Structural Health Monitoring of Aerial Vehicles After Impact

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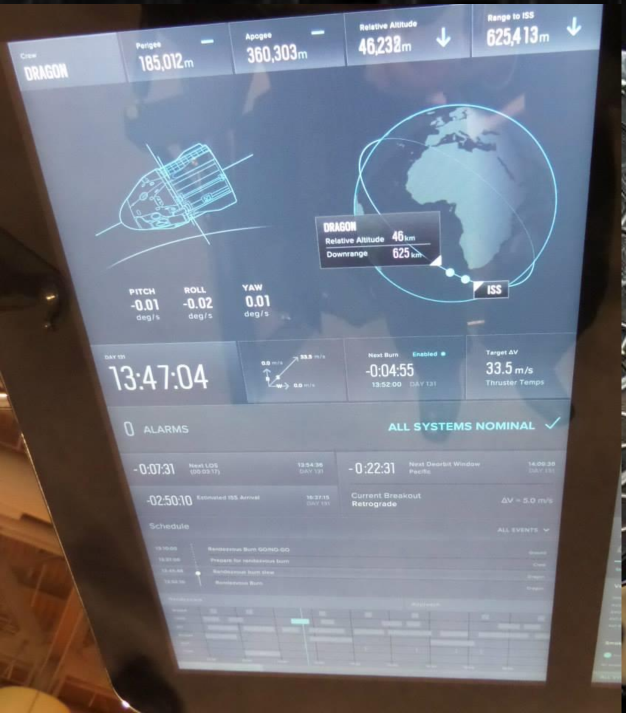
Agenda

- Health Concept
- Experiment Set-Up
- Results
- Possible Future Work


DRAGON
Perigee 185,012m
Apogee 360,303m
Relative Altitude 46,232m
Range to ISS 625,413m
DRAGON
Relative Altitude 46 km
Downrange 625 km
ISS
PITCH -0.01 deg/s
ROLL -0.02 deg/s
YAW 0.01 deg/s
13:47:04
Next Burn Enabled
-0:04:55
Target ΔV 33.5 m/s
Thruster Temps
0 ALARMS
ALL SYSTEMS NOMINAL
-0:07:31
-0:22:31 Next Deorbit Window
-02:50:10 Estimated ISS Arrival
Current Breakout
Retrograde
Schedule

