Marine Composites

Webb Institute

Senior Elective

Non-Destructive Evaluation

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Inspection Background Information

- Determine service life
- Age of vessel and percentage of time used
- Waters sailed
- Ownership history

Safe Haven Marine pilot boat (left) and boat advertised as "used very little" (right)

1958 Winner fiberglass runabout

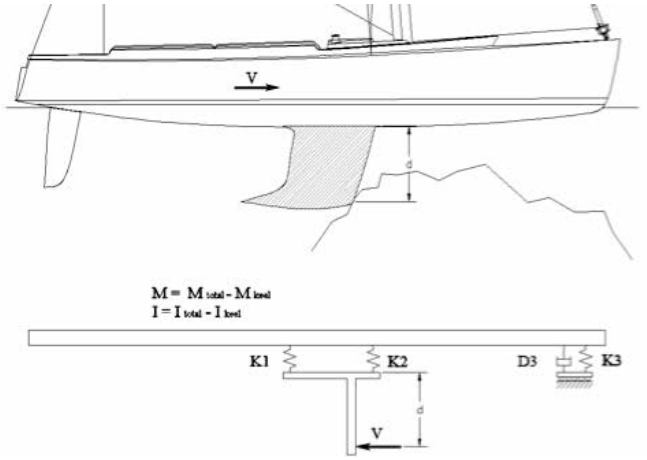
Defects Detected by NDE Methods

- Bonded joint failures
- Delaminations
- Moisture ingress
- Core shear failures
- Skin-to-core disbonds
- Voids
- Impact damage

Determine Damage Sources

- Collision
- Fatigue
- Extreme environmental conditions
- Design inadequacy
- Manufacturing problem
- Grounding
- Poor maintenance
- Thermal (fire, lightning, extreme freeze/solar)

Boat collision reconstructed by Miles Beam funded by the US Coast Guard [www.boatcrash.com]

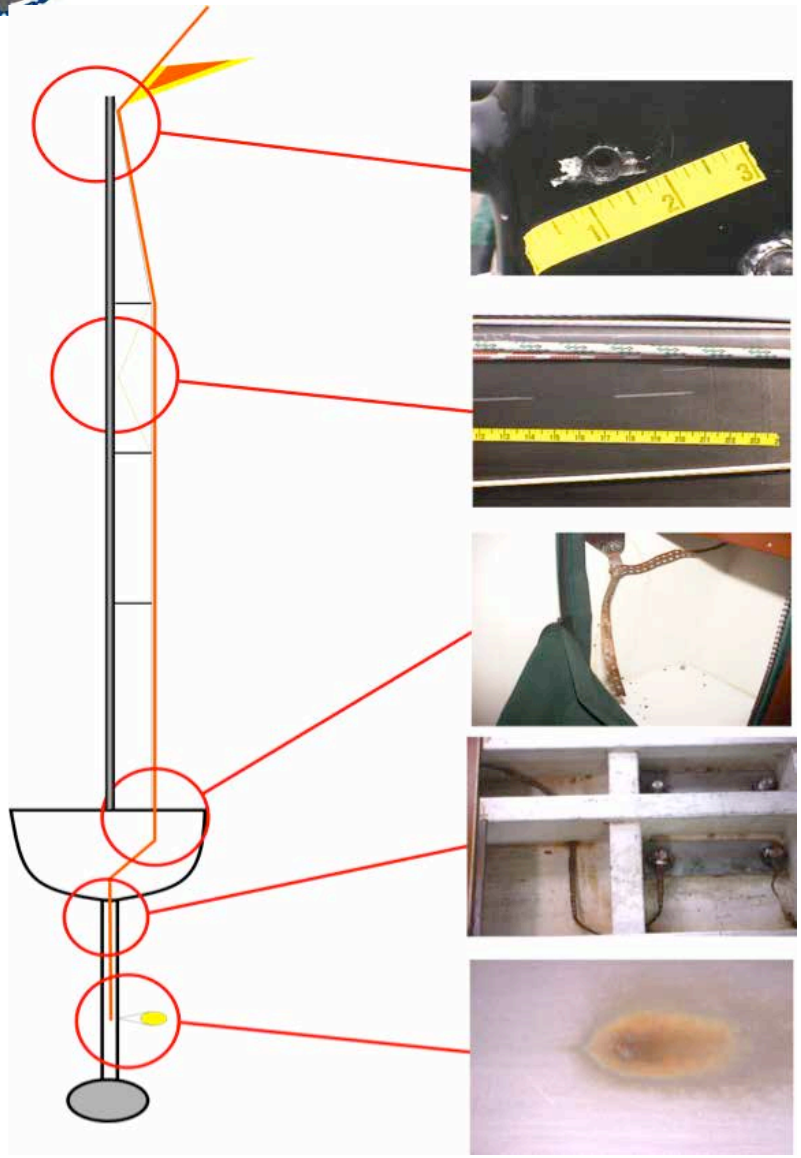


Schematic to illustrate grounding loads acting on hull [Paul Coffin, 2003]

Visual Inspection

- Visual inspection should always be the first NDE method used, even in conjunction with other methods
- Access and lighting are critical
- Digital cameras, magnification devices and borescopes can be helpful
- Use boat symmetry to highlight anomalies
- Establish a methodology that begins with overall inspection and proceeds to close-up inspection, especially in problematic areas

External Visual Inspection



Path of lightning from entry to discharge

- Geometry (stress concentrations)
- Waterline
- Structural distortions
- Surface appearance
- Cracks
- Blisters

Internal Visual Inspection

Bulkhead separated from stiffener

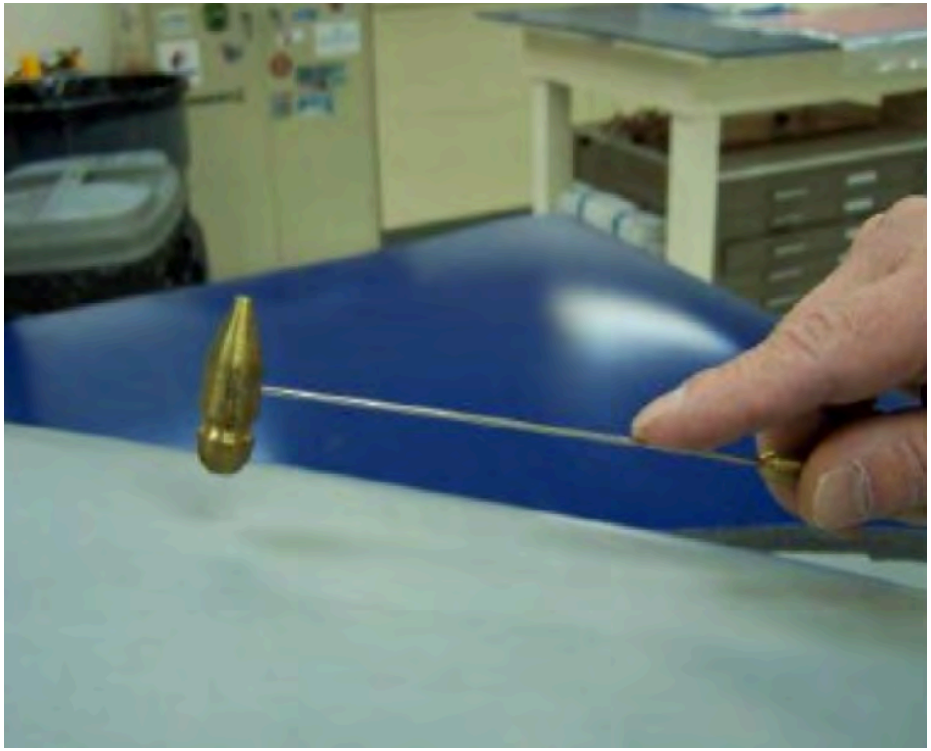
Inadequate tabbing detail

- Access to structure
- Tabbing integrity
- Watertight integrity
- Machinery and joinery alignment
- Mechanical attachment points
- Correlate external and internal anomalies

Tap Testing

- The accuracy of tap testing is very dependent on surveyor's experience
- Digital tap hammers can reduce subjectivity
- Tap testing can be very useful for finding large areas of delamination
- If repair is to be undertaken, grinding to good laminate is usually required to determine extent of damage

Hammer Sounding

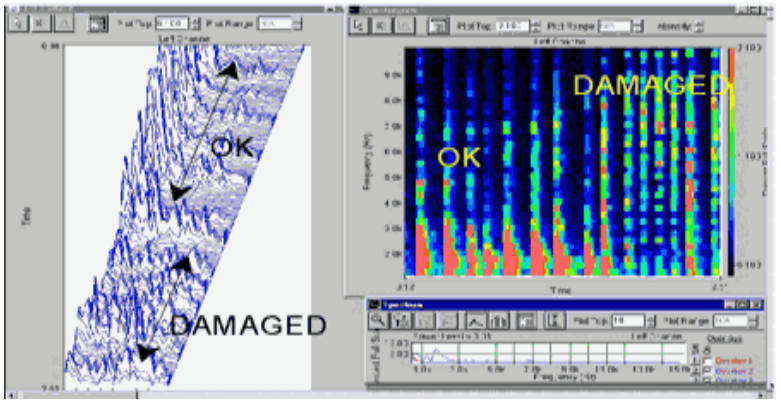


Military specification tap hammer

Marine surveyor Greg Davis uses sounding hammer on fiberglass boat hull

Digital Tap Hammers

Digital tap hammer used to examine test panel



Bruce Pfund shown demonstrating his Smart Hammer system [Bruce Pfund Special Projects]

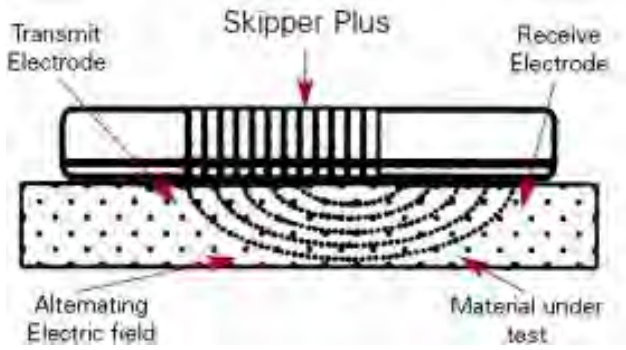
Moisture Meters

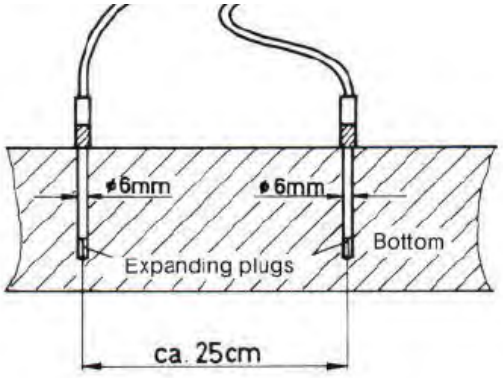
- Resistance type devices more accurate than capacitance devices but require surface penetration
- Capacitance devices will not provide readings with laminates that contain carbon fiber or over most copper-based bottom paints
- Ambient conditions such as recent rain or the presence of dew can produce false high reading
- Moisture meters more effective when used in conjunction with other NDE methods, such as hammer sounding to assess structural integrity

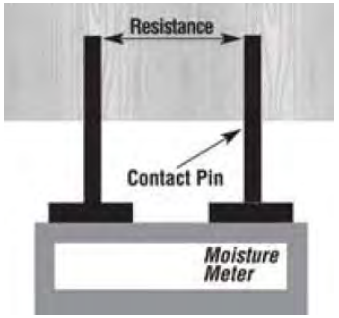
Moisture Meters

Capacitance moisture meter

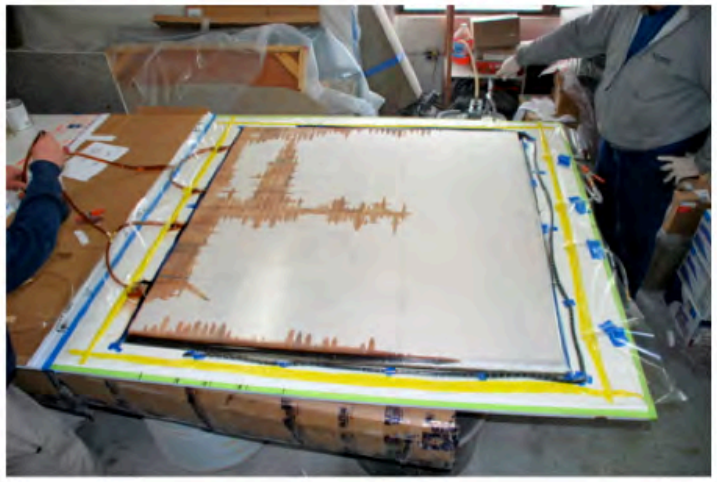
Resistance moisture meter



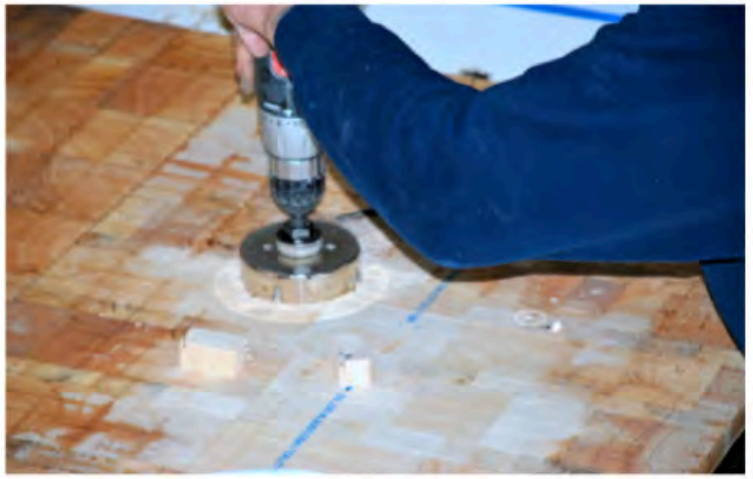




Fabricate Test Panels for NDE Study

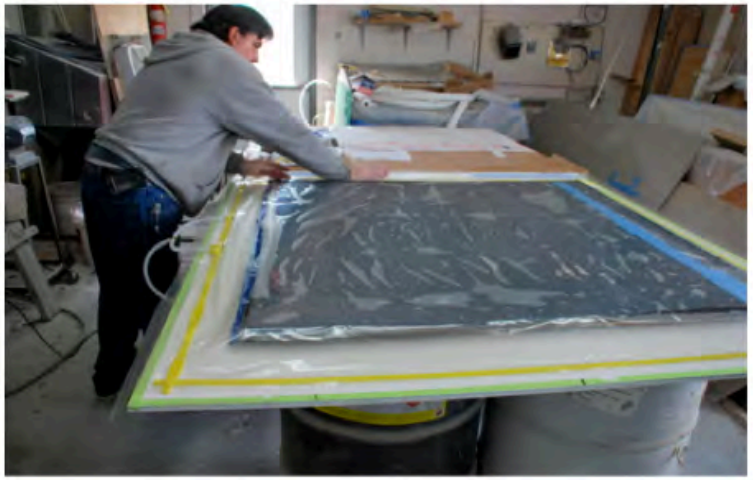


Beginning of infusion process used to wet-out the outer skin



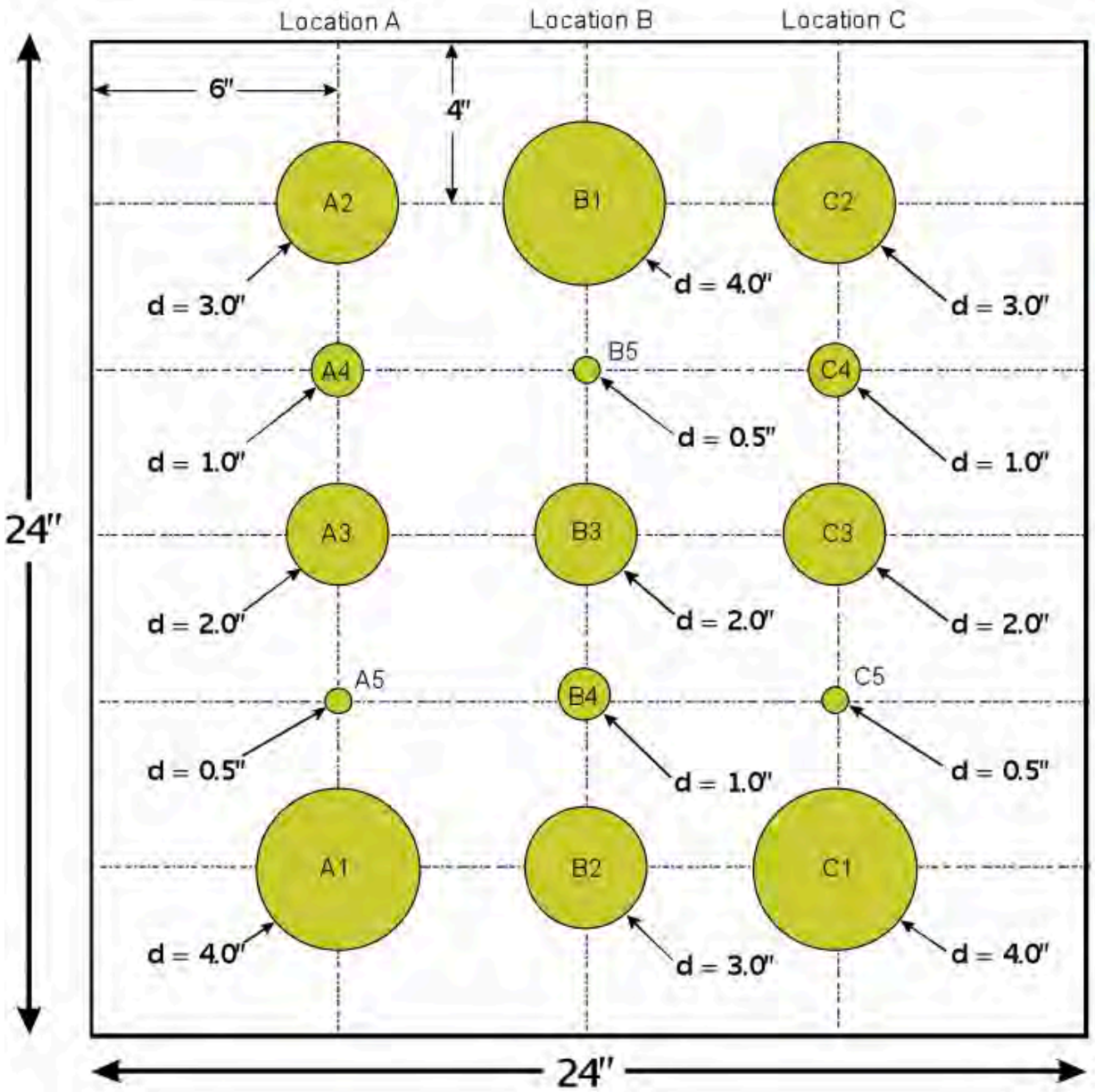
Hole saw is used to create a 1/8 inch deep void for water to be encapsulated

