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Sandia National Laboratories

Developing Technologies for Composite Overwrapped Pressure Vessels (COPV) Comparing Traditional Inspections to Advanced 3D Rendering Techniques

PRESENTED BY

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Outline:

- Background and COPV History
- Liner Inspection (Traditional Techniques)
- COPV Processing and Finite Element Analysis
- Advanced Inspection Comparison UT, IR and CT
- Inspection Considerations
- Pressure Experiments and Post Mortem
- Conclusions

BACKGROUND AND HISTORY

Carbon composite overwrapped pressure vessels (COPV)s have been widely used for storing gases under high pressure by NASA for space missions since the 1970s'. The principal advantage of using a solid carbon fiber reinforced plastic (CFRP) over a metallic liner is mainly for reducing weight.

Composite overwrapped pressure vessels (COPV)s are in essence pressure vessels which consist of a metal liners surrounded by a wound composite wraps.

304 Stainless Steel Threaded Float, Oblong, 3" Diameter, 6" Long

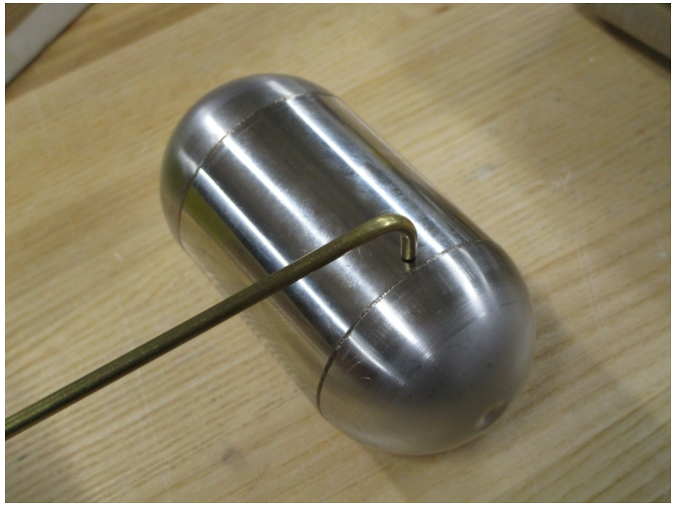
304 Stainless Steel Threaded Float, 2" Diameter, 1/4"-20 UNC Thread Size, 750 Maximum PSI

https://www.mcmaster.com

CONVENTIONAL INSPECTION OF THE LINER WELDS

Liner Inspection Fluorescent Penetrant and Eddy Current

Eddy Current Inspection



Capabilities

- Detection of VERY small defects on the surface (≈ 5 - 10 μm)
- Crack, pore, leak detection
- Ability to inspect complex shapes

Limitations

- Defects MUST be open to the surface and the surface must be free of anything that could interfere with penetrant material
- Excess surface roughness/porosity can hide relevant defects
- Visual acuity of inspector

Capabilities

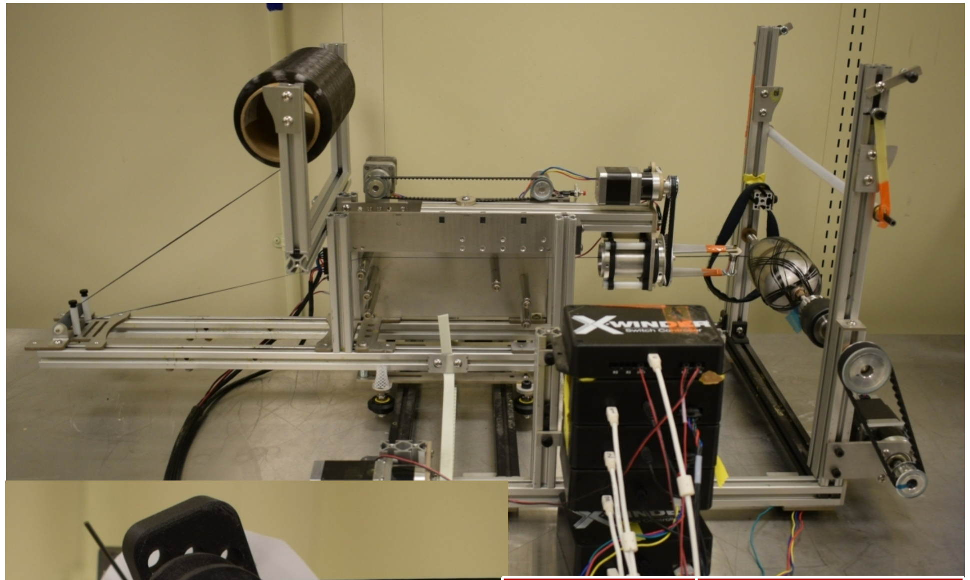
- Detect surface and some subsurface cracks detection.
- Metal identification and sorting using conductivity techniques.
- Measures thickness of thin metals, conductive coatings, and non-conductive coatings on conductive substrate.

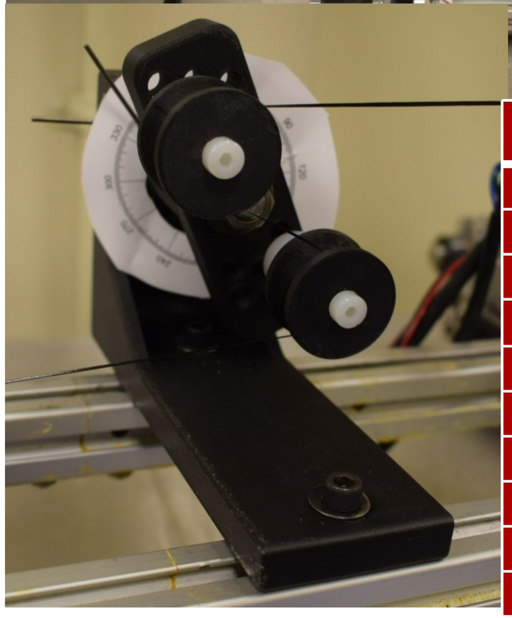
Disadvantages

- Hand-held systems are generally used in localized small areas but can be automated on surfaces.
- The surface of the inspection area must be clean.
- Several human factors: probe lift off and physical positioning can impact results. Effective inspection depth in a material is ¼” up to ½” max.

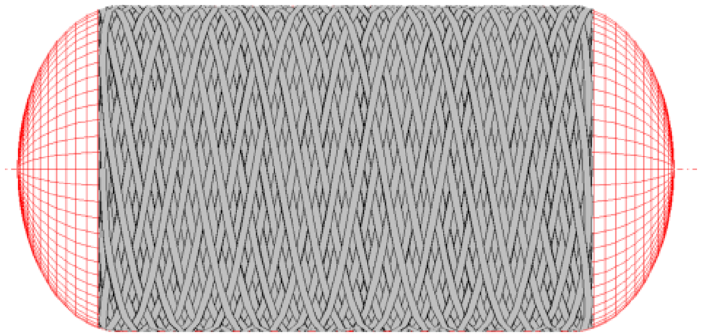
Winding Process (Steep Learning Curve)

Low cost X-winder with limited capability (no complex mandrel geometries).

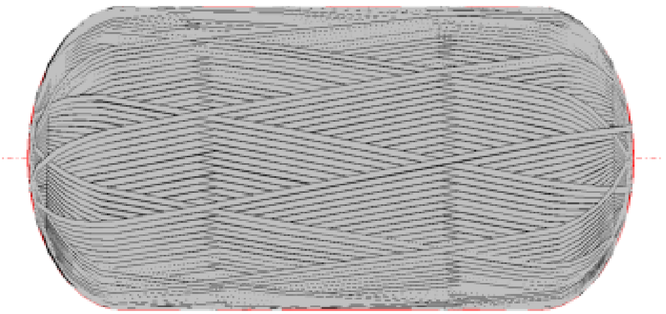




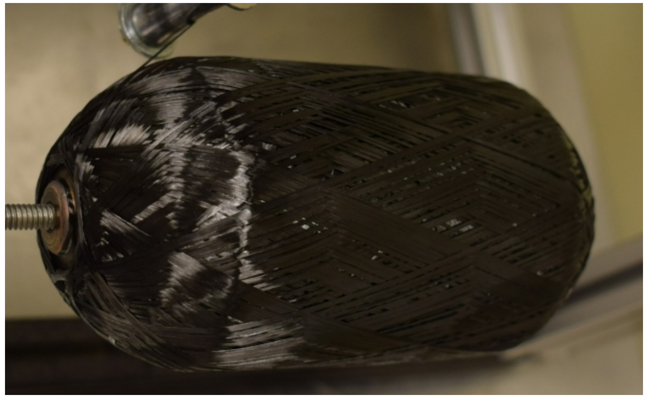
Layer	Angle (°)
1	5.8
2	65.0
3	11.5
4	75.0
5	80.0
6	20.0
7	85.0
8	90.0
9	7.0
10	90.0



80° Layer

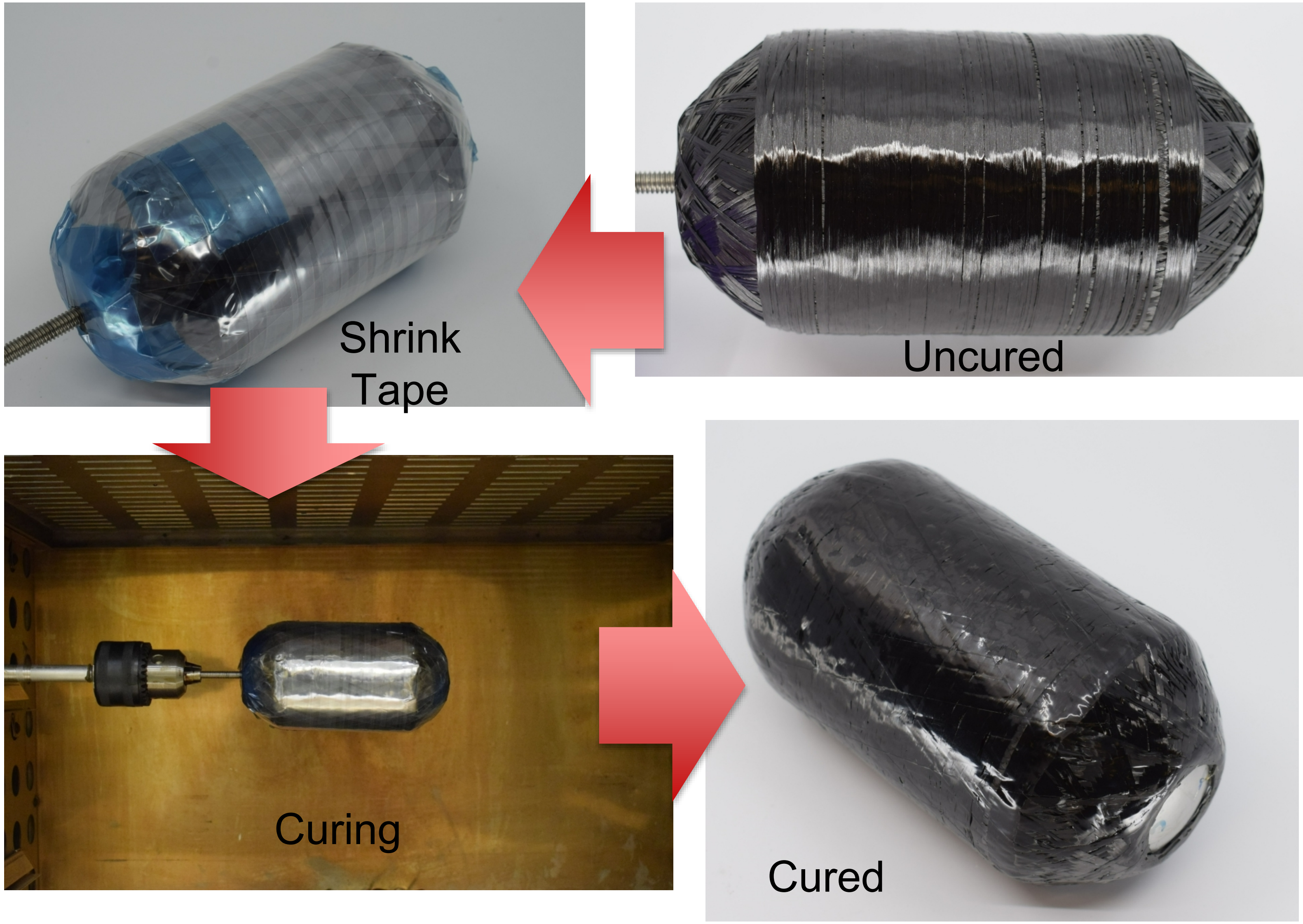


11.5° Layer



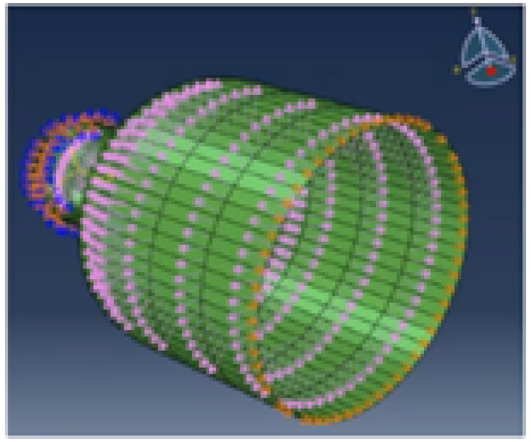
Curing Process

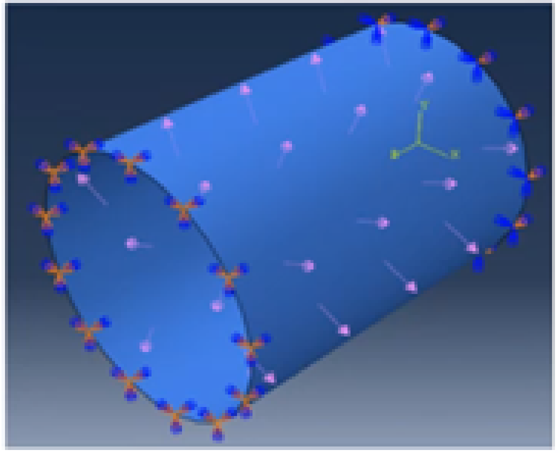
- Wrapped in heat shrink tape to aid with compaction
  - Developing vacuum bagging technique
- Cured in an oven with a "rotisserie" action
- Experienced some audible popping after cure
  - The composite is disbonding from liner due to residual thermal stresses (difference in linear coefficients of expansion).



