [43].
4.3 Selection of NDE Techniques

NDE provides information about the current condition of a component, that would otherwise be unknown. This may avoid unexpected failure, help plan future operation and inspection, and reduce operational risk. Often considered an additional cost, effective inspection can add considerable value over the lifetime of the component. For manufacturers, NDE will add value by increasing the quality of the component, and reducing the risk of subsequent failure in service.

The inspection regime for materials systems needs to take account of a number of factors, including:

- How critical the component is to the performance of the overall system,
- The nature of the defects that can occur,
- How the defects may develop under the operating conditions of the system,
- What is currently known about the condition of the component.

There are several factors that need to be considered to choose the optimum inspection technique, including:

- Relevant defect types,
- Location and likely size of the defects,
- Suitability of technique to material,
- Geometry and thickness of component,
- NDE performance required (sensitivity, speed, reliability, etc),
- Prior inspection history,
- Accessibility,
- Manufacturing versus in-service inspection,
- Availability of procedures & standards,
- Cost benefit,
- Time available for inspection,
- Prescriptive requirements,
- Defect characterisation required,
- Defect assessment and requirements.

For many material systems, the choice may be quite limited, because of the nature of the system and the type of defects that occur. If the nature of the damage that may occur is well known, then a very precise inspection could be specified. If the condition of the component is not well known and there are a variety of defects, then an alternative approach using a number of methods or techniques which are sensitive to different defect types should be employed.
5 Defect Criticality

5.1 Introduction

The assessment of defect criticality is aimed at determining the acceptability of a defect type so that decisions can be made on whether a component can continue to operate safely in-service or whether it should be repaired or replaced. The utility of any defect assessment framework depends heavily on the analysis methods selected to assess criticality. Where possible, existing accepted and validated methods have been recommended for use with the framework set out in this guide.

The approach followed for selecting suitable analysis methods was to consider methods applicable to specific defect or damage types. In a detailed classification, over one hundred individual types can be defined. Many of these defect types, while perhaps different in detail, retain broadly similar morphology and effect on material behaviour. As described in Chapter 3, the majority of defect types can be adequately considered to fit into one, or sometimes more, of a smaller number of broad defect definitions, namely:

- Process control
- Cracks
- Dispersed
- Stability
- Wear out

In order to simplify and reduce the number of analysis methods needed for assessing defect criticality still further, it has been assumed that the majority of in-service defects can be classified as delamination or matrix micro-cracking i.e. categorized as cracks, and hence analysis methods have been recommended for these two defect types only. (N.B. a review of methods for analysing the effects of defects and damage, particularly delamination and matrix micro-cracking, is detailed in [19]).

5.2 Methods for Assessment of Delaminations

5.2.1 Level 1

The Level 1 criterion is defined so that it depends on relatively straightforward calculations and retains a high degree of conservatism. Conservatism is incorporated in the treatment of several issues including:

- Definition of the geometry,
- Definition of the applied loads,
• Calculation of a total strain energy release rate,
• Comparison of the total strain energy release rate to the threshold condition for growth,
• Using the Mode I threshold condition as bounding all potential cases,
• Application of a factor of 2 on threshold.

Geometry

For a Level 1 assessment the following information regarding the delamination geometry should be determined by NDE inspection;

• Maximum planar extent of the delamination (s),
• Depth of the delamination (d),
• Location of the delamination so that the relevant loads can be calculated.

It should be noted that where inspection information is limited or uncertain, conservative assumptions should be made. Increasing the planar extent of the delamination over that measured or reported is clearly conservative, but the situation with respect to depth is more complex as it depends on the loading. There are some instances in which the effects of assumptions are readily interpreted, e.g. assuming the position of a delamination to be closer to the surface subject to compression in a structure loaded in bending will tend to make the delamination zone less prone to buckling. However, in many cases the effects of an assumption can only be identified following analysis, hence it is recommended that where doubt exists, the sensitivity of the results to the depth of the delamination should be assessed.

Loading

The delamination should be assessed using the loads for design conditions. The loads acting in the region of the delamination under design conditions must be estimated by methods known to be conservative. The analyses require that the most severe range of strain energy release rate under operational loads should be estimated. To this end, a total of twelve loads should be considered, namely, for each of the principal stress directions:

• Maximum and minimum bending moments (M),
• Maximum and minimum in-plane loads (N),
• Maximum and minimum through-thickness shear loads.

(N.B. for many structures the principal stress directions will be self-evident and coincident with some convenient set of structural reference axes, e.g. the axial and circumferential directions for a cylindrical structure). In many cases one or more of the above loads may be zero and not require any calculation. Furthermore, the critical load case may also be self-evident in which case not all the above loads need be calculated. Loads should be calculated on a per unit width basis since the analysis considers a unit width of material.)
Material Properties

The following material properties are used in the Level 1 assessment:

- $E_{\text{min}}$ – The minimum value of in-plane Young’s modulus for the laminate. This is the thickness averaged Young’s modulus of the individual layers making up the laminate. Laminates are usually orthotropic with the modulus varying according to direction. The value corresponding to the laminate material’s minor principal axis should be used in the calculations. When the material property data used in the design are not available, conservative assumptions should be applied in estimating this value.

- $\Delta G_{\text{th}}$ – growth threshold of strain energy release rate for Mode I. This value can be obtained by test (Chapter 6) or alternatively the lower bound values for different material types should be used.

Criteria for Delamination Growth

The loads considered to be distributed in the region of the delamination front are shown in Figure 9:

![Figure 9 - Delamination crack tip geometry and loads](image-url)
Where:

\[ N_1 = N + \frac{2M}{t} \quad \text{1} \]
\[ M_1 = M \quad \text{for } \xi \geq 0.5 \]
\[ M_1 = 0 \quad \text{for } \xi < 0.5 \]

\[ N_2 = N - \frac{2M}{t} \quad \text{2} \]
\[ M_2 = 0 \quad \text{for } \xi \geq 0.5 \]
\[ M_2 = M \quad \text{for } \xi < 0.5 \]

Where \( \xi \) is a constant defining the relative thickness of the delamination arms

The concentrated crack tip loads should then be determined for each load case as follows:

\[ N_c = \xi N - N_1 \quad \text{5} \]
\[ M_c = M_1 - \xi^3 M - \frac{\xi t}{2} N_1 + \frac{\xi^2 t}{2} N \quad \text{6} \]

The total strain energy release rate is given by:

\[ G_{tot} = \frac{1}{2} \left( c_1 N_c^2 + c_2 M_c^2 + 2c_{12} N_c M_c \right) \quad \text{7} \]

Where the parameters \( c_1, c_2 \) and \( c_{12} \) are given by:

\[ c_1 = \frac{4}{E_{\min} t^2 \xi (1-\xi)} \quad \text{8} \]
\[ c_2 = \frac{12}{E_{\min} t^3} \left( \frac{1}{\xi^3} + \frac{1}{(1-\xi)^3} \right) \quad \text{9} \]
\[ c_{12} = \frac{6}{E_{\min} t^2} \left( \frac{1}{(1-\xi)^2} - \frac{1}{\xi^2} \right) \quad \text{10} \]
The strain energy release rate should be calculated as above for each of the load cases considered and the peak value determined. Acceptability of the delamination, at Level 1, is then determined by comparing the peak value of strain energy release rate to the Mode I strain energy release rate growth threshold value using a margin of two. Hence the acceptability criterion is:

\[ G_{\text{tot}} \leq \frac{\Delta G_{\text{th}}}{2} \]

**Criteria for Buckling/Stability**

Acceptability with respect to buckling/collapse should also be assessed whenever part of the delamination is subject to compressive loads. The peak compressive load, as determined by equations (1) and (2), for each of the delamination arms is obtained by consideration of the most severe load case. This load is then compared to the Euler buckling load for a simply supported beam having length \( s \) (the maximum planar dimension of the delamination) and thickness corresponding to that of the relevant delamination arm \( t_1 \) or \( t_2 \). The buckling load is given by:

\[ N_{\text{cr},i} = \frac{\pi^2 E t_i^3}{12s^2} \]

The delamination is acceptable provided the peak compressive loads in each of the arms do not exceed the relevant buckling load as given above.

Caution should be exercised when dealing with delaminations in curved regions of a structure as curvature can significantly increase susceptibility to failure by instability. A Level 1 analysis should only be applied in these situations when it is clear that the assessment remains conservative despite the curvature. A Level 1 assessment should not be applied to cases where the curvature makes the delamination more prone to failure by instability, e.g. when the delamination is on the convex side of a curved region subject to bending moments whose direction is such as to decrease the curvature.

**5.2.2 Level 2**

The Level 2 approach allows for a reduction in some of the conservatism employed at Level 1 as it is based on a more detailed analysis reliant on fewer simplifying assumptions.
Geometry

For a Level 2 assessment the following information should be determined by inspection:

- Diagram clearly showing the planar extent of the delaminated region,
- Depth of the delamination,
- Location of the delamination within the component (this is required in order to calculate the relevant loads).

The defective area should be characterised as a rectangular region having length $s$ and width $w$ such as to fully cover the underlying delamination. The edges of the rectangular region should be defined to align with the principal stress axes, indicated by $p$ and $q$ in Figure 10. (N.B. The principal stress axes to be considered are those for the most severe loading with respect to promoting growth of the delamination. In many cases the most severe load case with respect to delamination is readily identifiable, however there may be situations where a quantified comparison between different load cases is required). Where there is uncertainty as to the dimensions of the delamination, conservative assumptions should be made.

![Figure 10 - Characterisation of delamination geometry](image)

Loading

The loads should be calculated assuming that the delamination covers the full extent of the rectangular area as defined above. Loads, as shown in Figure 9, should be calculated at the mid-points of each of the four sides of the rectangle, i.e. at points $a$, $b$, $c$ and $d$ as indicated in Figure 10. These loads should consider the design load case(s) and be determined by stress analysis.
No specific recommendations regarding analysis type are provided here since the approach chosen will depend heavily on the geometry and loading and also to a large extent on the preferences of, and tools available to, the individual analyst. Generally, however, linear stress analysis (with respect to both material and geometry) is considered appropriate at Level 2. The only requirement is that any assumptions made in the analysis should be clearly stated and the methods used should be demonstrably conservative. It is worth noting that, for many situations, a conservative yet sufficiently accurate approach is to determine the loads based on a beam analysis only. Using this approach the local loads at the mid-points of the edges of the rectangular region are calculated by assuming the remote loading applied at the ends of a delaminated beam. This approach is conservative in that it ignores the constraining effects of the un-cracked material along the edges of the delaminated region. There may be cases where this approach is excessively conservative, e.g. where the delamination is very narrow and the constraint effect is significant. In such cases a more refined approach to stress analysis may be needed to better estimate the local loads.

When the delamination is in an area of curvature, particular attention should be paid in the stress analysis to ensuring that bending effects introduced by in-plane loads are properly accounted for. These effects may be significantly underestimated by a linear stress analysis and the analyst should be alert to situations in which a geometrically non-linear analysis may be essential to estimate behaviour with sufficient confidence. However, such an analysis will generally only be adopted in a Level 3 assessment.

Material Properties

The following material information is required for a Level 2 analysis:

- Laminate construction covering sequence of types and orientation of individual layers making up the laminate,

- Elastic properties for each of the layer materials. This should include the Young’s moduli in each of the layer’s principal material axes, i.e. $E_{11}$ and $E_{22}$, the in-plane shear modulus $G_{12}$ and major Poisson’s ratio $\nu_{12}$,

- The growth threshold strain energy release rates in Mode I ($\Delta G_{Ith}$) and Mode II ($\Delta G_{IIth}$).

Note that where materials information is not available, estimates or validated predictions may be used e.g. using design tools such as NPL’s Component Design Analysis (CoDA) software. Guidance on measurement of material properties is provided in Chapter 6.
Criteria for Delamination Growth

Strain energy release rates are to be calculated for each of the four mid-points, i.e. at \(a\), \(b\), \(c\) and \(d\) as shown in Figure 10. Strain energy release rates for Mode I and Mode II are to be calculated for each of these points as follows.

At each point the laminate in-plane (\(A\)), coupling (\(B\)) and bending (\(D\)) stiffnesses are required. These are defined as per conventional laminated beam theory such that:

\[
\begin{bmatrix}
N \\
M
\end{bmatrix} = \begin{bmatrix}
A & B \\
B & D
\end{bmatrix} \begin{bmatrix}
e^0 \\
\kappa
\end{bmatrix}
\]

with \(e^0\) being the mid-plane strain for the laminate under consideration and \(\kappa\) being the curvature due to bending. Note that for orthotropic laminates the stiffness terms vary according to direction and the terms required for points \(a\) and \(c\) (for which the values are calculated in direction \(p\)) will typically be different to those for points \(b\) and \(d\) (for which the values are calculated in direction \(q\)). Note also that, if the laminate construction varies from \(a\) to \(c\) then each of these points will have their own set of stiffness parameters and likewise if there is variation in the laminate construction from \(b\) to \(d\).

When subscripted the \(A\), \(B\) and \(D\) terms relate to the indicated beam ahead of the crack front and when not subscripted they relate to the single beam behind the crack front. The superscript \(\prime\) indicates inversion.