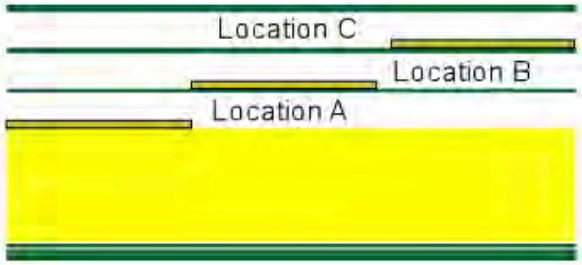
Inner skin is laminated by hand



Vacuum bag is used to consolidate hand-laminated inner skin

Simulated Delamination for NDE Study





1. Layout delamination disks on "peel ply" material and mark the centers of each circle.

2. Cut delamination disks 0.5" to 4" diameter from "peel ply" material.

3. Using spray-tac adhesive, position Location A disks on core material.

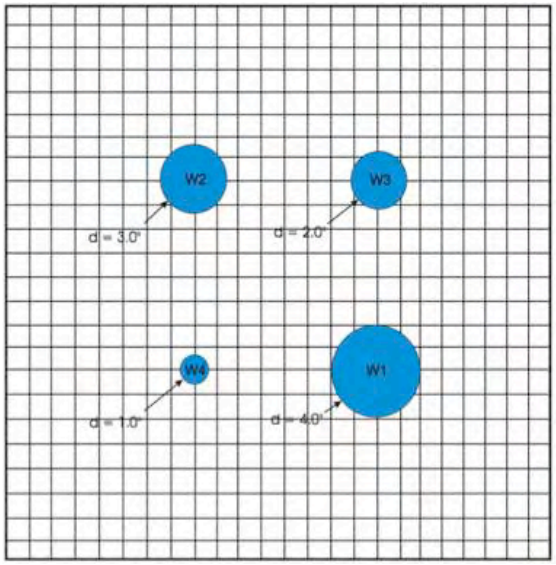
4. Using spray-tac adhesive, position LocationB and C disks onreinforcement material.

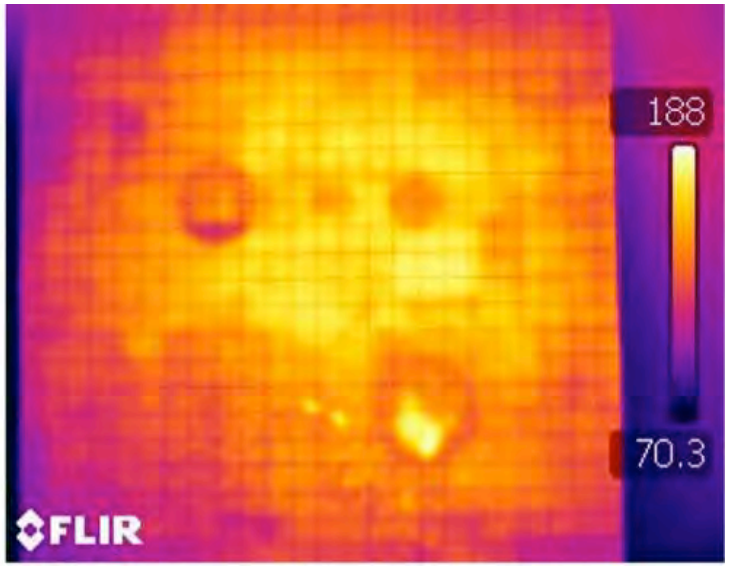
5. Carefully position reinforcement stack on molding table for single side infusion

Infrared Thermography

- Heat is uniformly applied to area
- An infrared camera measures the reflected heat
- Defects have thermal properties that vary from the base material – voids may create heat buildup while water ingress will locally cool the area
- Ambient lighting/heating conditions can strongly influence infrared image – beware of surface reflections
- Analysis of heat rate-of-change can provide more detailed information about potential defects

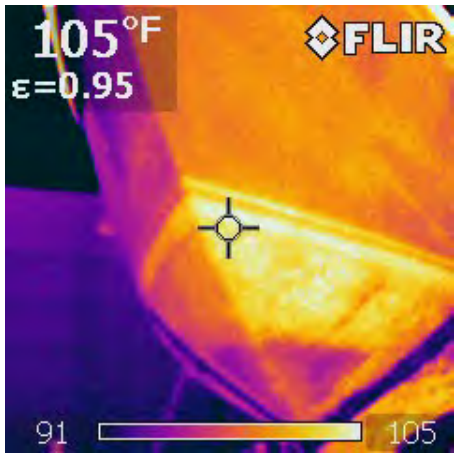
Infrared Thermography

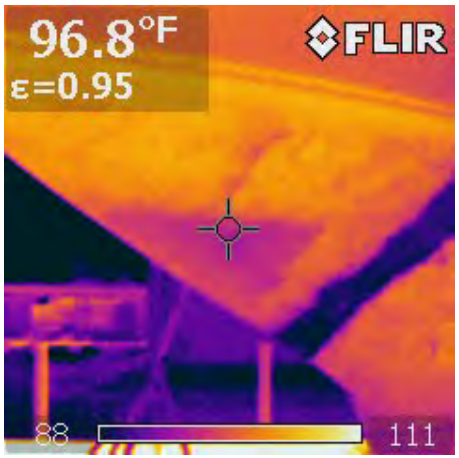


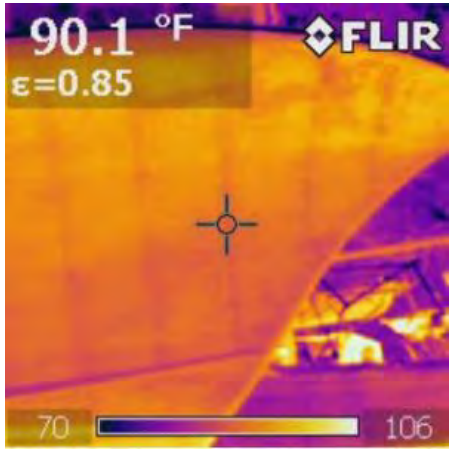


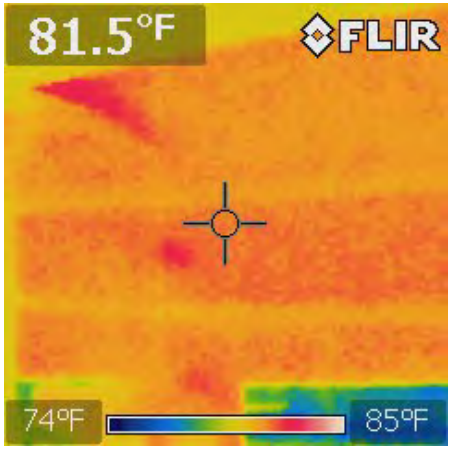
Panel with simulated defects (entrapped water) and IR image

IR image capture



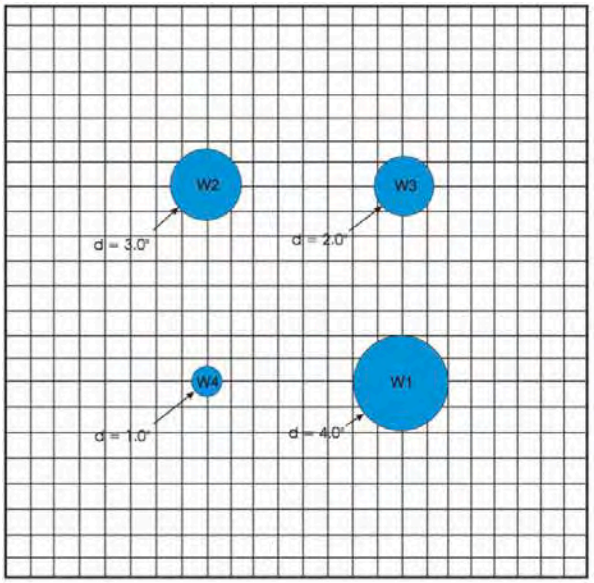




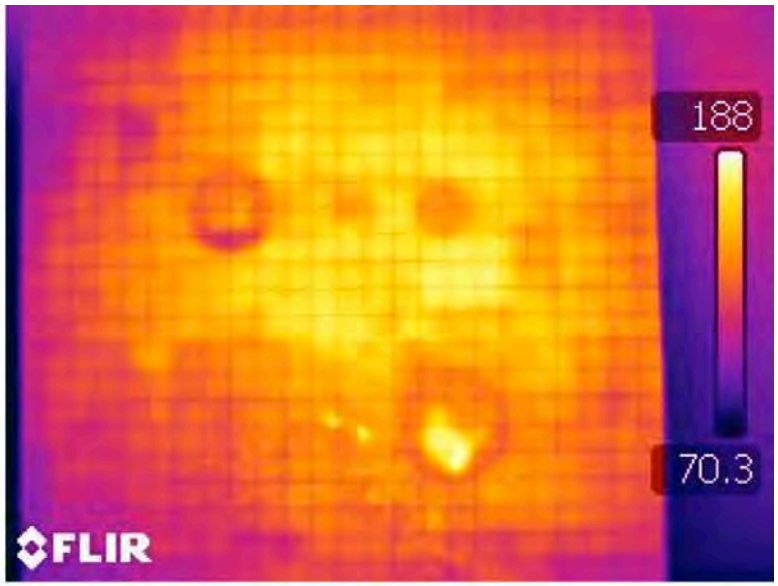


Typical boat inspection infrared thermography images

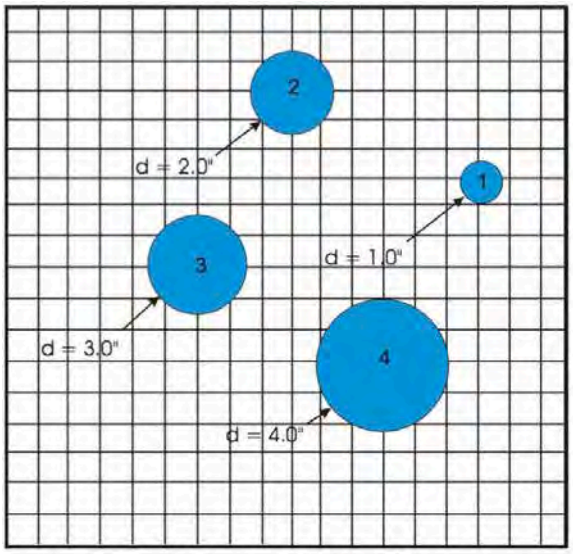
NDE Study IR Results



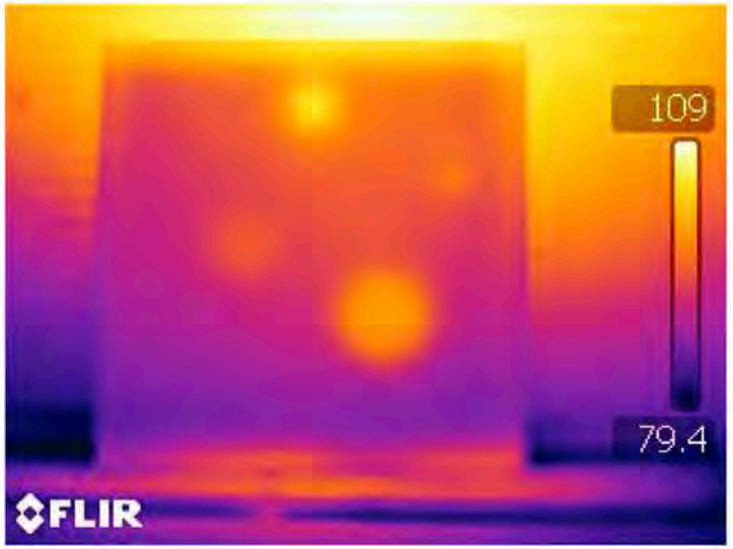
Simulated Defects



Thermogram

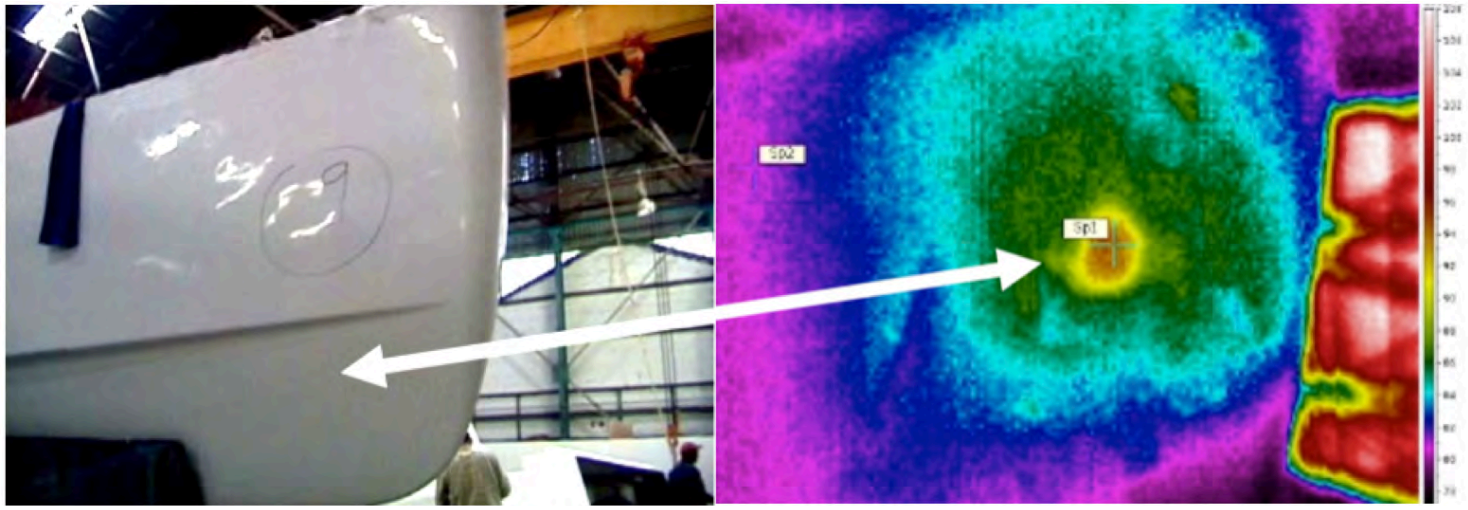


Machined Cavities

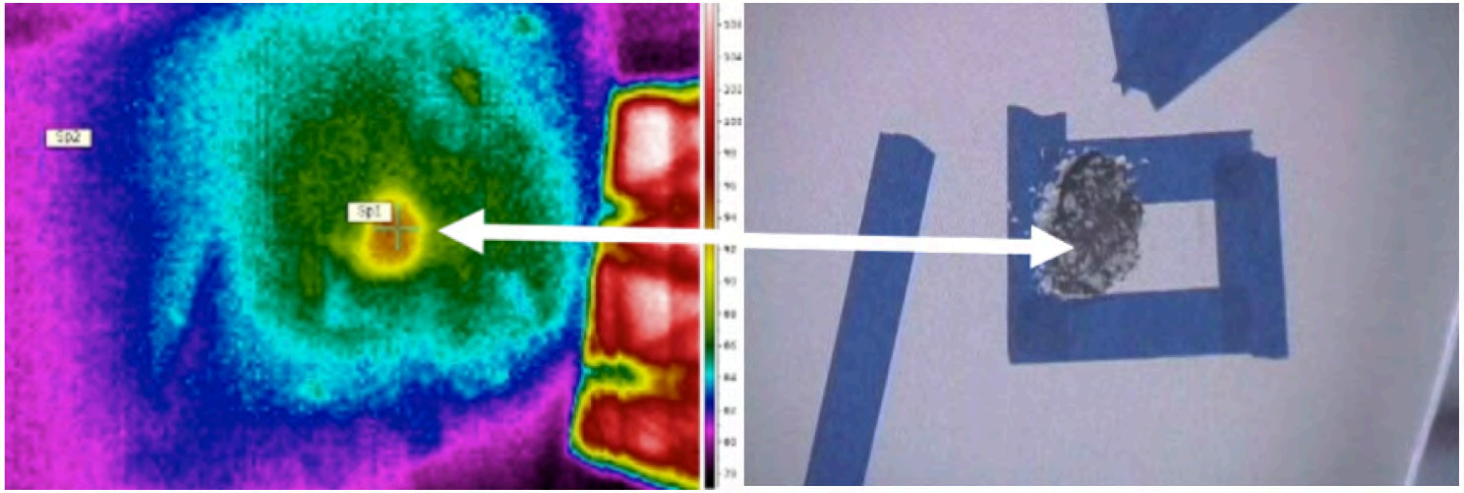


Simulated delamination (top) and simulated voids using machined cavities (bottom)

