



UK Ship Register

Large Yachts: Examination of Carbon Fibre Masts and Spars

Information and Guidance Report targeted at the examination and inspection of carbon fibre masts and spars of large commercial yachts built under the MCA Large Commercial Yacht Code (MSM 1792 (M)) and which have masts (and other major spars) which are constructed from composite carbon fibre material

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Inspection and Monitoring of Composite Carbon Fibre Spars on Large Commercial Yachts

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Preface

This document was prepared as part of a DTI funded project titled “Maintaining Structural Integrity in Yacht and Wind Turbine Spars: MSI Spar”. The project was undertaken because leading practitioners in the Yachting industry had recognised there was a lack of guidance on how quantitative inspection methods should be applied to carbon fibre spars.

The key questions raised by the industry were:

- In the event of damage when does a carbon spar need repair, or replacement?
- How does a manufacturing defect, or damage inflicted during installation or service, affect the structural integrity of a carbon spar?
- How do you determine if a carbon spar is still serviceable and safe?

The objective of this project was to provide best practice information and guidance in answer to the above questions. This guidance is given in the context of the inspection and monitoring of composite carbon fibre spars on large commercial yachts. The content is based on input from leading experts in the design, manufacture, inspection and structural analysis of carbon fibre spars.

The document is aimed at a wide range of groups including designers, manufacturers, surveyors, insurers and underwriters, skippers and owners, and possibly Classification Societies.

The document is arranged in 4 parts as follows:

- Part 1 covers general guidance for planning and executing of inspections including the types of inspection methods that can be deployed.
- Part 2 provides specific information relating to defect assessment and structural analysis that will be of specific interest to designers, manufacturers and Classification Societies.
- Part 3 provides information on recent developments in structural health monitoring which utilise fibre optic load sensing in carbon spars.
- Part 4 provides details of the contributors to the document and sources of further information.

Part 1: Spar Inspection

1 Introduction

- 1.1 This Guidance applies specifically, but not exclusively, to large sailing yachts within the scope of, and subject to, the Large Commercial Yacht Code (MSN1792) and with spars (and other major spar components) constructed from composite carbon fibre material.
- 1.2 The proportion of yachts with carbon spars has increased since the late 1980s and the majority of spars are now made from this material. The definition of spars includes mast(s), spreaders, boom(s), gaffs, spinnaker and other poles, and bowsprits. While priority is likely to be given to the mast as it has the highest safety and commercial risks, other spars should also be considered.
- 1.3 While the failure of large spars is rare, the safety and commercial implications can be considerable. This document offers an approach based on best practice which will assist in ensuring that owners and operators are aware of the condition of their spars and are able to undertake remedial maintenance when this is required.

2 Scope

- 2.1 This Guidance has been prepared primarily for “in service” management of structural integrity of masts (and other major spars) using monolithic and ‘sandwich’ cored carbon composite. It is also applicable for pre-service inspection of spars and where there may be deficiencies in the structure. While designers do not normally intend to include deficiencies in the structure, it is expected that it may be used to support surveys for safety, certification, purchase and insurance. The user may also consider the use of this guidance for admission of the vessel to Class subject to agreement by the relevant Classification Society.
- 2.2 The guidance offers suggested procedures and best practice in the absence of alternative standards for maintaining and inspecting carbon fibre spars.
- 2.3 This document does not aim to duplicate the design process which has been carried out by designers and manufacturers or the structural assessment process which is offered by one of the Classification Societies. It does not consider the inspection and assessment of aluminium and wooden spars, which have an extensive experience base that is well understood by surveyors. It also does not consider the standing rigging, which is also covered by surveyor experience and by guidelines which are available from standing rigging manufacturers.

3 Existing Information

3.1 Introduction

Before planning and carrying out inspections on carbon fibre composite spars, it will be of considerable benefit to ensure that a dossier or history of information is prepared that contains available information on the design, manufacture, operating service and previous inspections. This will be of assistance in planning the inspection, in deciding whether any remedial work is required and in identifying a subsequent monitoring and inspection programme. This information exchange can often be secured by the implementation of a simple non disclosure agreement between the parties concerned.

3.1.1 The minimum information required for a Non Destructive Testing (NDT) inspection is listed here for guidance:

- a. Engineering drawings of the spar including main dimensions
- b. Details of laminate thickness and reinforcements/local patching
- c. Laminate specification (ply type and orientations)
- d. Manufacturing method – e.g. male/female moulded, single or two part construction, autoclaved, pre-preg, tapewound
- e. Access to laminate core samples taken during build or repair

3.2 New spars

This section refers to either new build yachts with new spars or to replacement spars. While priority is likely to be given to the mast as it has the highest safety and commercial risks, other spars should also be considered.

3.2.1 If not already available, spar design information and history should be requested from the appropriate sources at time of purchase or otherwise drawn up. The following list is given for generic guidance in drawing up this history but is not exhaustive:

- a. Yacht designer: provide scope and extent of design, load data.
- b. Spar designer: provide full load and stress data, full lay-up and reinforcement details, set-up loads.
- c. Manufacturer: Provide method of manufacture e.g. male or female mould; jointing details e.g. joggle bond, axial spigot; filament wound, hand laid up; use of interlaminar filler, honeycomb or foam core, non-carbon reinforcement material; type of cosmetic fillers used.
- d. Manufacturer: provide Quality Certificate, identifying all departures from the design intent, including but not limited to: all dimensions; number of lay-up layers; weight; pre-service inspection results.
- e. Identify and list modifications to the rig or spar since designed.
- f. Log of events up to time of inspection: e.g. damage to spar or rigging, repairs to spar.
- g. Experience with spars of the same or very similar design and manufacture.
- h. Details of inspections carried out by manufacturer.
- i. Details of any structural analysis carried out to cover expected service conditions.

3.3 Spars which have been in service

When spars have seen previous service, owners will wish to ensure that their integrity is checked at regular intervals and when potentially significant events have occurred. While priority is likely to be given to the mast when it has the highest safety and commercial risks, the other spars should also be considered.

- 3.3.1 When it is not already available, design information and a history for the spar should be drawn up. The following list is given for generic guidance in drawing up this history.
- a. Recover historic documents, in particular establish if a history as defined in 3.2.1 has been created; also records of all subsequent inspections, including the types of inspection and the scope and extent of these.
 - b. Review and prepare documentation based on the items listed in Section 3.1.1 and 3.2.1 above.
 - c. Verify if the spar is the original supplied with the yacht, if it is a replacement, and record any original design changes.
 - d. Details on past repairs made to the laminate should be sought.
 - e. List of any engineering modifications made to the design including, but not limited to, changes in sail plan and dimensions, spreader angles, deck sealing/chocking arrangements, jacking ram loads.
 - f. Past record of type of sailing that spar has been subjected to e.g. number of hours or miles under sail and motoring.
 - g. Past record significant events – damage, repairs to spar/rigging, major storms, lightning strikes.
- 3.3.2 When the original design information is not available, a specialist structural assessment consultant with appropriate experience should be approached. As well as being able to offer advice on the significance of specific defects, the consultant should be able to undertake a “reverse engineered” assessment of the original design intent.
- 3.3.3 Further guidance on structural analysis and defect assessment is provided in Section 6 of this document.

4 Inspection Planning

4.1 Risk assessment

When considering where, and when on the spar to inspect, it can be useful to apply risk assessment methods. This will help the user identify the key structural elements and ensure that other parts of the structure that may be subject to high or repetitive loading are not missed.