The above terms are used to calculate the following:

\[
a_{i1} = A_i A^\prime + (B_i - A_i t_2 / 2) B^\prime
\]

\[
a_{i2} = A_i B^\prime + (B_i - A_i t_2 / 2) D^\prime
\]

\[
a_{21} = B_i A^\prime + (D_i - B_i t_2 / 2) B^\prime
\]

\[
a_{22} = B_i B^\prime + (D_i - B_i t_2 / 2) D^\prime
\]

\[
c_1 = A_i^\prime + A_i + B_i t_1 - B_i t_2 + D_i t_1^2 / 4 + D_i t_2^2 / 4
\]

\[
c_2 = D_i^\prime + D_i
\]

\[
c_{12} = D_i t_2 / 2 - D_i t_1 / 2 - B_i^\prime - B_i
\]

\[
\sin \Gamma = \frac{c_{12}}{\sqrt{c_1 c_2}}
\]
The concentrated crack tip force is given by:

\[ N_c = -N_1 + a_{11}N + a_{12}M \]  \hspace{1cm} (22)

and the crack tip moment by:

\[ M_c = M_1 - N_1t_1/2 + (a_{12}t_1/2 - a_{21})N + (a_{12}t_1/2 - a_{22})M \]  \hspace{1cm} (23)

The mode-mix parameter \( \Omega \) is defined by:

\[ \Omega = 23.53\eta - 6.84\eta^2 + 1.07\eta^3 \]  \hspace{1cm} (24)

where \( \eta = \log_{10}\left(\frac{t_2}{t_1}\right) \)  \hspace{1cm} (25)

The Mode I and II strain energy releases rate are determined as follows:

\[ G_I = \frac{1}{2} \left(-N_c \sqrt{c_1} \sin \Omega + M_c \sqrt{c_2} \cos(\Omega + \Gamma)\right)^2 \]  \hspace{1cm} (26)

\[ G_{II} = \frac{1}{2} \left(N_c \sqrt{c_1} \cos \Omega + M_c \sqrt{c_2} \sin(\Omega + \Gamma)\right)^2 \]  \hspace{1cm} (27)

The acceptability criterion is determined so as to ensure that no growth occurs under operational loads. Hence the combination of \( G_I \) and \( G_{II} \) should be such that the threshold conditions are not exceeded. The following acceptability criterion is recommended (refer to review of methods for analysis of delaminations \([19]\)):

\[ \frac{G_I}{\Delta G_{Ith}} + \frac{G_{II}}{\Delta G_{IIth}} < 0.5 \]  \hspace{1cm} (28)

This equation includes a margin of 2 on growth, the margin being considered necessary due to present limited data on growth criteria for mixed-mode conditions. It seems that having the right hand side of equation (28) equal to 1 would imply no growth in most cases but there are some data to suggest otherwise.

Note that each of the four points considered in Figure 10 must be checked in the assessment of acceptability.
Criteria for Buckling/Stability

The potential for buckling should be assessed by treating the delaminated region as consisting of two adjacent rectangular plates, of thickness $t_1$ and $t_2$, each simply supported (N.B. this is a key assumption in ensuring conservatism in Level 2) at all edges. For each plate, the assessment should consider the maximum compressive in-plane load calculated for points $a$ and $c$ as continuously applied across the edges with length $w$. This should be taken to act in combination with the maximum compressive in-plane load calculated for points $b$ and $d$ as continuously applied across the edges with length $s$.

Acceptability should be determined by comparison of the in-plane loads (for the most severe design condition) with the buckling loads for the delamination as estimated by a linear bifurcation analysis. A variety of methods are available for estimating the linear bifurcation loads and the analyst should select the most appropriate for the situation under consideration.

For delaminations in flat plates where the minimum planar dimension, i.e. $\min(s, w)$ is more than twenty times the maximum thickness dimension, i.e. $\max(t_1, t_2)$, the following can be used to estimate the buckling load:

\[
N_{p,cr} = \pi^2 \left( D_{11}\left(\frac{m}{s}\right)^4 + 2(D_{12} + 2D_{66}\left)\left(\frac{m}{s}\right)^2 \left(\frac{n}{w}\right)^2 + D_{22}\left(\frac{n}{w}\right)^4 \right) \right)
\]

Where

\[
N_q = k_q N_p
\]

Alternatively, for cases where $N_p$ is zero or small relative to $N_q$, it is more convenient to use:

\[
N_{q,cr} = \pi^2 \left( D_{11}\left(\frac{m}{s}\right)^4 + 2(D_{12} + 2D_{66}\left)\left(\frac{m}{s}\right)^2 \left(\frac{n}{w}\right)^2 + D_{22}\left(\frac{n}{w}\right)^4 \right) \right)
\]

With

\[
N_p = k_p, N_q
\]

$D_{11}$, $D_{12}$, $D_{22}$ and $D_{66}$ as used in Equations (29) and (31) are the flexural stiffness terms as obtained by conventional laminated plate theory.

Note that the buckling load is obtained by minimisation of Equation (29) or (31) with respect to integer values of $m$ and $n$ (which are the buckling mode descriptors).
Caution should be exercised when any of the following apply in the case under assessment:

- The delamination is in an area of significant curvature (e.g. when the radius of curvature is <20 times thickness). In curved regions, in-plane loads can give rise to significant additional bending moments. While the effect of this bending should be included in the stress analysis for determination of the delamination crack tip loads, it can significantly reduce the loads at which instability occurs. This is a particular concern when the loading and geometry is such that the convex surface laminate containing the delamination is in compression. If this is the case, the linear bifurcation analysis at Level 2 can potentially underestimate the load at which instability occurs or behaviour becomes significantly non-linear. Hence, for these situations, demonstration of acceptability is not possible at Level 2 and a Level 3 assessment is recommended.

- The material on either side of the delamination is significantly asymmetric. Asymmetric laminates display extension-bending coupling. The bending deformation induced under compressive loads may be such as to promote instability at loads lower than suggested by a linear analysis. The potential for non-conservative buckling loads as a result of extension-bending coupling should be investigated by the analyst. Note that even when the extension-bending coupling is implicitly included in a linear analysis the results can be non-conservative.

- The delamination length is short relative to the plate thickness. If this is the case the analyst should ensure that through thickness shear flexibility is included in the buckling load estimation.

5.2.3 Level 3

Level 3 assessment allows for sophisticated analysis, based on the use of finite element modelling, with fewer simplifying assumptions. Assessment at this level may be demanding hence it is normally only applied when it is not possible to demonstrate acceptability at a lower level or the geometry is such that assessment at the lower levels is not appropriate. Some of the conservatism inherent in the treatment of loads at Levels 1 and 2 is removed at Level 3, through separate consideration of operation loads (with potential to cause delamination growth by fatigue) and limit loads corresponding to the design condition(s).

Geometry

The information as described for Level 1 - Geometry should be available from inspection. The defect can be characterised, for the purposes of modelling, as a rectangular delamination as shown in Figure 10. In addition, at Level 3 other shapes may be used to characterise the defect, provided the shape chosen bounds the full extent of the delamination. It may, for example be more accurate to characterise a near circular delamination as a circular region.
rather than as rectangular. Also, in certain cases analysis of the actual delamination geometry, which might not conform to that of a regular shape, may be appropriate.

**Loading**

Level 3 allows a more comprehensive treatment of loads through separate consideration of regular operational loads and the limit or design loads. The former are considered in the context of their potential for promoting growth of the delamination by fatigue mechanisms and the latter are considered in the context of their potential for causing unstable growth or catastrophic failure. Definition of the design load case(s) is clear and would normally be obtained from the design documentation for the structure under assessment.

Definition of the operational loads that are of concern in promoting growth of the delamination by fatigue is less straightforward however and depends, in part, on the judgement of the analyst. In principle, these loads should be selected as the maximum that are likely to occur on a regular basis during normal operation. No firm definition is provided here, as selection of loads will depend on the structure under consideration. Furthermore, in many instances, the relative significance of different load levels with respect to fatigue life can only be established after some delamination fracture mechanics analysis has been performed. This should ensure that any loads at a level between that defined as regular operational and the limit condition(s) do not occur at a frequency such that the delamination can grow to a critical condition within the design lifetime. In addition, the potential for loads, not falling within the regular operational category, in imposing additional inspection requirements on the structure should be investigated. This could drive a revised definition of regular operational load level.

The loads in the region of the delamination should be accurately determined or conservatively estimated. A variety of approaches can be used provided they meet the preceding criteria. For example, in some cases analytical solutions will be available for the geometry under consideration while for other situations a detailed finite element analysis may be more appropriate. There are numerous issues to be considered in generating load values that are satisfactory for use in Level 3 analysis. A brief discussion of some of these issues is provided below.

The loads calculated should represent those existing in the region of the delamination and include consideration of the effects of the delamination itself. In many instances it will be conservative to first estimate the loads in the region, without considering any effect the delamination might have on redistribution, and use these as a basis for establishing the loads in the region of the delamination crack front. The loads in the region, when there is no delamination present, can, for many practical structural geometries, often be calculated reasonably accurately by available analytical solutions. There will however be situations in which determination of the loads in the region of the delamination will depend on finite element analysis.
Regardless of the approach adopted, the analyst should keep in mind that the strain energy release rates and buckling loads are to be estimated by a reasonably detailed finite element model of the delamination. The load analysis for the region containing the delamination should therefore be such as to allow rapid application of the appropriate loads to this detailed finite element model. Note that, as a consequence of the intensive computation demands that would otherwise arise, it is unlikely that the analyst will choose to incorporate the delamination in a model of the structure as a whole. Hence a sub-structure approach is more likely to be appropriate and the loadings as applied to the sub-structure are required.

(N.B. The loading analysis must consider bending induced by in-plane loads in regions of curvature. Potential for geometric non-linear behaviour should also be considered. The most severe load case may often correspond to compression even when the magnitude of the peak compressive stress is smaller than that of peak tensile stress).

**Material Properties**

The following material information is required for a Level 3 analysis:

- Laminate construction covering sequence of types and orientation of individual layers making up the laminate,

- Elastic properties for each of the layer materials. This should cover Young’s moduli in each of the layer’s principal material axes, i.e. $E_{11}$ and $E_{22}$, the in-plane shear modulus $G_{12}$ and major Poisson’s ratio $\nu_{12}$,

- Growth threshold strain energy release rates in Mode I ($\Delta G_{Ith}$) and Mode II ($\Delta G_{IIth}$),

- Critical strain energy release rates in Mode I ($G_{Ic}$) and Mode II ($G_{IIc}$).

Note that where materials information is not available, estimates may be used. However, for a Level 3 analysis, testing to establish the required material properties is more likely to be justifiable. Guidance on the measurement of material properties is provided in Section 6.

**Criteria for Delamination Growth**

The strain energy release rates for both Mode I and II corresponding to the regular peak operating load, i.e. $G_{Iop}$ and $G_{IIop}$, should be determined at sufficient points on the perimeter of the region characterised as a delamination to allow the maximum values to be established.
The strain energy release rates can be determined by either of the following:

(i) The analysis method outlined in Level 2 - Criteria for Delamination Growth i.e. equations (14) to (27), using the appropriate loads applied to the delamination crack tip,

(ii) A detailed finite element analysis. It is recommended that this make use of the virtual crack closure technique as an efficient means of estimating strain energy release rates. However other approaches, such as determination of the J-integrals, are acceptable.

Note that it will usually be more efficient to use the first approach in the case of simpler geometries where the delamination front loads are relatively straightforward to determine. The second approach is likely to be required when the delamination is in a region of complex geometry, e.g. within a region having a small radius of curvature.

Acceptability, with respect to delamination growth, depends on demonstration that the following criterion is met:

\[
\frac{G_{I_{op}}}{\Delta G_{I_{th}}} + \frac{G_{II_{op}}}{\Delta G_{II_{th}}} < 0.5
\]  

Note that the results for several different points around the perimeter of the delamination may be required to establish the point for which the combination of \(G_{I_{op}}\) and \(G_{II_{op}}\) is most severe.

**Criteria for Delamination Failure**

Delamination failure is assessed by consideration of the limit or design load case(s). The strain energy release rates for both Mode I and II, i.e. \(G_{I_{d}}\) and \(G_{II_{d}}\), corresponding to the design load conditions are to be determined at sufficient points on the perimeter of the region characterised as a delamination to allow the maximum values to be established. The strain energy release rates can be determined by either of the approaches defined above.

The acceptability criterion is defined as:

\[
\frac{G_{I_{d}}}{G_{I_{c}}} + \frac{G_{II_{d}}}{G_{II_{c}}} < 0.5
\]

Note that the results for several different points around the perimeter of the delamination may be required to establish the point for which the combination of \(G_{I_{d}}\) and \(G_{II_{d}}\) is most severe.
Criteria for Buckling/Instability

At Level 3 the buckling loads calculated for the delamination are compared to the most severe design load case. Linear bifurcation analysis can be used to define the onset of buckling in cases where both the following apply:

- The delamination is not in a curved region of the structure.
- There is no significant asymmetry in either of the two sub-laminates formed by delamination.

The bifurcation load can be estimated using available analytical solutions or by finite element modelling. At this level, the edges of the delamination can be considered fixed in the analysis.

In cases where one or both of the above conditions are not met, a geometrically non-linear analysis should be performed to determine the load-deformation behaviour of the delamination faces. The effective buckling load is to be defined as the minimum of:

(i) the lowest bifurcation load identified in the analysis
(ii) the load for which one of the delamination arms experiences a transverse, i.e. out of plane, deflection equal to its thickness.

Note that when the results indicate significant out of plane pre-buckling deformation, further investigation of the effects of such deformation on the loading used to calculate the strain energy release rates may be warranted.

Acceptability depends on demonstrating that the most severe loads with respect to buckling, within the design loads envelope, are less than one third of the corresponding buckling (or effective buckling) loads. Taking \( P \) to represent the most severe combination of axial loads and bending moments and \( P_{cr} \) to represent the corresponding loads at the onset of buckling, this criterion can be expressed as:

\[
P < \frac{P_{cr}}{3}
\]
5.3  Methods for Assessment of Matrix Micro-Cracking

5.3.1 Level 1

The Level 1 approach is designed to allow a rapid but inherently conservative assessment of regions of matrix micro-cracking. The basis of the Level 1 approach is to assume that the region of micro-cracking does not contribute to load carrying, i.e. it effectively has no stiffness.

Geometry

The region of micro-cracking is represented as a cut-out which should fully bound the extent of the micro-cracking in the structure, for examples see Figure 11.

![Material that has micro-cracking](image)

Bounded by circular region

Bounded by square region

Figure 11 - Definition of geometry for region of micro-cracking

The shape of the cut-out and its orientation is not prescribed in this guidance, the only requirement being that it includes all of the material which contains cracking. It is recommended, however, that the user consider defining the shape and orientation such that it facilitates a straightforward stress analysis, e.g. the geometry for analysis is defined such that existing standard solutions/approximations can be applied. Considerable simplification may be possible by careful consideration of the orientation of the cut-out with respect to the structural reference and primary load axes.

Loading

The stress analysis should be based on the maximum operating loads considered in the design of the structure, i.e. the stresses calculated should not include the safety or design
factor. Combined loads should be included according to the same approach used in the original design. The case giving rise to the highest principal strain should be identified.

**Stress Analysis**

Methods of stress analysis for the assessment of micro-cracking at Level 1 are not prescribed in this guidance. It is a requirement, however, that the analysis method used be one that is widely accepted as accurate (e.g. typical handbook type solution) or can be shown to be conservative.

