Non-Destructive Testing of Fibre-Reinforced Plastics Composites

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Introduction

- Composite Materials
- Non-Destructive Testing
  - electromagnetic
  - chemical spectroscopy
  - mechanical vibration
- Conclusions
Composite materials

- FRP = fibre-reinforced plastic
  - reinforcement
    > fibres/fabrics
  - polymer matrix
    > thermoset/thermoplastic/elastomer
  - interface/interphase
Fibres

- aramid (Kevlar, Twaron)
- boron
- carbon
- glass
- polyethylene (Dyneema, Spectra)
Matrix

- Thermoset
  - polyester
  - vinyl ester
  - epoxy
- Thermoplastic
  - polypropylene
  - nylon
  - PEEK
Interface/interphase

- sizing agent
- coupling agent
- resin rich regions between layers
- orientation close to the fibre surface
Voids

- “... regardless of the resin, fibre type or fibre surface treatment, the interlaminar shear strength of a composite decreases by about 7% for each 1% of voids up to a total void content of about 4%”

- Judd and Wright
  - SAMPE Journal, January 1978
NON-DESTRUCTIVE TESTING

Functions

- initial inspection of test samples
  - confirmation of structural integrity
- monitoring sample tests in progress
  - monitoring components under service loads
  - especially where changes occur over time
- analysis of reasons for failure
Non-destructive testing for

- structural integrity
  - global inspection/proof tests
- fibre
  - orientation/breaks/waviness
- matrix
  - state-of-cure/porosity/cracking
- interface
  - debonding/delamination/moisture ingress
Probability of Detection vs Damage Size for regions 1-6

- Not Detectable Damage
- Maximum Ultimate Damage
- Good Damage Detectability
- Easily Detectable Damage
- Maximum Allowable Damage

% Probability of Detection

Damage Size region
ELECTROMAGNETIC SPECTRUM

- radiography
- light
- heat
- microwaves
- eddy current
- dielectric
- electric
Radiography

- X-ray
  - electrically generated
  - broad band of wavelengths

- gamma, beta or neutron beams
  - generated by radioactivity/synchrotron
  - discrete frequencies

- shadow pictures on fluorescent screen/film

- tomography available

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
### Periodic Table
**Strong Absorbers**

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Periodic table (reinforcements)

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
**Periodic table (resin matrix)**

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Non-Destructive Testing of Fibre-Reinforced Plastics Composites
White light

- observation
- triangulation
- shadow and projected fringes
- photoelasticity
- fibre optics
Lasers (coherent light)

- interferometry
- speckle
- holography
- shearography
- fibre optics

Image from Insight, January 2001, v44, n1, p6
(Loughborough University)
Optical fibres

- **Step-index multimode optical fibres**
  - thick fibre - thin skin of different optical properties
  - carries signals in different propagation modes
  - uses reflection from the skin-core interface

- **Graded-index multimode optical fibres**
  - thick fibre with a gentle change in refractive index
  - carries signals in different propagation modes

- **Small-core monomode optical fibres**
  - thin fibre core - thick skin
  - carries signals in a single propagation mode
Optical fibres

- Step-index multimode optical fibres
- Graded-index multimode optical fibres
- Small-core monomode optical fibres
Non-Destructive Testing of Fibre-Reinforced Plastics Composites

Optical fibres (embedded sensors)

- crack detection
- strain measurement
  - interferometry
  - Bragg gratings
- acoustic emission sensor
- interfacial corrosion
Optical Fibre Bragg Grating (OFBG)

Thermography

- **EATF** = externally applied thermal field
  - thermal paints and coatings
  - infra-red cameras
- **SGTF** = stress generated thermal field
  - vibro-thermography
  - thermosonics
- **SPATE**: Stress Pattern Analysis by Thermal Emission
  - **TSE**: thermally stimulated emission
Thermography of B737 radome

Figure 1. California Radomes’ Quality Assurance Manager, Dana Pratt, scans the nose of the radome from a Boeing 737 using the Thermovision camera

Non-Destructive Testing of Fibre-Reinforced Plastics Composites

Image from Insight (Br J NDT), November 1996, 38(11), 771.
From the “moulds” lecture