4.1.1 As a guide the risk assessment process for inspection may follow the format below:

- a. Identify critical regions within the structure.
- b. Assess the structural importance and risk of failure including susceptibility to damage.
- c. Select inspection techniques to manage and control identified risks.
- d. Implement and maintain control measures.

4.1.2 In such large structures as yacht spars, inspecting every square centimetre is a significant exercise. However, a 100% inspection of the composite should be considered for new build or for structures that do not have an inspection history. In any event priority for evaluation should be given to regions within the structure that have the highest risk. In this case risk can be defined as:

- a. An area within the structure where an in-service damage event is a possibility.
- b. A structural design feature that results in stress raisers.
- c. A highly loaded region, (static, fatigue, vibration, environmental, etc.).
- d. A region where the manufacturing quality cannot be fully controlled.

4.1.3 For each structure an exercise must be carried out to identify the above regions with a ranking given in order of risk which includes the types of damage or defects that can be expected. This does not need to be a complicated exercise and a list of damage and defect types and a simple risk based methodology using a tabulated approach is given in Appendix A. The exercise will require input from the involved parties such as composite structural engineers, designers, manufacturing engineers and the operators or end users.

4.2 When to inspect

4.2.1 Inspection applies to new build (production) structures as well as existing in-service masts and other spars. The requirement for inspection may depend on several factors:

- a. The complexity of the carbon fibre mast and spar fittings.
- b. The anticipated operating conditions.
- c. Whether there have been any events (during production, shipping, installation or in-service) that may have compromised the structural integrity of the spar.

4.2.2 In addition to localised invasive methods (e.g. use of cut-outs for porosity analysis) and visual inspection, Non Destructive Testing (NDT) should be considered as a means to validate the structure subject to agreement with relevant bodies such as Classification Societies. The types of inspection that are available are detailed in

Section 5.2 and Appendix B which include visual inspection and ultrasonic NDT techniques among others.

4.2.3 Note that visual inspection of damaged laminates can be misleading and may result in under estimating the severity of the internal damage to the spar. For this reason NDT should be used on suspected impact zones even if there are no significant external damage indications.

4.2.4 Care should be taken to ensure that the inspection method and reporting documentation is of sufficient quality and consistency to be of use for future inspections on the spars. Further guidance on this is given in Section 5.4.

4.3 New build

4.3.1 For new design and build, comprehensive NDT inspections should be carried out throughout the programme at appropriate stages during the project to help the design team and manufacturer reach the desired design specification for the laminate structure. These inspections can also form part of the pre-service baseline data for the spar which can be used as a benchmark for future inspections (see 4.4.2).

4.3.2 If it is considered that NDT inspection shall be required during the project build an initial inspection of the composite materials to be used during production should be made to help determine the best NDT method. This process should include the manufacture of reference panels using the same materials and processes as the spar which contain representative 'indications' or defects that the NDT method is expected to find (e.g. voids, porosity, resin richness). NDT practitioners can provide advice on how representative indications can be prepared. The reference panels can then be used to help verify the condition/quality of the production laminate using NDT methods.

4.3.3 In addition to reference panels, all cut-outs taken from the mast should be documented and held by the mast manufacturer throughout the service life of the spar. These samples can be made available to NDT inspectors for calibration purposes to ensure that any inspection methods to be used on the spar are fit for purpose.

4.4 Pre-service inspection - new build or refurbished spars

4.4.1 Following manufacture of a newly built spar or the refurbishment of a spar, a pre-service inspection of the spar should be considered.

4.4.2 Pre-service inspection data should be obtained from all areas of the composite structure or in the very least from critical areas of the spar at a suitable point in time (e.g. at the end of manufacture or after initial installation). The pre-service inspection data can also include NDT inspections of the spar laminate conducted during manufacture. The aim is to provide a baseline report of NDT inspection data which contains the type, size and position of indications that have been found in the spars and any other relevant information on the condition/quality of the laminate. This report can then be used as a benchmark for future in-service inspections (see Section 4.5).

4.4.3 If shipping/transit or installation damage to carbon fibre laminate on the main spars or sub-components is suspected then NDT should be carried out.

4.5 In-service inspection

4.5.1 In-service inspection data should be of sufficient quality and consistency that it can be compared to early pre-service inspection and future in-service inspections. Care should be taken by the inspection company to ensure that the NDT inspection equipment has an equivalent detection capability and setup to that used and reported in previous inspections, this can be verified by the use of reference panels, production spar cut-outs, and calibration measurements on the spar itself (see also section 5.4)

4.5.2 In-service inspection should be carried out on all spars. This will be done to a depth and with a periodicity which takes account of:

- a. The safety or commercial significance of serious damage or failure of the spar.
- b. The sailing miles endured by the spar.
- c. The operating conditions it has experienced.
- d. Routine inspections/maintenance to be carried out on the standing rigging.
- e. Inspection intervals specified by insurance schedules

4.5.3 For guidance the following table is provided which defines three recommended levels of inspection.

Inspection Level	Period	Content	Reporting
Level 1	Several times per annum *	Mast in; visual by a competent rigger, structural engineer or marine surveyor.	Record of scope and extent; referral of specific items for further investigation. Update service log and next service schedule
Level 2	At least annually	Mast in; visual by a competent rigger, structural engineer or marine surveyor with ready access to certified ultrasonic NDT operators to assess suspect areas on the spar.	Record of scope and extent; referral of specific items for further investigation. Update service log and next service schedule
Level 3	Between 4 & 10 years, depending on operating conditions and guidance from spar and rigging manufacturer and insurance schedule	Mast out; comprehensive visual inspection, by a competent rigger, structural engineer or marine surveyor followed by comprehensive NDT inspection by a formally trained and certified NDT operator.	Full report comparing previous and current inspection results. Update service log and next service schedule

* Note: Additional NDT inspections are recommended to check to the integrity of the spar laminate immediately following events such as lightning strikes, impact damage and suspected overloading of the structure,

4.6 Repairs

Repairs may be carried out during manufacture and in-service to remove damaged or defective areas of laminate. In these cases NDT may have been used to locate and identify the damaged areas and the subsequent use of NDT to verify the quality of repair should be seriously considered as follows:

- a. NDT may be used to assess the quality of the repair laminate in comparison with the surrounding laminate by qualitatively assessing how well consolidated the material is (e.g. presence of porosity) and for the detection of voids.
- b. NDT may be used to ensure that the integration of the repair laminate in the parent laminate is of sufficient quality this may require the inspection of laminate scarfing interface or additional reinforcing laminate planks that are bonded to the structure
- c. NDT of repaired laminate during the service life should be considered as part of the normal inspection and maintenance programme.

4.7 What level to inspect at

- 4.7.1 The level of inspection required will depend on the complexity of the spar structure and base laminate and the degree of uncertainty concerning the type and extent of damage and the results from any risk assessment that has been carried out. See Section 4.1 and the Table in Appendix A.
- 4.7.2 The accuracy of the NDT inspection method and the required level of information should be used to determine which inspection method is utilised. See Section 5.2 for an overview of inspection techniques and their capabilities.
- 4.7.3 Damage may be identified by visual inspection due to cracking in the paint layers at which point the exact location and extent of the damage needs to be confirmed as follows:
 - a. If the damage is associated with a fitting, the nature of the damage may be easily confirmed by removal of the fitting and further visual inspection.
 - b. If the observed damage is extensive enough to require repair then the actual extent of the damage can probably be ascertained during the repair process itself (e.g. grinding and removal of damaged material).
 - c. If the suspected damage cannot easily be confirmed by removal of the fitting then an NDT method such as ultrasound should be considered. In this case the extent of the damage can be quantified non-invasively so decisions whether to repair or regularly monitor the area can be made.