The stress analysis shall be used to estimate stress, and hence strain, in the structure surrounding the region of micro-cracking which has been considered as a cut-out. Note that in many situations the peak stress/strain will occur at the edges of the region considered as a cut-out (due to the stress concentration associated with the geometry). This will not always be the case however and the user is to ensure that the location (and value) of the most highly stressed material in the structure has been properly identified.

The primary outputs of the stress analysis are (i) the maximum principal strain calculated for the loading as defined in Level 1 - Loading and (ii) an estimate of the failure load(s) for the structure.

**Material Properties**

At Level 1 it is acceptable to use estimates of the material properties. These estimates are, however, to be such that the requirements of the stress analysis can be met.

Properties required will typically include the following:

- $E_{xx}$ - Laminate Young’s modulus in material reference direction $x$,
- $E_{yy}$ - Laminate Young’s modulus in material reference direction $y$,
- $G_{xy}$ - Laminate in-plane shear modulus with respect to material reference directions,
- $\nu_{xy}$ – Laminate Poisson’s ratio with respect to material reference directions.

Note that the material reference axes can be defined by the user and should consider the laminate construction (e.g. a dominant fibre orientation or set of laminate material principal directions), any natural structural reference axes (e.g. hoop and circumferential in a tubular structure) and primary loading axes.

The above properties are for the laminate. They can be estimated, when the laminate construction is known, according to known or approximate ply properties. It is also acceptable to make use of the properties used in the original design.
In most cases using lower bound estimates for modulus will make for a conservative estimation of strains. However, there are situations in which the stress concentrating effects of the cut-out will be severely underestimated by consideration of an excessively low material stiffness.

In addition to the elastic properties mentioned above, the assessment requires an estimate of the strain limit for the onset of micro-cracking. It is recommended that this property be measured by testing for the laminate in question.

The assessment also requires an estimate of the failure loads for the structure, hence the laminate strengths are required. Estimation of the failure load will typically require the following laminate strengths:

\[ S_{xxt} \] – Laminate tensile strength in material reference direction \( x \),
\[ S_{xxc} \] – Laminate compressive strength in material reference direction \( x \),
\[ S_{yyt} \] – Laminate tensile strength in material reference direction \( y \),
\[ S_{yye} \] – Laminate compressive strength in material reference direction \( y \),
\[ S_{xy} \] – Laminate in-plane shear strength with respect to reference axes,

Conservative estimates can be used for the above. The strength values can also be estimated based on ply properties and laminate construction. The use of particular failure criteria is not prescribed herein, however, the user should ensure that any criterion used is conservative for the loading conditions under consideration.

**Acceptability Criterion**

The acceptability conditions are as follows:

(i) The structure has at least 90% of the load carrying capability demanded in the original design,
(ii) The maximum principal strain at the perimeter of the micro-cracked region is less than half the strain value for the onset of micro-cracking.

### 5.3.2 Level 2

The Level 2 approach removes some of the conservatism included at Level 1. The basis of the Level 2 approach is to assume that micro-cracking reduces the transverse stiffness of all layers making up the laminate to zero. This allows a new set of (lower) stiffness parameters to be determined for the laminate as a whole. The region of micro-cracking is treated a zone of reduced stiffness, with a corresponding increase in stress in the surrounding un-cracked laminate.
Geometry

The region of microcracking is defined as for Level 1, Figure 11.

Loading

The loading is defined in the same way as for the Level 1 assessment.

Stress Analysis

Methods of stress analysis for the assessment of micro-cracking at Level 2 are not prescribed in this guidance. It is a requirement, however, that the analysis method used be one that is widely accepted as accurate or can be shown to be conservative.

The stress analysis shall be used to estimate stress, and hence strain, in the structure surrounding the region of micro-cracking which has been considered as an area of reduced stiffness.

Note that existing solutions, for embedded regions of lower stiffness than the surrounding structure, are unlikely to be available for all but a few simple cases. Hence, in order to realise the benefits of a Level 2 assessment (compared to a Level 1 assessment) it is likely that the stress analysis will rely on finite element modelling.

The primary outputs of the stress analysis are (i) the maximum principal strain calculated for the loading as defined in Level 1 - Loading and (ii) an estimate of the failure load(s) for the structure.

Material Properties

Assessment at Level 2 uses reduced laminate elastic properties. The laminate stiffness values are recalculated by taking the stiffness of each ply, transverse to its fibre direction, as zero. This relies on the use of ply properties. The following properties are required for each ply:

- $E_{11}$ – Young’s modulus in ply principal direction 1,
- $E_{22}$ – Young’s modulus in ply principal direction 2 (zero for micro-cracked material),
- $G_{12}$ - In-plane shear modulus with respect to ply principal directions 1 and 2 (zero for micro-cracked material),
- $\nu_{12}$ – Ply major Poisson’s ratio.

The above can be estimated if test results are not available. The reduced laminate stiffness applies only to the micro-cracked part of the structure. For the remainder of the structure the
laminate properties can be estimated as per Level 1 - Material Properties. The allowable strains and material strengths are to be defined in the same way as for the Level 1 assessment.

**Acceptability Criterion**

The acceptability conditions that should be met are as follows:

(i) The structure has at least 90% of the load carrying capability demanded in the original design,

(ii) The maximum principal strain at the perimeter of the micro-cracked region is less than half the strain value for the onset of micro-cracking.

**5.3.3 Level 3**

Level 3 allows for detailed analysis with few simplifying assumptions. Provision is to be made for estimation of loads by FEA and prediction of micro-cracking onset by finite fracture mechanics approaches.

**Geometry**

The geometry for the region of micro-cracking can be as defined for the Level 1 and 2 assessment. Alternatively the actual geometry of the region of micro-cracking can be used. The primary requirement is that the representation must fully include the affected material.

**Loading**

The loading to be considered is to be as defined at Level 1.

**Stress Analysis**

The stress analysis should consider the changes in laminate stiffness predicted according to the level of damage assessed. The stresses should be determined by a method that is accepted as accurate or can be shown to be conservative. Analysis by the finite element method will usually be appropriate for estimating the stresses for assessment at this level.

In addition to stress analysis on the ply and laminate level, Level 3 includes an estimation of the strain level for micro-cracking to proceed. This must include consideration of the existing level of damage, the loads acting and the laminate construction. This strain level can be estimated either by application of detailed failure criteria (as in the NPL approach described in the review of methods [19]) or by finite element fracture mechanics.
The primary outputs of the stress analysis for Level 3 are (i) the maximum principal strain calculated for the loading as defined in Level 1 - Loading, (ii) an estimate of the failure load(s) for the structure and (iii) an estimate of the strain level at which micro-cracking will proceed in the structure given the existing level of damage.

**Material Properties**

In order for the potential benefits of assessment at Level 3 to be realised, accurate material properties should be used. This includes the individual ply and laminate elastic properties. Where possible these properties should be based on test results. Likewise, the individual ply strengths and laminate strengths should be based on test data where possible.

Assessment at Level 3 includes detailed consideration of the strain levels at which micro-cracking initiates and proceeds. Estimation of these strain levels requires a number of additional material properties. These depend on the method adopted for analysis of micro-cracking and it is recommended that the user follow the procedures defined by the method selected.

**Acceptability Criterion**

The acceptability conditions that should be met are as follows:

(i) The structure has at least 90% of the load carrying capability demanded in the original design,
(ii) The stress/strain state is such that a margin of 1.5 applies to further micro-cracking, i.e. the loads would have to be increased by a factor of 1.5 in order for micro-cracking to proceed.

**5.4 The Role of Sub-Structure Testing**

The guidance provided for determination of defect criticality in this section focuses primarily on assessment by analysis. A number of limitations within the various analysis/modelling methods have been highlighted and a detailed Level 3 analysis will usually involve significant complexity. Hence assessments by analysis will often benefit from support and validation by testing to increase confidence in the results (particularly where acceptability is not attained by a large margin). This type of approach, making use of modelling and testing in parallel, is commonly adopted in the aircraft industry for determining damage acceptability criteria for different structural components.
6 Materials Characterisation

Although in practice there are over one hundred individual defect types, most defects, whilst perhaps differing in detail, retain broadly similar morphology and effect on material behaviour. These defects were categorised into generic defect classifications, e.g. process control, cracks, dispersed, stability and wear-out (see Chapter 3). In order to simplify the modelling approaches for the three levels of assessment, it was further assumed that most defects fit into either the delamination or matrix micro-cracking classifications. Therefore, the material data requirements and associated test methodology described in this guide only consider the material properties required by the theoretical models detailed in Chapter 5 for delaminations and matrix micro-cracking.

6.1 Material Data Requirements for the 3 Level Assessment Approach

The approach proposed in this project is based on a 3 level assessment (more detail is given in Chapter 5). Briefly, the Level 1 assessment has been defined so as to require the operator to undertake only a relatively simple analysis involving basic calculations and retaining a high degree of conservatism. The Level 2 approach allows for a reduction in some of the conservatism employed at Level 1, but is based on more detailed analysis reliant on fewer simplifying assumptions. A Level 3 assessment is the most complex and involved, with fewer simplifying equations and will typically involve a finite element analysis (FEA).

<table>
<thead>
<tr>
<th>Assessment level</th>
<th>Defect category</th>
<th>Degree of accuracy required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination</td>
<td>Matrix micro-cracking</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$E_{\text{min}}$, $\Delta G_{\text{th}}$</td>
<td>$E_{xx}$, $E_{yy}$, $G_{xy}$, $\nu_{xy}$, $S_{xxt}$, $S_{yyt}$, $S_{xxx}$, $S_{yyx}$, $S_{xy}$, $\varepsilon_{\text{mat crack}}$</td>
</tr>
<tr>
<td>2</td>
<td>$E_{11}$, $E_{22}$, $G_{12}$, $\nu_{12}$, $\Delta G_{\text{th}}$, $\Delta G_{\text{th}}$</td>
<td>$E_{11}$, $E_{22}$, $G_{12}$, $\nu_{12}$, $S_{xxt}$, $S_{yyt}$, $S_{xxx}$, $S_{yyx}$, $S_{xy}$, $\varepsilon_{\text{mat crack}}$</td>
</tr>
<tr>
<td>3</td>
<td>$E_{11}$, $E_{22}$, $G_{12}$, $G_{13}$, $G_{23}$, $\nu_{12}$, $\Delta G_{\text{th}}$, $\Delta G_{\text{th}}$, $G_{IC}$, $G_{IIc}$</td>
<td>$E_{11}$, $E_{22}$, $E_{33}$, $G_{12}$, $G_{13}$, $G_{23}$, $\nu_{12}$, $S_{xxt}$, $S_{yyt}$, $S_{xxx}$, $S_{yyx}$, $S_{yyz}$, $S_{zzt}$, $S_{zzc}$, $S_{zy}$, $S_{z\sigma}$, $S_{\sigma y}$, $\varepsilon_{\text{mat crack}}$</td>
</tr>
</tbody>
</table>
Although each assessment level requires a number of material properties, it is essential that for all levels, the assessor has a full knowledge of material type/format and ply stacking sequence for laminates. (N.B. Ply and laminate properties are designated using numeric and alphabetic suffixes respectively (Figure 12)).

In general ply ‘material’ properties will not be equivalent to ‘structural’ laminate properties as laminates consist of a number of differently oriented plies, the exception being when the laminate is fully unidirectional i.e. for this case $E_{xx} = E_{11}$, $E_{yy} = E_{22}$, $G_{xy} = G_{12}$ and $\nu_{xy} = \nu_{12}$. At the laminate level, the reference axes usually align with the dominant fibre direction, any natural structural reference or primary loading axes.

![Figure 12 - Fibre-reinforced plastic composite axes definitions for (a) ply and (b) laminate levels](image-url)

**6.1.1 Level 1**

The material properties required at this level are listed in Table 6. For the assessment of delamination type defects, a minimum value of Young’s modulus (this value corresponds to the laminate’s minor principal axis) and the Mode I threshold strain energy release rate ($\Delta G_{th}$) are required. Assessment of matrix micro-cracking defect types requires basic in-plane elastic and strength data at the laminate level plus an estimate of the strain limit for the onset of micro-cracking. For a Level 1 assessment, if measured material data are not available, conservative assumptions are permitted to be made in order to estimate values.
6.1.2 Level 2

In contrast to a Level 1 assessment, the analysis of delamination type defects at Level 2 requires the in-plane elastic properties at the ply level in addition to the Mode I and II threshold strain energy release rates. For matrix micro-cracking; in-plane elastic ply and laminate strength data, and an estimate of the strain limit for the onset of micro-cracking (Section 6.2.1) are required.

6.1.3 Level 3

In addition to the properties needed at Level 2, a Level 3 assessment requires the critical strain energy release rates for Mode I and Mode II, plus through-thickness elastic ply and laminate strength properties. The strain limit for the onset of matrix micro-cracking should also be measured and not assumed as for the previous levels.

6.2 Recommended Test Methods

Although estimated material data can be used for Level 1 and 2 assessments, accurate test data should be used at all 3 levels of assessment and always for a Level 3 assessment. The complexity and accuracy of a Level 3 assessment could be compromised if estimated material data are used. Synthesised data can be used as long as validation evidence is available.

The following sub-sections provide brief details on test standards that are recommended for use in generating the data listed in Table 6. The reader is advised to study the individual standards for full details on testing procedures.

The use of accurate load and displacement monitoring equipment is essential for precision measurements. For measurement of displacement, at the very least the test machine crosshead displacement should only be used in conjunction with a machine compliance correction, which may be non-linear. However, this is really only satisfactory for flexure tests. For tension and compression testing; clip gauge extensometers, strain gauges, non-contact video extensometers or linear variable differential transducers (LVDTs) with a low spring stiffness are recommended for displacement/strain measurement. Specimen dimensions should always be measured to the level of accuracy required in the test standard as small errors in the measurement of dimensions can make large differences to the results.
6.2.1 In-Plane Properties

This section details those test methods recommended for use in measuring in-plane properties, i.e. in the 1-2 or x-y plane (Figure 12). Test methods for measuring properties in the through-thickness direction (3 direction) are discussed in Section 6.2.2.

