Optical Marine Composite NDT to determine defects and residual life in a structure

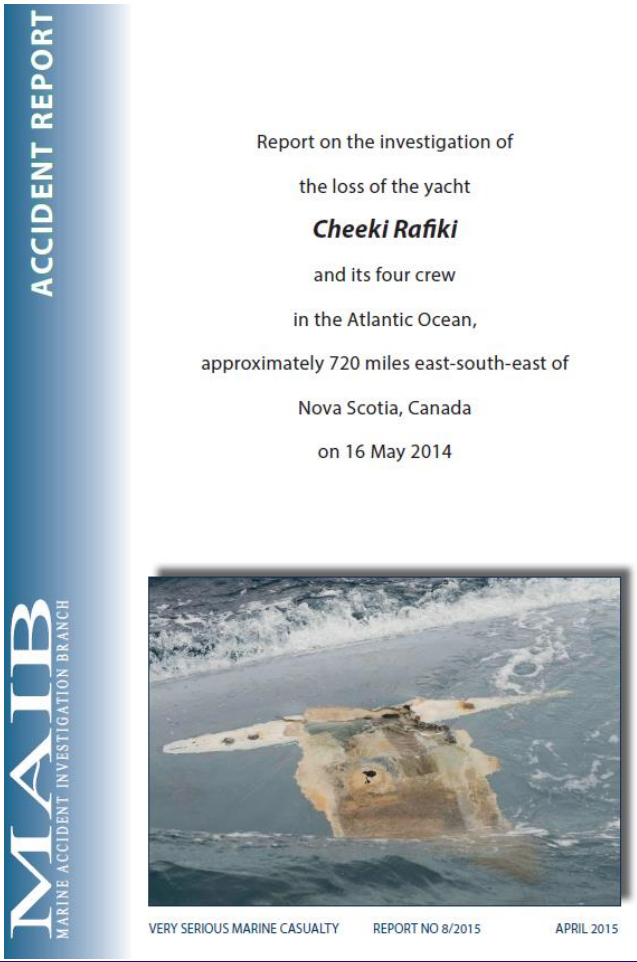
John R Tyrer
Professor of Optical Instrumentation
Department of Mechanical Engineering
Loughborough University &
Laser Optical Engineering Ltd

Shearography image:
Resin enriched detail
In composite panel

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind" Lord Kelvin 1824-1907

Loughborough University

Marine Accident Investigation Board (MAIB) report into the loss of the Cheeki Rafiki



"The sole objective of the investigation of an accident under the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012 shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

Loughborough University

Safety Lessons - Loss of the yacht Cheeki Rafiki and its four crew

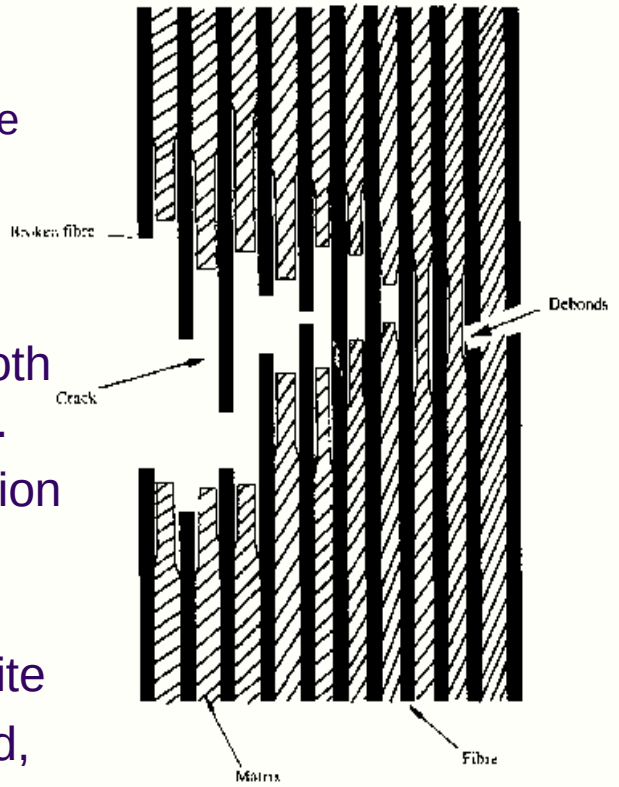
(Paul Goslin, James Male, Steve Warren and Andrew Bridge)

MAIB - FLYER TO THE LEISURE INDUSTRY

1. Matrix detachment is possible in yachts where a GRP matrix and hull are bonded together. The probability of this occurring will increase with longer and harder yacht usage. There is therefore a need for regular structural inspection by a nominated competent person as part of a formal verifiable procedure, as well as before embarking on an ocean passage.
2. Owing to the continuous nature of a matrix where solid floors are in place, particularly where the keel is attached to the hull, it may be difficult to readily identify areas where a detachment has occurred. There are differing opinions among surveyors and GRP repairers with regard to what are appropriate methods of inspection and repair, including the circumstances in which the keel should be removed. There is therefore a desire for best practice industry-wide guidance to be developed.
3. Any grounding has the potential to cause significantly more damage than may be subjectively assessed or visually apparent, including matrix detachment. It is therefore important that all groundings, including those perceived to be ‘light’, result in an inspection for possible damage by a suitably competent person.

FAILURE MECHANISMS IN COMPOSITE MATERIALS

- Previous studies have identified a large number of failure mechanisms in composites. These include:
  - intralaminar matrix cracking, plastic flow,
  - delamination fibre-matrix debonding, fibre pull-out, and fibre fracture.
- The relative contribution of each during fracture will depend upon a large number of parameters.
- The fracture process of a composite material involves both macroscopic as well as microscopic failure mechanisms.
- Both are extremely important in terms of energy dissipation in composite materials.
- The schematic shows representation of local failure processes as a crack propagates in a long fibre composite
- Here damage may involve failure of the fibre-matrix bond, fibre fracture, and plastic deformation, and failure of the matrix.



Loughborough University

Defect types

Manufacturing defects

- Delamination
- resin-rich areas either within an individual ply or at a ply interface
- distorted fibres such as ply waviness;
- Under cured/over cured parts
- Porosity and Voids
- broken fibres;
- inclusions such as dust or pre-preg backing paper.