4.8 Responsibilities for inspections

- 4.8.1 Inspections can be requested by those involved with the design, manufacture, operation or insurance of the spar structure including Classification Societies.
- 4.8.2 Good communication between the inspection company and relevant groups (e.g. owner, designer, manufacturer, insurance company) must be established in order to develop a suitable inspection procedure for the structure in question.

- 4.8.3 Where necessary the designer and manufacturer should provide drawings, laminate lay-up and production details to help the inspector to confirm the suitability of a particular inspection technique and to help interpret the NDT results.
- 4.8.4 Marine yacht surveyors provide services such as routine visual inspection of yacht structures. Those with suitable qualifications can also carry out more specialised inspection work such as ultrasonic NDT.
- 4.8.5 Care should be taken to ensure that the NDT inspectors are competent (i.e. have the relevant training and certification for inspection) and have been specifically trained to inspect composite materials (see Section 5.1).
- 4.8.6 Depending on the specific method used, inspection companies should be asked to provide as much quantitative data on any detected anomalies or defects as possible, including:
- a. Specific location of indications referenced to known datum point.
 - b. Sizing information on the extent and depth of indications in the laminate.
 - c. Thickness variations in laminate (ultrasound).
 - d. Unexpected localised areas of high signal attenuation (ultrasound).
- 4.8.7 The ability of the inspection company to fully quantify and evaluate the inspection results will depend on their familiarity with the design of the spar under inspection and the amount of supporting information provided by the designer and manufacturer including the availability of test laminates and reference samples.
- 4.8.8 It is important that the results are correctly presented by the inspection company to provide a good quality inspection report such that both the designer and manufacturer can easily interpret the information for their own use. This may include use of the NDT results and defect evaluation and sizing analysis to assess the effect of the defects on the localised area of spar laminate and the global structural integrity of the spar (see Section 6).
- 4.8.9 The responsibility for the interpretation of inspection results and the remedial action required will normally lie with the spar designer who will consult with the spar manufacturer and other parties such as composite structural engineers, material test laboratories and Classification Societies.
- 4.8.10 Where the NDT results suggest that quality of the laminate is suspect (e.g. excess porosity or voiding) additional visual analysis (micrographs of porosity) and mechanical analysis (interlaminar shear strength) of the laminate is recommended (see Section 6). This can be achieved by utilising production core samples (see Section 4.3.3) or taking new core samples from the spar with guidance and supervision from the manufacturer and designer. Cut-out areas can then be repaired and checked with NDT as required (see section 4.6)
- 4.9 Where to inspect
- 4.9.1 Visual inspection of a stepped spar can be made by a yacht surveyor to assess the general condition of the structure.
- 4.9.2 Limited handheld ultrasound NDT inspection can also be carried out on a stepped mast by an inspector with suitable experience of performing inspections aloft.

- 4.9.3 In most cases investigation with a full NDT method will be required with the mast un-stepped in order to develop a general inspection strategy.
- 4.9.4 The areas of the mast to be inspected should be clearly marked out by the surveyor or detailed drawings provided by the designer to enable the inspection company to plan the investigation and correlate measurements with the design drawings.
- 4.9.5 The locations to be inspected should be related to an agreed datum position on the mast and properly referenced in subsequent reporting.

4.10 Specific guidance on spar structures utilising composite sandwich materials

- 4.10.1 Whereas most carbon fibre spars are formed from relatively thick monolithic laminate the use of sandwich or cored structures is becoming more common and is already widely used for booms and in some applications such as wing-masts. In a sandwich material a lightweight core such as Nomex™ or Rohacell™ is placed between thin laminate skins. In a sandwich structure the overall strength and integrity of the component is largely derived from the bonding at the skin to core interfaces.
- 4.10.2 Any inspection methods that are employed to evaluate these types of structure must be shown to be sensitive to the skin to core interface bonding. For example many ultrasound methods are only capable of testing the laminate skin and not the skin to core bond. Typical methods suitable for testing skin to core bonding and core integrity include tap-testing, mechanical impedance, acoustic pitch catch, shearography and thermography techniques (see Section 5.2)

4.11 Guidance on related composite materials and yacht structures

The methods and inspection practices which apply to spars are in many circumstances applicable to other carbon structures found on yachts. In some cases these secondary structures will form some load bearing or structural role in the integrity of the primary spar.

- 4.11.1 On the main hull structure there may be other areas of carbon laminate that relate to the integrity of the main spar including:
 - a. Load areas on the hull for runner attachments and shroud plates.
 - b. Internal reinforcing beams around the mast foot area.
- 4.11.2 The design of these areas may vary greatly with different builds and may be fabricated from monolithic and cored (Nomex™, foam, balsa) laminates. In these cases extra supporting information from the designer and manufacturer will be required and a specialist expert in carbon fibre laminate inspection may be required in order to develop a suitable inspection procedure.
- 4.11.3 Carbon laminate may also be used on high performance rudder stocks, rudders, keel fins and dagger boards which can be inspected using ultrasound and other NDT techniques that are routinely used on spars and booms.

5 Non Destructive Inspection Techniques

5.1 Certification and standards

5.1.1 There are currently no published standards which specifically cover the non-destructive inspection of carbon fibre laminates. Verified procedures exist which have been developed by manufacturers and end-users of composite materials, primarily for the aerospace industry. These procedures and the companies that practice them can be employed in the marine composites sector. When deploying NDT on a carbon fibre spar the inspection company should be required to demonstrate the following:

- a. That the inspection technique has been shown to be suitable for the inspection of carbon fibre laminates using reference specimens with known representative defects.
- b. That an independently approved inspection procedure for carbon fibre laminates is being followed¹.
- c. That the inspection equipment has a valid calibration certificate.
- d. That the operator can demonstrate they hold a valid training and examination certificate (from an approved training school) and are part of an approved employer or employee based certification scheme for the technique being used (visual inspection, ultrasonic). Evidence of certification will help ensure that the operator has significant experience of inspecting composites. Where formal evidence of training and certification is not provided the NDT operator must clearly demonstrate that they have suitable expertise and experience in the inspection method when applied to composite materials.
- e. That the inspection company has an adequate knowledge of carbon fibre composite spar product technology including its manufacture, installation and operation.

5.1.2 There are internationally recognised organisations for the training and certification of inspection personnel for visual and ultrasonic inspection. Most inspection companies that offer a standard inspection service for carbon fibre laminates will be able to provide suitably qualified personnel. Two schemes that are employed throughout the world for the training and certification of non-destructive testing personnel are operated by the British Institute of NDT (PCN, employee based certification) and the American Society for Nondestructive Testing (ASNT, employer based certification)².

¹ Most inspection companies employ an independent “Level III Service Provider” (as required by the ASNT and PCN schemes) to approve the procedures that are being followed by the NDT inspector.

² See certification sections at www.bindt.org and www.asnt.org.

5.2 Inspection types

The following table summarises the commonly used inspection techniques for carbon fibre composite materials. This is for guidance only and the suitability of a particular technique for an inspection will depend on many factors including the type of material, the equipment used and the skill and experience of the operator. It is recommended that the sensitivity of a technique to a particular defect or anomaly is proven by the inspection company on representative test sample before an inspection is undertaken.