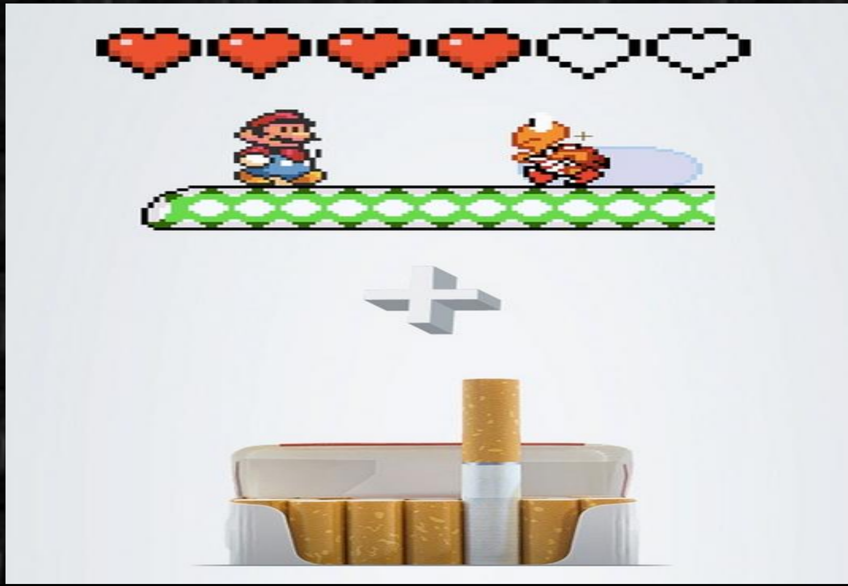

On Trunk
86%
100%
SPACEX
TIME
TIMER
ALARMS
PWR OVERRIDE
PWR RESET

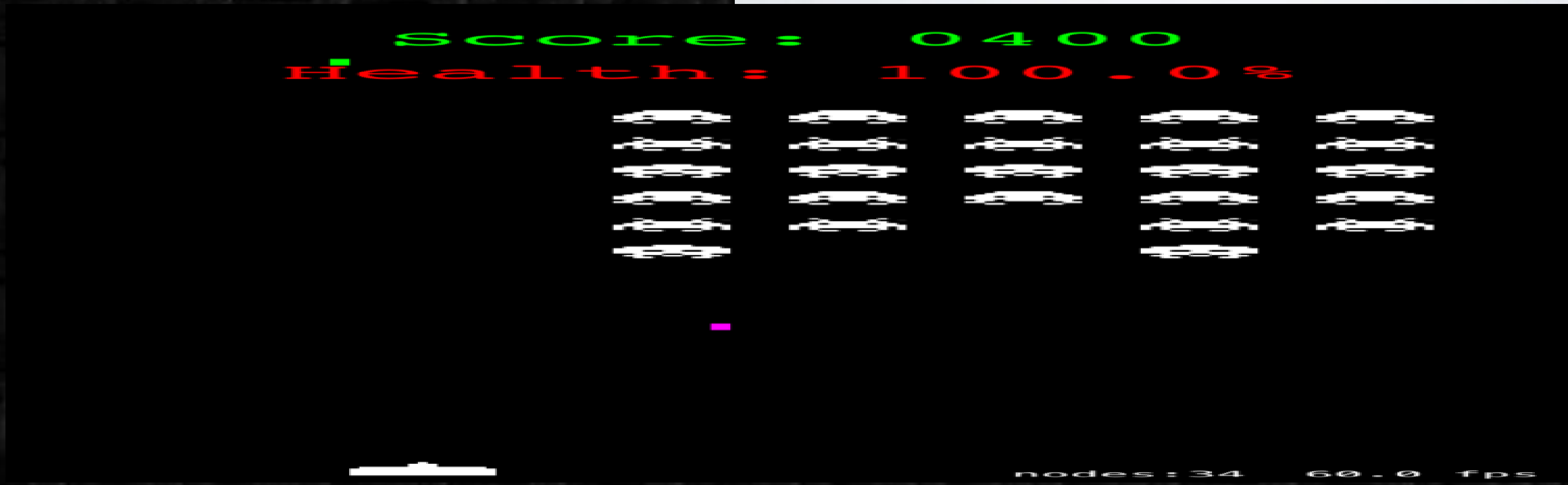
Trivial Health Monitor Examples

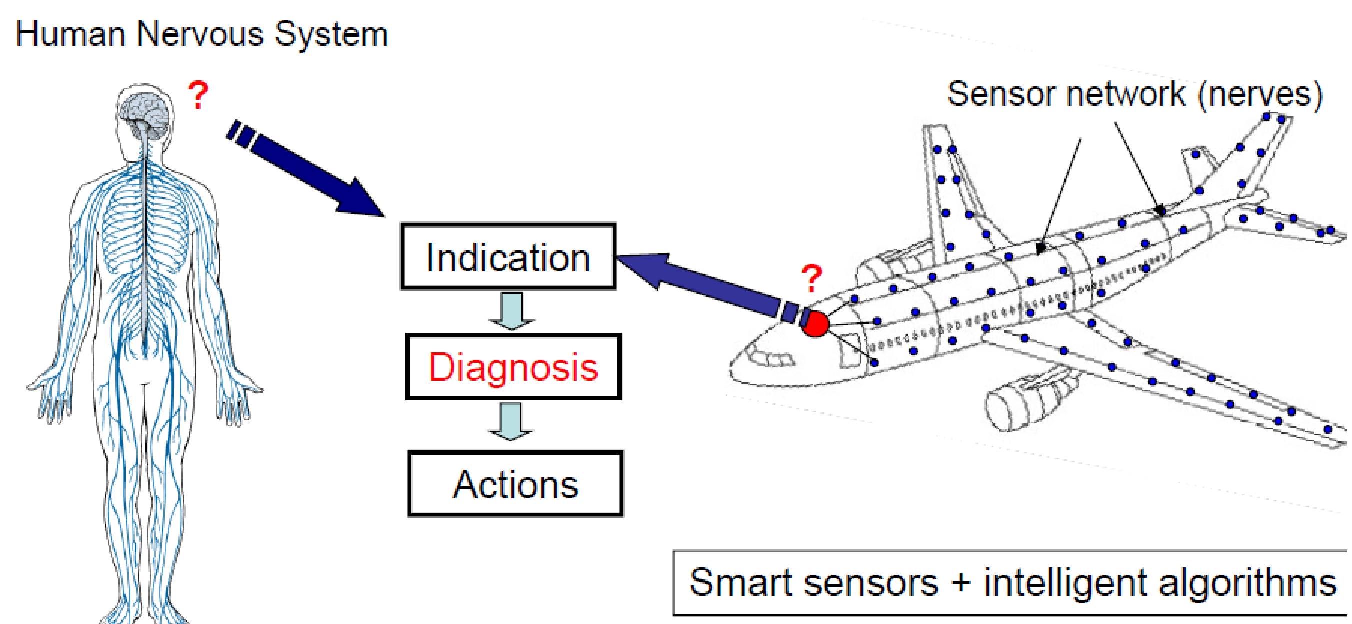
Health Monitoring

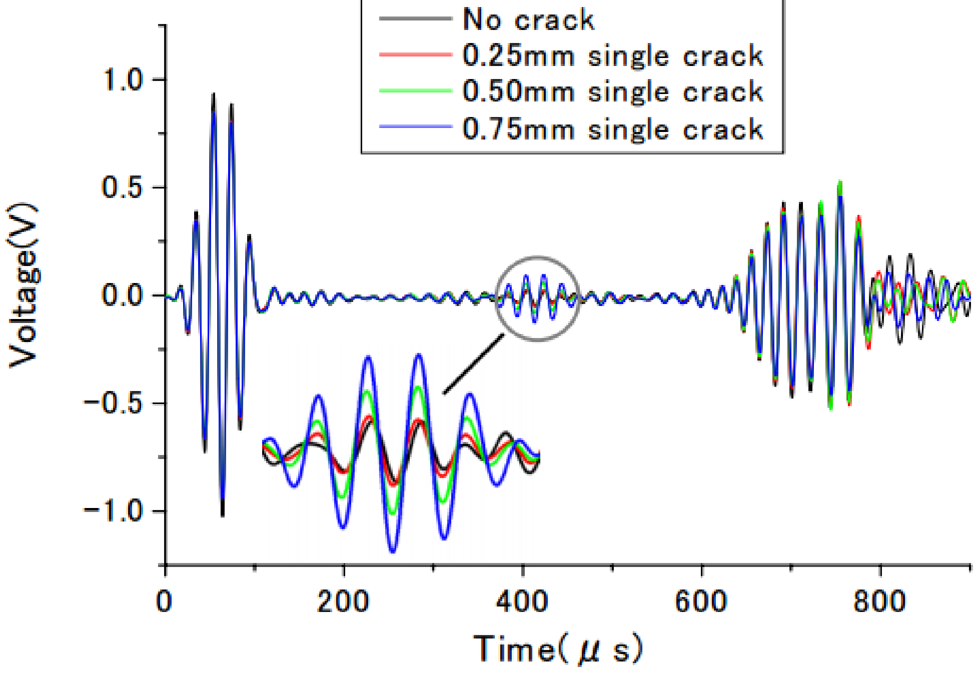
Nondestructive Inspection (NDI) – determine damage using technology without affecting its future usefulness

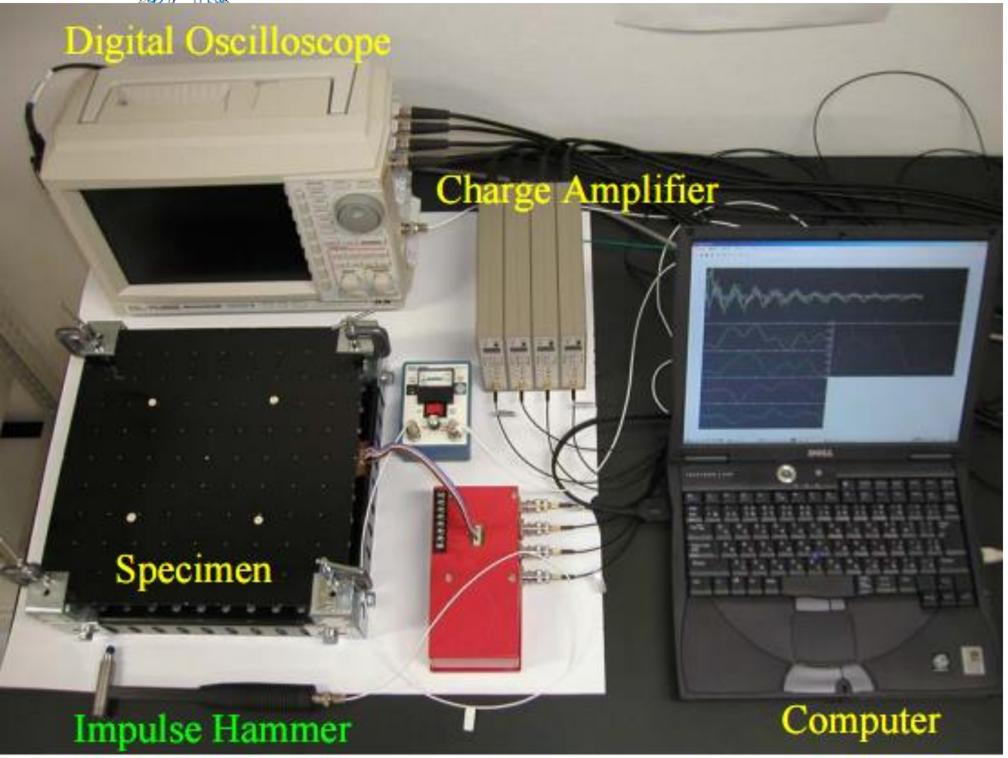
Structural Health Monitoring (SHM) – use of NDI coupled with sensing to allow for rapid, remote, and real-time condition assessments