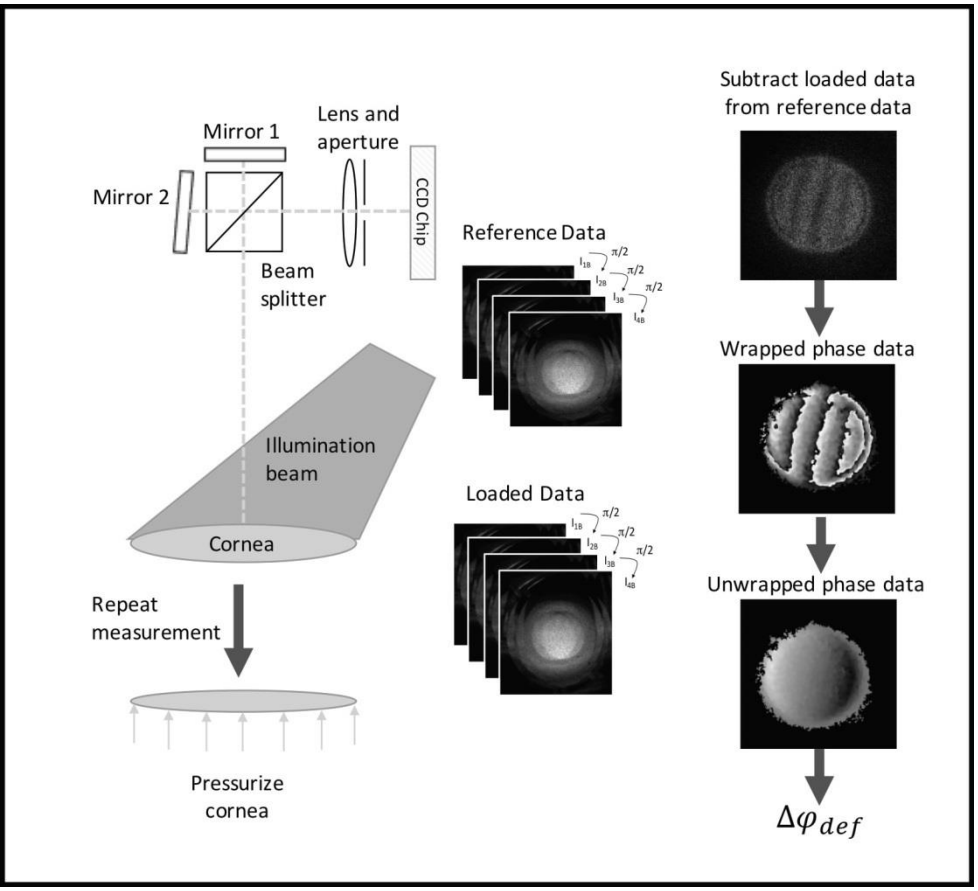
In service defects

- Mainly delamination defects occurs due to:-
- Impact
- Moisture/temperature degradation
- Heat/fire damage
- Fatigue
- Fibre breakage

✓ Fibre tensile strength is a structural requirement hence need for checking

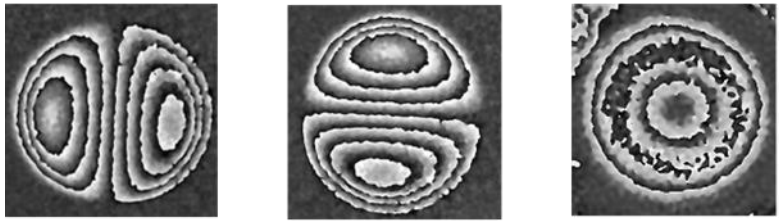
✓ Fibre/matrix interface is important for shear strength of structure

Shearing Interferometry



Different Sensitivities

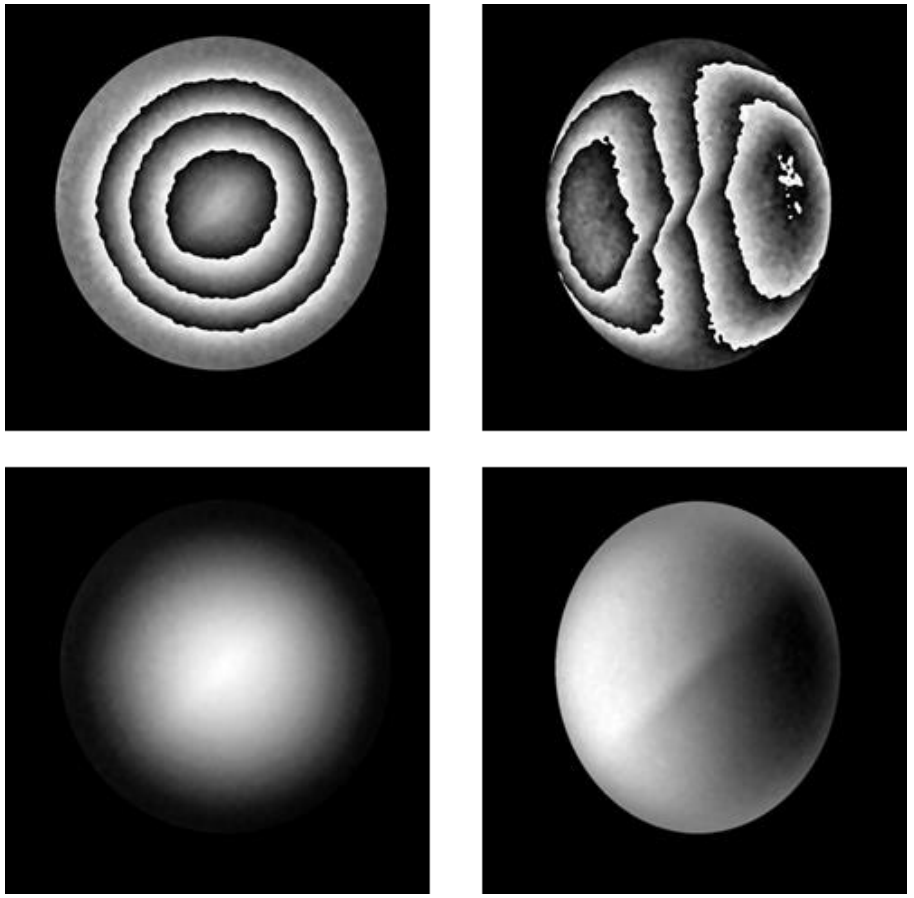
Lateral (horizontal)	Lateral (Vertical)	Radial
δx	δy	δr



Loughborough University

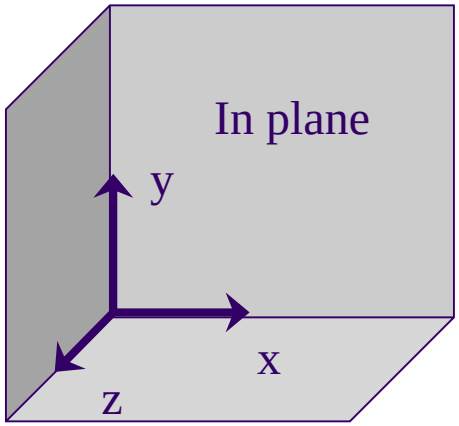
For Cracks we need to see the rate of change of displacement

- By examining the rate of change of displacement this gives indication to where high stress concentrations exist and areas of greatest strain.
- This can better highlight areas that may be most prone to failure as this information can be hard to decipher purely from displacement maps.
- Here a superficial cut has been introduced diagonally from bottom left to top right across a pressurised uniform flat rubber sample.
- These strain images define the presence of the defect and its position in the sheared data as opposed to the ESPI data

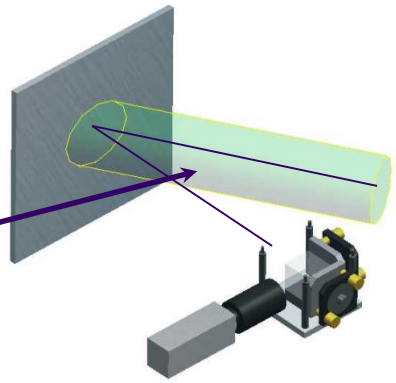


What are you measuring?