Test type	Defect/anomaly type				Operation consideration		
	Porosity	Voids	Adhesion	Impact	Skill	Cost	Coverage
Acoustic (tap test)		✓	✓	✓	Low	Low	Single point
Sonic (Resonance)		✓	✓	✓	Med	Low	Single point
Shearography		✓	✓		High	Med.	Large area
Thermography			✓	✓	Med.	Med.	Large area
Ultrasonic: A-scan	✓	✓	✓	✓	Med	Low	Single point
Ultrasonic: C-scan	✓	✓	✓	✓	Med. to high	Low to med.	Large area
Visual (may require removal of coatings)	✓			✓	Low	Low	Large area

Further information on damage and defect types is given in Appendix A and an example of the capability of ultrasonics for impact detection and further details on the various inspection techniques are provided in Appendix B.

5.3 Inspection procedures

Ultrasonic inspection is the most commonly used non-destructive inspection technique and a typical inspection procedure that would be followed by a suitably qualified inspector or surveyor is provided below for guidance and to provide an example of best practice. Similar procedures should be followed for other inspection techniques where appropriate.

5.3.1 Equipment and calibration

- The equipment used must be suitable for the ultrasonic examination of carbon fibre laminates with functions such as time corrected gain (TCG) used with ultrasound probes with contact faces or delay lines suitable for carbon fibre.
- The calibration of the equipment and function of the ultrasound probes must be checked on a known calibration sample manufactured from a carbon fibre laminate, preferably of the same material as the spar to be inspected.
- This calibration must then be checked on several locations on the spar to ensure that the measurement sensitivity, velocity calibration and ultrasound operating frequency is suitable. Typically this is performed at the foot of the spar and near cut outs where the thickness of laminate can be directly measured with callipers and the ultrasound readings verified.
- Adjustments to the calibration must be noted and recorded on the instrument when possible. During, and following the inspection the instrument calibration should be checked again to ensure that the equipment setup has not deviated during the inspection.

5.3.2 Detailed inspection planning

- a. The areas of the spar to be tested must be marked and accurately referenced to a known datum on the spar, for example the mast foot.
- b. Within each of the inspection areas the type of inspection to be carried out must be noted (e.g. thickness check, delamination check, porosity check) and a suitable scan path (lines of movement of the ultrasound probe over the structure and the spacing between consecutive lines) selected. The scan path and probe ultrasound probe diameter should be selected to ensure that the minimum defect size, usually specified by the spar designer/manufacturer, can be detected. Typically this is for defect sizes in the range of 6 mm x 6 mm (36 mm²)_through to 20 mm x 20 mm (400 mm²).

5.3.3 Location and referencing of measurements

- a. Thickness measurements on the structure should be confirmed by comparing them to engineering drawings and the laminate specification documentation for the spar.
- b. When there are uncertainties about whether a recorded thickness measurement is part of the normal spar structure or is a defect, the technical documentation for the spar should be consulted. Additional measurements should be made to confirm the reading, often these can utilise the symmetry of the spar structure; for example suspicious readings on a port panel can be compared with readings from the same area on the starboard panel.
- c. Mapping and referencing of defects must be done in such a way that they can clearly be re-identified by another person to effect a further inspection as part of a monitoring process or to make a subsequent repair.
- d. The defect location and size information should be recorded and marked on the structure, where possible screen captures or digital records of the ultrasound signals at the defect location should be saved to disk.
- e. The position of the defect relative to spar datum should be recorded and photographs of the indication made.

5.4 Reporting

5.4.1 A thorough report shall be provided to enable the owner, designer, manufacturer of the spar and any Classification Society (or regulatory authority) to make informed decisions on how to act on the inspection results. An example report format is provided in Appendix C.

5.4.2 The quality of the reporting should be such that another operator will be able to repeat the inspection with similar equipment and following the same inspection procedure obtains the same results.

5.5 Record keeping

5.5.1 In addition to the supplied report the inspection company should keep electronic copies of the instrument settings and recorded data and any other supporting documentation regarding the inspection which can be referred to for future inspections.

Part 2: Detailed Assessment of Damage and Defects

6 Structural Analysis to Assess Effect of Damage

6.1 Introduction

In most cases the NDT methods described in Section 5 and the operator performing the inspection will be unable to quantify what the effect of a particular damage or defect type will be on the structure. In some cases the safety and knockdown factors used in the original design process will provide some guidance on what level of damage or defect is tolerable without risking the structural integrity of the component. In most cases a repair strategy will be put in place by the designer and manufacturer to remove the defective material and replace it with new material.

In some cases a repair may not be viable due to reasons of complexity or cost. In this situation the use of structural analysis techniques to assist in identifying the effect that damage or defects may have on the structural integrity of the spar can be considered.

6.1.1 The analysis for defect assessment is an extension of any structural analysis conducted during the design phase. There are two aims for the analysis:

- a. To assess the effect of the damage on the overall performance of the spar based on stresses, strains, displacements and loads on the surrounding structure.
- b. To identify if the damage present will or could cause, or will grow to cause, a degradation of structural integrity requiring further inspections or repair.

6.1.2 Structural analysis may comprise an aspect of experimental testing to supplement and validate any numerical modelling.

6.2 When should analysis be conducted

Yacht spars are currently designed with suitable safety factors to accommodate variations in material properties. Damage tolerance methods involve the design of a structure to continue to operate safely with likely damage present.

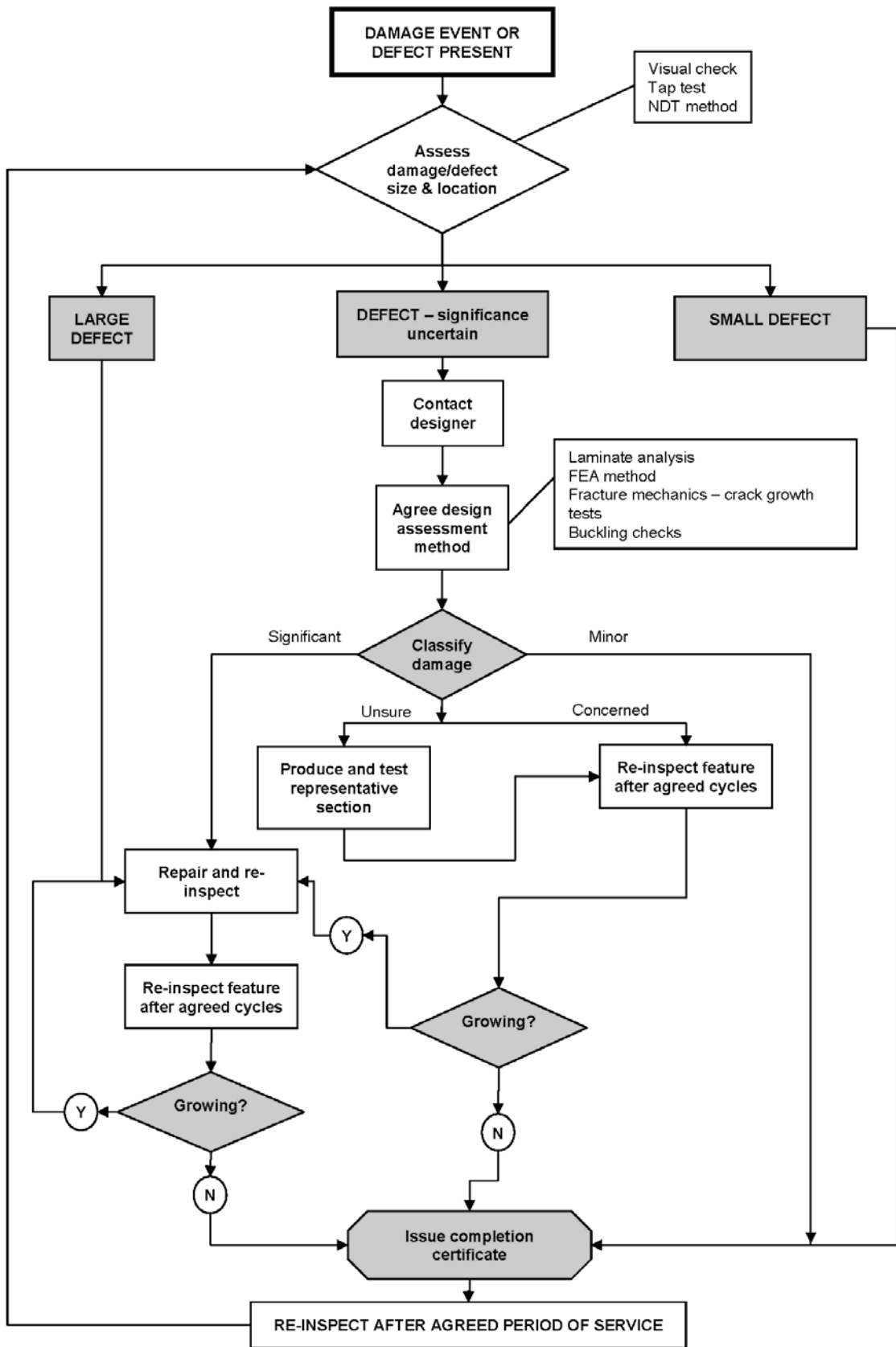
6.2.1 Analysis of a spar should be conducted when inspections (detailed in Section 5) identify that damage or defects are present and a recommendation is given by an authoritative individual or body that the structural integrity of the spar is in doubt.

