LsDyna3D Simulations and Analysis of Polish Governmental Airplane TU-154M Crash in Smolensk, Russia, April 10, 2010

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- ASCE Fellow
- Chairman of the Civil Engineering Department
  The University of Akron ("UA"), Ohio, USA
- Director "UA Gas Turbine Facility"
  - Impact Laboratory
  - Structural Laboratory
  - Material Testing Laboratory

- www.ecgf.uakron.edu/~civil/people/binienda/
- www.uakroncivil.com/researchlab/

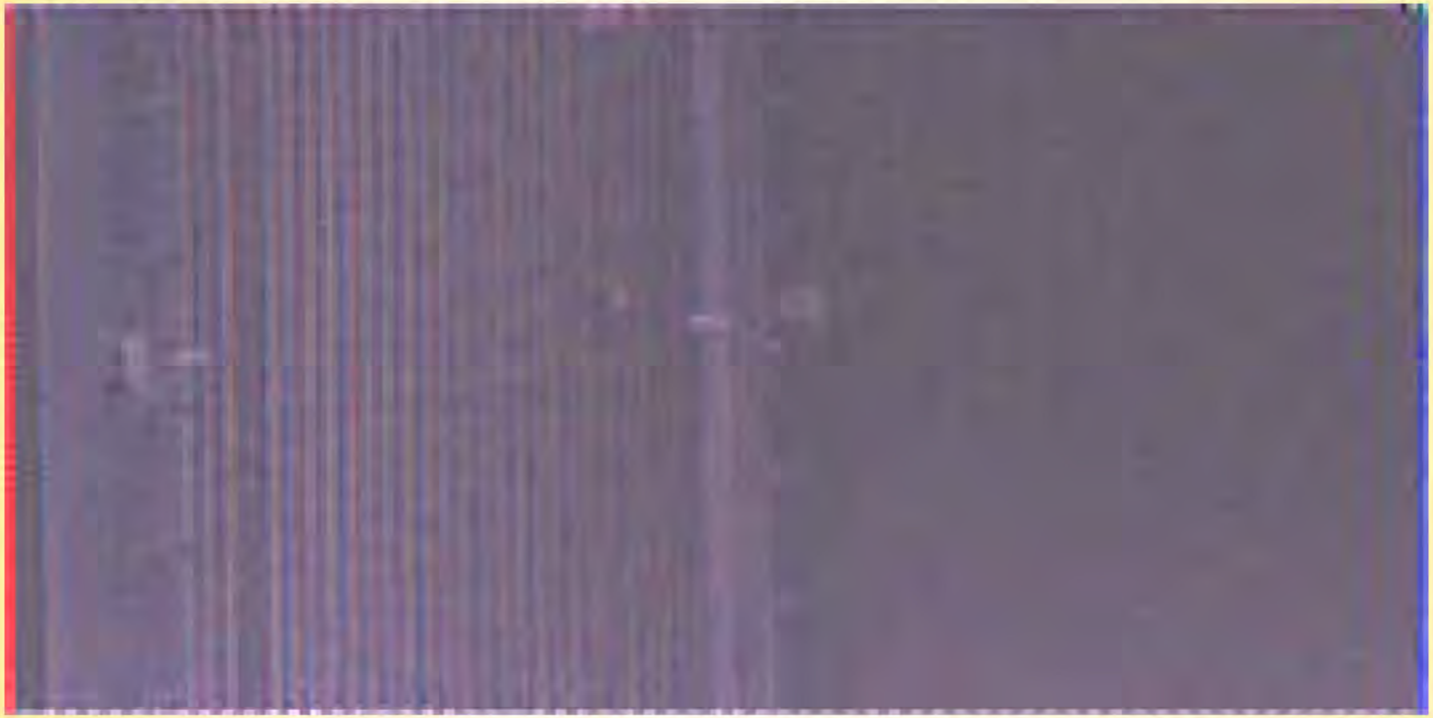
Member of the Aerospace Consortium consisting of:

- Arizona State University (ASU)
- Boeing
- Central Connecticut State University (CCSU)
- Federal Aviation Administration (FAA)
- General Electric Aviation (GE)
- George Washington University (GWU)
- Goodrich
- Hamilton Sundstrand
- Honeywell
- LSTC
- National Aeronautics and Space Administration (NASA)
- Ohio State University (OSU)
- Pratt & Whitney
- Rolls-Royce
- Snecma
- SRI International
- The University of Akron – Dr. Wieslaw K. Binienda
- Williams International

Methodology

Impact Video of (0+/-60) Composite Panel

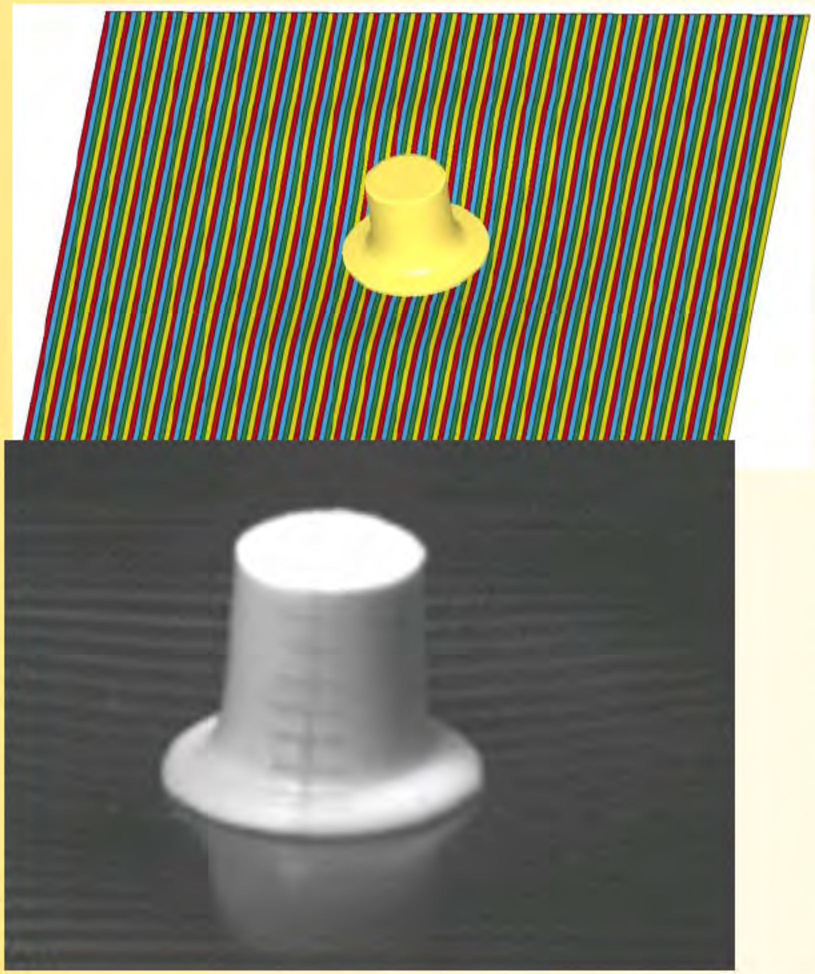
(Velocity below penetration threshold)

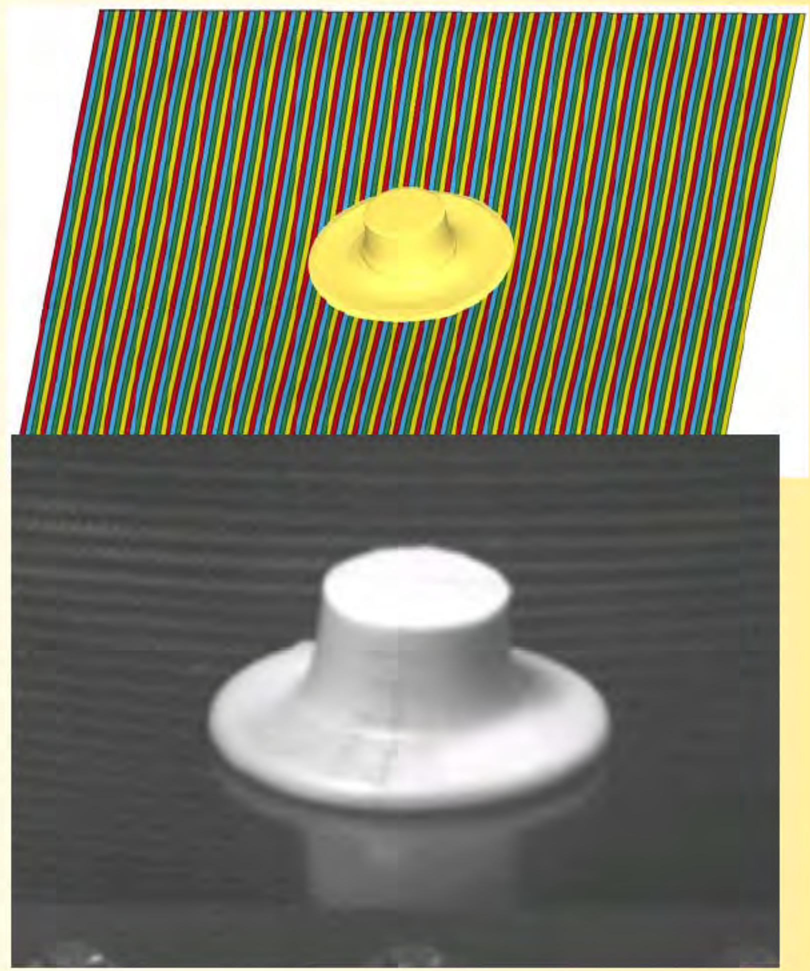


V = 491 ft/s (150 m/s)

(Test LG380, 7,100 pps)

Methodology

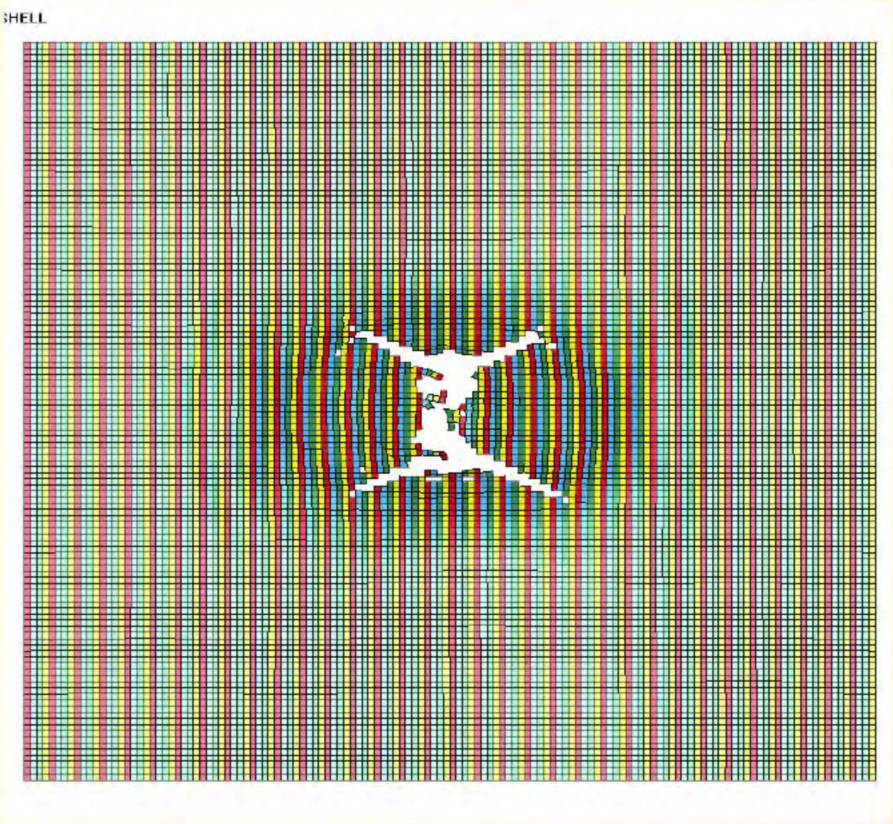




Methodology

Front

Back

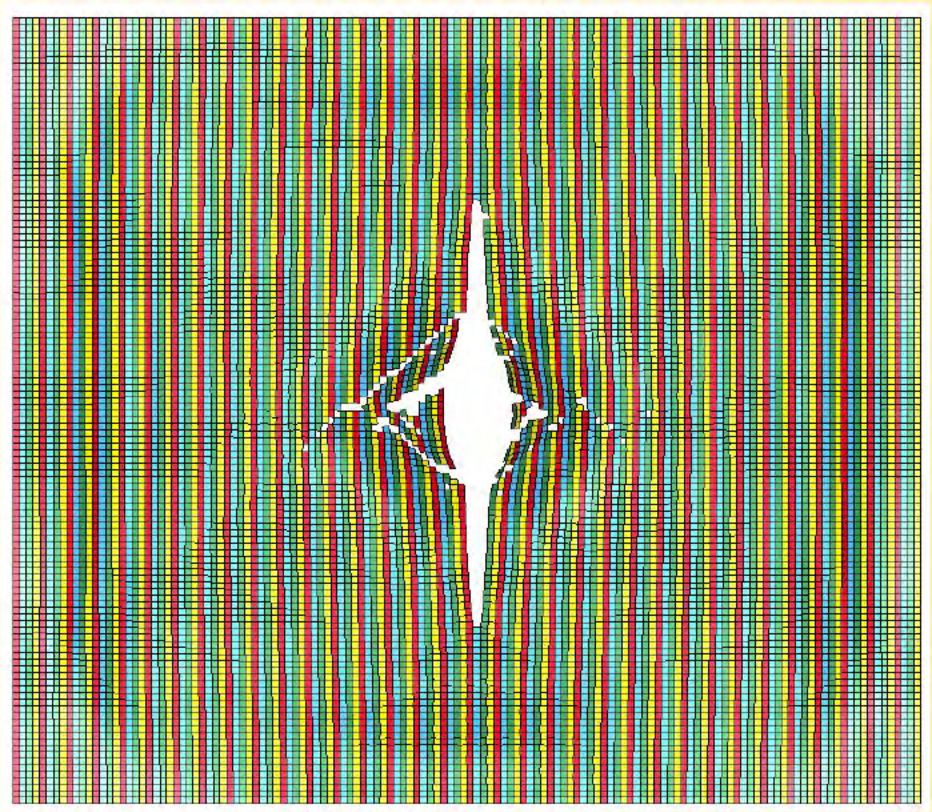


0° /±60° Composite plate after impact at 630 ft/s

Methodology

Impact Velocity =740ft/s

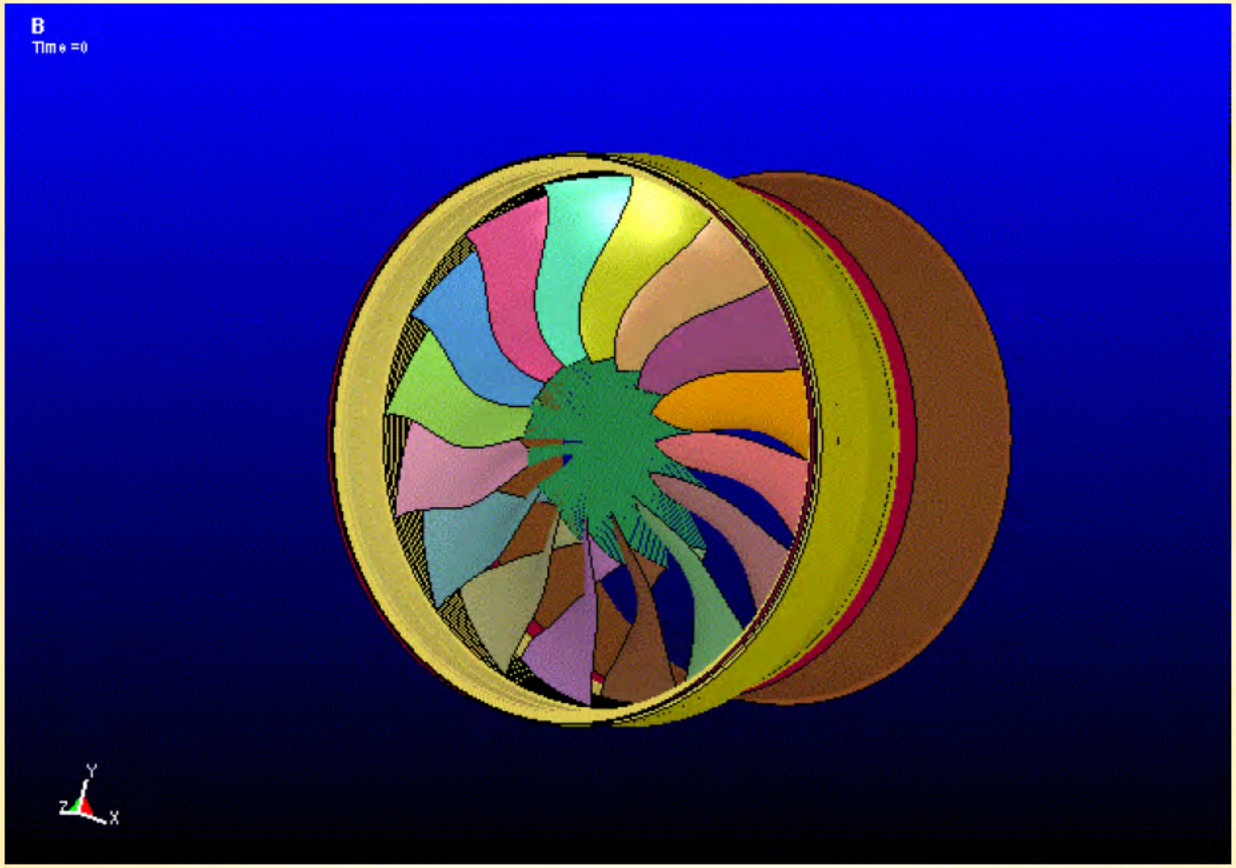
Impact Velocity = 823t/s



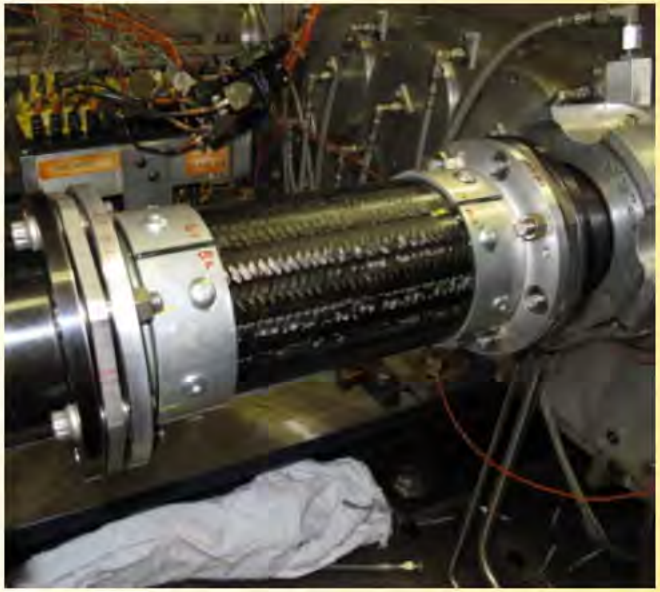
0°/±45°Composite plate after impact

FAA Blade-out Test

STRUCTURE - Blade-out Test Simulation



Aerospace Applications



- Composite fan blade and containment structures such as GEnx engine (top left)
- Composite drive system such as shafts (top right), gears, and cases
- Composite airframe structures such as the fuselage frames on Boeing 787