- For an out of plane system
  - Optical differential pattern requires further numerical differentiation to yield strain
- An In plane sensitive only system
  - Requires only optical differentiation to yield strain
  - $\delta L/L=\varepsilon$ useful for why things break
- Hybrid out of plane/in plane systems require understanding of the loading and surface shape



Out of plane

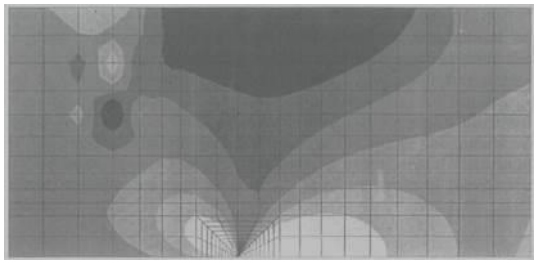


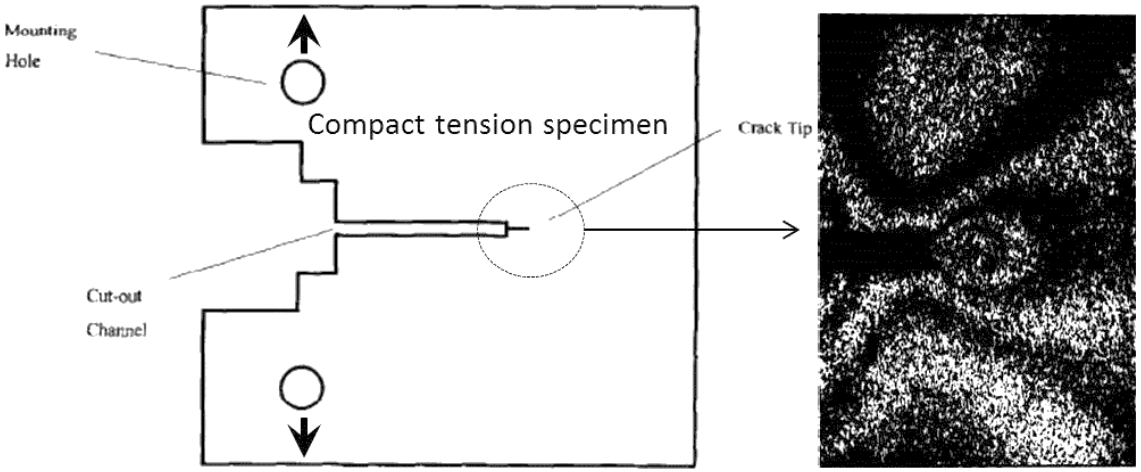
$$\Delta = \left[(1+\cos\theta)\frac{\partial w}{\partial x} + \frac{\partial u}{\partial x}\sin\theta \right]\delta x$$

delaminations adhesion, integrity

Loughborough University

What is in-plane shearing interferometry



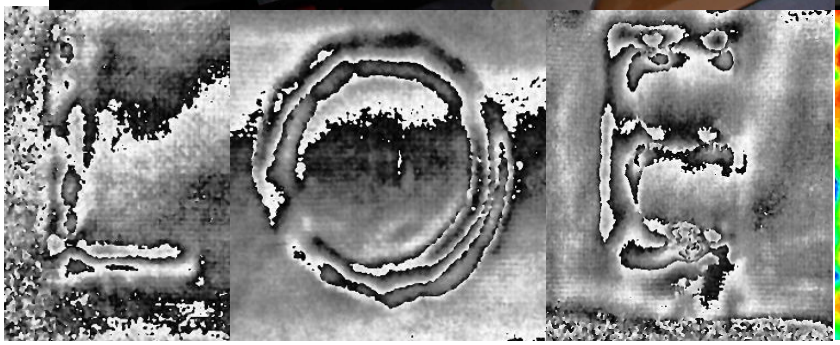


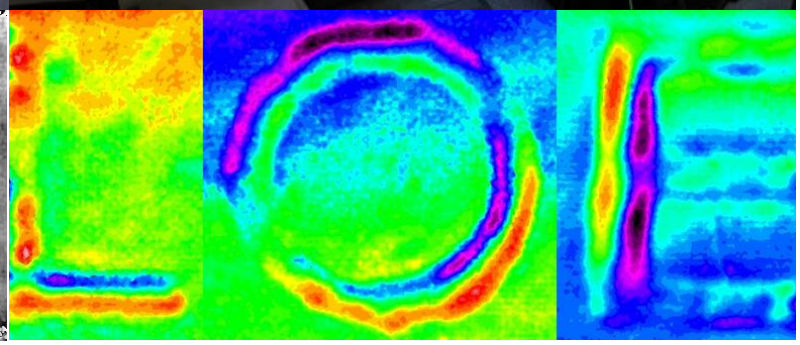
In-plane Shearing strain field visualisation around the crack tip $\partial v/\partial y=\varepsilon_y$

Tyrer, JR and Petzing, JN, "In-plane electronic speckle pattern shearing interferometry", Journal of Optics & Lasers in Engineering, 1997, 26, 4-5, pp.395-406, ISSN: 0143-8166.

Loughborough University

Manufacturing a composite beam with suitable resin enrichment



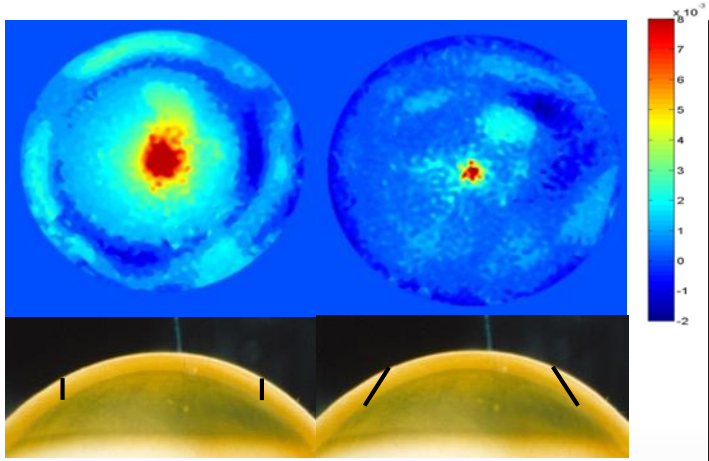


Loughborough University

Laser interferometry – measurement of the body

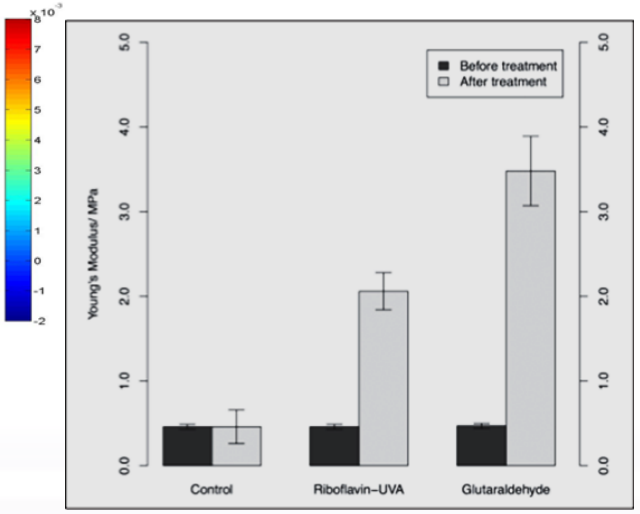
Radial shearing interferometry on human cornea

