TECHNOLOGY REPORT

. *Laser Technology Inc.*

Rapid Sensitive Inspection
Of
Marine Composites
Using
Laser Shearography

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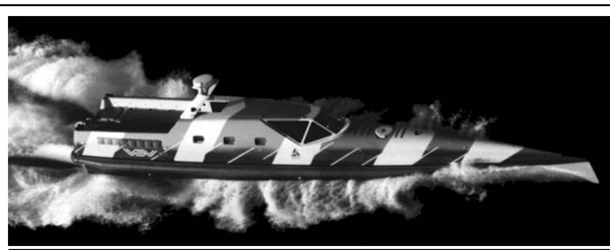
Abstract

Although Fiber Reinforced Plastics (FRP) have been the mainstay of boat hulls for many years, the almost universal adoption of aerospace style composites into marine environments has gradually taken place. Greater resistance to bending stresses has required the use of sandwich constructions to give high strength to weight ratio, with carbon fiber skins and honeycomb or foam cores. 'High tech' boats such as Americas Cup racing yachts for Oracle BMW , large super yachts as 'Mirabella V' and fast patrol/rescue craft such RNLI Lifeboats, now utilize this construction throughout.

Forming a structure from many different materials in the form of a composite increases the chance that a weakness is built into the final product. By the nature of their construction marine composites require 100% inspection. Statistical sampling on a grid principle has historically given results for residual life on homogeneous metal plates on marine vessels, however, composites by there nature are inhomogeneous. The risk of missing a disbond or debonded areas is not acceptable – whatever the statistical sampling may say. The problems therefore facing NDE inspections are that large areas require to be 100% inspected in a relatively short time frame, with a high degree of sensitivity.

Laser Shearography has been at the forefront of advanced composite inspections in aircraft space craft and marine NDE. This NDE technology is able to detect weaknesses in the composite caused by disbonds and un-bonds or by inferior adhesive bonds. The same parameters are then used to validate repairs. Rapid yet sensitive inspections at over 5 to 10 sq meters per hour, with overlapping scans giving over 100% coverage, are not uncommon.

Laser Shearography is able detect weaknesses in bonds as variations to the surface strain field in response to a variety of stressing mediums ranging from thermal to vacuum stressing. Advances in the optical arrangements and data processing enables sub-fringe resolution leading to advanced determination of how the material behaves under load.



1. Introduction

1.1 Marine Composite Build Problems Particular problems in the manufacture of foam and honeycomb sandwich constructions are that areas can occur where there is little or no adhesive bond between the skin and the core. A number of individual or a collection of causes can cause these defective areas. Either by entrapped air pockets, out-gassing from the foam core, inadequate mixing of the catalyst into the adhesive, failures of the vacuum bagging process, resin injection process, and the curing process. In our inspection experience these defects can vary in size from cm^2 to $meter^2$ in size. The disbonds or un-bonds can be individual, or be close but separate from neighboring disbonds at the same level in the composite structure.

The danger with these defective areas is that thermal and operational sailing stresses will Coalesce these individual disbonds into forming a larger area. In so doing the overall strength, especially the rigidity, in the form of the second moment of area drops dramatically.

Un-bonded areas typically do not show themselves during manufacture, where controlled temperatures and environments exist. These defects however, inconveniently wait until the boat is finished, painted and polished and delivered to the new owner. Only then do the unbonded areas tend to become visible when they turn into a blister caused by the action of raised ambient temperatures or exposure to sunlight. Not just an unsightly blemish, but a costly and time consuming job to repair. It is often a requirement that the disbonds are repaired from the inside (to maintain the integrity of the outer layers of the laminate); this often requires expensive internal paneling, fuel or ballast tanks to be removed to gain access. The instigation of a measured NDT program incorporated into the production process has therefore benefits in cost terms alone.

1.2 Effective NDI In Process Control At the heart of an effective process control lays the basic feature of effective feedback in the form of an adequate inspection. Without this basic action of verification, that the build process has made a defect free product, the process cannot function as an iterative control mechanism. Rapid large area coverage Non Destructive Testing (NDT) is able to determine the state of the composite structure, thereby closing the loop within the process control system

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Figure 1 What can happen when defective build goes undetected.