6.2.2 The structural analysis should be used to give guidance on whether:

- a. The spar can continue to be used normally.
- b. The spar can be used with restricted sailing conditions.
- c. The spar should be repaired.
- d. The spar should be replaced.

6.2.3 The spar designer should have carried out a substantial structural analysis before the spar was manufactured and if possible this should be accessed: it will contain essential information and should serve as a good basis for any further analysis that is required.

6.2.4 A flow chart which summarises the decision processes following the identification of damage or some other defect is given below.



6.3 Summary of analysis types

6.3.1 A number of methods of structural analysis are available to the specialist carrying out the work including:

- a. Finite Element Analysis method (FEA) which is the most commonly used numerical method for structural analysis.
- b. Beam Analysis methods are also used extensively.
- c. Laminate Analysis (also known as classical lamination plate theory) is an additional analysis for simple geometries and can be used with composite laminate failure criteria to determine ply cracking and ultimately laminate failure.

6.3.2 For evaluating the effect of defects in spars, the Finite Element analysis method is the predominant method because of the potential complexity of the problem.

6.4 GL “Global Analysis”²

6.4.1 In order to simulate the structural behaviour of a rig, a Finite Element Analysis of a rig model consisting of beam and truss elements is performed. This model represents the global characteristics of a rig system. For any particular rig, the real geometry and stiffness of major global components such as mast tube and standing rigging is replicated in the model. Computations include pre-tensioning, load simulation of in-service loads such as quasi-static sail loads and pertinent structural accelerations.

6.4.2 The results of the GL analysis include the global response (deflections and bend curves) and global loadings, all six sectional forces and moments in the mast and spreader beams and tensile loadings in standing rigging for each of the calculated load cases.

6.4.3 The results of the GL analysis can be post-processed to calculate stresses and strains at a sufficient number of points around the circumference of a spar section. These results can be superimposed with results from a local structural analysis or local damage assessment. This “local” analysis will give rise to the structural response of an area of limited size, such as an impact damage zone, a zone of local delamination, a joint, etc.

6.5 Finite element analysis

6.5.1 The FEA tasks should be performed by qualified engineers experienced in modelling composite materials.

6.5.2 Modelling experience is required to ensure the relevant coordinate system is correctly used, i.e. global, ply, laminate based, or element based. The approach used should be documented by the analyst.

6.5.3 Whenever possible, recognised, commercial FEA programs should be used which have been validated during their commercialisation.

² Guidelines for Design and Construction of Large Modern Yacht Rigs, Edition 2002, Germanischer Lloyd AG, Hamburg

6.5.4 If a commercial code is not used, then any results shall be validated against relevant analytical solutions or experimental test results or benchmarked against other commercial FEA programmes.

6.5.5 A decision to use 2D shell analysis or 3D solid analysis methods should be made depending on the level of significance that through thickness stresses have on the investigation. The approach and reasons for method selection should be documented by the analyst.

6.6 Incorporating damage and defect

6.6.1 Incorporating damage in the structural model depends on the level of detail of information that is required, on whether the modelling is global or local, and on the nature of the damage.

6.6.2 Damage can be incorporated into global models by degrading the overall material properties of the finite elements within the damaged region. The amount of the degradation of properties may be identified from a local model. This can include:

- a. Discrete modelling of the damage, or
- b. an experimental test of the damage region giving reduced overall laminate properties, or
- c. an estimate can be made assuming a worst case scenario and utilising laminate analysis to give effective modified laminate stiffness.

6.7 Global to local analysis

6.7.1 The response of the spar should be evaluated on the global or local level, or both, depending on the nature of the defect being examined.

6.7.2 Global analysis should be used to identify the potential for failures such as global buckling, shear stiffness of spar tubes, thin wall buckling and other stability evaluations used in the design process.

This guidance does not cover stress analysis at the discrete fibre and resin level, but provides conservative approaches for engineering principles including allowable laminate strains. Local analyses are used for identifying local stresses including through thickness (interlaminar) or modelling discrete damage such as delaminations. Further information on this is given in section 6.8 below.

6.8 Local modelling of damage and defects

Defects within composite spars can arise from manufacturing errors, installation and handling events or from service. As designers seek to develop higher performance structures, the effect of defects becomes more significant. At this point the ability to locally model and assess defects will be of great help to the designer. Such information can allow the designer to consider the local effect of defects as part of the structural analysis process described in earlier Sections. Having established what defects are significant, suitable inspection procedures for their detection and monitoring can be implemented as described in Sections 4 and 5.

Current commercial models cannot discretely model impact damage or defects such as disbonds and the following approaches should be taken:

- a. An experimental approach.
- b. Modelling approach using a simplified representation of the damage.

Either or both methods should be evaluated to assess the significance of the impact damage and these are covered in the following Sections.

6.8.1 Experimental methods for assessment of impact damage

Experimental methods involve conducting impact tests on sections cut from a similar spar, if available, or on specially manufactured test coupons representing the area within the spar containing the damage.

Similar boundary conditions and indenter type, velocity and mass should be used to closely represent the impact on the spar. If these are not known, then impact damage tests should be conducted and the spar parts ultrasonically inspected to ensure the damage maps are similar in the laboratory based lab tests to that observed in the spar.

Once the test coupons have been shown to have representative damage, the loss of mechanical properties must be identified.

The experimental data should be then analysed to determine the change in stiffness of the impacted and damaged sections. This data can then be used in a global model of the spar to help quantify the effect of the local impact damage on the global performance of the spar.

6.8.2 Modelling approaches for impact damage assessment

The modelling approach is used to produce a simplified local model of the damage in the local geometry of the spar. The damage can be simplified by assuming a single “predominant” delamination within the thickness.

An interlaminar fracture mechanics approach can be employed to determine if this predominant delamination will grow, and if so to what extent, during the loading applied to the spar. From this information, it will be possible to identify if the spar can be continued to be used, needs repair, or should be replaced.

The modelling results should be verified by the experimental test coupon approach if both approaches are to be used.