The effect of different cutting angles used in LASIK on mechanics of the cornea

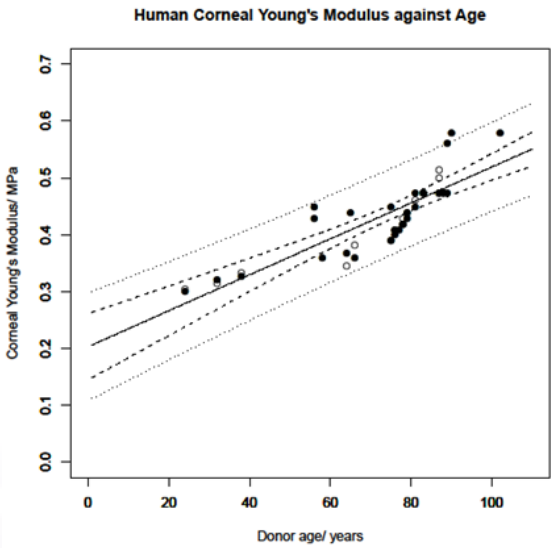


Conventional Scarf

The effect of UVA cross linking on corneal Young's modulus

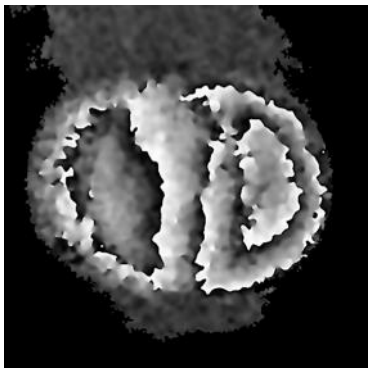


Age related stiffening of the cornea



Loughborough University

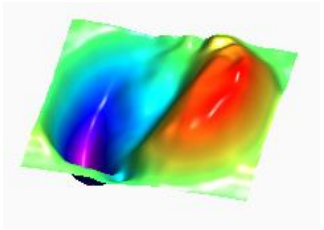
2 beam lateral shearing interferometer

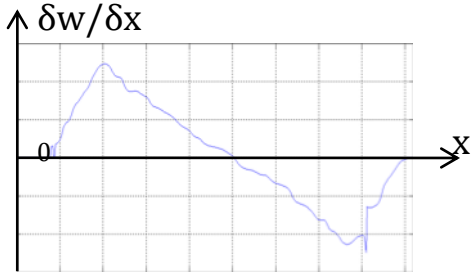


Horizontal shear

$$\frac{\partial u}{\partial x}, u, \frac{\partial w}{\partial x},$$

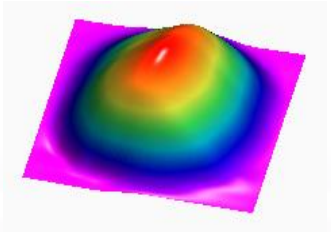
We can integrate strain data to give displacement





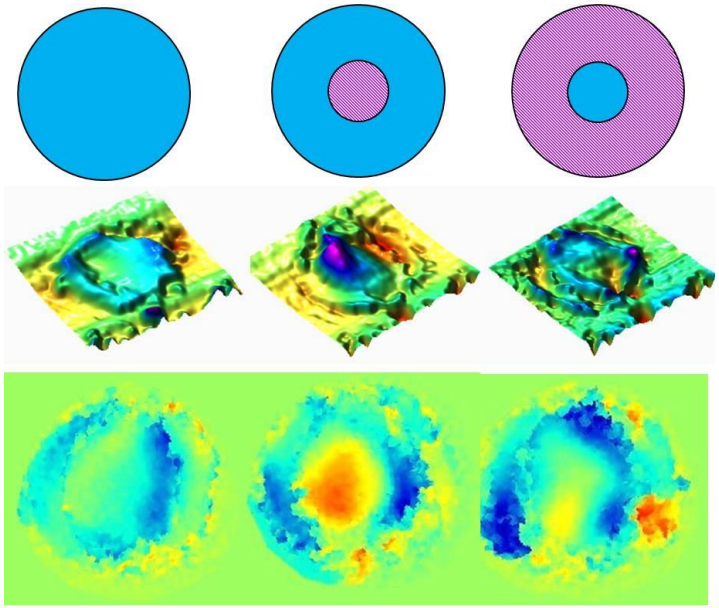
Vertical shear

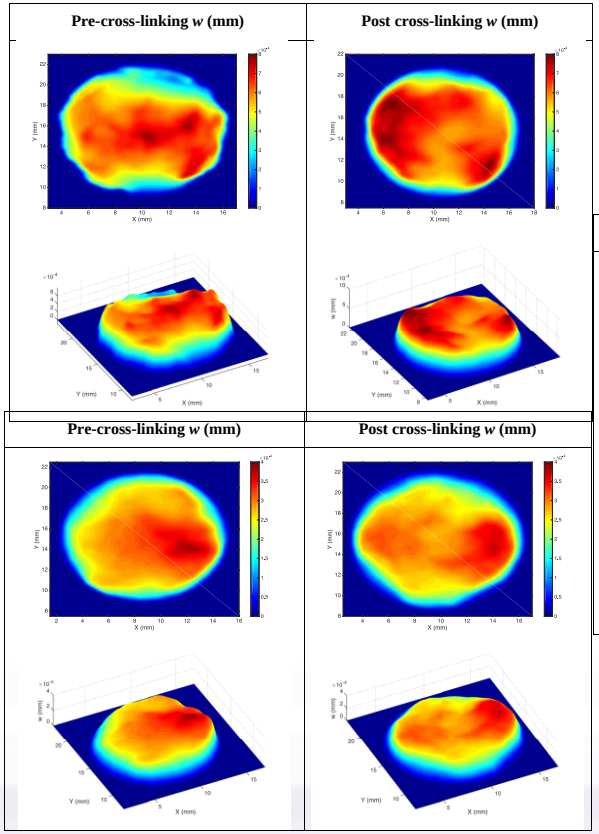
$$\frac{\partial v}{\partial y}, v, \frac{\partial w}{\partial y},$$