Figure 2 The 47 meter cruiser MY 'Teeth' inspected by 100% coverage using Laser Shearography during servicing / refit.

Often composite marine craft are delivered without inspection, with only the adhesion to programmed control procedures. A lot of work goes into laying down the correct procedures, documenting the method, recording batch numbers and such; they all have their place in ensuring the structure is built to a uniform standard. Batch testing of samples by peel tests, and other mechanical testing can ensure that the process is optimized, however when large areas of composite are laid down many factors come into the equation that cannot be fully addressed by procedures alone.

1.3 Non-Destructive Testing of Marine Composites Marine composites, as in the aerospace field require 100% inspection. Statistical sampling of marine craft, on a grid principle has historically given results for residual life on metals where corrosion across homogeneous steel plates can be extrapolated from a few points; however, composites by their nature are a different matter. The risk of missing a disbond or debonded areas is not acceptable. Statistical sampling, using point-measuring transducers on a grid principle has such a low probability of detection on composite materials that it is not worth contemplating. This statistical sampling grid method can lead to a 'False Negative' condition where unacceptable defects are missed.

1.4 Problems for NDT The problems therefore facing NDE inspection of composite marine structures are that large areas require to be inspected with 100% coverage, in a relatively short time frame, with a high degree of sensitivity. Traditional approaches to the Non Destructive Testing of Marine composites have revolved around Ultrasonics, however the low frequencies required to penetrate FRP have long wavelengths, which exclude the detailed sensitivity required. What is needed is a method of verifying the quality of a laminar bonded structure, such that;

- Is not dependant on the attenuation characteristics of the material,
- Does not require scanning frames to record and highlight trends in the data

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over a large area from the standard, point measuring probes.
- Can give results on the bond line between foam cores.
- Present results directly onto the structure for the repair team without recourse to maps of the structure.
- Effectively plot the out-of-plane strength of the laminar bond.
- Detect weaknesses and check condition of core splices and bulkhead attachments.

Although these features form a wish list for effective NDT of composites, they can be met by the introduction of Laser Shearography NDT into the process control or phased servicing program.

2. Laser Shearography Inspection

Laser Shearography has been at the forefront of advanced composite inspections in aircraft spacecraft and marine NDE testing. This NDT technology is able to detect weaknesses in the composite caused by disbonds and un-bonds, gas/air pockets entrapped in the structure, or by inferior adhesive bonds.

Laser Shearography is a form of video holography which provides more than 1/2 million real-time adjacent strain gauges on the surface of the structure being inspected. This technique does not require the vibration isolation that is a basic requirement of holographic inspection, from which this technology evolved.

Laser shearography is a non-contact, inspection technique that presents a visual qualitative map of the strain field of the surface of the structure in response to an applied stress. Subsurface features such as core splices, bulkheads and defective areas affect and distorts the surface strain field and are therefore monitored.

The sensitivity vector of these shearography systems is predominately out-of-plane; it is therefore sensitive to the weakest vector of the bonded laminate. Shearography derives its name from the requirement to laterally displace and overlap images, or to shear them. This gives the overall ability to detect a defect within a component. Often the shear vector is only millimeters; however the sensitivity in the out-of-plane vector is in the region of nanometers.

The basis of all shearography techniques is that the onboard CCD video system captures a sheared image of the laser speckle pattern formed of the surface at one stress state and stores this as a reference image. While the stress state is modified, new images of the surface are compared against the stored reference by image subtraction correlation; only the difference is presented on the screen in real time. This process is carried out, and the screen updated at the rate of 30 times a second until the predetermined second stress state is reached.

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The updated correlation is then frozen on the screen. The result presented on the screen is the first differential of out-of-plane displacement i.e. $\Delta l/l$ it is therefore closely akin to strain. It can be seen that if there is little response to the input stress, the material is strong and the output in the form of lines of iso-strain will be accordingly small. If however, there is a weaker area i.e. disbond, the material responds to the stress to a greater extent and there will be a concentration of strain related fringes.