Tension - BS EN ISO 527 Parts 1, 4 and 5 [44-46]

The recommended test standard for generating tensile material property data for isotropic and orthotropic, and unidirectional fibre-reinforced plastic composites is BS EN ISO 527 (Parts 4 and 5 respectively). These two parts of BS EN ISO 527 detail standard specimen geometries for different formats of composite material - see Tables 7 and 8. The standard is suitable for polymer matrix composites consisting of thermosetting or thermoplastic matrices and a wide range of fibre formats, e.g. unidirectional, cross ply, mats, woven fabrics, woven rovings, chopped strands, hybrids, rovings and short or milled fibres. The standard covers glass, carbon, aramid and other similar fibre reinforcements.

BS EN ISO 527 can be used to determine tensile strength, Young’s modulus, Poisson’s ratio, strain-to-failure and strain to onset of matrix micro-cracking (not included in standard). For

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Type 1B</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Initial distance between grips</td>
<td>115 ± 1</td>
<td>150 ± 1</td>
<td>136</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>L₀</td>
<td>Gauge length for extensometers</td>
<td>50 ± 0.5</td>
<td>50 ± 1</td>
<td>50 ± 1</td>
<td>50 ± 1</td>
<td>50 ± 1</td>
</tr>
<tr>
<td>L₁</td>
<td>Length of narrow parallel section</td>
<td>60 ± 0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L₂</td>
<td>Distance between end tabs</td>
<td>-</td>
<td>-</td>
<td>150 ± 1</td>
<td>150 ± 1</td>
<td>150 ± 1</td>
</tr>
<tr>
<td>L₃</td>
<td>Overall length</td>
<td>≥ 150</td>
<td>≥ 250</td>
<td>≥ 250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>L₄</td>
<td>Length of end tabs</td>
<td>-</td>
<td>-</td>
<td>≥ 50</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td>b₁</td>
<td>Width</td>
<td>10 ± 0.2</td>
<td>25 ± 0.5</td>
<td>25 ± 0.5</td>
<td>15 ± 0.5</td>
<td>25 ± 0.5</td>
</tr>
<tr>
<td>b₂</td>
<td>Width at ends</td>
<td>20 ± 0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>h</td>
<td>Thickness</td>
<td>2 to 10</td>
<td>2 to 10</td>
<td>2 to 10</td>
<td>1 ± 0.2</td>
<td>2 ± 0.2</td>
</tr>
<tr>
<td>h₁</td>
<td>Thickness of end tabs</td>
<td>-</td>
<td>-</td>
<td>1 to 3</td>
<td>0.5 to 2</td>
<td>0.5 to 2</td>
</tr>
<tr>
<td>R</td>
<td>Radius</td>
<td>≥ 60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of centring holes</td>
<td>-</td>
<td>3 ± 0.25</td>
<td>3 ± 0.25</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7 - In-Plane Tensile Test Specimen Dimensions
### Table 8 - In-Plane Tensile Test Specimens for BS EN ISO 527 Parts 4 and 5

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Geometry</th>
<th>Use</th>
</tr>
</thead>
</table>
| BS EN ISO 527-4 Type 1B | ![Image](image1) | - fibre-reinforced thermoplastics  
- fibre-reinforced thermosets that fail in the gauge length  
- not for multidirectional, continuous fibre-reinforced materials |
| BS EN ISO 527-4 Type 2 | ![Image](image2) | - for fibre-reinforced thermosets and thermoplastics  
- suitable for orthotropic (multidirectional) laminates  
- N.B. type 2 specimens are untabbed and type 3 are tabbed  
- to decide whether end tabbed specimens are needed tests should be carried out on Type 2 specimens first |
| BS EN ISO 527-4 Type 3 | ![Image](image3) | - for testing of fibre reinforced thermosets or thermoplastics  
- only suitable for unidirectional fibres, rovings, fabrics and tapes |
| BS EN ISO 527-5 Type A and B | ![Image](image4) | |
accurate measurement of displacement or strain it is essential that clip gauge extensometers (using a suitable gauge length of ~50 mm), strain gauges or LVDTs be used. The test machine crosshead displacement even with a compliance correction will give erroneous results.

![Figure 13 - Calculation of Young’s modulus](image)

The tensile Young’s modulus is calculated from the initial linear portion of the stress-strain response between the strain limits of 0.05 and 0.25% strain (Figure 13(a)). Alternative tensile standards use the same specimen geometry and sizes, but calculate the Young’s modulus slightly differently; ASTM D 3039 [47] takes the modulus between 0.1 and 0.3% strain limits (i.e. the same strain range of 0.2%) and BS EN 2561 [48] between strain levels corresponding to P_R/10 and P_R/2 (where P_R is the specimen failure load - see Figure 13(b)). The advantage of calculating the modulus between set strain limits is that results are obtained over the same range of the stress-strain curve for different materials/specimens, whereas for BS EN 2561 the strain range used will vary depending on the failure load. However, BS EN 2561 has the advantage that it will always give a modulus value for materials such as ultra high modulus (UHM) carbon fibre-reinforced plastics (CFRP) that may fail at strain limits below 0.25%. For these types of materials it is not always possible to calculate a modulus of elasticity according to the BS EN ISO and ASTM specifications, although in these cases the maximum strain achieved should be used as the top strain limit and noted in the test report.

Calculation of tensile strain to failure can be difficult as strain gauges can become de-bonded from the specimen and clip gauge extensometers can be damaged near to or at failure. For materials where the load-deflection response to failure is almost linear (i.e. not suitable for 0°/90° laminates), it is recommended that measurement of deflection be made up to 0.5% strain using a clip gauge extensometer or strain gauges, and for the remainder of the test the machine crosshead be used. To estimate the future strain project a best fit line through the
data recorded by the extensometer, and then calculate the strain corresponding to the failure load using the equation for the best-fit line (N.B. this procedure should be noted in the test report as it is not included in the standard). A strain to failure value can then be calculated using the gauge length of the extensometer, as illustrated in Figure 14.

![Figure 14 - Calculation of tensile deflection/strain to failure for plain tensile specimens](image)

The major Poisson’s ratio ($\nu_{12}$ or $\nu_{xy}$) is the negative ratio of the measured strain in the longitudinal direction (1- or x- direction) to the strain in the transverse direction (2- or y- direction). The ratio should be calculated using strain readings from the same points of the stress-strain curve as used for the modulus determination and longitudinal and transverse strain gauges or extensometers should be used.

The strain level corresponding to the onset of matrix micro-cracking can be determined in a number of ways. For some materials, such as 0°/90° cross-ply laminates, the stress-strain curve has a distinctive kink where matrix micro-cracking in the 90° plies has initiated - see Figure 15(a). For other formats of material, such a kink or “knee” will not be so obvious and it may be necessary to load and unload the specimen at increasing load levels until hysteresis in the stress-strain response is observed (Figure 15(b)). Acoustic emission monitoring can also be employed to detect the onset of micro-cracking and the corresponding strain level. For all of these approaches, fractographic analysis of the specimens after being loaded to just above the onset point is recommended to verify the presence of micro-cracks.
The recommended test standard for generating in-plane compressive material property data for fibre-reinforced thermoplastic and thermoset composites is BS EN ISO 14126. The standard can be used to determine compressive strength, Young’s modulus and strain to failure.

BS EN ISO 14126 allows the use of two loading methods; shear loading and end loading. For both loading methods the gauge length is unsupported. Two specimen types are detailed (see Figure 16 and Table 9); Type A (thickness of material is fixed) and Type B where the material thickness can be over a range. For Type B specimens, end tabs are optional. Type A specimens are typically used for unidirectional material (ply data) tested in the fibre direction, whereas for multidirectional composites (multidirectional laminates, fabrics, mats etc.) the Type B2 specimen geometry is recommended.

Figure 15 - Determining the strain limit for onset of matrix micro-cracking

Figure 16 - Schematic of in-plane compression test specimen for BS EN ISO 14126
Alignment fixtures appropriate to the loading method should be employed to ensure good alignment of the specimen during testing. The standard requires that two longitudinal strain measurements be made, via a strain gauge on each face of the specimen, in order to ascertain whether Euler buckling has taken place during loading. If the difference between the strain gauge readings is 10% or less, then the alignment is considered satisfactory and the test is acceptable.

Compressive Young’s modulus is calculated in a similar way and between the same strain limits (0.05 to 0.25%) as for tensile testing (to BS EN ISO 527 Parts 4 and 5). Strain values are taken as the average readings of the two faces. If transverse strain gauges are also used, the Poisson’s ratio can be determined in compression and generally gives good agreement to values determined in tension.

**Shear - ASTM D 5379 (Double V-notch beam (Iosipescu)) [50]**

The large number of test methods that can be used to measure shear properties can cause confusion when selecting the most appropriate procedure for the required properties. Some shear test methods produce data at the ply level, while others produce data at the laminate level. Consequently, the choice of test method directly relates to the stress analysis approach being used, i.e. ply or laminate level.

The recommended test standard for generating in-plane shear data (and through-thickness shear data - Section 6.2.2) for fibre-reinforced thermoplastic and thermoset composites is ASTM D 5379 [50]. The double V-notch shear test method (Iosipescu) uses a fixture of the type shown in Figure 17(a). The test specimen is a double edge-notched, flat, rectangular geometry (Figure 17(b)). Standard specimens are 76 mm in length and 20 mm wide with a nominal thickness of 5 mm. The two 90° notches have a root radius of 1.3 mm and are cut at ±45° to the longitudinal axis of the specimen to a depth of 20% of the specimen width (i.e. ~4 mm). The quality of the machined notch; in particular the radius, cut surface smoothness,
and alignment can all have an effect on the quality of measured shear properties. Specimens of insufficient thickness can fail prematurely in compression at the edges in contact with the test rig, or through buckling. Therefore, a specimen thickness of $\geq 5$ mm is used to avoid these occurrences. The loading fixture applies an in-plane shear stress between the notches. For calculation of shear modulus, a biaxial rosette strain gauge is attached at the specimen center at $\pm 45^\circ$ orientation to the loading direction (Figure 17(c)). Back to back strain gauges are required for calculation of shear modulus, $G_{12}$. A check for twisting of the specimen is performed at the shear strain mid-point between the shear modulus calculation points. Differences between shear moduli, due to out-of-plane deformation, can be as high as 10\% for a batch of nominally identical specimens. To ensure maximum accuracy, the shear modulus is determined from the average response of back-to-back biaxial rosettes. At present the standard requires only one specimen from a batch to be tested in this manner provided the amount of twist for the test specimen is no greater than 3\%. Improvements to the test fixture to reduce the differences in shear moduli obtained from the two sides of specimen and possibly eliminate the need for two biaxial rosettes have been proposed, namely; (i) keying the bearing post or adding a second post to prevent twisting of the specimen due to the fixture rotating on the bearing post, and (ii) lateral adjustment to minimise out-of-plane deformation. At present, the specimen is not centrally loaded through the specimen thickness. The crosshead displacement of each half of the Iosipescu specimen cannot be used for measurement of shear strain due to the compressive deformation that often occurs at the contact surfaces.

Figure 17 - (a) Iosipescu V-notch beam test rig, (b) fibre axes system for measuring in-plane properties $G_{xy}/G_{12}$ and $S_{xy}/S_{12}$, and (c) specimen with biaxial rosette strain gauge
The shear strength can be calculated from:

\[ S_{12} = \frac{P_{\text{max}}}{wh} \]

Where \( P_{\text{max}} \) = Maximum load
\( w \) = distance between the notches
\( h \) = thickness

And the shear modulus using:

\[ G_{12} = \frac{\Delta \tau}{\Delta \gamma} = \frac{\Delta P}{wh\Delta(\varepsilon_{45} - \varepsilon_{-45})} \]

Where the variables \( \Delta P \), \( \Delta \varepsilon_{45} \) and \( \Delta \varepsilon_{-45} \) are the change in applied load and \(+45^\circ\) and \(-45^\circ\) normal strains in the initial linear region of the stress-strain curve.

6.2.2 Through-Thickness Properties

**Tension and Compression - RARDE Waisted Block [51]**

The recommended test geometry for generating through-thickness (TT) data in both tension and compression is the RARDE waisted block (developed by the Defence Evaluation and
Research Agency (DERA) - now Qinetiq). The gauge-section is 12 mm long, with a rectangular cross-section of 10 mm (y-z plane or 2-3) x 16 mm (x-z plane or 1-3). Specimens are 40 mm thick, but thinner material (19-20 mm thick) can be tested provided the linear dimensions of the specimen are scaled in proportion to the standard geometry shown in Figure 18. However, it is difficult to apply strain gauges in this case. Tensile load is introduced to specimens via adhesively bonded bars which are then gripped in mechanical or hydraulic wedge action grips on the test machine. Care should be taken in selecting an adhesive that has a cure temperature lower than that of the material being tested. In compression, specimens are loaded between flat, parallel hardened steel platens and a four pillar die set is recommended to ensure uniform loading.

The TT tensile and compressive strengths, $S_{zzt}$ and $S_{zzc}$ respectively, can be calculated using the following expressions:

$$S_{zzt} = \frac{P_{\text{maxt}}}{a \times b}$$ 

$$S_{zzc} = \frac{P_{\text{maxc}}}{a \times b}$$

Where $P_{\text{maxt}}$ and $P_{\text{maxc}}$ are the maximum tensile and compressive load respectively, ‘a’ is the specimen width and ‘b’ is the specimen depth.

![Figure 19 - Calculation of modulus for through-thickness tension and compression](image)

The technique requires biaxial (longitudinal and transverse) gauges bonded on all four specimen faces. The use of gauges on all four faces enables average strains between opposite faces to be calculated, hence small deviations in specimen/load alignment can be taken into account. The strain readings are used to assess the uniformity of loading. Tests are deemed acceptable if the difference between strains on opposing faces is $\leq 3\%$. The through-thickness tensile and compressive moduli, $E_{zzt}$ and $E_{zzc}$ respectively, are calculated between the same strain limits (0.05 to 0.25%) as for in-plane tension and compression tests - see Figure 19.
Shear - ASTM D 5379 (Iosipescu V-notch Beam) [50]

As for in-plane shear properties the recommended test method for through-thickness shear is ASTM D 5379. Provided adequate material thickness is available (i.e. 20 mm for UD materials, 76 mm otherwise), the shear modulus and strength in the x-z (or 1-3) and y-z (or 2-3) planes can be measured for a range of composite materials. Figure 20 shows the orientation in which specimens should be machined for measurement of shear properties in these planes. Modulus and strength values can be calculated using similar expressions as for the in-plane V-notch beam tests detailed in Section 6.2.1.

