

THE PRACTICAL USE OF NDE METHODS FOR THE ASSESSMENT OF DAMAGED MARINE COMPOSITE STRUCTURES

P. J. Sheppard¹, H. J. Phillips¹ & I. Cooper²

¹Royal National Lifeboat Institution, West Quay Road, Poole, Dorset BH15 1HZ

²TWI NDT Validation Centre (Wales) Limited, ECM², Heol Cefn Gwrgan, Margam, Port Talbot.

psheppard@rnli.org.uk, hphillips@rnli.org.uk, ian.cooper@twi.co.uk.

SUMMARY

A range of Non Destructive Evaluation (NDE) methods have been used to identify the location and extent of damage to lifeboats constructed from advanced composites. Techniques traditionally associated with the inspection of aerospace structures were trialled against typical methods used for the assessment of marine structures and the results reviewed. Post-repair inspections have also been carried out and assessed.

Keywords: NDE, marine, composites, structure, damage, NDT, carbon

1. INTRODUCTION

As the operator of a large number of vessels throughout the UK and Republic of Ireland, the Royal National Lifeboat Institution (RNLI) has an extensive support network. This includes operators, surveyors, engineers and a management structure, however not all specialties can be covered in house. When significant structural damage is sustained to an operational lifeboat constructed from composite materials, specialist processing knowledge and repair methods [1] are required in conjunction with the technological and structural knowledge of the vessel involved. The RNLI has a wealth of in house experience and expertise regarding the writing of structural repair specifications [2] to maintain the original design intent. However, when specialist NDE methods are required the assistance of external suppliers who are experts in their fields is sought.

All inspection methods require trials and evaluation before the results can reliably be used. RNLI lifeboats are typically constructed from either stiffened single skin below the chine and thick foam sandwich above as in the case of the Severn and Tamar, or thick foam core throughout in the case of the Trent and Mersey. The construction materials used include glass and carbon fabrics, closed cell foam core and an epoxy resin matrix. The hull shells of modern lifeboats are constructed using resin film infused glass, with SAN core up to 108mm thick in the sandwich areas. The hull stiffening comprises wet laminated carbon top hat stiffeners that are vacuum consolidated over non-structural formers and structural PVC foam cores.

The practical and technical aspects of the NDE methods used to assess damage to these types of marine structures are described in this paper.

2. METHODS CONSIDERED

The RNLI has a long history of using NDE on composite structures. When damage has been sustained to a lifeboat and NDE is deemed appropriate one or more of the following methods is utilised.

2.1 Tap Testing

Tapping, either physically or mechanically has been used extensively in the composite industry and is still commonly used. As a basic NDE method it is both cheap and simple to conduct and can be carried out successfully with little experience. It is however time consuming to cover large areas and cannot detect deeper than skin to core defects. The tone of the tapping is also affected by changes to laminate thickness, skin ties, core density and similar influences that can mislead the tester.

2.2 Shearography

Laser Shearography has been used for the inspection of new All Weather Lifeboats since the mid 1990s and has proved to be reliable and effective. Large areas can be inspected quickly making it reasonably cost effective. Shearography can be carried out in a boatyard environment and if using the vacuum hood version refit and repair work can continue on the boat while testing takes place. Thermal stressing is utilised where the geometry of the test area prevents sealing of the vacuum hood. Its limited effectiveness in the detection of deep disbonds and the testing of stiff and thick monolithic sections is well known.

2.3 Ultrasonic Testing

Ultrasonic testing (UT) has also been carried out on specific areas of monolithic laminates, but this has been limited to single transducers. The attenuative and acoustically noisy material makes interpretation of traditional A-scan displays difficult and the resulting reporting relies on narrative descriptions of the inspection results. Where test areas are large the time taken for inspection can be prohibitive. A faster inspection technique with a permanent data record showing images of flaws was required.

