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Assessment and Criticality of Defects and Damage in Adhesively Bonded Composite Structures

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Workshop on NDT/SHM Requirements for Aerospace Composites
National Composites Centre, 9-10 February 2016

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Agenda

- Introduction
  - Requirements of SHM/NDE
  - Limitations of conventional NDE
- Production and in-service defects/damage
- Failure mechanisms
  - Adhesively bonded joints
  - Sandwich structures
- Kissing bonds
- SHM/NDE techniques
- Defect criticality framework
- Conclusions


Source: Airbus website

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Requirements of SHM/NDE Techniques

- Currently, there is a lack of design methodologies, reliable NDE techniques and useable data for adhesively bonded composite and metallic structures/systems
- Requirement for *in-situ*, real-time SHM techniques for accurate monitoring and quantification of deformation and damage (i.e. improved probability of detection (PoD) of safety critical defects), and remnant life of bonded composite and hybrid engineering structures for in-service performance assessment
- Improved predictive modelling of failure mechanisms (i.e. damage initiation and growth) in adhesively bonded composites and composite sandwich constructions under complex loading conditions (including static, cyclic fatigue and hostile environments) – fracture mechanics and stress-based failure criteria approaches
- Reliable techniques for simulating (reference defect artefacts (RDAs)), detecting and characterising safety critical defects in adhesively bonded composite structures

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Limitations of Conventional NDE Techniques

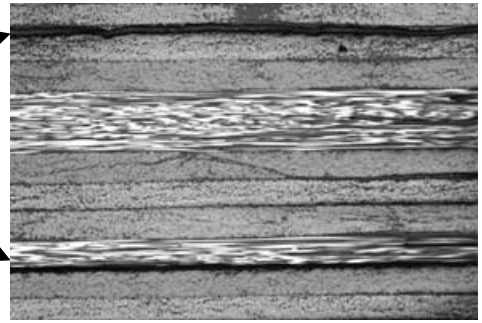
- Inability to detect small defects before they grow to a critical size
- Inspection of structural parts with complex geometries (i.e. bonded joints)
- Unable to dismantle critical parts in bonded structures for detailed inspection
- Limitations on technique efficiency and reliability for accurate localisation and detailed characterisation (shape/dimensions) of certain types of damage (i.e. kissing bonds/kissing de-bonds)
- Difficulty in detecting certain defects extends to the inspection of adhesively bonded repairs of composites
- NDE data - generally there is no direct feedback to *in-situ*, real-time engineering design software for rapid structural integrity monitoring and assessment (i.e. decision making software)

Production/In-service Defects/Damage in Composite Laminates

Thermal Effects

- Non-uniform cure (thick sections) - poor consolidation
- Poor cure and heat damage
- Exothermic chemical reactions (thick sections)
- Residual stresses ⇒ microcracking + delaminations

Delaminations



Fibre Related Defects

- Fibre breakage/fraying - inner radii of curved structures
- Fibre wash (or displaced fibres) or whorls
- Poor fibre alignment and incorrect stacking sequence
- Warpage/fibre folding (pultrusions)
- Wrinkling/kinking (i.e. out-of-plane deformation)

Production/In-service Defects/Damage in Composite Laminates

Matrix (Resin) Related Defects

- Microcracking
- "Unwetted" (resin starved or dry) areas
- Resin rich areas
- Voids (or porosity)

Mechanical Handling/Processing/Machining Induced Defects

- Inclusions (e.g. release film, chemical contaminants)
- Poor ply abutment
- Local buckling or bulging
- Steps (thickness variations)
- Fibre wrinkling/kinking and surface rippling
- Dents, nicks, gouges and scratches

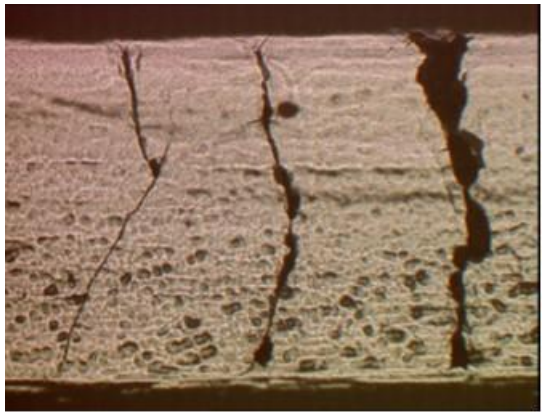
Production/In-service Defects/Damage in Composite Laminates

In-service Damage

- Fibre fracture and pull-out
- Impact damage – transverse cracking/delaminations
- Lightning strike – thermal and mechanical damage
- Moisture/chemical ingress
- Elevated and sub-zero temperatures
- Cyclic fatigue and creep rupture
- Corrosion/erosion (material thinning)
- Fire damage