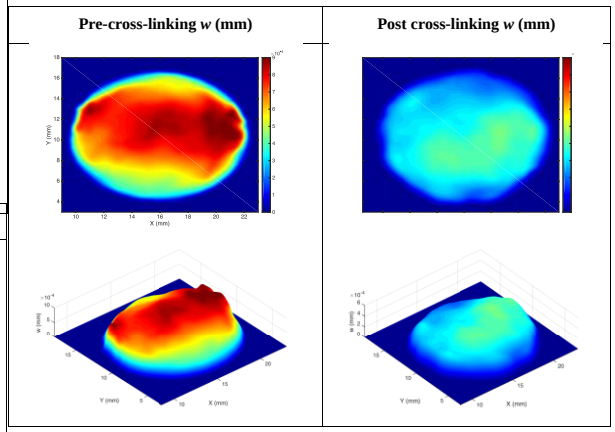


Loughborough University

Non-surgical structural changes to the cornea





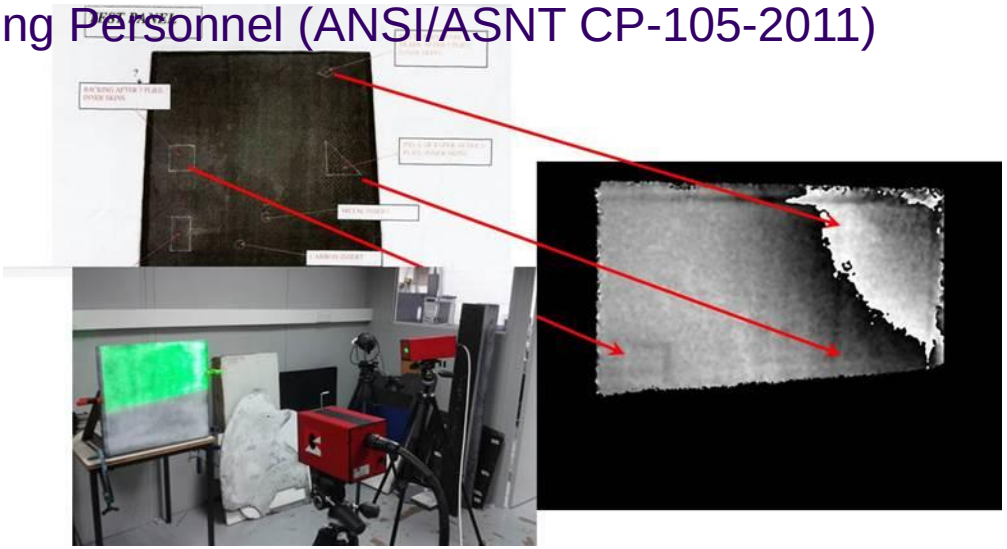


Central and annular ring cross linking

Loughborough University

Creating NDT Standards

- ASTM E2581 – 14, Standard Practice for Shearography of Polymer Matrix Composites and Sandwich Core Materials in Aerospace Applications
- BS EN 4179:2009; Aerospace series. Qualification and approval of personnel for non-destructive testing
- NAS410 4th Edition, December 19, 2014; NAS CERTIFICATION & QUALIFICATION OF NONDESTRUCTIVE TEST PERSONNEL
- SNT-TC-1A, 2011 Edition, and ASNT Standard Topical Outlines for Qualification of Nondestructive Testing Personnel (ANSI/ASNT CP-105-2011)



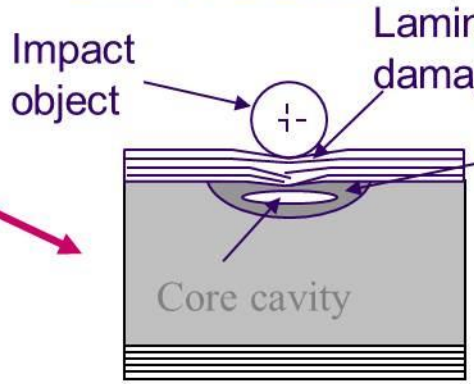
Loughborough University

Impact damage tolerance characterisation of a structural repair to RNLI sandwich structures

• Lifeboat

• Operational Damage

• Experimental simulation and evaluation



• Determination of a damage tolerance philosophy for impact damage to marine sandwich structures

Loughborough University

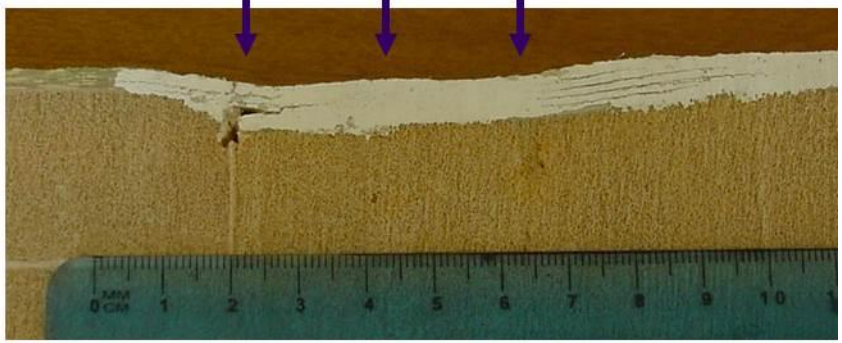
Impact damage tolerance characterisation of a structural repair to RNLI sandwich structures

Flat-nosed impact on structural repair at two different locations (1) at the start of the taper, (2) at the end of the overlaminate

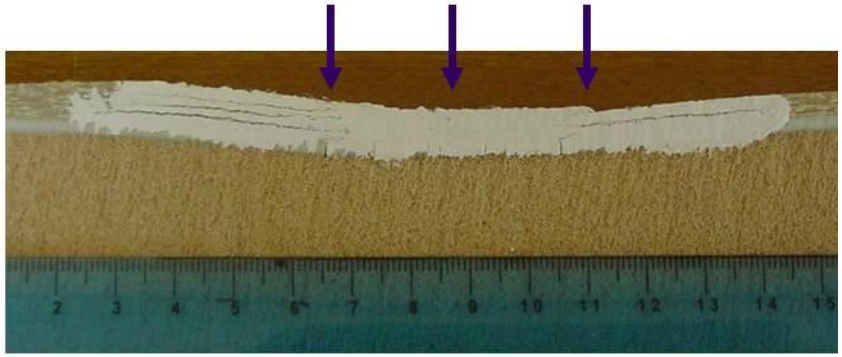
At location (1) damage concentrates within repair, parent and along the repair taper

At location (2), damage occurs within parent laminate. However, at 975J energy threshold the repair overlaminate separates from the outer skin.