Thermograms of an electrically heated ‘skeg’ mould

< top, heating

< back
90°C dwell
insulated

-top, at temp >

-ditto-, no insulation >

Thermograms of an electrically heated ‘skeg’ mould

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
TeraHertz ($\sim 10^{12}$ Hz)

- relatively new field
- facilitated by the development of
  - femtosecond pulsed lasers, and more recently
  - semiconductor Quantum Cascade Laser (QCL).
- problem of sources with significant power output
- attracting significant interest
  in the context of security applications
Microwaves

- precise distance & roughness measurement
- analysis of complex vibrations
- detection of internal flaws
- dielectric properties
  - density, porosity, state-of-cure, ageing, orientation, homogeneity and moisture content
Microwaves

- potential health hazard at high power!
- interference from communications networks leading to poor signal/noise ratios
- used by radome manufacturers to confirm electromagnetic performance of structures
Eddy current

- AC induces eddy currents in conductors
- limited use with carbon fibre composites
- not applicable to GRP/aramid
- thickness measurement of insulators
Dielectric

- relative permeability
- dissipation/loss factor
- sensitive to
  - state-of-cure
  - moisture content
- micro-fabricated inter-digitated sensors
- parallel plate configuration
Dielectric

- moisture meters used by marine surveyors
- manufacturers use different frequencies and electrode spacings
- consequently values of moisture content and depth differ between instruments
Electric

- Resistance is a function of
  - dimension
  - fibre orientation
  - state-of-cure
    - ion-graphing/phaseometry
  - moisture content
  - thermal decomposition
  - crack geometry and growth

- Imaging
  - electrified particles
  - applied potential tomography

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
CHEMICAL SPECTROSCOPY

- ultra-violet
- Raman (including optical fibres)
- infra-red (including optical fibres)
- electron spin resonance
- nuclear magnetic resonance
  - magnetic resonance imaging (tomography)
To be continued ...
To be continued ...
MECHANICAL VIBRATION

- Scanning acoustic microscopy (GHz)
- Ultrasonics (MHz)
- Acousto-ultrasonics (high kHz)
- Acoustic emission (low kHz)
- Vibration (Hz)
Ultrasonics 0.5-50 MHz

- widely practised in industry
- significant attenuation of signal by composites (cf metals)
- anisotropy of properties
Ultrasound wave propagation

- **Bulk waves**
  - longitudinal/compression
  - transverse/shear

- **Surface waves**
  - Rayleigh Stoneley
  - P-waves: head waves (pressure waves)
  - S-waves: SH or SV (shear waves: horizontal or vertical)
  - creeping waves

- **Plate waves**
  - Lamb Love rod waves
Ultrasound transducers

- Normally piezoelectric crystals
  - PZT = Lead (Pb) zirconium titanate
  - able to send and receive signals
  - produces a compression wave
  - converted to shear wave by wedge mounting

- Phased array
  - multiple transducer elements in one package
    > usually 8-, 16-, 32- or 64 elements
  - Array controller configures beam
    > Can simulate several transducers configurations
US A-scan without/with defect (voltage vs time trace)

Transducer
Void
<< no defect

Backwall echo
Transmission pulse

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
US A-scan without/with defect (voltage vs time trace)

- no defect
- full width defect - no backwall echo

Defect echo
US A-scan without/with defect (voltage vs time trace)

<< no defect

<< full width defect

<< part width defect
Ultrasonic displays

- A-scan: voltage/time at one position
- B-scan: size & position vs probe movement
- C-scan: attenuation/x-y position
- D-scan: attenuation/x-z position
- F-scan: feature scan
- P-scan: projection/tomography
- S-scan: sector scan (phased array technique)

Flash Movie animation from Wavelength-NDT
Convergent flow fronts (video)

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
Ultrasound C-scan convergent flow
Acousto-ultrasonics
\(~500~\text{kHz}\)

- pulser-receiver in the plane of sample
- energy in/out through rubber wheels
- waveform received interpreted as
  - stress wave factors (SWF)
Acoustic emission (broad band noise)

- transient elastic waves produced as a response to active defects
  - rapid release of stress from local sources within the material