2.4 Radiography

Radiography has been previously used by the RNLI to test small metallic components and is commonly used on composite samples in radiographic enclosures. Site deployable digital radiography systems are available, but the application of industrial site radiography in the busy boatyard environment is disruptive with the obvious associated health and safety considerations. In addition access to both sides of the

structure is not always available. The advantages digital radiography affords in terms of greater exposure latitude, reduced storage requirements and post-processing of images are well known. Demonstrations provided in the laboratory have shown good results on composites but the cost of large scale testing is currently prohibitive due to the time required to complete the exposures and interpret the results.

2.5 Microwave

In 2003 the RNLI took part in the SaNDI 'Inspection and Repair of Sandwich Structures in Naval Ships' project at Thales in which microwave NDE was trialled [3]. The system was shown to be capable of detecting back skin defects through the core on glass skinned panels and produced clear visual images of defects in real time. Flaws can be marked on the structure as they are found. Unfortunately although the method showed considerable promise, no suppliers could be identified that could offer this technology for large scale testing in a boatyard environment.

2.6 Thermography

Thermography was also tested in the SaNDI project and various suppliers are available and used in other industries. Unlike Microwave NDE the technology is well developed and commercially available. Pulsed Thermography appeared to have good potential for use within a boatyard and had few restrictions other than the size and weight of the power units. The quoted costs and coverage speeds were comparable to those of Shearography.

3. CASE STUDY

To give a better insight into the practical aspects of NDE on a damaged structure the descriptions in this section are taken from recent repairs to lifeboats. Following the vessel's return to port it was possible to provide a full assessment of the effectiveness of the techniques and the practicalities of applying them in a boatyard environment, on a structure that had sustained real damage while operating at sea.

3.1 Initial Survey

The initial survey was carried out by RNLI staff, and shearography was undertaken by a company regularly used to carry out laser shearography inspections, who have a good understanding and experience of the RNLI lifeboat structures. However, with other methods requiring trials, a different partner was sought who was able to offer a range of NDE techniques. TWI was subsequently selected to carry out pulsed thermography and UT whilst having knowledge of advanced composites across a range of industries.

3.2 Visual Inspection

Visual inspection and tap testing were employed extensively from the outset. An initial inspection was carried out with the sole panels and lockers still in place. It was immediately evident that there was damage to the glue lines and bonding of these structures, with areas of significant damage visible as fractured fibres and cracks in the interior paint along the bonding edges. Before any decisions were made regarding these structures the access and sole hatches were lifted to gain better access to the hull shell and stiffeners.

It was evident that one of the transverse frames had impacted with the underside of the survivors compartment sole moulding and there was a strong possibility of shear web failure in the transverse frame. Figure 1 shows the issues involved with traditional inspection methods in confined spaces, with damage only being accessible through a series of 150mm diameter inspection hatches. Accurately tapping to ascertain the extent of the damage was not possible as much of the area was out of reach and obscured from sight.

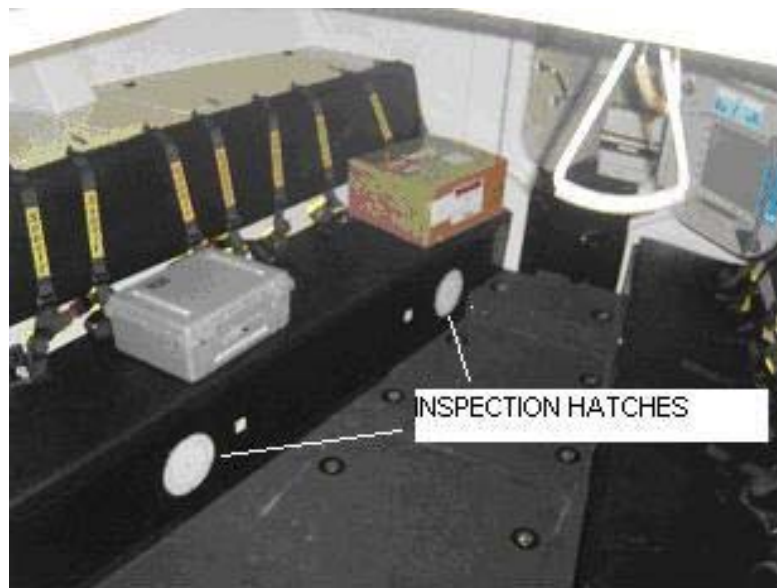


Figure 1 – View of survivors' space compartment

It was however possible through the limited access, to establish that there was a significant amount of delamination between the longitudinal stiffeners and the hull bottom although the full extent was unknown. It was evident that the secondary structure would require removal to carry out repairs. More advanced NDE methods would be needed to determine the extent of the delaminations whilst minimising the need to remove structure.