Thermography Case Studies



The surface looks free of defects using visible NDE (left) but thermal pattern shows anomaly when hull is gently warmed by an electric hot air gun [J.N. Allinson Associates]



Thermographic image of void in gel coat confirmed by percussion sounding followed by grinding it out for repair [J.N. Allinson Associates]

Ultrasonic Inspection

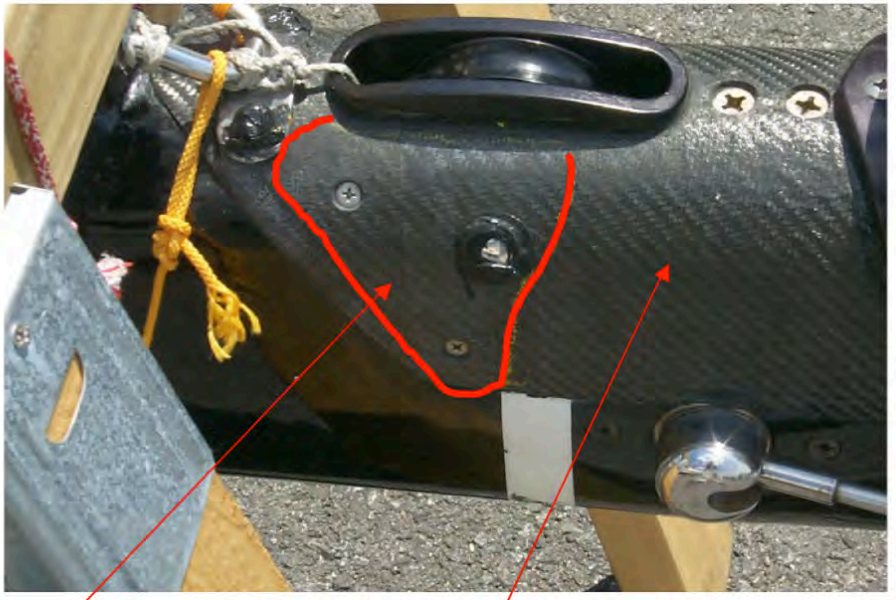
- Ultrasonic inspection transmits sound energy through a structure and measures the return signal
- Planar discontinuities will reflect the sound signal back before it reaches the back wall
- It is necessary to know the thickness of the part being measured and the speed sound travels through the material, which is why calibration blocks are typically used
- Transducers are small and require a couplant (water or gel) be applied to tested surface so it is not practical to inspect an entire boat

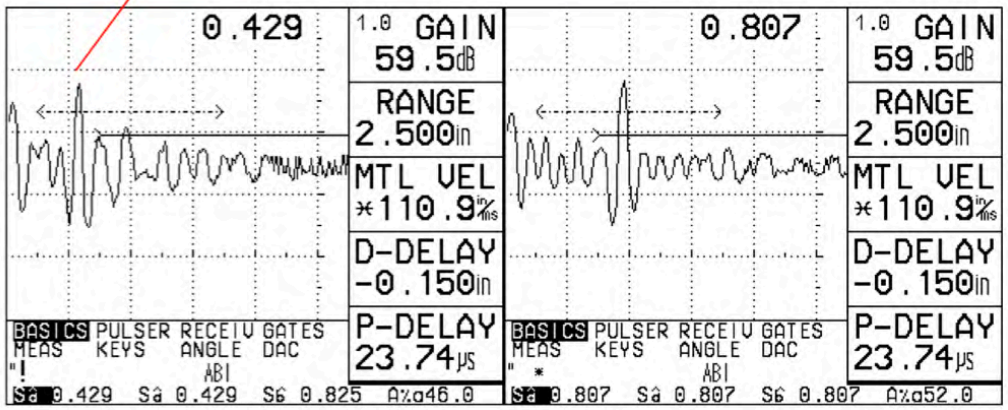
Ultrasonic Testing

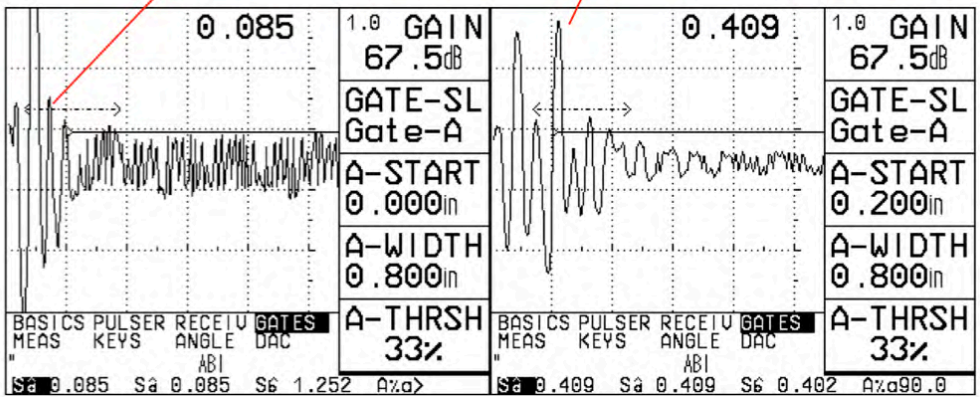
Olympus ultrasonic phased array flaw detector with simultaneous A-scan and S-scan display

Imperium Acoustocam used to inspect test panel with simulated defects

Ultrasonic Case Study

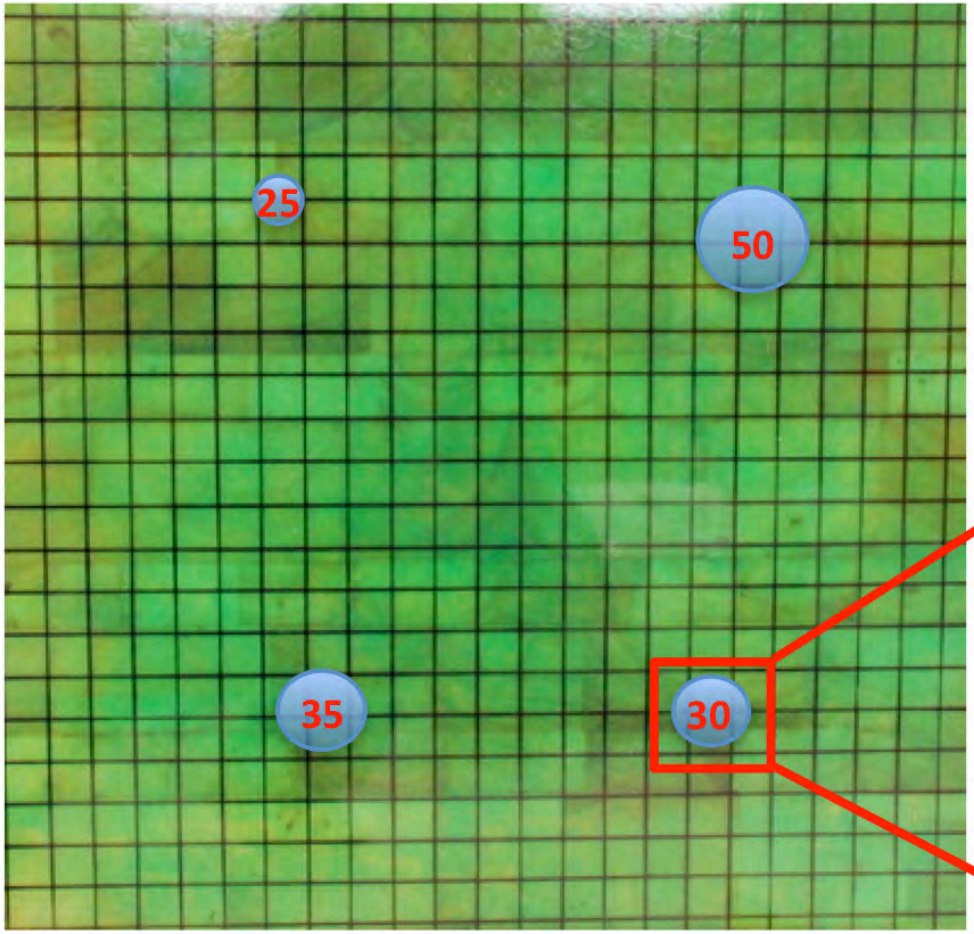


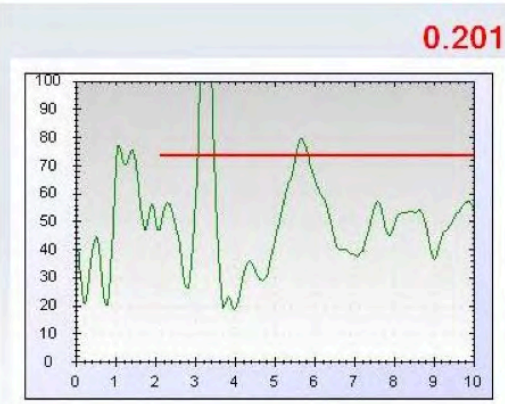




Carbon fiber mast struck by lightning examined with ultrasonic to find delamination below spreader (left) and delamination under first ply near masthead (right) [Bruce Bandos, 2002]

NDE Study Ultrasonic Test Results





A-Scan Settings

MATERIAL:	Fiberglass (50 v/o)
GATE START:	0.141"
GATE WIDTH:	1.205"
GAIN:	12.0 dB
ZERO OFFSET:	2.00 us
RANGE:	0.655"
VELOCITY:	0.124 in/us

C-Scan Settings

GATE START:	0.124"
GATE WIDTH:	1.260"
FREQUENCY:	3.5 MHz
PULSES PER BURST:	1
L1:	2716
L2:	9007
MATERIAL:	Fiberglass
VELOCITY:	0.124 in/us

Impact energies on E-glass laminate (left) and corresponding ultrasonic NDE data (right) [data courtesy of Imperium, Inc.]

Ultrasonic Transducers

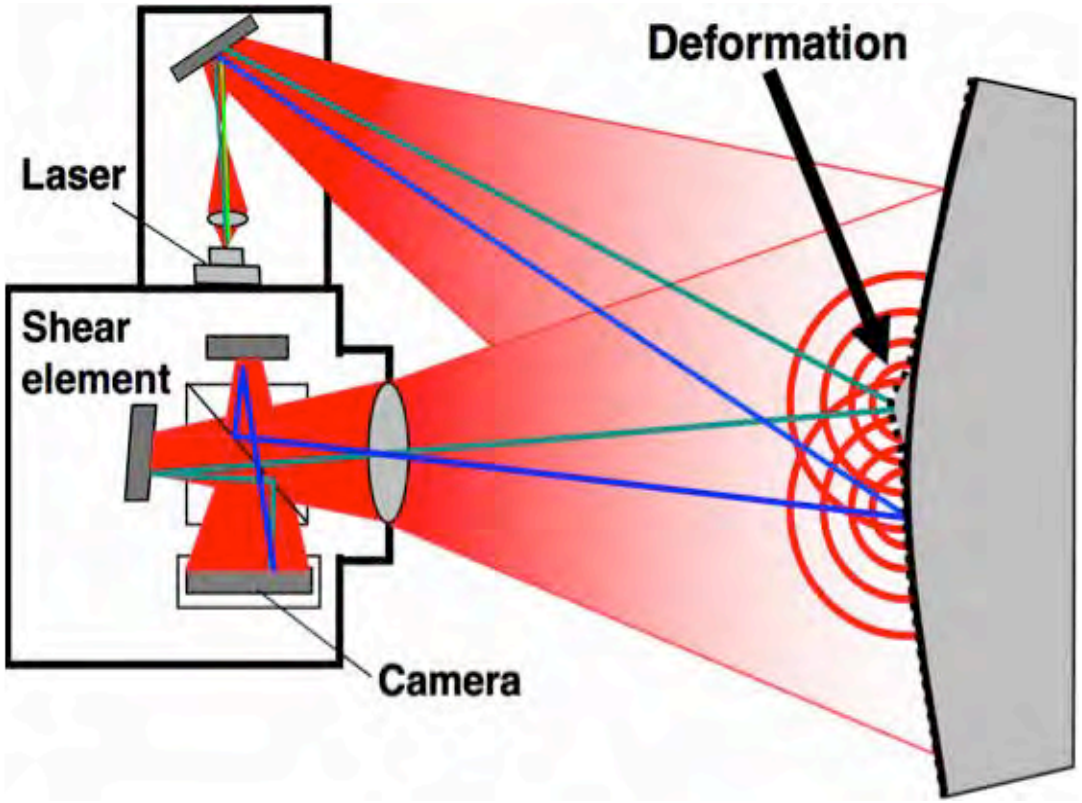
Frequency	Typical Spot Resolution	Typical Materials	Comments
0.5 MHz	0.31 – 0.39 ins. (8mm – 10mm)	Thick laminates (closer to 1 in./25 mm thick), complex multi-layer composites	Will penetrate almost anything, but resolution is inadequate for many purposes.
5 MHz	0.19 ins. (5 mm)	Thinner solid laminates (0.2 – 0.8 ins/5 mm – 20 mm thick)	Good compromise where max resolution is not required. Can penetrate most materials that are possible to test conventionally.
15 MHz	0.03 – 0.07 ins. (1mm – 2mm)	Solid laminates, single-layer honeycombs	Gives results comparable in resolution to practical production tests.