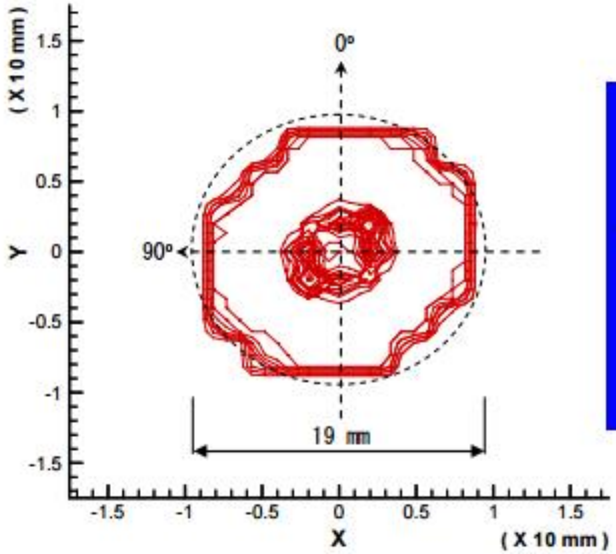


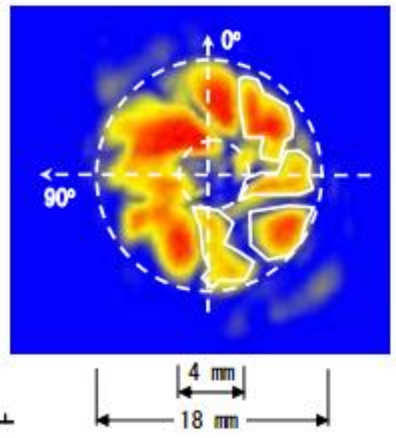



Human Nervous System
?
Indication
Diagnosis
Actions
?
Sensor network (nerves)
Smart sensors + intelligent algorithms

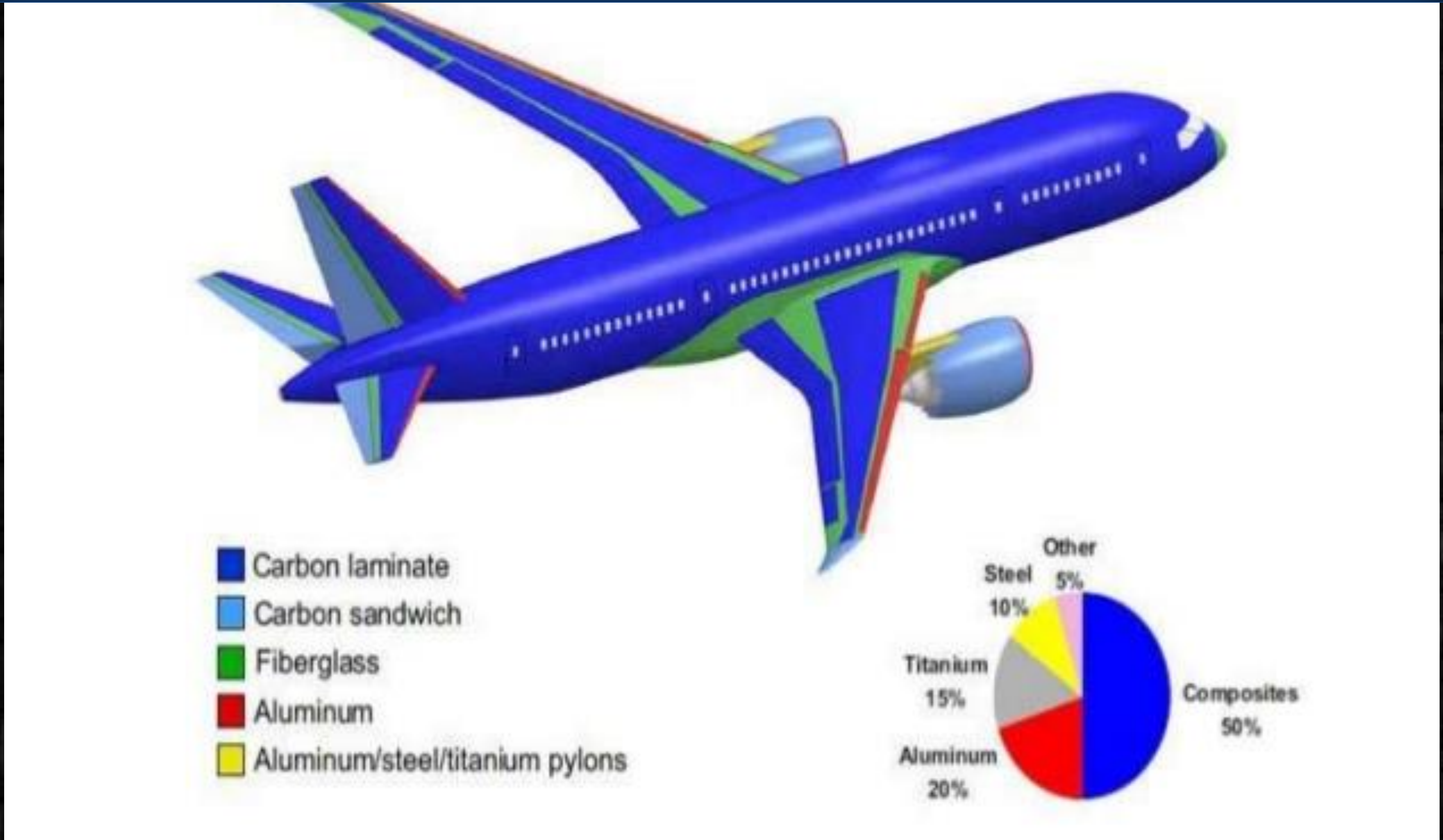

No crack
0.25mm single crack
0.50mm single crack
0.75mm single crack
Voltage(V)
1.0
0.5
0.0
−0.5
−1.0
0
200
400
600
800
Time(μ s)


Digital Oscilloscope
Charge Amplifier
Specimen
Impulse Hammer
Computer


(X 10 mm)
Y
1.5
1
0.5
0
-0.5
-1
-1.5
0°
90°
19 mm
-1.5
-1
-0.5
0
0.5
1
1.5
X
(X 10 mm)


0°
90°
4 mm
18 mm

Composite Materials Used in Boeing 787 Body



Material Acquisition: Thermo-Lite Board®

Fiber-reinforced urethane product ideal for applications subjected to static and dynamic loads including uses in