1200J impact at location 1



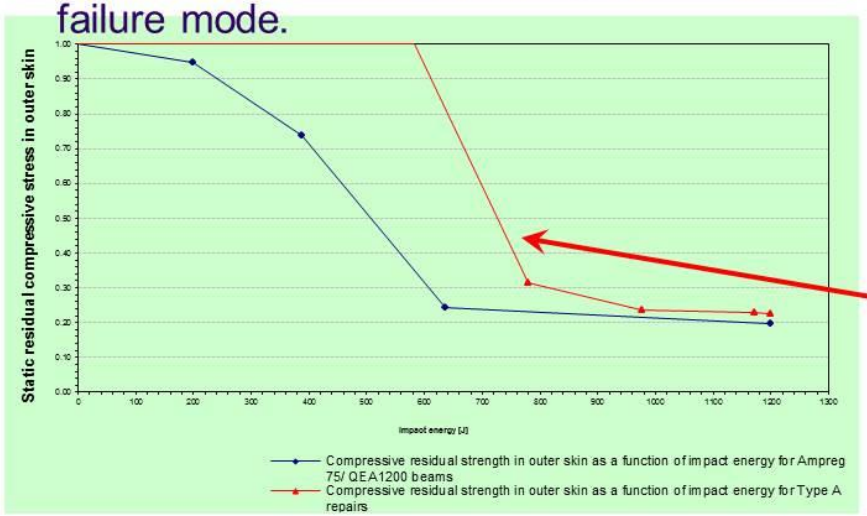
1200J impact at location 2

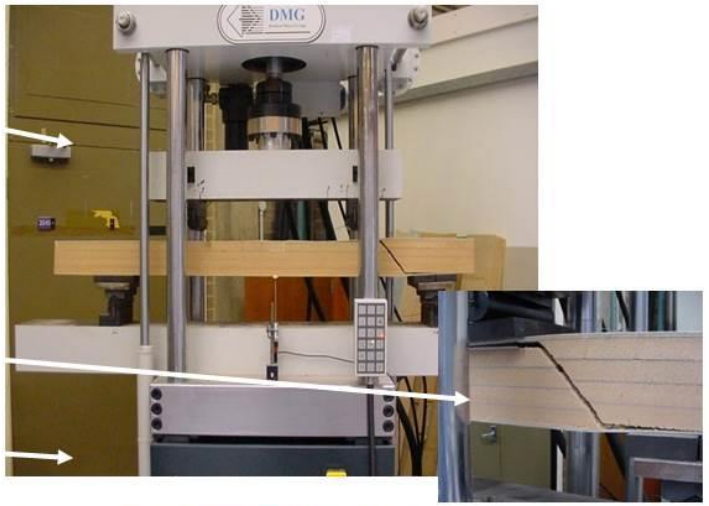


Loughborough University

Four-point bend structural integrity assessment - static

- Four-point bending test used to evaluate the static and fatigue performance of (1) Pristine beams, (2) Beams with structural repairs, and (3) Beams with damaged structural repairs
- In the pristine and repaired beams, core shear is the dominate failure mode.
- In the damaged beams and damage repaired beams, outer skin buckling was the dominate failure mode.





Rapid decline of compressive strength of both the virgin beam and the damaged repair beams (to buckling load).
However, it appears that the repair is more damage tolerant than the virgin beam.

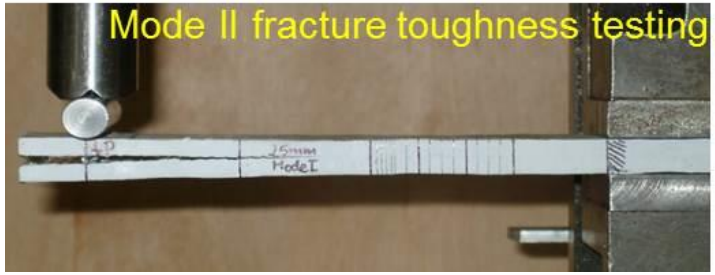
Loughborough University

Fracture toughness assessment of the ‘repair scheme’.

Experimental fracture toughness assessment using different mixed-mode fracture toughness ratios

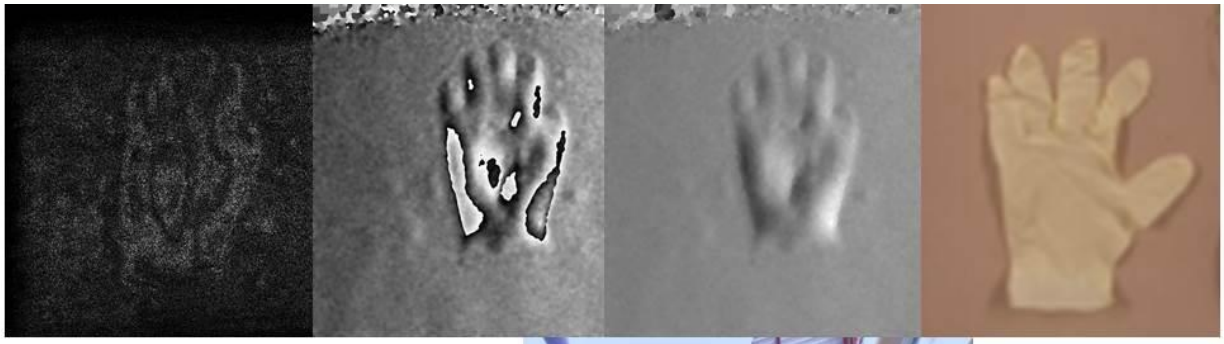
Determination of the energy threshold required for the formation of delamination damage in the repair interface, the repair and parent laminates.

The repair laminate requires the greatest energy to ‘drive’ the crack, i.e. it is the most damage tolerant.
The parent laminate is the least damage tolerant.



Loughborough University

Fault location and Repair

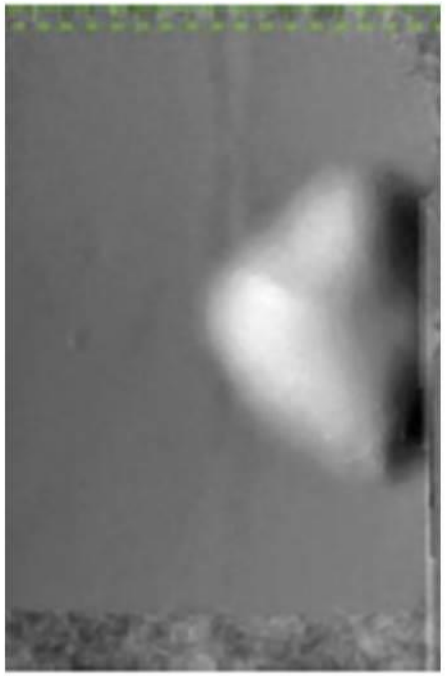


- Fault located,
- Sized and mapped on the inspected surface
- Weak area cut out -
- Ready for repair