Sandwich Structures

- Sandwich skin-to-core de-bonding
- Crushed sandwich core



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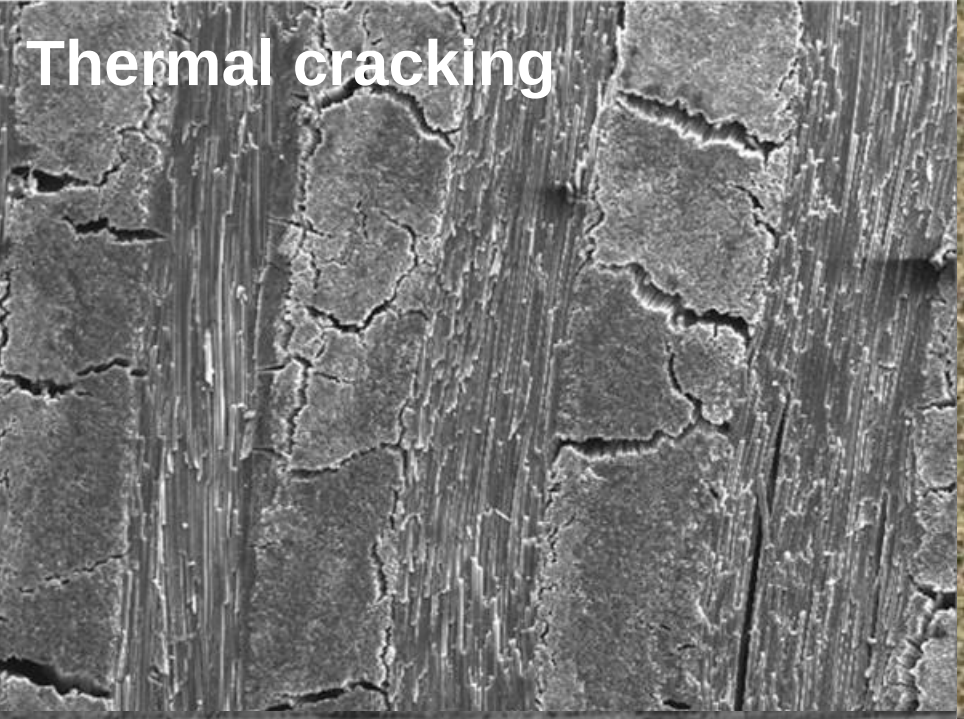
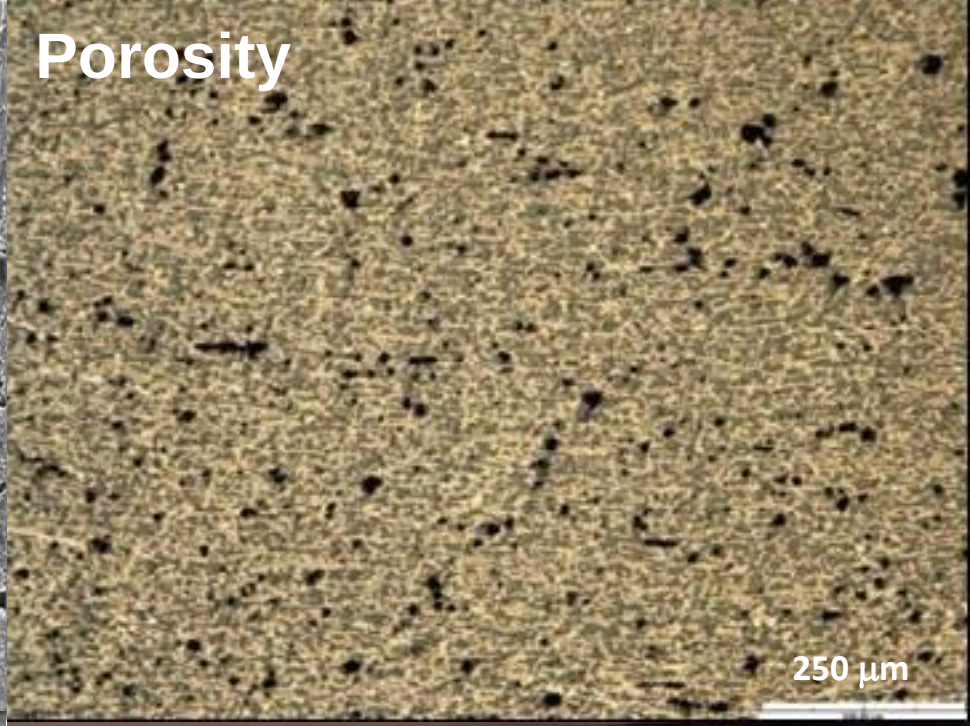
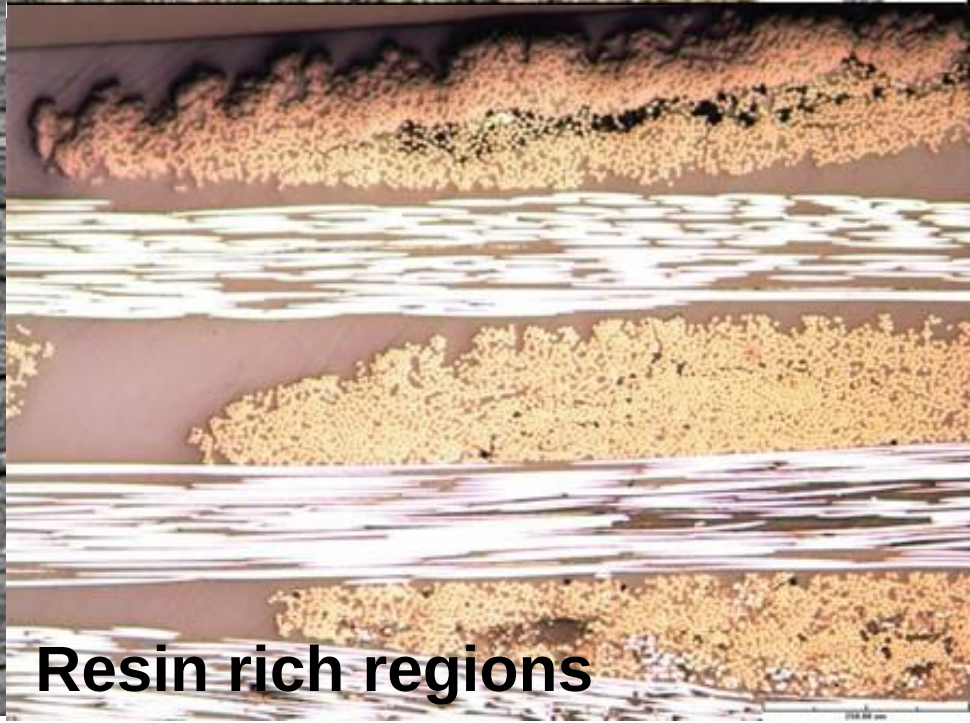