Effect of transducer frequency on UT inspection of composites [Ginger Gardiner, "Diagnosing the Dark Composite," Professional BoatBuilder, # 123, Feb/Mar 2010]

Laser Shearography

- With laser shearography, the surface of the laminate is stressed, either using vacuum, thermal or vibration excitation methods
- Scanning lasers are used to compare the unloaded and loaded surface strain fields by “shearing” the image reflected back to the recording camera
- Laser shearography can detect surface displacements as small as 10 nanometers
- Portable vacuum hoods are typically one foot square, so it is feasible to inspect an entire boat, although equipment know is about $100K

Laser Shearography

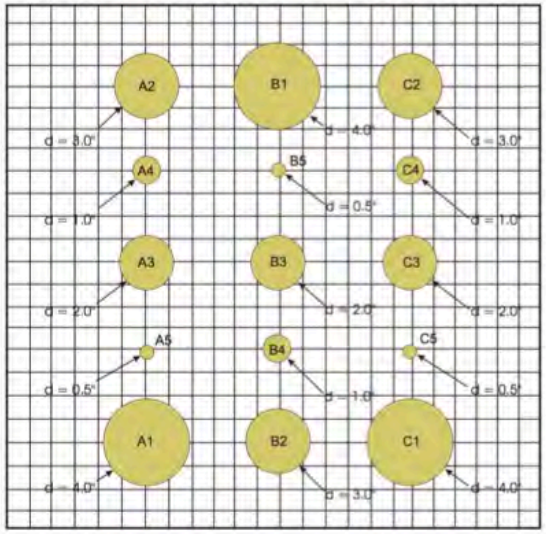


Shearography principal [Collrep 2006] and portable shearography device [Newman 2009]

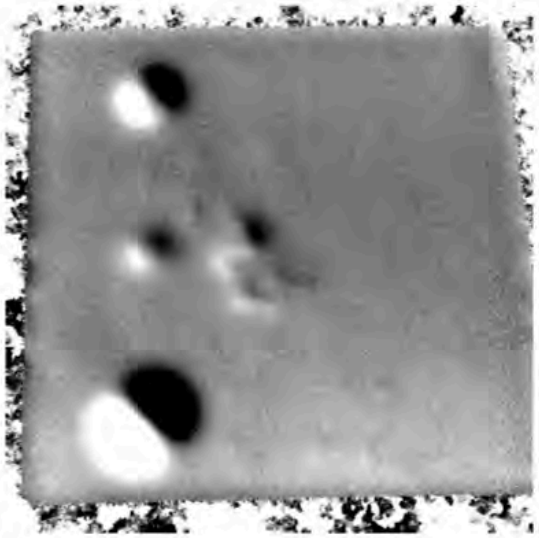
Laser Shearography

Laser shearography used to examine RNLI lifeboats [Laser Technology]

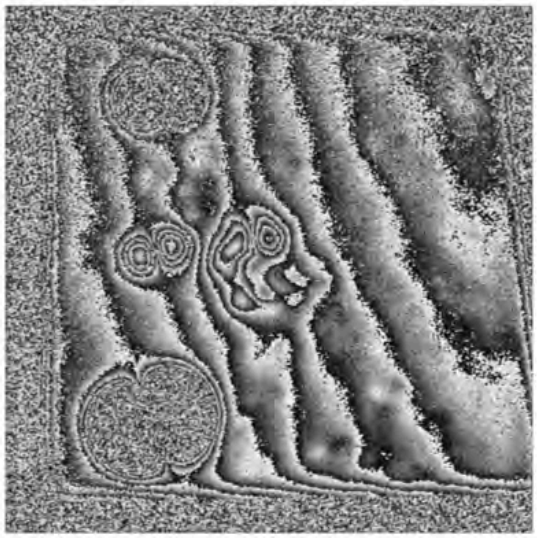
NDE Study Shearography Results



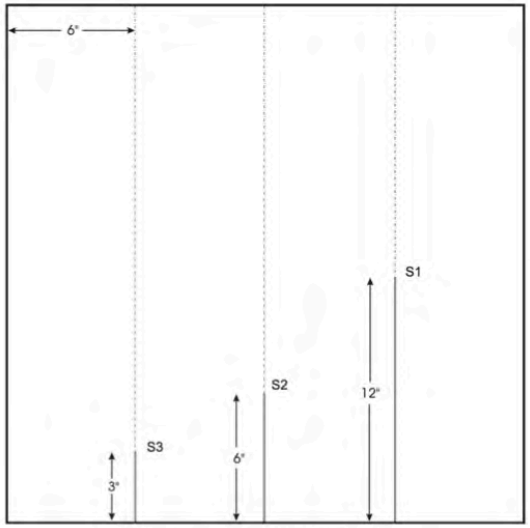
Simulated Defects



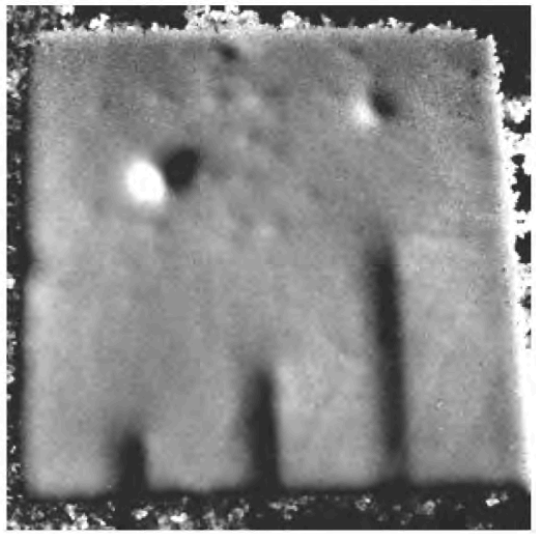
Unwrapped Phase Map



Wrapped Phase Map



Simulated Defects



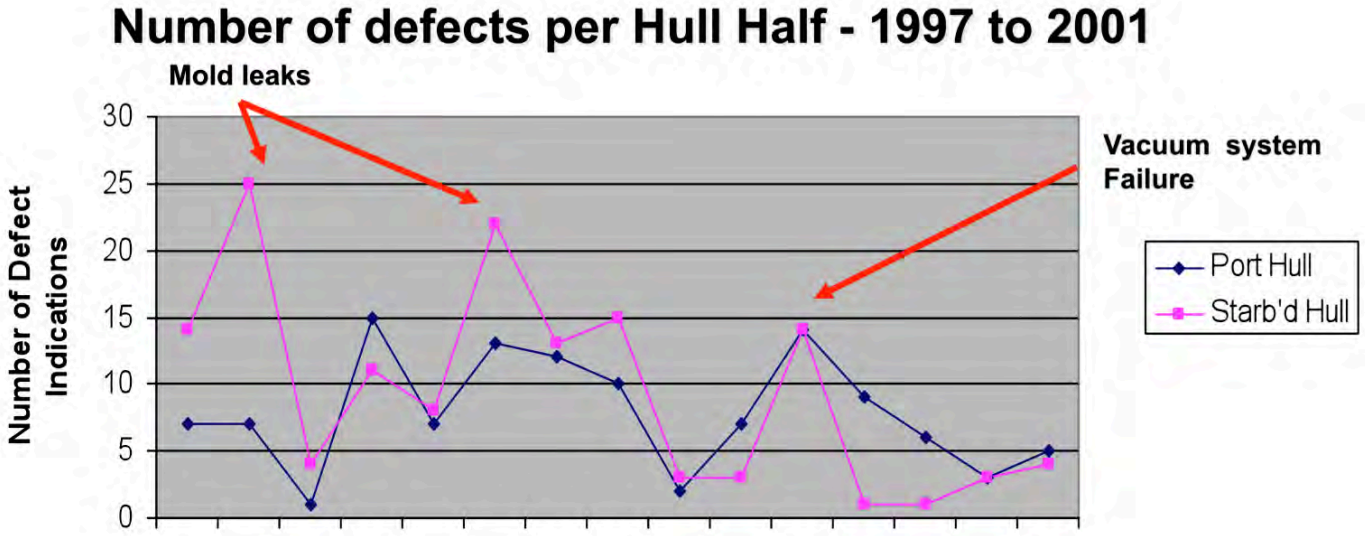
Unwrapped Phase Map

Simulated delamination (top) and core shear failure (bottom)

Shearography Case Studies

Full extent of impact damage to hull sandwich construction [Laser Technology, Inc.]

RNLI Severn class detected hull defects over time highlights systematic process failures during fabrication [Laser Technology, Inc.]



Summary of NDE Study

Defect		Laser Shearography	Ultrasonic Inspection	Infrared Thermography
Delamination	Min. Size Detected	2 inches	2 inches	3 inches
	Max. Depth Detected	1- 2 plies	1 ply	2 – 3 plies
	Overall Effectiveness	good esp. for kissing bonds	can't detect kissing bonds	can't detect kissing bonds
Water Ingress	Min. Size Detected	2 inches	4 inches	2 inches
	Max. Depth Detected	skin/core interface	skin/core interface	skin/core interface
	Overall Effectiveness	good	use higher frequency transducer	very good

Summary of NDE Study

Defect		Laser Shearography	Ultrasonic Inspection	Infrared Thermography
Impact Damage	Min. Size Detected	1 inch	2 inches	1 inch
	Max. Depth Detected	skin/core interface	1- 2 plies	skin/core interface
	Overall Effectiveness	very good	good	good
Void	Min. Size Detected	2 inches	2 inches	1 inch
	Max. Depth Detected	¼ inch	½ inch	¾ inch
	Overall Effectiveness	fair with thick laminates	good for uniform laminates	very good

Effectiveness of Various NDE Techniques

Defects	Visual	Ultrasonics		Thermography		Laser Shearogrphy		Tap Hammer	
		A-Scan	C-Scan	Steady	Pulsed	Vacuum	Heat	Manual	Digital
Adhesive bond failure	0	A	A	B	A	A	B	B	A
Air bubble	C	C	C	C	B	C	B	0	0
Blister	A	C	C	C	B	C	C	0	0
Core crushing	C	B	B	B	A	B	C	B	B
Core shear failure	0	C	C	B	A	A	B	C	B
Crazing	A	0	0	C	C	C	C	0	0
Delaminations	C	B	A	C	B	A	B	B	B
Fiber failure	C	B	B	0	C	A	A	C	C
Kissing bond	0	B	A	B	A	A	B	C	B
Local impact damage	B	C	B	B	B	A	B	C	B
Matrix cracking	A	C	B	C	C	B	C	0	C
Moisture ingress	C	C	B	A	A	B	A	C	C
Ply waviness	B	0	0	0	C	C	C	0	0
Pit (or pinhole)	A	0	C	0	0	0	C	0	0
Porosity	B	0	C	C	B	0	C	0	0
Resin rich area	0	C	B	B	A	0	C	C	C
Resin starved area	0	C	B	B	A	0	C	C	C
Skin-to-core disbond	0	C	B	B	A	A	B	B	A
Surface cracking	A	0	0	C	C	C	C	0	0
Thermal damage	B	C	B	B	B	C	B	C	C
Voids	C	C	B	C	B	C	C	C	C

A = High (best/optimal)

B = Average (works generally well)

C = Limited (may be used under certain conditions only)

0 = Not applicable (will not detect the defect)

Eric Greene, "Marine Composites NDE," Ship Structure Committee report SSC-463, 2012.

Ship Structural Failures

Mine Counter Measure Ship Collision with Dock

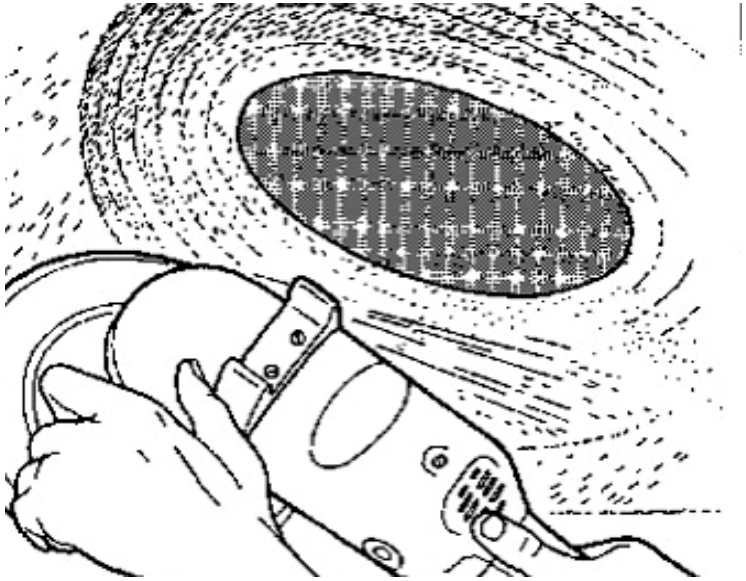
Christian Berggreen, Technical University of Denmark, 2008

Damage Assessment

Damages can be found either by visual inspection, probing, or hammer sounding of the structure. Damage can be found from indicators such as the following:

- Cracked or chipped paint of abrasion of the surface
- Distortion of a structure or support member
- Unusual build-up or presence of moisture, oil, or rust
- Structure that appears blistered or bubbled and feels soft to the touch
- Surface and penetrating cracks, open fractures, and exposed fibers
- Gouges
- Debonding of joints

Grind Laminate to Determine Extent of Damage



Resin Repair Selection

Laminate	Original process used	Repair resin options	**Typical repair process options
Epoxy	Pre Preg	Epoxy	Pre Preg, Wet vacuum bag, Infusion
	Wet vacuum bag	Epoxy	Wet vacuum bag, Infusion
	Infused	Epoxy	Infusion, Wet vacuum bag
	Hand lay up	Epoxy	Hand Layup
Vinyl ester (VE)	Infused	VE, Epoxy	Infusion, Wet vac bag (if epoxy)
	Hand lay up	VE, Epoxy	Hand lay up
Polyester (PE)	Infused	PE*, VE, Epoxy	Infusion, Wet vac bag (if epoxy)
	Hand lay up	PE*, VE, Epoxy	Hand lay up

* Ideally only use polyester for repair if same exact resin is used as in original laminate. Otherwise use VE or Epoxy.

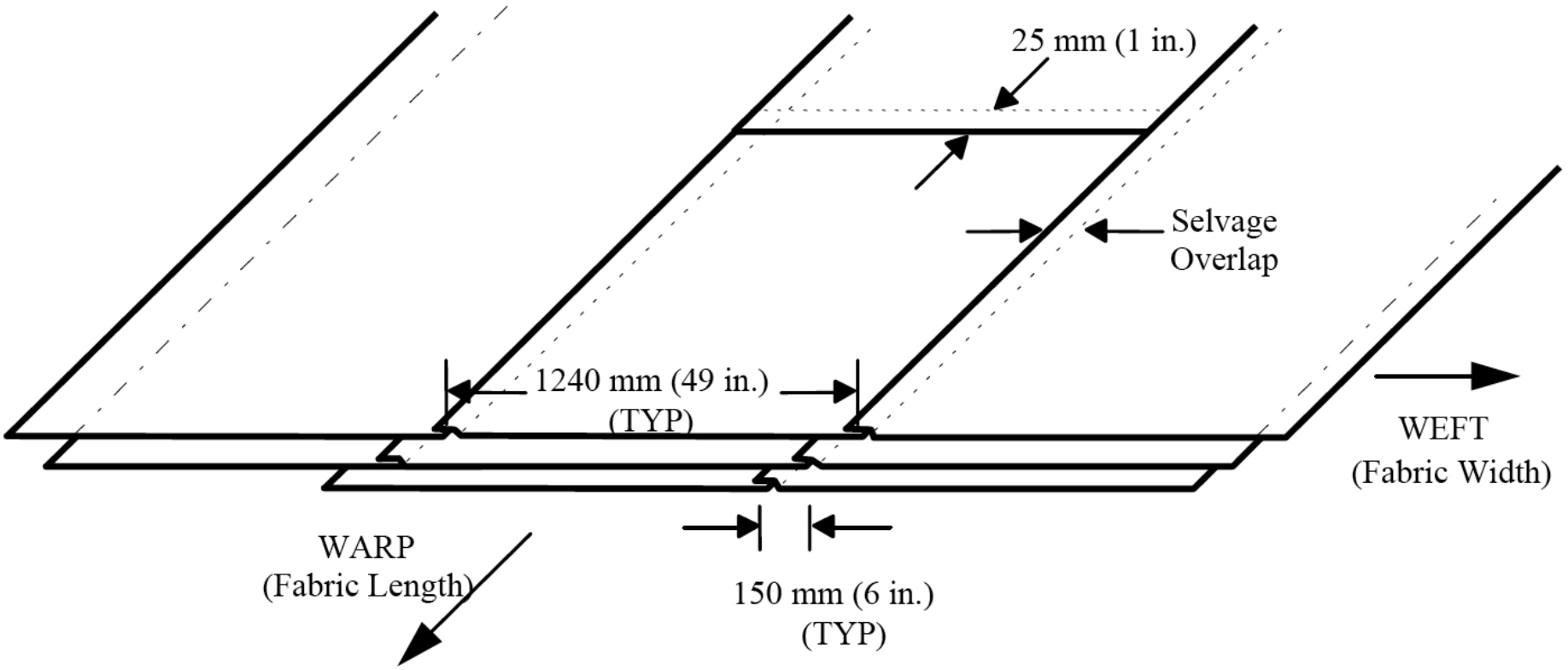
**Default to original designer/builder or laminate engineer recommendations if available.

