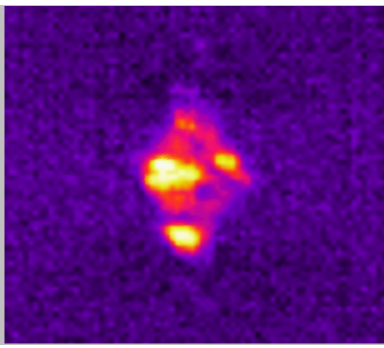
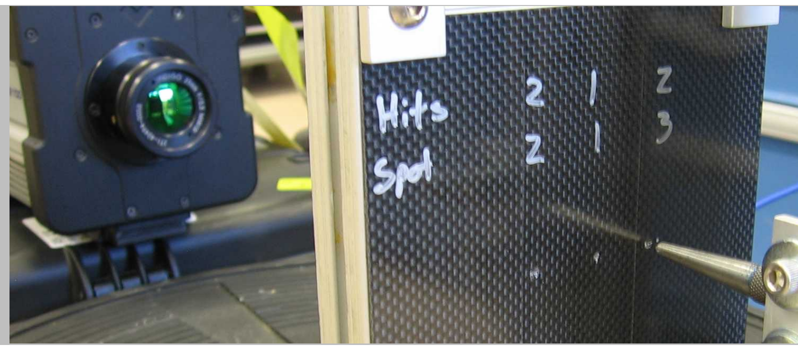
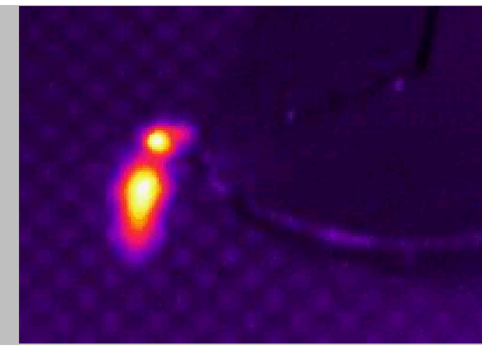
SAND2017-2597C







Low Mass Low Velocity Impact Assessment on Solid Laminate Composites using High Speed Infrared Imaging

SAND No. – P

David G. Moore (505) 844-7095

Ciji L. Nelson (505) 284-8447

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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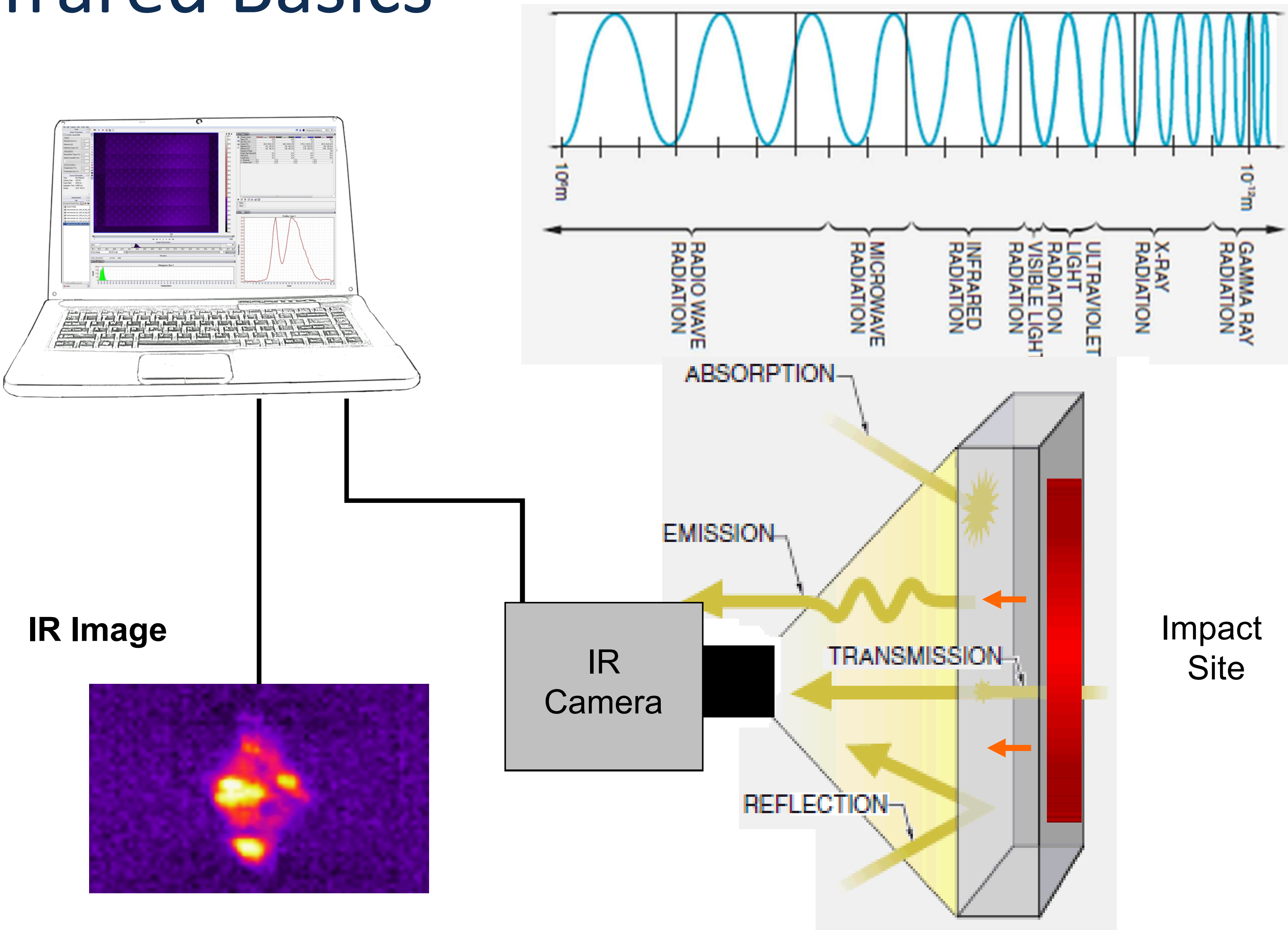
Infrared Basics



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 1×10^{-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

Thermography Camera Specifications

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Back Panel

1. Power Switch
2. Gigabit Ethernet
3. Status LEDs
4. SVGA-Video
5. Auxiliary Connector
6. Camera Link™
7. Trigger In, Sync In, C-Video, Genlock In, Sync Out, IRIG-B
8. Power In
9. S-Video
10. USB Host
11. USB Client

Source: www.FLIR.com

Lens Used 13, 25, 50 mm

Frame Rate 640 x 512 = 126 fps
320 x 256 = 430 fps
160 x 128 = 1322 fps

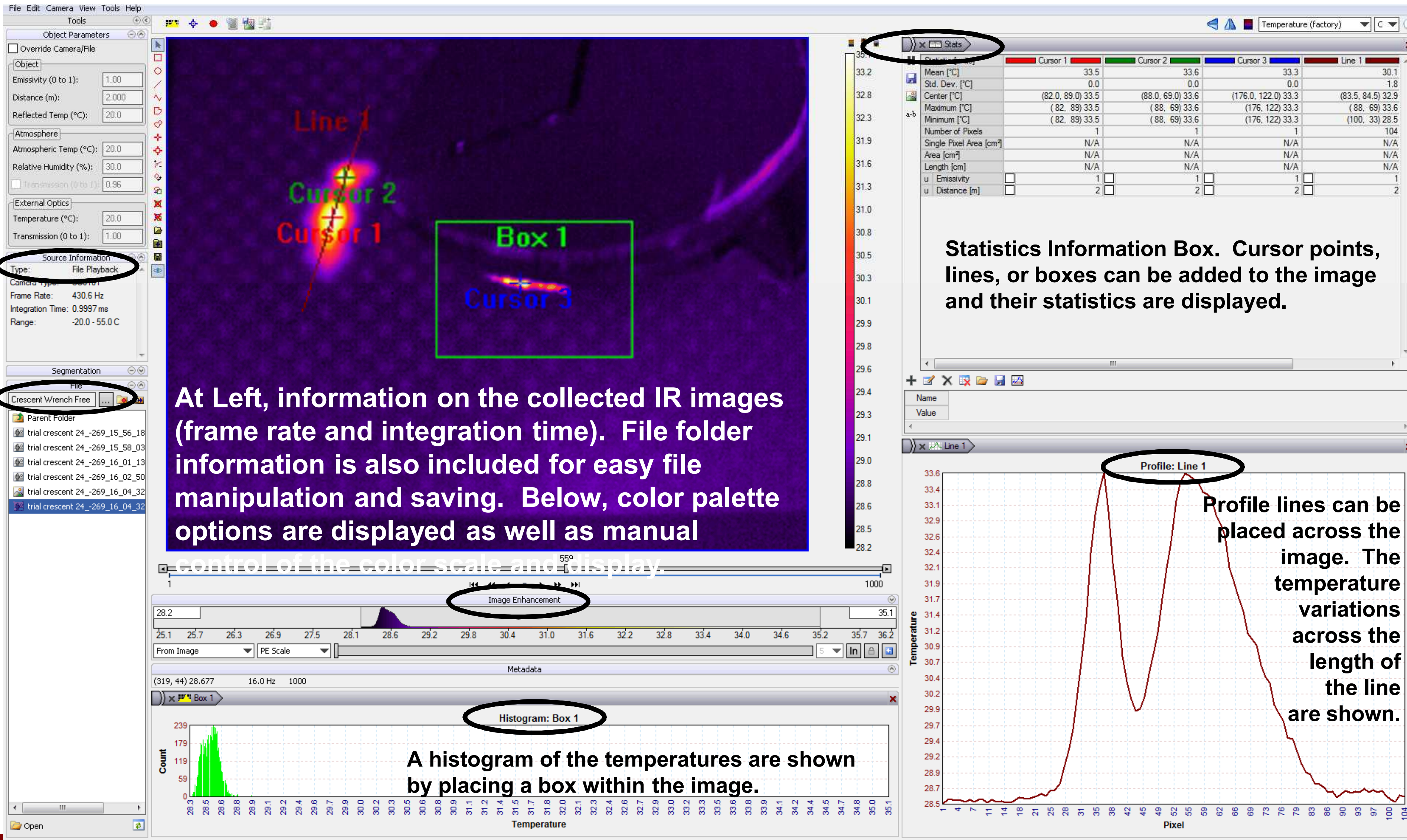
Temperature Ranges -20 to 55˚C
10 to 90˚C
35 to 150˚C
80 to 200˚C
150 to 350˚C