Thermal cracking


Porosity
250 µm

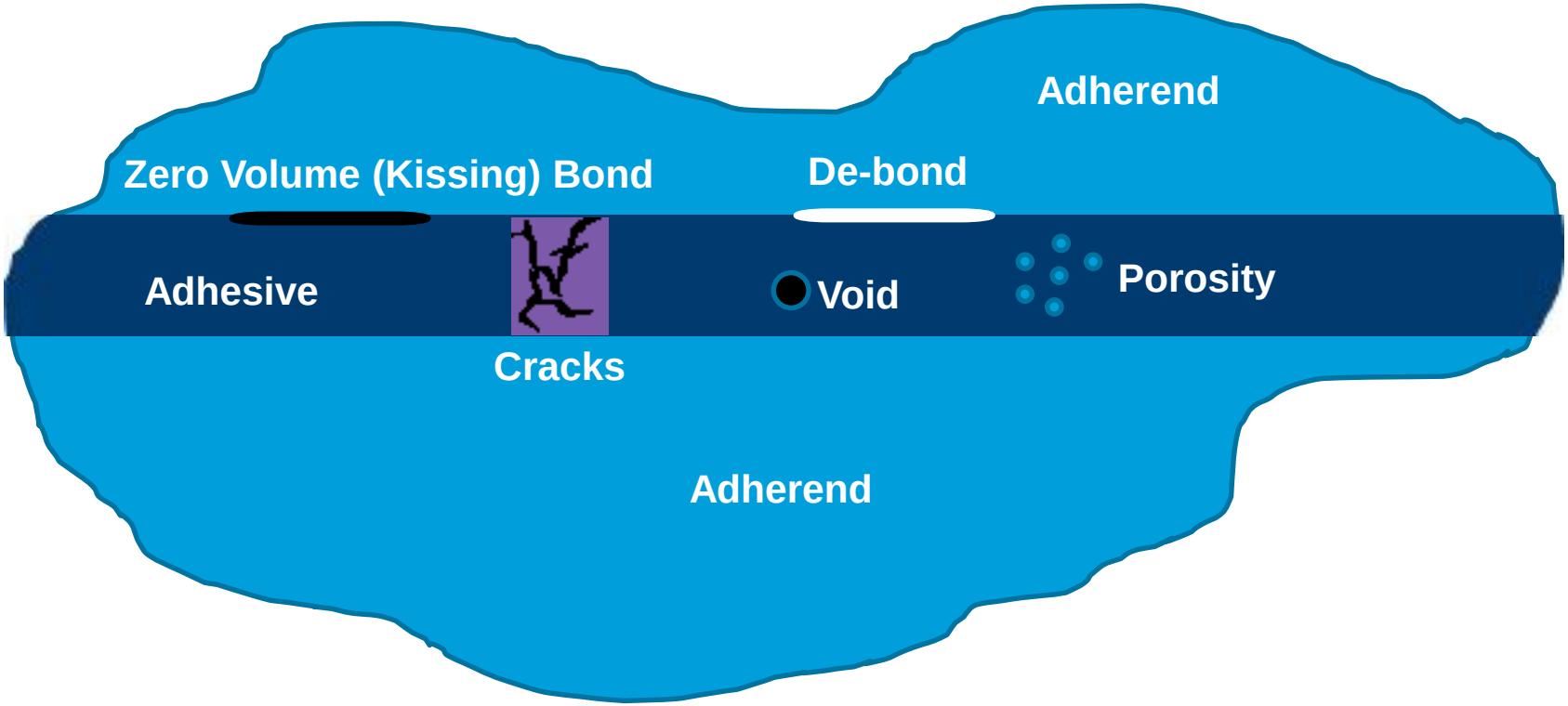

Impact Damage


Resin rich regions

Production/In-service Defects/Damage in Bonded Joints

- Fibre Disbonds – interfacial failure between adherend and adhesive or the surface treatment (e.g. primer)
- Zero-volume disbond (kissing bond) – interface is bonded, but bond strength is not assured
- Poor cure ⇒ poor cohesive strength resulting from either poor mixing, inadequate temperature control, light or other form of energy to activate cure, or pressure during the cure cycle
- Porosity and voids – due to volatiles (e.g. water vapour) within the adhesive, entrapped air or insufficient application of adhesive
- Cracking within adhesive - due to incorrect cure or brittleness of cured resin (brittle resins are susceptible to cracking under impact loading and thermal cycling)
- Residual stresses in adhesive layer due to differences in the coefficient of thermal expansion (CTE) between the adherends and adhesive resulting from processing at elevated temperatures
- FRP delamination – occurs when the interfacial strength at the adhesive/adherend regions is stronger than the fibre/matrix interface

Production/In-service Defects/Damage in Bonded Joints



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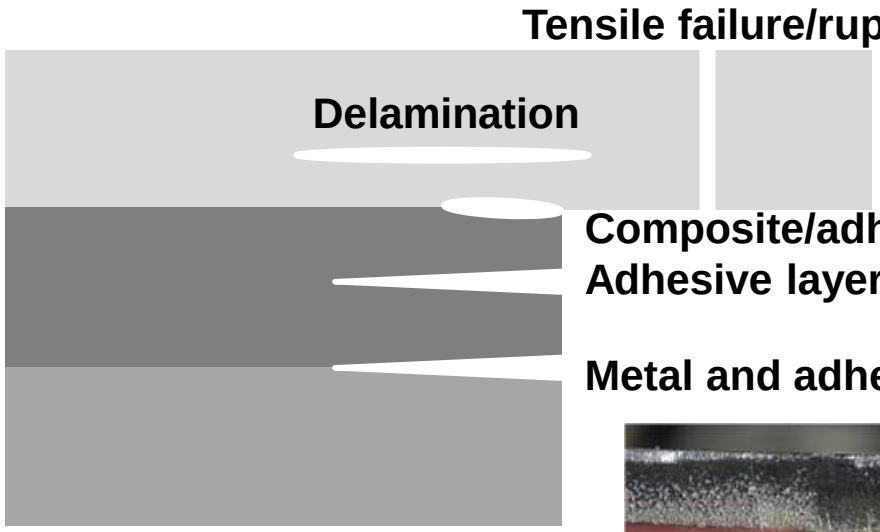
Failure in Adhesively Bonded Joints