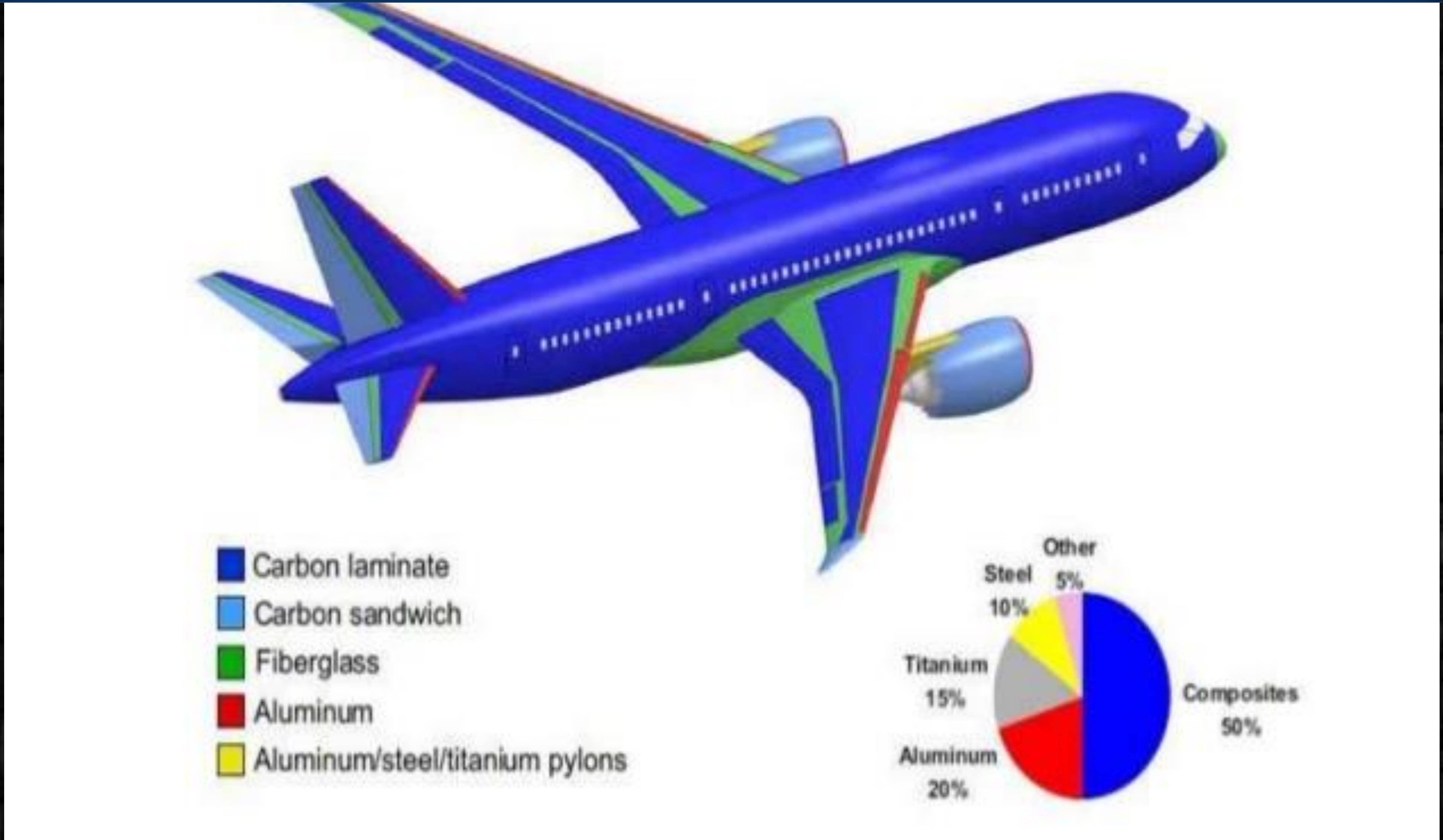
- Boat Hulls
- Ambulance
- RVs
- Multipurpose Arenas

SpaceAge Synthetics, LTD.

Industrie

Fibre Glast Developments Corporation

Composite Materials Used in Boeing 787 Body



Experimental Plan of Attack

Prepare/Acquire Material

Conduct Impact Tests

Evaluate Damage

Simulate Effect on Flight Attitude

Predict/Test Residual Strength

Low Velocity Impact Tests

NDSU Steel Bridge Team

→ Design Steel Drop Tower

$$PE = mgh,$$

here *PE* = *potential energy*, measured in Joules (J); *m* = *mass*, measured in kilograms (kg);
g = *gravitational force* = 9.81 m/s^2 on Earth; and
h = *height*, measured in meters (m)

Low Velocity Impact Tests

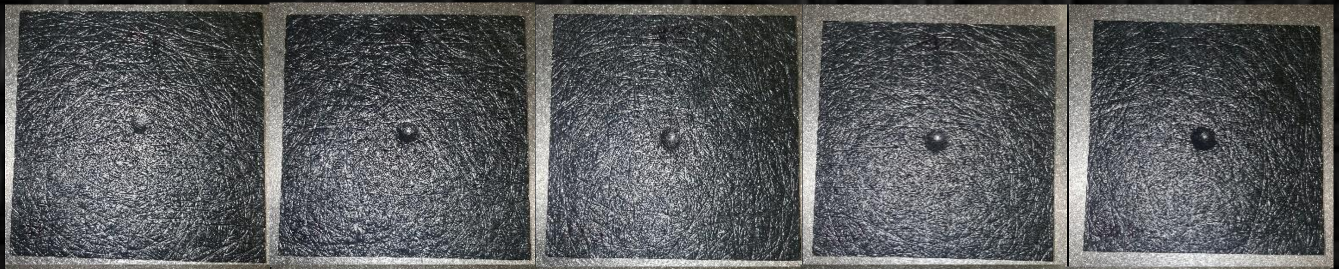
Instron 9250 HV Dynatup Shock Tower

- Applications in aerospace, automotive, and the biomedical materials
- Pneumatic hydraulic system used to raise and lower weight
- Follows ASTMD2444 Testing Standard
- Spectrometer used to collect velocity data
- Calibration of load cell prior to tests
- Electronic control to jog the height of weight

Low Velocity Impact Data

Summary of 5 4”x4” Specimens

- Heights: 0.05 – 0.25 m
- Velocities: 1.00 – 2.25 m/s
- Energies: 4 – 20 J

Impact Energy Level *(J)*:	4 J	8 J	12 J	16 J	20 J
Drop Weight *(kg)*:	7.7271	7.7271	7.7271	7.7271	7.7271
Height *(m)*:	0.0528	0.1056	0.1585	0.2113	0.2642
Input Velocity (m/s):	1.0175	1.4389	1.7624	2.035	2.2752
Measured Velocity (m/s):	0.9808	1.421	1.7389	2.026	2.2695
Impacted elephant skin side image					
Opposite sanded side image					