Top left image: http://www.gereports.com/etihad-airways-inks-ge-contracts-worth-over-45b/

Background Information on Smolensk Crash

Russian Investigating Committee Final Report on the Crash of Polish Tu-154M on April 10, 2010 in Smoleńsk

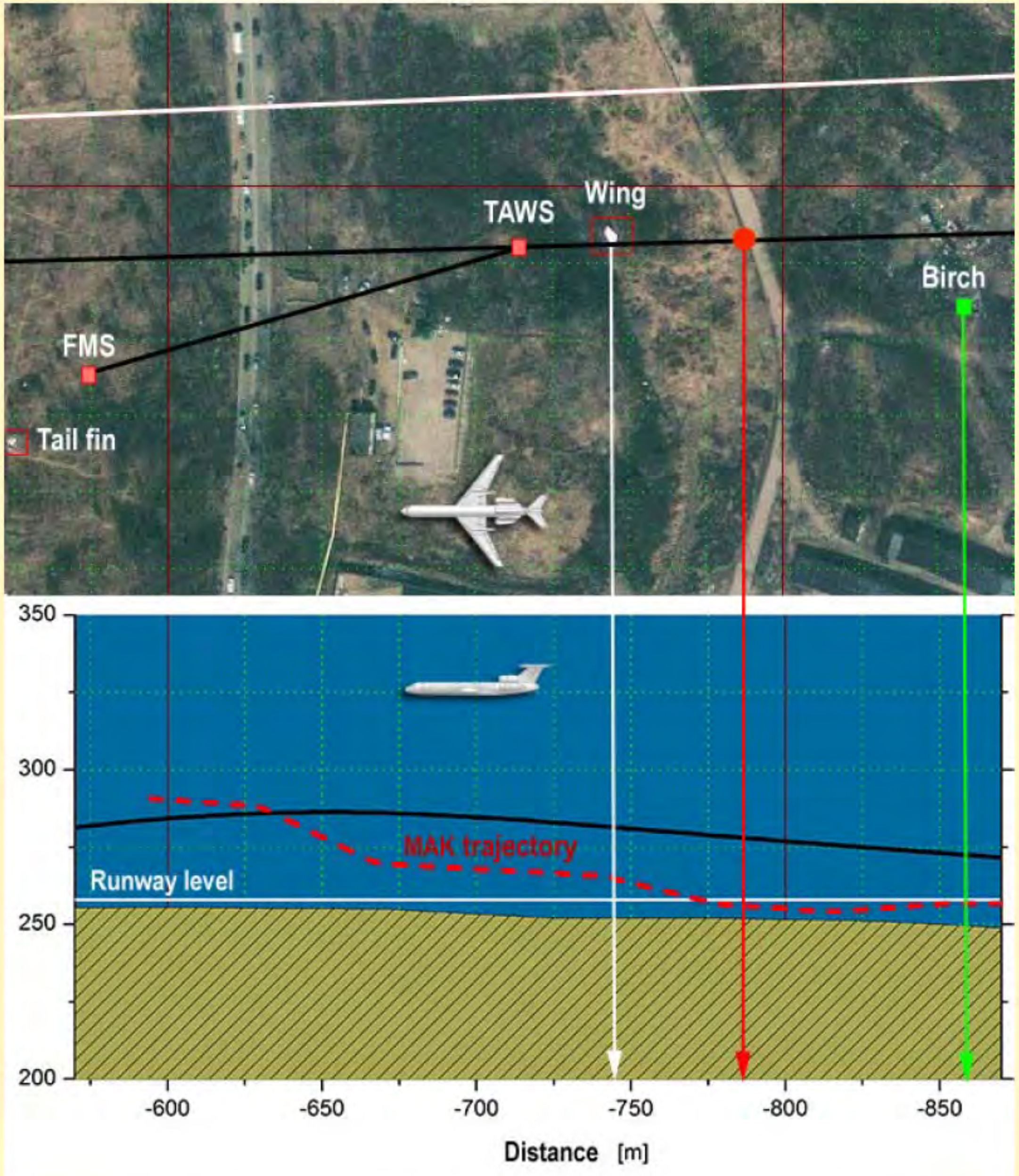
Section 3.1.69

- The aircraft collided with the birch with a trunk diameter 30-40 cm, which led to the left outer wing portion of about ~~4.7~~ 6.5 m long ripped off and intensive left bank.

Section 3.1.70

- In 5-6 more seconds, inverted the aircraft collided with the ground and was destroyed

Last Seconds Before the Crash



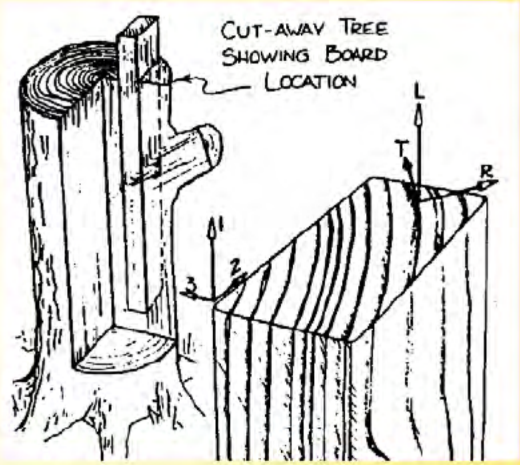
Satellite Images of the Area Where the Last TAWS Event Has Occurred (April and June 2010)

Material Parameters – Dry Birch Wood

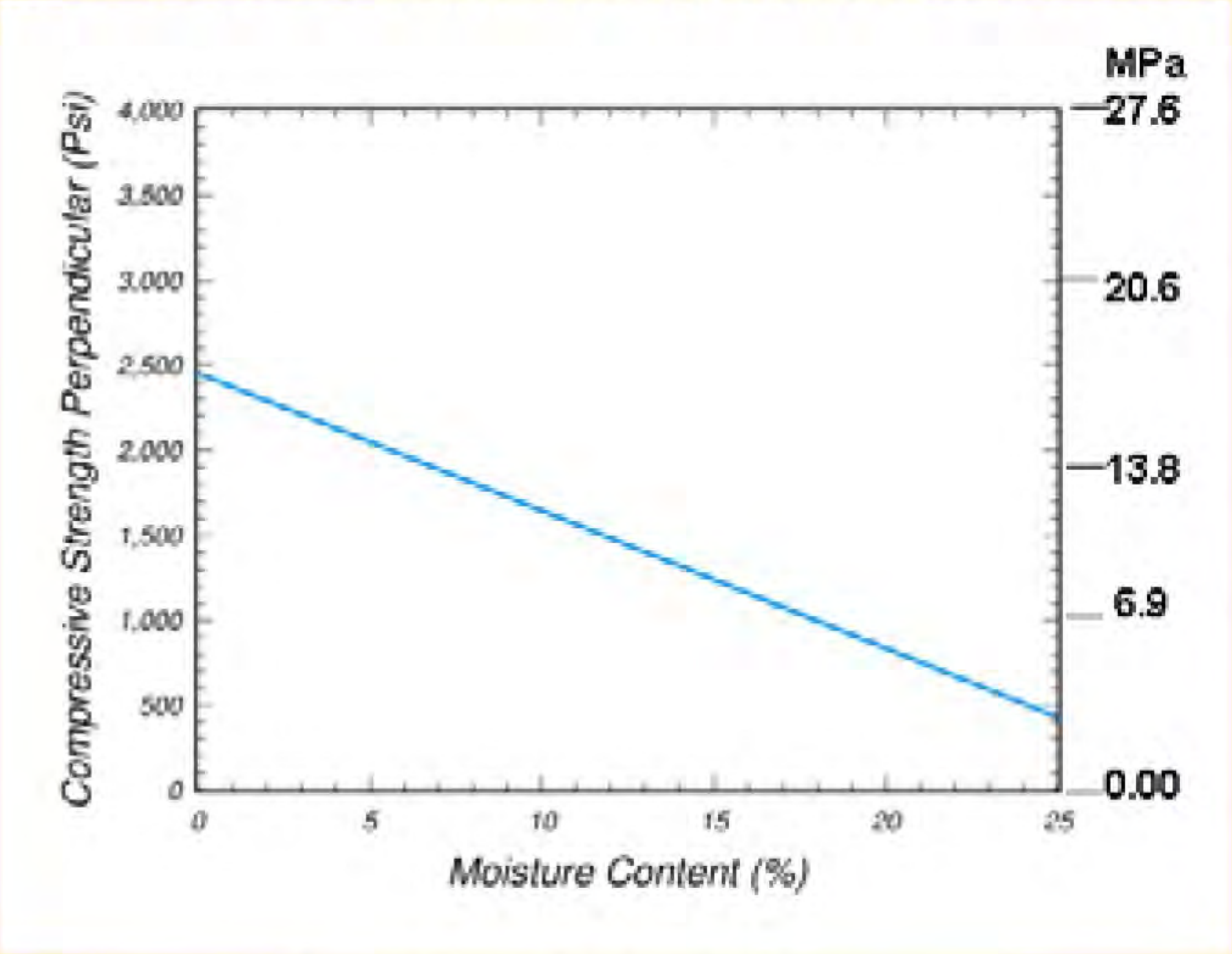
	Young's Modulus (MPa)			Poisson Ratio			Shear Modulus (MPa)			Density (Kg/m³)
	E_L	E_R	E_T	ν_{LT}	ν_{RL}	ν_{RT}	G_{TL}	G_{LR}	G_{RT}	
Generic 4x	16000	1600	1100	0.451	0.043	0.697	700.4	762.2	175.1	1000

- Generic Birch Model: elastic, cylindrically, orthotropic (Failure Max Strain)
- Mat143 - New Birch Model: nonlinear (Modified Hashin)

MAT143							
mid	ro	nplot	iters	irate	hard	ifail	ivol
6	700	1	1	1	0	0	0
el	et	glt	glr	pr			
1.14E+10	2.43E+08	5.88E+08	8.70E+07	0.39			
xt	xc	yt	yc	sxy	syz		
1.61E+08	3.59E+07	3.45E+06	3.75E+06	9.90E+06	1.40E+07		
gf1||	gf2||	bfit	dmax||	gf1p	gf2p	dfit	dmaxp
223.39999	838.4	3	0.99	2.1	7.88	3	0.99
flpar	flparc	powpar	flper	flperc	powper		
4.50E-06	4.50E-06	0.107	9.62E-05	9.62E-05	0.104		
npar	cpar	nper	cper				
0.5	400	0.4	100				

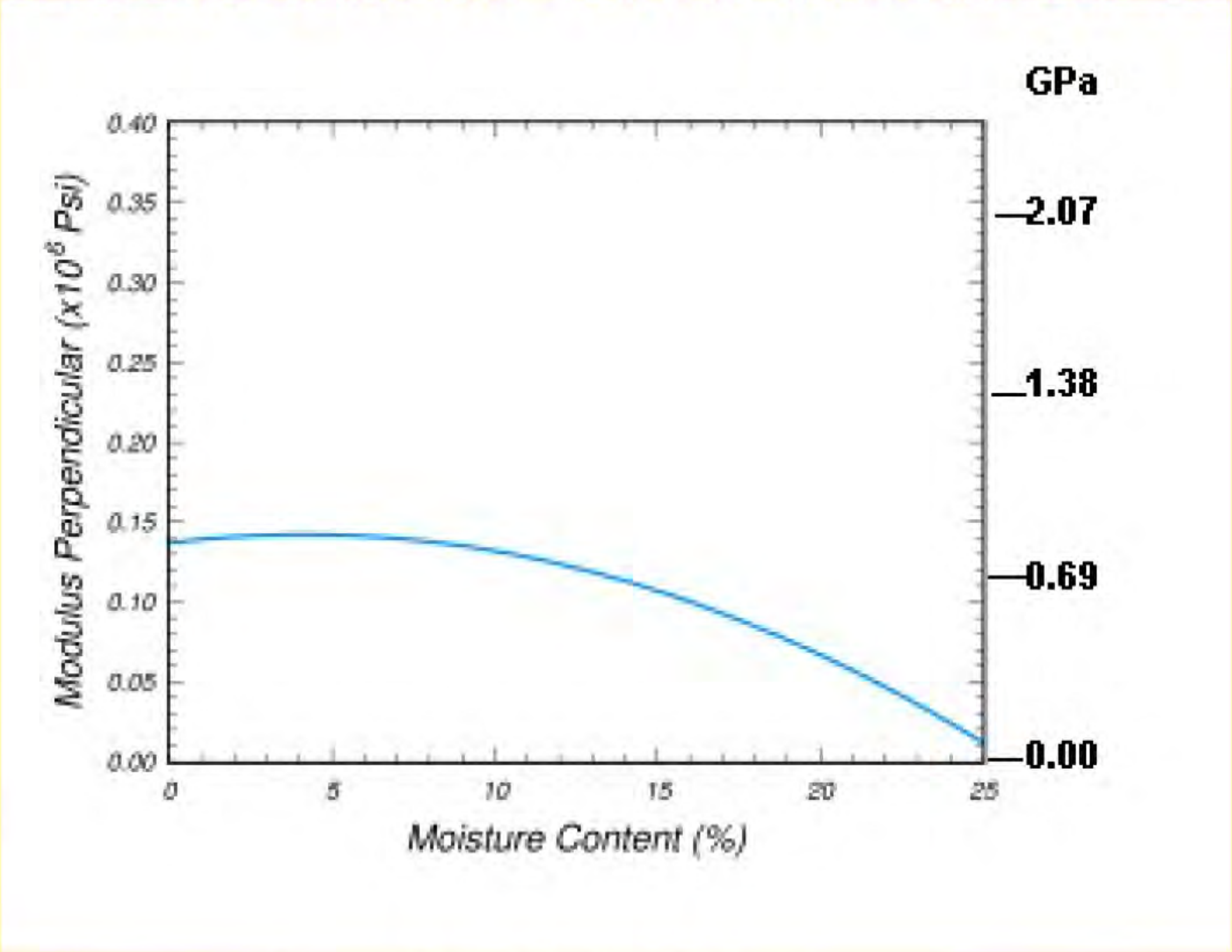


Wood Moisture Effect: The more humid wood the weaker it is!



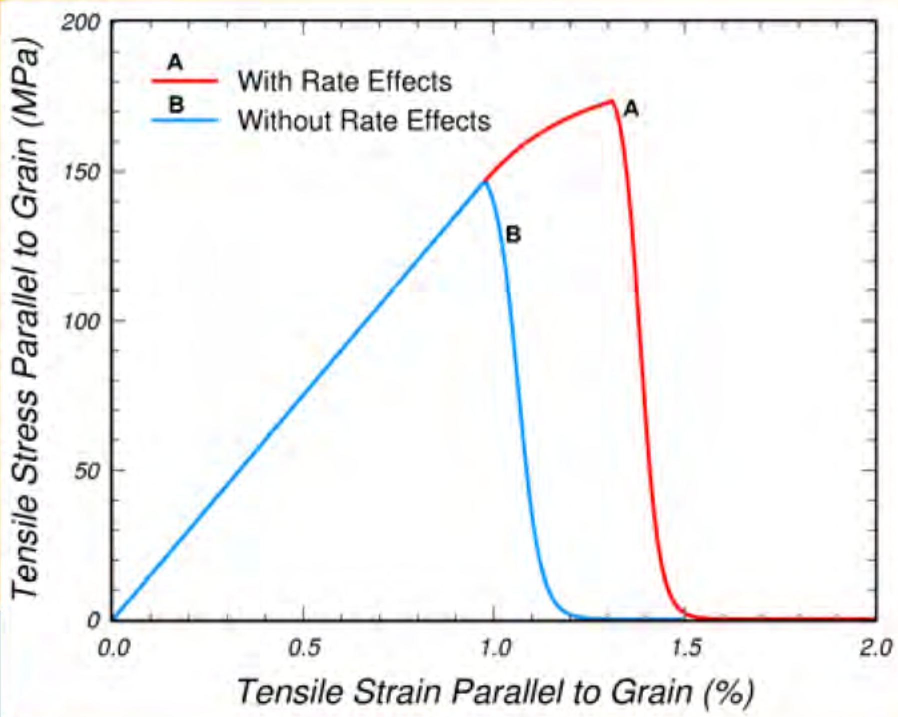
Source: Forest Products Laboratory

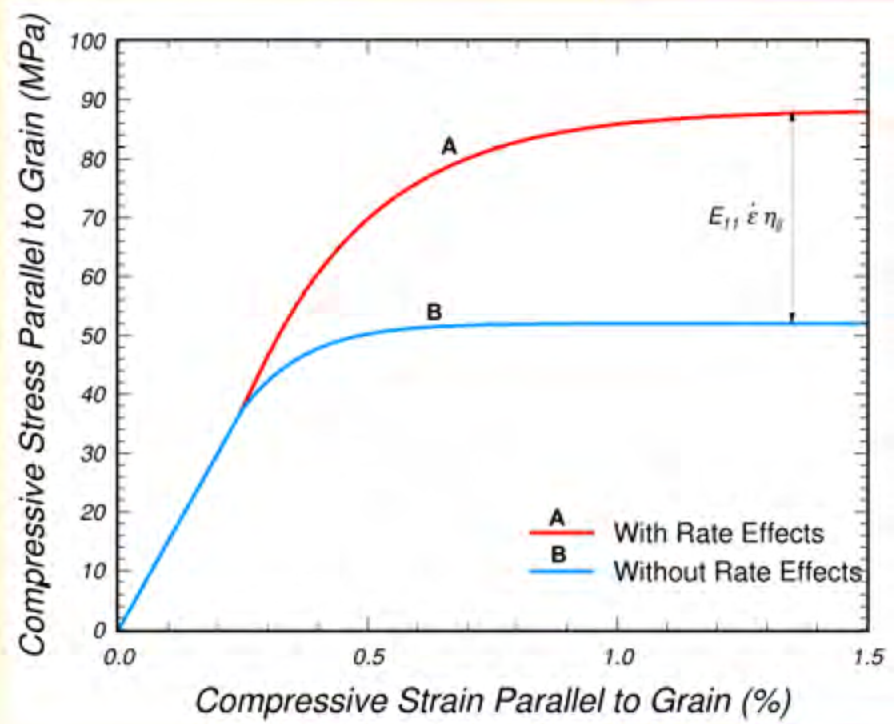
Wood Moisture Effect
The more humid wood the softer it is.