Adherend

- ❑ Metal (titanium/aluminium) tensile yielding - in-plane/bending loads
- ❑ Composite tensile failure/rupture - in-plane/bending loads
- ❑ Composite delamination - interlaminar shear
- ❑ Composite transverse tensile stress (Poisson's effect for 0° plies)

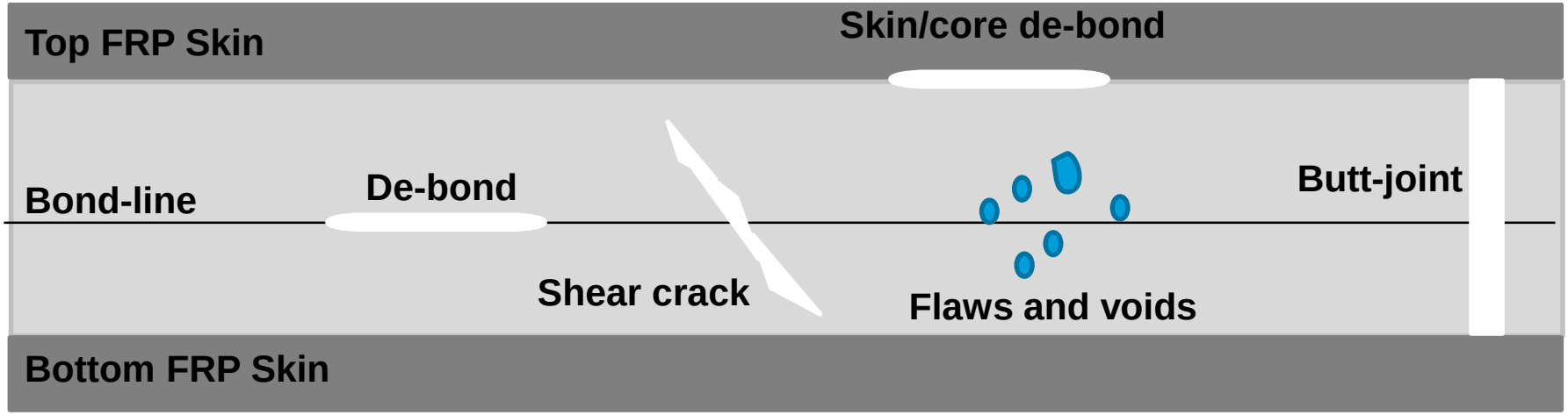
Interface

- ❑ Interface - shear or peel stresses

Adhesive Layer

- ❑ Cohesive failure - shear and peel stresses

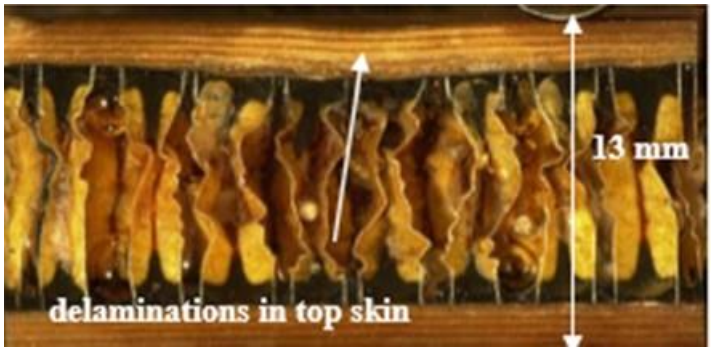
Production/In-service Defects/Damage in Sandwich Construction



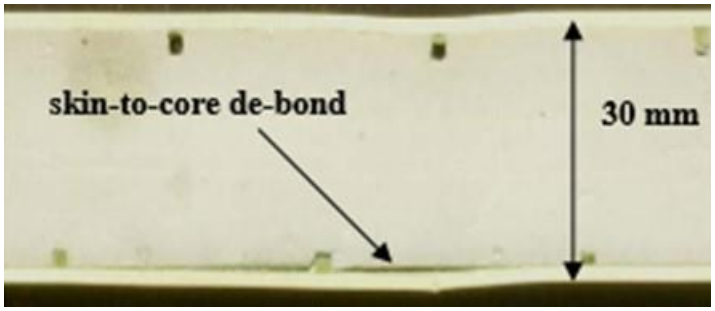
- Damage is difficult to detect due the multi-layered structure of sandwich construction; especially if access is limited to one surface

In-service Damage of Sandwich Constructions

Impact delaminations in top skin of sandwich construction

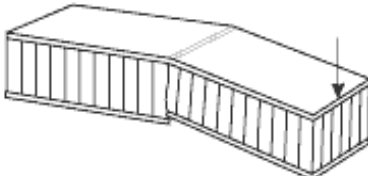


Skin-to-core de-bond in GFRP/PU foam sandwich construction

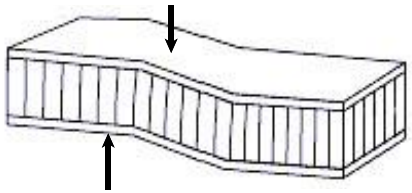


Core crushing of CFRP/Nomex construction

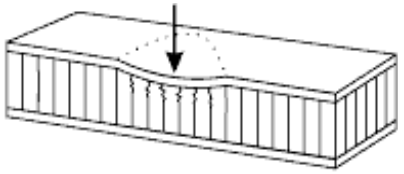
Failure Modes in Sandwich Constructions



Facing

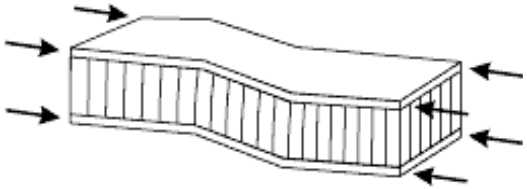


Transverse shear

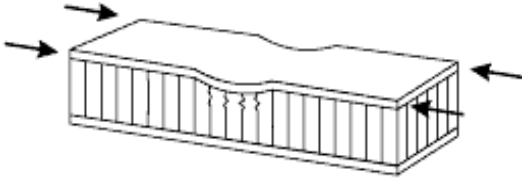


Local crushing

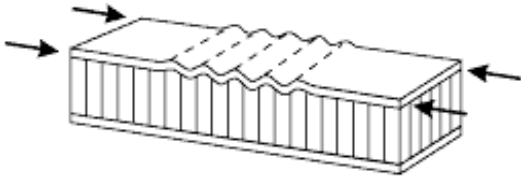
Panel Buckling



Shear Crimping



Face Wrinkling



Intracell Buckling (Dimpling)