6.2.3 Fracture Energy Properties

Mode I

Figure 20 - Ply orientations of specimens for measurement of through-thickness shear properties

Figure 21 - Double cantilever beam specimen for measurement of Mode I properties
The recommended test method for measuring the critical strain energy release rate for Mode I loading (G\text{IC}) is ISO 15024 [52], which is equivalent to ASTM D 5528 [53]. The method is suitable for unidirectional carbon and glass fibre-reinforced thermoset and thermoplastic materials. The standard recommends the use of a double cantilever beam (DCB) specimen which is loaded in tension through loading blocks (as shown in Figure 21 - dimensions in Table 10) or piano hinges. Specimens contain a thin (≤ 13 µm) layer of PTFE at mid-thickness to act as an initial delamination. The specimens are quasi-statically loaded until delamination growth from the tip of the starter crack is observed at which point the load is removed. The specimens are then re-loaded and the onset of stable delamination growth is monitored. During loading the delamination length is measured by observing the crack growing through a series of lines marked at set intervals (1 and 5 mm) on the side of the specimen. The points at which the delamination front passes through the marked intervals are marked on the load-deflection trace. Data reduction is then performed to determine the strain energy release rates for crack delamination initiation and propagation, using a spreadsheet in an annex to the standard.

The Mode I growth threshold strain energy release rate (\(\Delta G_{\text{Ith}}\)) can be determined using ASTM D 6115 [54]. DCB specimens are cycled between a minimum and maximum displacement in tension-tension fatigue at a specified frequency. The number of cycles (N) to the onset of delamination growth is recorded and a corresponding Mode I cyclic strain rate can be calculated using corrected beam theory (CBT) or the modified compliance calibration (MCC) method as set out in [52]. \(\Delta G_{\text{Ith}}\) can be calculated in a similar way but for an acceptable (specified by the end-user or designer) value of delamination growth rate \(\text{da/dN}\) instead of a number of cycles.

**Table 10 - Dimensions for Mode I DCB Specimen**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Width</td>
<td>20 (but can use 15-30)</td>
</tr>
</tbody>
</table>
| 2h     | Thickness  | ~3 for CFRP  
          |            | ~ 5 for GRP   |
| l      | Length     | ≥125       |
| \(l_1\) | Loading block width | ≤15       |
| \(l_2\) | Loading block hole centre | \(l_1/2\) |
| h      | Mid-plane depth | half thickness |
| A      | Insert length | 60       |
| a      | Delamination crack length | \(a_0 + \text{measured delamination length}\) |
| \(a_0\) | Initial delamination crack length | 60-\(l_2\) |
The recommended test method for measuring the critical strain energy release rate for Mode II loading (\(\Delta G_{\text{IIc}}\)) is the four-point bend end notch flexure (4ENF) test [55]. The specimen and test geometry are illustrated in Figure 22. The specimen is typically ~3 and 5 mm thick for carbon and glass fibre-reinforced materials respectively. The specimen width is the same as for the DCB test (20 mm) and a PTFE film \(\leq 13\, \mu\text{m}\) thick should be used to provide a starter delamination. Specimens are loaded quasi-statically in the jig shown in Figure 22 and a delamination is initiated and grown from the PTFE insert. In the same way as for Mode I testing, the crack growth is monitored throughout the test and related to the load displacement response. Data reduction is then performed to give a value for the strain energy release rate.

A standardised method for determination of the Mode II growth threshold strain energy release rate (\(\Delta G_{\text{IIth}}\)) does not currently exist. The current procedure is to adopt the approach for Mode I. The 4ENF test is suitable for static work but in fatigue the small deflections make it difficult to control at low values of \(G\). A specimen configuration that has been used with more success in fatigue is the end-loaded shear (ELS) specimen [56]. The ELS specimen dimensions are the same as for the DCB specimens. In a similar manner for measurement of \(\Delta G_{\text{Ith}}\) in Mode I loading, \(\Delta G_{\text{IIth}}\) can be determined at an acceptable value of delamination growth rate \(da/dN\).

---

**Figure 22 - 4-point end notch flexure (4ENF) specimen for measurement of Mode II properties**

**Mode II**

The recommended test method for measuring the critical strain energy release rate for Mode II loading (\(G_{\text{IIc}}\)) is the four-point bend end notch flexure (4ENF) test [55]. The specimen and test geometry are illustrated in Figure 22. The specimen is typically ~3 and 5 mm thick for carbon and glass fibre-reinforced materials respectively. The specimen width is the same as for the DCB test (20 mm) and a PTFE film \(\leq 13\, \mu\text{m}\) thick should be used to provide a starter delamination. Specimens are loaded quasi-statically in the jig shown in Figure 22 and a delamination is initiated and grown from the PTFE insert. In the same way as for Mode I testing, the crack growth is monitored throughout the test and related to the load displacement response. Data reduction is then performed to give a value for the strain energy release rate.

A standardised method for determination of the Mode II growth threshold strain energy release rate (\(\Delta G_{\text{IIth}}\)) does not currently exist. The current procedure is to adopt the approach for Mode I. The 4ENF test is suitable for static work but in fatigue the small deflections make it difficult to control at low values of \(G\). A specimen configuration that has been used with more success in fatigue is the end-loaded shear (ELS) specimen [56]. The ELS specimen dimensions are the same as for the DCB specimens. In a similar manner for measurement of \(\Delta G_{\text{Ith}}\) in Mode I loading, \(\Delta G_{\text{IIth}}\) can be determined at an acceptable value of delamination growth rate \(da/dN\).
6.3 Summary

Test standards and procedures have been recommended for the generation of in-plane and through thickness tension, compression and shear data, as well as Mode I and II fracture toughness properties. For the highest degree of accuracy when undertaking a Level 1, 2 or 3 assessment of defect criticality, measured data should ideally be used, however it is acceptable at Levels 1 and 2 to use assumed data provided that any assumptions made are valid and justifiable. Certainly for a Level 3 analysis it is recommended that only known, measured data be used.
7 Case Studies

The following chapter details four case studies that have been selected to demonstrate how the defect criticality assessment approach can be applied. The case studies represent a range of applications in four industrial sectors: construction, aerospace, oil/gas and marine/off-shore.

7.1 Composite Over-Wrap Repairs on Metallic Pipes

Composite repairs, manually over-wrapped composite laminates, are used in the oil and gas industry for the repair of corroded pipe-work and pipelines. The repairs are used to rehabilitate pipe-work systems suffering either internal or external corrosion. Composite repairs are also applied to pipe systems that are leaking, i.e. a through pipe wall defect, usually caused by excessive internal corrosion.

The materials used in composite repairs are:

Fibre types - Glass or carbon
Matrix types - Epoxy, vinyl ester or polyurethane.

The repair laminate construction used in commercially available composite repairs is either quasi-isotropic or bi-directional. A typical example of a repair to an off-shore pipe system, in this instance a pipe-work tee, is shown in Figure 23.

Figure 23- Repair to a pipe-work tee
(Photograph courtesy of Walker Technical Resources Ltd.)
7.1.1 Design Considerations

The nature of the application implies that the composite repair has in most instances to withstand bi-axial loading. This bi-axial loading comes from the internal pressure (causing hoop loading) and system loads such as thermal expansion and bending (causing axial loading). For repairs to leaking pipe-work, the laminate also has to withstand directly the internal pressure of the pipe system such that the pressure load will not cause the laminate to de-bond or delaminate from the outer pipe surface.

The design of a specific repair solution consists of two calculations, one to determine the thickness of the repair, the other to determine the repair axial length or extent.

To determine the thickness of the repair, a laminate strength calculation and a strength of bond calculation are performed. The larger of the two calculated values of thickness is taken as the design value. In essence the design calculations answer the following two questions:

(i) **Strength calculation** - is the repair strong enough to carry the load induced by the internal pressure?

(ii) **Strength of bond calculation** (for leaking repairs or through wall defects) - is the adhesion of the bond between the repair laminate and the pipe substrate strong enough to withstand the internal pressure and the applied pipe loads and prevent leakage?

For defects caused by external corrosion only the strength calculation is required. For defects caused by internal corrosion, both strength and bond calculations are required as the composite laminate will not stop the growth of internally growing defects. The composite repair, however, will prevent further growth of defects caused by external corrosion.

The failure mode of the repair laminate when over-stressed is initially cracking of the resin. Depending on the nature of the laminate further multiple matrix cracking or fibre breakage may occur. Either mechanism leads to a significant reduction in strength of the laminate or loss of containment.

The failure mode of the repair for leaking repairs is growth of the interfacial delamination of the repair laminate from the substrate, again leading to a loss of containment at the edge of the repair. An example of failure of a repair by delamination growth is shown in Figure 24.

Generally, for leaking repairs the repair system will fail through interfacial delamination growth rather than multiple matrix (resin) cracking.
Figure 24 - Failure of a composite repair due to interfacial delamination growth (under test conditions) (Photograph courtesy of Devonport Marine Ltd.)

7.1.2 NDT of Composite Repairs

For this case study the non-destructive examination involves the detection and sizing of interfacial delaminations.

Broadly, inspection techniques fall into the following categories:

- optical techniques (such as visual and laser shearography),
- mechanical techniques (such as tapping),
- thermography,
- radiography,
- acoustic (such as ultrasonic).

A discussion on the merits of the various inspection methods cited above that can be used for the evaluation of interfacial delaminations are given in Table 11. All of the NDT methods listed are available on a commercial basis as products and/or services.
Table 11 - Comments on NDT Techniques for Delaminations

<table>
<thead>
<tr>
<th>Inspection Method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>Sensitivity is adequate for internal defects provided laminate is translucent.</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Tapping sensitive to delamination typically &gt; 50 mm²</td>
</tr>
<tr>
<td>Ultrasonics</td>
<td>Sensitive to delamination typically &gt; 50 mm² for thin laminates (&lt; 5 mm thick). The surface form of either CFRP or GRP can show considerable variation, which influences the performance of ultrasonics and the optimum choice of probe frequency. For thin, high quality GRP laminates, frequencies of up to 2 MHz can be used. Resolution is improved with CFRP materials with frequencies of ~5 MHz.</td>
</tr>
<tr>
<td>Thermography</td>
<td>For GRP, thermal imaging is successful for thicknesses up to 15 mm. For CFRP, typical resolution is 6 mm.</td>
</tr>
<tr>
<td>Radiography</td>
<td>Sensitivity depends on the separation between the faces of the delamination (defect gap). Assuming a separation of 0.5 mm, the sensitivity should be 1-2% of the total path through the laminate (i.e. chord length) provided a near optimum X-ray energy is used. However, proximity to the (opaque) steel wall is likely to reduce the sensitivity of the technique.</td>
</tr>
<tr>
<td>Laser shearography</td>
<td>Sensitivity is determined by laminate stiffness being such that measurable strain levels occur at the surface. Surface strains of 10 µ strain can be resolved.</td>
</tr>
</tbody>
</table>

The recommended techniques for detecting interfacial delaminations in this case are (from Table 11):

- Mechanical
- Thermography
- Laser shearography
7.1.3 Material Data Requirements

To perform both the strength calculation and the strength of bond calculation, the in-plane tensile material properties of the repair laminate, i.e. modulus and Poisson’s ratio, are required in both the hoop ($h$) and axial ($a$) pipe directions (measured according to BS EN ISO 527 [44, 46]). Also required is the shear modulus (measured according to ASTM D 5379 [50]).

The strength calculation requires the allowable long-term strain to failure of the laminate. These allowable values are based on GRP vessel and pipe design, prEN 13121 [57] - “GRP tanks and vessels for use above ground”. These levels are based on experimental evidence and are defined such that no matrix cracking will occur within the laminate during the lifetime of the repair. These allowable strain levels are a function of design lifetime and are presented in Table 12.

The data presented in Table 12 assumes that the strain to failure of the un-reinforced resin is greater than 2%. Furthermore, it is also assumed that the short-term strain to failure of the repair laminate is at least 4 times that taken from Table 12. The strain to failure is derived from the test carried out to determine the tensile properties of the laminate (BS EN ISO 527 [44, 46]).

Table 12 - Allowable Strains for Composite Laminates as a Function of Repair Lifetime

<table>
<thead>
<tr>
<th>Material type</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair lifetime (years)</td>
<td>2</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>For $E_a &gt; 0.5 E_h$</td>
<td>0.40%</td>
<td>0.32%</td>
<td>0.25%</td>
</tr>
<tr>
<td>For $E_a &lt; 0.5 E_h$</td>
<td>- hoop</td>
<td>0.40%</td>
<td>0.32%</td>
</tr>
<tr>
<td>- axial</td>
<td>0.25%</td>
<td>0.16%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

Note: In Table 3, design strain allowables are a function of repair Class. Effectively the Class of the repair is related to the severity of the application. Class 1 repairs are to systems where the consequence of failure is low, Class 3 repairs are to systems where the consequence is high.
For the strength of bond calculation, which is designing against the growth of a delamination along the interface between the laminate and the underlying pipe, the design method used involves the derivation of a fracture energy term that characterises the adhesion between the composite and the substrate. Figure 25 shows the situation.

**Figure 25 - Delamination of repair laminate**

It can be shown that the derivation for the delamination pressure is based on an energy balance between that stored under the deformed laminate and that required to cause delamination, i.e.:

\[
\gamma_c = \frac{1}{4\pi} P \frac{\partial V}{\partial a} = \frac{1}{2\pi d} P \frac{\partial V}{\partial d}
\]

Where:
- \( a \) is the radius of the defect (interfacial delamination) or leaking region
- \( d \) is the diameter of the defect (interfacial delamination) or leaking region
- \( V \) is the volume under the delamination
- \( P \) is the internal design pressure.

In the above equation, \( \gamma_c \) is termed the critical energy release rate (J/m²). The value of this parameter is a function of both the repair laminate and the pipe (substrate) material. It is derived experimentally from a series of tests outlined in ASME Boiler and Pressure Vessel Code – PCC-2 – Repair Standard [58].