Results: manufacturing defects – resin enrichment

Wrapped image:
Resin enriched

Wrapped image:
Resin enriched



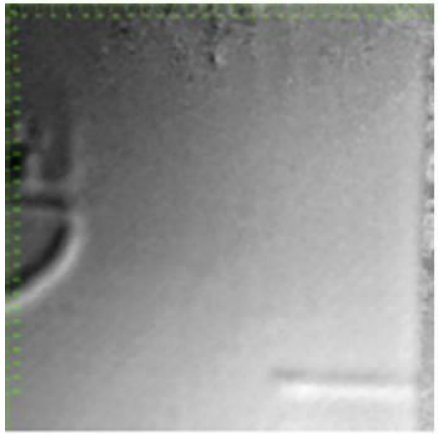
Unwrapped image:
Resin enriched

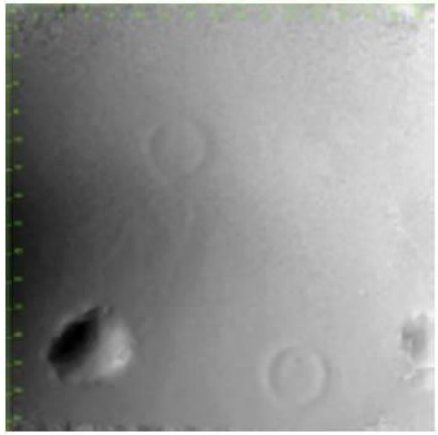
Loughborough University

Results: In-service defect

Side Hole defect

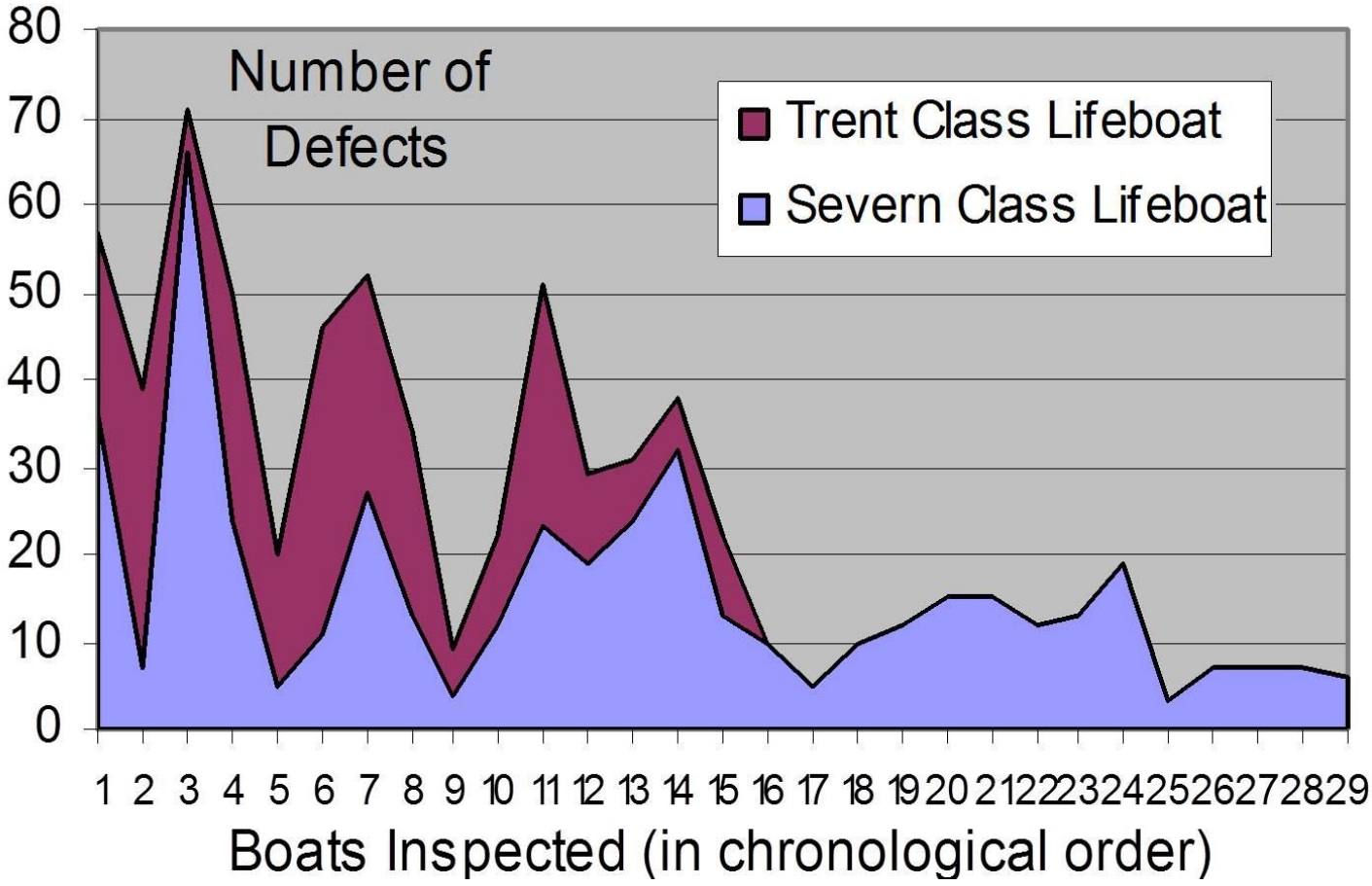
Crush Defects





Loughborough University

Improvements due to the introduction of shearography



Loughborough University

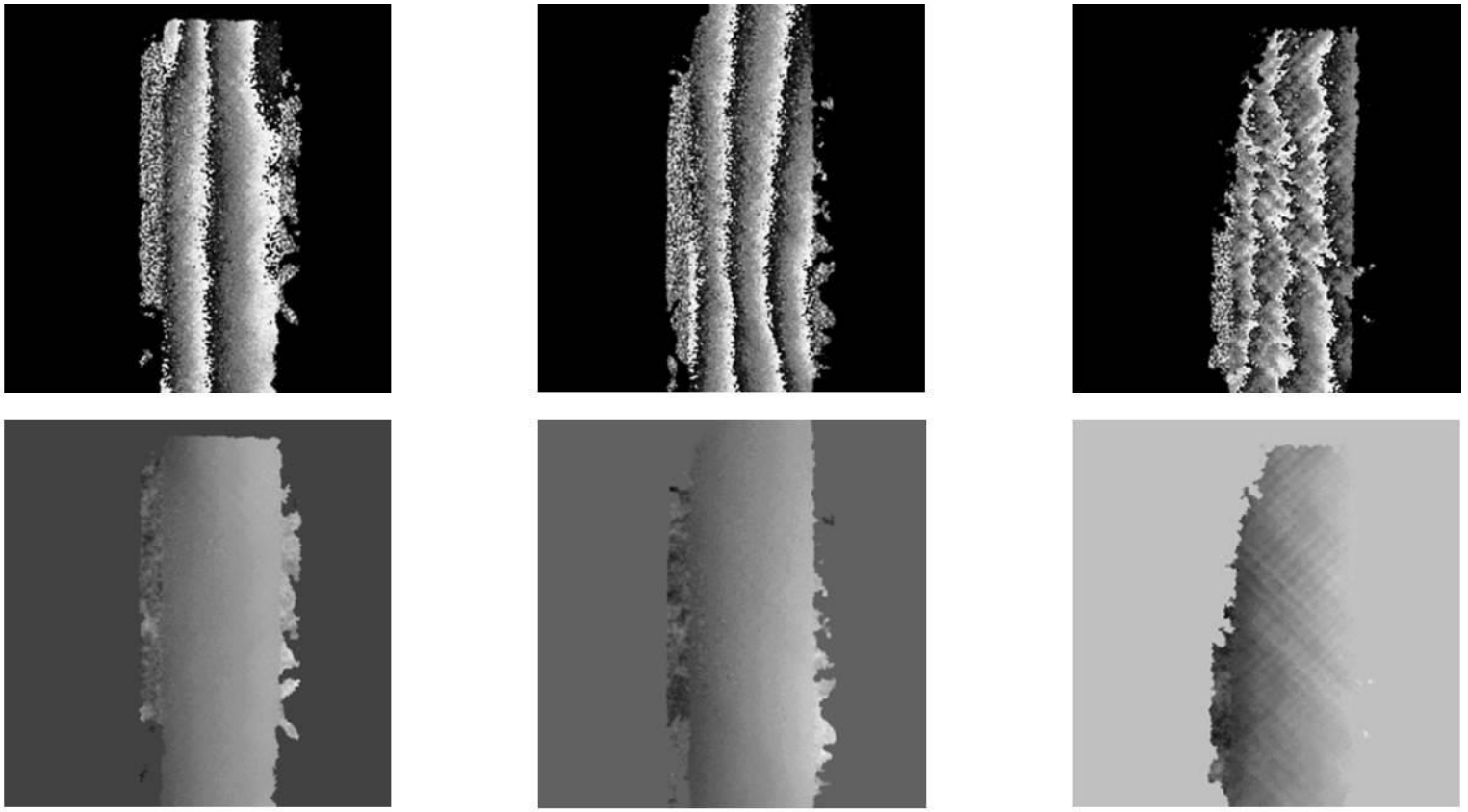
External audit leading to further investigatioon

Internals of a Tamar being removed after defect found from the outside, goes either side of the bulkhead

Internals of a pilot boat that had a fire in the engine room and the automatic fire prevention system didn't kick in.

Loughborough University

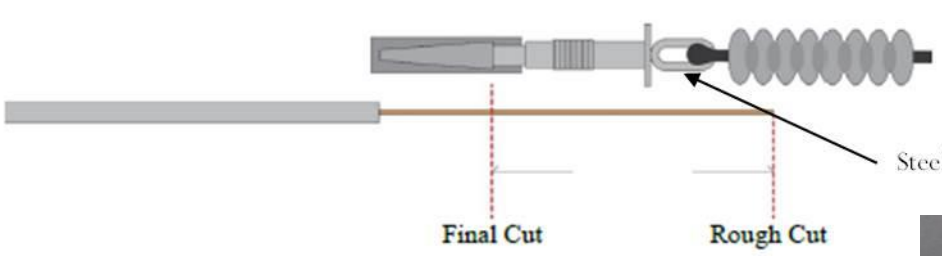
Inter-comparison of fatigue specimens – important for composite structure life extensions

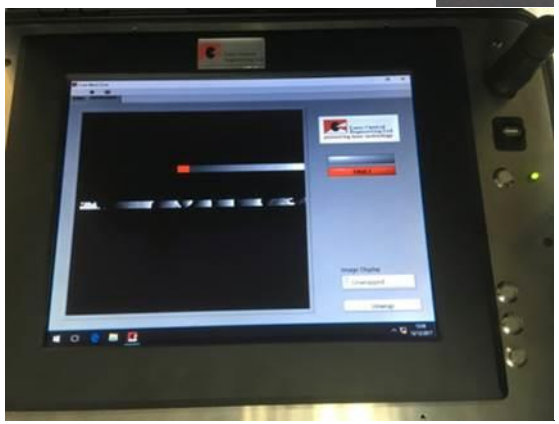


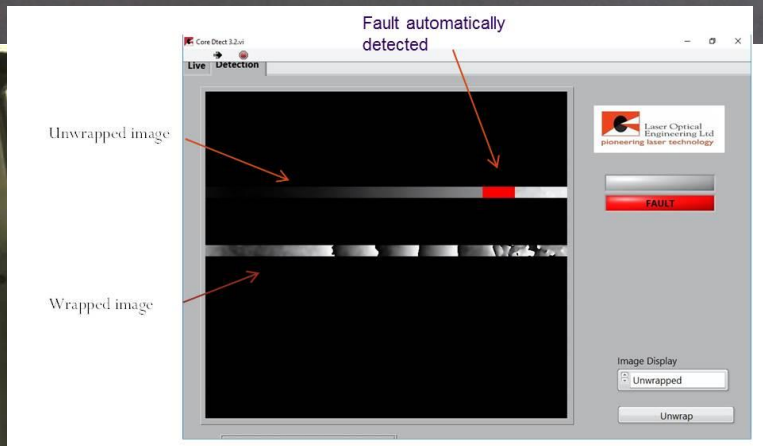
undamaged 30g 45g

Loughborough University

Fully Automatic Solid Carbon Cable NDT







Loughborough University

Current requirements as defined by MAIB

- There is therefore a need for regular structural inspection by a nominated competent person as part of a formal verifiable procedure, as well as before embarking on an ocean passage – 20 years of RNLI experience
- There are differing opinions among surveyors and GRP repairers with regard to what are appropriate methods of inspection and repair, including the circumstances in which the keel should be removed. There is therefore a desire for best practice industry-wide guidance to be developed – established procedures based upon RNLI/University research