A method was also required to test the monolithic glass hull bottom. With the damage already identified it was possible that interlaminar shear could have occurred in the hull bottom shell. With limited access internally and paint covering the external surfaces tell

tail visual indications would be hidden and reliably tapping an area of approx 2m x 7m would be difficult. A through thickness method that was capable of detecting disbond between skin and stiffener as well as interlaminar flaws in the monolithic laminate was required.

Areas of cored material in the topside structures also required inspection. Although it was possible to detect some flaws in these areas using tap testing, the time required to cover the large surface area was excessive and other methods were required to enable inspection to be completed in a timescale that would fit the repair program.

3.3 Shearography

Shearography is an optical, laser-based technique that can detect structural defects in real time. It is a qualitative method that does not require calibration and is able to detect cracks, bond line defects, impact damage, delaminations and core damage in sandwich structures.

The method uses the coherent, monochromatic properties of Laser light to generate speckle patterns. When illuminated by the laser, the surface reflects the light creating a speckle pattern at the viewing plane, which can be processed to provide information such as the presence of defects. The system digitises and stores a reference speckle pattern, after which the structure is then stressed and a new speckle pattern generated, recorded and stored. The speckle patterns are superimposed, forming an image made up of a series of black and white fringes, representing the surface strain. If a defect such as a void or disbond exists, this will affect the surface strain and the defect can be revealed by the fringe pattern developed [4].

In order to improve the resolution where phase difference is close to 360 degrees, phase stepping may be used, where the laser path length is changed by fractions of a wavelength producing additional fringes. These can be processed further by the analysis software to make the fringe pattern easier to interpret through the use of ‘unwrapping’ or 3D effects as shown in Figure 2.

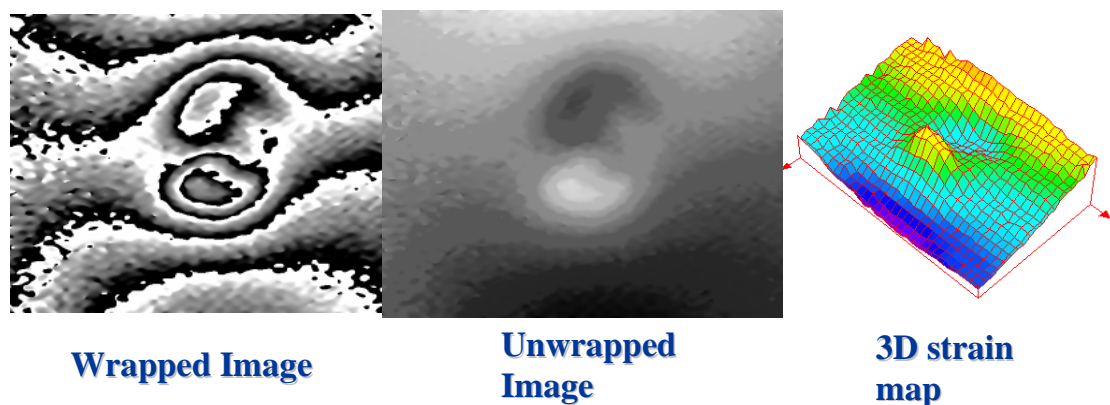


Figure 2 - Typical defect images produced by skin/core disbond in a honeycomb panel.

Whilst there are some limitations in terms of thickness of the laminate that can be inspected, this method is a single sided technique where rapid coverage is achievable making it an attractive system for a production environment.

The RNLI have used this method of inspection of the lifeboats built from advanced composites since the mid 1990s and it has shown itself to be a reliable technique in finding defects particularly in sandwich structures. Lifeboats are inspected at new build and as part of the through life management and monitoring. In these instances the structures are only inspected from the outer surface since due to the construction method this is historically where most defects have occurred.