2.1 Types of Laser Shearography for the Composites Industry Laser Shearography as an NDT technique have many forms depending on the optimum stressing method required to find the defects. The optimum Laser Shearography method of inspection takes into consideration the combination of equipment, stressing mechanism and the material / structure under inspection.

There are two main methods of Laser Shearography that are applicable to large area inspection associated with marine composite structures.

2.2 Image Subtraction Correlation Shearography Developed and world patented by YY Hung in1988 this technology found is first real major application in the inspection Stealth Materials for the B2 'Spirit' bomber. It is a 'real time' system where the resultant lines of iso-strain are viewed as they are created. This feel for the structure under inspection is of enormous value and is more rugged but slightly less sensitive than the later generation shearography technologies. The Royal Air Force and Boeing use this rugged equipment in the inspection of the B2, and for the inspection of the AWAC's E3D radome.

Under this technology is the LTI4200 system (Figure 3) of either a vacuum hood, which applies a direct out-of-plane stress to the laminate and is used to cover large areas of composite at up to 10 m^3 / hr or a free- standing camera, which detects the response to thermal and mechanical applied stressing. The benefit of these real time systems in a boatyard or factory is their speed of operation and immunity to vibration.

Figure 3 LTI 4200 Vacuum Hood System rugged design for aerospace and marine composite inspection testing an AWAC E3D radome.

2.3 Phase Stepping Shearography Advances in both optics and computer power have enabled a highly sensitive phase stepping instrumentation that in many ways has superseded the image subtraction equipment both in sensitivity and in the analysis of the material response to the applied stress leading to enhanced indication characterization.

Under this technology is the LTI 5100 free-standing camera (shown in Figure 4), which is at the heart of the systems used at the major aerospace composite manufacturing and operating facilities, such as Boeing Lockheed Martin, Northrop and NASA. Incorporation of this technology into the vacuum hood as shown in Figure 5 has increased the sensitivity of inspection by an order of magnitude. The image is processing and the ability of phase stepping systems to present the data in different modes and different types of image, aids the analysis of inspection.

Figure 4 LTI 5100 Free standing Phase Stepping Laser Shearography camera.

Figure 5 LTI 5200 Phase Stepping vacuum hood system for enhanced sensitivity.

2.4 Effective Stressing and Stability To enable optimum interrogation of the material, the material has to be effectively stressed, in a way that maximizes the potential for the defects to be found. The stressing can be any of the following: - thermal, vacuum, either with surface operating or vacuum chamber applications, and vibration stressing, with a mechanical or acoustic excitation.

The stressing is closely coupled with the ability of the system to determine the reaction of the material to that stress alone, without outside influences or inherent instrument related motion compromising the inspection procedure. To that end instrument and optical stability is of the utmost importance. Many years experience of the application of shearography to space, aircraft and marine structures have created a range of equipment that is simple to use, safe and effectively finds the defects sought in a wide range of materials under a wide range of stressing regimes. Running parallel to these capabilities is the ability of the systems to work on structures that are actually moving. Often bulkheads are being fitted and other work in process, while the Laser Shearography examination is being carried out, this capability is invaluable in order to maintain both production and inspection schedules.

2.5 Application of Vacuum Stressing Shearography to Marine Inspection
Was developed to provide an on-aircraft system for the B2, so that areas of the aircraft could be inspected on site immediately after flight. A system based around a vacuum hood was developed. This system created a controlled out-of plane stress to the stealth laminate. This same system that is part of the tool kit for the B2 'Spirit' and is in use on many aerospace applications such as the AWAC radome for the RAF, it is also ideally suited to the marine composites inspection. As it forms its own seal, with the surface becoming one half of a vacuum chamber, the unit can be operated in bright sunlight, immune to gross vibration, and has the same laser safety classification as a CD player.

3. The Inspection Process

The different equipment used for these inspections each have their optimum methods of operation and methods of operation.