Camera FLIR 6106;
60 Hz 14 bit

Window Size
640 x 512 Pixels
InSb detector

Detector Pitch 25 µm
Spectral Range
3.0 to 5.0 µm
1.5 to 5.0 µm

ExaminIR™ Capabilities

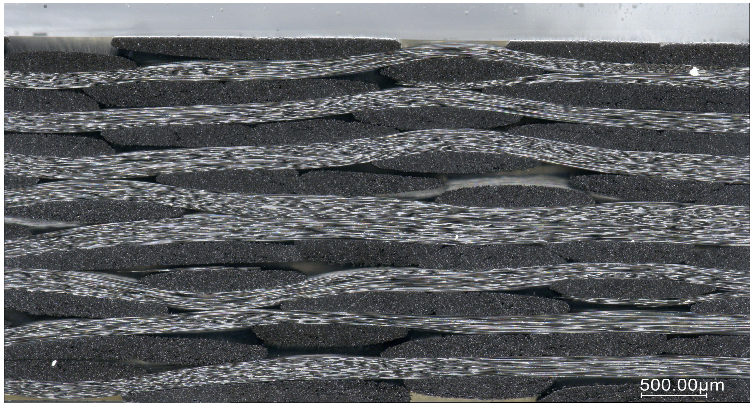


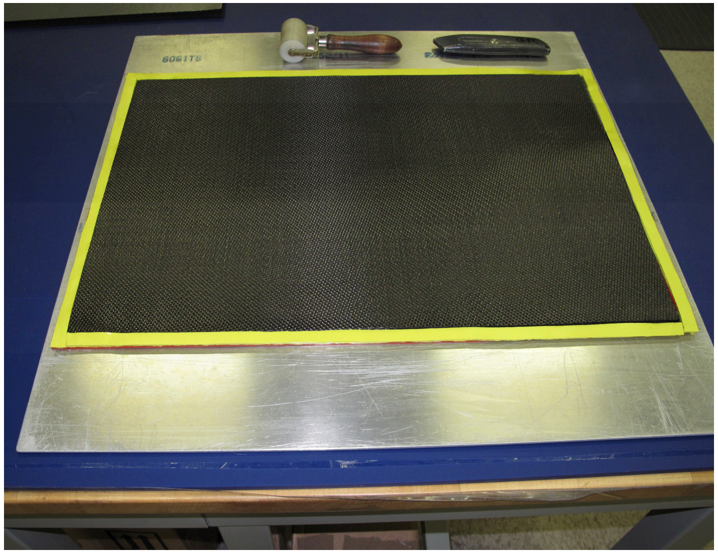
Composite Materials

Composite materials are generally solid laminates which are fabricated in either sheet or molded form. They are made by bonding together two or more layers of material with a polymeric adhesive.

Fibers act as reinforcement and can be oriented in various configurations with varying size and shape. Solid laminates consist of strands, chopped fibers, reinforced mats, and are woven into a fabric. Laminates are generally formed by use of wet lay-ups or prepregs.

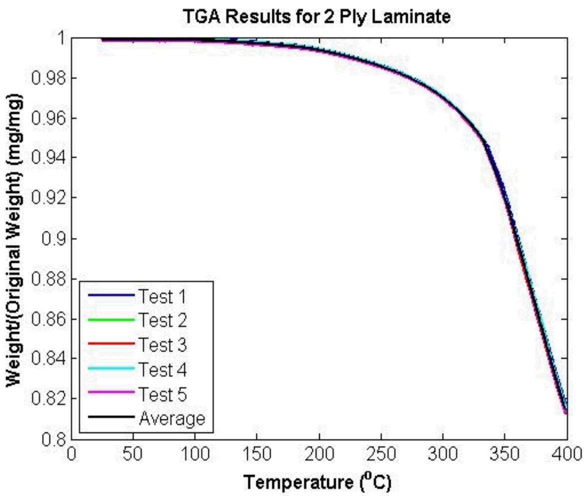
The wet layup method involves the application of the matrix material to the dry reinforcement at the time of the buildup of the part to be fabricated.



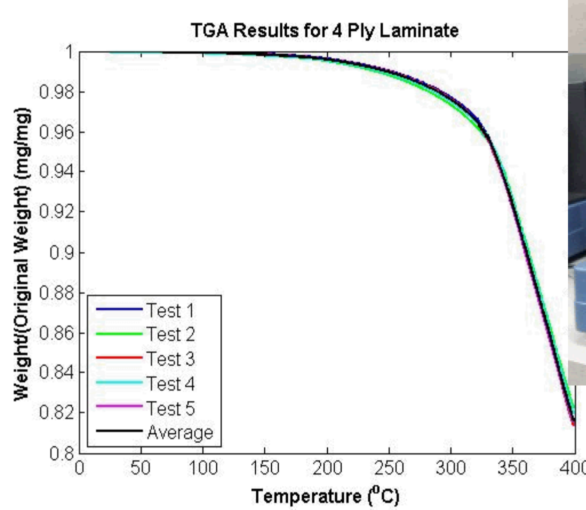


Thermogravimetric Analyzer (TGA) Results

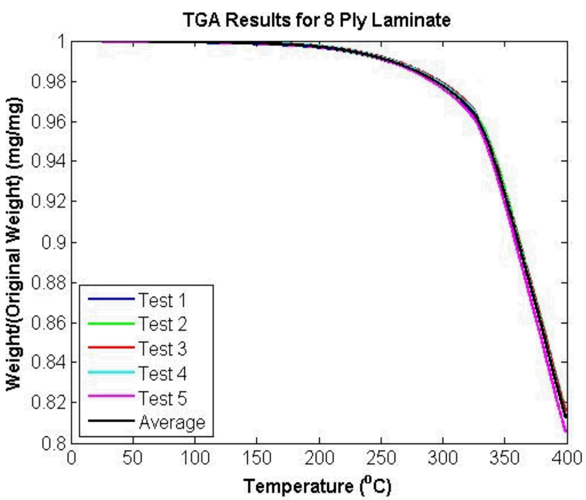
(A)



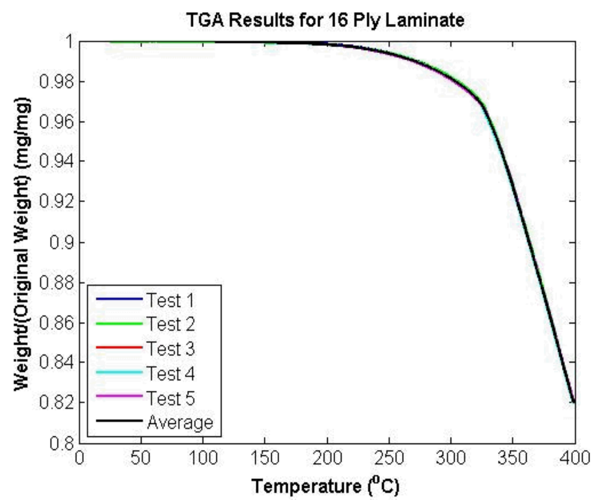
(B)

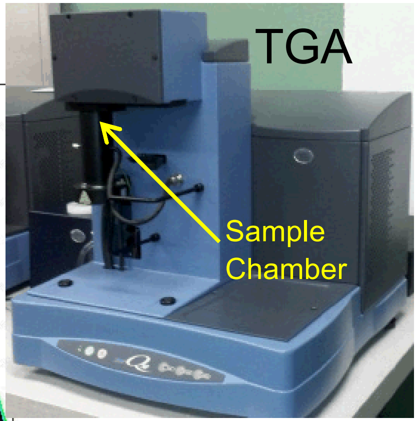


(C)



(D)





- Resin begins to significantly degrade near 330°C.
- Resin actually experiences some weight loss starting between 150°C and 200°C.

Orthotropic Materials Properties

Isotropic materials independent of direction (metals and thermoset plastics).

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

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.

FEM Results from Open Literature[1]

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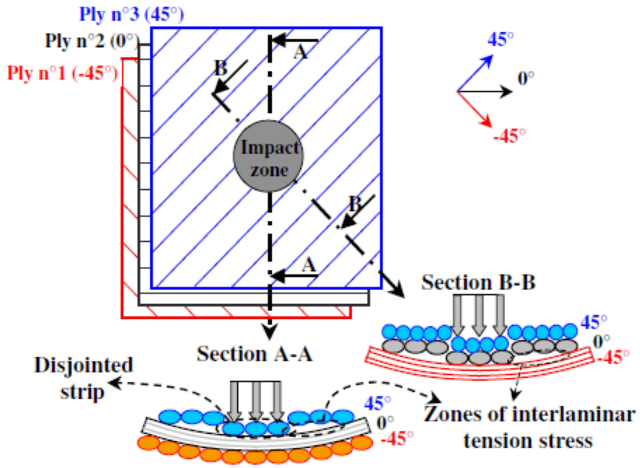
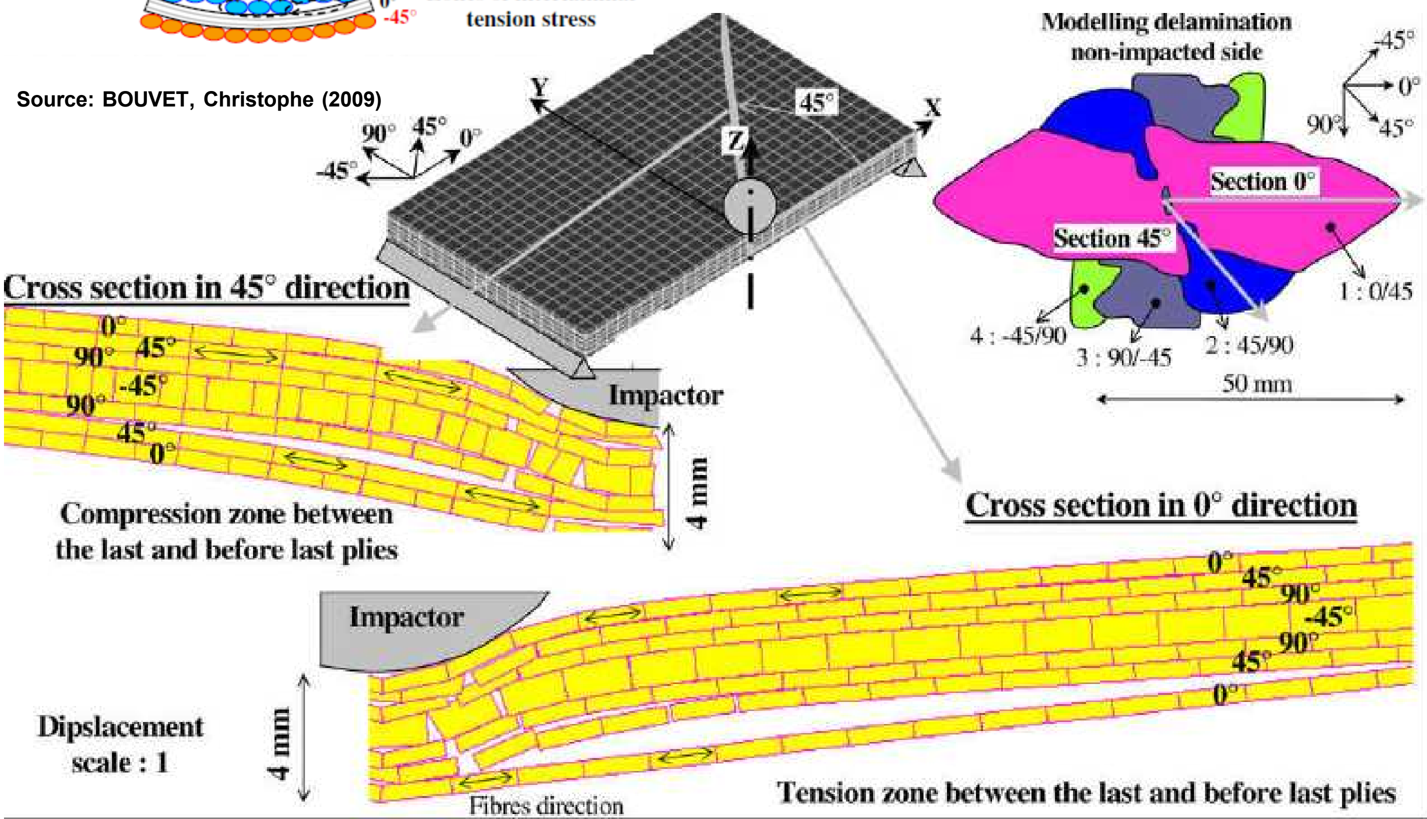


M.Renault, *et. al.* (1994; EADS) proposed the damage mechanism for low (velocity – energy) impact on solid laminate composites is matrix cracking below the surface of the impactor. This failure then leads to ply delamination and structure failure.