High Velocity Impact Tests

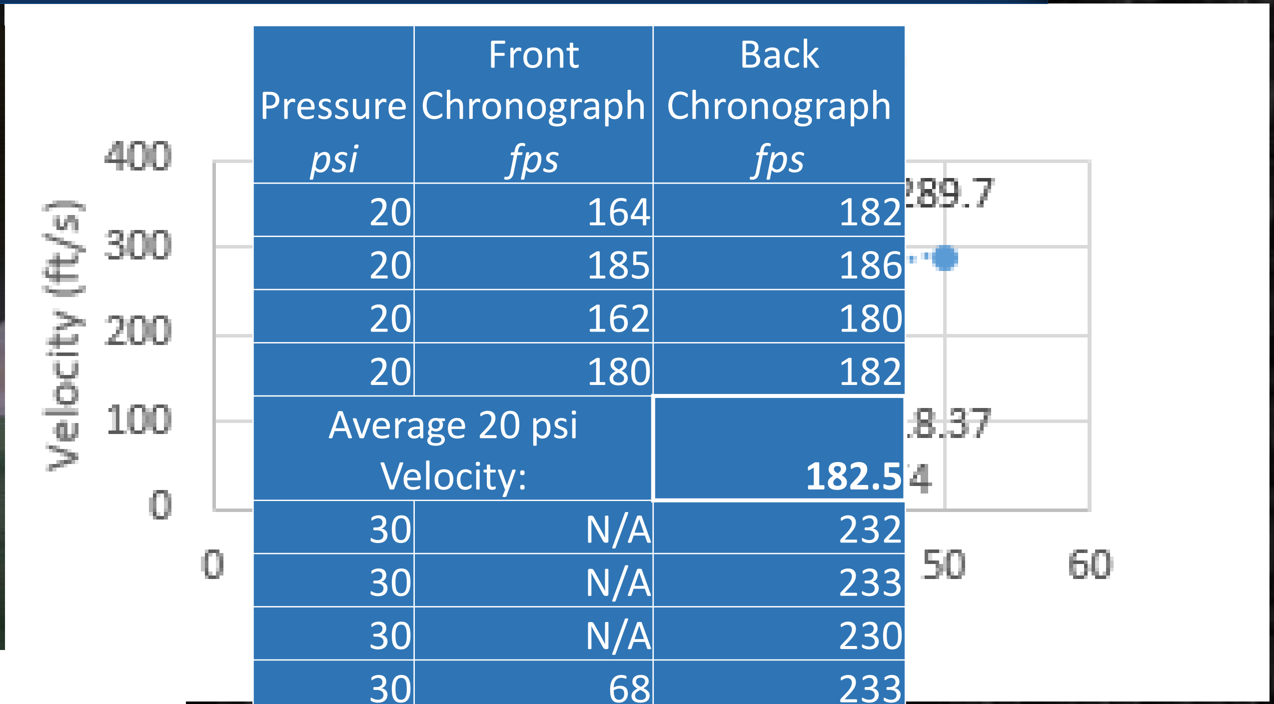
Ballistic Gas Gun

- Gas tank rated at 350 psi
- Electronic control system
- Pneumatic ball valve
- Aluminum bullet-shaped sabot

$$KE = \frac{1}{2}mv^2$$

where *KE* = *kinetic energy,* measured in Joules (J); *m* = *mass,* measured in kilograms (kg); *and v* = *velocity* of the projectile, measured in meters per second (m/s).

Velocity Calibration of Infrared Chronographs

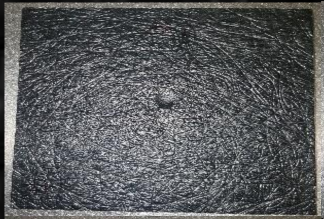
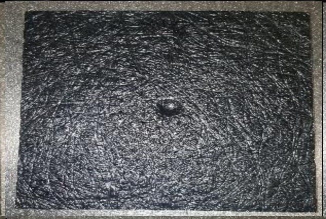
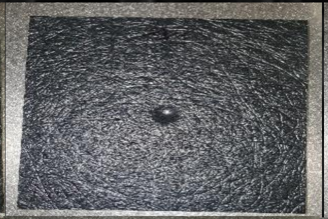
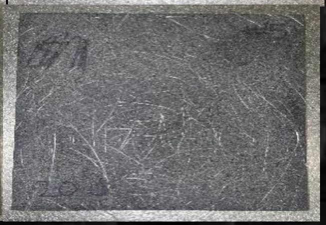


Pressure *psi*	Front Chronograph *fps*	Back Chronograph *fps*
20	164	182
20	185	186
20	162	180
20	180	182
Average 20 psi Velocity:		**182.5**
30	N/A	232
30	N/A	233
30	N/A	230
30	68	233
Average 30 psi Velocity:		**232**
40	230	263
40	227	264
Average 40 psi Velocity:		**263.5**
50	77	290
50	81	291
50	0	288

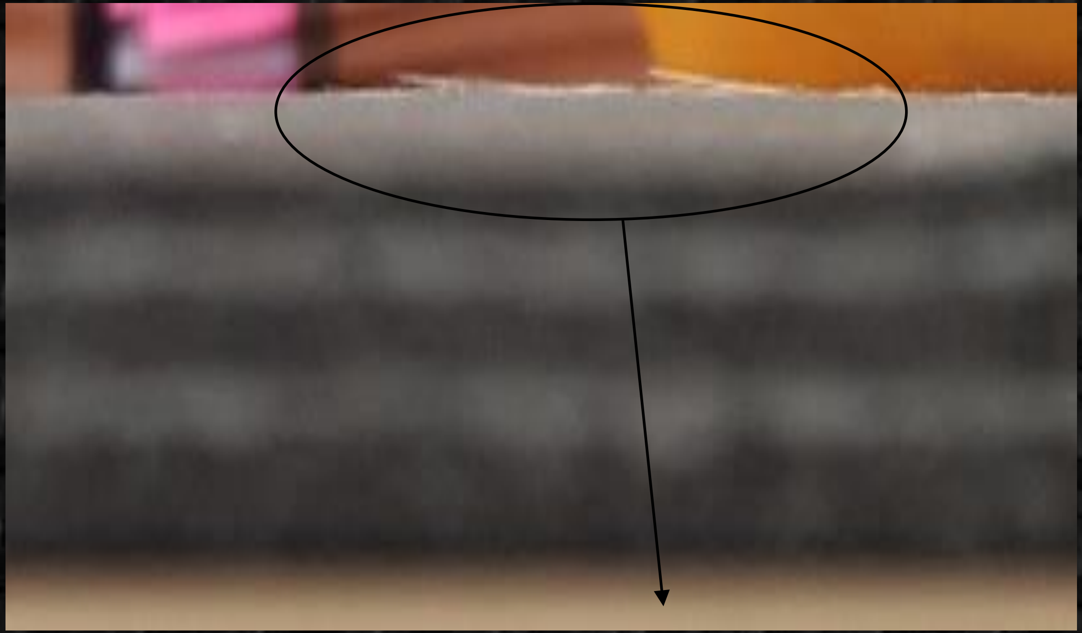
Chronograph Reading Raw Data

Input Pressure	*psi*	30	20	30	50	40
Front Chronograph Velocity	*ft/s*	197	164	N/A	N/A	N/A
Back Chronograph Velocity	*ft/s*	N/A	182	232	233	23