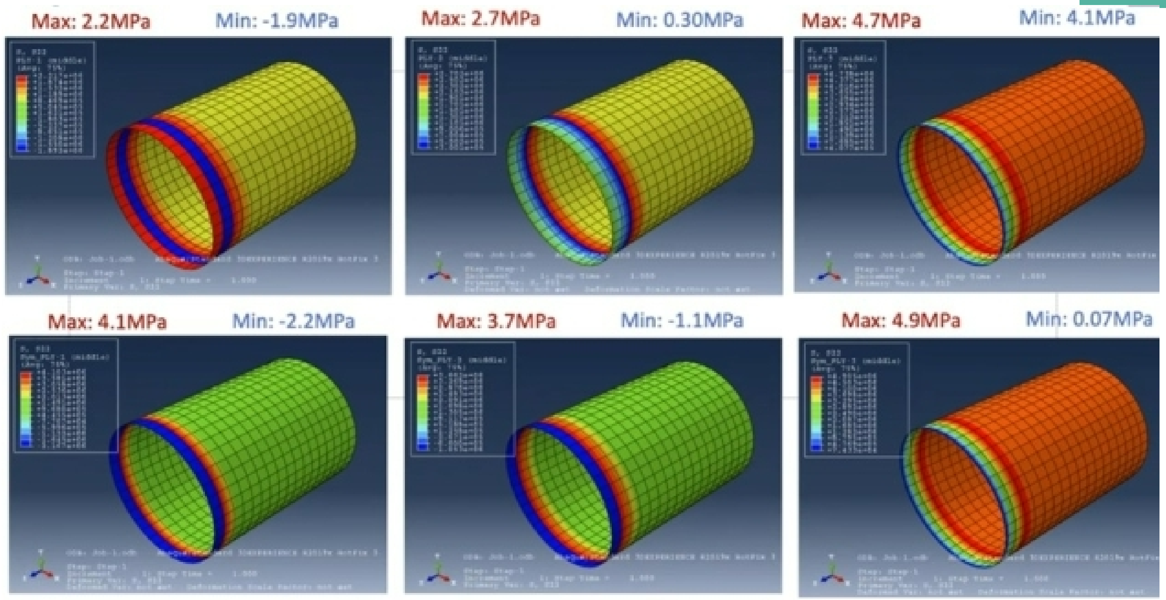
Finite Element Analysis of Composite Layup

- Isolate center section
  - 32mm radius
  - 86mm length
  - 0.1414mm ply thickness
  - Material: elastic lamina
    - Density 1583
    - E11 = 165 Gpa, E22 = 8.83GPa, nu12 = 0.3, G12=G13=G23 = 4.3GPa
  - number plies = 6plies (0, 15, 70)sym
  - Boundary conditions:
    - Fixed end: u1=u2=u3=ur1=ur2=ur3=0
    - Sym end: u3=0, ur1=ur2=ur3=0 (just z-dir)
  - Loading: pressure 1MPa

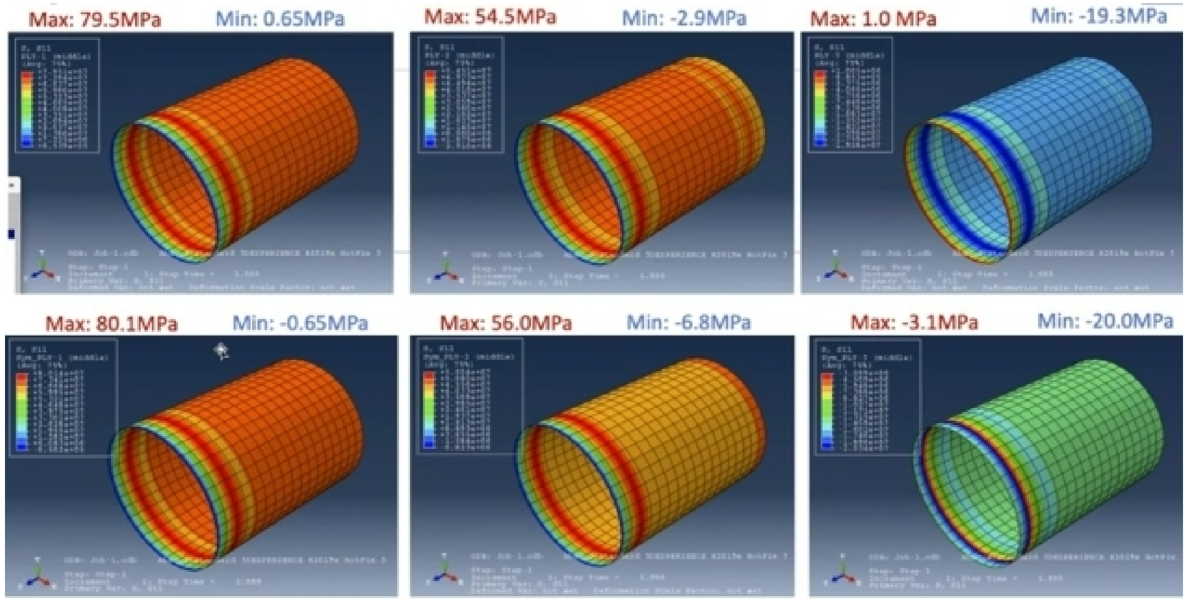




Axial Stress



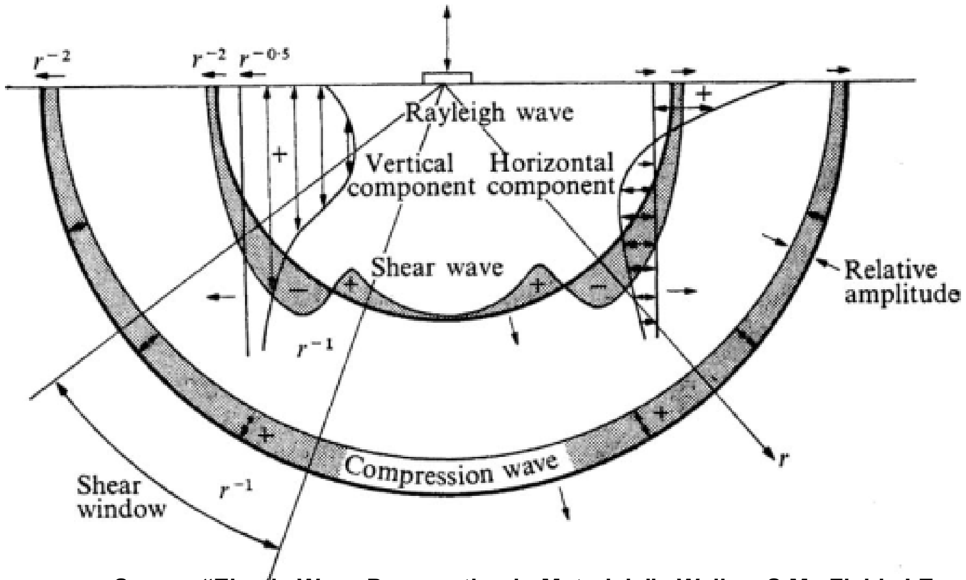
Hoop Stress



ADVANCED INSPECTION COMPARISON UT, IR AND CT

Wave Scatter Theory

Materials that demonstrate frequency dependent velocity variation are known as dispersive materials. In these types of materials there is a distinction made between the group velocity and the phase velocity.



Source "Elastic Wave Propagation in Materials" , Walley, S.M., Field, J.E. Materials Science and Technology, Elsevier 2005.

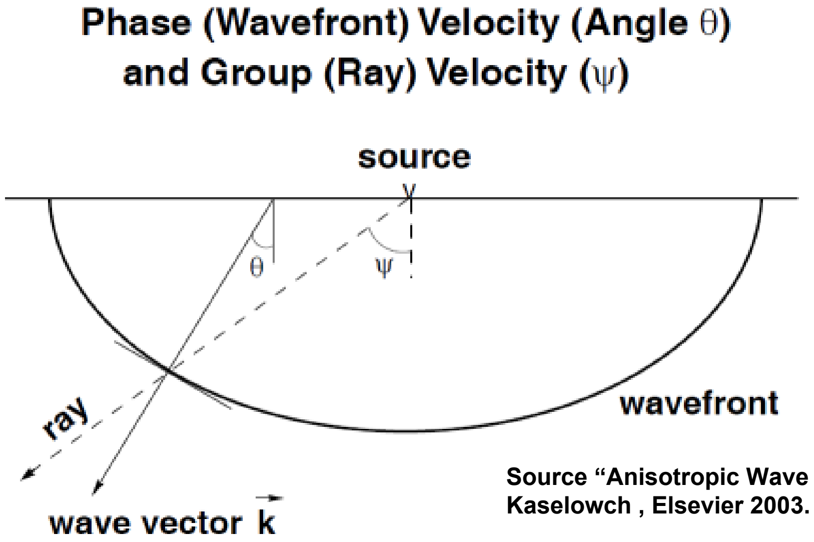
$$v_g = v_p + f\,\frac{\delta v_p}{\delta f}$$

Group velocity (v_g) is defined as a rate at which the point of maximum amplitude in the ultrasonic pulse (many frequencies) propagates through the material.

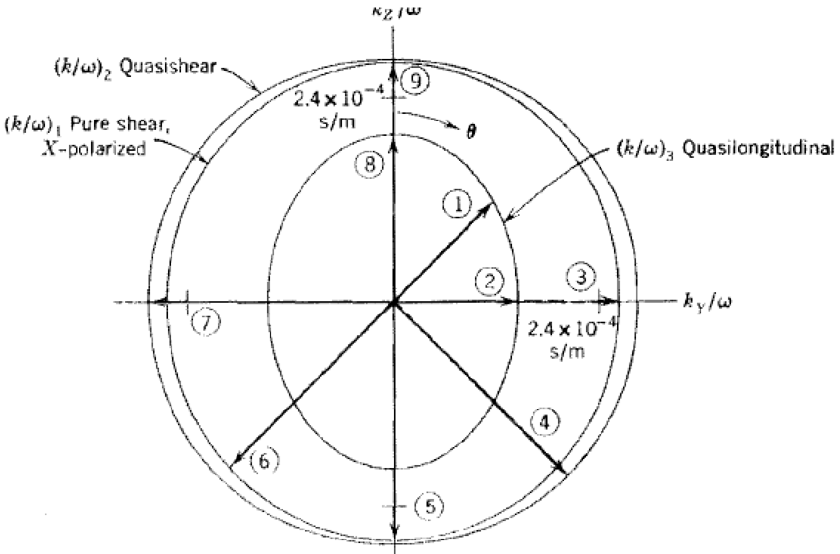
Phase velocity (v_p) is defined as the velocity of a continuous sinusoidal wave (one frequency) in the material.

These two velocities are related to each other through dispersive properties (frequency dependence of the phase velocity).

Plane Wave in Orthotropic Materials



Source “Anisotropic Wave Propagation”,
Kaselowch , Elsevier 2003.