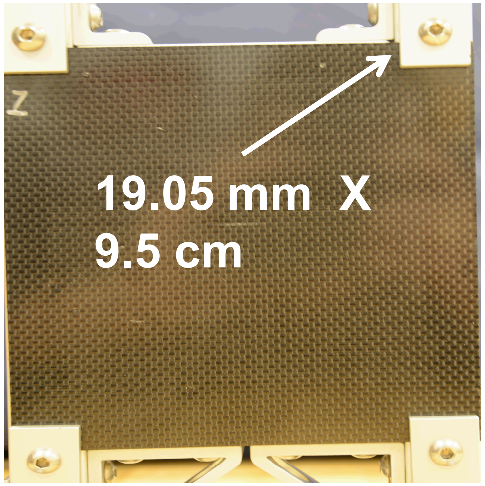
Source: BOUVET, Christophe (2009)

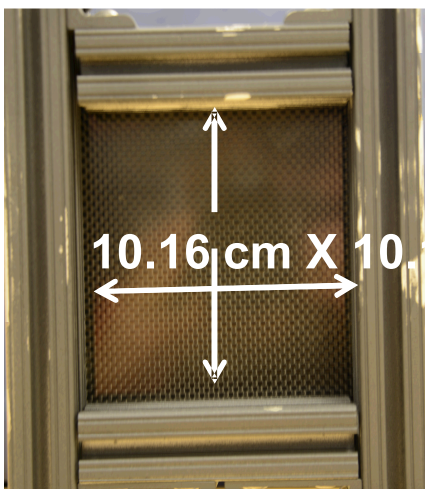


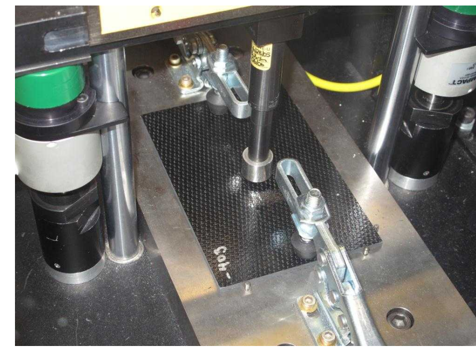
Fibers and resin are released from the composite and gives off energy (heat).

[1]BOUVET, Christophe, CASTANIÉ, Bruno, BIZEUL, Mathieu, BARRAU, Jean-Jacques. Low velocity impact modelling in laminate composite panels with discrete interface elements. *International journal of solids and structures, 2009*, vol. 46, no14-15, pp. 2809-2821. ISSN 0020-7683

Boundary Conditions for Impact

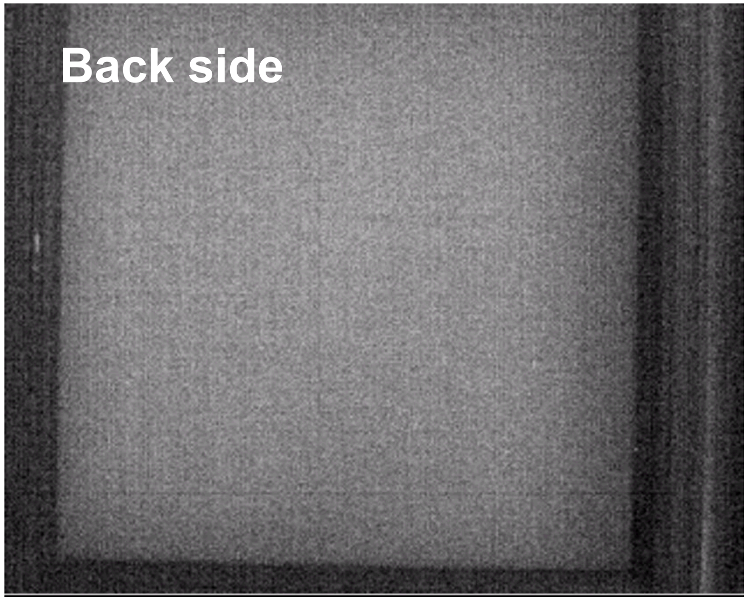




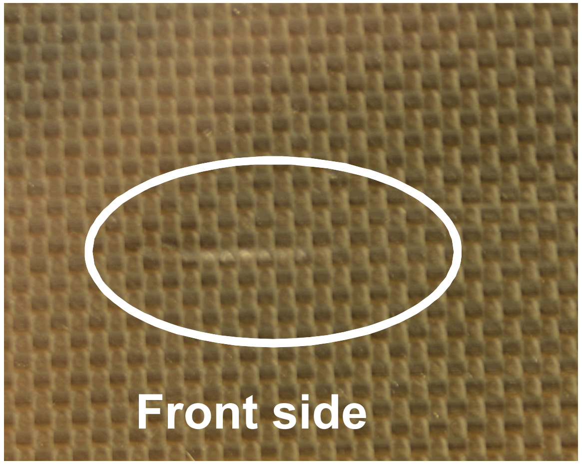


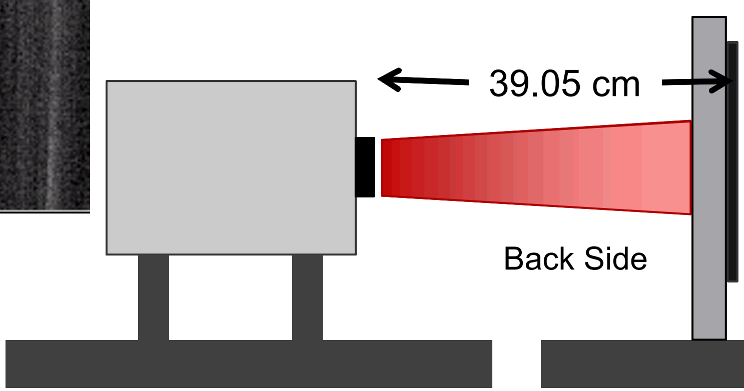
Blunt Tool Impact Test Setup

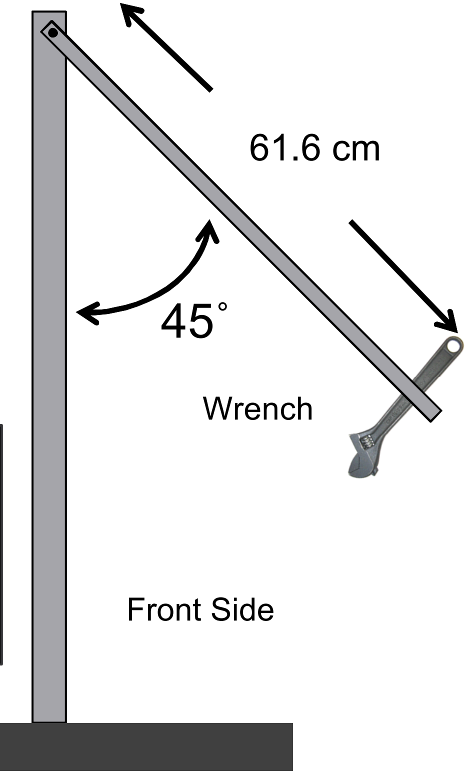
The IR Camera is centered on the impact area. Data recording is set at 1300 frames per second. The wrench impacted the test panel at a velocity of approximately 1.8 meters / second.