6.8.3 Delaminations, other than from impact events

These may be evaluated by local models of the damaged area imposing the loads from the global analysis.

6.8.4 Incorrect bonding

These may be treated in a similar manner to delaminations and a fracture mechanics approach taken to identify if this defect will grow in service.

6.8.5 Incorrect lay-up.

In some instances errors can be made in the lay-up of the spar or plies can shift during curing. This defect is a quality control issue and can result in global stiffness being different to that intended leading to unplanned stresses or additional amounts of bend-twist coupling if the laminate becomes un-symmetrical. The effect of this defect can be identified using the modelling techniques used in the design process, where the misalignment is discretely modelled and the overall performance and behaviour of the spar evaluated.

6.8.6 Misaligned ply drops for local reinforcement areas.

The use of global-local modelling, with local models discretely modelling the new locations of the moved plies can be used to determine any effect of this local defect on the overall performance and behaviour of the spar.

6.8.7 Lightning strike damage

In some cases, the lightning will char the outside of the spar and this must be modelled as material loss in that local area, the extent of which can be identified using inspection methods.

6.8.8 Other types of damage

Other damage modes may exist in other parts of the spar that have not been covered above. These may include wear at highly loaded holes, fretting at deck level etc. These should be treated on a case-by-case basis using the approaches discussed above analysing the repair on a local and global level.

6.9 Relating defect assessment to repair, monitoring and inspection strategies

The results from the testing and analysis methods above should be used to give guidance on the defect significance and should instigate the following steps:

- a. Ignore the damage, because it is below a threshold value and will not grow within the normal service life, or
- b. establish an inspection plan to monitor the damage to ensure its growth is within acceptable parameters, or
- c. limit the service loads on the spar, or
- d. initiate a repair programme to bring the spar back to its original properties, or
- e. declare the spar as unserviceable and replace.

Further details on damage and defect types and a tabulated risk assessment methodology are given in Appendix A. A risk assessment (see Section 4.1) will help the user assess the potential impact of damage and defects on the structural integrity of the spar.

Part 3: Structural Health Monitoring

7 Structural Health Monitoring

7.1 Introduction to fibre optic sensing

Structural health monitoring is now common place in market sectors where high demands are placed on composite components including marine spars, wind turbine blades, aerospace spars and oil and gas pipelines.

Fibre optic load sensing, which can be simply retrofitted, is a recent monitoring technique based on optical telecommunication technology. Early development projects demonstrated that the technology could be simply retrofitted to or embedded in composite structures to give reliable, absolute strain data in severe environments.

Commercial fibre optic sensing systems for deployment on yacht spars comprise of fibre optic arrays, low cost interrogation systems and enhanced software to enable them to be extensively employed in composite components to monitor strain in real time.

7.2 Measurement capability

Fibre optic sensing systems measure the strain at discreet points (sensors) along the fine (125 micron diameter) fibre optic cable. Each sensor comprises a short length, usually 2 to 3 mm of the fibre optic cable which has an optical interference pattern "written" into it by laser to create a diffraction grating.

As this sensor is strained (i.e. extended or compressed) it changes its light transmission/reflection characteristics in such a way that the wavelength of the light is changed. This change in wavelength is directly proportional to the strain the cable is experiencing at that point. By measuring this wavelength the strain is determined.

Multiple sensors can be placed in a single cable and hardware is available to run several channels (or cables) simultaneously, thus permitting networks of tens or even hundreds of sensors to be formed in cables of several hundred metres in length. The hardware comprises an electro-optical interface box (about the size of a book) which can be coupled to laptop or PC.

These systems capture data at rates of up to 500 Hz, enabling real time load data to be monitored. The data can be handled conventionally through dedicated software to provide real time strains or provide the data records for long-term structural health monitoring.

7.3 Benefits to the designer and owner.

A fibre optic strain sensing systems have a number of features that make it particularly suitable for maritime applications including:

- a. Low mass (the fibre optic cable weighs very little, only a few grams per km length).
- b. The fibre optic cable simultaneously acts as carrier and sensor (multiple sensors in a single cable are possible).
- c. The fibre optic is not affected by electromagnetic radiation nor by the maritime environment.

- d. the fibre optic is inert and by including it in the laminate it can be totally protected from physical damage.

The sensor measures absolute wavelength (and thus absolute strain) and therefore does not need recalibration.

The use of novel fibre-optic based strain monitoring systems opens new opportunities for structural and performance measurement, particularly in composites where the fine fibre-optic cable networks can be embedded within the structure to provide ongoing, absolute and repeatable data.

7.4 Applications in the marine sector

To date fibre optic sensing systems have been deployed for a wide range of marine vessels including super-yachts, Americas Cup racing yachts and large merchant ships. Applications of fibre optic sensor in the marine sector include:

- 7.4.1 Design validation - comparing the theoretical values generated from FEA models with data from model scale testing of structural components.
- 7.4.2 Structural load indication - structural load indication during sailing, permanently connected into the sailing system controls to give a clear indication of loads on each subject spar, expressed as a percentage of allowable load.
- 7.4.3 Trim optimisation - real time optimisation of the rig by providing drive and drag force information to the operator. The sensor arrays and sensors are positioned in order to give clear load read-out values to the operator indicating the amount of load expressed as an allowable percentage on a simple rig graphic located on the rig control console.

Data from the rigs on board will provide the operator with real load against design limits and background data for design corroboration and ongoing monitoring. Driving and heel force figures from each spar will be presented in real-time.

- 7.4.4 Structural health monitoring - structural health monitoring is the long-term measurement and analysis of the strains and loads within a system, with the purpose of minimising critical failure, operational downtime, and preventative maintenance scheduling.

This provides an early warning mechanism for structural component damage, thereby increasing safety and preventing complete or part degradation and critical failure of components.

Ongoing data recording can provide the basis of post event evaluation of high load cases and could be used to help ascertain the probability of damage.

7.5 Installation in existing spars – retrofit installation

The most versatile methods for installing sensing fibres in a structure are to (i) surface mount or (ii) embed an optical fibre. Materials and methods have been developed to enable optical fibres to be embedded directly into a composite structure with minimal effect on the structure. Optical sensors in this form may be bonded to almost any material including aluminium, steel and composite structures.

For quick and easy installation of individual sensors, ready-made patches are available and can be applied to the inside or outside of composite structures using conventional composite manufacturing techniques.

7.6 Specifying for new spars

Optical fibres lend themselves to integration within composite structures during the manufacturing phase due to their small size and fibrous nature. The fibre can be placed between laminate layers and is bonded into the structure when the resin is subsequently applied and cured. In its bare form optical fibre requires careful handling by competent persons to prevent damage during installation.

Embedding the fibre during manufacture enables the sensor to be placed exactly where required by the designer for optimum information.

Part 4: Further information

8 Further Information

The following have contributed to the preparation of this document:

Richard Freemantle – Wavelength NDT and Marine Results
Peter Hansen and Rod Martin – MERL
Kenneth Hay – EMCL
Hasso Hoffmeister – Germanischer Lloyd
Dan Jones – Gurit
Phil Rhead - Insensys

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<http://www.merl-ltd.co.uk/msi-spar>

The following Technical Notes can be downloaded from the project website at the following address:

<http://www.merl-ltd.co.uk/msi-spar/tech-notes.shtml>

These cover the following subjects:

“GL Approach to Structural Analysis”
“Fracture mechanics in Structural Composites”
“NDT Inspection Certification”
“Structural Analysis and Defect Assessment”

Appendix A – Typical Damage and Defects

A.1 Impact damage

Impact damage is a complex combination of matrix cracks, delaminations and fibre breakage (see Appendix B for diagrams showing typical delamination patterns). The extent of the damage is dependent on many factors including the impactor type, its velocity and mass and the structural stresses in the vicinity of the damage.