A lifeboat has a high gloss paint finish that limits the effectiveness of the shearography. To overcome this, the area is either sanded or a layer of chalk dust is applied before the inspection takes place. The chalk can then be removed leaving the paint surface undamaged.

Where possible a vacuum hood is used to induce stress into the test surface. This is because the hood anchors firmly to the test surface and prevents de-correlation of the image caused by any movement of the test subject relative to the inspection head. A free-standing camera and stressing by heat is used on the smaller hulls and where the highly curved geometry limits the use of a vacuum hood and occasionally where damaged areas are suspected. Whilst the inspection and details recorded using this method are good the structure being tested needs to be completely still and free of vibration. In order to achieve this in practice all work on the boat has to stop and systems shut down. On the larger boats this could mean stopping work for up to two days depending on the extent of the damage and can be difficult to schedule in to the overall program.

Some areas of hull are manufactured from cored structure consisting of outer skins of glass and several layers of foam core. This material can be up to 108mm thick. Only defects relatively close to the surface are fully defined. It has become evident that with experience and knowledge of the structure being tested a skilled operator can find indications of defects between the outermost to second and occasionally second to third layers of core. These indications give much less defined fringe patterns and are unreliable for obtaining the depth or size of the defect. Further investigation by destructive methods is usually required in these cases. Additional detail can sometimes be found by re-testing the area from the inner face, but this is often restricted by fit-out and internal structure.

In the particular damage case described above shearography was carried out on the single skin areas of the hull in addition to the topsides. The aim was to look for interlaminar shear damage and as a trial to establish if material bonded to the internal surface could be detected externally.

The ability to determine if components were structurally adhered to the inner surface after damage has occurred without having to dismantle internal fit-out would be very advantageous and cost effective in fully establishing the extent of structural damage prior to strip-out.

Trials were carried out with both vacuum and free-standing heat stressing methods. The vacuum stressing proved able only to detect areas of reduced stiffness where the skin was detached from the internal structure. However the heat stressed trial initially showed potential but the lifeboat was not sufficiently still to obtain results despite being ashore on blocks. During the timescale put aside for NDE it was not possible to shut down all the equipment and re-test with the boat completely still.

A second example of when shearography has been used to assist in damage assessment is shown in Figure 3. The hull has been marked up to show the extent of defects detected during the shearography inspection. This corresponded closely to the final extent of the damage that had to be removed. In these situations the NDE results are used to place the initial cuts when removing the damaged structure.



Figure 3 – Damage marked up after inspection and with damaged material removed

3.4 Ultrasonic Testing

A method was required to determine the extent of the damaged area of the hull and in particular, to determine whether the frame at station seven within the survivors' space was well bonded to the monolithic hull and could be left in place. Tap testing on the internal surfaces had revealed some obvious damage, but a more accurate and faster method was required to define the damaged area. Further the method would be used to scan the repaired structure and to make a comparison with the original data. Any system selected would need to meet the following criteria;

- Speed. Single transducers were too slow. A multi element probe would be required
- Coupling. The outer surface of the hull was protected by anti fouling paint. Good coupling would be required to overcome the rough surface but high levels of water spillage could not be tolerated in the presence of other ongoing maintenance work.
- Data presentation. The hull shell was very noisy and simple A-scan presentations would be difficult to interpret. A C-scan imaging system would be required to aid flaw recognition and to provide easy orientation and sizing of flaws.

The basic principle of UT inspection is that an ultrasonic wave is transmitted into the material and reflected and/or mode converted by a defect or other feature within the

component. A receiver detects the reflected signal and analysis of the amplitude and arrival time can allow characterisation and location of the reflector.