Total Video Length
0.001 second

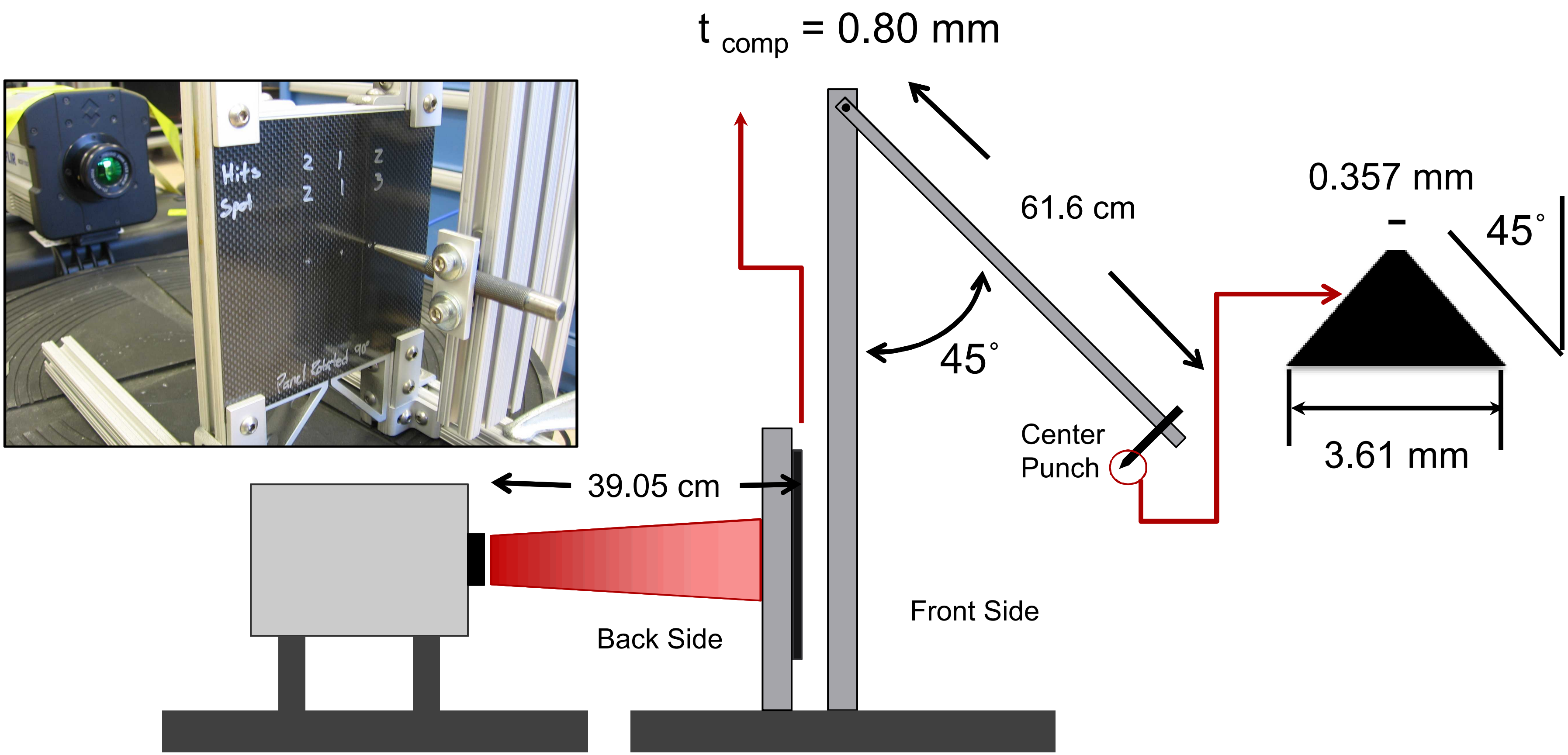






Sharp Object Impact Test Setup

The IR Camera is centered on the impact area. Data recording is set at **1300 frames per second.** The start time is triggered with the release of the pendulum arm. The center punch impacted the test panel at a velocity of approximately 1.8 meters / second (simple pendulum equation).



IR Data Collection

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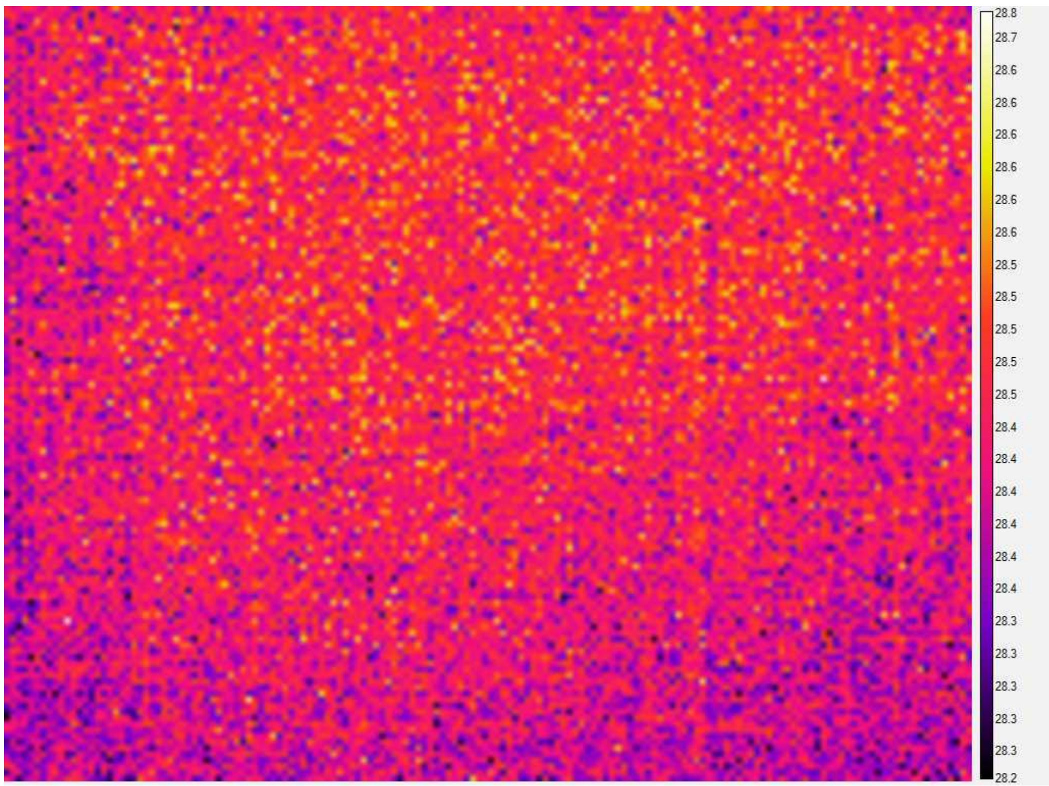
Center Punch Impact, Single Hit
Impact Velocity 1.8 meters / second
Impact Force of 2.2 Joules

Calculated Pixel Size = 0.38 mm,
Window Size 160 x 128 pixels,
6.1 cm Vertical x 4.9 cm Horizontal

Total video length
0.04 seconds

Back Side Impact Image



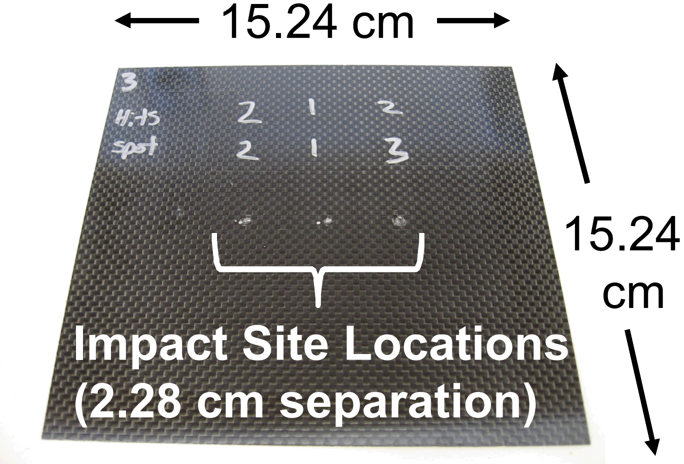
Delta T = T_{max} - $T_{background}$

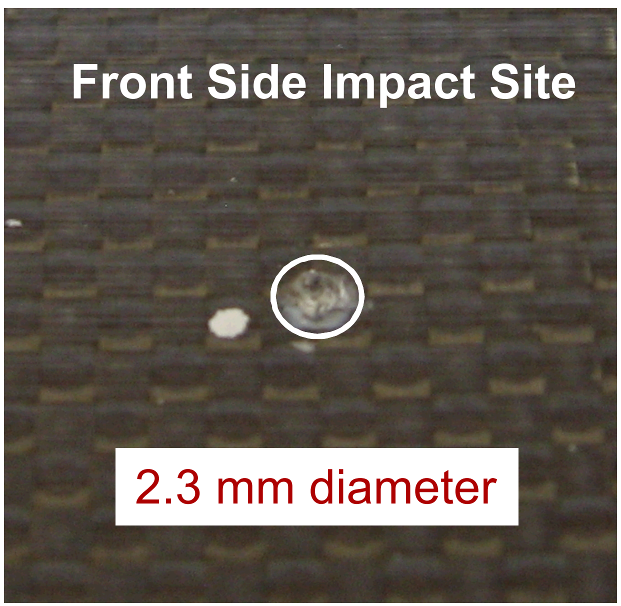
Delta T = (94.8 – 28.2) °C
66.6 °C

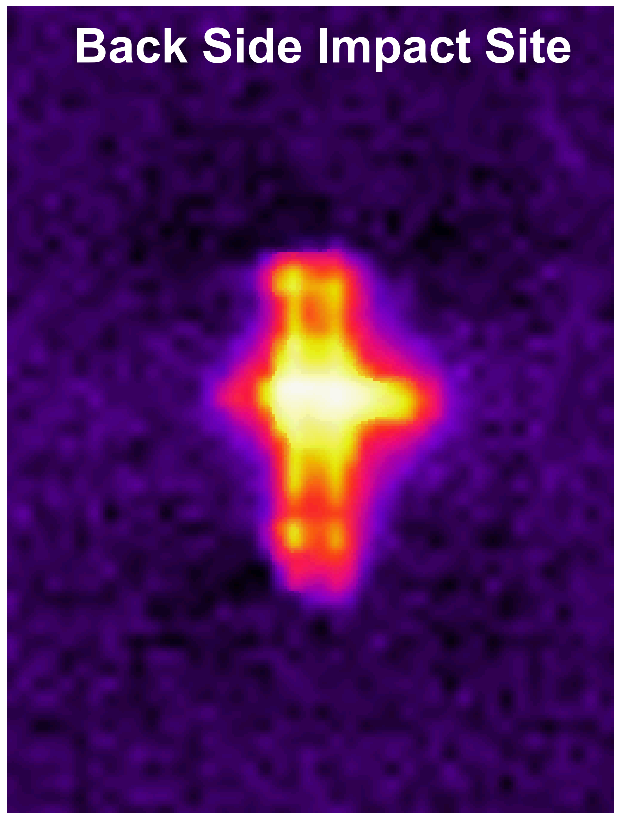
Post Inspection of Composite after Impact

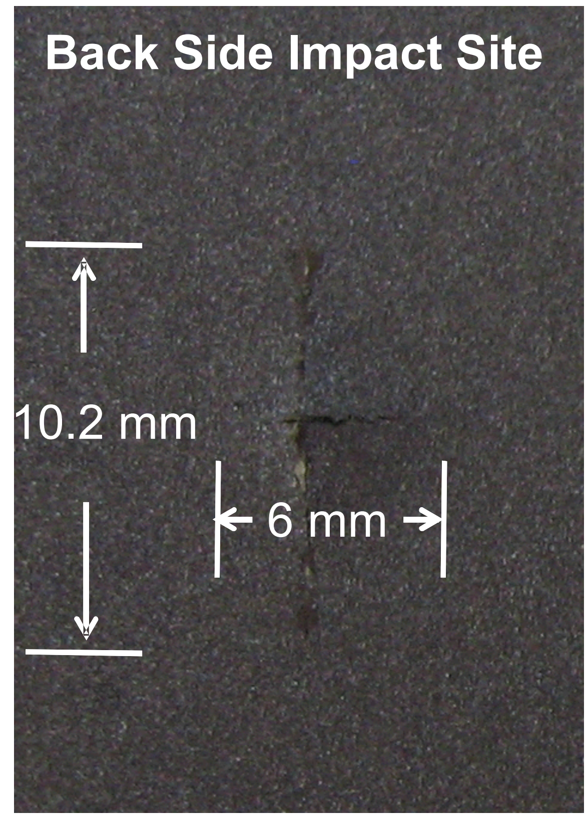
Sharp Object (Center Punch) Impact, Single Hit