Source: Hexcel website

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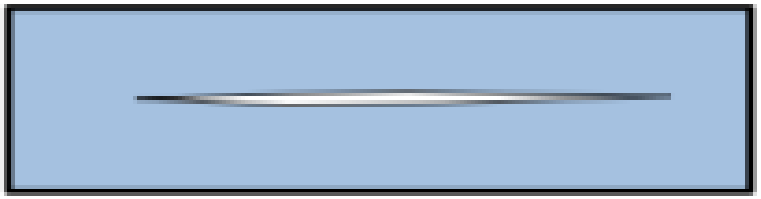
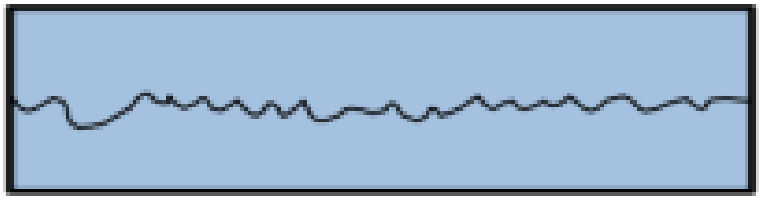
Kissing Bonds

Delaminations



Separation between FRP plies, zero strength

Kissing Bond

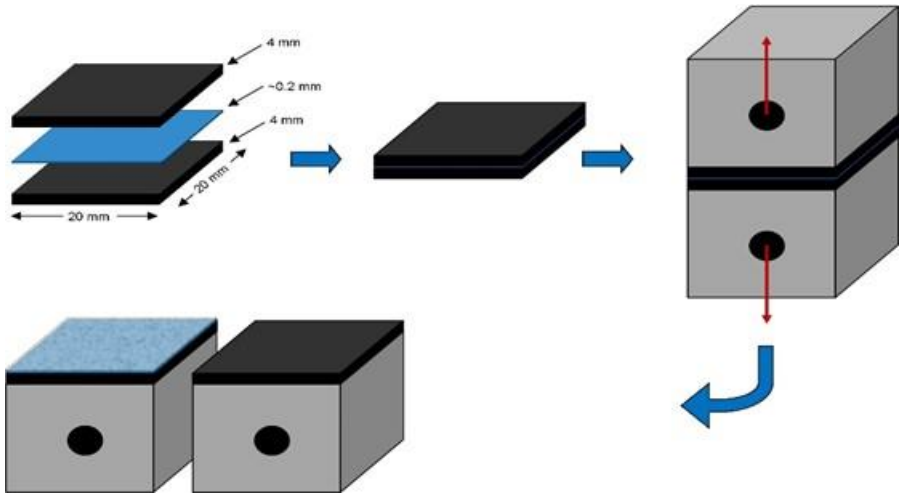


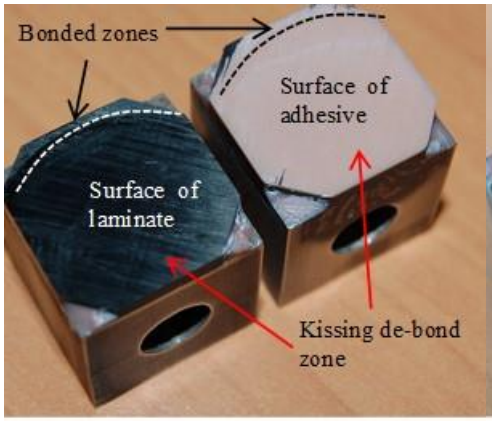
Mechanical/frictional contact without chemical bond

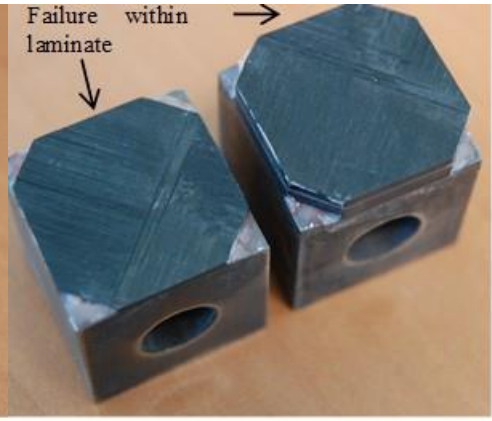
Characteristics of a weak bond (defective adhesive bond) are defined below:

- **Strength as measured by mechanical testing is below 20% of the nominal bond strength,**
- **Mode of failure must be adhesive in type (i.e. purely at the adherend/adhesive interface), and**
- **Undetectable from normal bonds with conventional NDE techniques – includes kissing bonds (weak adhesive bond) produced through surface contamination with release agent**

Kissing Bond – Simulation Using Different Surface Pre-treatments in CFRP Laminates







Note: Non-defective material failed in one of the parent laminate at 42 MPa, indicating that the adhesive bond strength was superior to the interlaminar (through-thickness) tensile strength of the laminate

Surface Treatment*		Failure Stress (MPa)	
N°.	Detail	"As Received" Surface Pre-treatment	Grit Blasted Pre-treatment
1	Tygacote® (release agent)	failed removing from bonding alignment rig	2.74
2	Graphite (powder spray)	1.84	1.73
3	Beeswax (release agent)	9.92	12.60
4	Silicone (release agent)	8.76	14.14
5	PTFE (dry lubricant spray)	6.17	1.83