Meade Gougeon, “Fiberglass Repair Tips,” U.S. Sailing, 2013

Recreational Boat Repair Guidelines

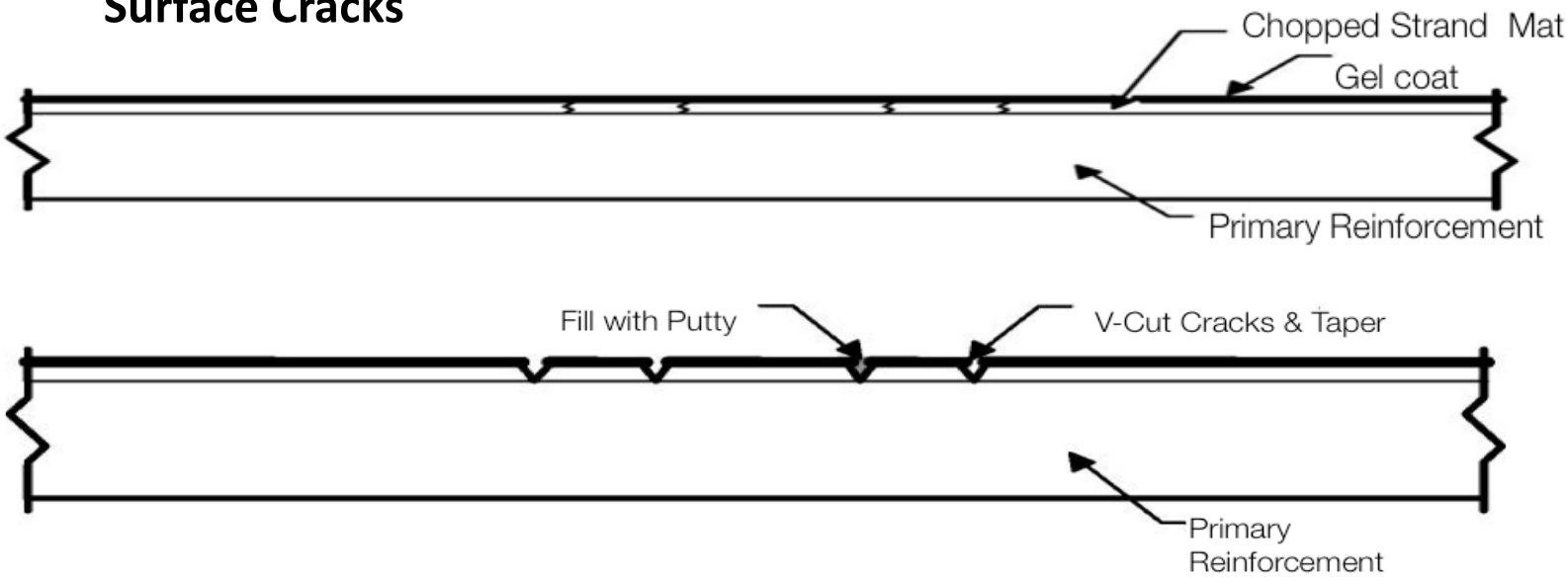
Depth of defect	Repair
Less then 1/32 inch	gel repair
Less then 1/16 inch	putty
Greater the 1/16 inch	laminate