Source: Forest Products Laboratory

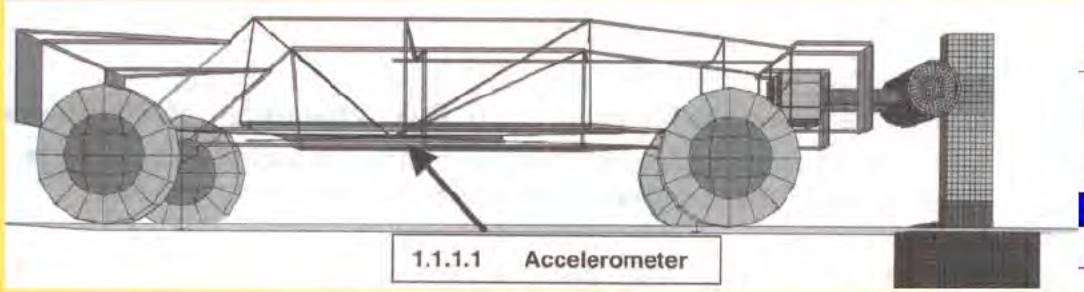
Wood Load Rate Effect

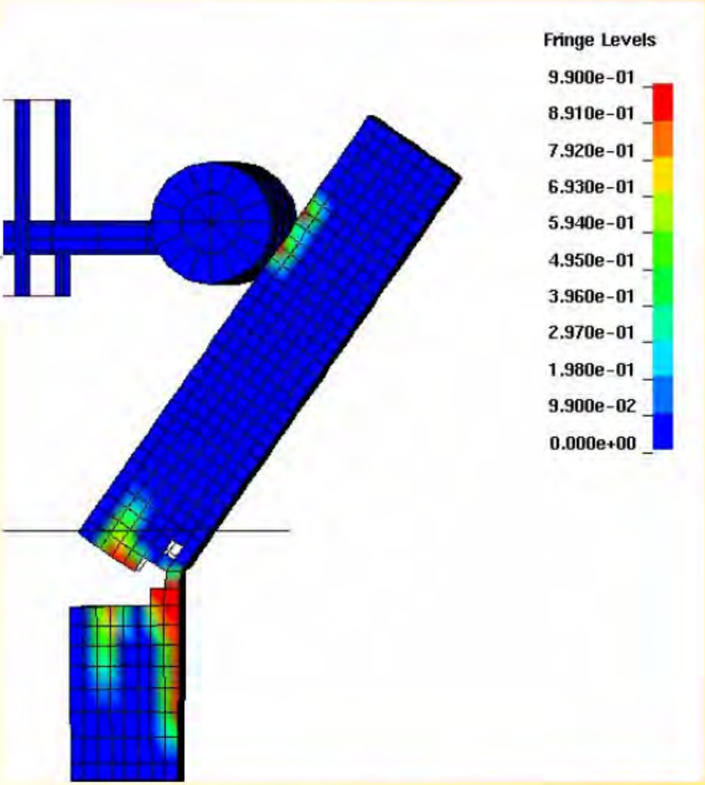




Based on Model developed by Federal Highway Administration (FHWA) **Manual for LS-DYNA Wood Material Model 143, Publication No. FHWA-HRT-0R-097, Aug. 2007**

Validation of the State of the Art Nonlinear Wood Model (Mat143) using FHWA Vehicle Crash Test



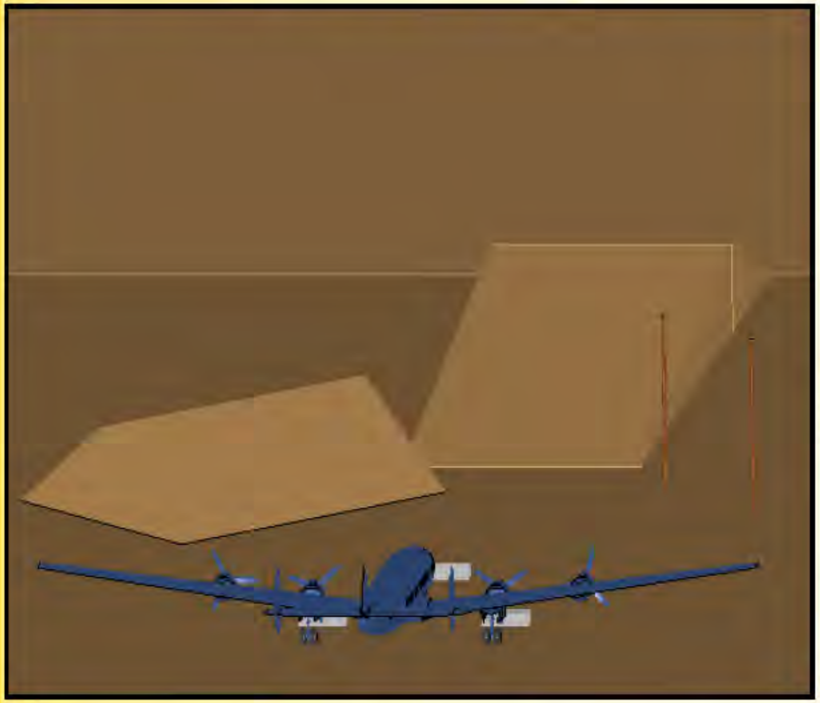


Bogie and Pole Models Used to Validate Wood Material Model used for Pole Barriers

Note: Pole model breaks without any splinters due to the homogenized (Macro-level) material model

Manual for LS-DYNA Wood Material Model 143, Publication No. FHWA-HRT-0R-097, Aug. 2007

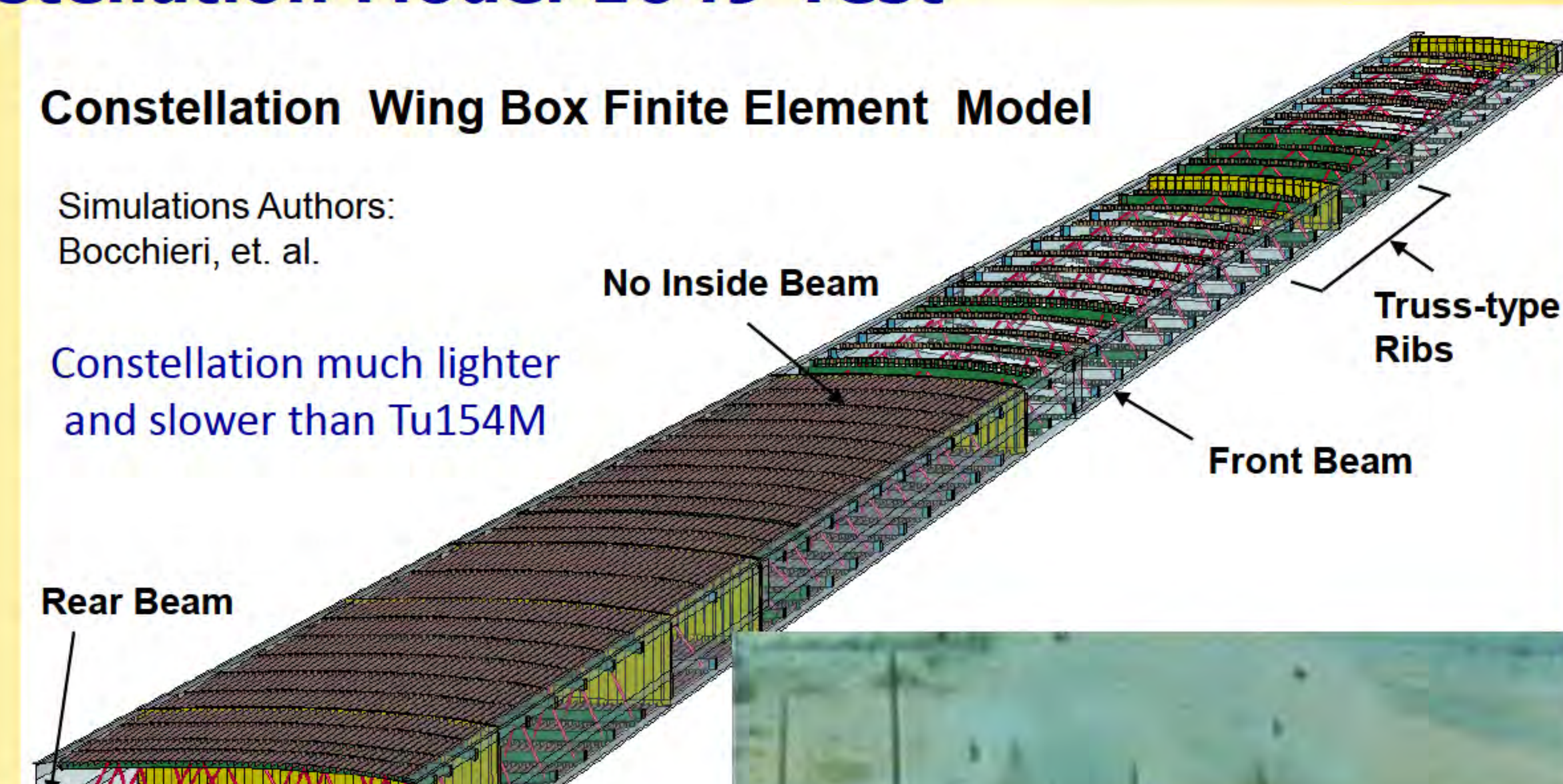
Validation of the Mat143 using FAA Test - 1965



Simulations Authors: Robert T. Bocchieri, Robert MacNeill, Claudia Navarro-Northrup, Douglas S. Dierdorf.

- Mass of the airplane 40T, initial impacts at 112 knots (207 km/h) sheared the landing gear causing the aircraft to be airborne and slide on its belly.
- The left wing struck an earthen barrier and the right wing struck two vertical telephone poles.

Application of the Wood Model to Lockheed Constellation Model 1649 Test



Constellation much lighter and slower than Tu154M

Reed, W.H., S.H. Robertson, L.W.T. Weinberg, L.H. Tyndall, "Full-scale Dynamic Crash Test of a Lockheed Constellation Model 1649 Aircraft", FAA-ADS-38, October, 1965.

Validation of Nonlinear Wood Model

Simulations by the Applied Research Associates

Simulations' Authors: Bocchieri, at. al.

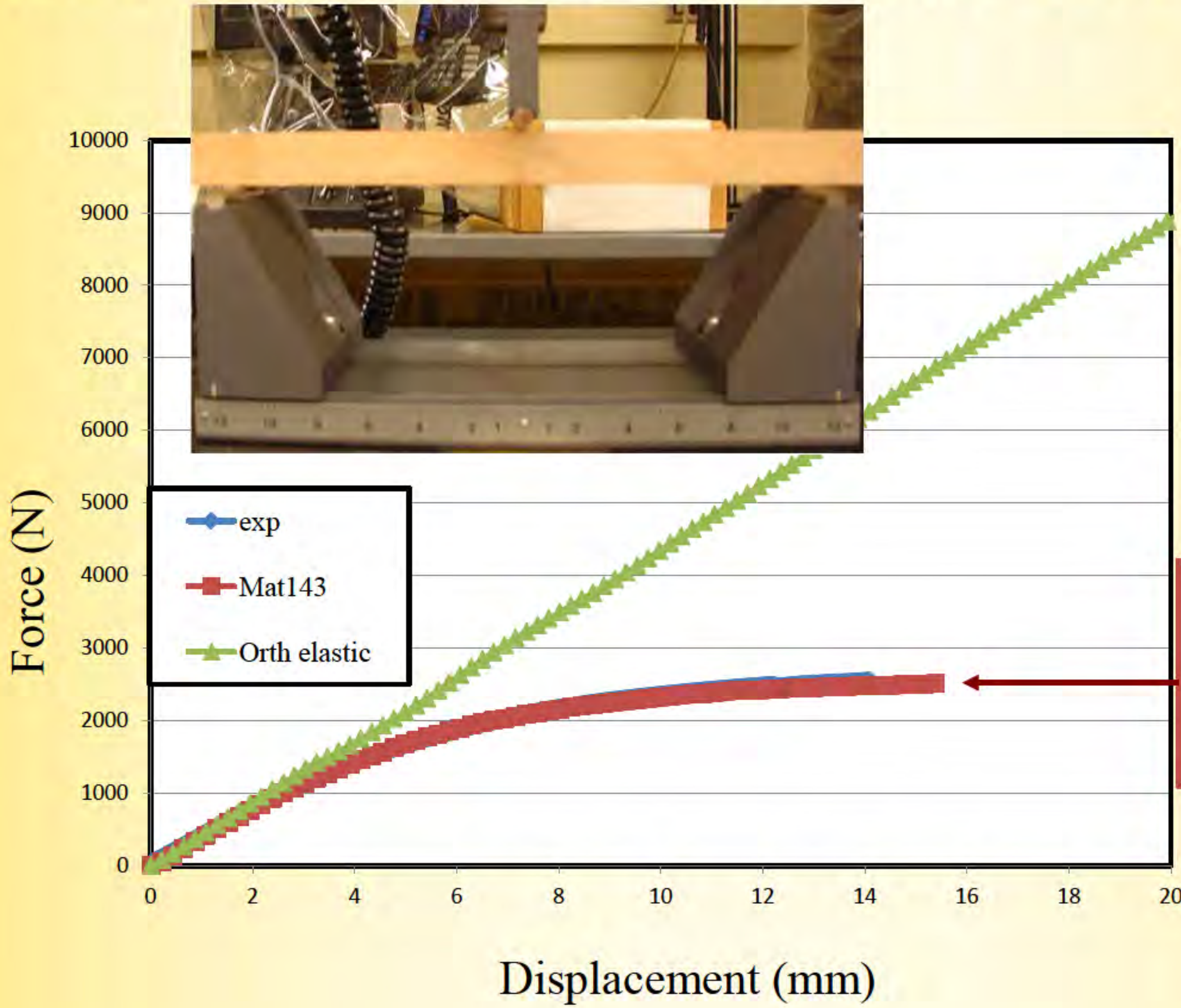
Outboard Pole Impact

Inboard Pole Impact

Simulation Agreed with FAA Experiment

- Inboard pole is cut by the wing
- Inboard tank compromised after impact with ground
- Outboard tank damaged by impact with the second pole, outboard pole is also cut
- Both poles fell in the direction of the airplane movement

Validation of the Original and Nonlinear Wood Models using Birch Three Point Bending Test



Very accurate nonlinear behavior
Exp = Mat143

Parameters of the Aluminum Tu-154

- Parameters of Aluminum D16, V95, AK6, etc. http://www.splav.kharkov.com/en/

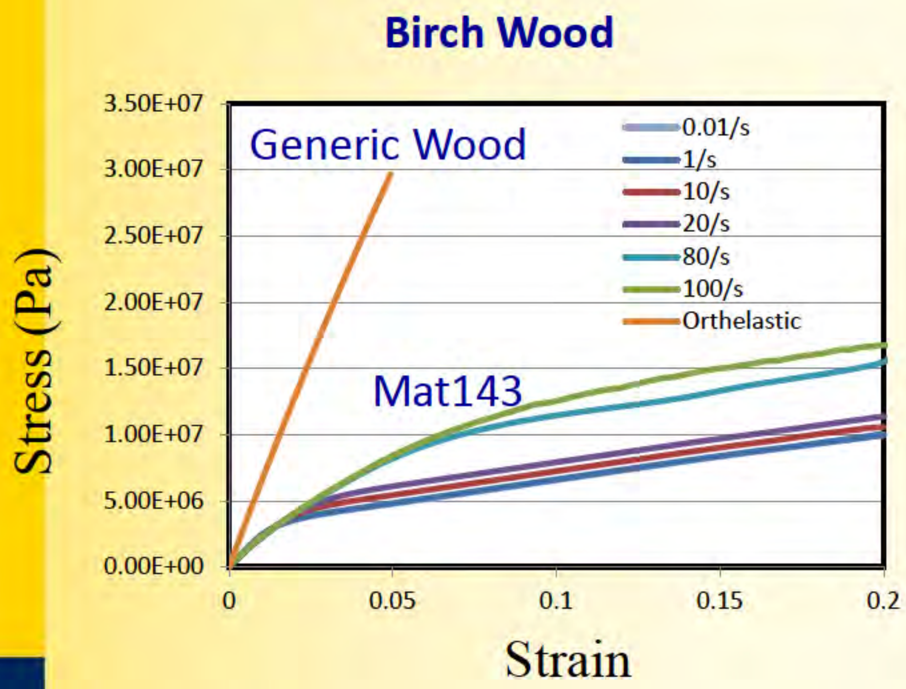
Generic AL Material Density(Kg/m³)	Young's modulus, E(Pa)	Yield Stress(Pa)	Tangent Modulus, Ec (Pa)	Poisson Ratio, v	Failure Strain
2850	7.4E+10	4.44E+8	5.738E+8	0.33	0.14