- also known as
  - stress wave emission (SWE)
  - micro-seismic activity
  - materials scientists stethoscope
    - clinking (martensitic transformations)
    - tin cry (twinning), dunting in ceramics
    - creaking ships’ timbers/pit props
Acoustic emission detection

- microphones
- piezo-electric transducers
- strain gauges
- optical fibres
- lasers
Typical AE burst type event

Event duration

Amplitude

Threshold

Time
AE count (+ve crossings)

Amplitude vs time

Counts vs time

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
several counts = one event
Typical AE burst type event

Amplitude

Time

Peak amplitude

Rise time
AE signals analysed by:

- number of counts (or events) vs time
- event duration
- rise time
- amplitudes plotted as histogram
  - distribution over discrete time periods
- frequencies/spectra
  - for broadband transducers only
AE calibration

- Fracture of a glass capillary
- Grinding of powders
- Ball drop
- Air abrasive
- Helium gas jet
- Electric spark discharge
- Ultrasonic transducer
- Capacitive transducer
- Pulsed laser
- Martensitic transformation
- Fracture of boron particles in aluminium
- Stress corrosion, and ...
AE calibration II

- breaking a 0.5 mm 2H pencil lead
  - PTFE collar to control flexing of lead
  - known as the Nielsen or Nielsen-Hsu source
  - adopted as a standard ASTM E976-84
    > Image from http://www.ndt.net/article/az/ae/img/pencil.gif

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
AE can be problematic due to:

- **effect of mounting condition**
  - couplant (silicone gel or petroleum jelly)
  - mounting pressure
- **sensor sensitivity**
- **degradation of the sensitivity**
  - wiring faults
  - deterioration of electronics
Kaiser effect

- Josef Kaiser (Munich, 1950):
  - number of emissions increases with the applied stress
  - after unloading, no acoustic emissions upon reloading until the previous maximum load exceeded
Felicity effects

- Timothy Fowler (Monsanto USA, 1977):
  - emissions occur upon reloading at a specific fraction of the previous maximum load
    > known initially as the Modified Kaiser Effect
    > now usually referred to as the Felicity Effect
  - formalised by CARP (Committee on Acoustic Emission from Reinforced Plastics) codes, *e.g.*
    > FRP tanks/vessels, ASTM E1067-01.
    > plastic piping, ASTM E1118-05.
    > insulated aerial personnel devices, ASTM F914-03.
ASTM E1067 (CARP) pressure tank stressing sequence

Phase I
- Background noise check
- 4 minutes

Phase II
- 32 data record points
- 4 minutes

Percentage of max. test stress
- 20%
- 40%
- 60%
- 80%

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
### AE intersensor distance

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<th>FREQUENCY</th>
<th>RANGE</th>
<th>MATERIAL</th>
<th>APPLICATION</th>
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<td>30 kHz</td>
<td>100 m</td>
<td>steel</td>
<td>pipelines</td>
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<td>75 kHz</td>
<td>10 m</td>
<td>composites</td>
<td>tanks</td>
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<td>175 kHz</td>
<td>10 m</td>
<td>steel</td>
<td>tanks</td>
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<td>375 kHz</td>
<td>1 m</td>
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<td>welds</td>
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<td>750 kHz</td>
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<td>--- high noise situations ---</td>
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AE source location

- zone location/transducer hit sequence
- triangulation from time of arrival
- plotting position of each located event produces a map of sites on the component
  - build up a picture of where events occur
  - locate where failure is likely to occur.

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
Vibration

- wheel tap (whole structure resonates)
  - changes in resonant frequency & damping
  - subjective: potential for modal analysis
- coin tap (only a localised area excited)
  - comparative response of good vs bad areas
  - automated as Tapometer/Woodpecker
## CONCLUSIONS I

<table>
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<th>Frequency (Hz)</th>
<th>1 mHz</th>
<th>1 Hz</th>
<th>1 kHz</th>
<th>1 MHz</th>
<th>1 GHz</th>
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**CONCLUSIONS II**

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<th>NDT of FRP composites</th>
<th>State of cure</th>
<th>Porosity</th>
<th>Moisture</th>
<th>Fibre orientation</th>
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<th>Delamination</th>
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*Established technique*

*Potential technique*