Ply Overlap Requirements

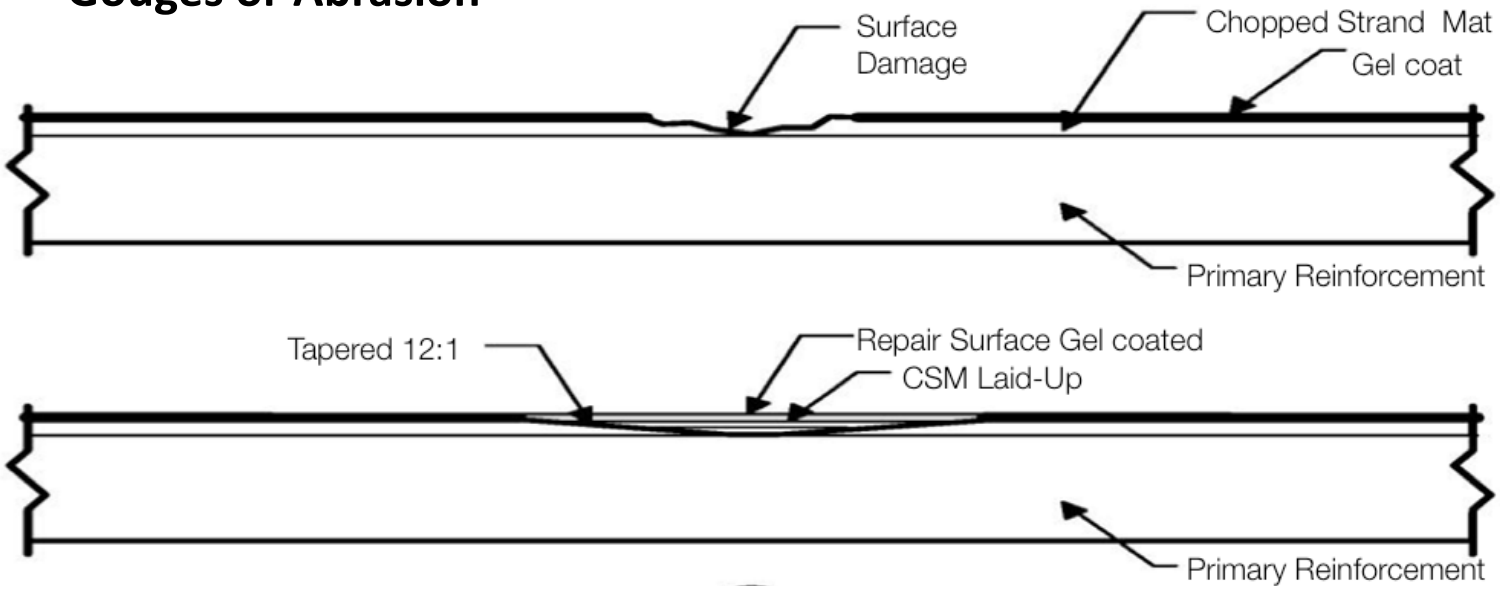


Surface Damage Repair

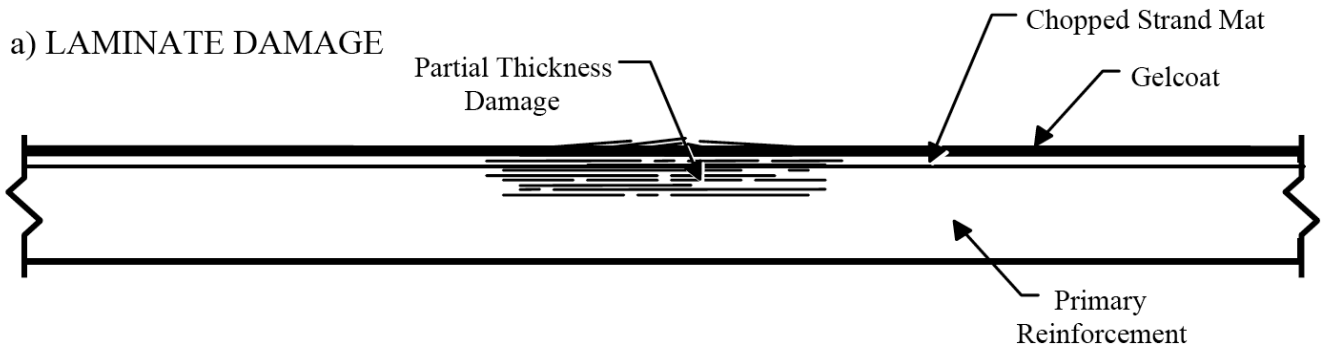
Surface Cracks

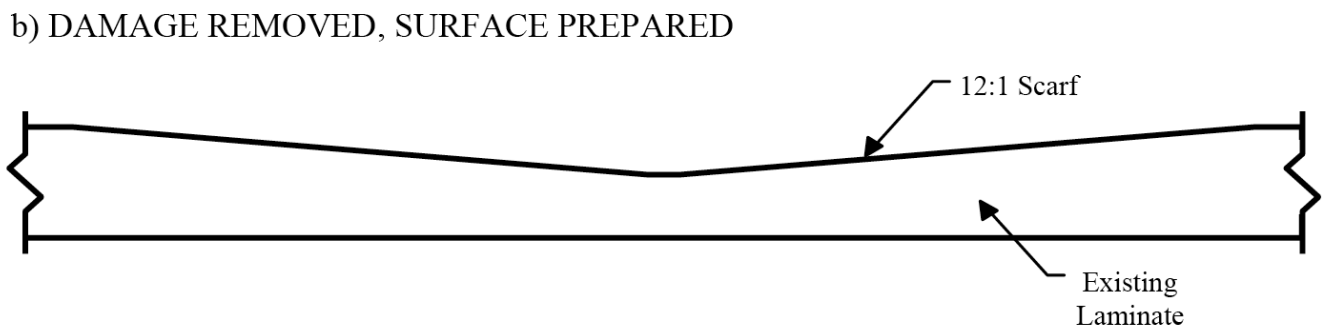


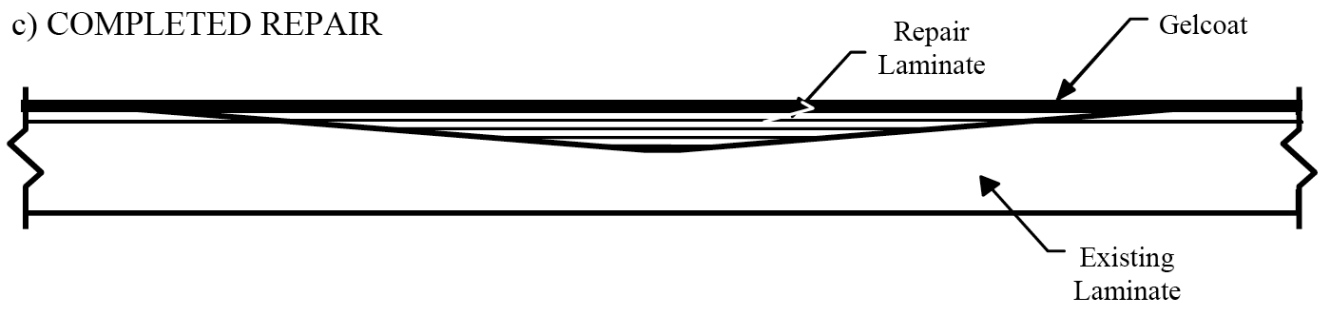
Gouges or Abrasion



Partially Through Thickness Damage Repair

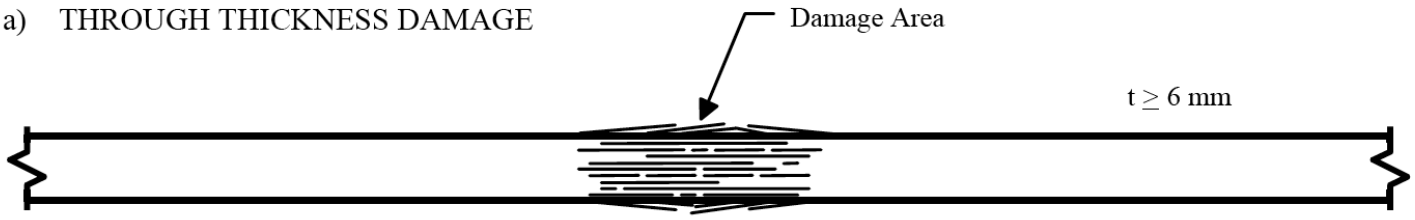




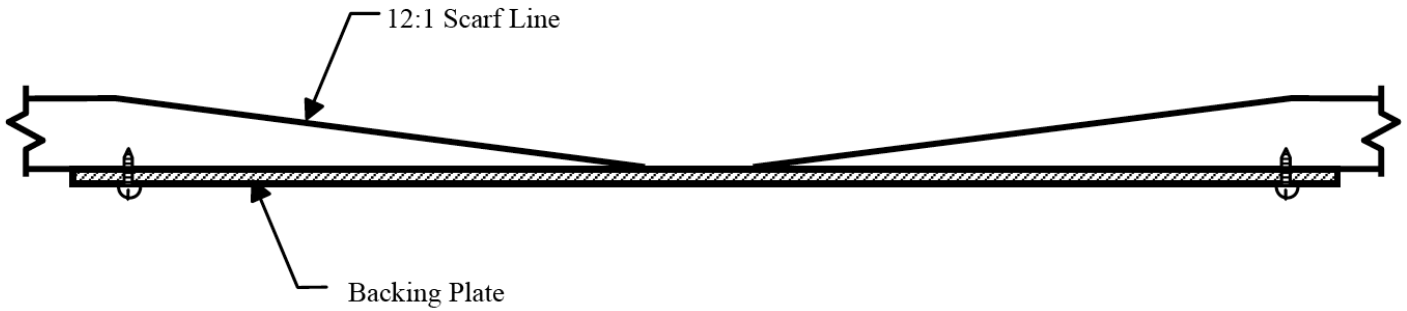


Single Sided Scarf Repair on Solid Laminate

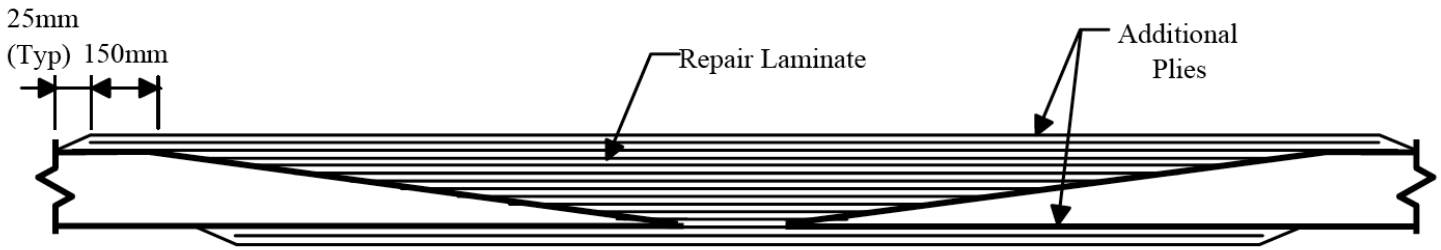
a) THROUGH THICKNESS DAMAGE



b) BACKING PLATE INSTALLATION



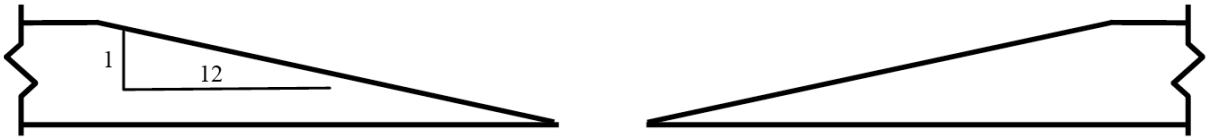
c) COMPLETED REPAIR



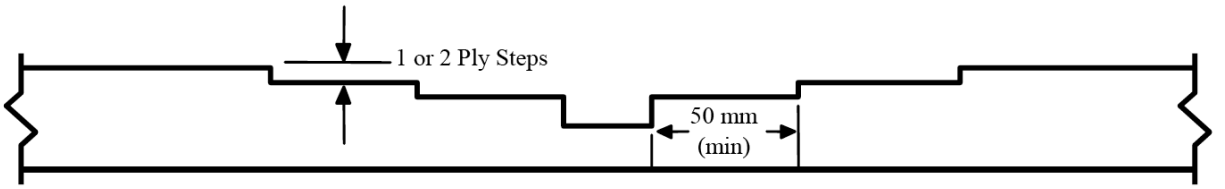
Scarf Joint Preparation

Single-Sided Scarf

12:1 Tapered Scarf

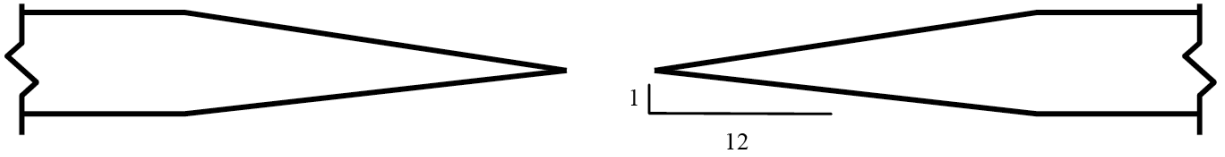


12:1 Tapered Scarf Through Thickness Damage

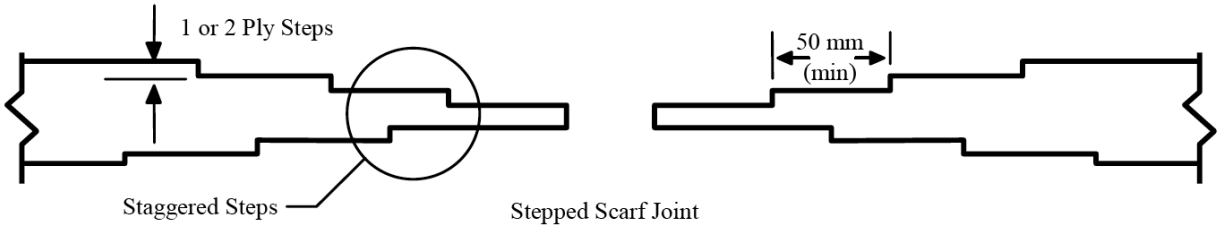


Stepped Scarf Joint

Double-Sided Scarf

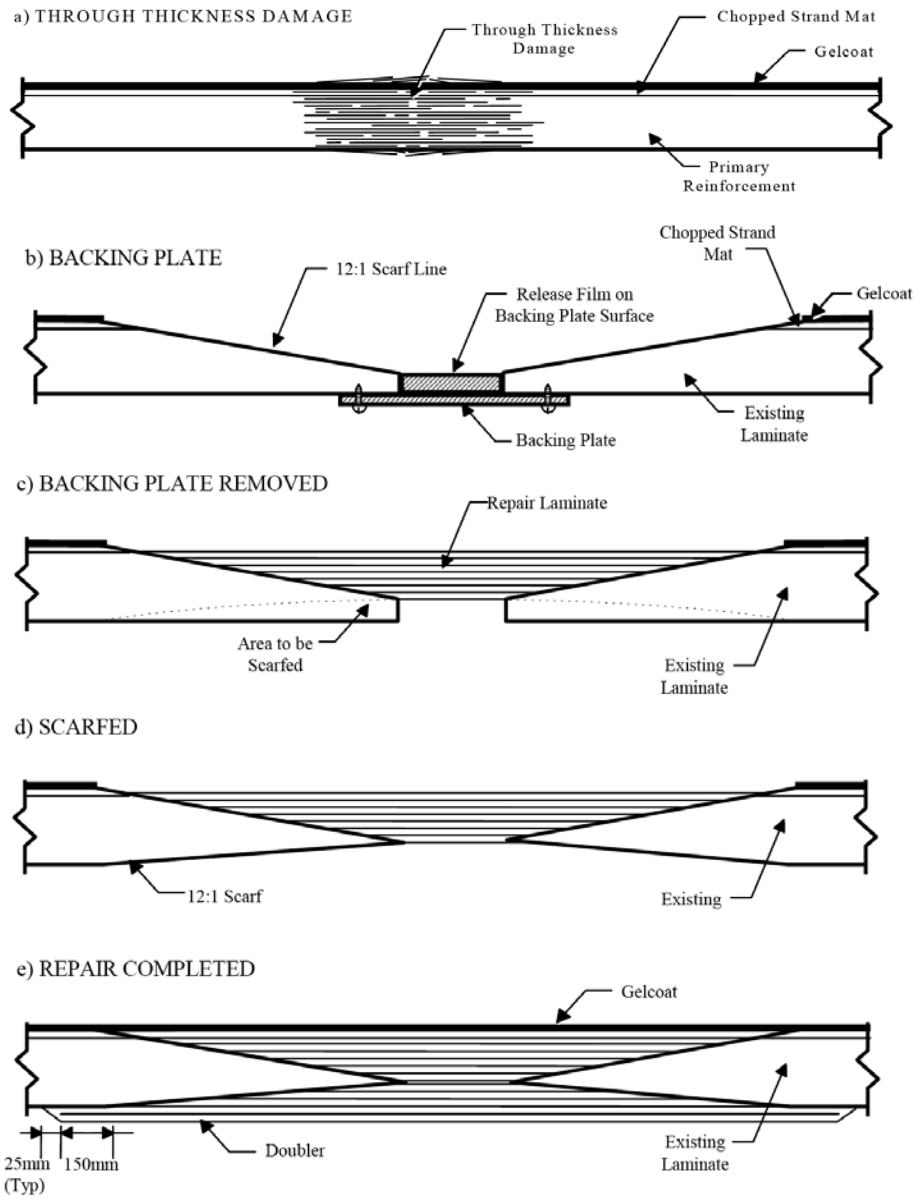


12:1 Tapered Scarf



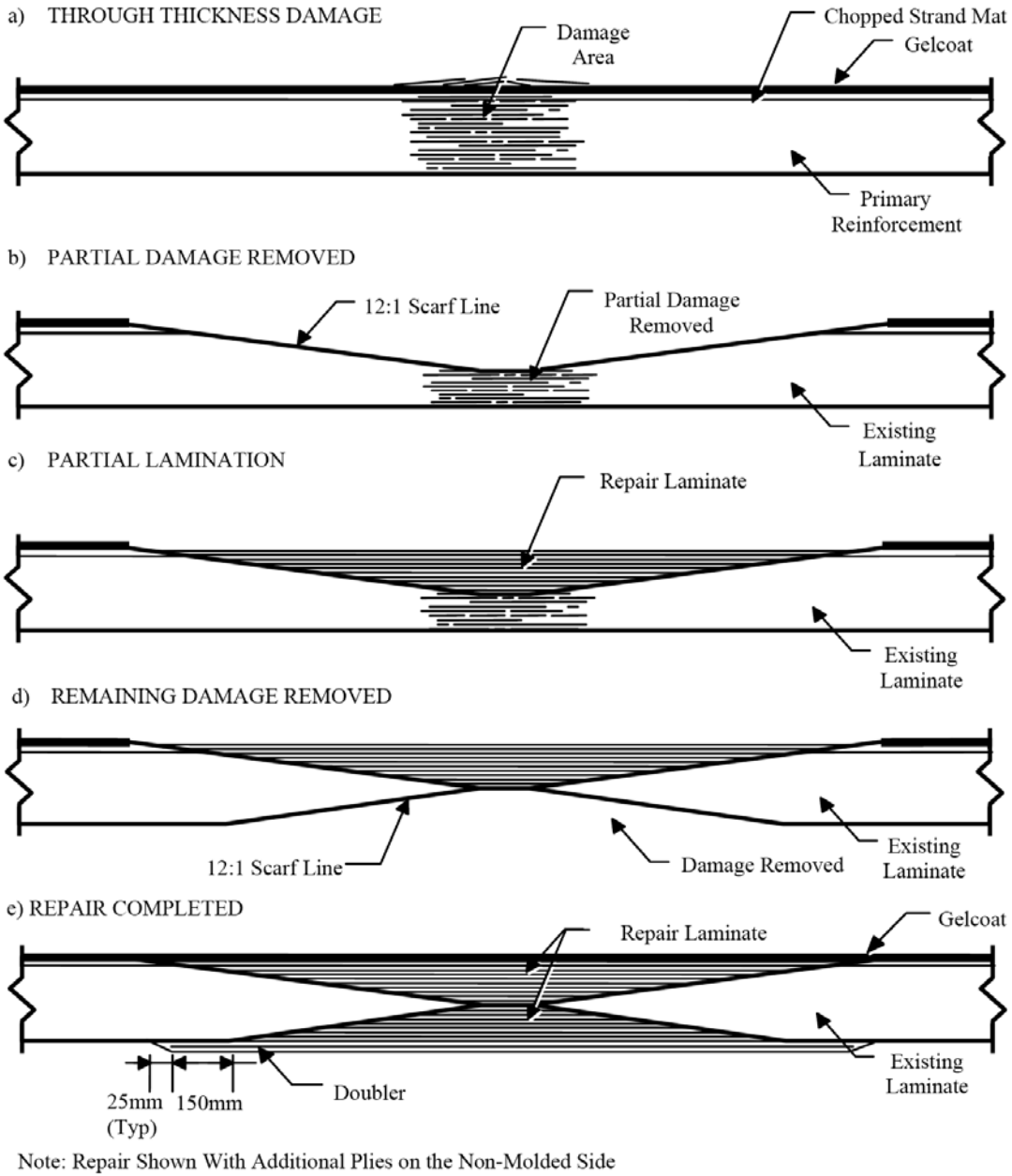
Stepped Scarf Joint

One Sided Scarf Repair Backing Plate Installation



Note: Repair Shown With Additional Plies Onto Non-Molded Side

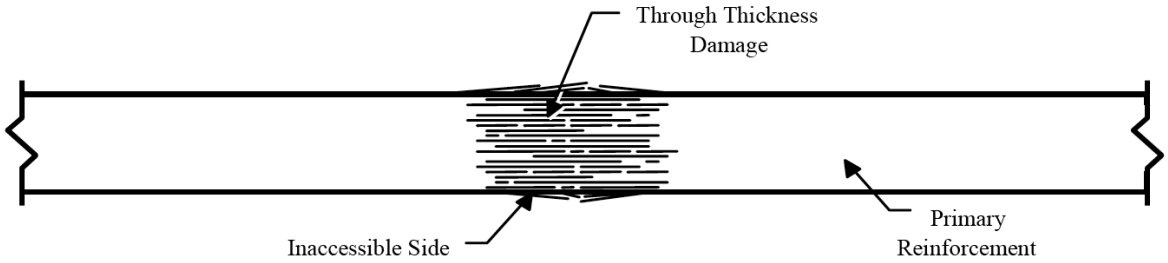
Repair Using Damaged Section as Backing Plate



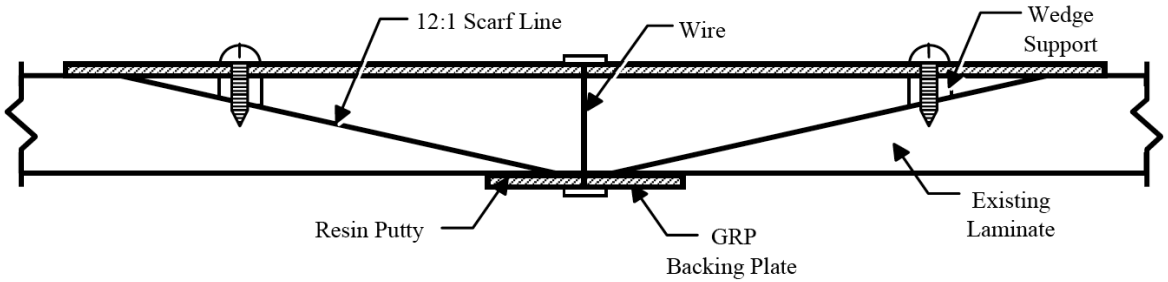
Note: Repair Shown With Additional Plies on the Non-Molded Side

Backing Plate Installation - Access from One Sided Repair

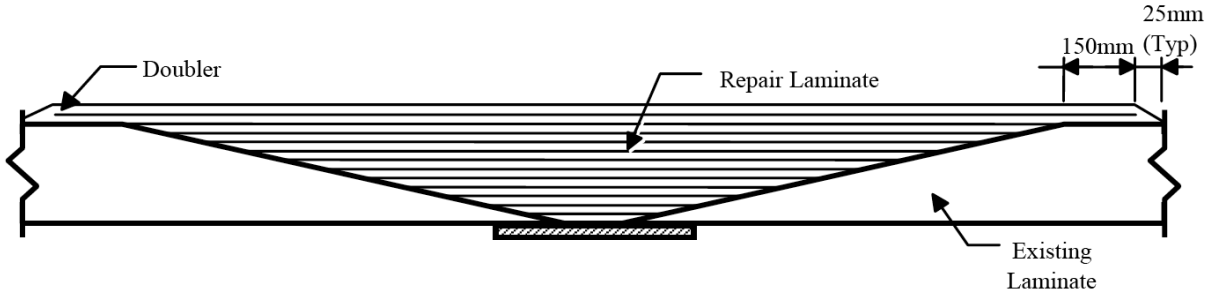
a) DAMAGED LAMINATE



b) BACKING PLATE INSTALLATION



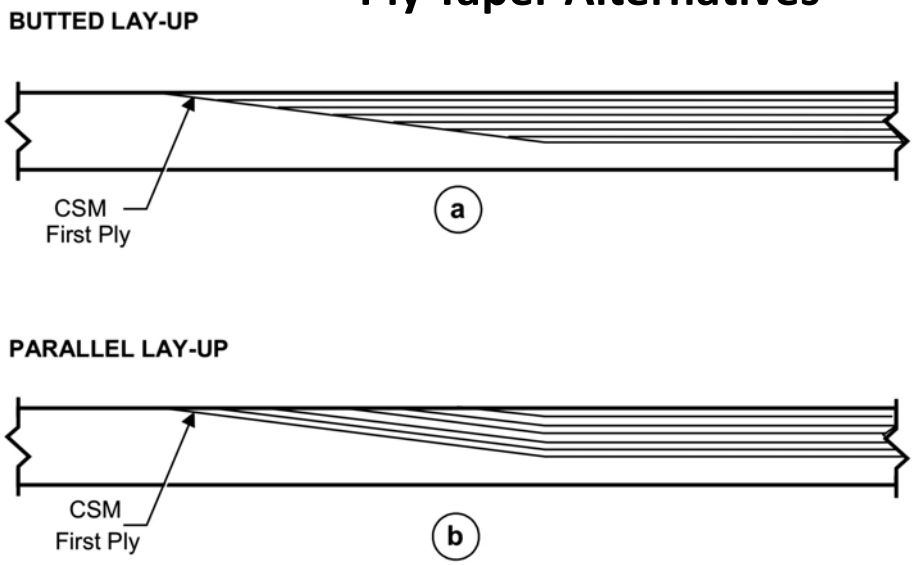
c) COMPLETED REPAIR



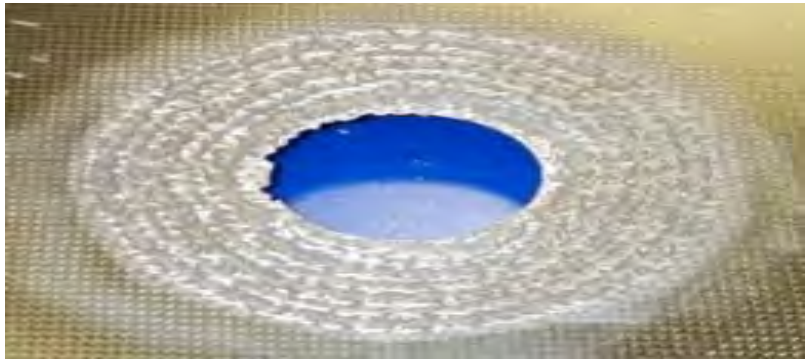
Note: Repair Shown With Additional Plies for Added Reinforcement

Planning Composite Repair

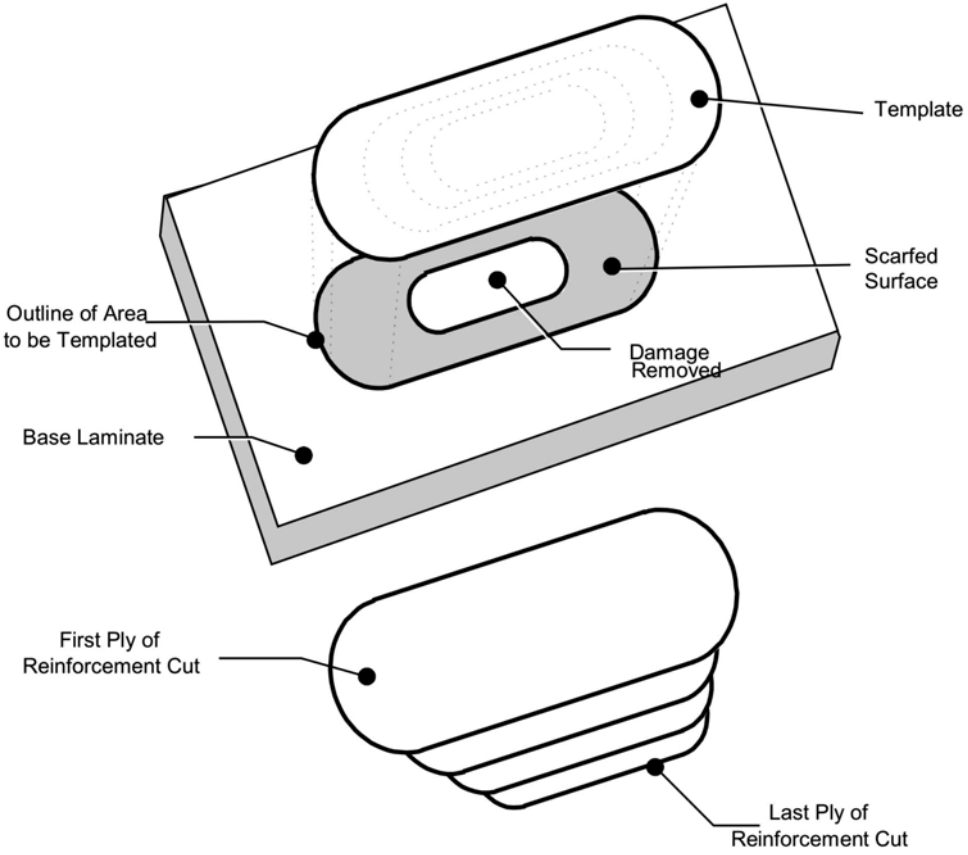
Ply Taper Alternatives



Placing largest ply last provides best moisture resistance – placing largest ply first provides best bond