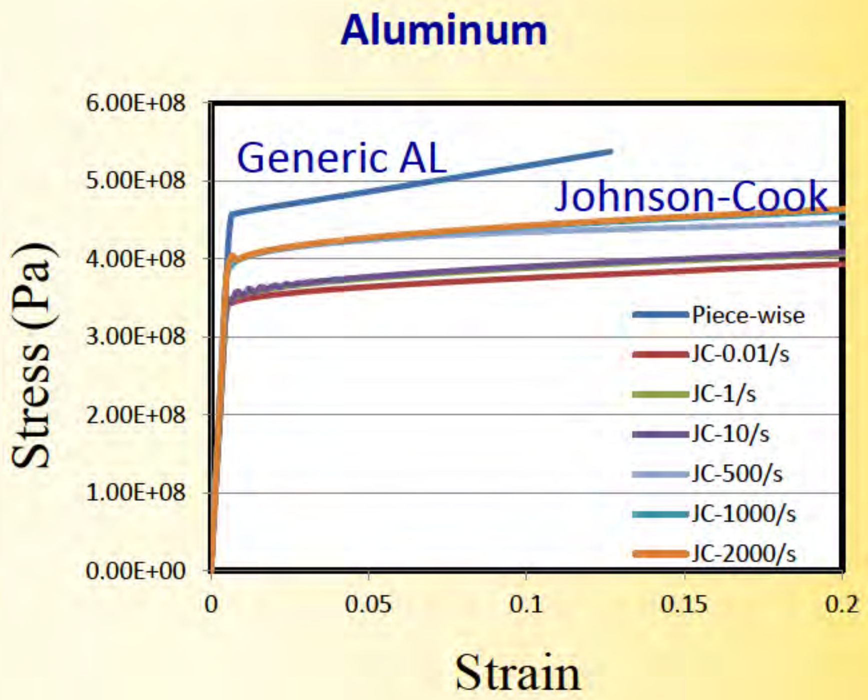
- **Aluminum**:
  - Original - isotropic, elasto-plastic hardened (Max Strain)
  - Johnson-Cook - nonlinear, strain rate dependent

*MAT_JOHNSON_COOK							
mid	ro	g	e	pr	dtf	vp	rateop
4	2700	2.59E+10	6.89E+10	0.33	0	0	0.1
a	b	n	c	m	tm	tr	epso
3.24E+08	1.14E+08	0.42	0.002	1.34	925.16	193.16	1.00E-05
cp	pc	spall	it	d1	d2	d3	d4
0	0	2	0	0.13	0.13	-1.5	0.011
d5	c2/p	erod	efmin				
0	0	0	0				

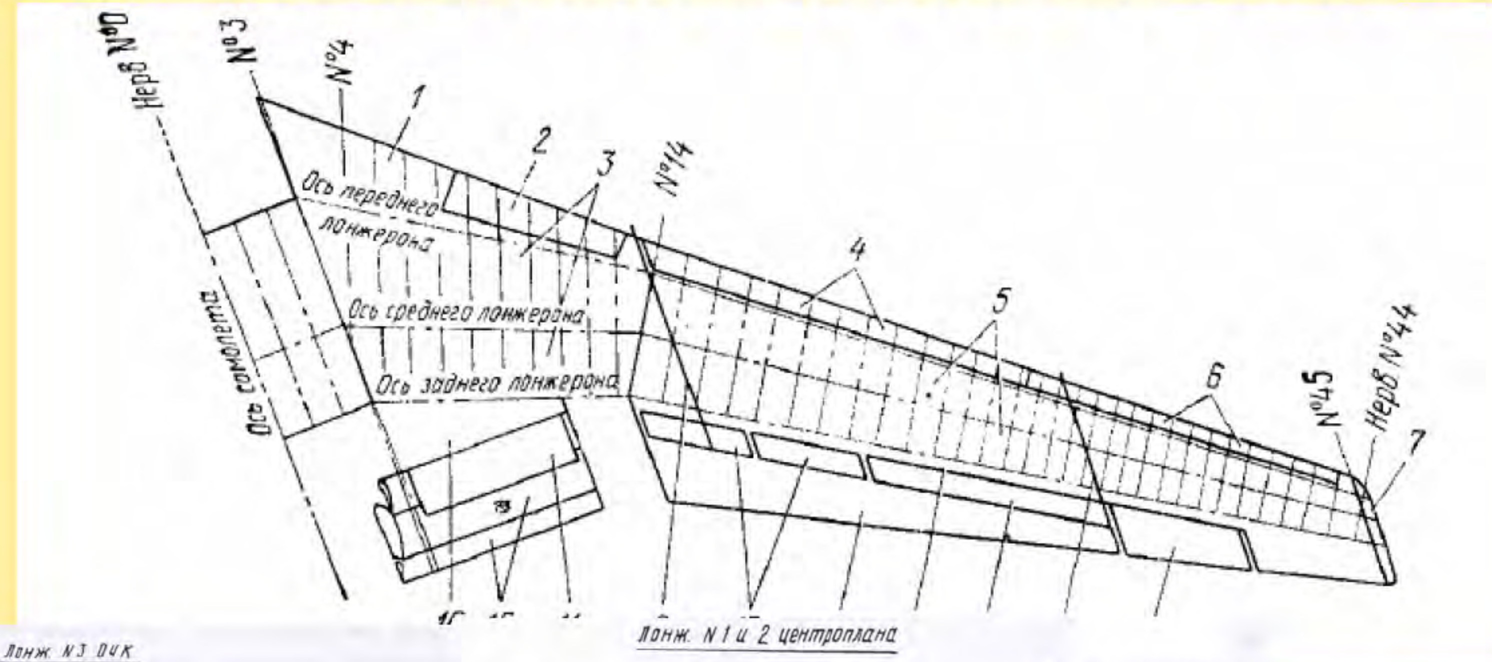
Buyuk et. al, JAE Vol22, No3, pp.287-295

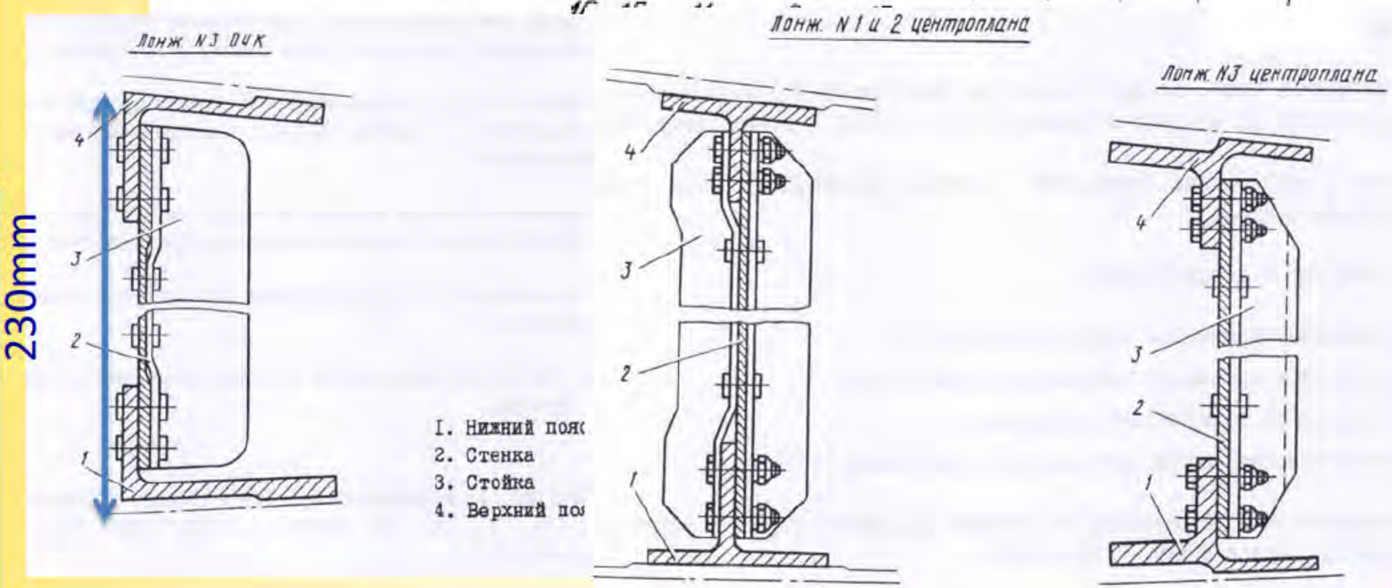
Plots for the Birch Wood and Aluminum Strain Rate Effect





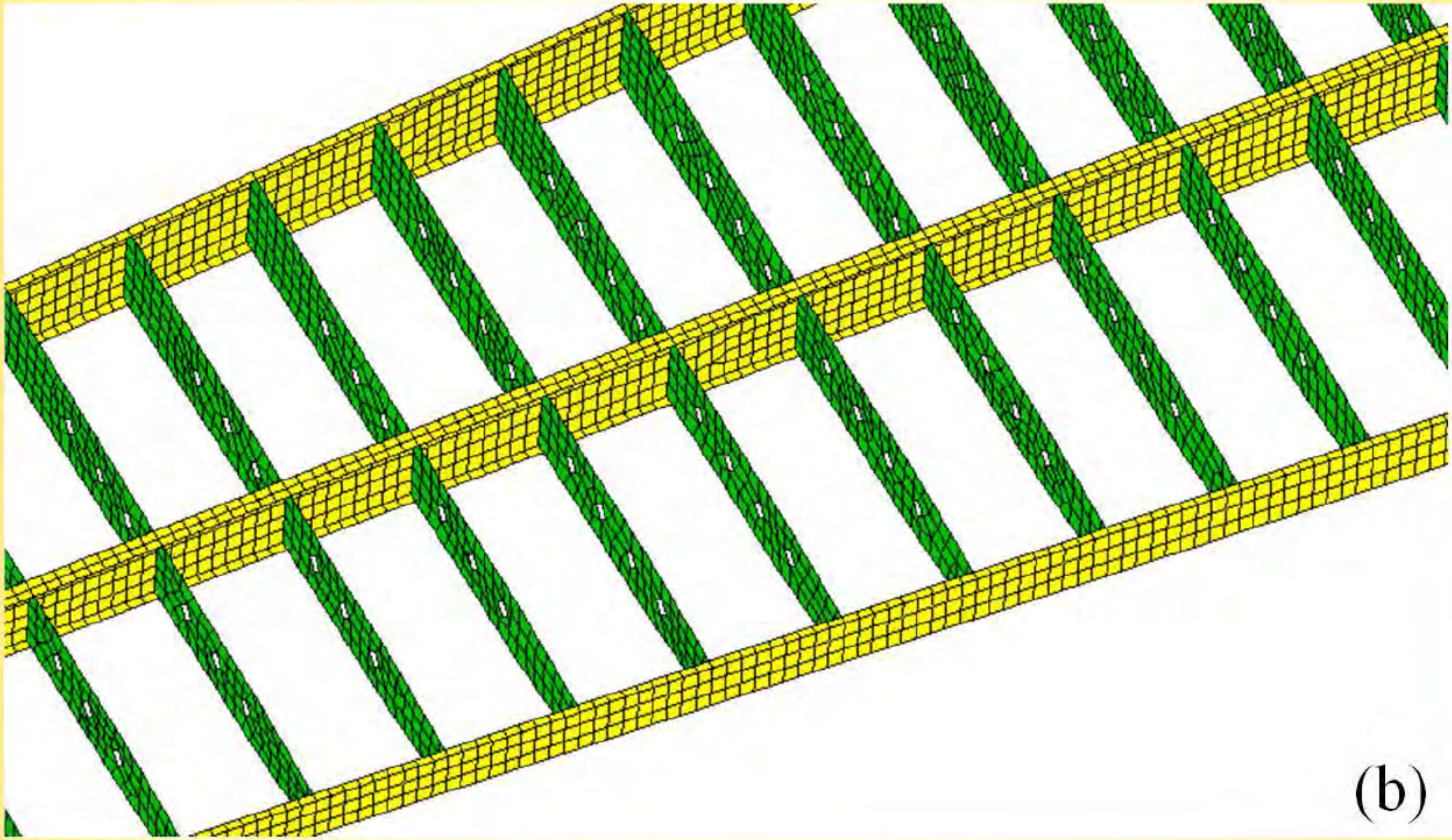
Internal Structure of the Tu-154M Wing





Boeing 727
Inner Structure of the Wing

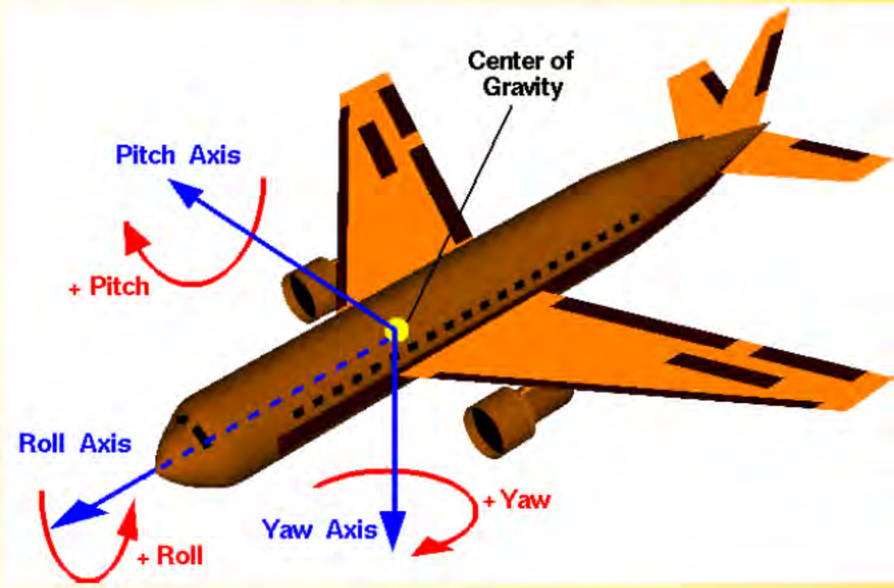
FEM Representation of Internal Structure of the Tu154M Wing


(b)

Input Parameters

- Velocity: **77-80 m/s horizontal, 0-19.2 m/s vertical up**
- Plane mass: **78600 kg**
- Distance from the base to the tree cut : **6.0m**
- Birch diameter at the cut section: **44cm**
- Birch density: **700 - 1000 kg/m^3**
- Location of the impact on the wing from its tip: **6.5m**
- Several plane orientations:

1. Horizontal
2. Nose up: 5°–20°
3. Roll-5°, horizontal
4. Roll-5° & pitch 5°–20°

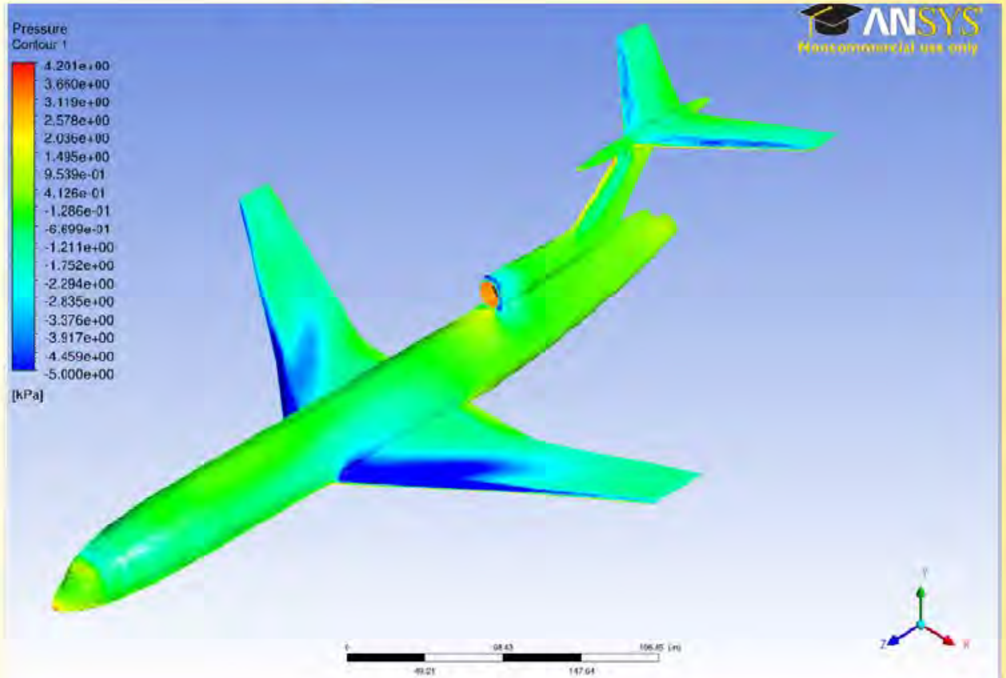


Math and Physics Background in CFX

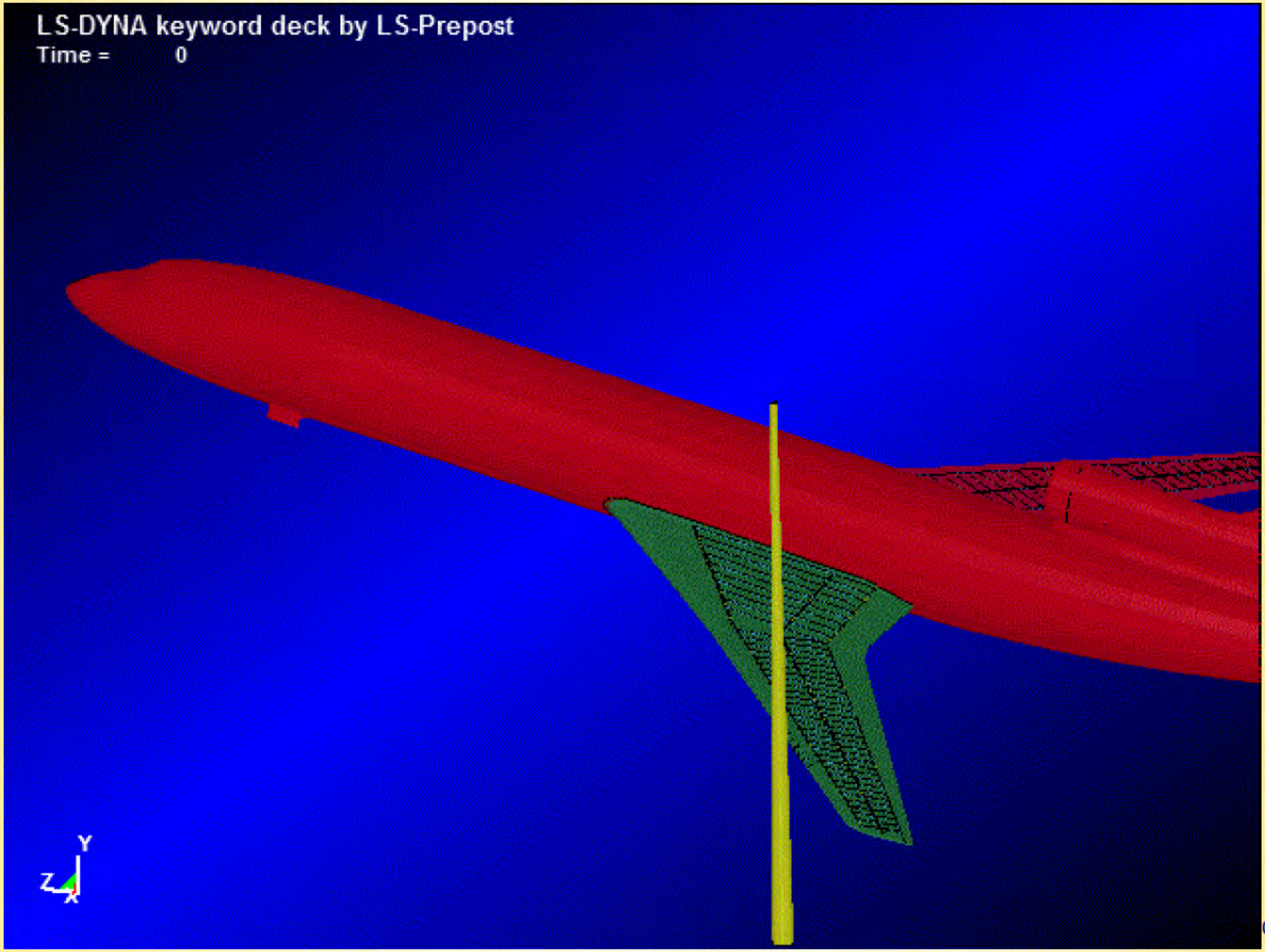
- Ansys- CFX analysis conducted by UA Research Fluid Mechanics Laboratory.
- Full form of Navier-Stokes equations with continuity of the flow.

$$\frac{\partial(\rho u_i)}{\partial t} + \nabla \cdot \left(\rho \overrightarrow{V} u_i\right) = -\frac{\partial p}{\partial x_i} + \nabla \cdot (\mu \nabla u_i) + S_{Mx_i}$$

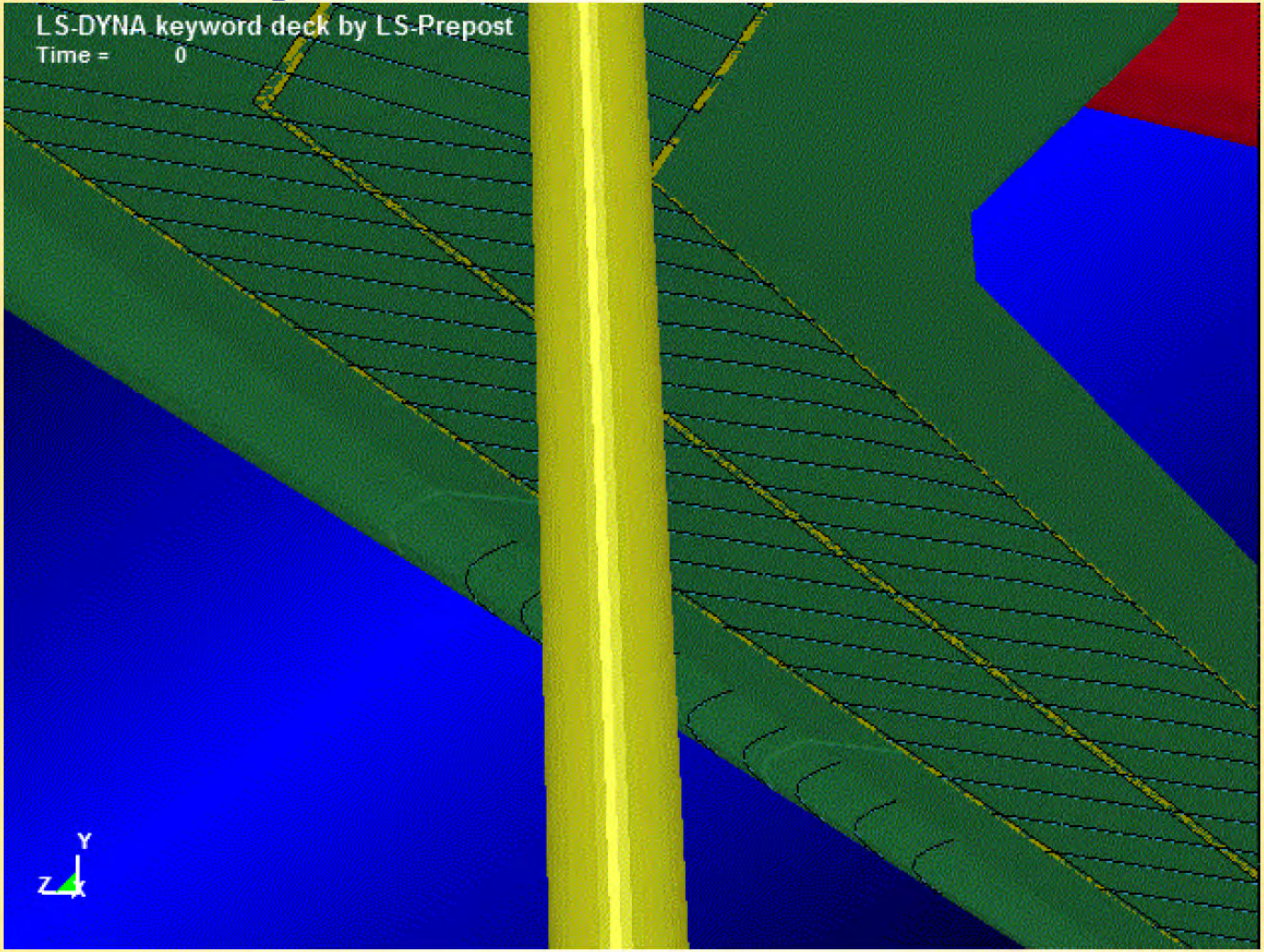
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \overrightarrow{V}\right) = 0$$



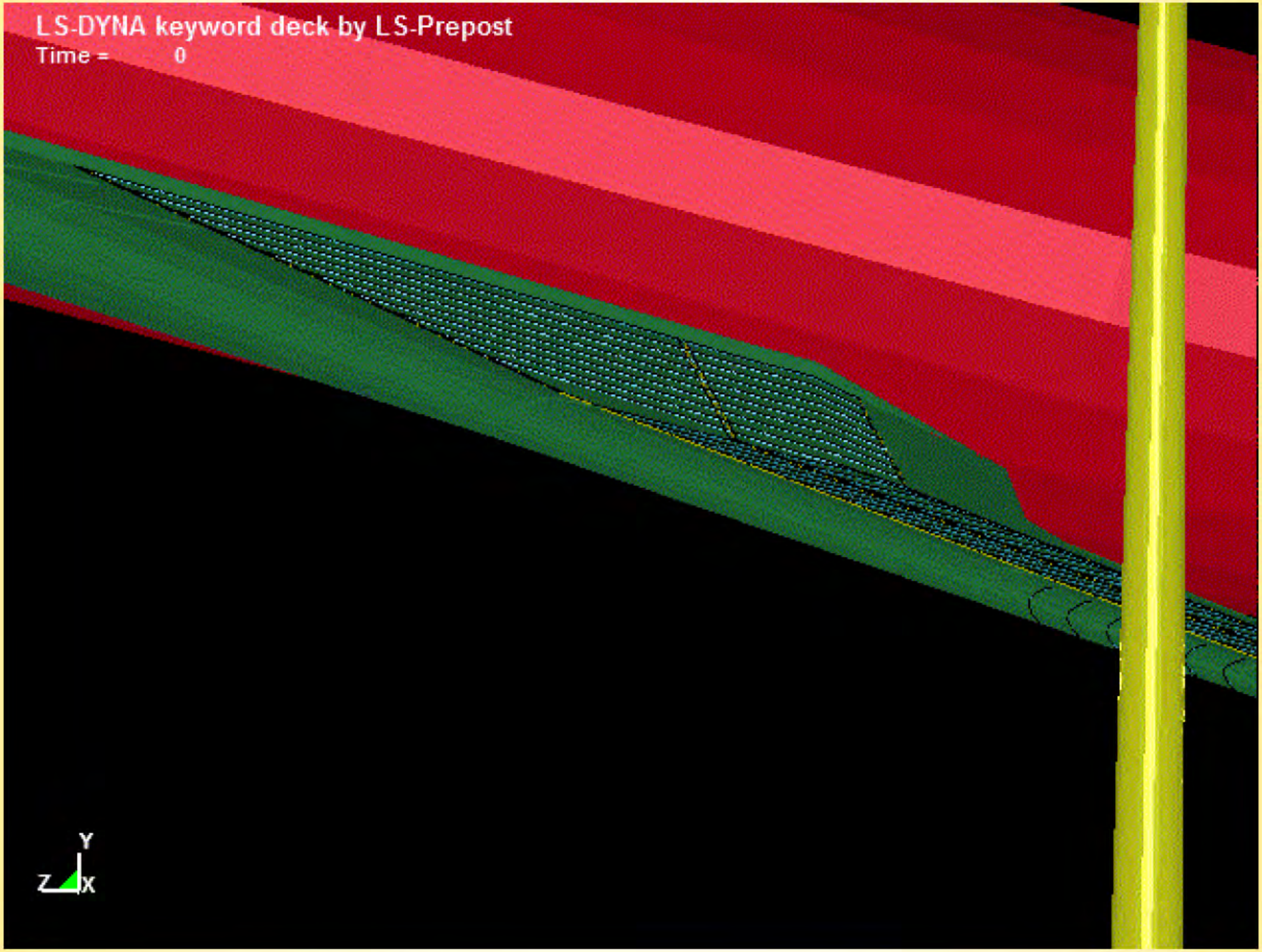
Simulation – view from the left side



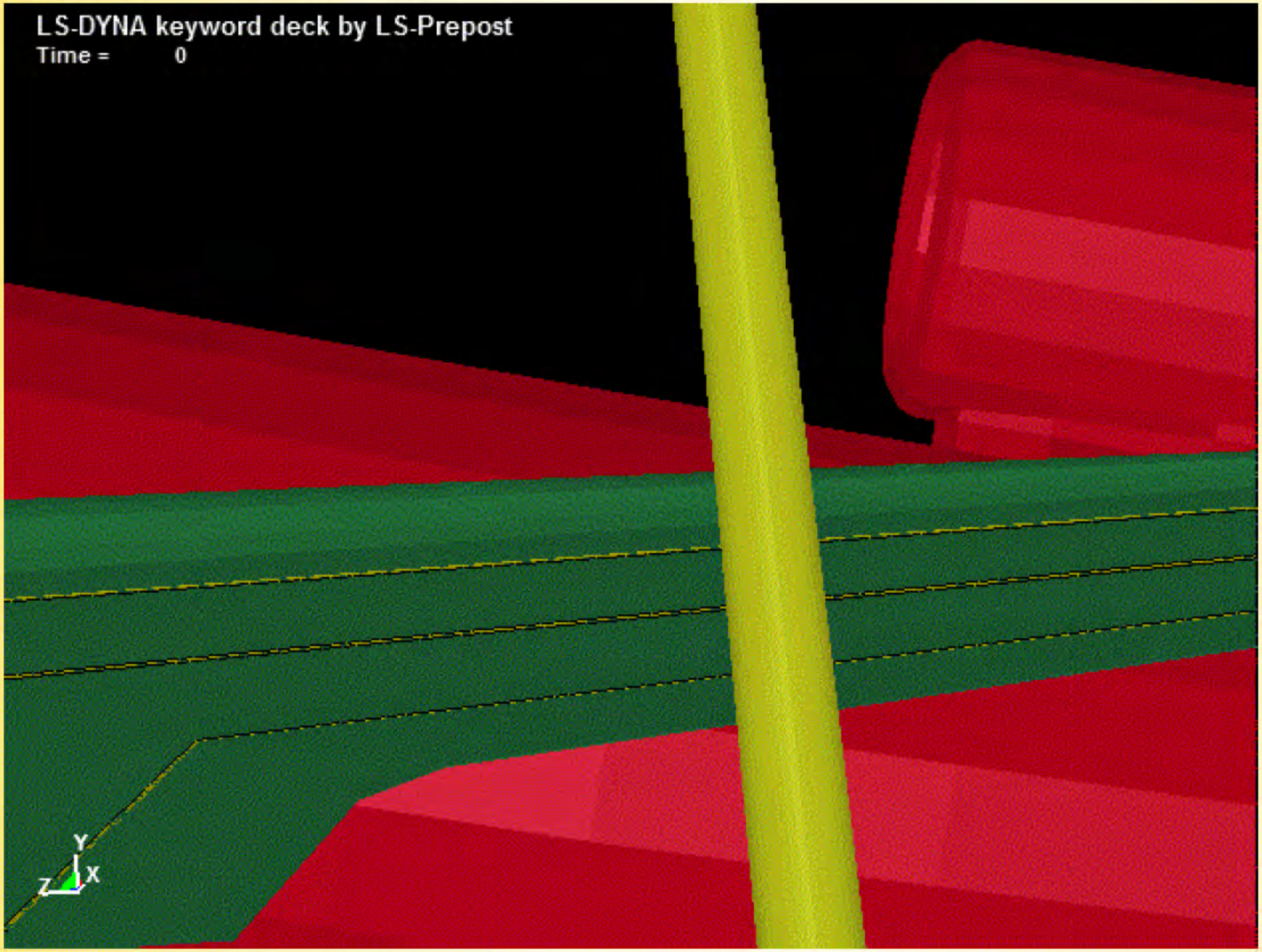
Close-up 1



Refined Case – Flight Horizontal, Mat143 and JC

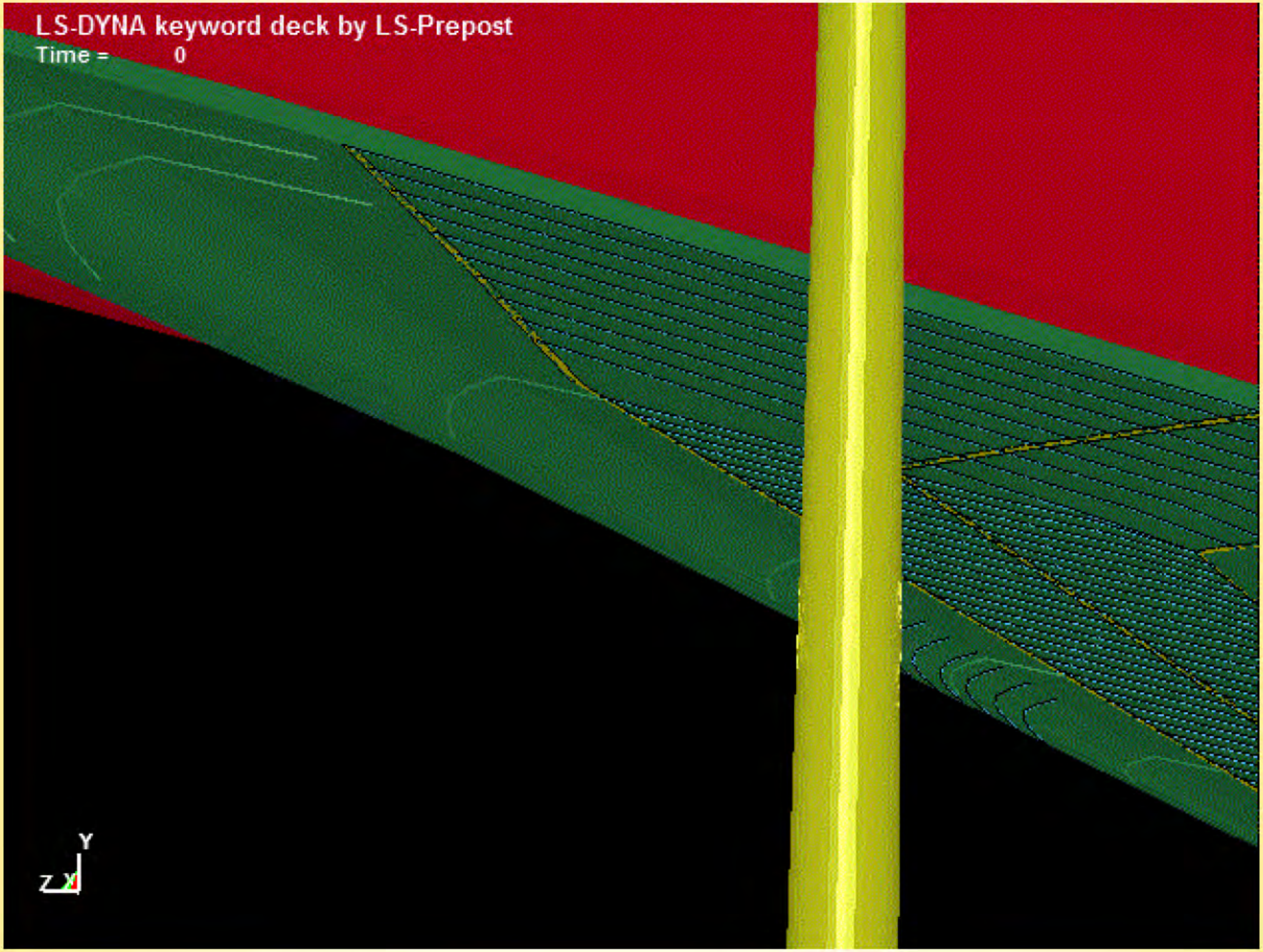


Refined Case – Flight Horizontal, Mat143 and JC



View from the bottom

Refined Case – Flight Inclined, Mat143 and JC



Conclusions from Wing/Birch Simulations

- Using parameters provided in the official Russian and Polish reports, the LsDyna Finite Element Method Model shows that:

  THE WING OF THE TU-154M PLANE CUTS THROUGH THE BIRCH

  - **for every analyzed scenario**
  - **for all original & nonlinear rate dependent material models,**
  - **for the finest mesh.**

- **THE DAMAGE TO THE WING IS LOCALIZED ON THE EDGE,**

  DOES NOT DETERIORATE THE LIFT SURFACE OF THE WING, THUS

  SHOULD NOT SIGNIFICANTLY REDUCE THE ABILITY OF THE PLANE TO FLY.