** - 4 coats (layers) applied in each case*

SHM/NDE Techniques for Inspection of Adhesively Bonded Joints

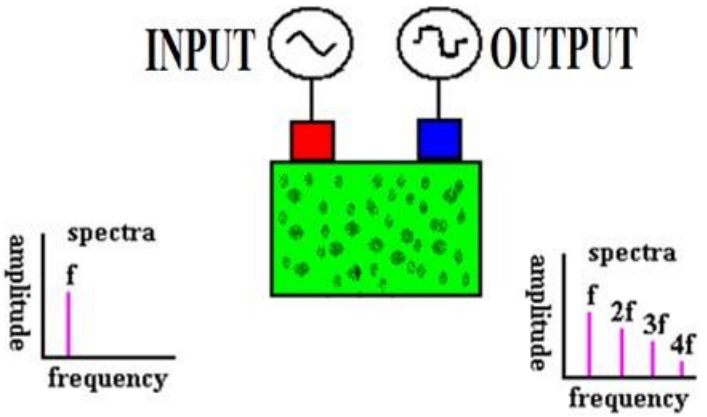
NDE Techniques

- Visual inspection (CCTV cameras, endoscopes)
- Tap test (coin, Woodpecker)
- Ultrasonics (contact, immersion)
  - C-scan
  - Scanning acoustic microscopy (SAM): 5-400 MHz
  - Non-linear Elastic Wave Spectroscopy (NEWS): 0-500 KHz
- X-radiography and X-ray computed tomography
- Pulse thermography (including thermal shock)
- Microwave
- Eddy current (metallic and CFRP systems)
- Laser shearography

SHM Techniques

- Acoustic emission
- Strain gauges
- Fibre Bragg grating (chirped FBGs) sensors
- Digital image correlation (DIC)
- Electrical self-sensing

Single Frequency NEWS



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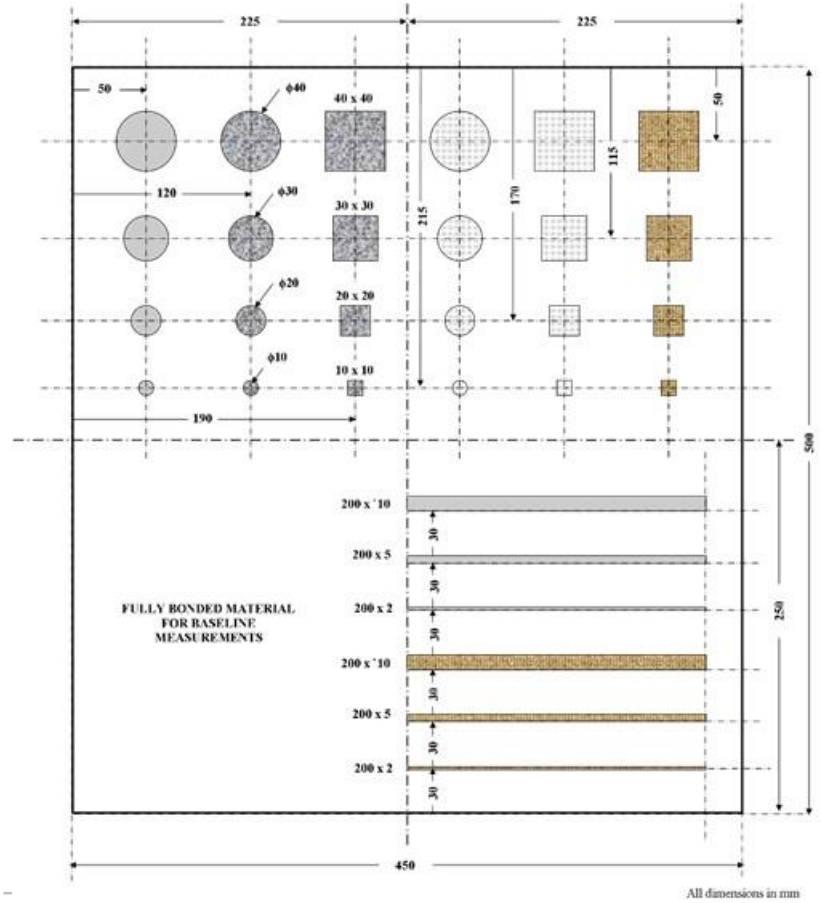
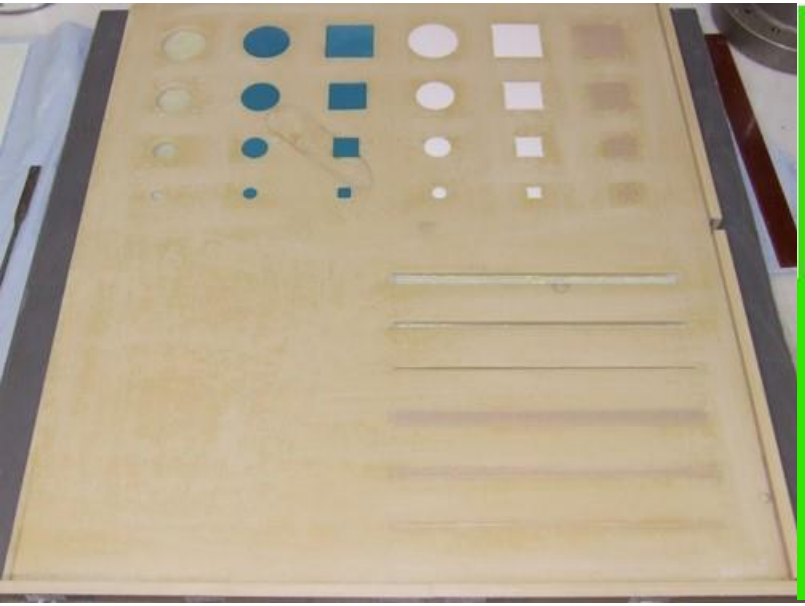
Reference Defect Artefacts (RDAs)