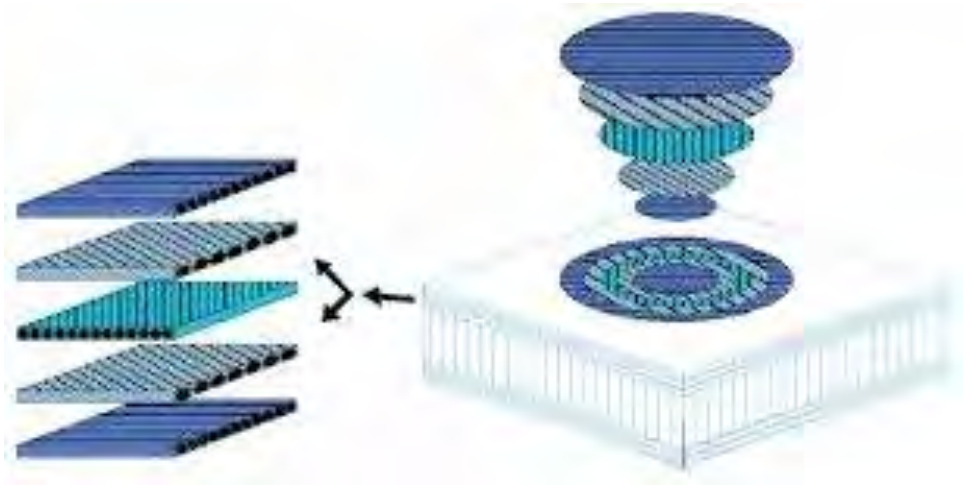
Reinforcement Preparation

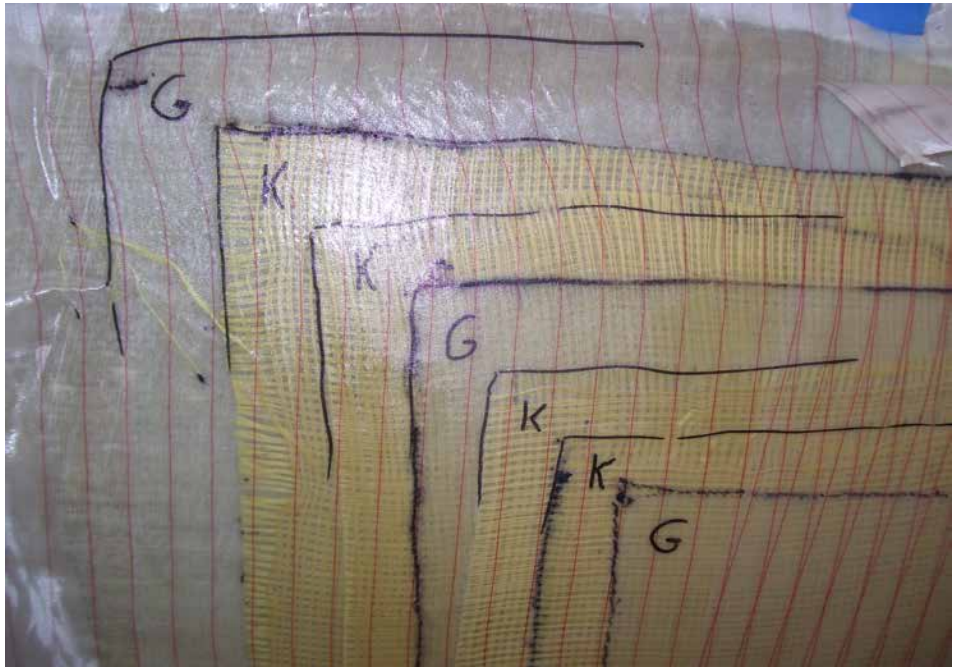


Template repair plies

Layout Repair Laminate

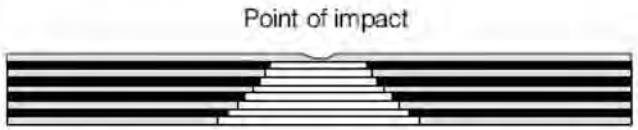
It is necessary to first determine what materials were used in the original manufacturing process, the matrix resin, fibers/fabrics and their ply orientations





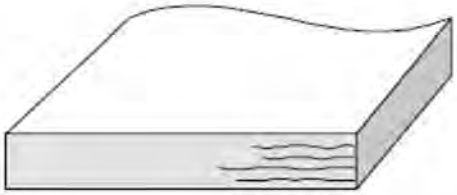
Types of Sandwich Damage

Delamination following impact on a monolithic laminate

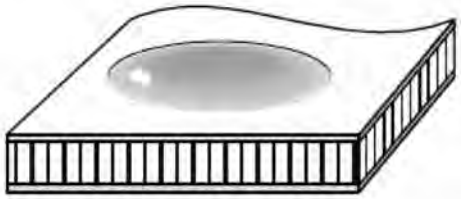


Underlying damage can extend to a much greater extent in laminate structures.

Laminate Splitting
The damage does not extend through the full length of the part. The effects on the mechanical performance depend on the length of split relative to the component thickness.

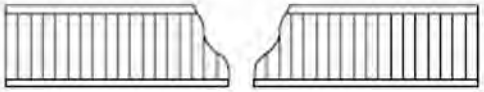


Heat Damage
A local fracture with separation of surface plies. Its effect on the mechanical performance depends on the thickness of the part.



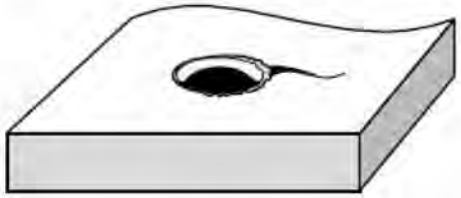
Dents in Sandwich Structure

Puncture Damage in a Sandwich Structure



Both skins may be damaged.

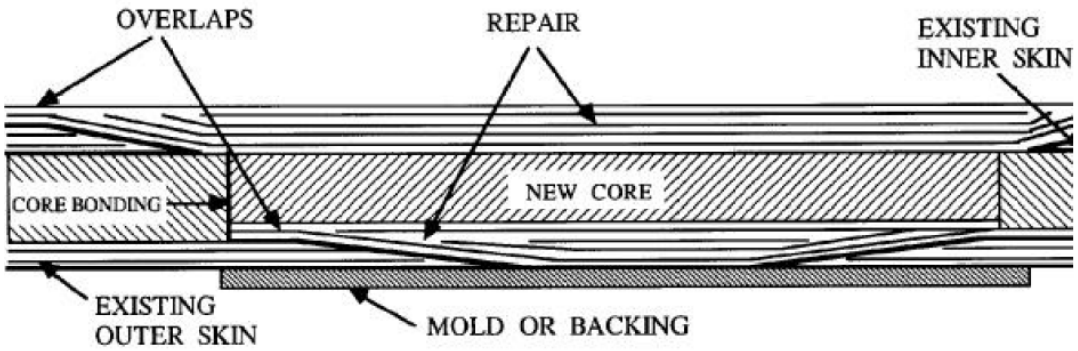
Bolt Hole Damage
The damage could be elongation of the hole causing laminate splitting, or damage to the upper plies.



from Hexcel "*Guide to Composite Repair*"

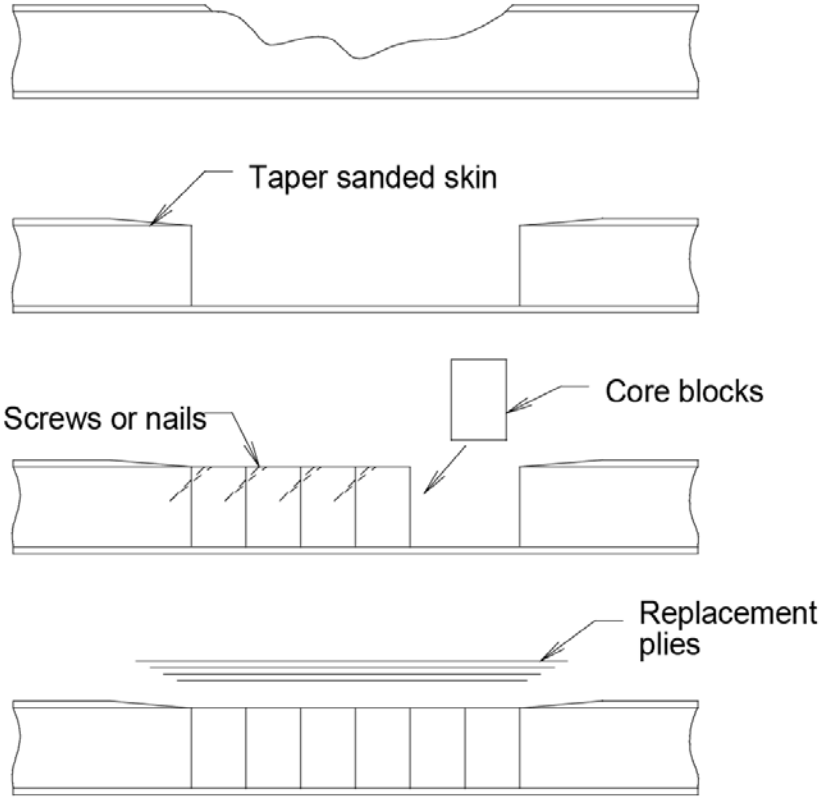
Sandwich Laminate Damage Repair

Sandwich Repair Schematic



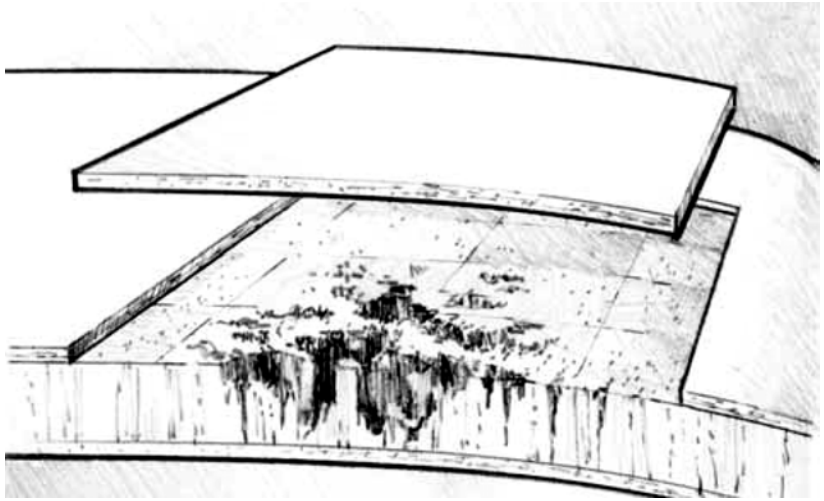
Technique for Repairing Damage to Sandwich Construction
[USCG NVIC No. 8-87]

Repair technique for damage to GRP/foam sandwich panels developed for the Swedish MCMV

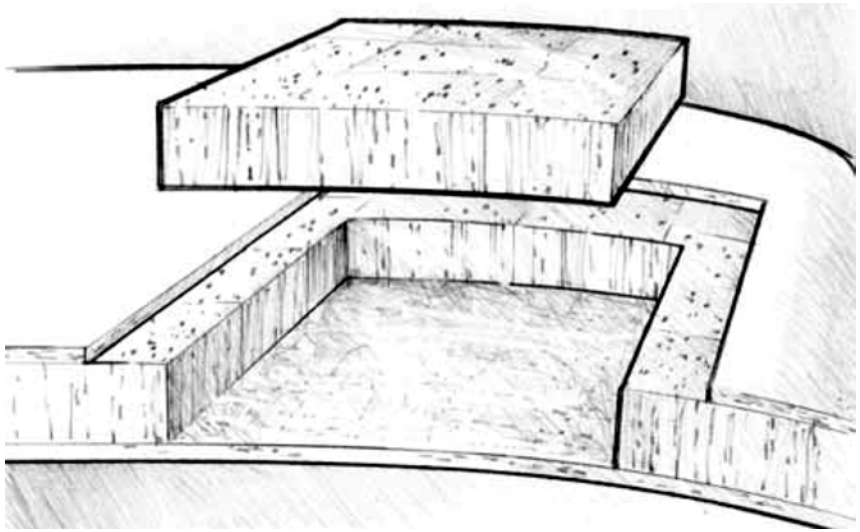


Core Repair

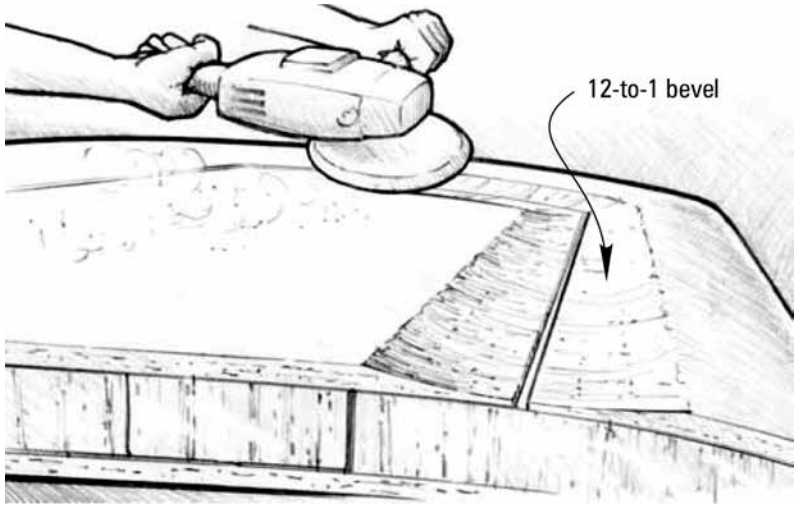
Cut through the skin only, outside of the area of delamination



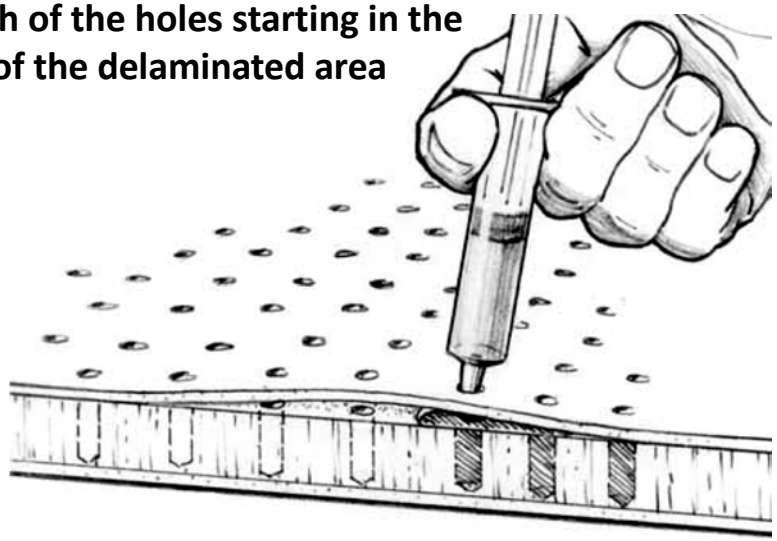
Fit a new piece of core material to match the shape, thickness and density of the damaged core material



Grind a bevel on the edges of the joint, so the joint repair patch can be faired flush with the surface



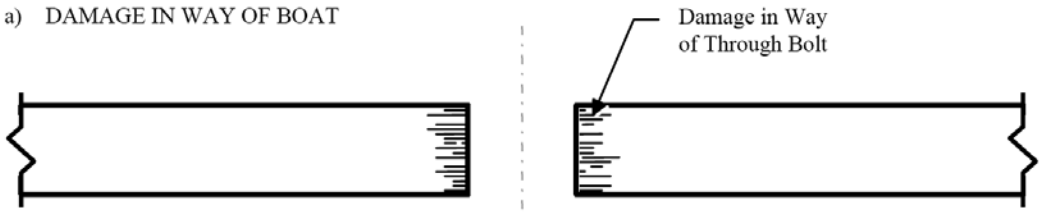
Inject the epoxy mixture under the skin through each of the holes starting in the center of the delaminated area