$$\text{Delta T} = T_{max} - T_{background} = 66.6\ ^\circ\text{C}$$



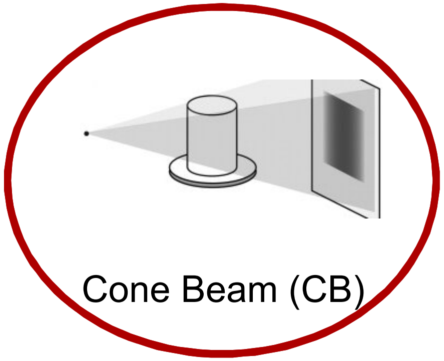


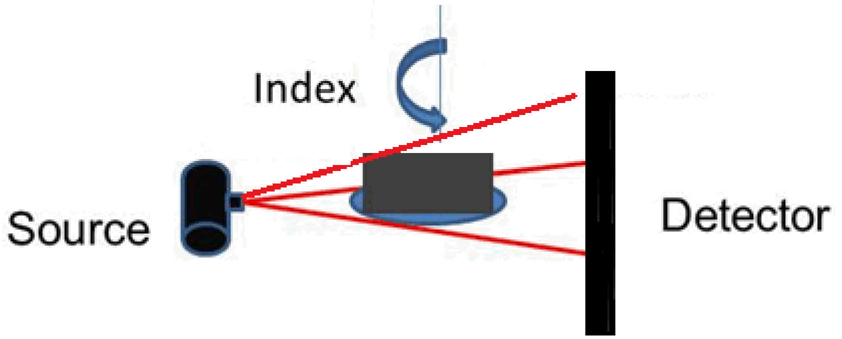




Computed Tomography (CT) Setup

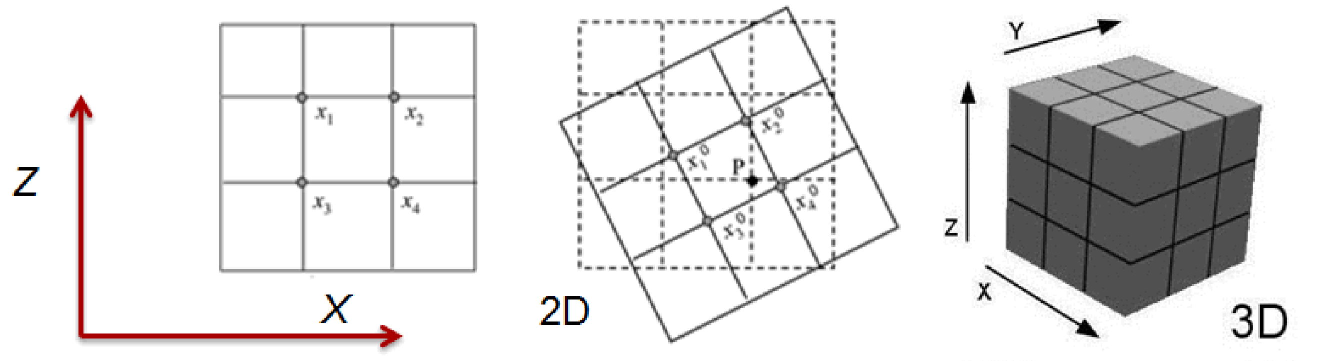
- Penetrating radiation (X-Ray) attenuated by composite material
- Digital sampling of the (photon) radiation
- Multiple images taken at different angles
- Images mapped into a three dimensional data set
- Data can be shown as single "slice" or rendered





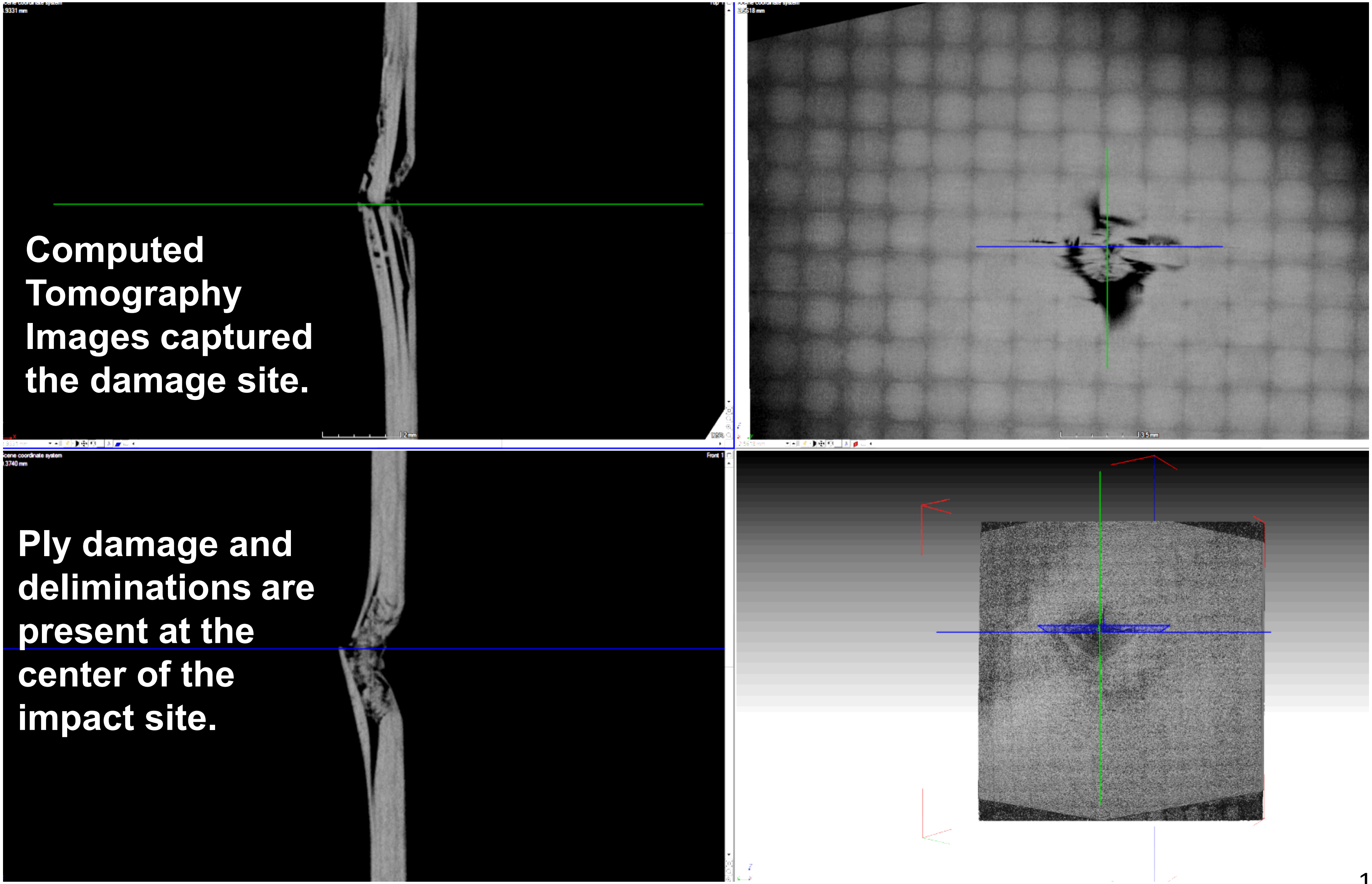
Cone Beam

- **A 3D volume is reconstructed from 2 dimensional projection images.**



- **More contrast sensitivity and signal to noise than 2D radiology**
- **Increases the discrimination of attenuation coefficients (material analysis)**

Post Inspection using CT



Computed Tomography Images captured the damage site.

Ply damage and deliminations are present at the center of the impact site.

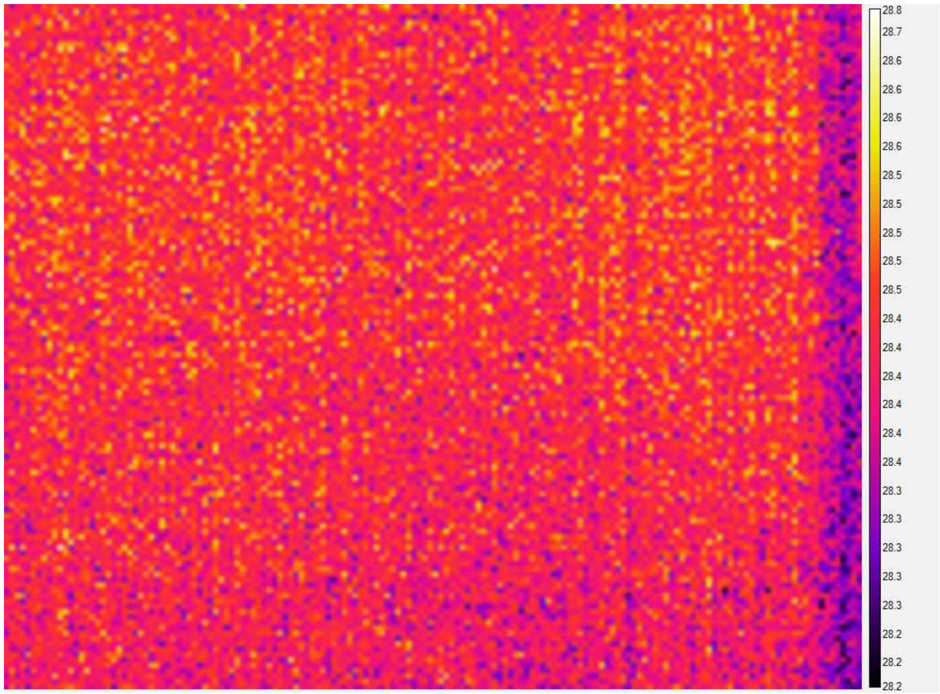
IR Images of Multiple Impact

Center Punch Single and Double Hit
Impact Velocity 1.8 meters / second
Impact Force of 2.2 Joules

Calculated Pixel Size = 0.38 mm,
Window Size 160 x 128 pixels,
6.1 cm Vertical x 4.9 cm Horizontal