- Any grounding has the potential to cause significantly more damage than may be subjectively assessed or visually apparent, including matrix detachment. It is therefore important that all groundings, including those perceived to be 'light', result in an inspection for possible damage by a suitably competent person – standards have already been established.
- A recommendation to the British Marine Federation to co-operate with certifying authorities, manufacturers and repairers to develop best practice industry-wide guidance on the inspection and repair of yachts where a glass reinforced plastic matrix and hull have been bonded together. An opportunity for a suitable PCN

Concluding statements – The Need for a PCN in Marine Composite Inspection

- Given an analysis of the types of failures experienced in fibre composite materials
- Shown the influence of the defects and this goes beyond their outline perimeter – also how this influences residual life and repair strategies
- Shown how an ‘active’ detection strategy offers benefits over conventional ‘passive’ techniques
- 20 years of learning about marine composite ndt and the RNLI haven’t lost a lifeboat!! – had a number of damaged ones!!!
- We are now able to predict residual life in FRP composite structures
- There is now a requirement to answer the challenge posed by the MAIB
- The interesting challenge is the definition of requirements for the PCN

Thank you for listening

Any Questions?

John Tyrer
Wolfson School of Mechanical and Manufacturing Engineering
Loughborough University
LE11 4TU
UK

j.r.tyrer@lboro.ac.uk

Tel: +44 (0)1509 227531
Mob: +44 (0)7710 357117

Loughborough University