Above simulations have been positively evaluated by

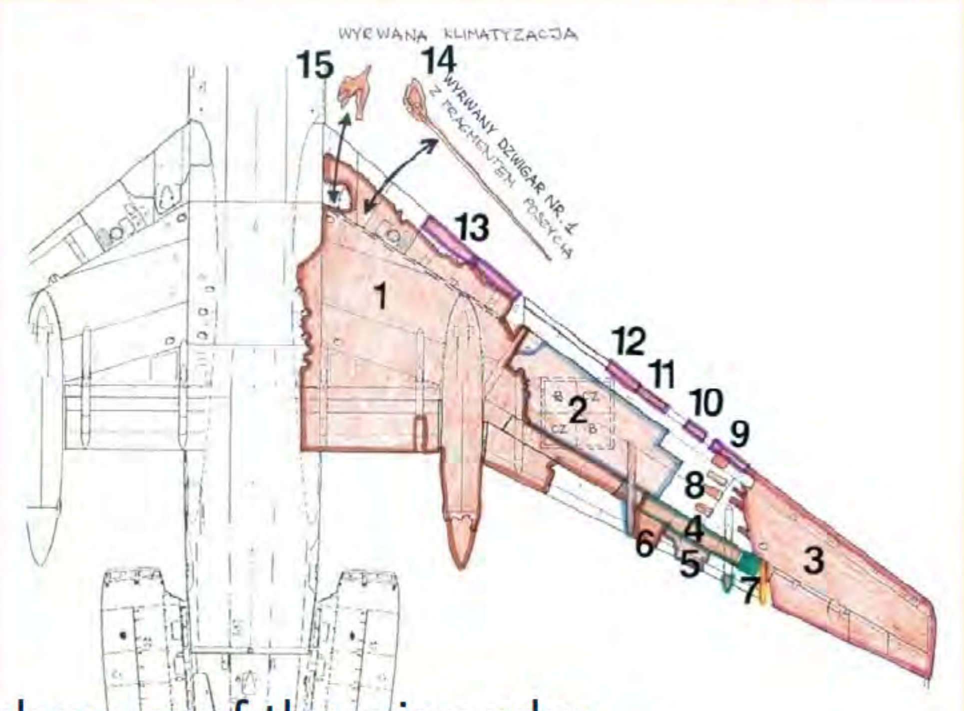
BOEING Principal Structural Engineer

Dr. Waclaw Berczynski.

Front Slots are not Destroyed!

http://mdabrowski.salon24.pl/377564,slot-2#comment_6096695

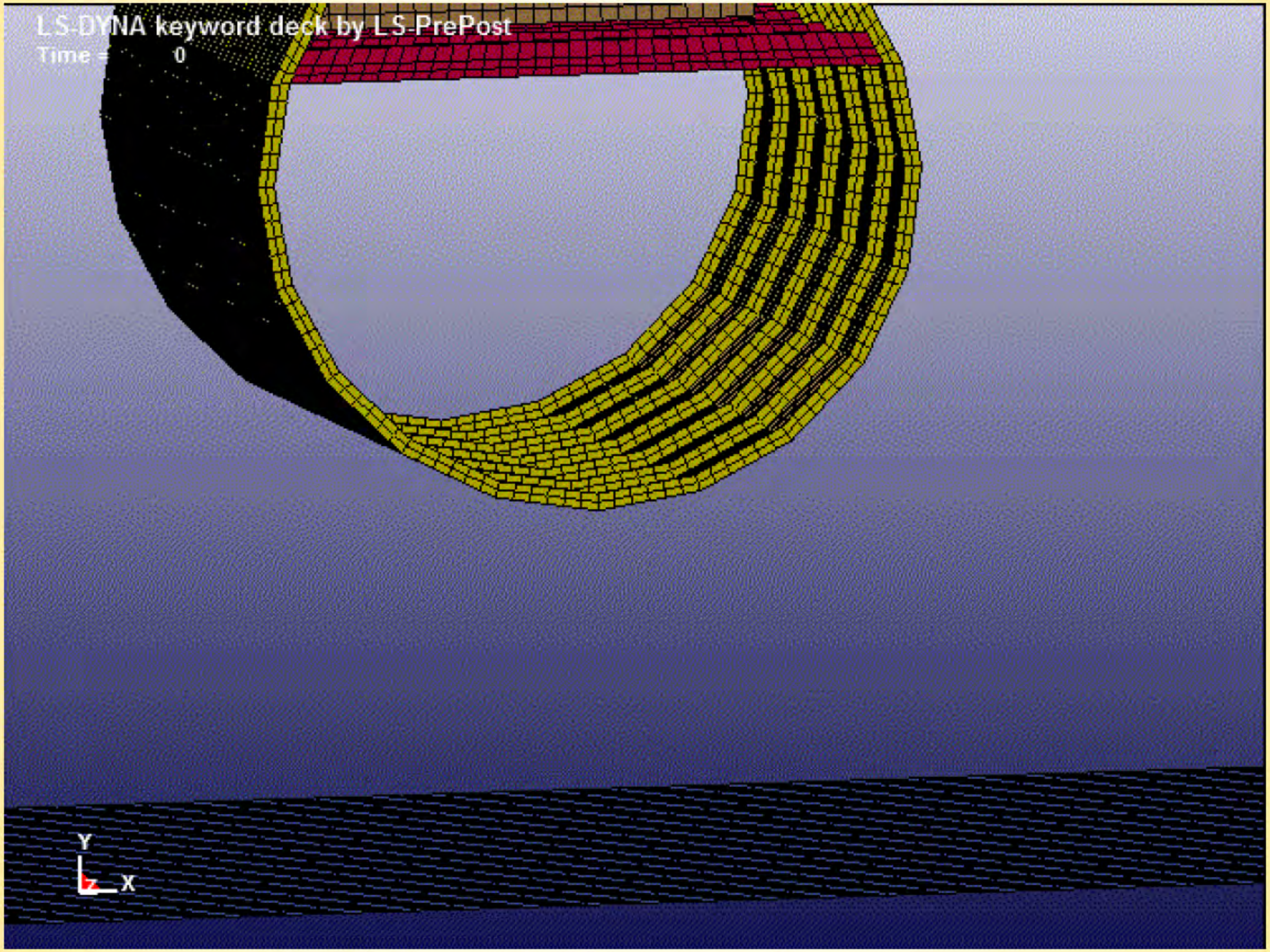
Left Wing Reconstruction
View From the Bottom Up



-There is no visible damage of the wing edge,
-real tree lays perpendicular to the airplane flight direction, and
-there is an extensive internal wing damage including ripped off rivets suggest:

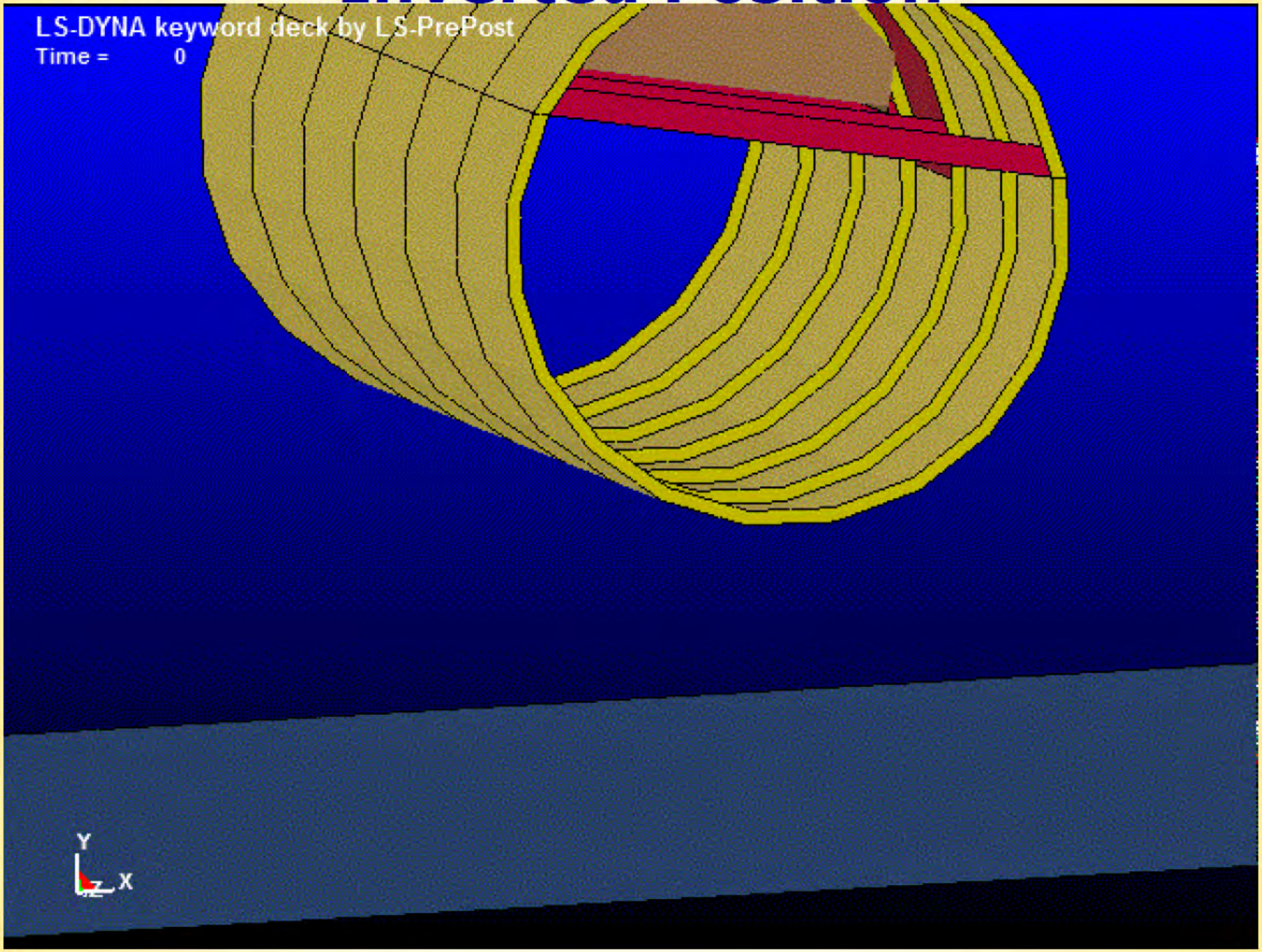
- **there was no impact between the birch tree and the left wing, and**
- **an explosion near the point TAWS could explain the damage of the wing and rapid turn left of the airplane**