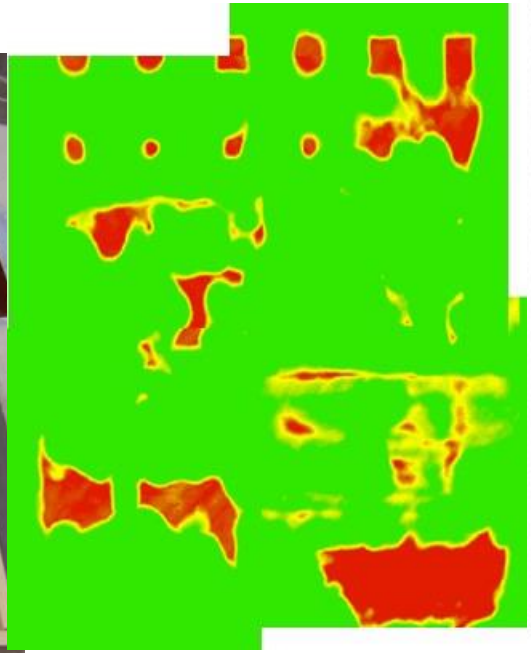
Defect Key:

	Void - simulation of regions starved of adhesive, circles machined through-the-thickness of the adhesive layer
	PTFE pocket - 2 layers of 50 µm thick PTFE film sealed around their edges with heat resistant tape to ensure an air gap
	PTFE sheet - 0.5 mm thick depending to simulate a volumetric inclusion
	Peel ply - 0.2 mm thick peel ply included as a common manufacturing defect type

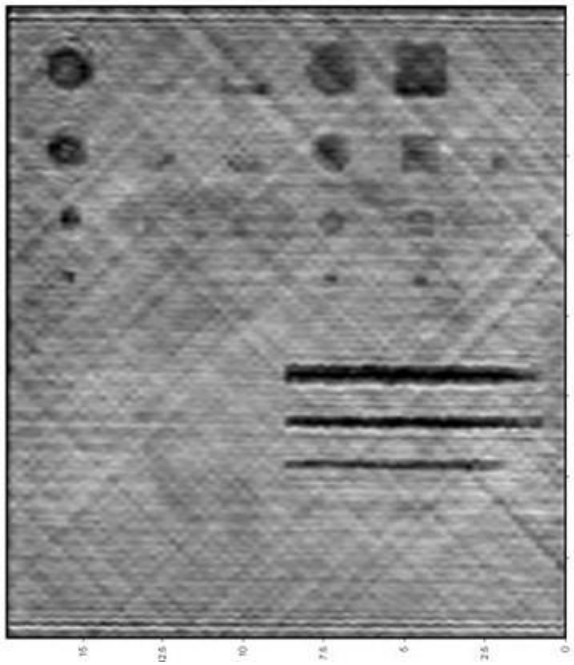
Reference Defect Artefacts (RDAs)



Manufacture of Reference Defect Artefacts (RDAs)



1MHz thru-transmission ultrasonic c-scan



Microwave of thick bond-line containing artificial defects (24 GHz)

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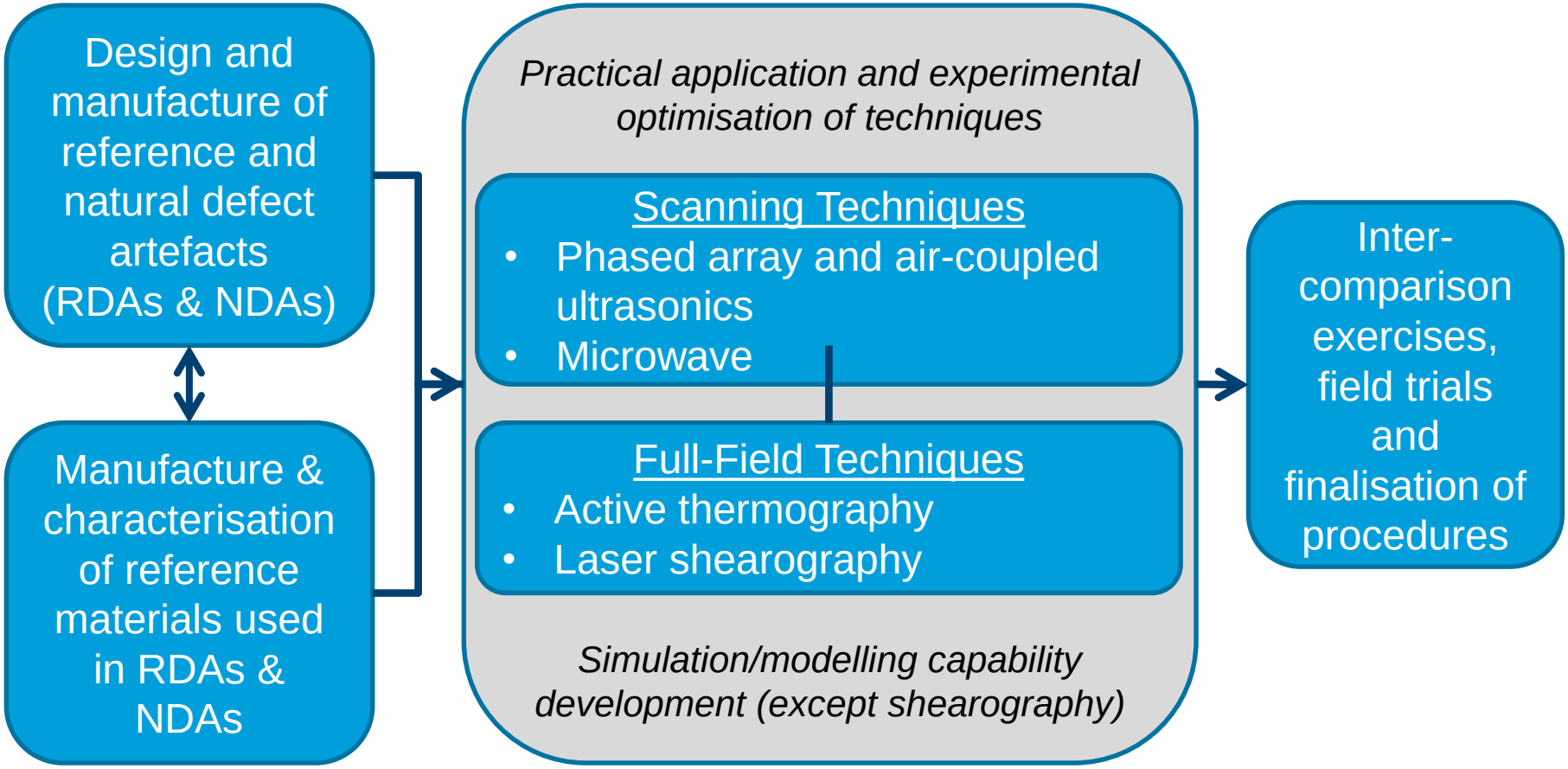
EMRP JRP ENG57
Validated Inspection Techniques For Composites In Energy Applications (VITCEA)