3.1 Vacuum Hood Inspection Individual placing of the vacuum hood cover an area of approx 900 cm^2. The system captures a shearography image while a small holding vacuum is applied, which locks the vacuum hood to the surface. This preload ensures that the hood locks to the surface, removes any independent motion and allows the hood to move in unison with the structure. This is important feature, in that the inspection can be carried out without interrupting the build or service schedule.

This initial image is used as a baseline for subsequent shearography images to be compared against while the vacuum differential is increased by approx 1 psi. The result is the real-time formation of fringes indicating the either normal wide spaced uniform fringe pattern of as well bonded material or the doubles bulls-eye fringe set associated with a fault.

Each placing of the vacuum hood covers approximately 900 cm^2, with an examination of that area carried out in less than 5 seconds. With overlapped placing, a coverage rate of 5 m^2 to 10m^2 per hour can be achieved on a defect free, uniform surface, Figure 6.

Figure 6 Up to 10 sq meters per hour at 100% coverage can be achieved. Disbond indications are marked onto the hull surface.

Each placing is inspected with up to 3 refresh cycles per placing, each inspection cycle taking approx 1 second per placing. With a 50mm overlap of scans in both the vertical and horizontal, the whole area is assured in its coverage. This inspection regime that has been honed over 60 boats. The inspection team can within reason start the inspection at any point on the surface to fit in with the production schedule, Figure 7 & 8.

Figure 7 Example of a Laser Shearography vacuum hood attached during hull inspection

Figure 8 Example of in process manufacturing Laser Shearography inspection

Indications are marked directly onto the surface of the craft, - therefore the repair team does not have to rely on separate 'C Scan style" maps to locate a defective area.

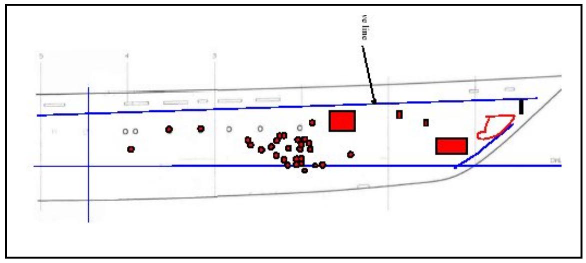

Figure 9A Disbond indications marked on the boat hull.

Figure 9B Disbond indications mapped on the boat drawing

3.2 Application of Phase Stepping Equipment The increased sensitivity of Phase Stepping Laser Shearography equipment coupled with the point a shoot capability enable inspections to be carried out in restrictive areas or in geometries where the vacuum hood is unable to fit. The differing stressing methods available give another dimension to the inspection. The application of thermal stressing to composites is a powerful inspection tool. Unlike thermographic inspection, where the passage of thermal energy is monitored, Shearography looks at the response of the material in terms of the changes in the surface strain field to the input of thermal energy. However the stress required to reveal a particular defect can differ from thermal through to mechanical.

Common to both types of shearography camera is the ability to transmit the extent of a defect onto the surface of the structure for the repair teams. However, the point and shoot capabilities have an added feature. The output from single video camera is split between the shearography component and the live video image, as they are common; a digital overlay from one image is transferred to the other. This facility enables defects depicted in a shearography result to be accurately marked on the surface of the structure where a disbond within a repaired area of a boat hull is shown.

4. Results of Trails – Representative Defects.

The ability of any NDT method to find defective areas is best verified with representative defect samples, bracketing the minimum defect size at the levels in the laminate that the designers / stress engineers require. The optimum construction of these panels is of paramount importance, trying to include representative defects, inclusions of backing film, disbonds and including defective areas of bond is very difficult. However once built, these panels can act in many ways, Firstly in verifying that the method will find the defects sought, and secondly in fine tuning the method parameters to optimize the inspection process. These parameters act then as a baseline for the inspection of the structure. The results of an examination are shown in Figures 10 to 12. The programmed disbonds detected easily by thermal stressing phase stepped Laser Shearography.