The Rapidscan 2® system selected for the inspection comprised a rapid scanning phased array system utilising a 128-channel pulsar receiver that is capable of generating beams from up to 32 active channels. The 64 element array is deployed in a water filled tyre to permit rapid scanning using very little couplant. The 2MHz probe scans a 45mm wide swath at speeds of up to 500mm/s. The full ultrasonic waveform is captured at every data point enabling full post acquisition analysis of data. Each scan is automatically numbered and saved and can be reassembled into a large area map or ‘T-Scan’. The hull of the vessel comprised approximately 12mm of solid glass laminate to which are bonded a number of stiffeners. These consist of a non-structural foam core over which a ‘top hat’ section of structural PVC core is added. Plies of carbon fibre are then applied and cured under vacuum.

The glass laminate is an acoustically noisy structure with many reflections and high levels of attenuation being generated by the fibres within the matrix. Even so, voids, cracks and inclusions within the solid laminate are relatively easy to detect as they provide a clear reflection that can be seen easily against the background noise. Detection of stiffeners bonded to the inner face of the hull and identification of unbonded areas is more complicated and relies upon the conservation of sound energy at the hull/stiffener interface. In well bonded and consolidated structure the signal from the inner face of the hull all but disappears and a signal from the back surface of the stiffener is detected. In many areas the rough surface of the stiffener and the presence of carbon plies at the glue line attenuate the sound within the stiffener and no signal is received. Where no bonded structure is present almost all the sound is reflected from the interface and a strong signal is received from the back surface of the hull laminate. Detection of un-bonded structure relies on precise monitoring of the amplitude variations of this signal.

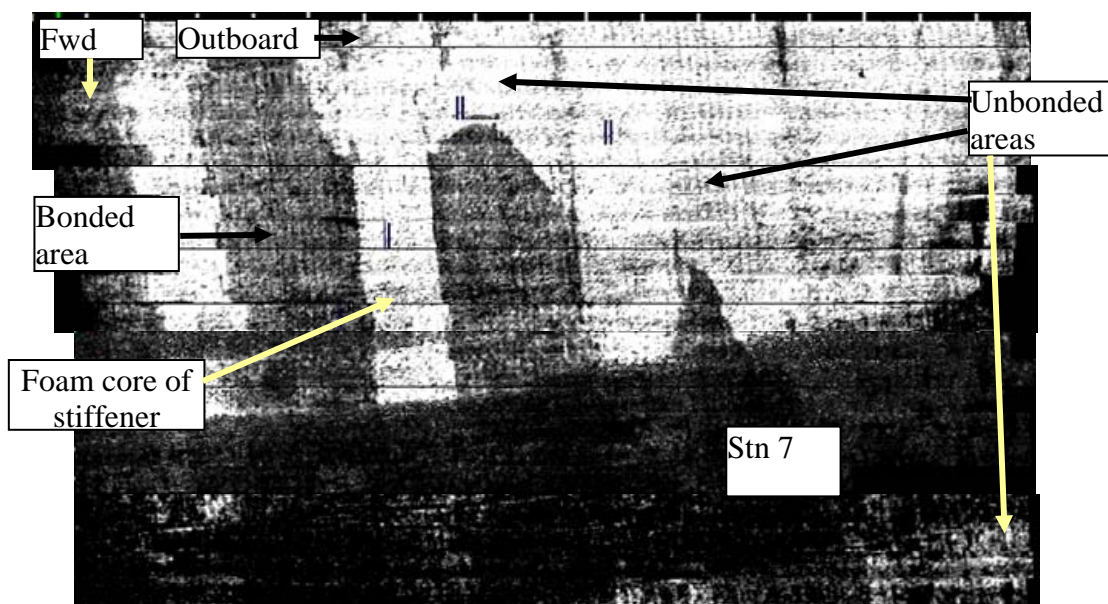


Figure 4 - Composite image of amplitude C-scans from the area around stn 7.

The area around stn 7 was tested and a composite image of around 30 amplitude C-scans is shown in figure 4. The foam cores of the longitudinal stiffeners and the disbanded areas are clearly seen as light areas. The dark areas correspond to the well bonded areas and the transverse frame at stn 7.

The stiffeners and secondary structure were cut away and the actual damaged areas corresponded well with the results obtained from the area scanning. When repairs had been effected the area was scanned again using the markings on the hull from the previous inspection. Figure 5 shows this same area following repair.