July 2014 – June 2017

European Metrology Research Programme (EMRP) – EURAMET/NMS (EMRP Call: Energy 2013)

VITCEA Project Structure



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http://projects.npl.co.uk/vitcea/

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Defects - Probability of Occurrence and Impact on Structural Integrity

Defect	Probability of Occurrence	Impact on Structural Integrity
Adherend Surface Contamination	Low-Medium	Severe
Delaminations/Debonds	Medium	Severe
Partial/Local Cure	Low	Moderate
Inclusions	Low	Severe
Voids/Porosity	Moderate	Medium
Residual Stresses/Thermal Cracking	Low-Medium	Moderate
Non-uniform Adhesive Distribution*	High	Moderate
Crushed Sandwich Core	Low	Severe
Sandwich Skin/Core De-bonding	Low-Medium	Severe

*** Non-uniform bond-line - resin rich and depleted regions**

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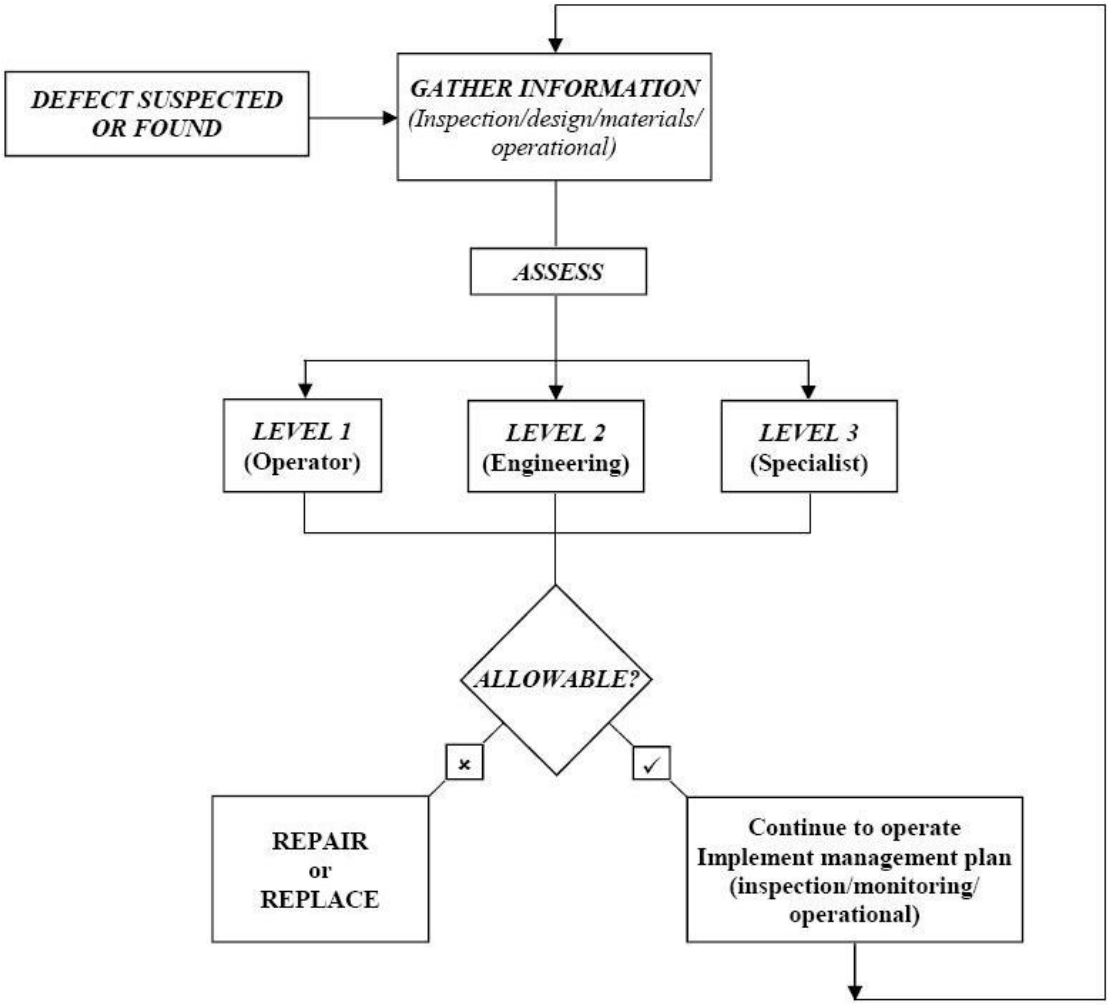
Three-Level Approach to Assess Damage in Structures



NPL Measurement Good Practice Guide No. 78 "Assessment and Criticality of Defects and Damage in Material Systems", M Gower, G Sims R Lee, S Frost, M Stone and M Wall

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