Delta T = 65 °C

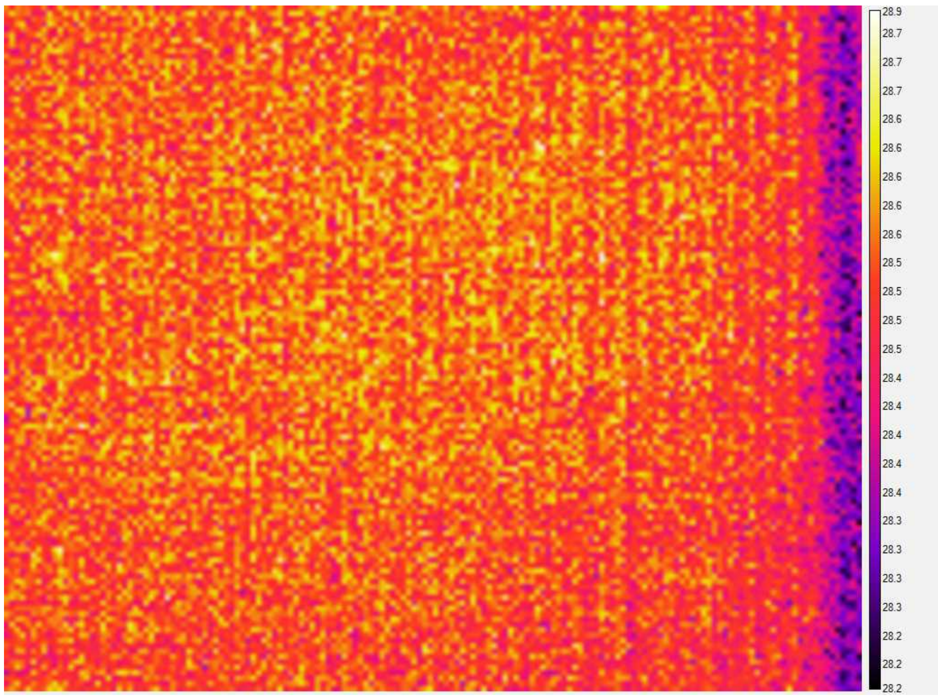
Impact 1 – 1322 FPS



Total Video Length 0.03 seconds

Delta T = 36.6 °C

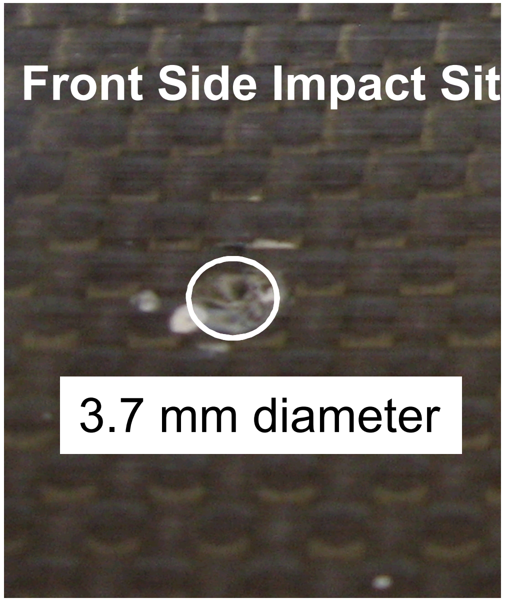
Impact 2 – 1322 FPS



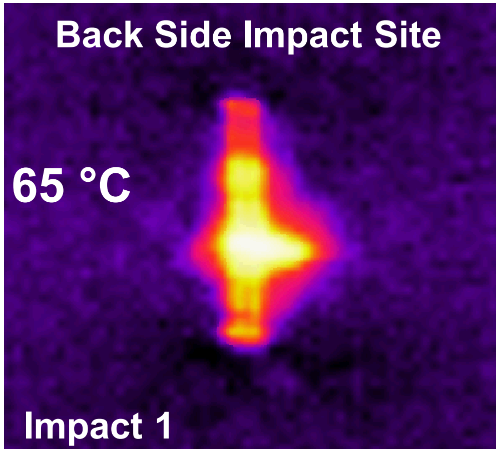
Total Video Length 0.03 seconds

Post Inspection of Composite After Impact

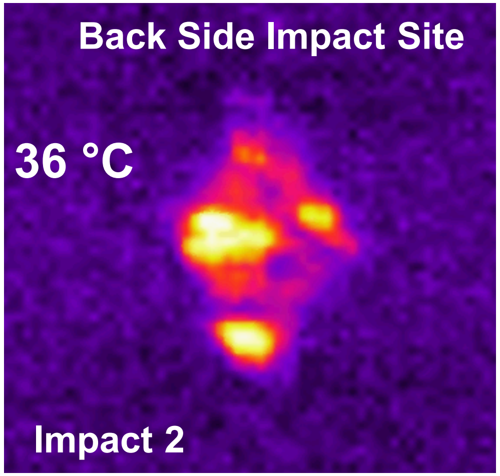
Center Punch Multiple Impacts
Impact Velocity 1.8 meters / second
Impact Force of 2.2 Joules

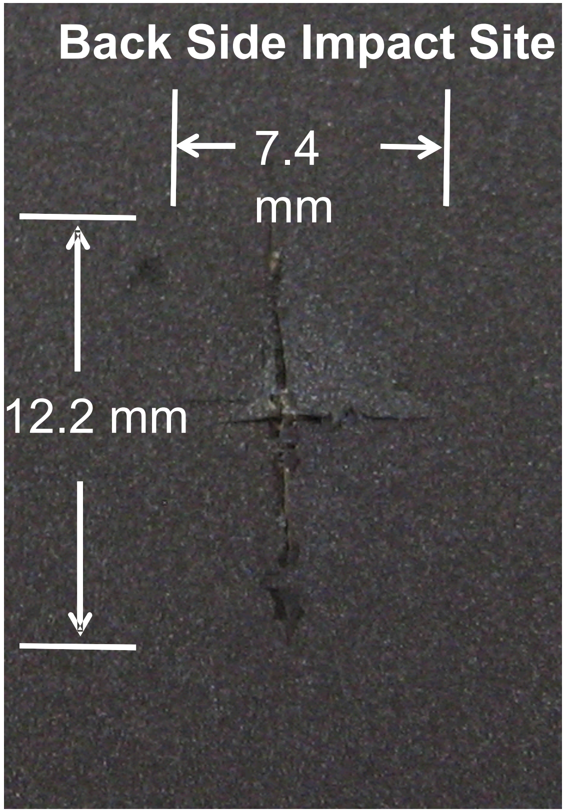


Delta T = 65 °C

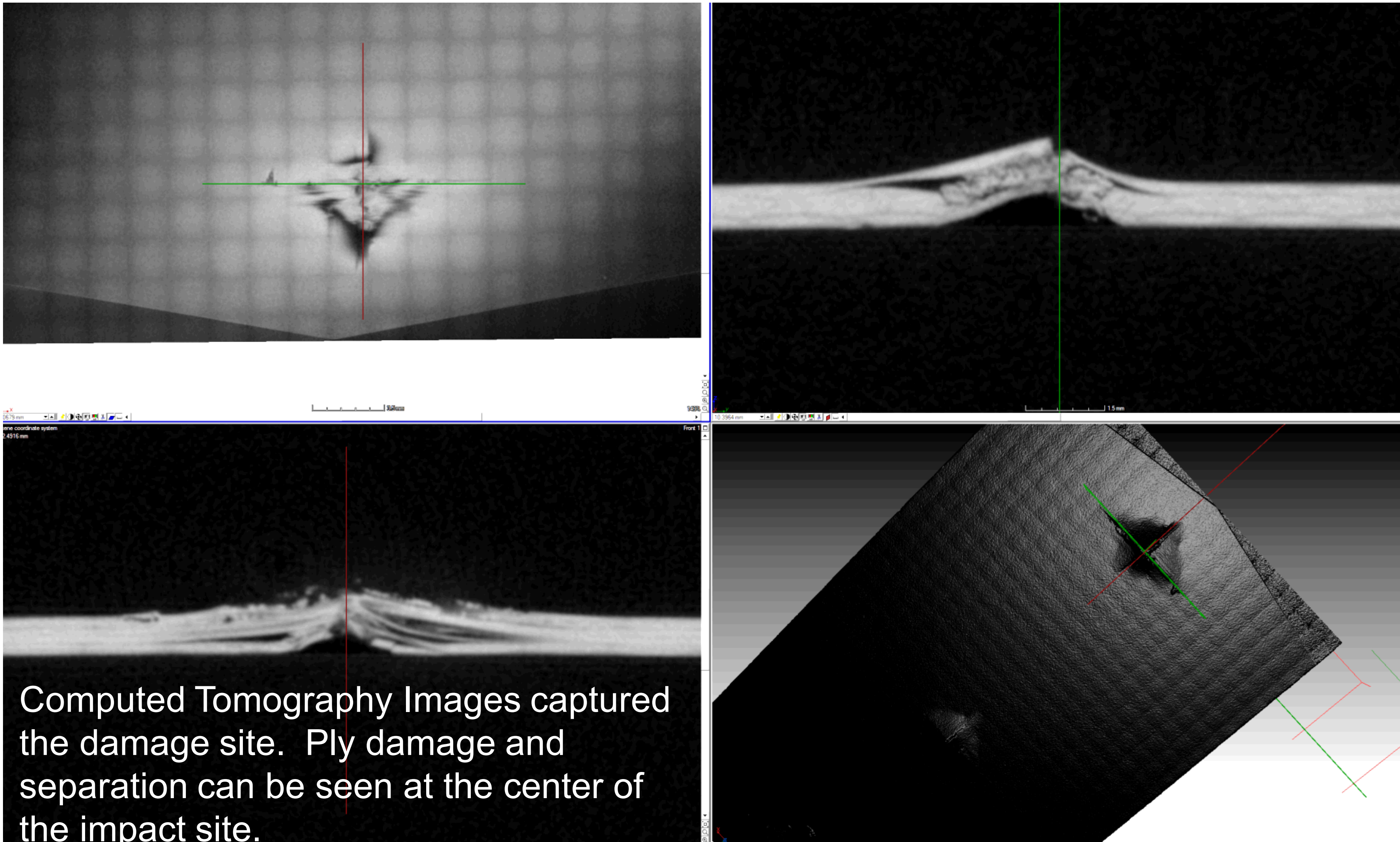


Delta T = 36 °C





Post Inspection Using CT

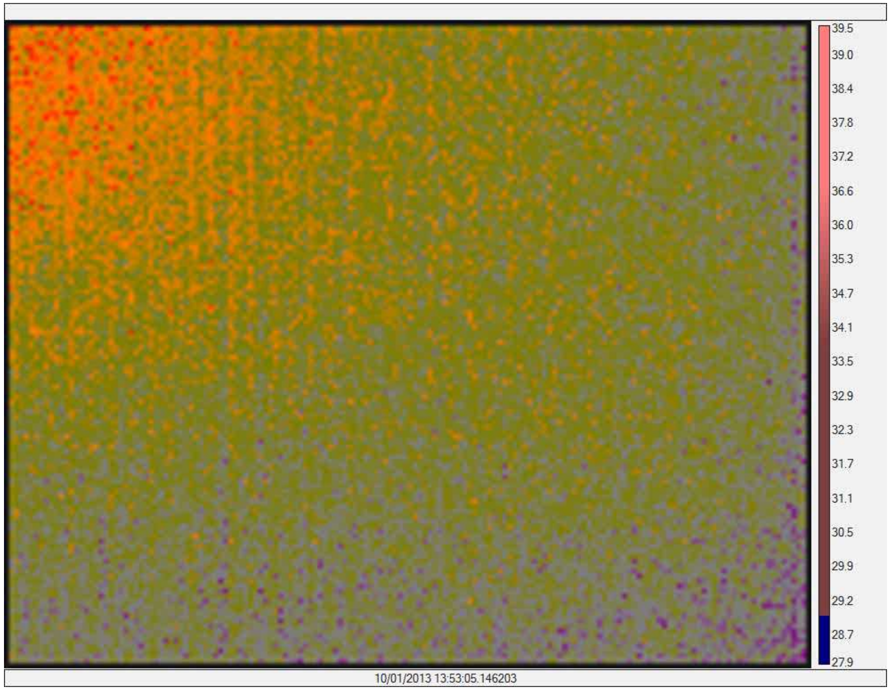


Computed Tomography Images captured the damage site. Ply damage and separation can be seen at the center of the impact site.