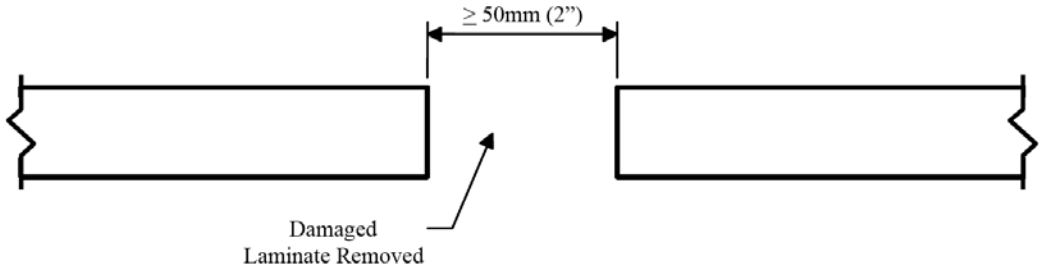
Gougeon Brothers Inc., "WEST System Fiberglass Boat Repair & Maintenance," 15th Edition, April 2011

Repair in Way of Through Bolt Failure

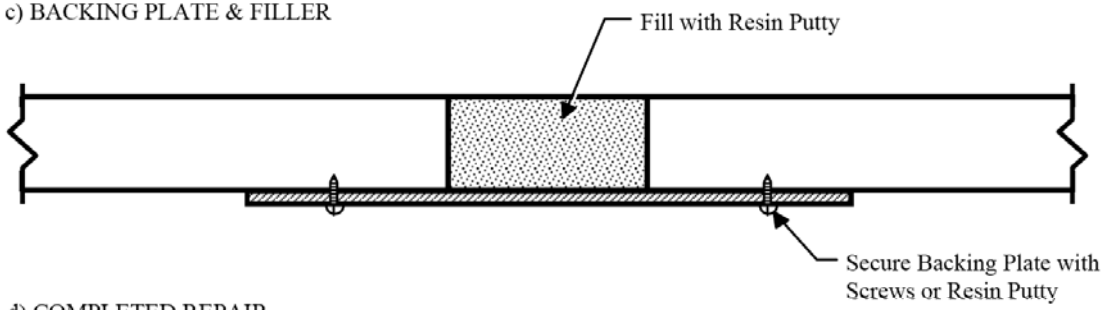
a) DAMAGE IN WAY OF BOAT



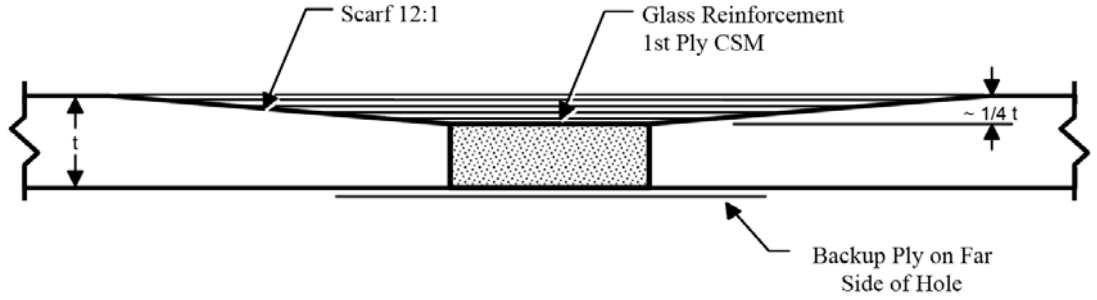
b) LAMINATE REMOVAL



c) BACKING PLATE & FILLER

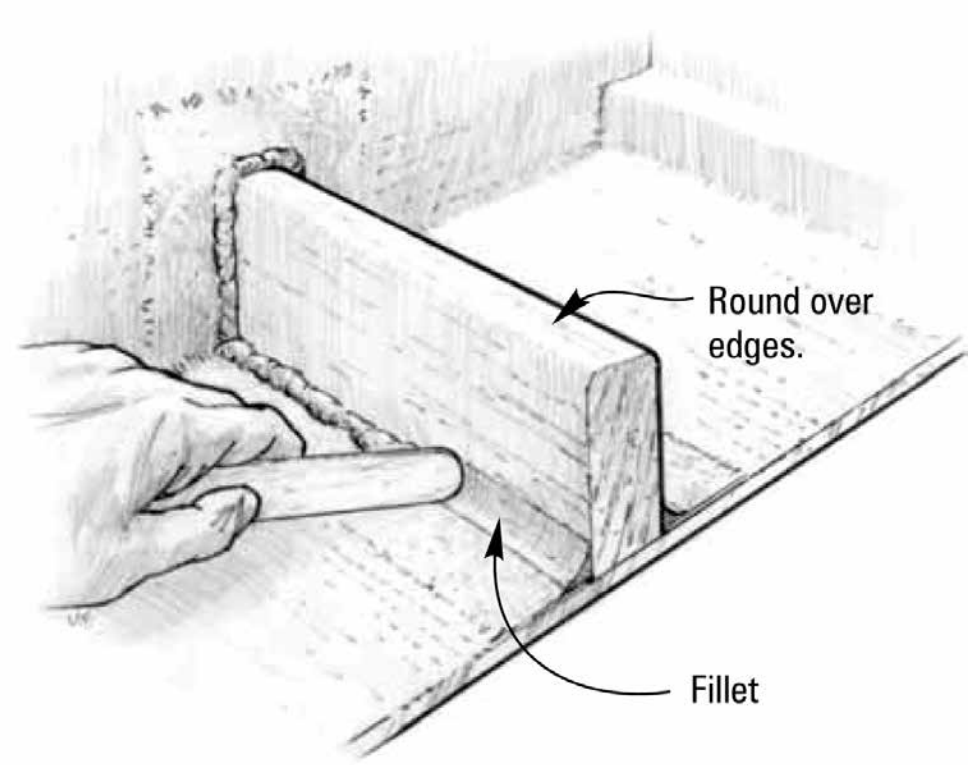


d) COMPLETED REPAIR

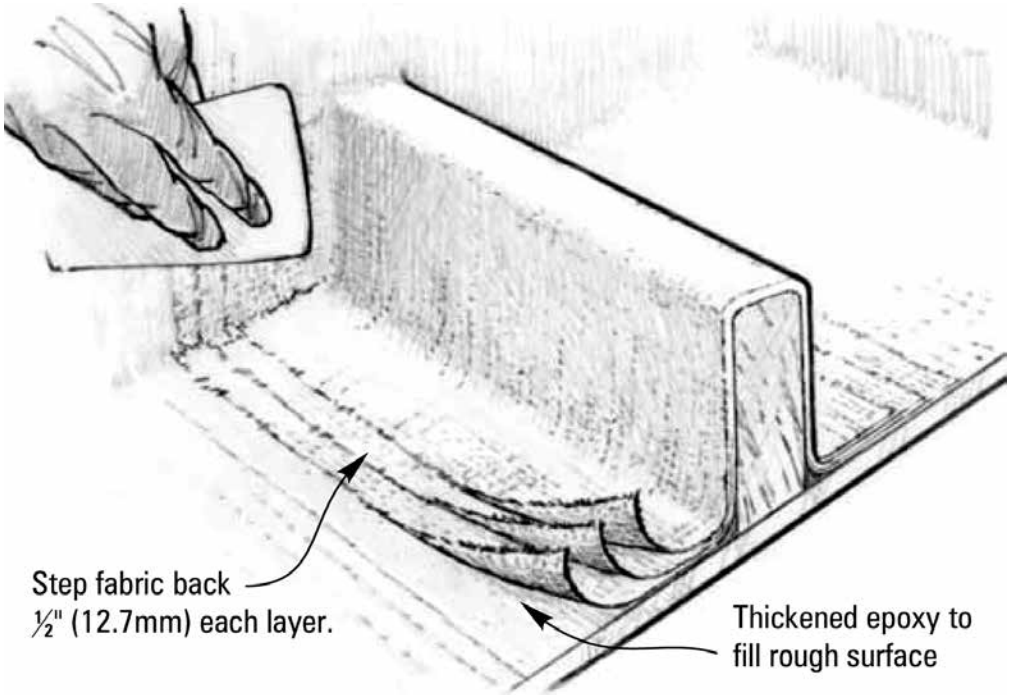


Stiffener Repair

Create Fillets

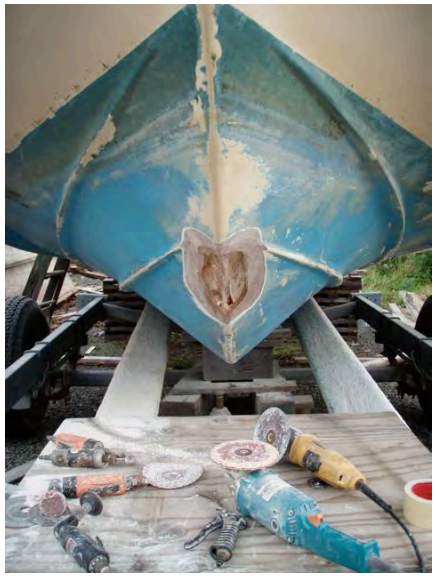


Taper Reinforcement Layers

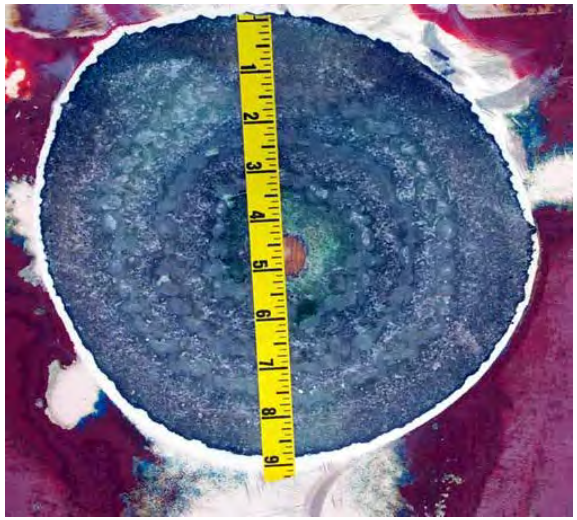


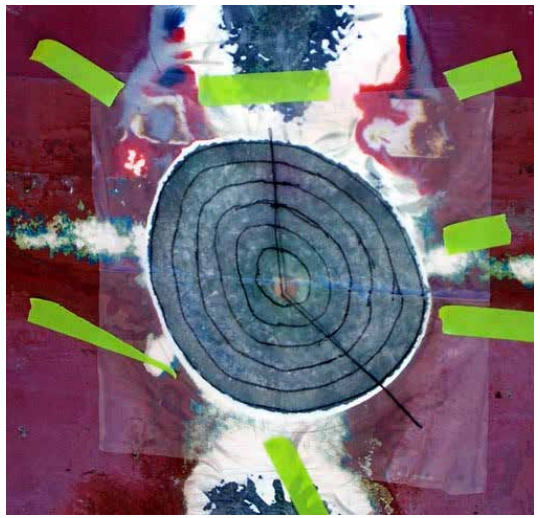
Gougeon Brothers Inc., "WEST System Fiberglass Boat Repair & Maintenance," 15th Edition, April 2011

Small Boat Repair Example



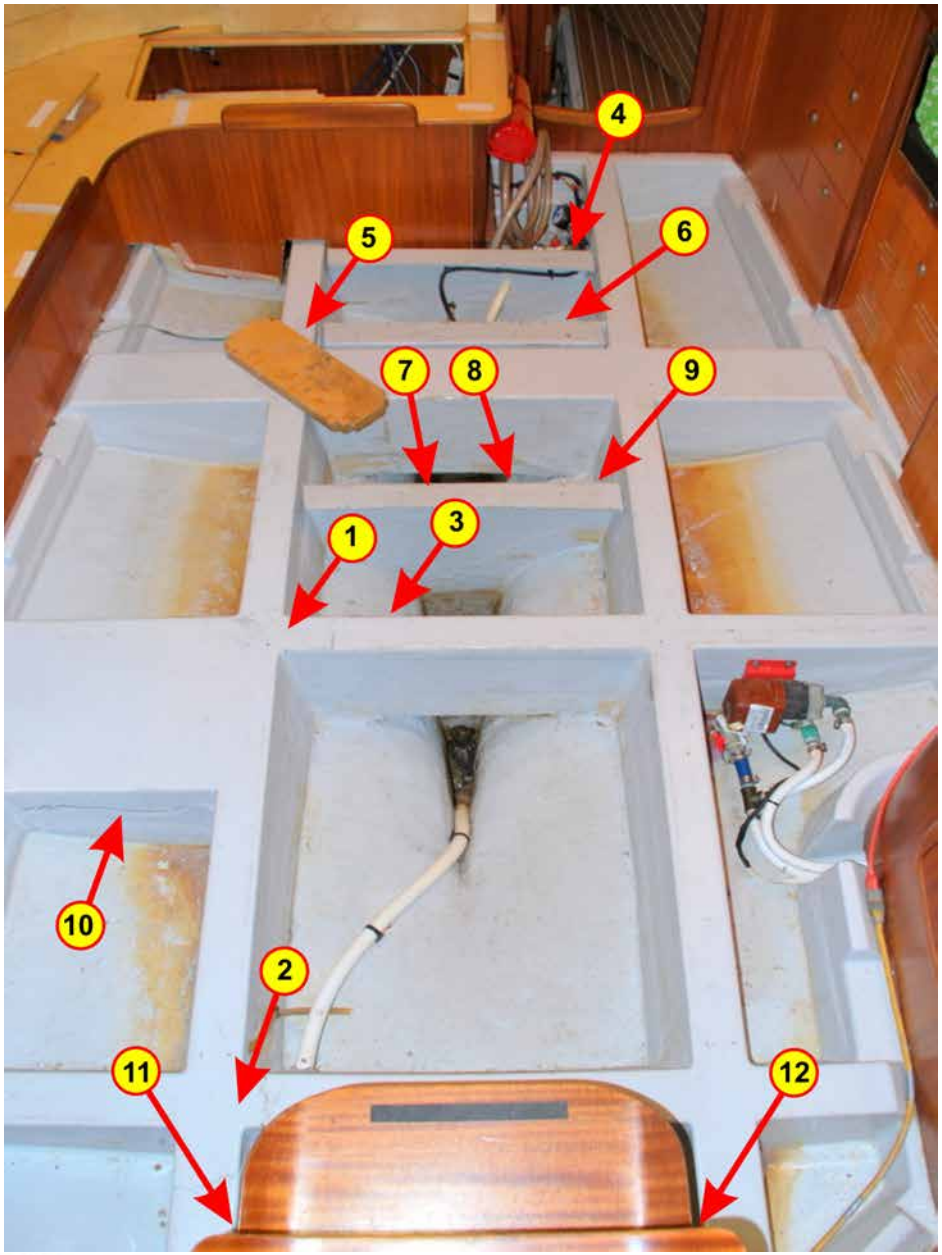
Repair Reinforcement Geometry





Tony Guild, Maritime Technical Services

Framing Repairs



2

1. Grind laminate 9" beyond detected damage
2. Repair with structural laminate up to 16 layers for full thickness

5

1. Grind laminate 4" beyond detected damage
2. Create corner radius with structural putty
3. Repair tabbing with E-BXM 1708/E-LTM 1808/E-BXM 1708 with 1" taper (smallest first)

Overhead Repair

Osprey Marine Composites

Install Transverse Frames

Repair to 120-Foot Motoryacht

Peeling started on starboard side bow area, failed fairing, delamination and failed bottom paint

Multiple layers of existing fairing

Delamination

Mark area for repair reinforcements

Waterline lamination in progress

Using vacuum bags to consolidate repairs

Fosters Yacht Service, Ft. Lauderdale, FL

Damaged Core Replacement

Roby Scalvini, Marine Survey Bureau

Laminate Quality Requirements

The repair should be inspected prior to finishing and the following should not be observed:

- No open voids, pits, cracks, crazing, delaminations or embedded contaminates in the laminate;
- No evidence of resin discoloration or other evidence of extreme exotherm;
- No evidence of dry reinforcement as shown by a white laminate; and
- No wrinkles in the reinforcement and no voids greater than ½" (12 mm). (Voids greater than ½" (12 mm) should be repaired by resin injection. Two 3/16" (5 mm) diameter holes can be drilled into the void; one for injecting resin and the other to let air escape and verify that hole is filled).

The surface of the repair should be smooth and conform to the surrounding surface contour. The degree of cure of the repaired laminate should be within 10% of the resin manufacturer's specified value, as measured by a Barcol Hardness test.

Repair to Offshore Metal Structures

‘Clockspring’ repair to an externally corroded pipe

Carbon fiber repair of 14 inch tee joint on a seawater return header

“The cost effective use of fibre reinforced composites offshore,” University of Newcastle Upon Tyne for the UK Health and Safety Executive, 2003

Repair Summary

- In-plane properties are always degraded for repaired composite structures
- 20:1 scarf repairs are more effective than repairs made involving less area
- Special skills, materials and environmental controls required for effective repairs
- Aerospace level repair methods not envisioned for typiccal marine structures
- Single-skin, E-glass laminates are easier to repair than carbon fiber sandwich constructions