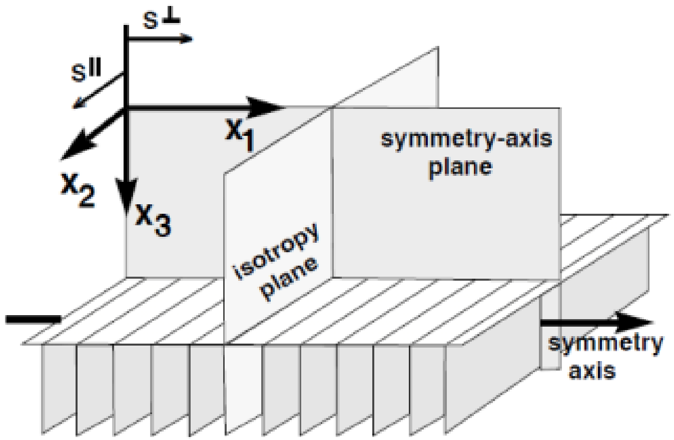
Source “Acoustic Fields and Waves in Solids”,
Appendix 3 , B. A. Bauld, Wiley, New York 1973.

The elastic modulus for composite materials is generally not isotropic in nature, but is orthotropic. Most composites contain voids and micro-cracks within the structure. These manufacturing anomalies result in; a higher ultrasonic noise and texture appearance in the inspection images.

Sound dispersion and absorption causes signal losses as thickness increases. All these variables make the bondline interface between metals and composites more difficult to detect and quantify.

Orthotropic Materials Properties

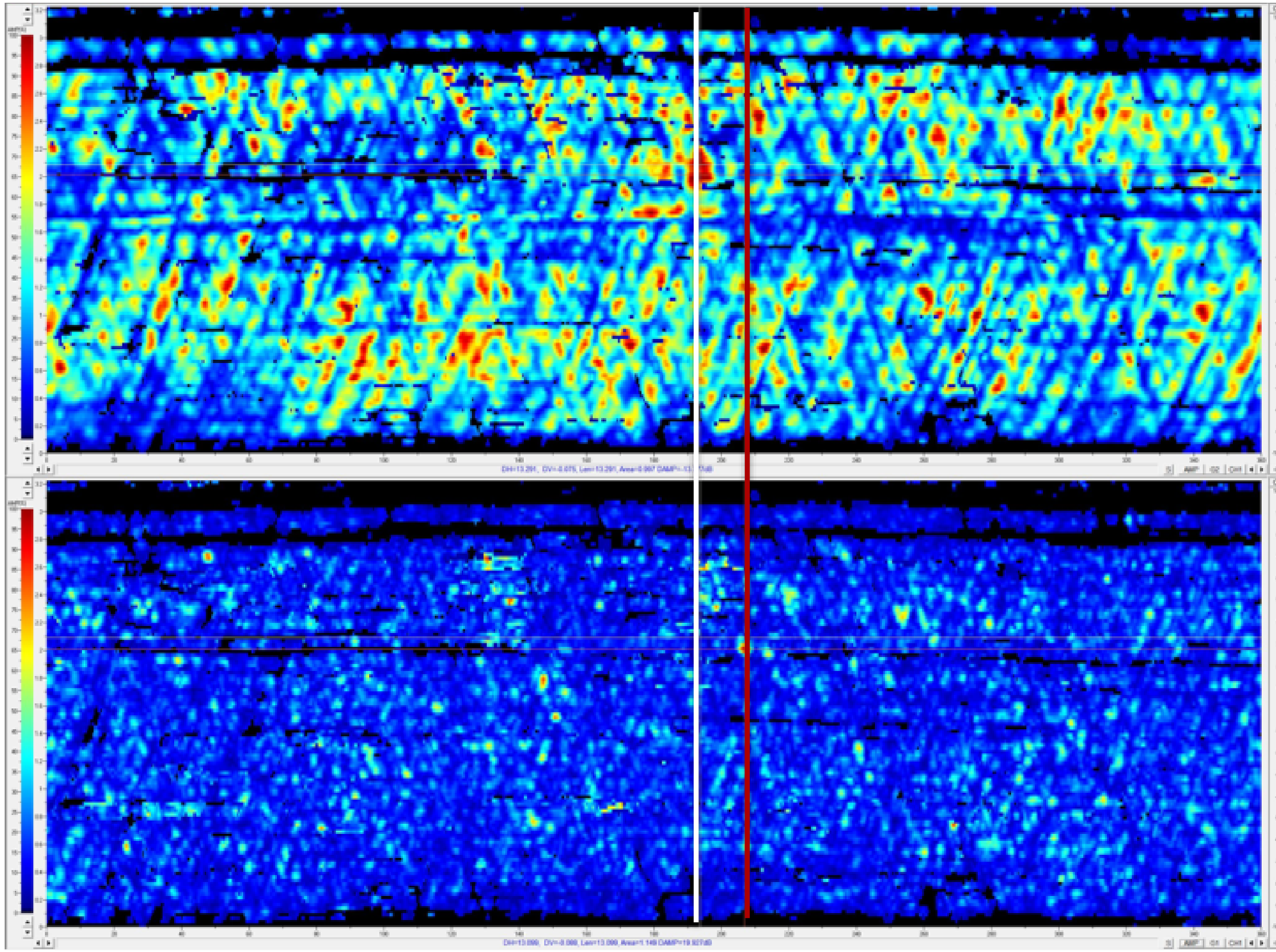
$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{v_{yx}}{E_y} & -\frac{v_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{v_{xy}}{E_x} & \frac{1}{E_y} & -\frac{v_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{v_{xz}}{E_x} & -\frac{v_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}$$

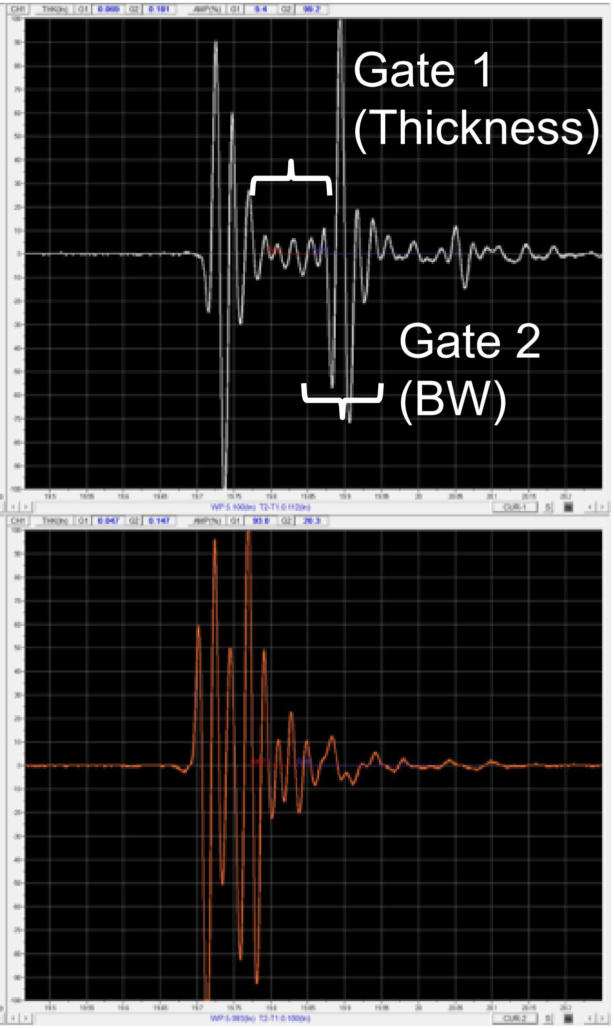


Source: Horizontal Transverse Isotropic axis defination, MIT OpenCourseWare http://ocw.mit.edu/terms/

Orthotropic constitutive equations has two orthogonal planes of symmetry and properties are independent of direction within each plane. These materials require 9 independent variables (i.e. elastic constants) in their constitutive matrices. This equation is based on orthotropic elasticity up to failure.

ULTRASONIC INSPECTION/RESULTS (COPV 4)



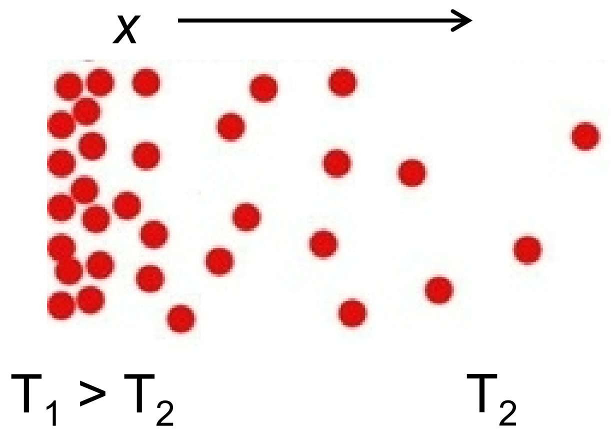


Frequency 5 MHZ
Probe Diameter 25.4 mm
Focal Length 12.7 cm

Ultrasonic C-scan images above reveal the weave pattern of COPV 4 (barrel section only) sample. Top image (gate 2) shows composite wrap backwall signal amplitude and the dependence of the liner interface. The lower image displays the signal amplitude between the outside surface and backwall of the composite wrap (composite thickness).

Thermal Material Properties

Conduction: energy transfer from a more energetic particles to less energetic particles within a material. Interactions between particles are due to a thermal gradient.



Fourier's law defines time rate of heat transfer through a material. The heat flux is proportional to the negative gradient in the temperature and to the area. The proportionality constant is the transport property thermal conductivity W/(m °C).

$$\vec{q} = \mathbf{q''}$$

Heat flux **q"** is the heat transfer rate in direction *x* per unit area perpendicular to the direction of transfer. Since heat transfer rate is a vector quantity it can be written in general of the conduction rate equation:

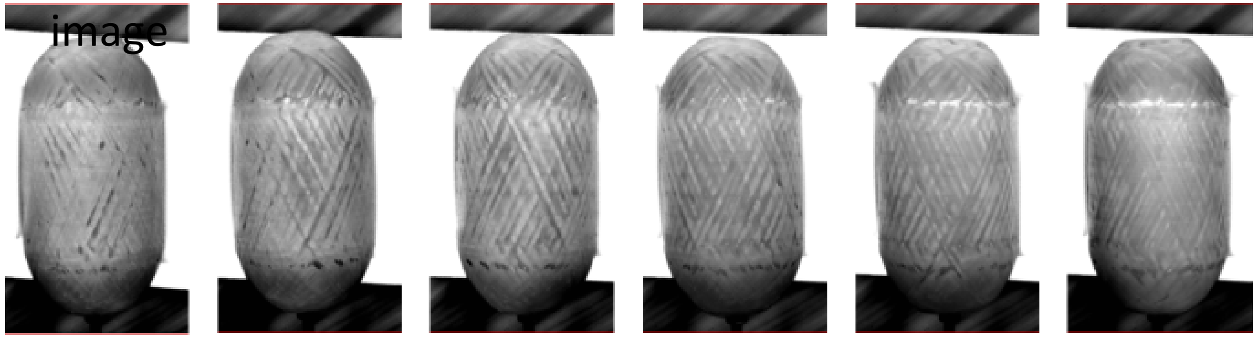
$$\mathbf{q''} = -k\nabla T = -k\left(\boldsymbol{i}\frac{\partial T}{\partial x} + \boldsymbol{j}\frac{\partial T}{\partial y} + \boldsymbol{k}\frac{\partial T}{\partial z}\right)$$

Thermal Properties

Material	Conductivity, k W/(m °C)	Specific Heat, c_p J/(kg °C)	Density, ρ kg/(m^3)	Diffusivity, α m^2/sec 1 x 10 $^{-7}$	Effusivity ε J/(m^2 °C) √s
Phenolic (resin pressed)	0.3766	1255	1380	2.174	807.667
Teflon	0.2510	1004	2170	1.152	739.6
Carbon Graphite	167.36	707.1	2250	1052	16317.6
CFRP Parallel Carbon Fibers	7	1200	1600	36.45	3666.06
CFRP Perpendicular Carbon Fibers	0.8	1200	1600	4.167	1239.45
Epoxy (hysol)	0.1945	1172	1210	1.372	525.271
Aluminum 2024 T3	121	875	2780	497.43	17156.1
Copper	397.48	384.9	8940	1155.	36982.8
Stainless Steel 304	14.644	502.1	7920	36.83	7631.1
GRP Parallel Glass Fibers	0.38	1200	1900	16.67	930.81
GRP Perpendicular Glass Fibers	0.30	1200	1900	13.16	827.04

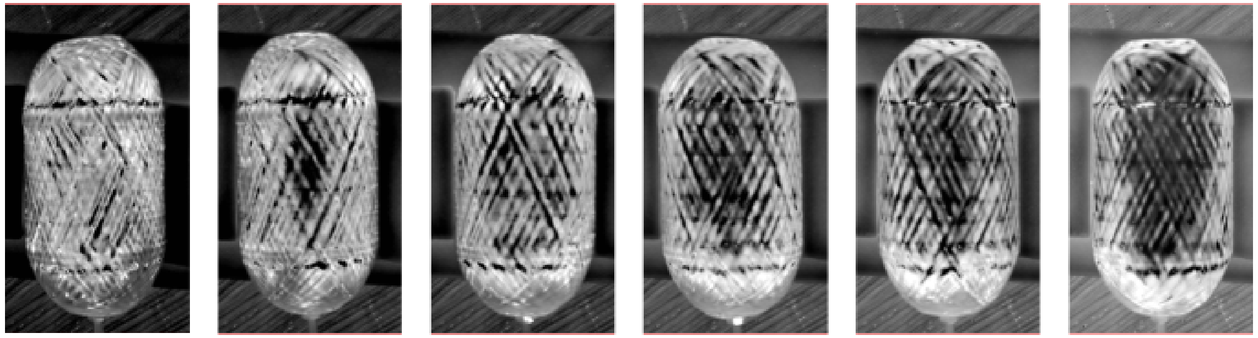
FLASH THERMOGRAPHY INSPECTION/RESULTS (COPV 4)