A.2 Delaminations, other than from impact events

Delaminations may arise from high interlaminar stresses caused by geometry such as the opening of curved sections (e.g. rear quarter of a “D” Cross-section spar) or by and excessive loading. Delaminations can also occur over time at areas where there are stress singularities (e.g. from dropped plies, attachments, etc.) or at areas where the incomplete removal of ply release film during production has occurred.

A.3 Incorrect bonding

Adhesive secondary bonding may be used in several areas including the joggle joint, the gooseneck and secondary reinforcements. The predominant defects with bonding include poor adhesion (difficult to detect with NDT) or incomplete filling of the adhesive bondline.

Another defect that may occur with adhesive bonding is the incorrect properties of the adhesive being achieved, from incomplete curing or the presence of porosity. This is a fundamental quality control defect and is accounted for by a suitable reduction in the strength and properties of the adhesive.

A.4 Incorrect lay-up.

In some instances errors can be made in the lay-up of the spar or plies can shift during curing. This defect is a quality control issue and can result in global stiffness being different to that intended leading to unplanned stresses or additional amounts of bend-twist coupling if the laminate becomes un-symmetrical.

A.5 Misaligned ply drops for local reinforcement areas.

Often additional plies are used on the internal surface of a spar to locally reinforce areas for example where there are holes or attachments. These plies can sometimes move during curing and the end position is different to that of the original design.

A.6 Lightning strike damage

Lightning strikes are a relatively common in-service hazard and may result in damage. The damage may often appear analogous to an impact damage where the lightning strikes or exits the spar.

A.7 Other types of damage

Other damage modes may exist in other parts of the spar that have not been covered above. These may include wear at highly loaded holes, fretting at deck level and transit damage.

A.8 Example tabulated risk assessment of structural effect for various damage and defect types

This table is a model which must be amended for each yacht as each of the headings will vary in terms of the component, and the probability and significance of the respective fault. Some specimen entries have been put in as a guide.

R = Risk Factor = Probability x Significance, with Low = 1, Medium = 2, High = 3.

Component	Fault	Impact Damage			Overload			Delamination			Joint			Layup deficient			Lightning strike		
		Prob	Signif	R	Prob	Signif	R	Prob	Signif	R	Prob	Signif	R	Prob	Signif	R	Prob	Signif	R
Shrouds & all loaded holes with doublers		Low	Med	2	Med	High	6												
Masthead		Low	Med	2															
Spreaders		High	Med	6															
Halyard exits (all unloaded holes)																			
Doublers																			
Axial mast tube (joggle) bond																			
Sleeved tube joints																			
Gooseneck (+other lower mast swivels)																			
Deck to mast foot																			
Boom																			
Poles																			
Other monolithic car-bon (rudder stocks, swing keel mounting etc)																			

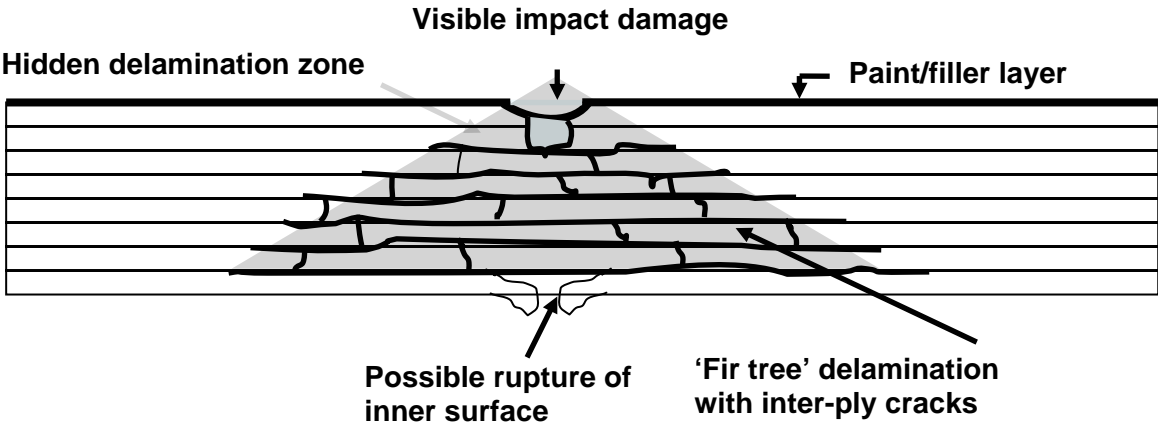
Appendix B – Inspection Technologies

B.1 Ultrasonic A-scan

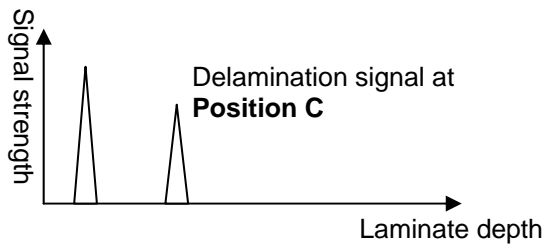
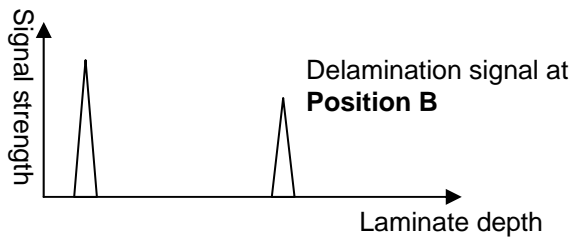
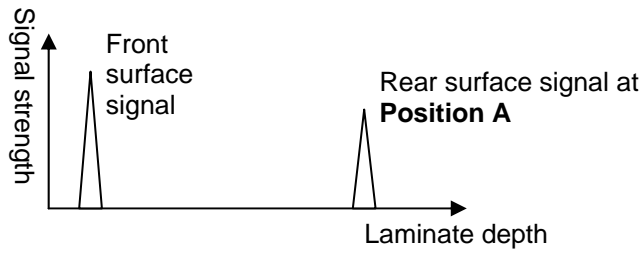
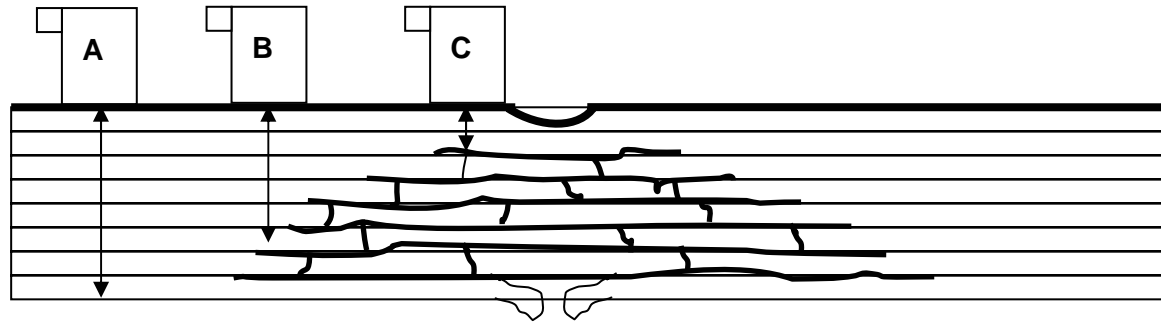
This is the most widely used technique for the inspection of most monolithic carbon fibre composite materials. The technique sends pulses of ultrasound into the structure which are reflected back by surfaces and interfaces in the laminate. Defects in the laminate such as voids and delamination reflect the ultrasound pulse back at different times providing a means to locate and measure the depth of the defect.