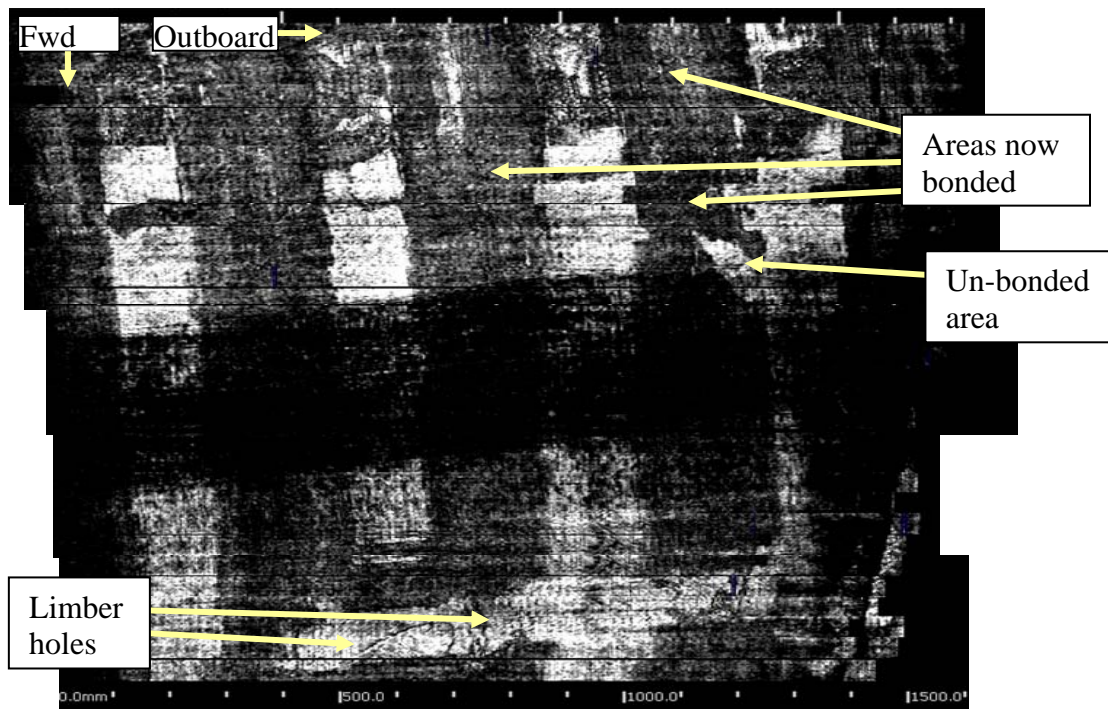


Figure 5 - Composite image from the area around stn 7 after repair.

The large un-bonded area is now not present, as expected. One small un-bonded area remains as indicated in the Figure that was later locally repaired. The limber holes forward of stn 7 can also be seen.

3.5 Thermography

The RNLI wished to evaluate other NDE methods that may prove able to provide information on the condition of the solid laminate skin and the bonding of the internal stiffeners. Pulsed thermography would be trialled as follows:

- The extent of the, as yet unrepaired, external damage to the skin at station 5 would be investigated and the results compared with those achieved using tap testing
- An attempt would be made to detect the bonding of the stiffeners to the inside surface of the solid laminate, and the results would be compared with the ultrasonic scanning previously undertaken.

Pulsed thermography uses a thermal excitation source to rapidly heat the surface of a component. A highly sensitive infrared camera then monitors the surface temperature as it cools. Any sub-surface flaws will affect the way in which heat is conducted into the material, resulting in temperature variations at the surface that change with time. The Echotherm[®] system used in this trial has two flash lamps, which are mounted within a hood along with a Stirling Engine cooled medium wave infrared camera. The hood has a 300mm square field of view and a rubber “skirt” in front of the aperture to protect the operator’s eyes from the effects of the high power flash. The flash lamps are triggered after which the camera records a series of thermal images of the surface. This data is then processed to facilitate review with a suite of sophisticated analysis tools. Figure 6 shows a typical pulsed thermography inspection set-up.