Using the above definition, the relationship between the repair laminate thickness, internal pressure and the critical energy release rate for a circular defect can be shown to be:

\[
P = f \left[ \frac{\gamma_c}{E} \left\{ \frac{3}{512r^2} d^4 + \frac{1}{\pi} d + \frac{3}{64Gt} d^2 \right\} \right]
\]
Where: $E$ is the modulus for the composite laminate, defined as $E = \sqrt{E_a E_h}$

$f$ is the service (or safety) factor

$G$ is the in-plane shear modulus for the composite laminate

$t$ is the repair laminate thickness

$\nu$ is the Poisson's ratio for the composite laminate, defined as $\nu = \sqrt{\nu_a \nu_h}$

7.1.4 Defect Assessment

Composite repairs to pipe systems are designed for both strength and adhesion. The latter consideration involves the experimental measurement of the critical energy release rate for the repair system. In practice, this critical energy release rate will have been determined for a range of circular defects of up to 30 mm in diameter, with the typical value of $\gamma_c$ ranging from 100-400 J/m$^2$.

For repairs to leaking pipe-work, it is the size of the through-wall defect or interfacial delamination between the pipe substrate and the repair laminate that is the defect of concern. Growth of this defect to its critical size must be prevented to maintain integrity of the repair. For a given set of operating conditions, i.e. internal pressure and known material properties of the repair laminate it is possible to perform a defect assessment for a given, measured size of interfacial delamination. The issues associated with the non-destructive measurement of interfacial delaminations have been previously described in Section 7.1.2.

The guidance presented in [19, 20] (review and definition of suitable models for analysing the effects of delaminations and matrix-microcracking), is used to assess the criticality of a circular interfacial delamination for a composite repair located far from the edge of the repair. As actual data for commercially available repair systems are proprietary, an actual assessment using measured data is not possible. However, an assessment of the conservatism at each level can be made as can an outline of how the assessment should be performed if data were available both in terms of a generic and specific assessment. For full details of the defect assessment the reader is referred to [19, 20].

For the specific assessment, the following material properties are used:

\[
\begin{align*}
\gamma_c &= 150 \text{ J/m}^2 \\
E &= 15 \text{ GPa}
\end{align*}
\]

The applied pressure is assumed to be 50 bar and the repair thickness is 8 mm.
Level 1 assessment

Geometry

Maximum planar extent = a (i.e. the radius of the delamination)
Depth of delamination = t (i.e. the thickness of the repair laminate)
The location of the delamination does not require definition as the pressure acts over the total area of the interfacial delamination.

The nomenclature used is the same as in [19, 20] with the exception of the repair thickness, which is defined as \( t \) rather than \( t_1 \). All subsequent derivations are with respect to the repair laminate thickness.

Loading

It is assumed that the internal pressure acts over the complete area of the interfacial delamination. Essentially, the assumption used in a Level 1 assessment of delaminations is to reduce the dimensions of the problem to an equivalent 1-D beam.

The maximum bending moment, \( M = \frac{Pa^2}{3} \) (assuming the ends of the beam are encastre, i.e. no crack tip rotation)

There are no in-plane and shear loads, i.e. \( N=0 \)

Assuming that the pipe substrate wall and repair laminate thickness are equal implies that \( \zeta = 0.5 \) and the loads acting on the regions in front of the delamination front are:

\[
N_1 = \frac{M}{t} \quad N_2 = -\frac{M}{t} \quad M_1 = M \quad M_2 = 0
\]

(N.B. where \( N_1, N_2, M_1 \) and \( M_2 \) are in-plane loads and bending moments, see [20])

Material properties

The in-plane tensile modulus is defined as \( E = \sqrt{E_a E_h} \)

The growth threshold of strain energy, \( \Delta G_{th} \), is taken as the critical energy release rate with only the tensile bending component considered, i.e.

\[
\Delta G_{th} = \gamma_c = \frac{3P^2a^4}{32Et^3}
\]

where \( a_c \) is the critical delamination extent and the Poisson’s ratio term is small.
Criteria for delamination growth

The concentrated crack tip loads are therefore:

\[ N_c = -\frac{M}{t} \quad \text{and} \quad M_c = \frac{3M}{8} \quad \text{(46)} \]

The material parameters, \( c_1, c_2 \) and \( c_{12} \) are given by:

\[ c_1 = \frac{8}{Et} \quad c_2 = \frac{24}{Et^3} \quad c_{12} = 0 \quad \text{(47)} \]

Therefore the total strain energy is given by:

\[ G_{TOT} = \frac{91M^2}{16Et^3} = \frac{91}{144} \frac{P^2a^4}{Et^3} \quad \text{(48)} \]

Using the exact derivation for the strain energy release rate, then the acceptability criterion becomes:

\[ G_{TOT} \leq \frac{\Delta G_{th}}{2} \quad \text{(49)} \]

\[ \frac{91}{144} \frac{P^2a^4}{Et^3} \leq \frac{3}{64} \frac{P^2a_{c}^4}{Et^3} \]

Therefore, in terms of calculated energy release rate for a given (measured) defect size, for this assessment of composite repairs, the ratio to the critical value is:

\[ \frac{\gamma}{\gamma_c} < 0.074 \quad \text{(50)} \]

In terms of the measured delamination length, the ratio to the critical delamination length is:

\[ \frac{a}{a_c} < 0.52 \quad \text{(51)} \]

In terms of defect size, for a Level 1 assessment the maximum allowable defect diameter for the given material properties and service pressure is:

\[ a \leq \sqrt[4]{\frac{\gamma_c}{2} \frac{144 Et^3}{91 P^2}} \leq 14 \text{ mm} \quad \text{(52)} \]
Level 2 assessment

Geometry

Maximum planar extent (in both directions) = a (i.e. the radius of the delamination)  
Depth of delamination = t (i.e. the thickness of the repair laminate)  
Location of the delamination does not require definition as the pressure acts over the total area of the interfacial delamination.

Loading

It is assumed that the internal pressure acts over the complete area of the interfacial delamination. Essentially, the assumption used in a Level 2 assessment of delaminations is to reduce the dimensions of the problem to an equivalent 2-D plate.

The maximum bending moment in both directions, \( M = 0.2052 \, Pa^2 \) (assuming the ends of the beam are encastre or built in, i.e. no crack tip rotation)

There are no in-plane and shear loads, i.e. \( N=0 \)

Assuming that the pipe substrate wall and repair laminate thickness are equal implies that \( \zeta=0.5 \) and the loads acting on the regions in front of the delamination front are:

\[
N_1 = \frac{M}{t} \quad N_2 = -\frac{M}{t} \quad M_1 = M \quad M_2 = 0
\]

Note: these loads act in both principal directions

Material properties

The laminate is assumed to be quasi-isotropic, both behind and in-front of the crack tip. Therefore, the laminate moduli are given by:

\[
A_{ij} = \frac{t}{(1-v^2)} \begin{bmatrix} E & vE & vE \\ vE & E & 0 \\ 0 & 0 & G \end{bmatrix} \quad B_j = 0 \quad D_j = \frac{t^3}{12} A_{ij}
\]

The growth threshold of strain energy taken for Mode I is equated to the critical energy release rate with only the tensile bending component considered, i.e.

\[
\Delta G_{th} = \gamma_c = \frac{3P^2 a^4}{32Et^3}
\]
where $a_c$ is the critical delamination extent and the Poisson’s ratio term is small. For the purposes of this example the Mode II growth rate is not known, but it can be estimated to be large, i.e. the growth of the delamination is controlled principally by the Mode I component.

**Criteria for delamination growth**

The material parameters $a_{11}, a_{12}, a_{21}, a_{22}$ are given by:

$$a_{11} = \frac{1}{2} I$$  \hspace{1cm}  $$a_{12} = -\frac{3}{2} I$$  \hspace{1cm}  $$a_{22} = \frac{1}{8} I$$

Therefore the total strain energy (Mode I and II) is given by:

$$G_{\text{TOT},I} = \frac{1}{2} M^2 c_2$$  \hspace{1cm}  $$G_{\text{TOT},II} = \frac{1}{2} N^2 c_1$$

Using the exact derivation for the strain energy release rate, then the acceptability criterion becomes:

$$G_{\text{TOT}} \leq \frac{\Delta G_{\text{th}}}{2}$$

$$0.071 \frac{P^2 a^4}{E t^3} \leq \frac{3}{64} \frac{P^2 a^4}{E t^3}$$

Therefore, in terms of calculated energy release rate for a given (measured) defect size, for this assessment of composite repairs, the ratio to the critical value is:

$$\frac{\gamma}{\gamma_e} < 0.66$$
In terms of the measured delamination length, the ratio to the critical delamination length is:

\[
\frac{a}{a_c} < 0.9
\]

In terms of defect size, for a Level 2 assessment the maximum allowable defect diameter for the given material properties and service pressure is:

\[
a \leq 4\sqrt{\frac{Y_c}{2}} \frac{1}{0.071} \frac{E t^3}{P^2} \leq 24 \text{ mm}
\]

A generic assessment of the severity of an interfacial delamination between a composite repair and a metallic substrate has been undertaken. As there is no data publicly available for these commercial repair systems a generic defect assessment was performed to both Levels 1 and 2. The generic nature of the assessment compared the approximations used within each assessment level against an analytical solution for the critical energy release rate.

For this example the degree of conservatism in the energy release rate for a Level 1 assessment is a factor of 13. This is reduced to a factor of 1.5 for the Level 2 assessment.

In terms of measured defect sizes, these factors imply that for a Level 1 analysis the defect size is approximately one half the critical size, i.e. for a Level 1 assessment the measured defect becomes critical when it is one half the size of the actual critical defect size. For a Level 2 assessment, the measured defect size becomes critical at 90% of the actual critical defect size.

### 7.2 Carbon Fibre-Reinforced Plastic (CFRP) Bridge Strengthening Plates

This case study covers the use of ultra high modulus (UHM) CFRP in the civil engineering industry. The material is used for bonded over-wrap repairs for strengthening and/or repair of ageing bridge structures. The UHM CFRP over-wraps are laminated and then bonded to the appropriate section(s) of the bridge.

#### 7.2.1 Design and Material Data Requirements

The design of CFRP strengthened systems is generally based on the ultimate limit state of strength, although other limit states designed to might include serviceability, durability etc. The key components of a strengthened system are the substrate to which the reinforcement is to be bonded (in this case, a bridge), the adhesive and the reinforcement plate itself. A schematic is shown in Figure 26. Several industrial guidelines deal with the design of bonded FRP strengthened structures [59-62] and some of the key design requirements and considerations detailed in these guidelines for each of the key components are listed in Table 13.
Efficient and successful design of CFRP plates for structural strengthening or repair depends on an accurate knowledge of material properties and, in particular, the tensile properties (i.e. the strength, modulus and strain to failure) of the CFRP laminate material. The same is true for an accurate assessment of defect criticality. A Level 1 assessment, allows for conservative estimated values of tensile strength and modulus to be used, although a far more efficient assessment can be made if accurate measurements are made on the actual material being used (essential at Levels 2 and 3). For the defect assessment undertaken in this case study (Section 7.1.4), a Level 1 assessment provides sufficient analysis and no significant benefit is gained by performing more complicated analyses encompassed by Levels 2 and 3. However, in order to reduce conservatism, measured materials data are used.

**Figure 26 - Schematic of a CFRP strengthening/repair plate**

<table>
<thead>
<tr>
<th>Substrate Adhesive CFRP laminate</th>
<th>Substrate Adhesive CFRP laminate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete: [59]</strong></td>
<td><strong>Concrete:</strong></td>
</tr>
<tr>
<td>maximum bending moment,</td>
<td>Adhesive strain capacity dictated by maximum allowable strain in the composite reinforcement such that de-bonding is prevented [59].</td>
</tr>
<tr>
<td>risk of CFRP plate peel,</td>
<td>Maximum principal stress in bond-line less than tensile fracture strength of concrete [62].</td>
</tr>
<tr>
<td>risk of de-bonding,</td>
<td></td>
</tr>
<tr>
<td>shear capacity of section,</td>
<td><strong>Metal:</strong></td>
</tr>
<tr>
<td>ductility of strengthened structure,</td>
<td>Analysis routes available for predicting elastic adhesive stress distribution (takes into account thermal stresses due to differential thermal expansion [60]).</td>
</tr>
<tr>
<td>compliance with serviceability limit states,</td>
<td><strong>Metal:</strong></td>
</tr>
<tr>
<td>e.g. cracking, deflection, creep rupture and fatigue.</td>
<td>Tensile strain capacity of composite reinforcement must exceed maximum strain seen by structure in-service [59, 62].</td>
</tr>
<tr>
<td><strong>Metal: [60]</strong></td>
<td></td>
</tr>
<tr>
<td>failure of CFRP by fibre rupture,</td>
<td></td>
</tr>
<tr>
<td>fracture or yield of metal,</td>
<td></td>
</tr>
<tr>
<td>local and global buckling of strengthened structure,</td>
<td></td>
</tr>
<tr>
<td>risk of de-bonding,</td>
<td></td>
</tr>
<tr>
<td>local buckling or delamination of CFRP,</td>
<td></td>
</tr>
<tr>
<td>delamination or strain due to differential thermal expansion between metal and CFRP.</td>
<td></td>
</tr>
</tbody>
</table>
The tensile strength, modulus of elasticity and strain to failure of two UHM CFRP pre-preg materials were measured according to three of the standards recommended in [63], namely; BS EN ISO 527-5 [46], ASTM D 3039 [47] and BS EN (Aerospace) 2561 [48]. Both materials consisted of 640 GPa pitch based carbon fibres. All three standards require tensile specimens to be end-tabbed with a GRP material and a study of the effect of quality and thickness of end-tabbing material on tensile properties was undertaken. Two batches of tests were carried out using two different end tab materials; (i) a 1 mm thick GRP material and (ii) 2 mm thick Tufnol® (an electrical grade woven GRP).

The major difference between the standards is the way in which the tensile Young’s modulus is calculated as noted in Figure 13 and Section 6.2.1.

A summary of the test results is given in Table 14 and Figures 27-29. As expected, due to the low failure strains for both materials it was not always possible to calculate a modulus of elasticity according to BS EN ISO and ASTM specifications, but where it was possible, the ASTM gave the highest value of modulus followed by the ISO and then BS EN 2561. It should also be noted that the 2 mm thick end-tab material gave higher strength and strain to failure results than for the 1 mm thick tabbing material as the use of thicker, homogeneous end-tabs prevented gripping damage and premature failure was avoided. Therefore a more representative value for tensile strength was achieved.