Time slice of reconstructed raw thermography image



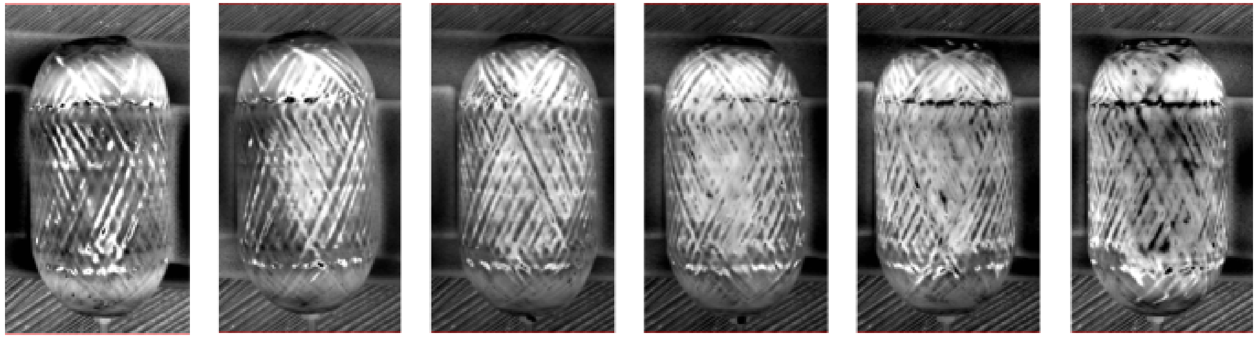
0°-60° 60°-120° 120°-180° 180°-240° 240°-300° 300°-0°

Time slice of reconstructed (first derivate) thermography image



0°-60° 60°-120° 120°-180° 180°-240° 240°-300° 300°-0°

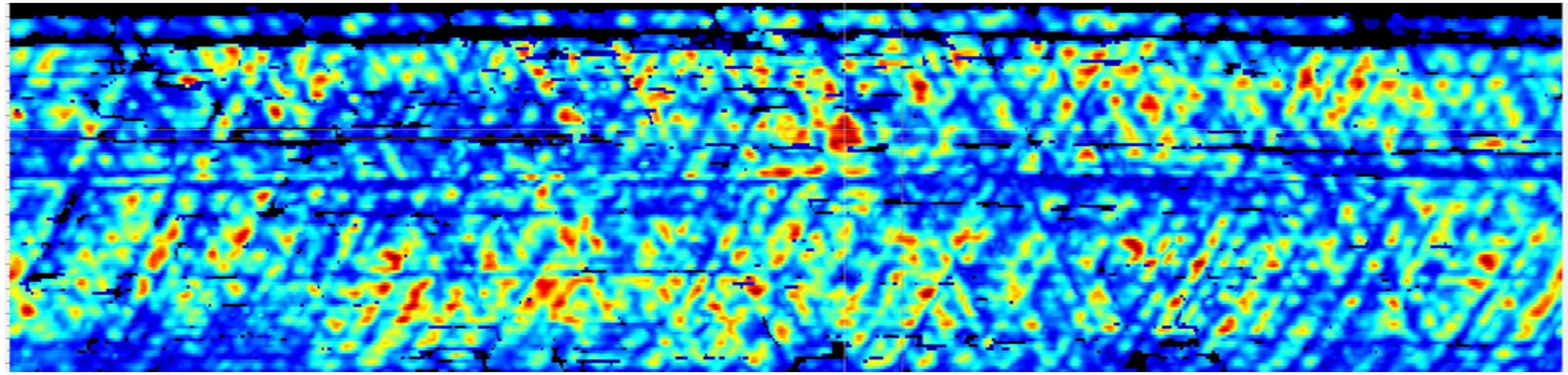
Time slice of reconstructed (second derivate) thermography image

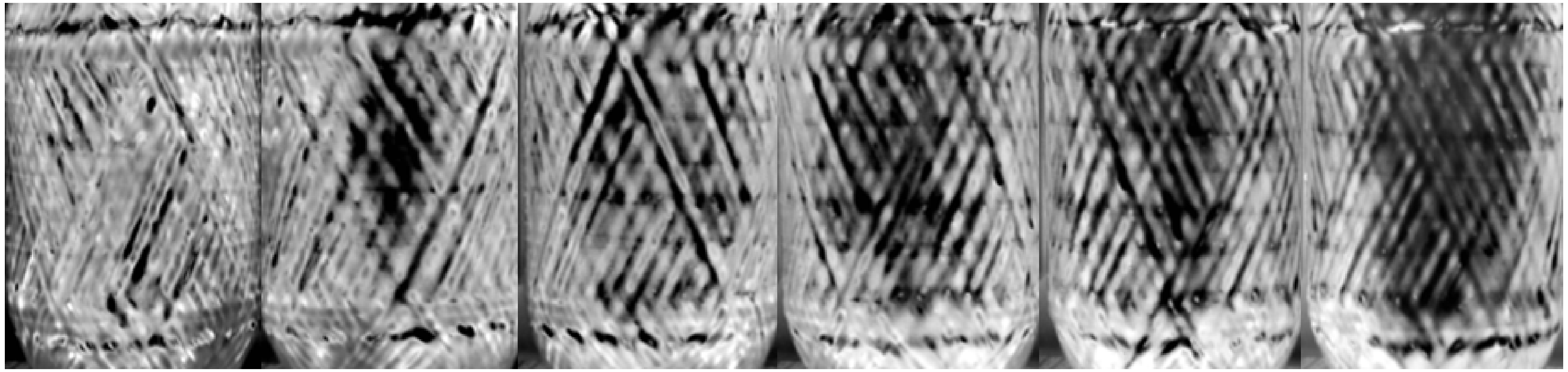


0°-60° 60°-120° 120°-180° 180°-240° 240°-300° 300°-0°

All images at 12.9 seconds after flash sample COPV 4

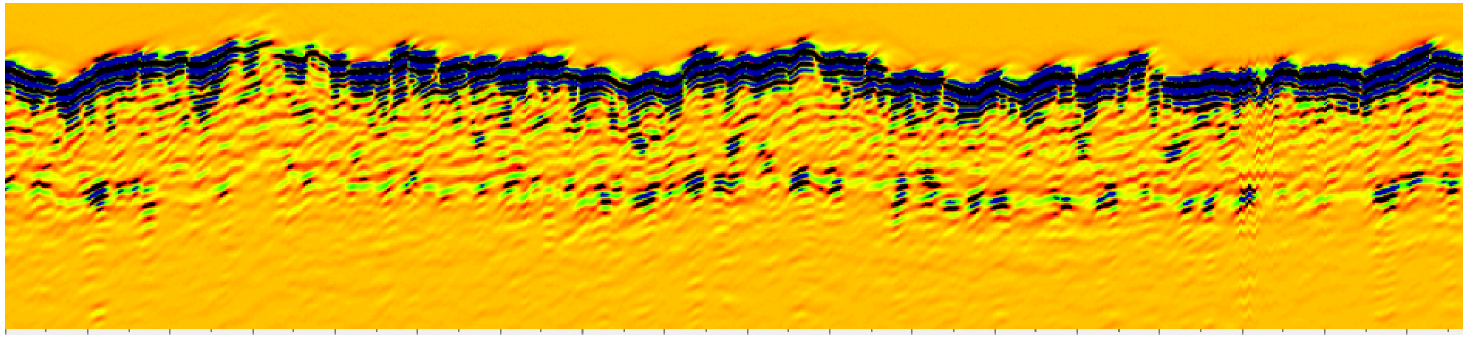
ULTRASONIC AND FLASH THERMOGRAPHY COMPARISON (COPV 4)





Bonded area reflects sound into the liner and sends a weaker reflection back to the probe (blue). Poorly bonded areas return no interface signal from the liner this results in a higher amplitude signal (red). The thermography reveals cool spots where the composite wrap has lack of resin and air pockets.

B-scan of composite thickness reveals voids in the wrap.



Computed Tomography Set-up

Computed Tomography (CT) collects penetrating radiation measurements from the sample's x-ray opacity using an amorphous silicon digital detector array. This technique generates an image from a thin slice of an object's volume.

These projections are collected and mapped together to create a volumetric data set. The fraction of the x-ray beam that is attenuated will directly relate to the density and thickness of the material through which the photon has traveled. The computer software program Volume Graphics™ is used to characterize the integrity by displaying planes of reconstructed data through the volume.

Sample	Carbon Wrap Over Stainless Steel Liner		
Energy	125 kV	Projections	3000
Current	400 µA	Effective Pixel Size	~ 91 µm
Magnification	n/a	Detector Type	Varian L08
Filter	0.52mm Cu, 0.4mmAl	X-ray Head Type	XRayWorX
Time	72 minutes	Frame Average	*8.25 Frame average per projection*

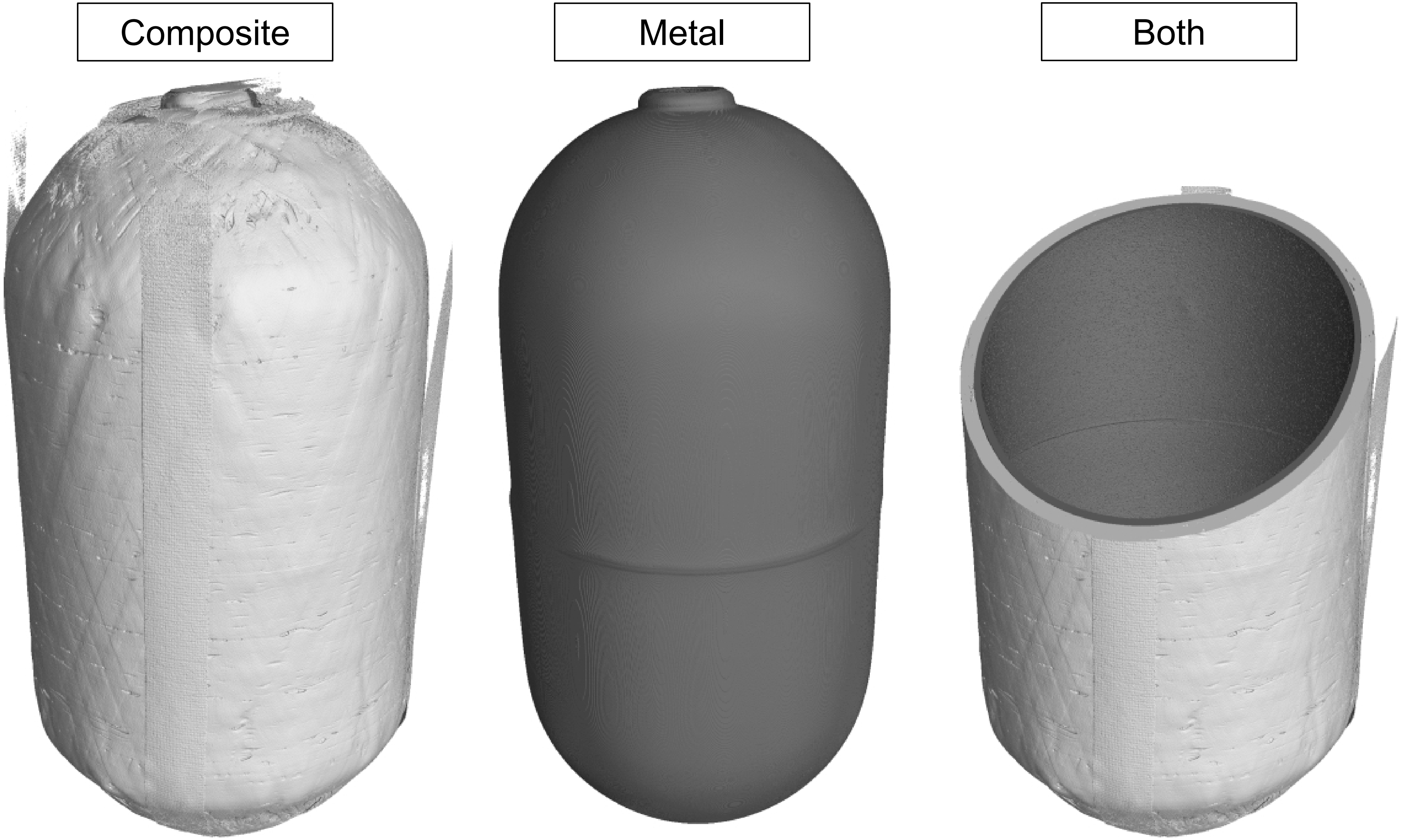
COPV Image Registration

- Liner were digitally registered using the metal section of the scan data.
- The coordinate system was defined using:
  - A cylinder defined using points on the outer metal surface
  - A sphere (shown on right) created by averaging two spheres defined with points on the top/bottom hemispheres
  - A line defined using the tapped hole to “clock” the sample
- The origin of the coordinate system is the middle sphere center location.