Composite Sample Turned 90 Degrees

Center Punch Impact, Single Hit
Impact Velocity 1.8 m/second Impact Force of 2.2 Joules
Calculated Pixel Size = 0.38 mm, Window Size 160 x 128 pixels,
6.1 cm Vertical x 4.9 cm Horizontal

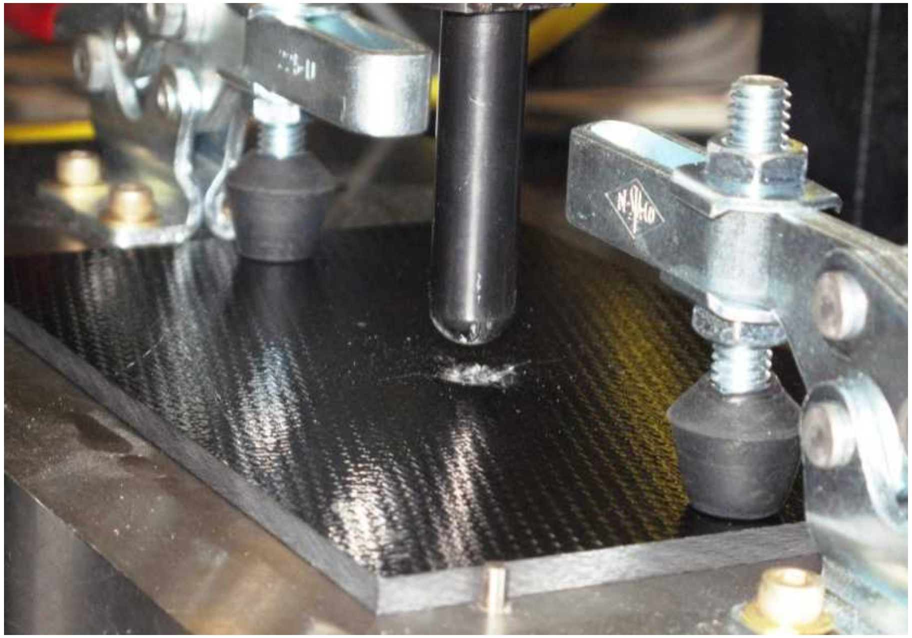
Back Side Impact

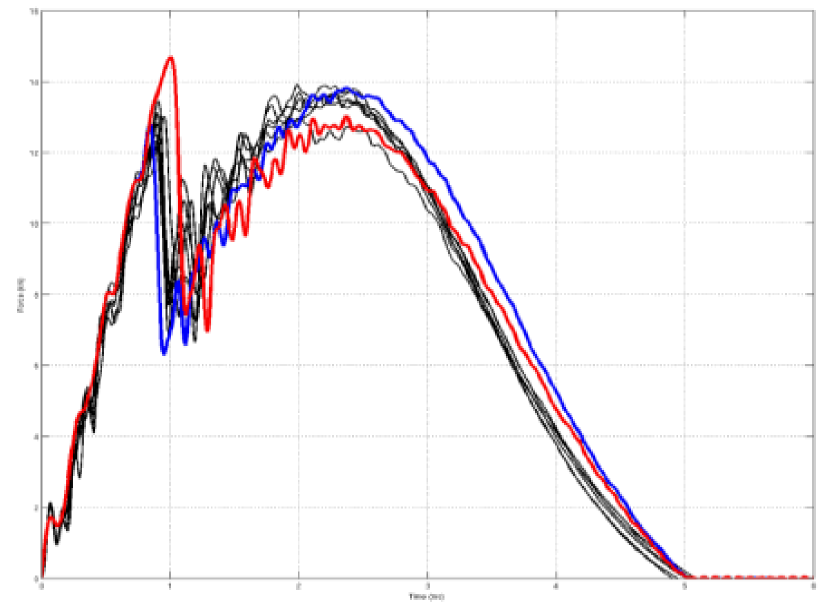


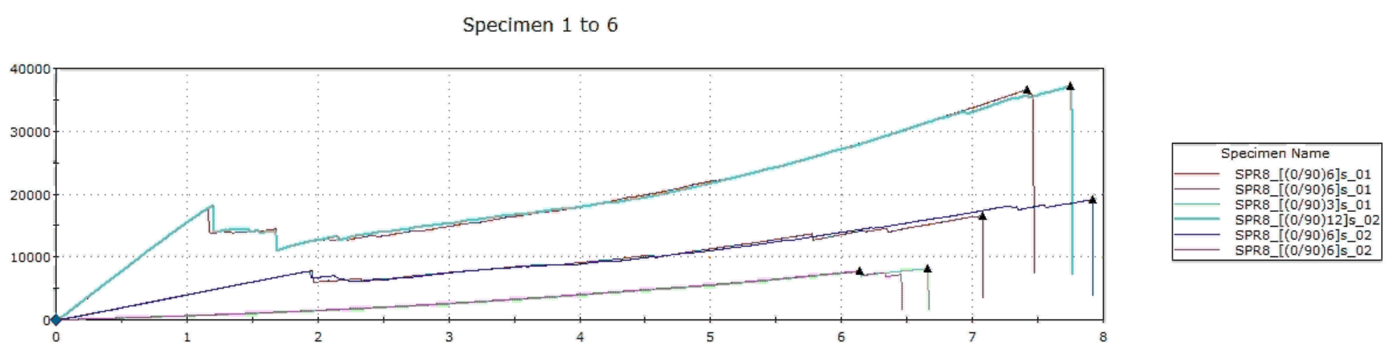
Total Video Length
0.0017 seconds

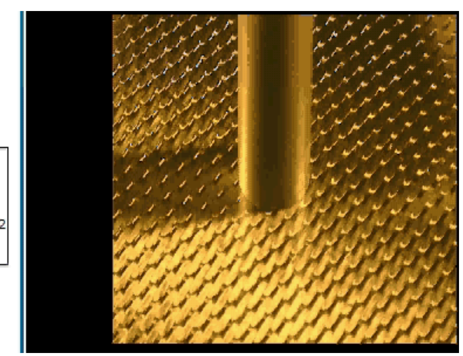
Delta T = 65 °C

ASTM D 7136 Test Apparatus









Conclusions

Damage initiation energy is the sum of energy due to bending, shear deformation and local fiber microcracking. The initial damage occurs by matrix cracks, then fiber breaks followed by delaminations (detectable with IR). Interlaminar damage is not detectable with IR.

The imparted energy and temperature rise depends strongly on the diameter of the impact object and the type of backing materials. Low energy blunt tool pendulum impact causes slight temperature increases (~2 °C). After several impacts the composite behaves in a brittle manner. Low energy sharp tool pendulum impact causes large temperature increases (~65 °C). The composite does heat up substantially from the background.

Research has documented the relative loss of the composite transverse stiffness and temperature rise. Damage is as a function of : impact energy, elastic response, damage initiation and propagation. IR techniques can only measure temperature changes.

Fundamental damage mechanism is a function of fiber direction. Fiber failure will then determine delamination direction. The last ply influences the delamination area.

Peak impact load is absorbed by the composite. Damage continues through the material. The elastic energy absorbed by the plate does rapidly change the temperature because damage formulation is between ply layers. In-plane ply failure controls the facture direction and depth of penetration into the structure.

Future Work

Frame averaging to reduce background noise (monitor and measure background effects).

Measure impact velocities more accurately. Establish failure criteria for surface and intraply matrix cracking by determining size of the interface delamination in the composite.

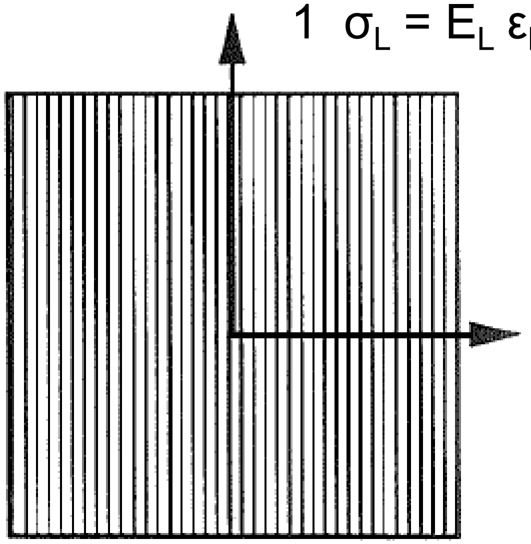
Adjust the window sizes to optimize temperature measurement (sensitivity analysis). Correlate camera distance and lens selection and its effect on measuring temperature.

Effect of camera angle on temperature measurements. Monitor IR response under low impact loads when manufacturing variables are changed: 1) resin content, 2) fiber areal weight, 3) cured per ply thickness, and 4) fiber volume.

Monitor IR response at extreme operating temperatures: resin impregnation composites and verify damage qualification

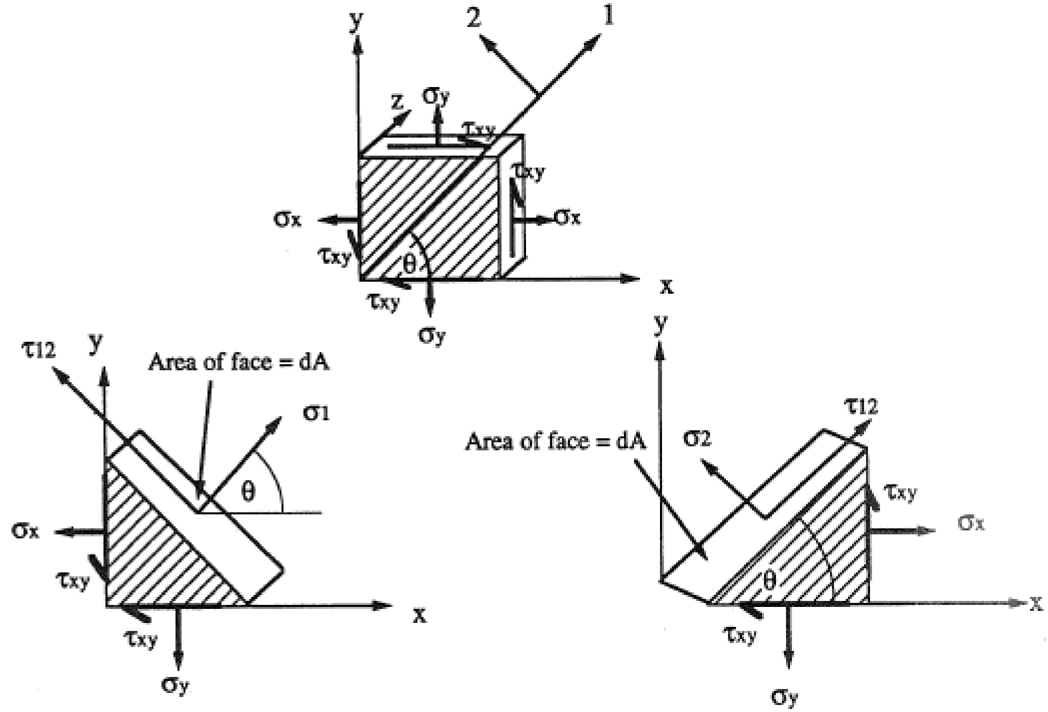
Stress and Strain for Orthotropic Composite Plates

The stiffness of a orthotropic plate is described by two modulus values, along the direction of the fibers E_L and transverse to the direction of the fibers E_T.