B.1.1 Example A-scan inspection of impact damage

The following diagram shows a typical cross-section view of impact damage in a monolithic carbon fibre laminate showing the smaller visible impact damage zone and larger hidden delamination zones spreading in a characteristic 'fir tree' shape.



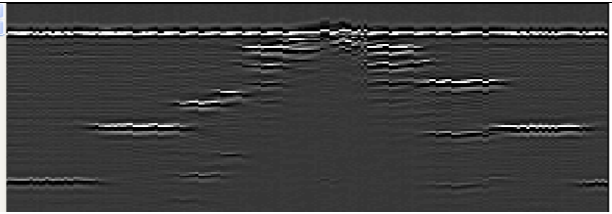
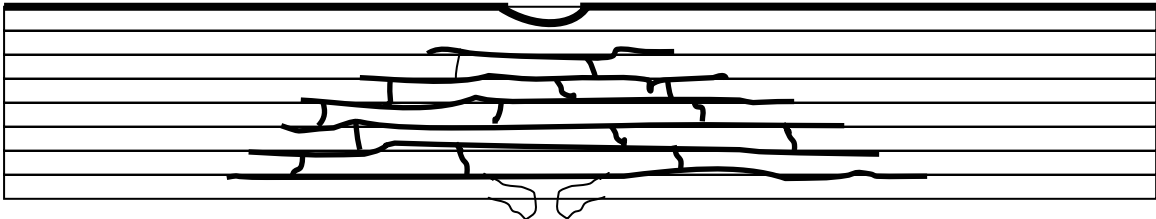
Examples of ultrasonic signals from different locations over the impact zone are shown below.



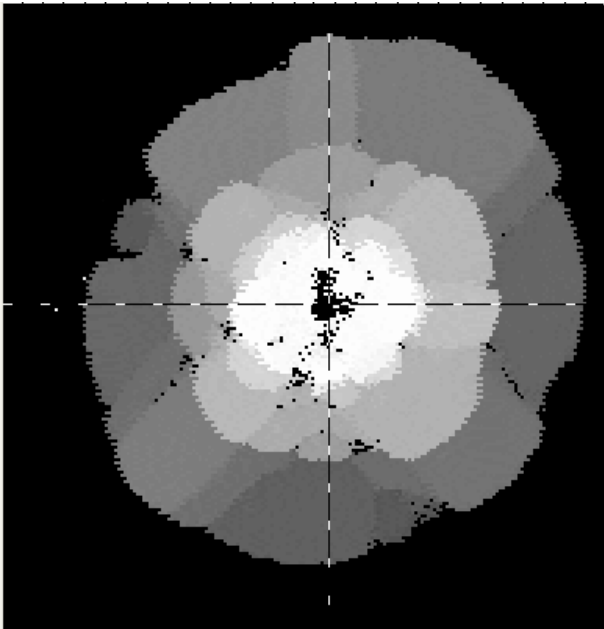
Although a point measurement technique, hand mapping of the structure can be used to provide a good assessment of the location and extent of defects such as large voids, delaminations and lack of bonding. The ultrasound signals are also sensitive to local variations in the laminate quality such as porosity and dry fibres which can be detected by observing reductions in signal amplitude of the rear surface signal.

B.1.2 Ultrasonic B-scan & C-scan

B-scan images are similar to medical ultrasound images and provide a cross-section view of the laminate. C-scan images provide a plan-view of laminate in the form of a colour thickness map. These methods are becoming more widely used as techniques and equipment developed for the Aerospace sector enters the Marine market. Some service providers are routinely using C-scan methods for spar inspection and the technique provides large area colour thickness maps of the laminate showing the expected changes in laminate thickness around fittings and unexpected thickness changes due to voids, delaminations and impact damage. Bonding of reinforcement areas can be monitored. The following figure shows how the impact damage zone relates to the B-scan and C-scan ultrasonic views.



B-scan cross-section view of delamination zone



C-scan plane view of delamination zone

B.2 Tap testing

Tap testing is commonly used for testing of thin skins bonded to a core material. Results can be very operator dependant, relying on their skill and experience with a particular structure developed after many inspections. Instrumented tap testers provide a calibrated measurement capability and are less operator dependant. Tap testing techniques rely on detecting changes in local stiffness caused by the delamination of the core material to the thin skin. For this reason thicker laminate structures (typically greater than about 4 mm) are more difficult to test as the changes in local stiffness caused by skin to core delamination are smaller and less easy to detect.

B.3 Sonic

In addition to tap testing other acoustic methods include sonic resonance testing, vibration testing and mechanical impedance testing which depend on exciting vibrations in a specimen and then measuring the change in properties of the vibrations, e.g. resonant frequency, decay time, etc.

B.4 Shearography

This is a laser optical technique which uses an interferometer to measure the surface strain on the laminate. The method measures strain concentrations caused by defects in the laminate, often a vacuum hood containing the optical sensors is placed over the structure to help increase the sensitivity of the measurement. The technique is well established and widely used for the inspection of thin laminate (typically less than 4 mm) and cored composites. Interpretation of results requires a skilled operator and inspection of complex geometries (curved sections) or corners can be difficult.

B.5 Thermography

This is a thermal imaging technique which can be used to detect near surface delaminations and large voids in composites on flat sections. For reliable detection an active thermography system is required which uses a heating source (usually a flash lamp) to momentarily heat the structure in the region of interest. The thermal camera then measures the emitted heat from the structure which will be higher in regions where there are insulating voids and delaminations in the laminate. Although not commonly used in marine inspections there may be specific applications that would benefit from this technique. As the technique relies on thermal diffusion through the material the imaging and detection capability for a given defect size is depth dependant. Thermal imaging methods can accurately size the extent of a defect but are unable to provide information on the depth of the defect within the thickness of the laminate.

B.6 Visual inspection

Visual inspection should not be underestimated and can be used to make general assessments of degree of porosity in localised areas by examining the edges of cut-outs at halyards and spreaders and at the mast foot. Examination of adhesive bonds is possible by looking for squeeze-out on bonds (endoscope can be used for internal joints). Visual assessment of impact damage is difficult due to the unpredictable nature of delamination patterns deeper into the laminate, however potential signs of internal damage may be seen on surface coatings and by cracking of fillers etc around fittings.

Appendix C – Format for Typical Inspection Report

C.1 Inspection reports should follow a similar format to that given below and contain detailed information on the operator certification, equipment, inspection procedure used and detailed information on the results found and where on the structure they were obtained.

C.2 The report should provide sufficient information to allow repeat inspection to be carried out to the same standard by another inspector, for example when the spar is examined for in service deterioration in another part of the world.

C.3 Typical report format:

C.3.1 Summary of inspection and findings

- 1 page summary detailing methods used, key findings and recommendations.

C.3.2 Equipment used and operator certification

- List of equipment and sensor types.
- Detail operator certification and training (e.g. level 1, level 2).

C.3.3 Calibration procedure

- Procedure used to check equipment operation.

C.3.4 Inspection strategy and procedure followed

- Procedure used to calibrate to the structure (velocity, inspection frequency).
- How the structure is marked and referenced to datum points.
- Procedure for inspection (e.g. number of areas scanned, scan resolution).

C.3.5 Results

- Images of results (e.g. extent of damage indicated on structure).
- Example typical data and equipment settings.
- Defect evaluation and sizing

C.3.6 Conclusions

- Key findings.
- Recommendations.