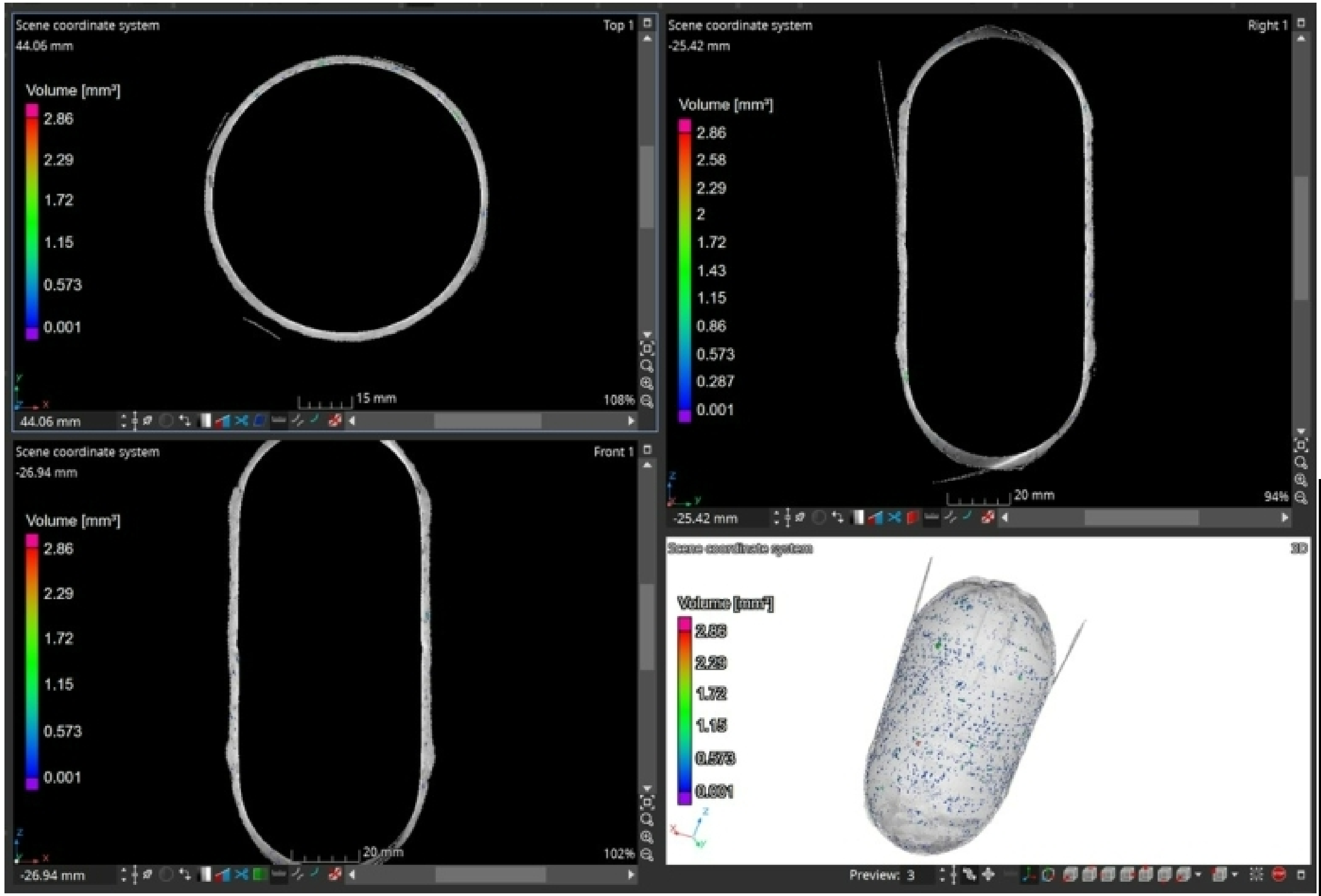
Image Segmentation

- Image segmentation was completed by using a region growing to separate composite from metal and aid in the analysis.
- The following procedure was used:
  - Perform advanced multi-material surface determination with an over-sized composite region
  - Use material region growing to create ROI of metal
  - Invert this metal ROI so that new ROI is everything but metal
  - Use region growing (not material) with the following settings
    - Mode: Static: Tolerance: 1.5
    - Starting Point: in composite ~halfway up z-direction
    - Radius: 120 mm
  - Use material region growing to remove any significant defects from new ROI
  - Intersection new ROI with inverted metal ROI to remove any metal parts, creating a composite ROI
  - Extract metal and composite ROIs to create new volumes

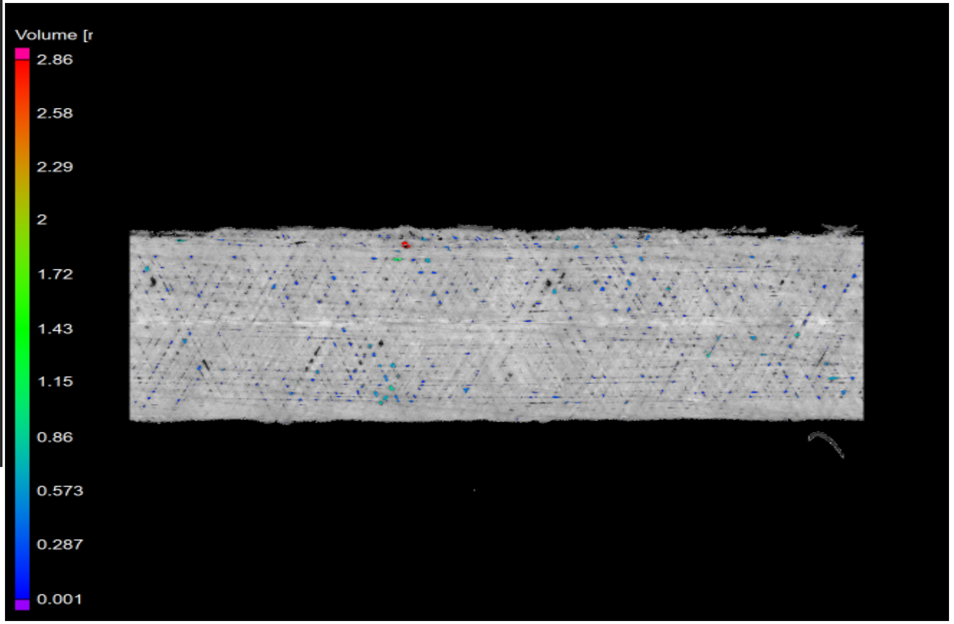
Image Segmentation (Continued)



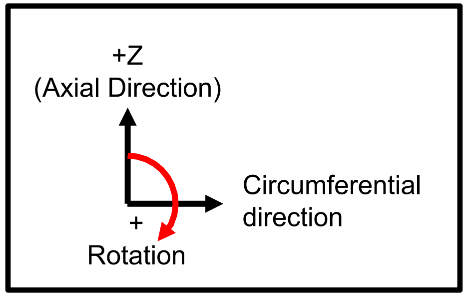
THREE DIMENSIONAL IMAGING USING COMMERCIAL CODE