The results of the tensile testing undertaken as part of this case study has illustrated the importance of selecting the correct test method for determination of tensile modulus as different methods will give different results. If a conservative design is being followed then the test method giving the lowest result would be used and vice versa.

<table>
<thead>
<tr>
<th>CFRP material</th>
<th>End-tab material</th>
<th>Specimen geometry</th>
<th>ASTM D3039</th>
<th>BS EN ISO 527-5/BS EN 2561</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strength (MPa)</td>
<td>Failure strain (%)</td>
<td>Modulus (GPa)</td>
</tr>
<tr>
<td>1</td>
<td>1 mm thick GRP</td>
<td>916 (21)</td>
<td>0.268 (18)</td>
<td>354 (1.4)</td>
</tr>
<tr>
<td>2</td>
<td>1 mm thick Tufnol®</td>
<td>576 (5.0)</td>
<td>0.185 (8.5)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>2 mm thick GRP</td>
<td>1198 (5.7)</td>
<td>0.343 (6.5)</td>
<td>346 (2.9)</td>
</tr>
<tr>
<td>2</td>
<td>2 mm thick Tufnol®</td>
<td>638 (9.5)</td>
<td>0.215 (13)</td>
<td>-</td>
</tr>
</tbody>
</table>

*N.B. Figures quoted are mean values (coefficient of variation in brackets)*
Figure 27 - Variation of tensile strength for 1 and 2 mm thick end tabs (ASTM and BS EN ISO/BS EN methods for both materials)

Figure 28 - Variation of tensile modulus (to BS EN 2561) for 1 and 2 mm thick end tabs (ASTM and BS EN ISO/BS EN methods for both materials)

Figure 29 - Variation of failure strain for 1 and 2 mm thick end tabs (ASTM and BS EN ISO/BS EN methods for both materials)
7.2.2 NDT of Bonded CFRP Plates

As for the previous case study, the NDT examination involves the detection and sizing of interfacial delaminations, although in this particular application the delamination is at the edge of the bonded region between the FRP plate and the bridge substrate. The range of techniques that can be used to check for interfacial delaminations were listed in Section 7.1.2, however, amongst the most widely used are techniques such as visual inspection, tap testing, thermography and ultrasonics. The more sophisticated the NDT technique used, the more accurately the delamination length can be measured, however, this entails a greater degree of complexity in the inspection.

7.2.3 Defect Assessment

For the structural strengthening of bridges (beams) using composite plates it is the size of the edge interfacial delamination between the bridge substrate and the composite plate (laminate) that is the defect of most concern. Growth of this defect to its critical size must be prevented to maintain integrity of the strengthening system. For a given set of operating conditions (i.e. live loads and known material properties of the bridge material composite laminate) it is possible to perform a defect assessment for a given, measured size of interfacial delamination. The issues associated with the non-destructive measurement of interfacial delaminations are presented in the next section.

The guidance presented in [19, 20] is used to assess the criticality of an edge interfacial delamination within a structural strengthening system of a beam. As actual data for commercially available systems are proprietary, an actual assessment using measured data is not possible. However, an assessment of the conservatism can be made, as can an outline of how the assessment should be performed if data were available both in terms of a generic and specific assessment.

The problem presented in [19] only addresses composite laminates with internal delaminations. It does not address the case in question, i.e. an interfacial delamination between two different materials. For this case, the energy release rate is given by (only for applied moment loads) [64]:

\[
G_{\text{tot}} = \frac{1}{2} \left[ \frac{M_1^2}{E_b I_b} + \frac{M_2^2}{E_r I_r} - \frac{(M_1 + M_2)^2}{(EI)_{\text{combined}}} \right]
\]

The moments are defined in Figure 9 of Section 5.2.1. The subscripts, _b_ and _r_, refer to respectively the bridge beam and the reinforcement, while the subscript _combined_ represents the combined material property, i.e. beam and reinforcement.
For this example, only a Level 1 assessment is performed as in practice the strengthening system is designed on a 1-D basis. Also edge delaminations can be modelled effectively as 1-D defects, i.e. occurring throughout the full width of the interface.

**Level 1 assessment**

**Geometry**

Figure 30 presents the schematic diagram of the defect and the definition of variables.

**Loading**

It is assumed that the live load, $P_L$, acts uniformly over the bridge. The applied moments are as follows:

$$M_1 = M = \frac{P_L}{2}(a + b)(a + b - L) \quad M_2 = 0$$

A nominal value of $P_L$ of 100 kN/m is used.

There are no in-plane and shear loads, i.e $N=0$

![Schematic diagram of beam and reinforcement](image)

**Figure 30 - Schematic diagram of beam and reinforcement**

Length of edge delamination = $a$
Distance from reinforcement to bridge support = $b$ (N.B. assumed that support is pin-jointed)
Applied (live) load = $P_L$ (assumed uniform across length of bridge)
Length of bridge = $L$
Material properties

The in-plane tensile modulus of the bridge (substrate) is taken as $E_b = 138$ GPa (i.e. cast iron)

The in-plane tensile modulus of the reinforcement is taken as $E_r = 320$ GPa (N.B. this is an average modulus value calculated from CFRP materials 1 and 2 and measured according to BS EN 2561 - Table 14).

The critical strain energy release rate, $\Delta G_{th}$, is taken as 50 J/m$^2$

Dimensions and geometry

Length of bridge, $L = 10$ m

In reality, the shape of the beam requiring reinforcing will be of an I-shape. However, for this example the beam will be assumed to be rectangular with a depth such that flexural rigidity is comparable to actual examples. Therefore for this example, the depth or thickness of the beam, $t_b$, is taken as 250 mm.

The thickness of the reinforcement, $t_r$, is taken as 10 mm.

Criteria for delamination growth

Substituting the equation for the applied moment into the total strain energy release rate equation implies:

$$G_{TOT} = \frac{M^2}{2} \left( \frac{1}{E_b I_b} - \frac{1}{(EI)_{combined}} \right)$$

It is possible to simplify the flexural rigidity term using the assumption that $E_b I_b >> E_r I_r$ to:

$$\left( \frac{1}{E_b I_b} - \frac{1}{(EI)_{combined}} \right) = \frac{12}{E_b I_b^3} \left( 1 - \frac{1}{1 + 4 \frac{E_r t_r}{E_b t_b}} \right)$$
Furthermore, the length $L$ is much greater than the sum, $(a+b)$, therefore the total train energy release simplifies further to:

$$G_{TOT} = \frac{3P_L^2L^2}{2} \frac{(a + b)^2}{E_b t_b^3} \left(1 - \frac{1}{1 + 4 \frac{E_r t_r}{E_b t_b}}\right)$$  \hspace{1cm} (68)

The acceptance criterion for the critical strain energy release rate is:

$$G_{TOT} \leq \frac{\Delta G_{th}}{2}$$  \hspace{1cm} (69)

Implying:

$$3P_L^2L^2(a + b)^2 \left(\frac{1}{E_b t_b^3}\right) \left(1 - \frac{1}{1 + 4 \frac{E_r t_r}{E_b t_b}}\right) \leq \Delta G_{th}$$  \hspace{1cm} (70)

Re-writing the above in terms of the critical defect size, $a_c$, and assuming that $a_c >> b$, implies:

$$a_c = \frac{1}{P_L L} \sqrt{\frac{\Delta G_{th}}{3 \frac{E_b t_b^3}{\left(1 - \frac{1}{1 + 4 \frac{E_r t_r}{E_b t_b}}\right)}}}$$  \hspace{1cm} (71)

Inserting the material and geometric data into the above equations results in $a_c = 364$ mm.
7.3 Effect of Fibre Waviness on Longitudinal Compression Strength of CFRP Pultrusion

For aligned fibre systems (unidirectional, multidirectional, etc.), fibre misalignment can be a major cause for concern and extremely detrimental to material performance. Figure 31 illustrates the effect of the angle between the applied load and the fibre direction on the longitudinal/transverse compressive strengths ($S_{11C}$, $S_{22C}$) and shear strength ($S_{12}$) of a unidirectional CFRP laminate. A 5° or 10° misalignment of the fibres from the true zero direction has a significant effect on the laminate strength. For balanced ‘±’ multidirectional laminates, this effect will be less pronounced.

![Figure 31 - Effect of the angle between the applied load and the fibre direction on various strengths of a unidirectional laminate](image)

This case study has looked at the experimental and theoretical assessment of the effect of fibre misalignment in a carbon fibre-reinforced pultruded material system. The material is used in an application where the design driver is compression performance.

Test work undertaken in this case study has evaluated the static compression performance of a unidirectional carbon fibre-reinforced pultrusion. The tests were undertaken using the parallel-sided specimen (110 x 10 x ~2 mm) specified in BS EN ISO 14126 [49]. The results showed significant scatter in the compression failure strain and strength of the material, with two distinct groups of results around 0.5-0.6% and 0.7-0.8% failure strain with the mean strength results for the two groups of specimens at ~700 MPa and 876 MPa respectively, a difference of approximately 20%. It was anticipated that the material would fail at around 0.8% strain so the failures at 0.5-0.6% were considered premature and it was suspected that the premature failures might have been due to regions of fibre waviness present in the gauge length of test specimens. The suspicion of the presence of fibre waviness as a manufacturing
defect represents the starting point of the assessment framework shown. Subsequently, experimental and theoretical assessments of the criticality of fibre misalignment were undertaken.

7.3.1 Detection of Fibre Waviness

There are currently no effective NDE techniques capable of accurately detecting and measuring the degree of internal fibre misalignment or waviness in composite materials. Visual inspection with backlighting (if access to both sides of the material is possible) of translucent materials is one technique that may yield evidence as to fibre misalignment, but it is not suitable for thick or painted components, situations where backlighting is not available or for non-translucent materials such as CFRP. It is often the case that fibre misalignment will only be detected by visual inspection if it is apparent on the surface of a component. In this case study, areas of fibre waviness could be seen on the edge of machined (good surface finish) compression specimens and further micrographic analysis (destructive) was used to confirm the presence and degree of misalignment (Figure 32). The micrographic technique used for assessing the degree of fibre waviness in this study is detailed in [65].

![Figure 32 - Appearance of fibre waviness in CFRP material by; (a) visual inspection and (b) optical micrograph](image)

7.3.2 Defect Assessment

Experimental

It was not possible to prove that regions of fibre waviness were the cause of premature compression failure by microscopic inspection due to the damage caused in the specimens at failure. Therefore, in order to investigate whether fibre waviness was acting as a trigger for compression failure at low strain levels, a series of four-point flexure tests (based on BS EN
ISO 14125 [66]) were undertaken. Sections of material were machined containing high and low proportions of fibre waviness as viewed with the naked eye. Where possible, specimens with a high degree of fibre waviness were cut so that the defective area of material was positioned in the centre span of the four-point flexure set-up and nearest to the specimen face in compression. In this manner, regions of material containing fibre waviness could be loaded in compression and the effect on flexure strength, and the behaviour under compression loading observed. The test configurations are shown in Figure 33.

The results of the flexure tests showed that specimens with a low proportion of fibre waviness had a mean strength 25% higher than those with a high degree of waviness. It was concluded that fibre waviness did act as a trigger for premature failure, and the results provide evidence to corroborate the theory that fibre waviness is the cause, or contributing factor, of compression failures occurring at lower than expected strains.

Theoretical

It is possible to estimate the effect of fibre misalignment on the compression modulus and strength of a CFRP material using packages such as the Component Design Analysis (CoDA) material synthesis and design software formulated and validated by NPL. If half the fibre content is misaligned by ±5° in a nominally fully aligned material with 60% fibre content, the predicted modulus falls by 2.4%. For the strength, a 20% reduction is obtained, although the micro-mechanics within CoDA does not include any additional effect of the misalignment on triggering a local compression crippling failure.

For a ±10° misalignment of half the fibre content, the effects are a 9.5% and 40% reduction for modulus and strength, respectively. Interestingly if all the misalignment is in the same direction, such as, -10°, the effects are larger at 15% and 53% reduction for modulus and strength, respectively. Misalignment in one sense, could occur in a thick filament-wound component i.e. inwards towards the mandrel.
The use of simple micromechanics models as used in CoDA, is typical of a Level 1 approach. A micromechanics model that includes the effects of imperfection-sensitive plastic micro-buckling, where the imperfection is in the form of fibre misalignment, is the Budiansky-Fleck-Soutis (BFS) compressive failure criterion shown schematically in Figure 34. (N.B. this failure criterion is included in the commercially available Laminate Analysis Program (LAP) software).

The theoretical assessment using the BFS failure criterion performed in this case study has investigated the effect of varying degrees of fibre misalignment on the compression strength of a CFRP material. As the materials data for the material are proprietary, an actual assessment using measured data is not possible. Therefore, typical values for the shear strength of a resin (K) and transverse and in-plane shear strengths of a fully UD carbon fibre-reinforced plastic (σ_{22}, σ_{12}) have been used. Figure 35 shows a micrograph of a microbuckle ‘kink’ band in a typical CFRP compression failure and the angle of microbuckle propagation (β≈17°) has been measured. In order to show the effect of fibre misalignment, the normalised unnotched longitudinal compression strength has been calculated for a generic CFRP material using the BFS failure criterion in LAP using the kink band propagation angle determined from Figure 35. The results are plotted in Figure 36 together with the normalised compression strengths calculated using CoDA. For small degrees of fibre misalignment (< 5°) it can be seen that CoDA tends to give a slightly more conservative value for compression strength but when the fibre misalignment is more severe

\[
\sigma_{11} = \frac{\alpha k - \sigma_{12} - \sigma_{22} \tan \beta}{\phi}
\]

Where:
- \(K\) is the matrix shear strength (MPa)
- \(\phi\) is the angle of fibre waviness (or imperfection)
- \(\beta\) is the angle of propagation of the micro-buckle
- \(\alpha\) is equal to \(1+R^2\tan^2\beta\), and \(R\) is taken as 1.5 [67]
- \(\sigma_{11}\) longitudinal compressive stress (MPa)
- \(\sigma_{22}\) transverse tensile stress (MPa)
- \(\sigma_{12}\) in-plane shear stress (MPa)

**Figure 34 - The Budiansky-Fleck-Soutis (BFS) failure criterion for unnotched longitudinal compression strength taking into account initial fibre misalignment**
Figure 35 - Determination of propagation angle of a micro-buckled region in a compression kink band in a CFRP material

(10-20°) the predictions for both software packages show close agreement. This degree of analysis is typical of a Level 2 assessment as it requires a greater knowledge of material properties and a more detailed examination of the failure mechanism i.e. propagation angle of compression kink band.