Vertical Drop of the Fuselage at Inverted Position

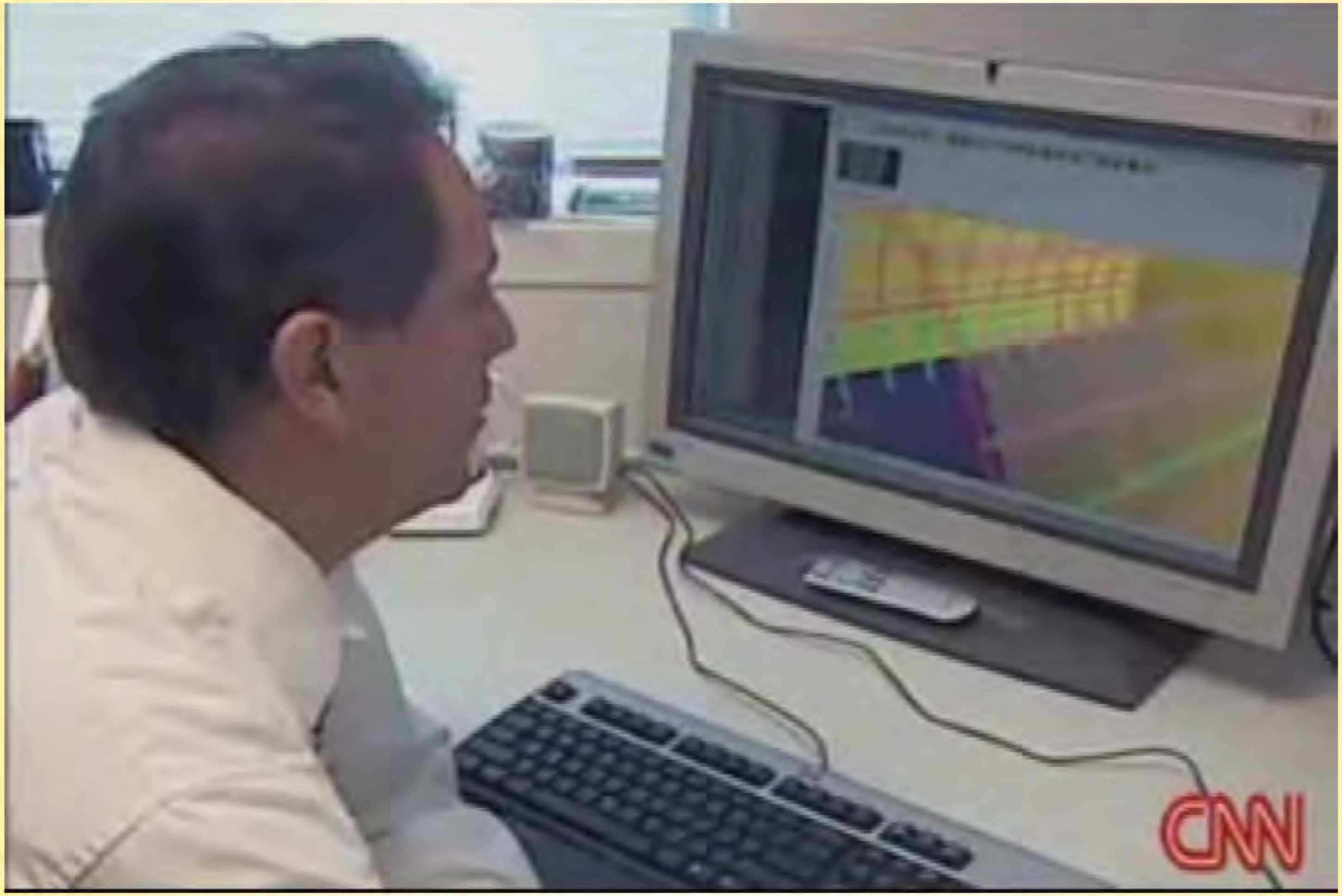


Vertical Impact with v_y= -9.8m/sec

Vertical Drop of the Fuselage at Inverted Position

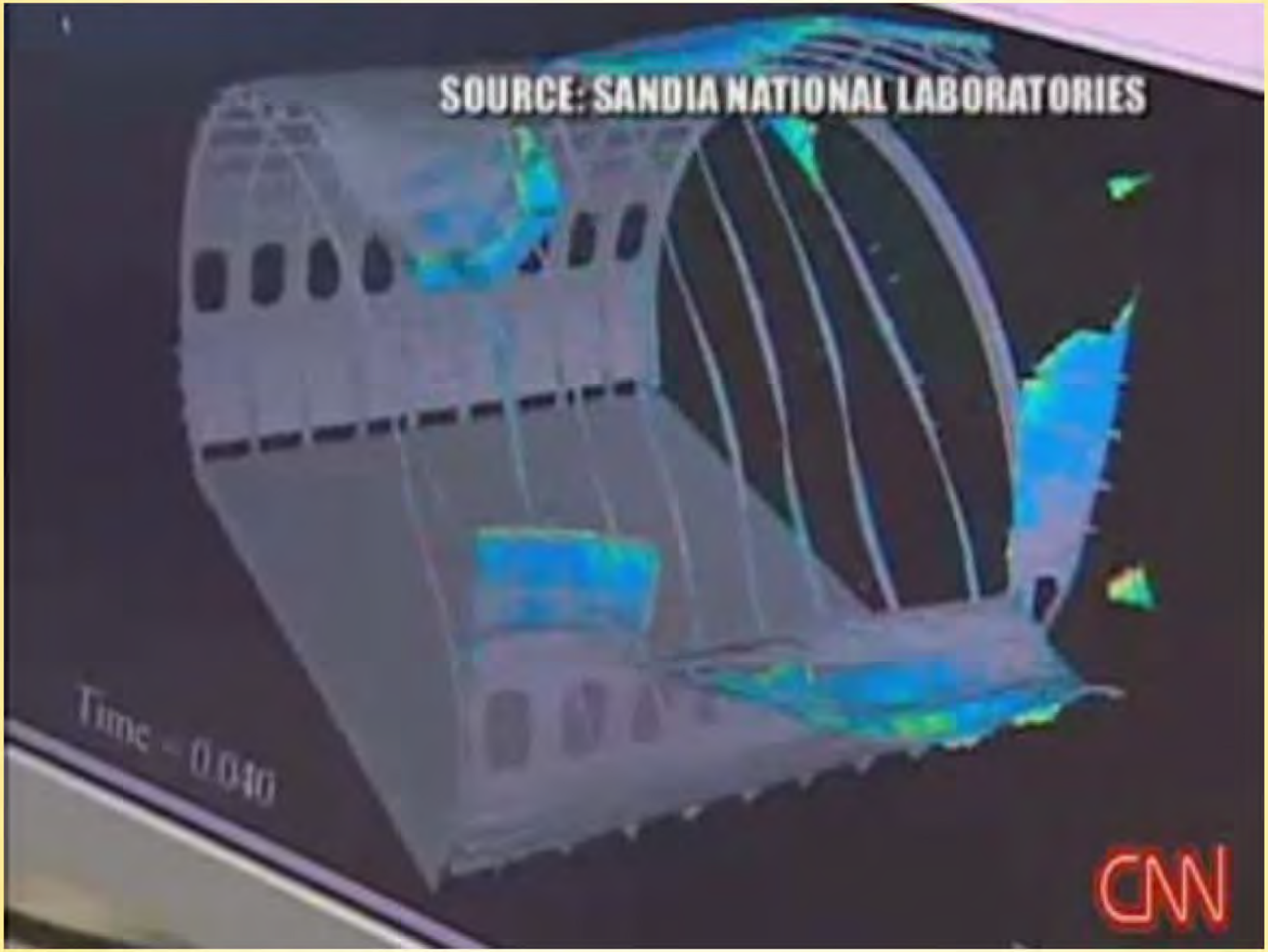


Simulation of Fuselage with Explosion Sandia National Lab – CNN 2008



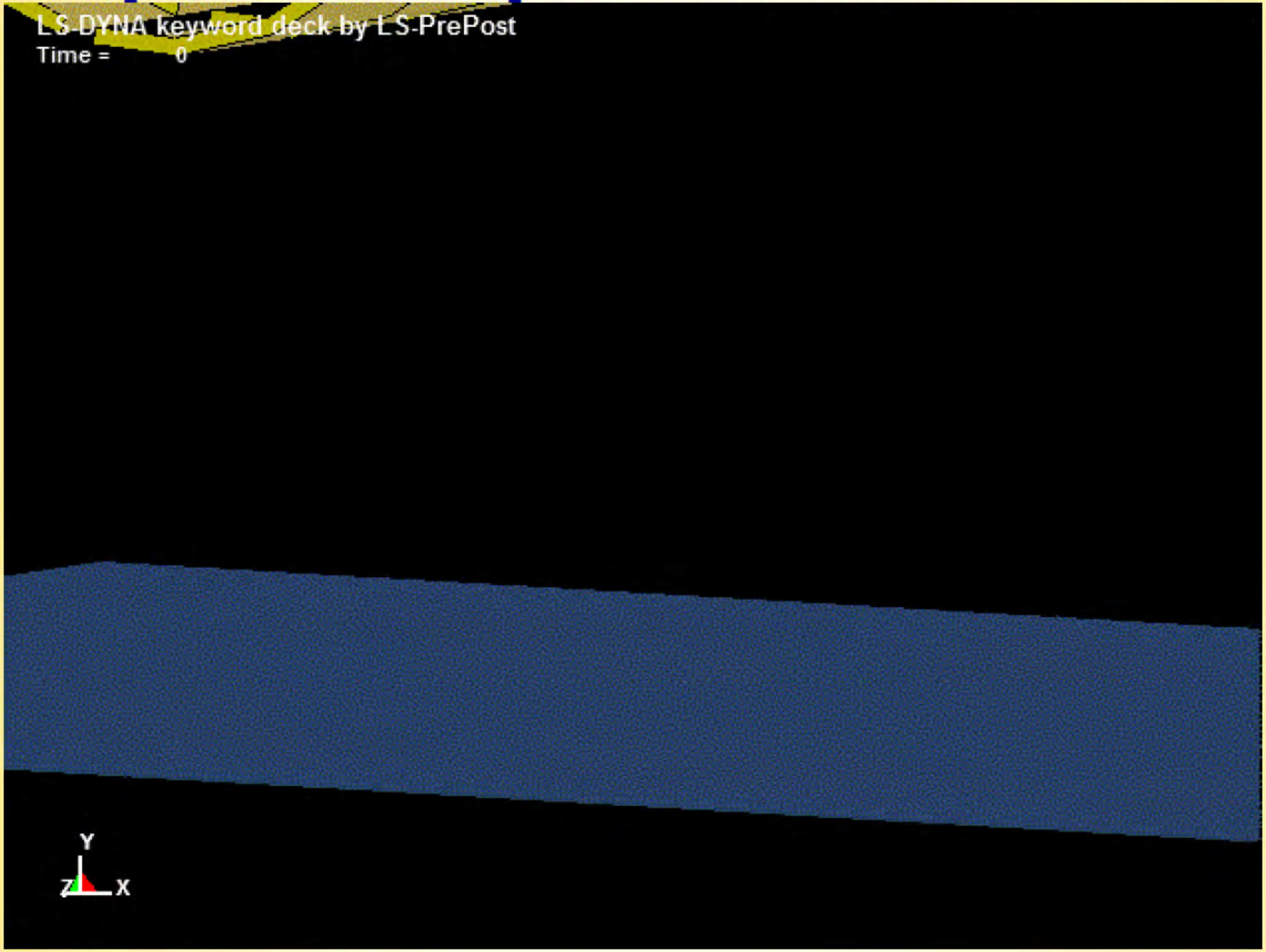
http://www.youtube.com/watch?feature=player_embedded&v=PPDJzh2C9Es

Simulation of Fuselage with Explosion Sandia National Lab – CNN 2008



Both Fuselage Walls Open Outside

Drop after Explosion in the Air



Shrapnel from Smolensk Crash Scene

Prof. Obrebski - http://pomniksmolensk.pl/news.php?readmore=2640

State of the Art Soil Material Model Mat147 Developed by FHWA

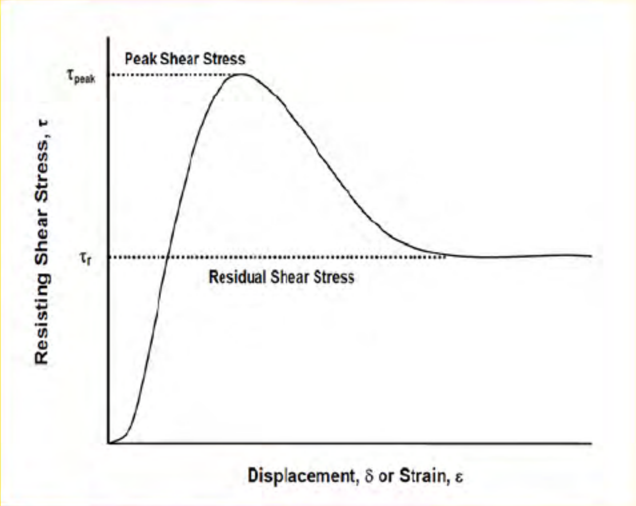


Fig.1 General direct shear performance of soil

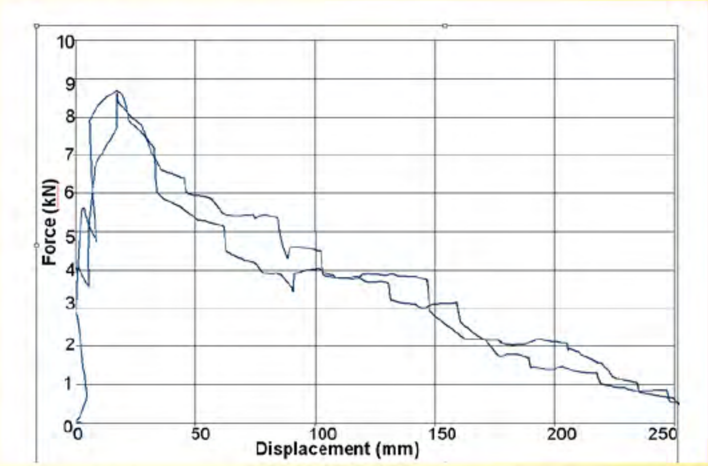
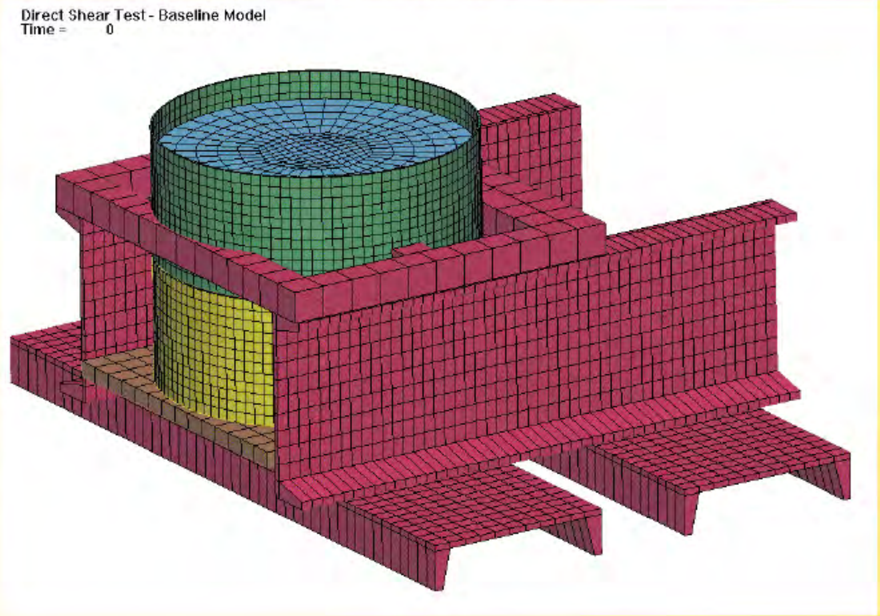
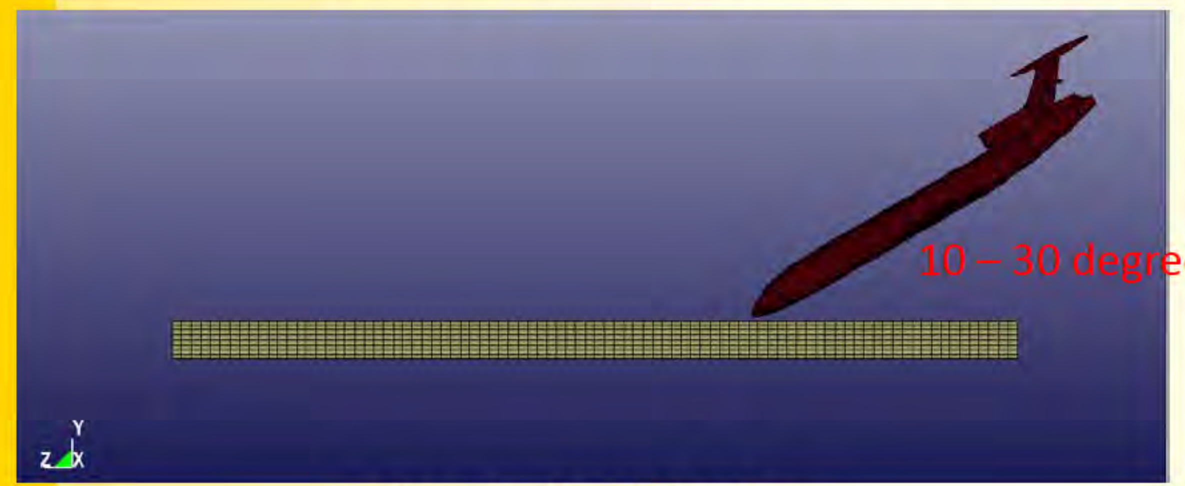


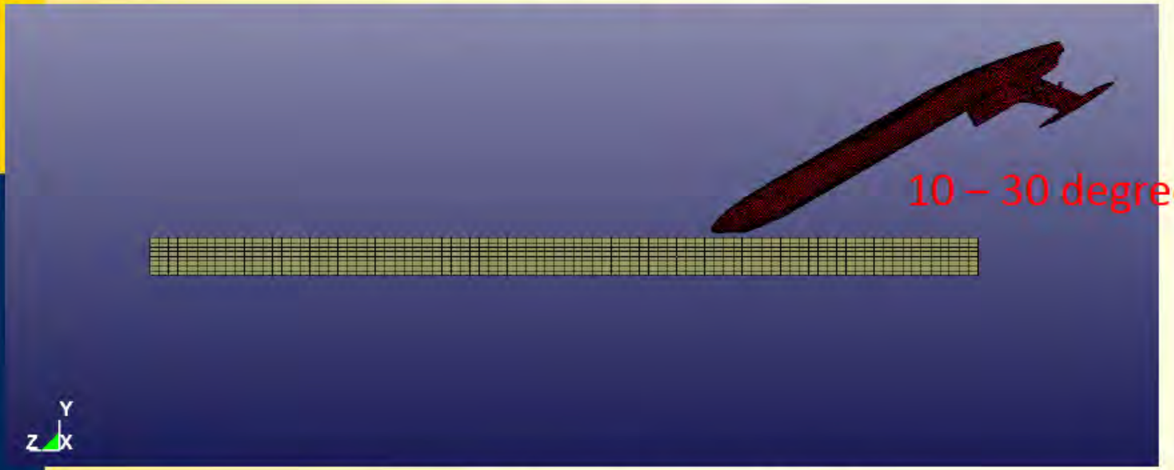
Fig.2 Results of two direct shear tests



Crash Simulation using the Soil Model Mat147 in LsDyna



Regular Crash Mode



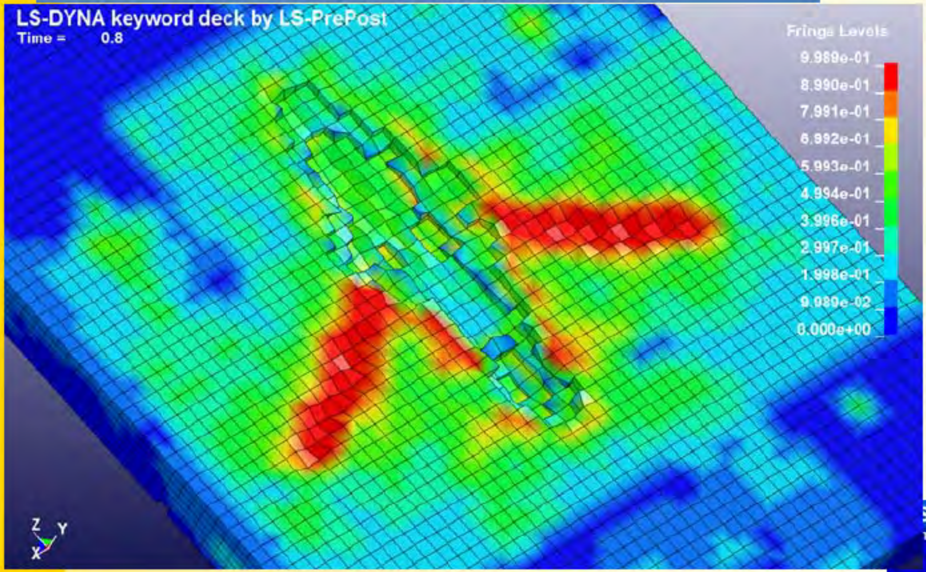
Upside down Crash Mode

Element Size (Unit-meter):
Ground: 1by1 in plane (x-z) and 0.5 thick (y) solid elements;
Aircraft: 0.2by0.2 shell elements