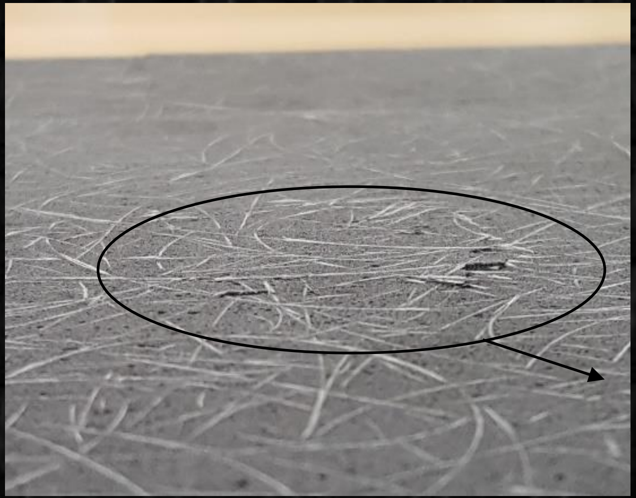
High Velocity Impact Data

Impact Energy Level *(J)*:	4 J	8 J	12 J	16 J	20
Drop Weight *(kg)*:	7.7271	7.7271	7.7271	7.7271	7.7
Height *(m)*:	0.0528	0.1056	0.1585	0.2113	0.2
Input Velocity (m/s):	1.0175	1.4389	1.7624	2.035	2.2
Measured Velocity (m/s):	0.9808	1.421	1.7389	2.026	2.2
Impacted elephant skin side image					
Opposite sanded side image					

Invalid test by ASTM standards



Fiber Delamination & Breakage



Barely visible damage

Damage Characterization

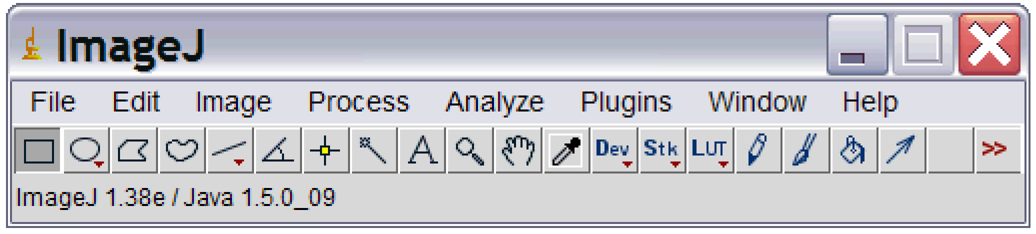
Damage Characterization

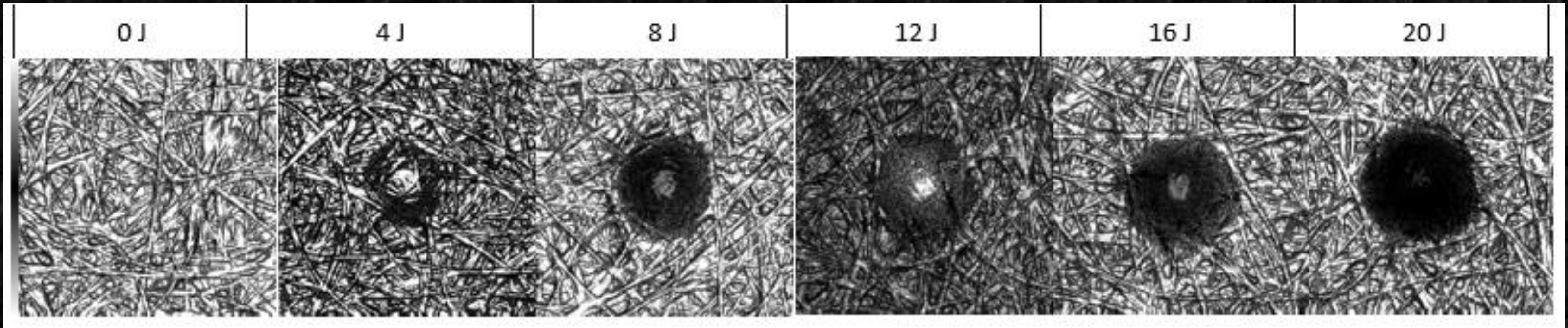
NDSU RESEARCH AND TECHNOLOGY PARK

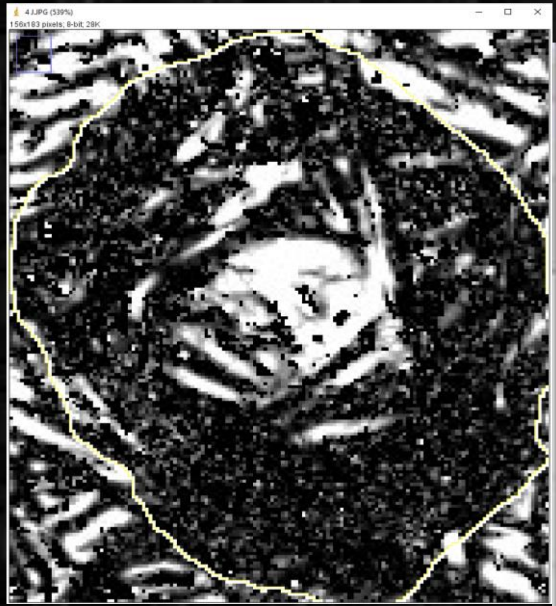
Sonoscan Gen5™ C-Mode Scanning Acoustic Microscope (C-SAM)

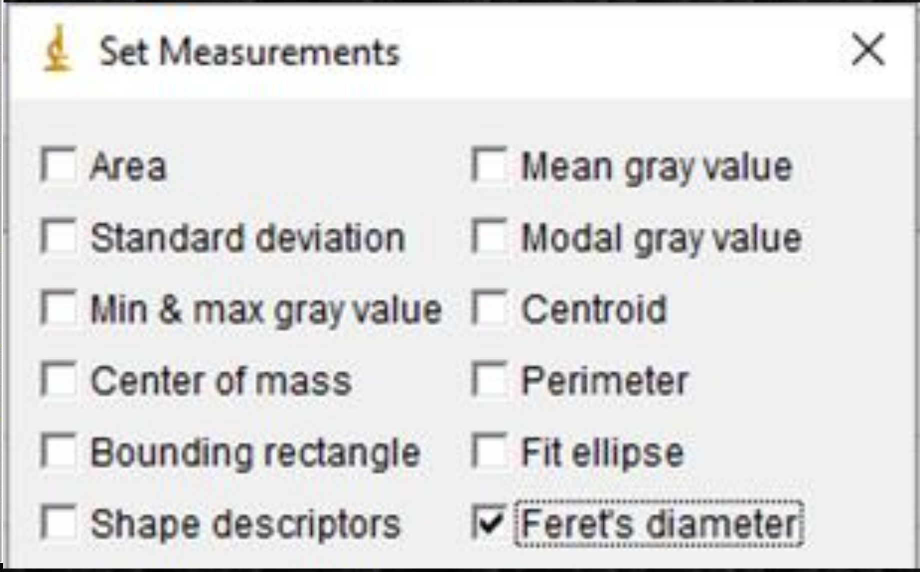
Input Parameters
- Frequency of wave = 30 MHz
- Time of flight = 17.2 μs
- Trigger = 1.165
- Top gain = 33.0 dB
- Bottom gain = 26.5 dB
- Scanning area = 1.008” x 1.008”
- Resolution = 512 x 512 pixels (this resolution was sufficient compared to higher resolutions, but did not take as long to scan)