1 $\sigma_L = E_L \varepsilon_L$

2 $\sigma_T = E_T \varepsilon_T$

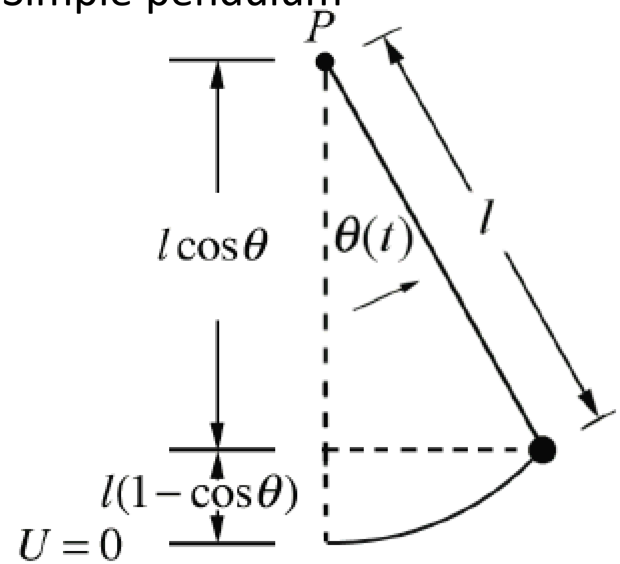


A. T. Nettles, "***Basic Mechanics of Laminated Composite Plates***", **NASA Reference Publication 1351, October 1994**

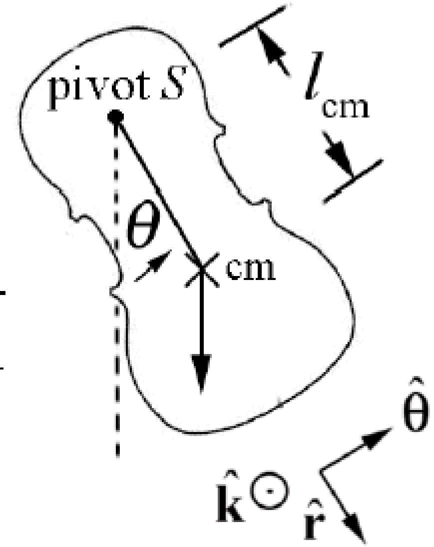
Energy Balance

Sandia National Laboratories

Simple pendulum



Physical pendulum



$$\omega_0 \approx \sqrt{\frac{m g\, l_{cm}}{I_S}}$$

Angular frequency

Period

$$T = \frac{2\pi}{\omega_0} \cong 2\pi \sqrt{\frac{I_S}{m\, g\, l_{cm}}}$$

$$E_i = K_i + U_i = m\, g\, l\,(1 - \cos\theta_i)$$ Mechanical Energy

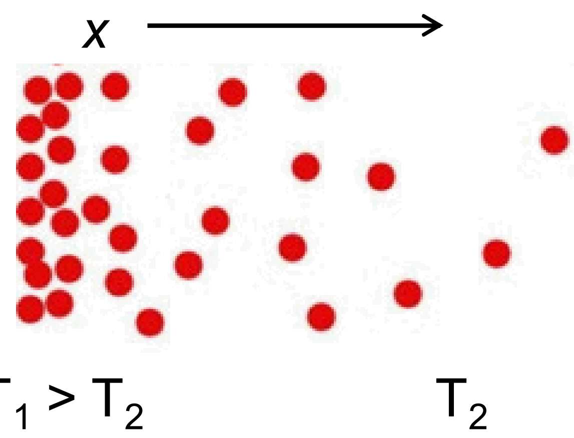
$$\omega^2 = \omega_0^2 + 2\alpha\theta$$

$$K_f = \frac{1}{2} m v^2 = \frac{1}{2} m \left(l \frac{d\theta}{dt} \right)^2$$ Kinetic Energy

$$KE = \frac{1}{2} I\, \omega^2$$

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 k is the transport property thermal conductivity W/(m °C).

$$q_x = -k\frac{dT}{dx}$$

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:

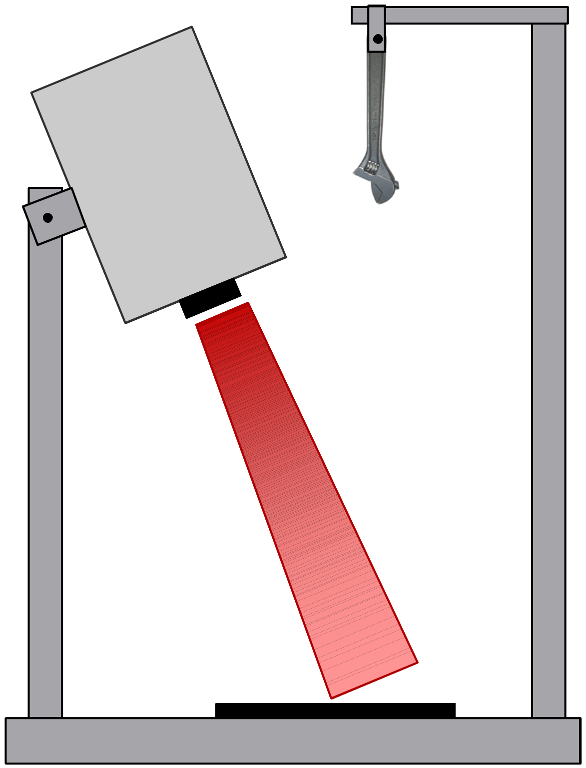
$$\vec{q} = \mathbf{q''}$$

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

Wrench Drop Test Setup

The IR Camera is centered on the impact area (camera to sample distance 45.7 cm). The wrench is dropped from 61.6 cm. **The frame rate is 430 frames per second.** The start time after the crescent wrench is dropped (total data collection time is 15 seconds).

A wrench (0.41 kg) impacted the test panel at a velocity of 3.46 meters / second.

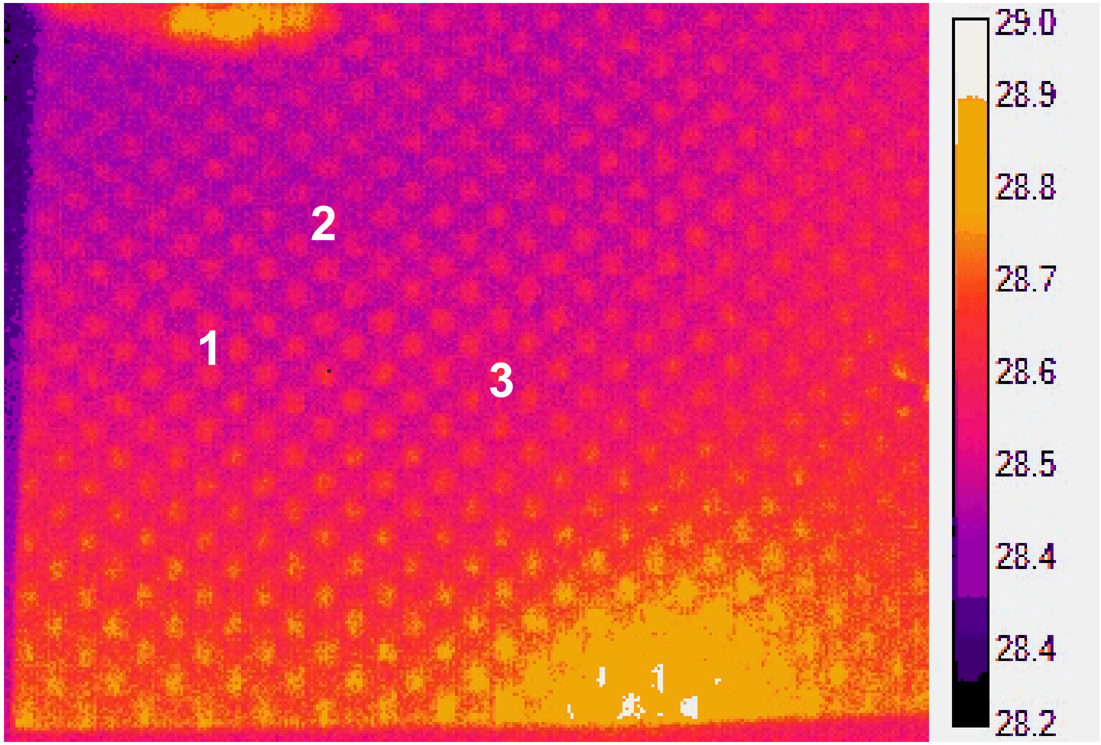


IR Images of Wrench Drop

Crescent Wrench Impact

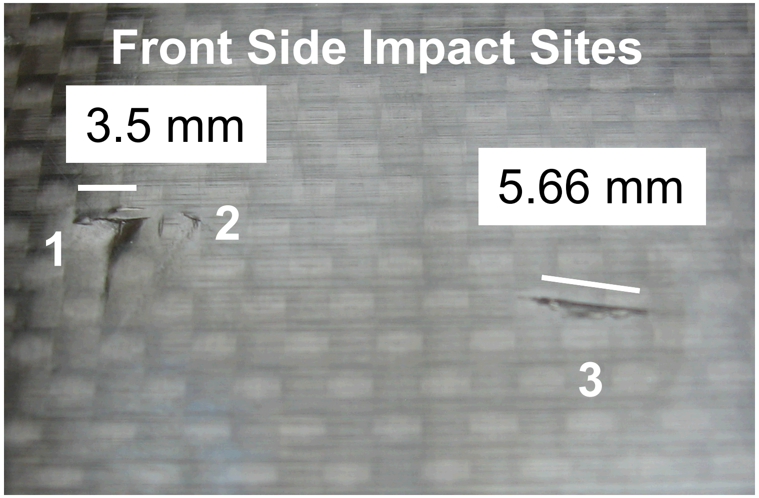
Impact Velocity 3.46 meters / second Impact Force of 2.45 Joules

Front Side



Total Video Length 0.7 seconds

Post Inspection of Damage



Crescent Wrench Impact, Single Drop
Impact Velocity 3.46 meters / second
Impact Force of 2.45 Joules