Element number:
Ground:18304 elements;
Plane: 32450 elements

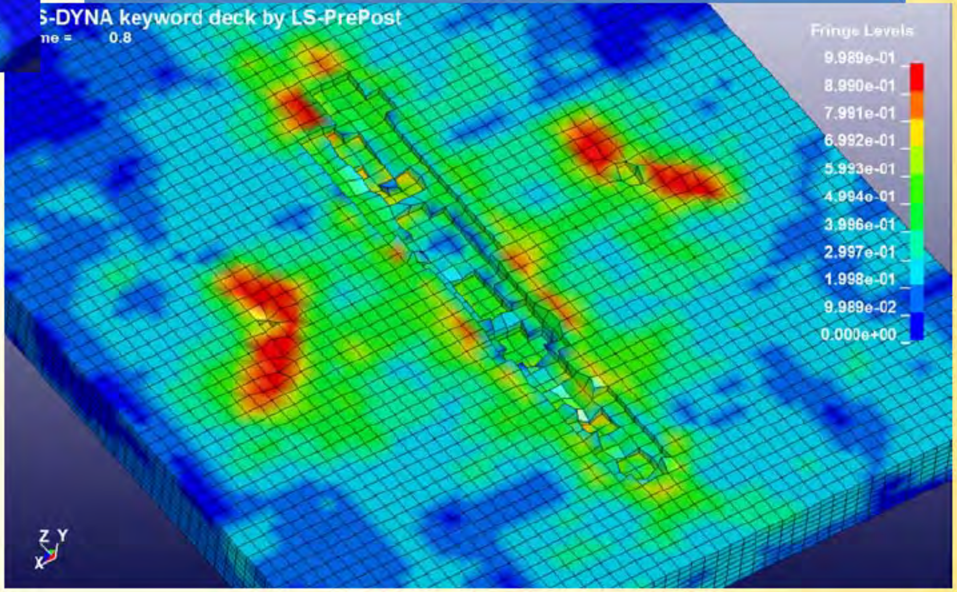
Crash Simulation 30° with Mat147

Damage Contour of Regular Case



Initial Velocity:
Horizontal (z): 69.28 m/s;
Vertical (y): -40 m/s

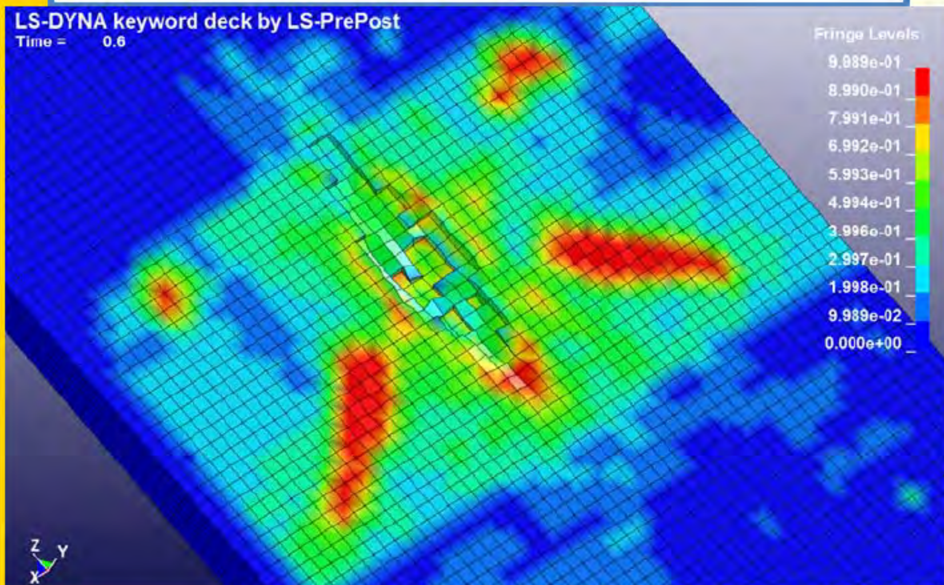
Damage Contour of Inverted Case



Crater 1-2m deep.

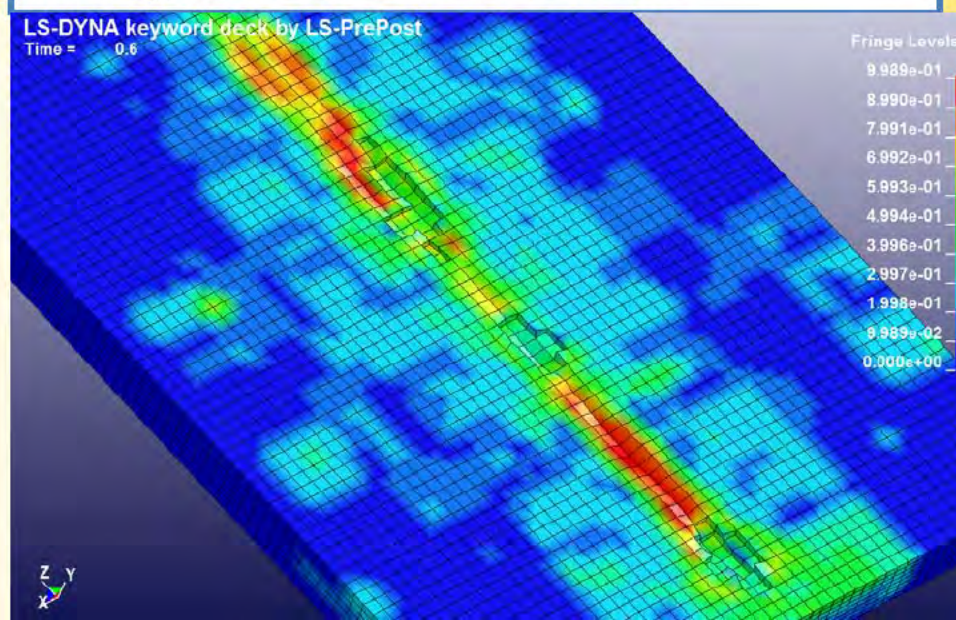
Crash Simulation 10º with Mat147

Damage Contour of regular case



Initial Velocity:
Horizontal (z): 78.78 m/s;
Vertical (y): -13.89 m/s

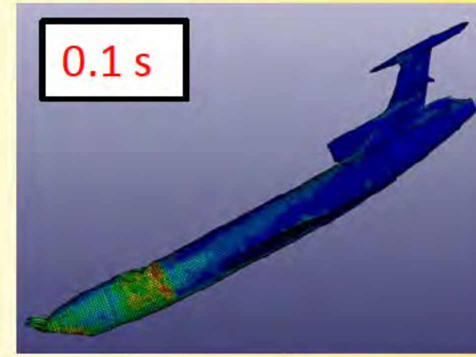
Damage Contour of Inverted Case

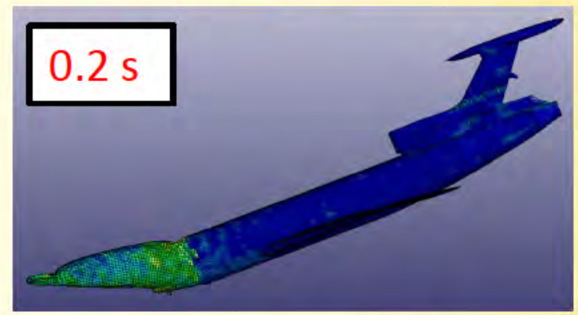


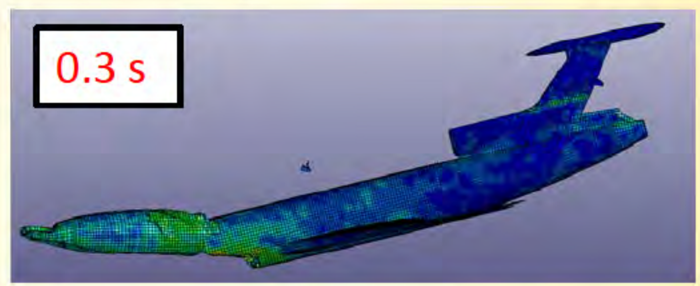
Conclusions Based on Soil Impact

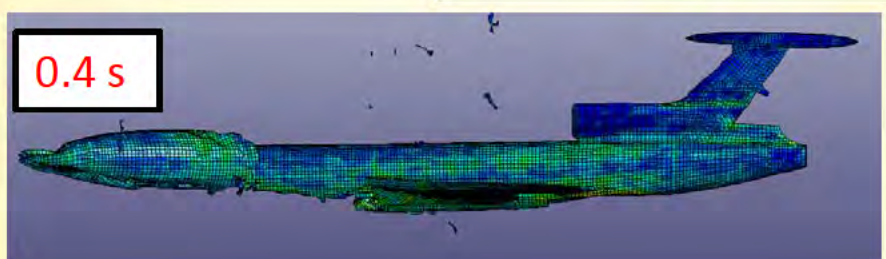
- Large and deep crater should be visible if the entire mass of the airplane was intact at the moment of the crash
- No crater detected at the scene but large field of debris suggest that the airplane disintegrated in the air

Crash Damage Process (Regular)



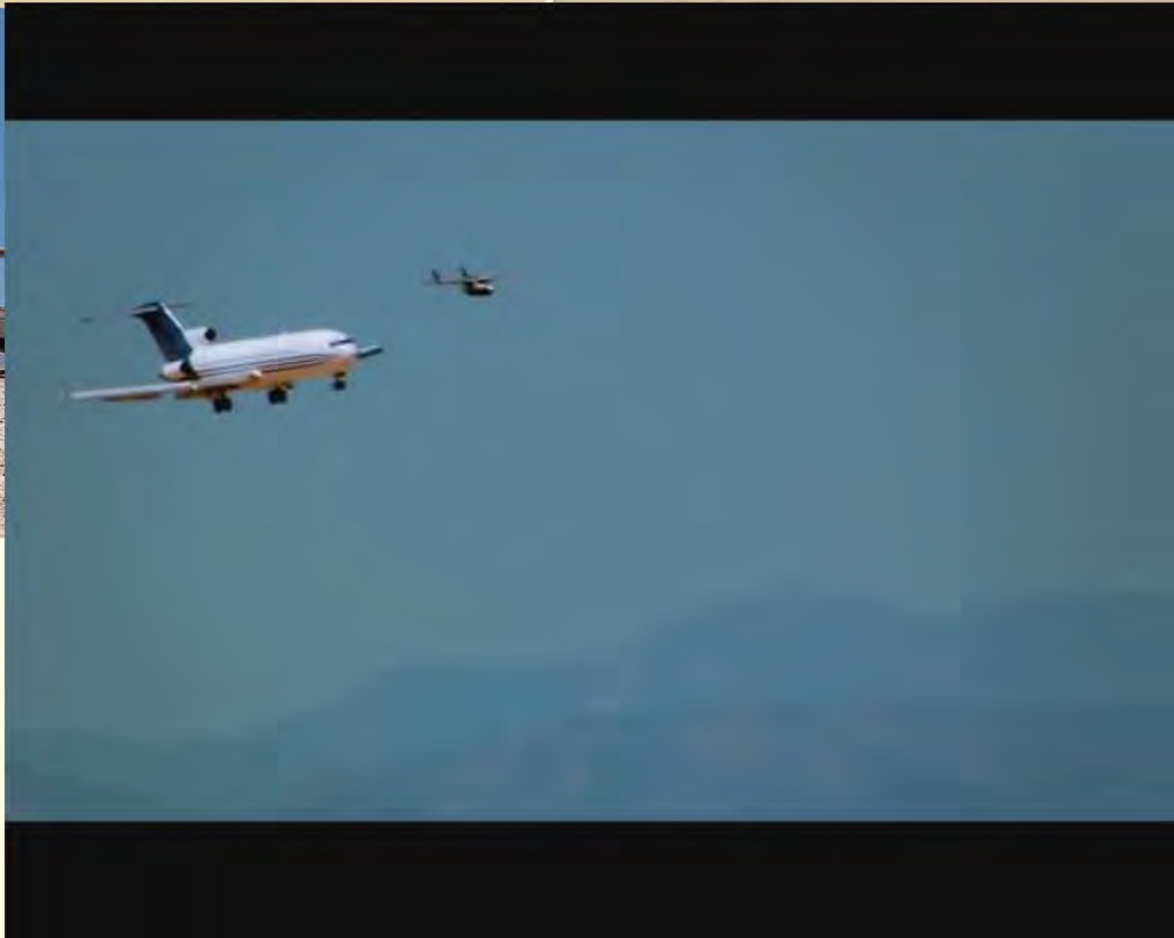




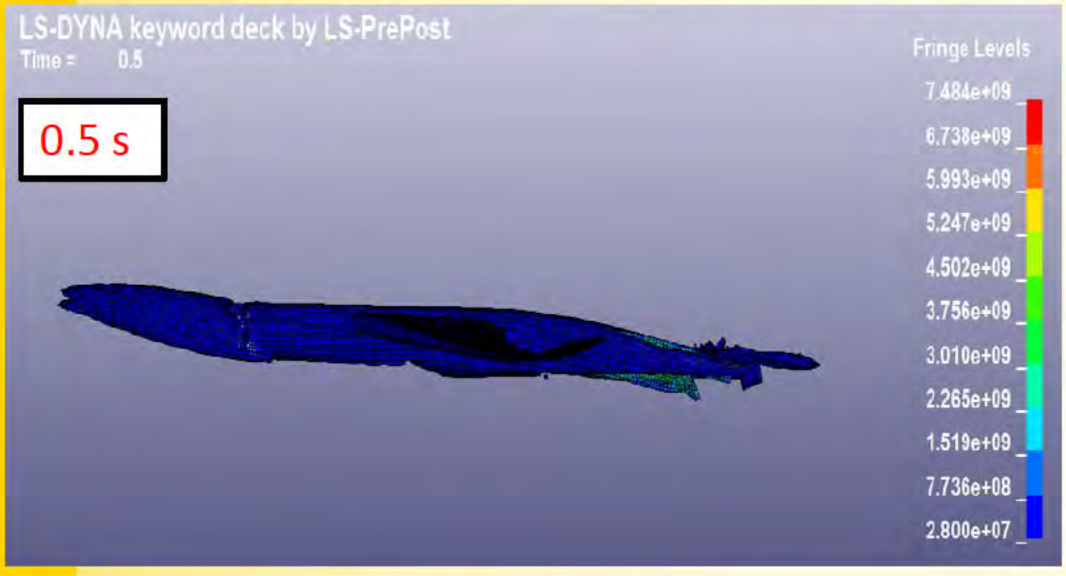


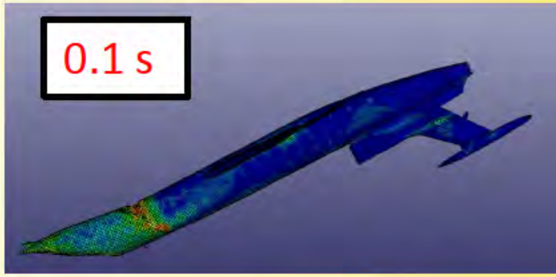
Boeing 727 Crash Test

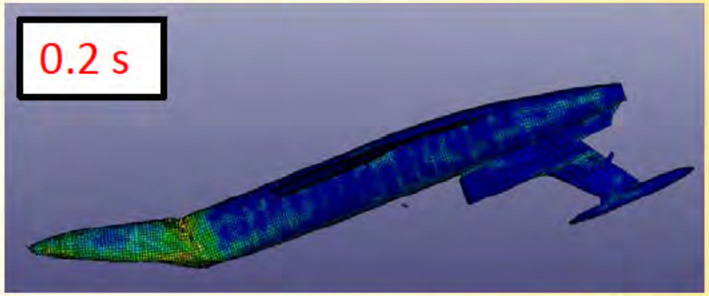
http://dsc.discovery.com/tv-shows/curiosity/videos

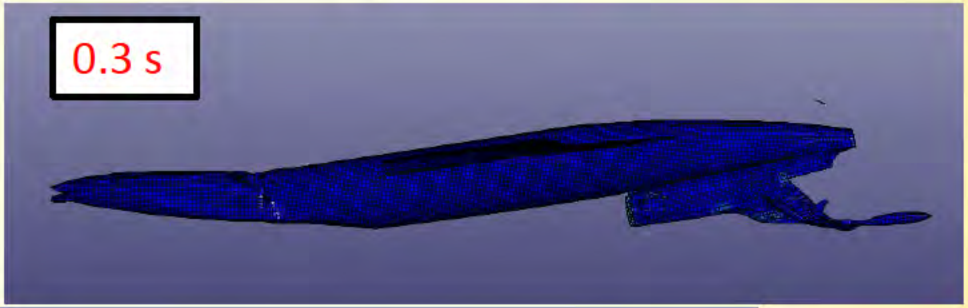


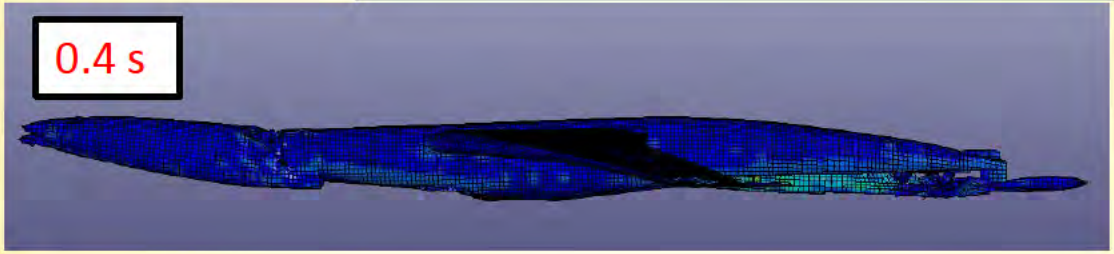
Crash Damage Process - Inverted Case











Kyrgyzstan Jet Crash (no explosion) All Survived, 31 Injured

TU-154 Airplane Crash - Dec 5, 2010
No explosion, all survived, 83 injured

Tupolev Tu-154 passenger plane belonging to Dagestan Airlines, as it crashes at Domodedovo airport in Russia
Photograph: AFP/Getty Images

Airplane Tu-154M Crash
Unusually High Disintegration

Final Conclusions

- Separation of 1/3 of the left wing could not be caused by the impact with the birch tree. Most probably separation of a fragment of the left wing was caused by explosion in the air.
- Open walls outside of the fuselage indicate mid-air explosion.
- The unprecedented degree of damage and the large number of shrapnel indicate high energy mid-air explosion.
- Lack of a visible crater at the crash scene indicate that the airplane disintegrated in the mid-air.
- Without a mid-air explosion, most of the passengers in the center and aft sections of the airplane should survive any crash from 30-40 meters into the soft soil.
- Official Russian report attributed death of the passengers to 100G accelerations. Such accelerations could be explained by i) explosion in the fuselage, ii) shock wave produced by explosion, and/or iii) a direct impact of the passengers with the ground at 80m/s without any protection of the fuselage.