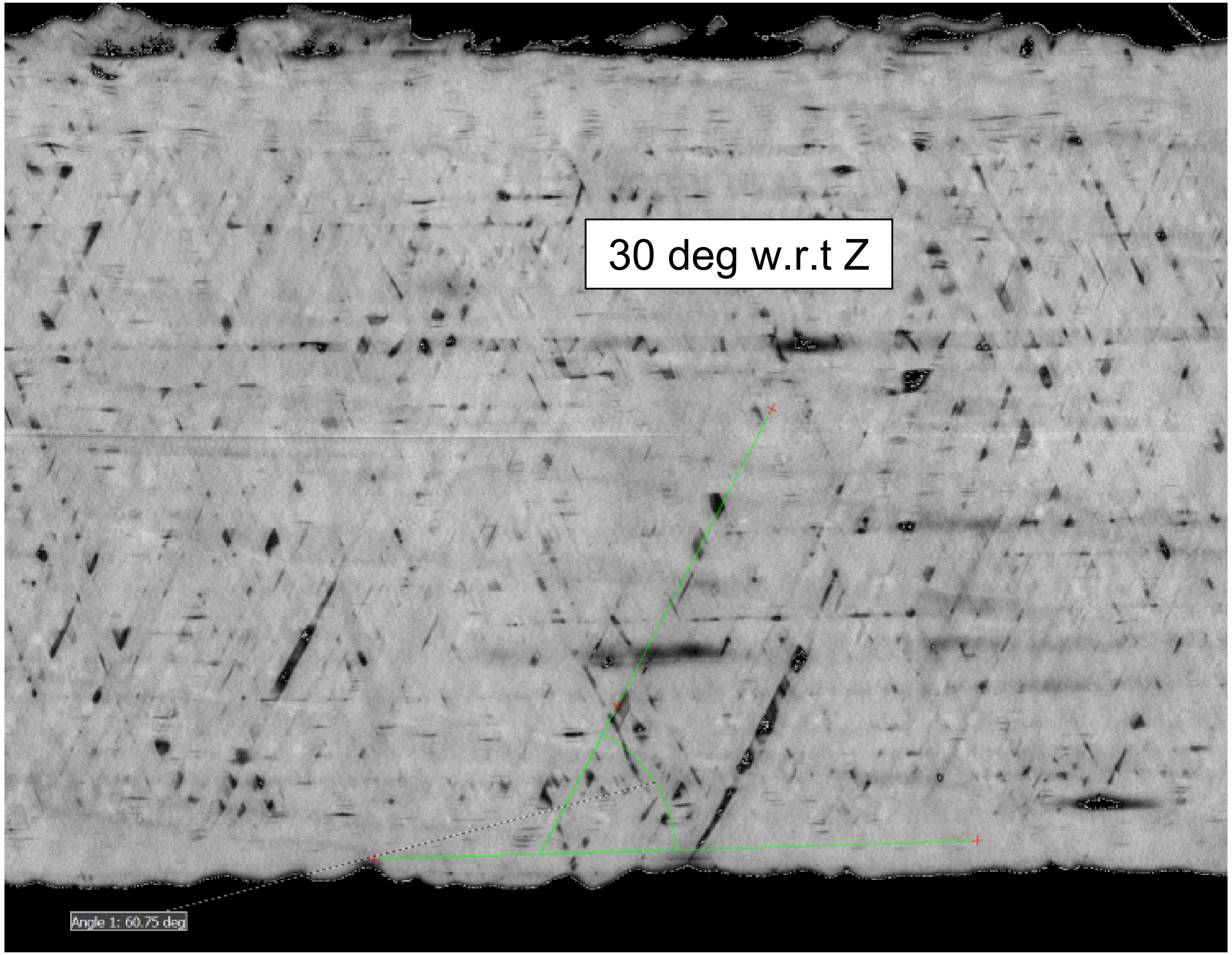
Non-planar window



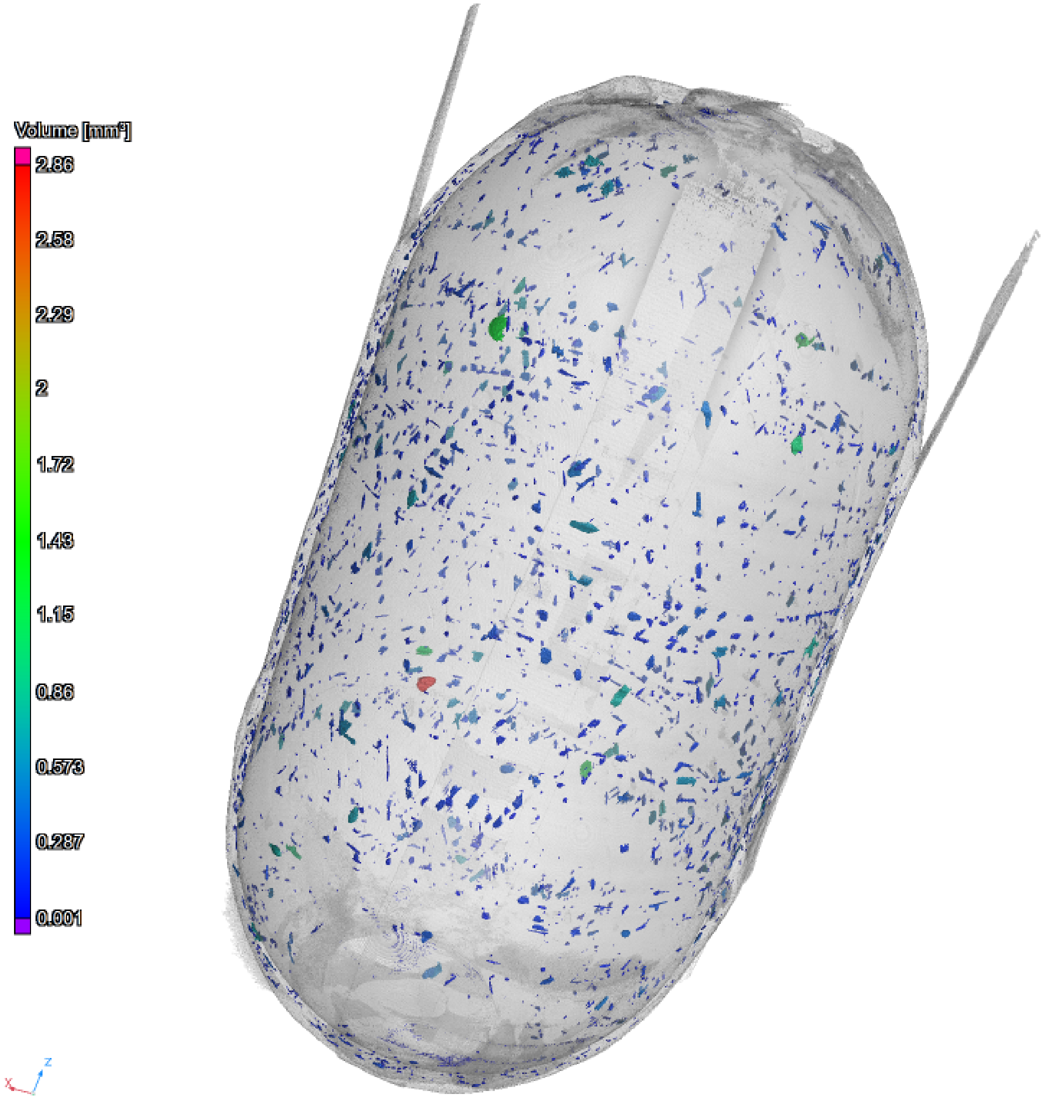
CT Results of COPV 4

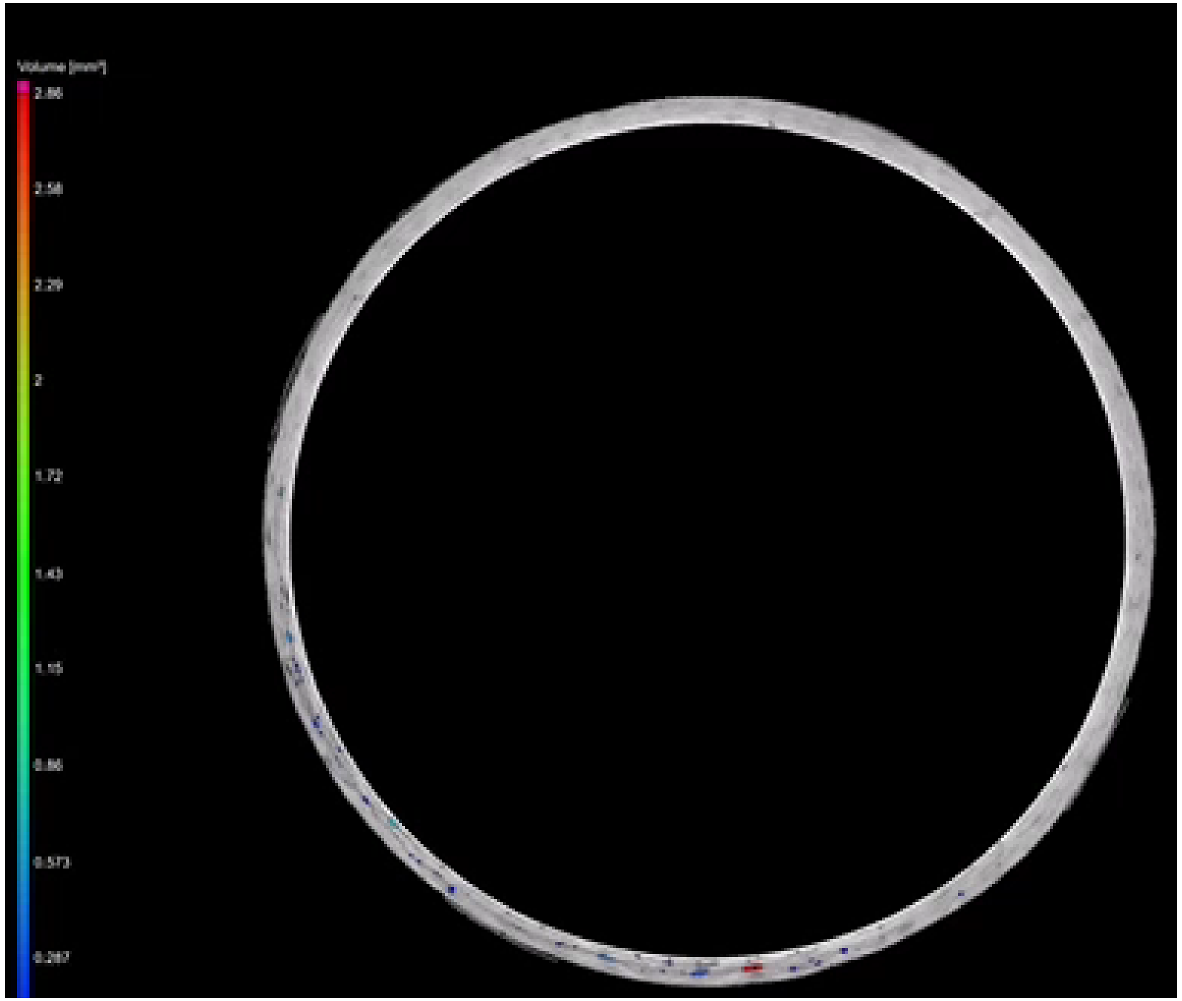


- Wrap angle estimated at 30 deg w.r.t. cylinder Z-axis (60 deg w.r.t. XY tangential direction)
- Stochastic gaps in wrap (black in image) are wrap imperfections and inconsistent winding tension.
- Wrap direction seems consistent through radial direction (nonplanar image stack)



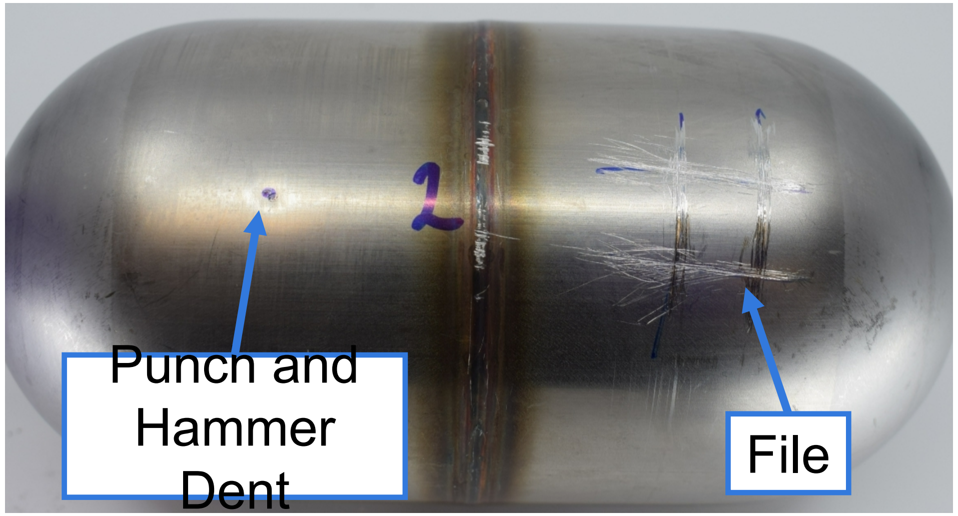
CT MISSES SOME OF PORES WITHIN COPV 4

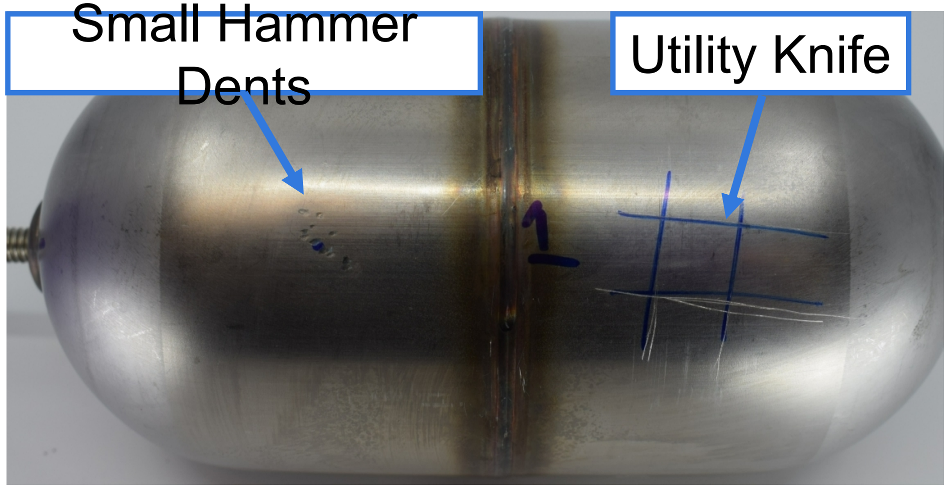


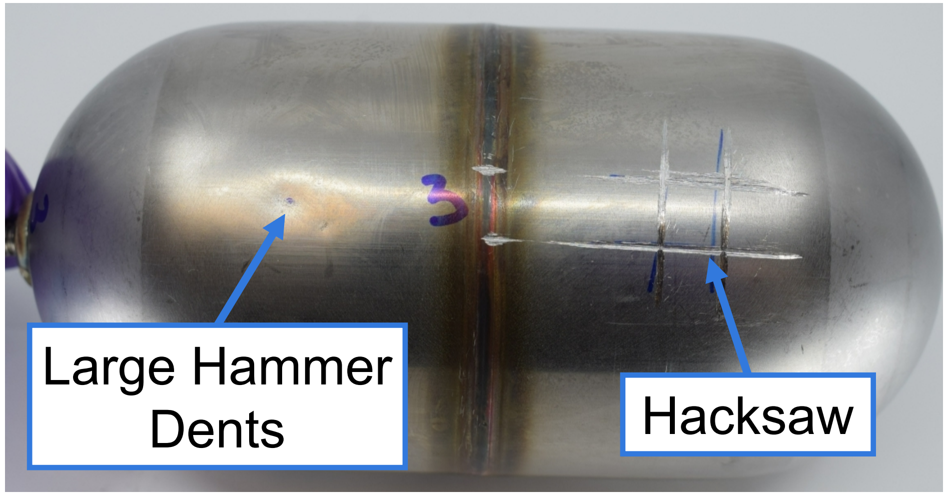


Introduction of Manufacturing “Defects”