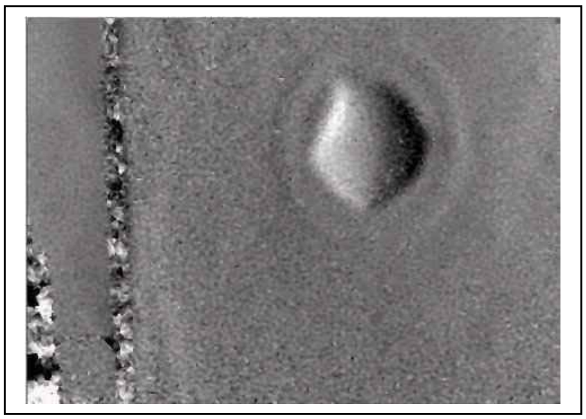

Figure 10 Programmed disbond detected within a FRP/Foam sandwich, Notice the concentric circle of stronger material (extra bond line) from a sealing cap.

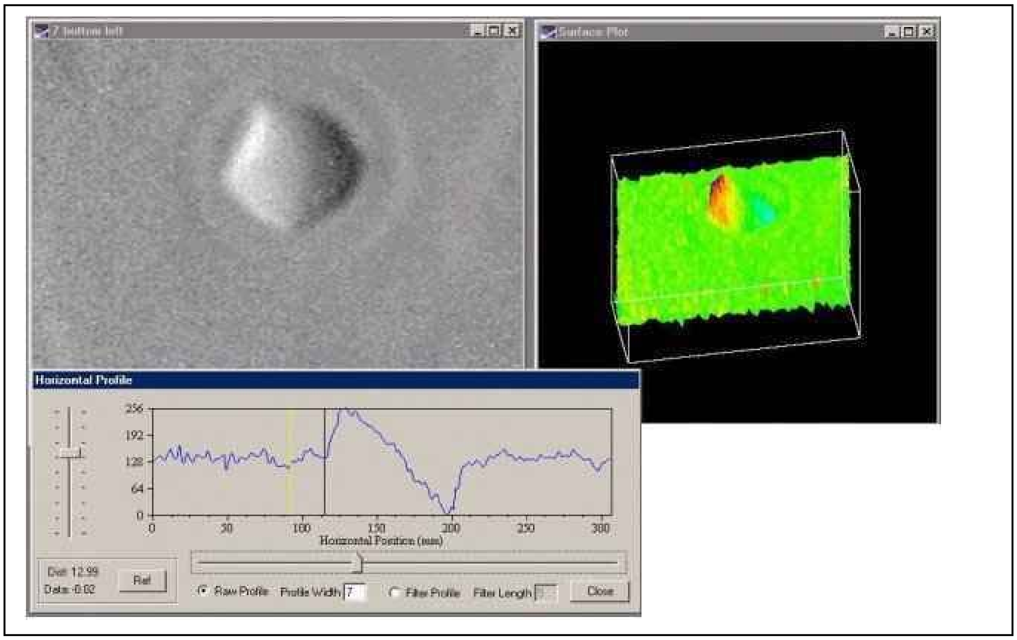

Figure 11 Shearography Analysis of programmed disbond showing the 3D image and the unwrapped profile of the 1st differential of out of plane displacement.

4.1 FRP/Foam Sandwich Constructions. The results of one such trial are shown here, to ensure prefabricated voids were not compromised in the build of the sample, sealed compartments were machined into the foam core, these were then rebated and a flush fitting cap bonded into position. The foam core panel was then incorporated into the sandwich construction under multiple plies of FRP. Thermal stressing with the LTI 5100 phase stepping camera was able to detect not only the programmed disbonds, but also give detailed information on how the disbonds were constructed and their dimensions. In Fig 12, the ability of the technology to detect and monitor breather holes, verifies the overall inspection sensitivity, as well as verifying the bonding process of the core to the skin.