The compression test results measured for the CFRP pultrusion showed a difference of approximately 20% between those suspected of failing prematurely due to fibre misalignment and those that did not. Using the normalised compression strength plot in Figure 36 it is therefore possible to determine the approximate degree of fibre misalignment present to cause this reduction in compression strength, i.e. ~ 4° using the BFS failure criterion.

Figure 36 - Effect of fibre misalignment on normalised longitudinal compression strength using the Budiansky-Fleck-Soutis (BFS) failure criterion in LAP and CoDA
If a more complex level of defect assessment is required (i.e. Level 3) then a numerical procedure, such as that described in [68] can be employed, although a far more detailed knowledge of the geometry of the fibre waviness and material properties is required.

The experimental assessment undertaken in this case study has shown that the compression strength of a unidirectional pultrusion is significantly reduced by areas of fibre waviness. Due to the confidential nature of this case study it is not possible to provide a detailed calculation as to the criticality of the degree of fibre waviness, but briefly it is typically determined by comparison of the measured characteristic compression strength, usually defined as the mean compression strength minus twice the standard deviation, to a specified design allowable that includes appropriate safety factors. The theoretical assessment using micromechanics approaches such as those used in CoDA and LAP, has shown that the degree of reduction in compression strength can be predicted and is significant (20%) for fairly small levels of fibre misalignment (i.e. ~4°).

### 7.4 Lightning Strike of CFRP Wing Panels

This case study looked at investigating the types and extent of damage that occur when a relatively thin wing skin fabricated from a carbon fibre-reinforced epoxy material is subjected to lightning strike. This type of phenomena can give rise to considerable damage in composite structures and in the worst case can lead to fuel ignition from sparking in the fuel tanks. In addition to damage such as delamination, matrix micro-cracking and fibre fracture, the plastic matrices typically used in CFRP can undergo chemical and physical changes (thermal damage) which can significantly reduce mechanical properties.

In order to reduce the damage caused by lightning strike, a thin metal (copper or aluminium) mesh can be incorporated into the outer plies of material (N.B. a combination of carbon and aluminium should be avoided due to galvanic corrosion). In this case study, the damage present in two panels, one containing a metal mesh and one without (Figure 37 (a) and (b) respectively), has been investigated and in particular the extent of thermal damage to the plastic matrix in the panel containing a protective mesh. In order to determine the criticality and effect of the lightning strike damage on the residual strength of the CFRP material, the panels were compression loaded to failure by BAE Systems as detailed in [69].

#### 7.4.1 Investigation of Damage Extent

From visual inspection it is obvious that both panels contain damage, but the extent of damage needs to be further investigated in order to assess its criticality fully. In the case of wing skins, a simple visual inspection performed by an operator at the Level 1 stage is inadequate for assessing the extent of damage as internal defects may go undetected. Indeed, internal damage can often exist with little or no apparent surface damage. In addition it is
Figure 37 - Lightning strike panels; (a) without protective mesh and (b) containing copper mesh

Figure 38 - Micrographs of (a) resin burn-off and matrix micro-cracking in CFRP panel containing lightning strike protection and (b) large scale delaminations in unprotected panel
often the case that only one surface of the skin will be accessible and therefore damage on the back face of the skin will also go undetected. Prior to ‘compression-after-lightning strike’ loading, both panels were ultrasonically C-scanned (undertaken by BAE Systems) to determine the extent of the damage area due to delamination. This level of inspection is typical of a Level 2 or 3 damage assessment. It is noted that although ultrasonic inspection is the main NDE technique used for inspection of composite wing panels, other techniques such as thermography and X-radiography (using a radio-opaque penetrant) can be used.

The damage evident in Figure 37 (a) is mainly resin burn-off and matrix micro-cracking, whereas for the unprotected panel (Figure 37 (b)) the main damage types are ply splitting, matrix micro-cracking, fibre fracture, multi-level delaminations and resin burn-off. It is clear that the panel containing the copper mesh has a much smaller damage area and this is due to the lightning strike being conducted across the surface of the panel, rather than being driven through-the-thickness of the material in the case of the unprotected panel. Damage types have been characterised in [69] and also optical micrographs of the damage through-the-thickness have been produced to show the difference in damage present in the two panels (Figure 38).

However, doubt remained over whether the seemingly unaffected resin below the obvious damage zone of the panel containing the copper mesh had actually been damaged. Therefore, a series of differential scanning calorimetry (DSC) tests were undertaken on material from a number of different areas of the panel in order to determine if the glass transition temperature (Tg) of the material had been effected by the lightning strike as an indicator of thermal damage to the plastic resin. Figure 39 shows the locations from where samples were taken for DSC tests for the panel containing the protective mesh. Location A represents an area of material well away from the epicentre of the strike and is undamaged. Location B is in the upper section of the strike zone and location C is directly underneath position B, but in seemingly undamaged material. In addition, a sample of material was taken from the panel (location A) containing no protective mesh. It is noted that this area of material was undamaged.

![Diagram of DSC sample locations for CFRP lightning strike panel containing mesh](image-url)
DSC tests were undertaken according to ISO 11357-2 [70]. For each sample two runs were performed in order to assess whether the material was fully cured i.e. if any post cure occurred on the second run. The results are detailed in Table 15. In general, there was no difference in the $T_g$ of the resin between the various locations and panels sampled, providing evidence that the resin within and beneath the damage zone was probably not thermally damaged by the lightning strike.

Table 15 - DSC Results for Lightning Strike Panels

<table>
<thead>
<tr>
<th>Panel</th>
<th>Sample location*</th>
<th>Run</th>
<th>1st heating ramp</th>
<th>2nd heating ramp</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak exotherm (°C)</td>
<td>Onset (°C)</td>
<td>Inflection (°C)</td>
<td>Endpoint (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No protective mesh</td>
<td>‘A’ - corner away from strike zone</td>
<td>1</td>
<td>233.0</td>
<td>214.1</td>
<td>225.1</td>
<td>229.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>238.6</td>
<td>213.8</td>
<td>224.7</td>
<td>230.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>221.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With protective mesh</td>
<td>‘A’ - corner away from strike zone</td>
<td>1</td>
<td>234.6</td>
<td>214.9</td>
<td>220.2</td>
<td>226.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>232.9</td>
<td>217.8</td>
<td>219.9</td>
<td>223.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>220.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘B’ - upper section in strike zone</td>
<td>1</td>
<td>237.5</td>
<td>209.2</td>
<td>218.9</td>
<td>233.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>236.9</td>
<td>221.4</td>
<td>223.3</td>
<td>229.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>221.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘C’ - lower section beneath strike zone</td>
<td>1</td>
<td>236.3</td>
<td>207.9</td>
<td>222.8</td>
<td>229.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>238.8</td>
<td>212.1</td>
<td>223.1</td>
<td>231.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>222.9</td>
<td></td>
<td></td>
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</tbody>
</table>

* details on sample locations are given in Figure 39

7.4.2 Defect Assessment

Experimental

The critical loading mode for aerospace wing skins is compression, and under this mode of loading the critical damage type is delamination. The failure mechanism of CFRP laminates, that have been subjected to lightning strike (for unprotected panels) or low velocity impact, under uniaxial compression is governed by buckling of the delaminated sub-laminates and propagation of delaminations transverse to the loading direction to the edges of the panel resulting in catastrophic failure. For panels containing a protective mesh, the damage due to lightning strike is limited to the extent that the residual compression strains were close to those obtained for the undamaged panels [69].

The most commonly used method of experimentally determining the effect of the damage caused by low velocity impact and/or lightning strike is the compression-after-impact (CAI) test. The test is conducted by introducing damage to the panel by either impact or lightning
strike followed by a separate in-plane compression test on the damaged panel. There are several variations of the CAI test but concerns still exist over; (i) the choice of test geometry and impact energy level for the CAI test; and (ii) the lack of an ISO standard test method for CAI. The most important concern is whether the CAI test, as normally conducted [71], is applicable to other material systems, such as thicker aerospace panels, sandwich structures, and non-aerospace materials where the predominant impact damage mode is not delamination. For low velocity impact, the level of energy input is set to that which will not cause penetration, but that does create internal delaminations leaving little or no evidence on the impacted or back surface i.e. barely visible impact damage (BVID). In laboratory testing, a dent of a specified size or a delamination of a certain area is used to set the required energy level. Alternatively energy inputs equal to the anticipated threats can be used. This last approach would be most applicable to the phenomenon of lightning strike. Work undertaken at BAE Systems has proposed a new CAI method [72-73] for the generation of design allowable data (as opposed to materials data), designed to mimic the real structure and provide more realistic CAI results.

CAI testing of the lightning strike panels investigated in this case study is currently being conducted by BAE Systems [74], however the results to date are confidential and have not been published.

The following section details how the critical damage size (i.e. area of delamination or depth of dent on impacted face etc.) can be experimentally determined. The approach recommended is similar to that followed in previous work conducted by BAE Systems [69], [72] and [73]. A series of impact or lightning strike tests are performed with the energy level input ramped from below that needed to cause BVID (considered as a threshold impact energy level in [69], [72] and [73]) to well above that required to cause BVID. Visual and ultrasonic C-scan NDT techniques are used to determine the area of delamination or dent depth after each impact. CAI tests are conducted on each of the damaged panels and the compression strength and/or failure strain measured. By plotting the residual compression strength or failure strain against damage area for each test, the critical damage size, and associated energy level, can be determined with regard to the design allowable compression strength or failure strain. The approach detailed here is typical of a Level 2 or 3 analysis where a considerable degree of testing and knowledge of the material system in question is required for a full experimental assessment of the criticality of the damage.

It is recognized here, that damage is more likely to propagate to a large size, or catastrophically, under a long-term cyclic load rather than a one-off overload. Within the current DTI funded Performance Programme, Project F12 - “Development of test methods for determining the criticality of defects in composite materials systems under long-term loading”, is looking at providing a generic approach to residual property assessment, allowing the evaluation to be linked to the type of damage occurring and the important properties related to the material behaviour, the application requirements (fatigue) and the stress field.
Theoretical

Although an actual theoretical analysis of the effect of damage caused by lightning strike on the residual compression strength has not been undertaken in this case study, a suitable analysis method is recommended. As with low velocity impact, for an unprotected laminated CFRP panel, lightning strike results in a complex distribution of a number of different damage types, with delamination being the most critical. It is highlighted here that the extent of the damage caused by low velocity impact increases through-the-thickness of the panel, whilst for the case of lightning strike it decreases. However, for both phenomena, the theoretical analysis is one of modelling the behaviour of delamination under compressive loading.

In [73], two methods, theoretical buckling analysis and finite element analysis (FEA), were used to analyse the compression performance of unimpacted panels loaded using the newly proposed CAI jig designed by BAE Systems. For the analysis of impacted panels containing delamination, it is recommended that a Level 3 assessment using FEA modelling should be used. Two reports produced as part of this project [19, 20], reviewed and defined suitable models for analysing the effects of delamination and matrix-microcracking, and a further report [21] detailed the material properties required for each modelling approach and assessment level, and provided recommendations as to appropriate test methodologies. Full details of the Level 3 assessment are detailed in Section 5, but briefly it allows for a more sophisticated analysis than prescribed at Levels 1 and 2, with the delamination being modelled as a circular region (or in some cases the actual shape of the delamination can be modelled if it has been determined by a Level 2/3 NDE assessment) rather than a rectangle. In addition to criteria for buckling/instability, criteria for delamination growth and failure are recommended in [20] which are based on the growth threshold and critical strain energy release rates for Mode I and II. These properties were measured for two GRP materials, in a programme of test work undertaken in the project as detailed in [75].

8 Conclusions

This guide details a defect criticality assessment framework that has been formulated based on a multi-level assessment approach similar to that detailed in API 579 [13]. The framework recommends 3 Levels of assessment, with an increasing degree of sophistication from Level 1 - Operator to Level 3 - Specialist. At each level, guidance has been provided on materials characterisation, NDE, defect criticality and materials characterisation. The defect criticality guidance has focused on two “crack-like” defect types; delamination and matrix micro-cracking.
Four industrial case studies, representing a range of sectors, have been undertaken in order to validate the procedural guide for the criticality and assessment of defects and damage in composite material systems. The case studies were chosen so as to be representative of true material systems, hence the choice of two bonded applications. Each case study has focused on various aspects of damage assessment and criticality, including the importance of accurate material property measurements using suitable test methodologies, correct choice of NDE technique for defect detection, identification and sizing, and use of appropriate defect assessment methods. This work has demonstrated how the assessment procedure can be applied to a range of applications and with varying levels of assessment complexity.
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Appendix A: Defect Appearances

Figure A1 - Micrograph of fibre fracture in a multidirectional CFRP laminate

Figure A2 - Micrograph showing fibre pull-out in a woven GRP material

Figure A3 - Micrographs of matrix micro-cracking in (a) a woven GRP and (b) a multidirectional CFRP laminate
Figure A4 - Micrographs of voidage in (a) unidirectional pre-preg and (b) filament wound CFRP materials

Figure A5 - Digital photograph of resin starved areas in a woven GRP laminate

Figure A6 - Micrograph of resin rich areas in a filament wound CFRP material
Figure A7 - Digital photograph of centrally located delaminations on the impact surface of a GRP skin on a Nomex sandwich construction

Figure A8 - Digital photograph of back surface impact damage showing delamination and fibre fracture in a CFRP panel

Figure A9 - X-ray image of impact delaminations within a CFRP panel

Figure A10 - X-ray image of edge delaminations around a drilled hole in a CFRP panel
Figure A11 - Micrograph of an edge delamination within a CFRP panel

Figure A12 - Digital photograph of impact delaminations in top skin of a sandwich construction

Figure A13 - Digital photograph of skin-to-core de-bond in a GRP skin, PU foam sandwich

Figure A14 - Digital photographs showing core crushing in (a) GRP-high density Nomex and (b) CFRP-medium density Nomex sandwich constructions