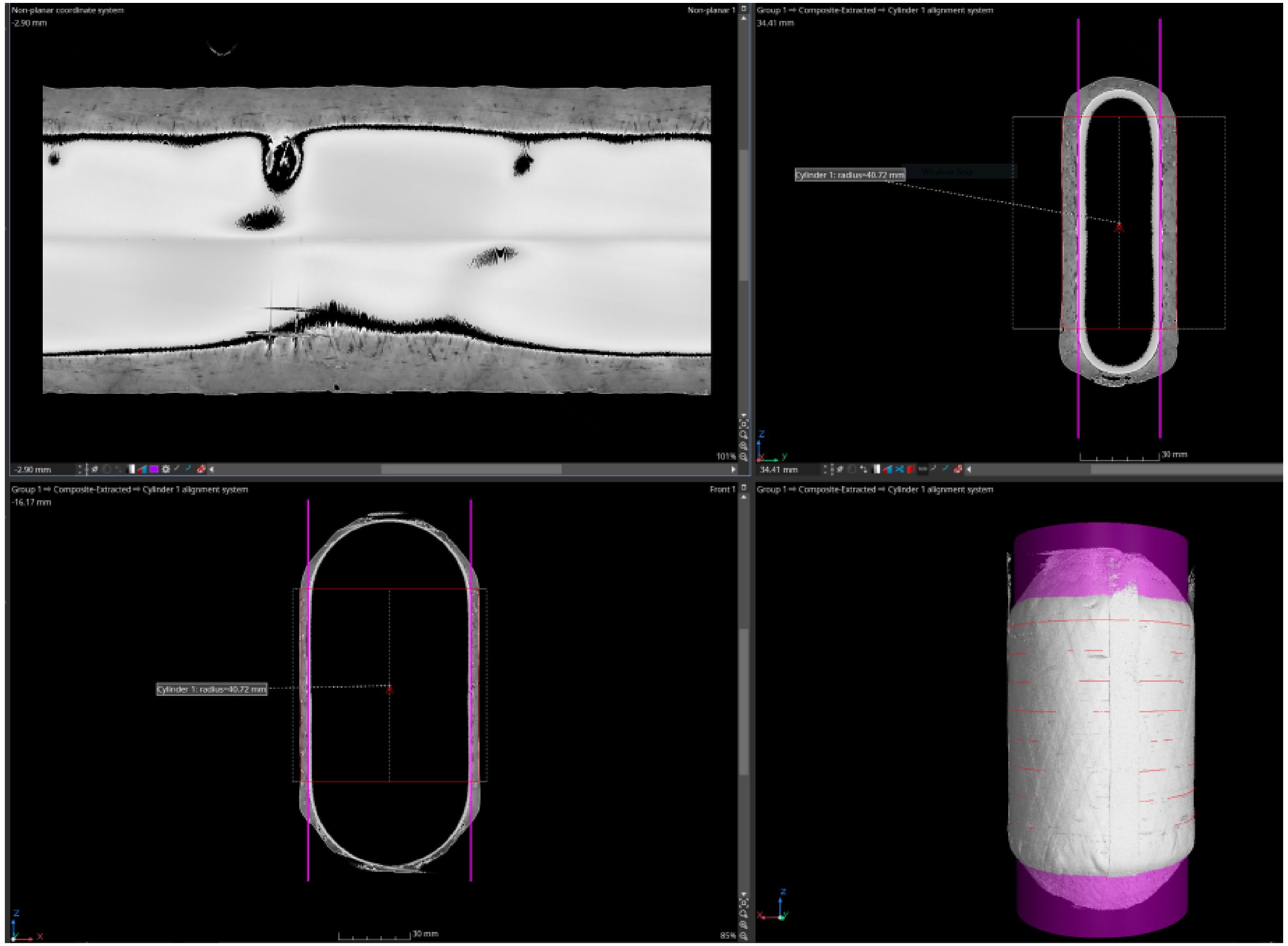
- Introduced intentional defects in metal liner for to determine if NDI can detect
  - Linear defects with utility knife, file and hacksaw
  - Point defects with hammer or hammer and punch

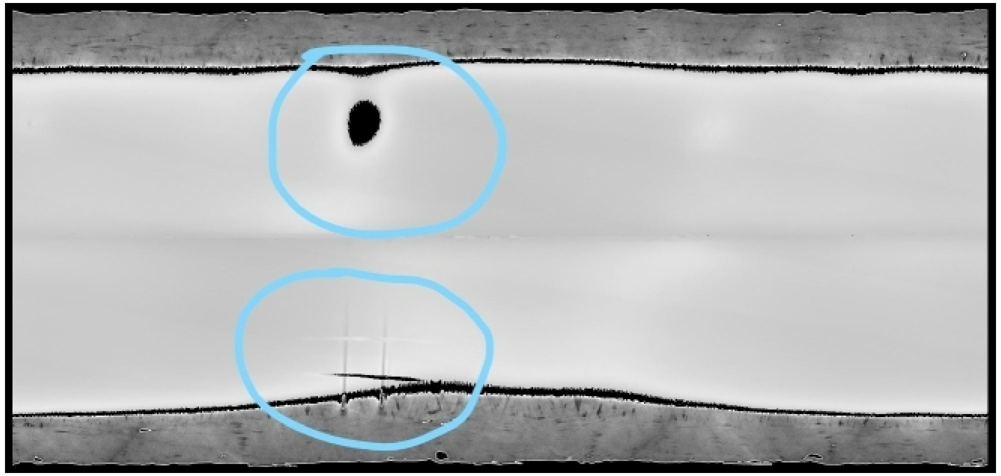


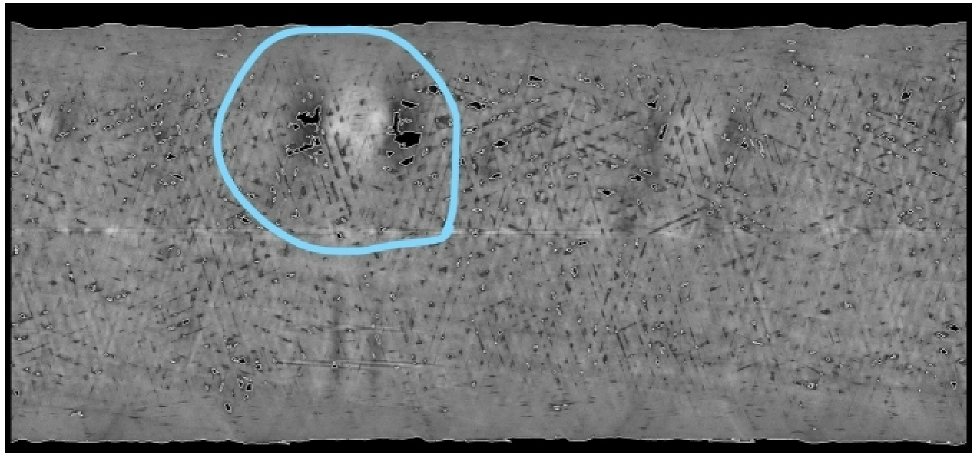




Computed Tomography Detection of Liner Defects







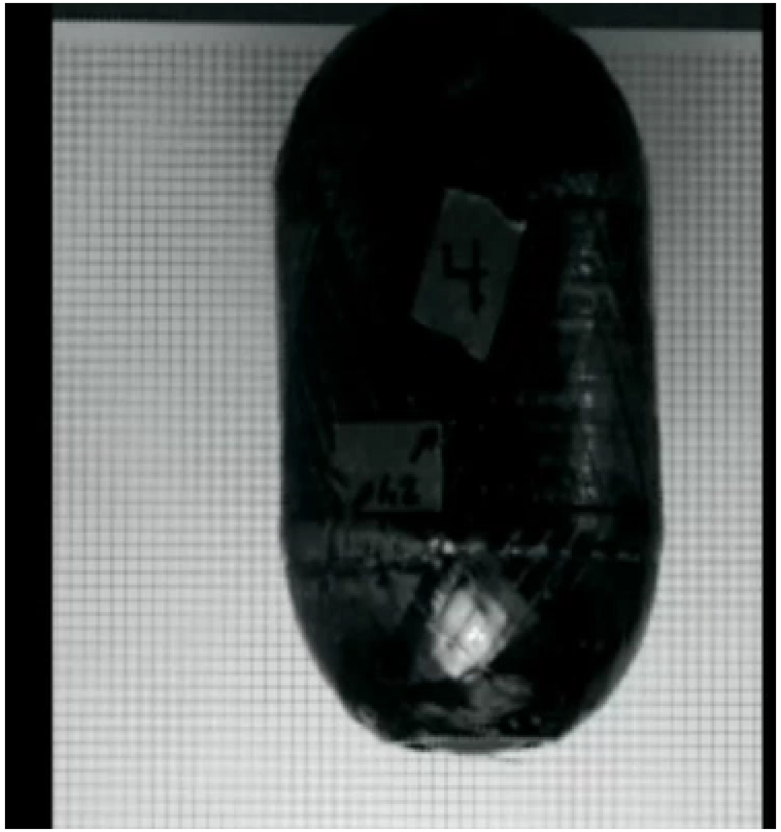
COPV #6 reveals engineering generated defects are detectable with computed Tomography.

BURST TESTING RESULTS (MOVIES)

Liner 1 (real time and high speed video)

COPV 4 (real time)

COPV 4 (high speed video)

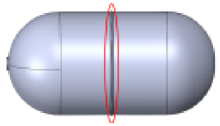


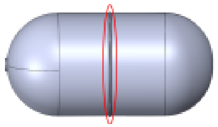
Edgertronic Camera: frame rate was 10k frames per second with a camera resolution of 1280 by 128.

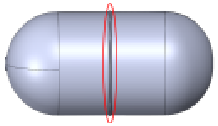
BURST TESTING RESULTS

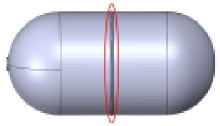
Float SN	Weight (g)	Diameter (inches)	
Liner 01	254.64	120°	2.99
		240°	3.01
		360°	2.97
Liner 02	249.52	120°	2.99
		240°	2.99
		360°	3.00
Liner 03	249.94	120°	2.98
		240°	3.00
		360°	3.00
COPV 04	365.80	120°	3.14
		240°	3.14
		360°	3.14
COPV 05 Adhesive	416.76	120°	3.25
		240°	3.24
		360°	3.23
COPV 06	398.64	120°	3.22
		240°	3.21
		360°	3.21

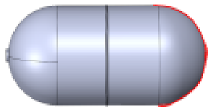
SN	Float Type	Burst Pressure psi	Time elapsed	Location of failure
01	Liner	3873psi	12: 05 min	Waist weld
02	Liner	3733psi	8:55 min	Waist weld
03	Liner	3601psi	6:54 min	Waist weld
04	Overwrap marked “1”	7413psi	10:00 min	Waist weld
05	Overwrap w/adhesive marked “3”	5250psi	~5 min	Top Curve
06	Overwrap marked “2”/Flawed	No burst; leaked around 7ksi	~10 min	Inside











Conclusions

- The ultrasonic elastic wave interacts with the wound fiber structure. Factors that affect the ability to detect bondline variance are: composite surface texture (random or periodic surface roughness, fiber orientation and binder concentration.
- Sound dispersion and absorption causes signal losses. These variables make the bondline interface between the liner and composite wrap difficult to detect and quantify.
- If the surface is shiny the infrared technique will reflect large “noise” signals. This may not allow enough heat to be deposited into the COPV (low signal). A coating of low reflective paint (black) is needed. Painted surfaces can be deceptive however, the IR emissivity and optical absorption may be enough to produce usable data.
- A CT inspection technique was developed which segments the multi-material data into composite and metal regions. Wrapping patterns are difficult to estimate. The damaged liner was easy to detect.

QUESTIONS

BACKUP

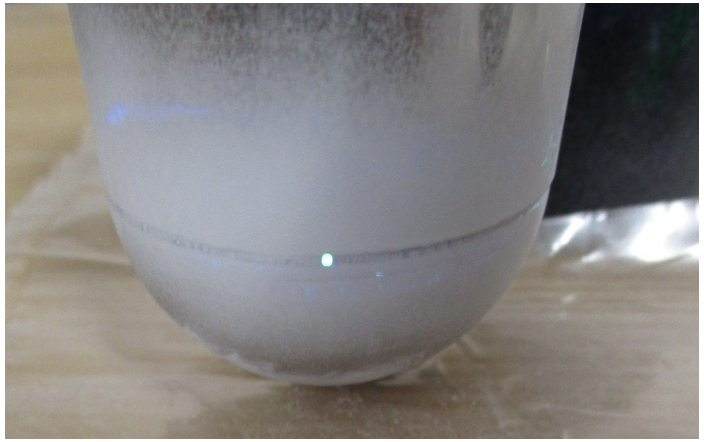
Abstract

Carbon composite overwrapped pressure vessels (COPV)s have been widely used for storing gases under high pressure by NASA for space missions since the 1970s'. The principal advantage of using a solid carbon fiber reinforced plastic (CFRP) over a metallic liner is mainly for reducing weight for flight.

A Type III COPV is defined as a thin metallic liner overwrapped with a high strength fiber/epoxy composite. This configuration allows for a significant portion of the pressure load during operation to be transferred to the fibrous composite overwrap. Currently, COPVs are being used in the beverage, aerospace, automotive, and defense industries. The mechanical properties of the composite material are derived from the combination of the constituents (carbon fiber and resin).

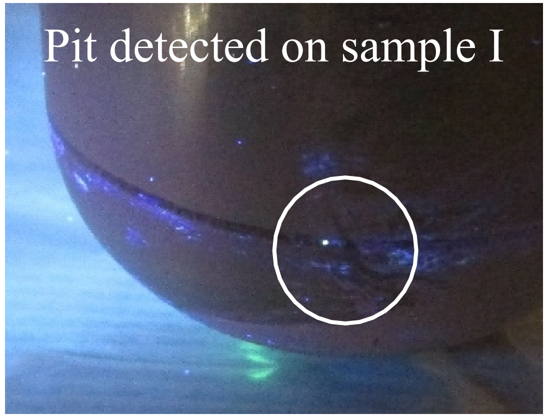
Traditional inspection techniques as well as developing technologies are being deployed at Sandia National Laboratories to verify the integrity of composite layups over thin pressure liners. This presentation describes each inspection technique used to evaluate ply layers and adhesive interfaces. Advanced three dimensional (3D) rendering methods will be also be presented and a review of current equipment capabilities and deployment challenges encountered while scanning COPVs will also be discussed.