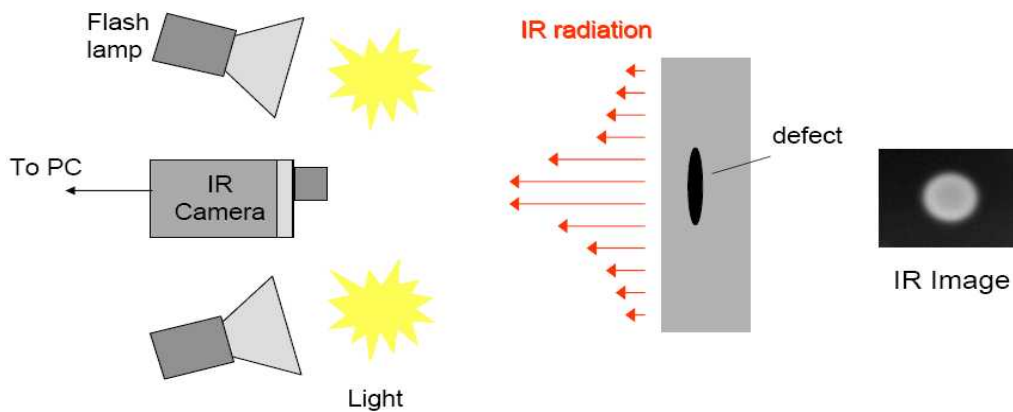


Figure 6 - Typical pulsed thermography system.

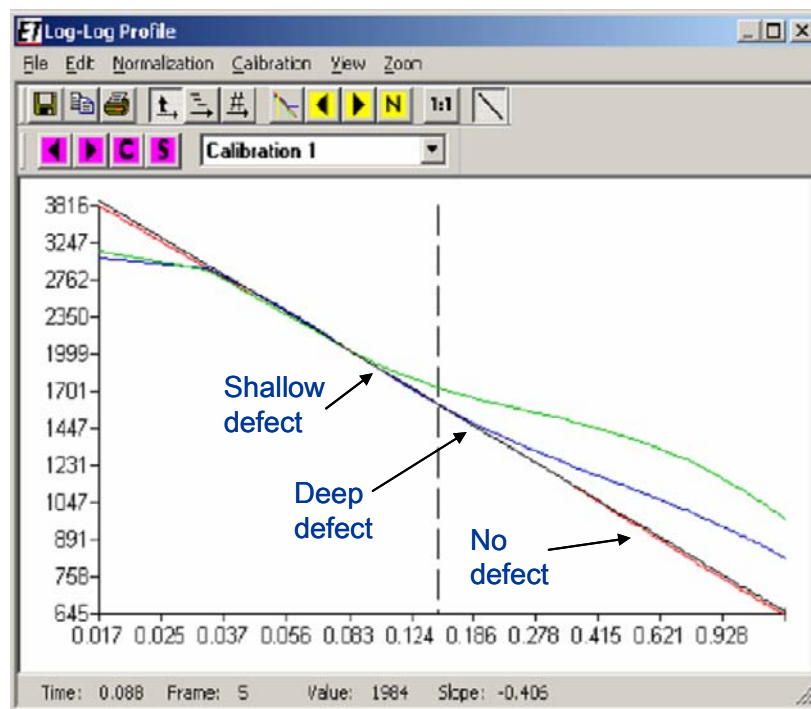


Figure 7 - Graph showing Log of time against Log of Temperature of the front surface.

Heat diffuses into the material in much the same way as a drop of ink diffuses into a glass of water. If we heat the front surface of a solid isotropic material and plot the Log t Log T curve, we get a straight line at about -0.5. When the diffusing heat reaches an obstacle the Log t Log T curve breaks away from the -0.5 slope. The deeper the obstacle the later the curve breaks away. See Figure 7 above.