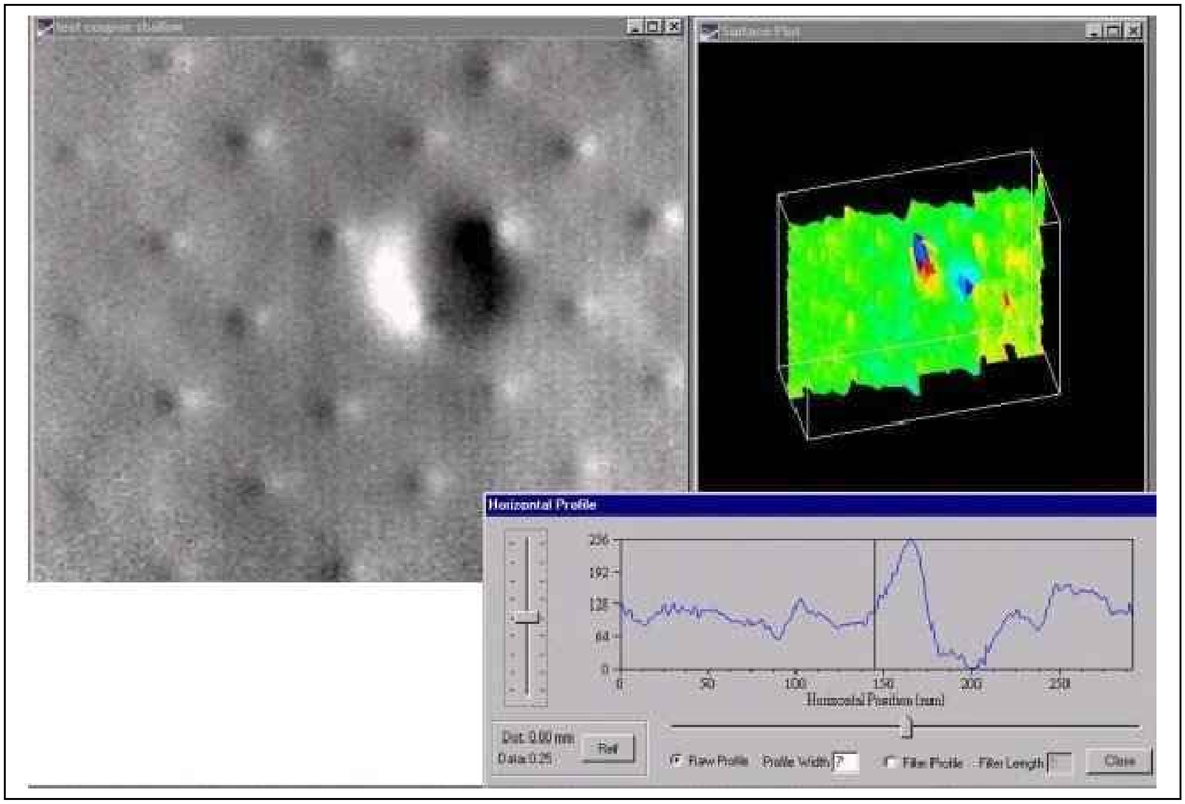

Figure 12 Breather holes full of core bond clearly stands out under examination – notice they exhibit a 180 degree phase exchange from the programmed weaker disbond, indicating their strength in relation to the weaker disbond.

4.2 Repair Validation Laser Shearography is able detect anomalies to the structure in the form of weak areas such as disbonds and accurately map them, but the benefit of the Inspection is shown in the ability to inspect and validate the repair. A total service can be provided that locates defects, ensures the removal of a disbond, and then checks the repair once cured. Often the repair is of slightly different material and will incorporate bond lines that are thicker and do not match the original structure. Laser Shearography will, however, compare the strength of the bond lines with regard to the out-of-plane displacement which is the weakest vector of the bond, within the repair itself, as well as the repair to parent material bond. This goes a step further than the information that is gained from destructive tests made to samples.

5. Conclusion

The capability of Laser Shearography to provide effective non-destructive data from 'difficult' materials has created a revolution in aerospace and now within the marine composites industry. This advances inspection technology in its many various forms is able to provide a rapid, 100% coverage inspection, with a high degree of probability of detection for marine composite manufacturers.

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