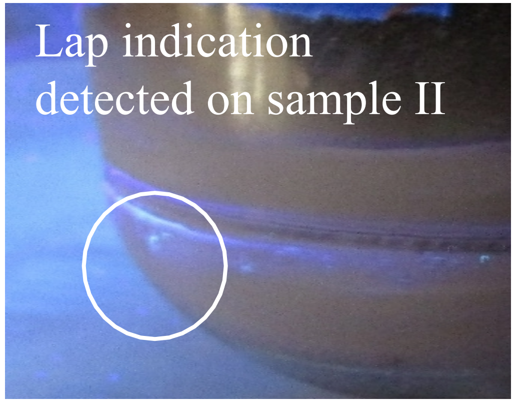
Liner Inspection Penetrant Process: Level III (Method C) Solvent Removal



Nonaqueous developer applied to the inspection surface.

- A nonaqueous solvent was used to clean the samples.
- A level III fluorescent penetrant was strategically applied and allowed to dwell on the weld and heat effected zone for 45 minutes. The excess penetrant was wiped away using dry wipes.
- A nonaqueous developer was applied and allowed to dwell for 30 minutes.
- The parts were inspected using a black-light, looking for surface breaking defects. The parts were also visually inspected under low magnification for defects. After the inspection, the samples were cleaned once again with the nonaqueous solvent.





Penetrant Results

Part No.	Indications	Notes
I	Yes, pit	A pit was detected on the weld surface during the penetrant inspection.
II	Yes, lap	Small lap was detected during the penetrant inspection.

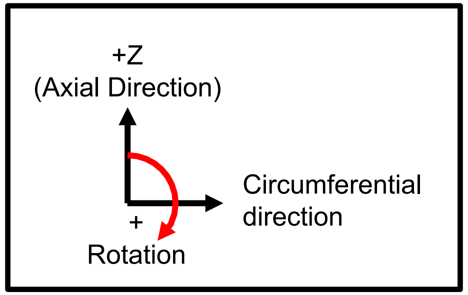
No indications were detected with eddy current

Computed Tomography: Parameter Optimization

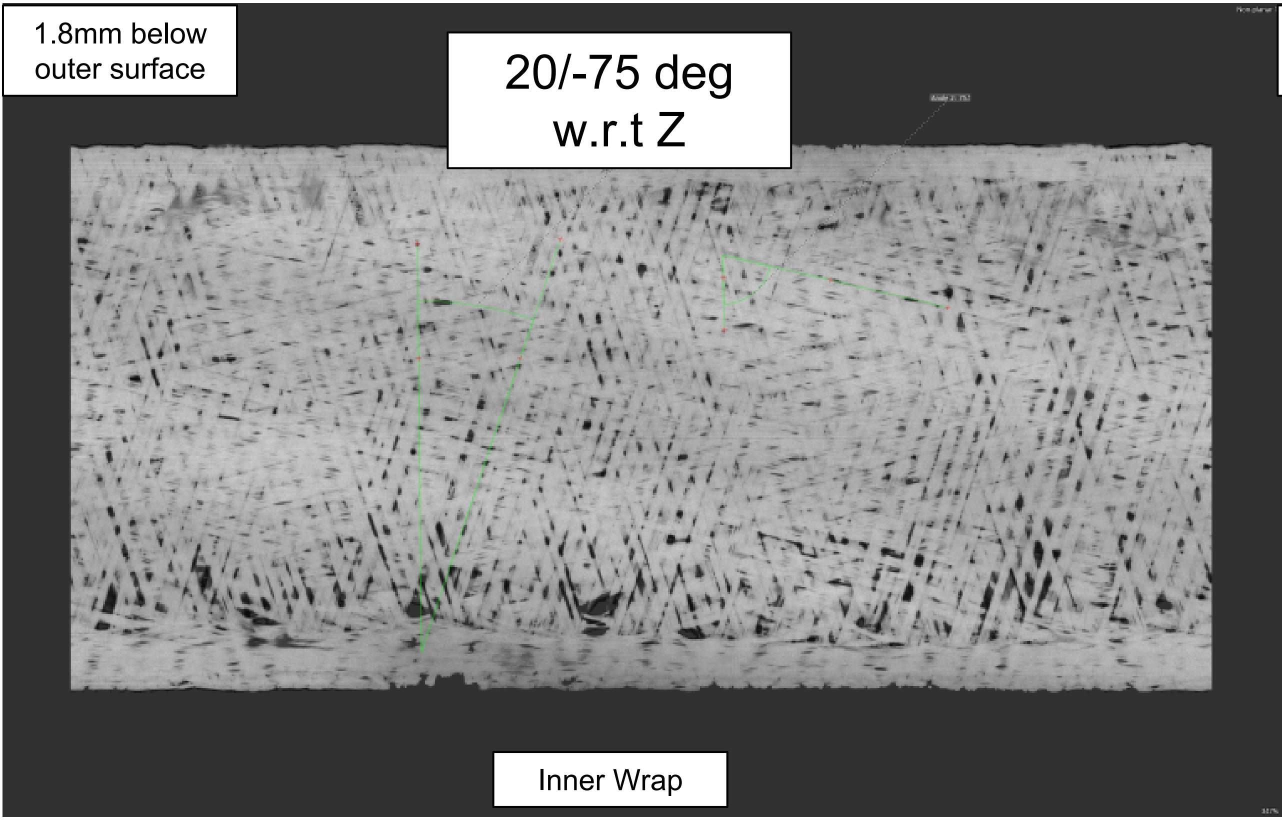
Before data analysis is conducted artifacts must be identified and reduced.

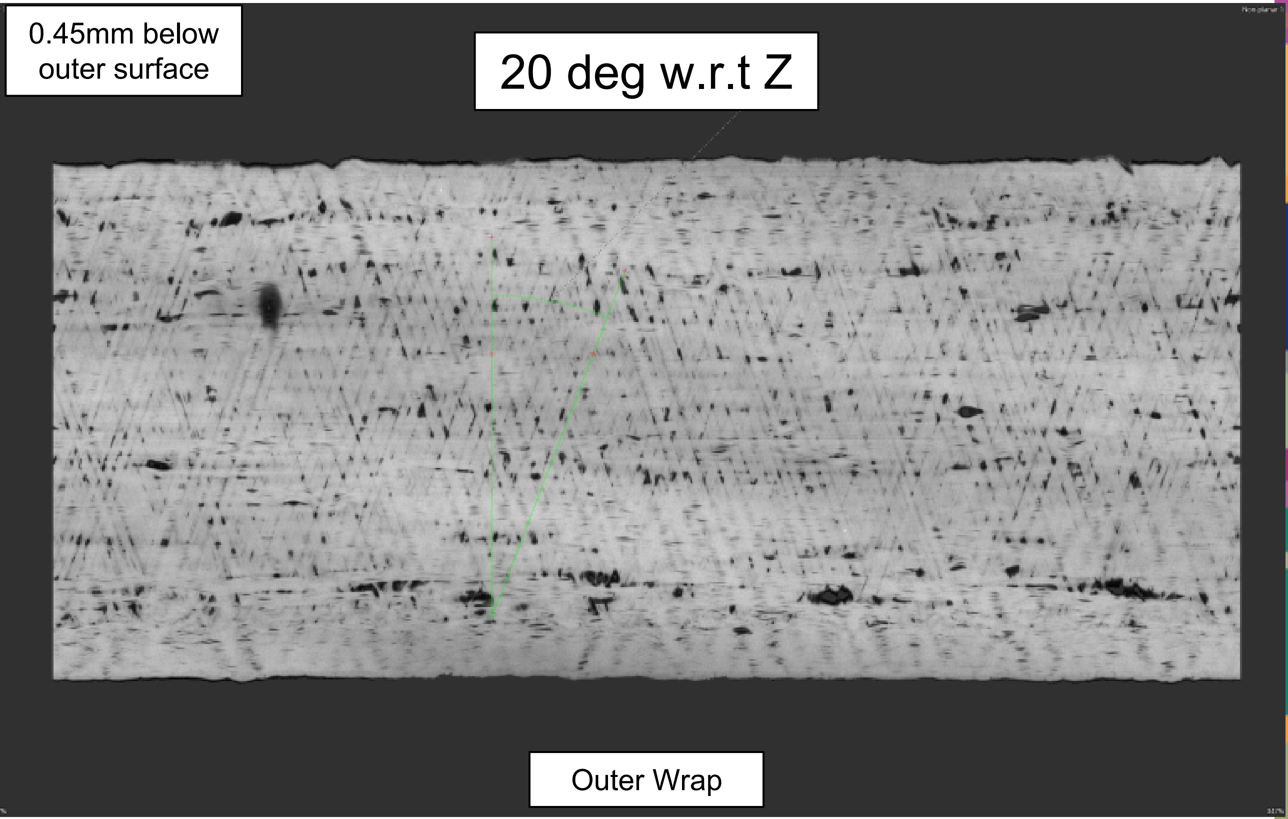
- Creation of High Signal to Noise Ratio is obtain through Artifact Reduction
  - Beam Hardening and Under Sampling
  - Cone Beam
  - Unsharpness
  - Motion and Centering
  - Ring
- Creation of High Pixel Resolution is obtained by Smaller Detector Pixel Size
  - More pixels per sample area (magnification) = higher resolution images
  - Less sensor area = increased sampling times
  - Smaller focal spot sizes = less x-ray power

Sample (COPV - 5)

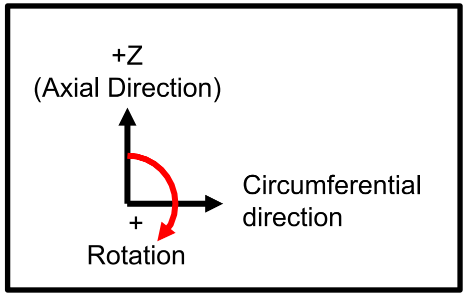


Wrap pattern on inner layers is a 20/75 degree pattern (left), whereas it moves to just a 20 degree pattern on the outer layers (right).

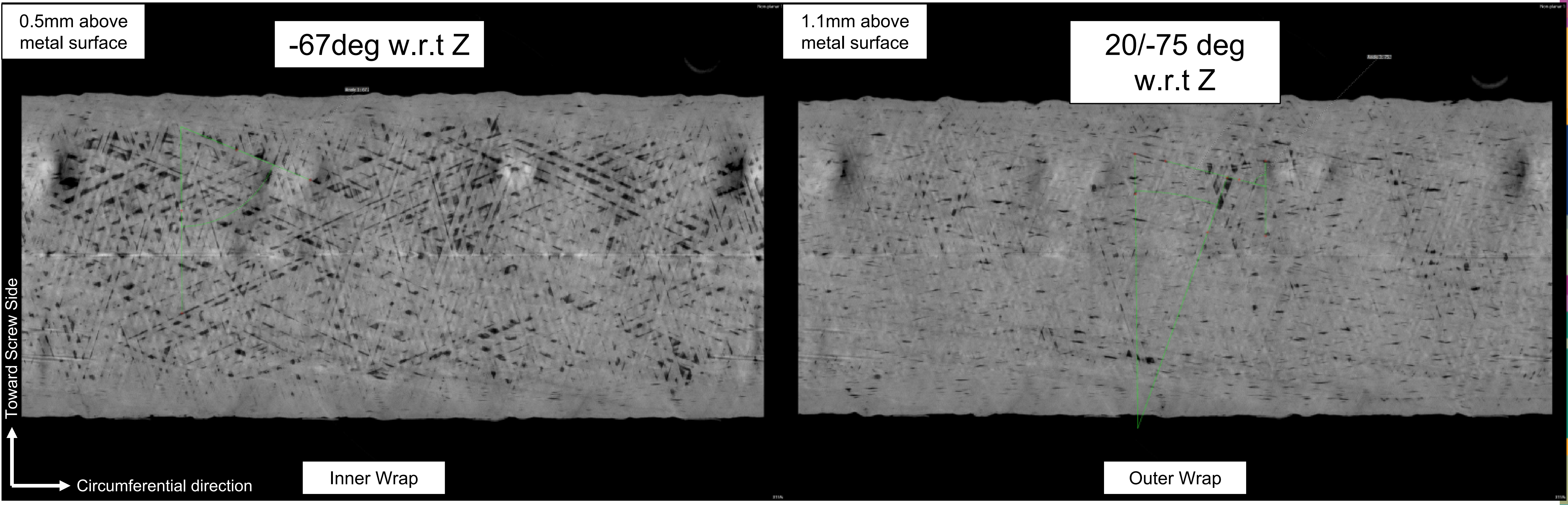




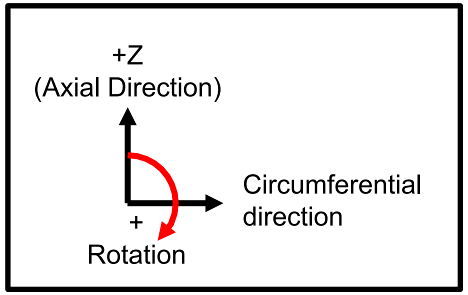
Sample (COPV - 6)



Wrap pattern on inner layers is -67 degree pattern (left), whereas it moves to a 20-75 degree pattern on the outer layers (right).



Sample (COPV - 7)



Wrap pattern on inner layers is a -25/+25 degree pattern (left), whereas it moves to just a -70/+22.5 degree pattern on the outer layers (right).