An area of visible damage could be seen at the forward edge of stiffener 5 at station 5. The damage appeared to consist of a vertical crack of approximately 200mm in length running along the line of station 5. In the upper part of the crack an area of approximately 134mm in vertical length appeared to have delaminated for a distance of approximately 50mm aft. Two 40mm diameter holes had been drilled into the delamination to determine the depth of the damage. Tap testing had been carried out and the extent of the suspect damage had been marked on the skin.

Several shots were taken of the area around the damage site and the technique was optimised. Figure 8 shows an image of the damage area and the subsequent repair. The delaminated area and the crack can be seen. The delaminated area shown as white was indicated to be approximately 25% larger than that detected by tap testing as marked on the hull. The vertical crack indication appeared to match the visible length.

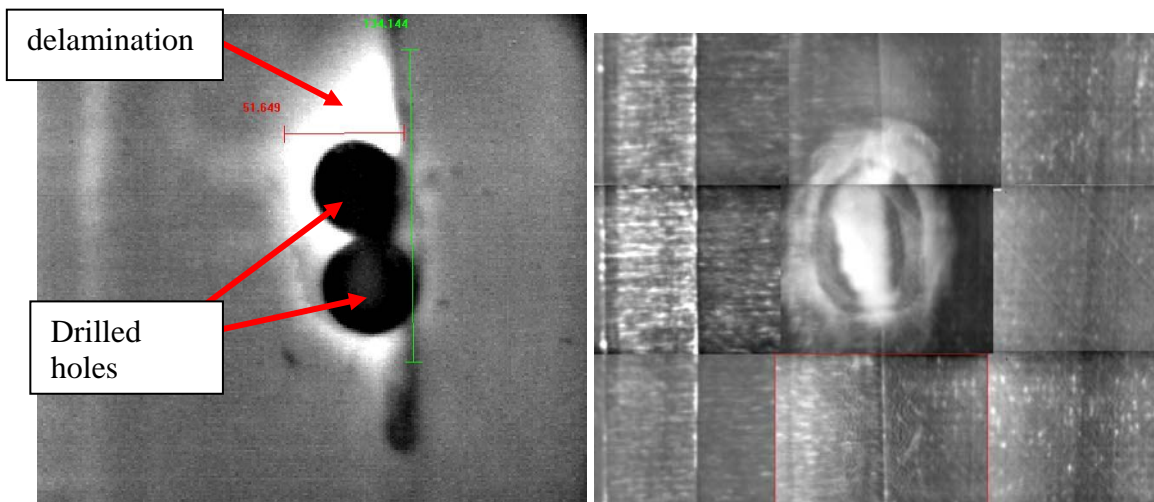


Figure 8 - Thermogram of damage site

The right side of Figure 8 shows a composite image of a meter square area centred on the damage site. The scarf repair can be seen with detail, also visible are the glass prepreg cloth overlaps seen as vertical stripes.

Trials were also carried out to assess the effectiveness of the method to detect unbonded structure on the inside surface of the monolithic hull. The results from unpainted samples of structure up to 10mm thick were promising initially, but tests on painted structure were inconclusive. This is thought to be because the flash is transmitted further into the translucent laminate where it is not painted, but on painted surfaces the heat dissipates laterally along the fibres before it reaches the far surface. Further investigation is required to determine if the technique can be optimised for painted surfaces.

4. CONCLUSIONS

Whilst some believe that a single NDE technique can suit all applications this has been found not to be so. Currently laser shearography continues to be the best available method for use on large sandwich structures. With a skilled operator who has knowledge of the structure, near surface defects can be detected and are well defined, indication of deeper disbonds at around 50mm depth can be detected but not accurately sized.

Much of the damage seen could be found visually or with traditional tapping when the damage is accessible however UT testing has proven efficient and can effectively be used through the monolithic panels to check bonding of structure. In the future this will prove invaluable in assessing the full extent of damage in inaccessible areas before having to cut into secondary structure. Further trials on cored structure and a wider wheel probe may give additional benefits.

Pulsed thermography has also shown potential on thick composite skins. Good detail could be seen on small panels tested alongside the boat in a yard environment but results on the large structure were not of comparable quality. Further testing and investigation is required to fully establish its usefulness on a typical lifeboat structure.

ACKNOWLEDGEMENTS

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