Ultrasonic Images









Residual Strength Predictions

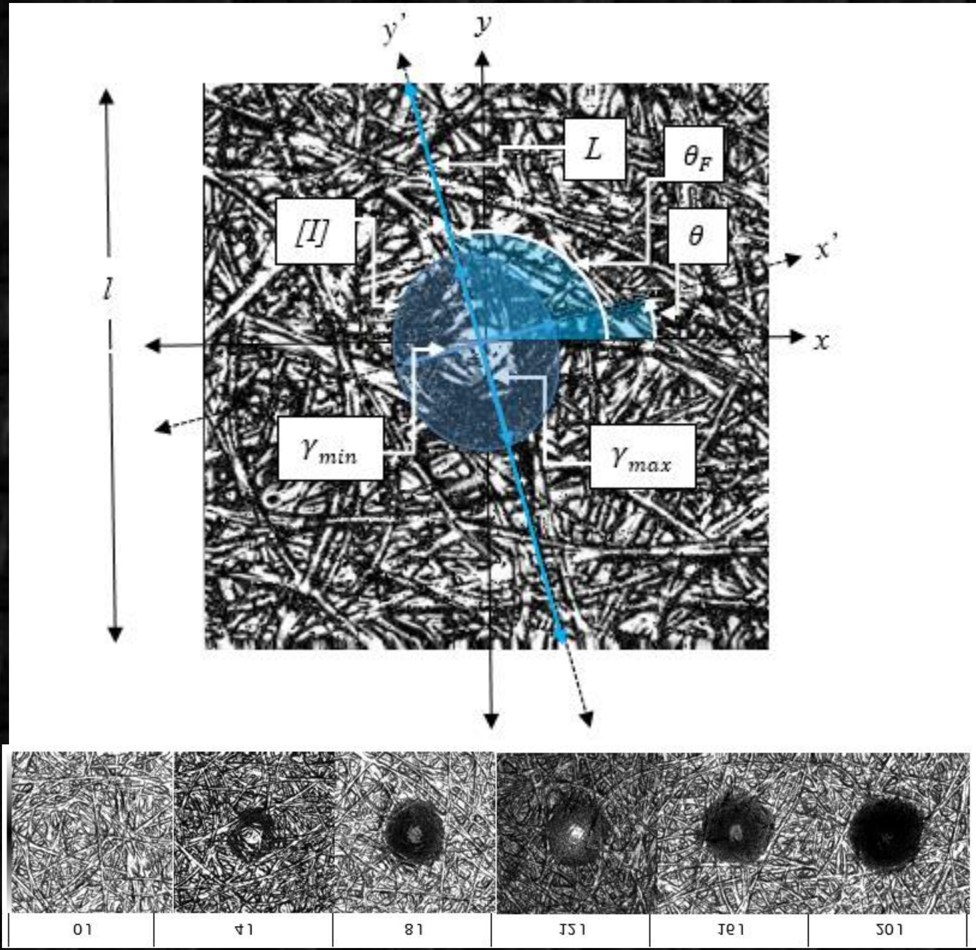
$$I = T^T dT$$

$$T = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix},\ d = \begin{bmatrix} \gamma_{max} & 0 \\ 0 & \gamma_{min} \end{bmatrix},\ and\ \ T^T = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix},$$

$$I = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \gamma_{max} & 0 \\ 0 & \gamma_{min} \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

$$Health\ Points = HP = \left\{ 1 - \frac{[I(\gamma_{max})]}{L} \right\} U_0$$

Impact Energy Level	Maximum Feret Diameter	Minimum Feret Diameter	Maximum Feret Diameter	Minimum Feret Diameter	Feret Angle	Length Along Maximum Damage	Health Points
KE	γ_{max}	γ_{min}	γ_{max}	γ_{min}	θ_F	L	HP
(J)	(pixels)	(pixels)	(inches)	(inches)	(°)	(inches)	% of U_0
4	185.7	149.4	0.366	0.294	101.5	4.285	0.915
8	217.2	190.0	0.428	0.374	147.4	4.947	0.914
12	220.0	197.8	0.433	0.389	95.5	4.211	0.897
16	240.1	223.9	0.473	0.441	163.3	4.361	0.892



$**U_0 = original\ health\ or\ strength$

Future Work

For publication,

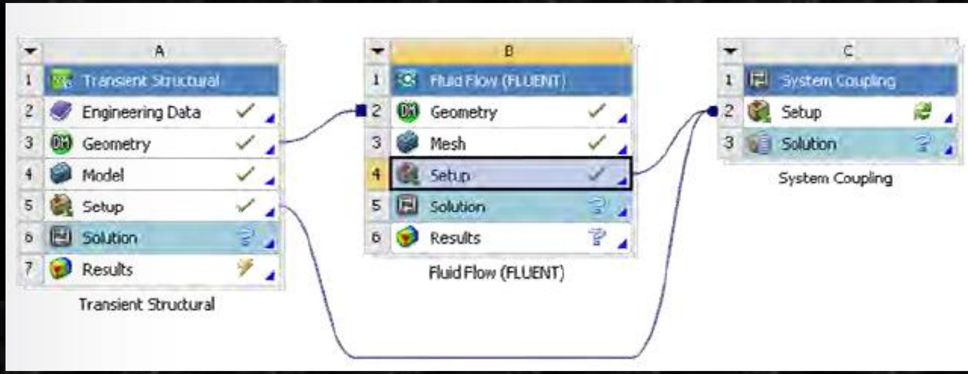
- Tensile testing
- Scans of high-velocity impacts
- Verify compare residual health prediction
- Aerodynamic model?

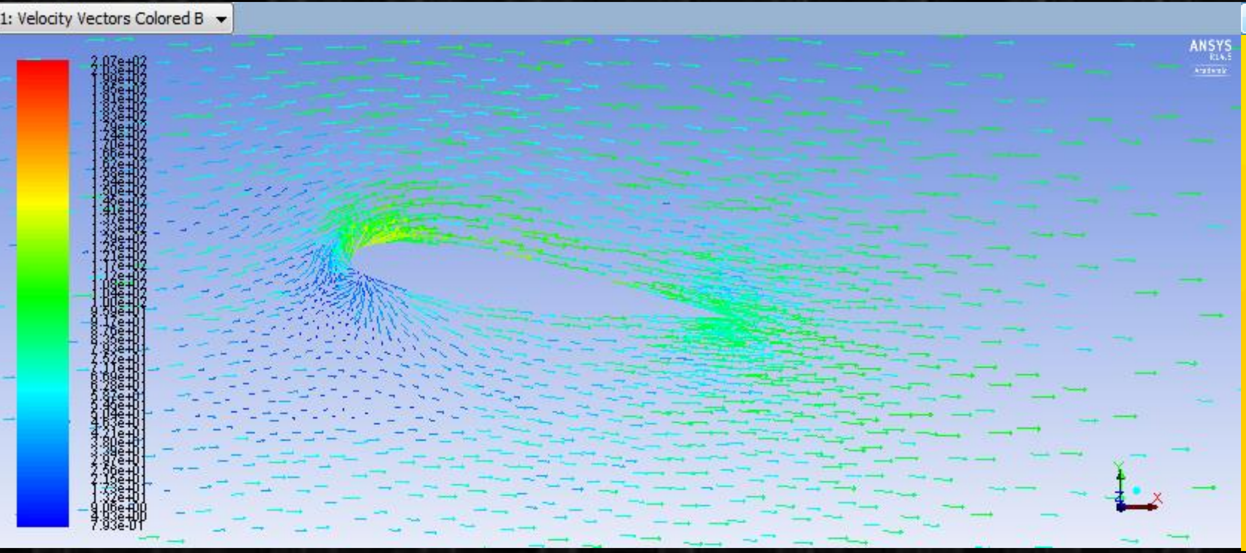
For research topic,

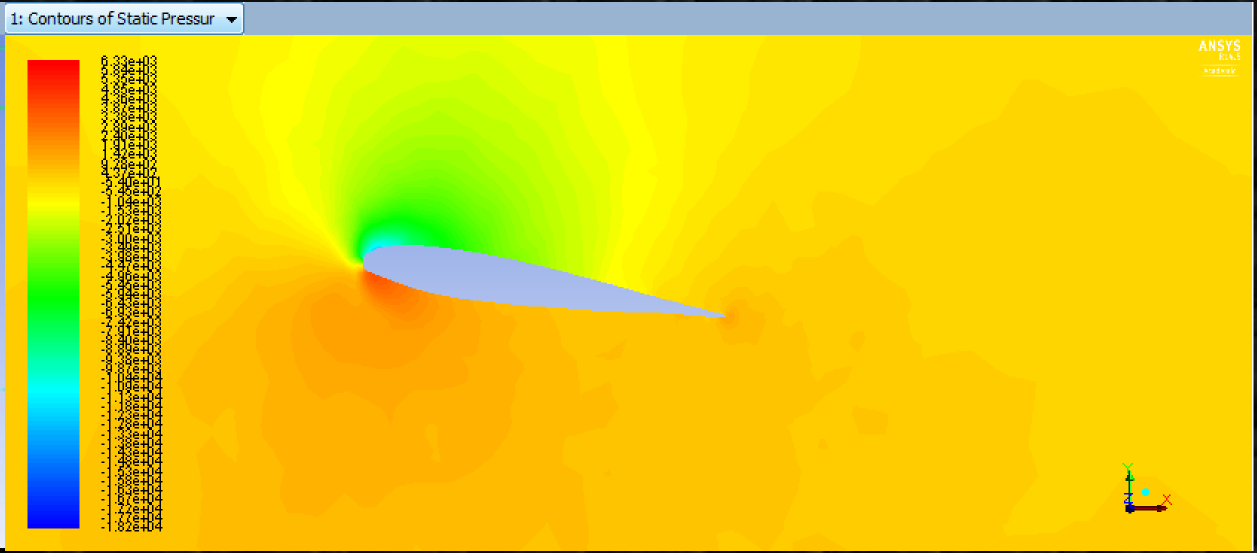
- More impact data (effect of multiple impacts?)
- Varying material
- Defining how much damage is critical
- Building full-circle algorithm
- Optimizing software
- Lab testing & In-service testing
- Validation
- Standardization
- Proving its cost-benefit

Stacking Sequence	Material Properties of Lamina
cfm/90/0/core/0/90/cfm	Young's Modulus = E = 4,269 MPa Density = ρ = 40 lbs/ft^3

Aerodynamic Response







Acknowledgements

NORTH DAKOTA
SPACE GRANT CONSORTIUM

NASA
EPSCoR

NDSU

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ELECTRICAL AND COMPUTER ENGINEERING

NDSU EXPLORE
UNDERGRADUATE EXCELLENCE IN RESEARCH AND SCHOLARLY ACTIVITY

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Material Preparation

- Manufacture In-House
- Seek Donation

Good News

Good News:
Flying manned/unmanned aircraft/spacecraft is beneficial

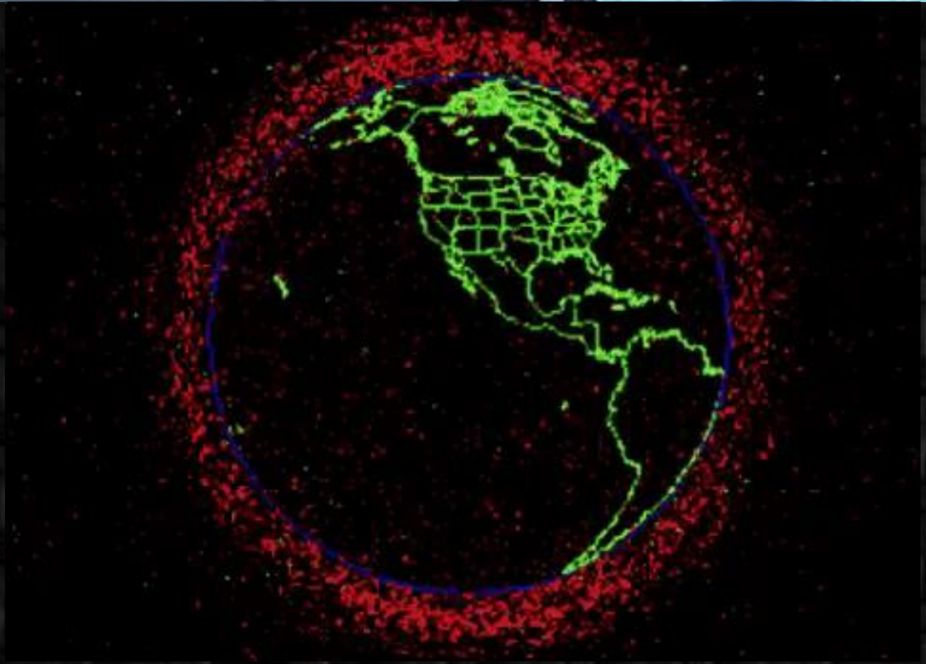
- Speed
- Comfort
- Cost
- Safety
- Space
- Science!!


Bad News

Aerial vehicles are vulnerable to external impacts such as

- Birds
- Debris
- Micrometeorites,

Which can be costly as well as life-threatening.



Fibre Glast Developments Corporation

	Name	Cost		Quantity	Total Cost
Carbon Fiber	3K, Plain Weave Carbon Fiber Fabric	$ 59.65	per 1-yd. roll	1	$ 59.65
Resin	System 2000 Epoxy Resin	$ 44.95	per quart.	1	$ 44.95
Tubing	Superthane Polyurethane Tubing Ester	$ -	-	2	$ -
Vacuum Bagging Film	Polyethylene Bagging Film	$ 10.25	per 5-yd. roll	1	$ 10.25
Tape	Gray Sealant Tape	$ 7.95	per 25-ft roll	2	$ 15.90
Breather and Bleeder	Breather and Bleeder	$ 7.95	per 1-yd. package	1	$ 7.95
Peel Ply	Nylon Release Peel Ply	$ 13.45	per 1-yd. package	1	$ 13.45
Spiral Tubing	Spiral Tubing	$ 19.95	per 10-ft spool	1	$ 19.95
Mixing Cups	1 Pint Plastic Cups	$ 8.05	per sleeve	1	$ 8.05
				∑	$ 180.15

NEWAGE INDUSTRIES

Low Velocity Impact Data