# Analysis of the Polish Governmental Plane Crash in Smolensk, Russia, on 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**

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- SRI International
- The University of Akron – Dr. Wieslaw K. Binienda
- Williams International

# Question # 1

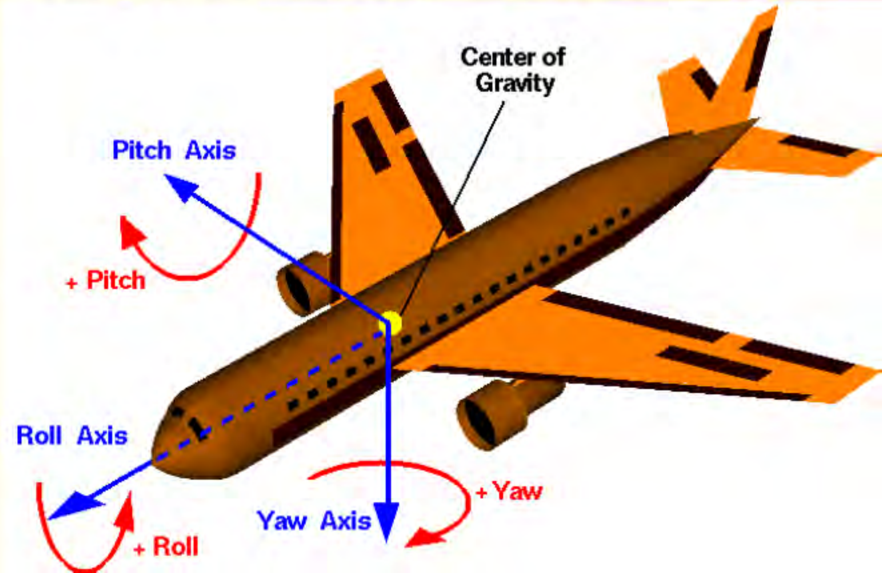
Is it possible that the Tu-154M airplane lost a major part of the wing as a result of hitting the Birch?

# Methodology of Analysis

## LsDyna3D Simulation

### Parameters

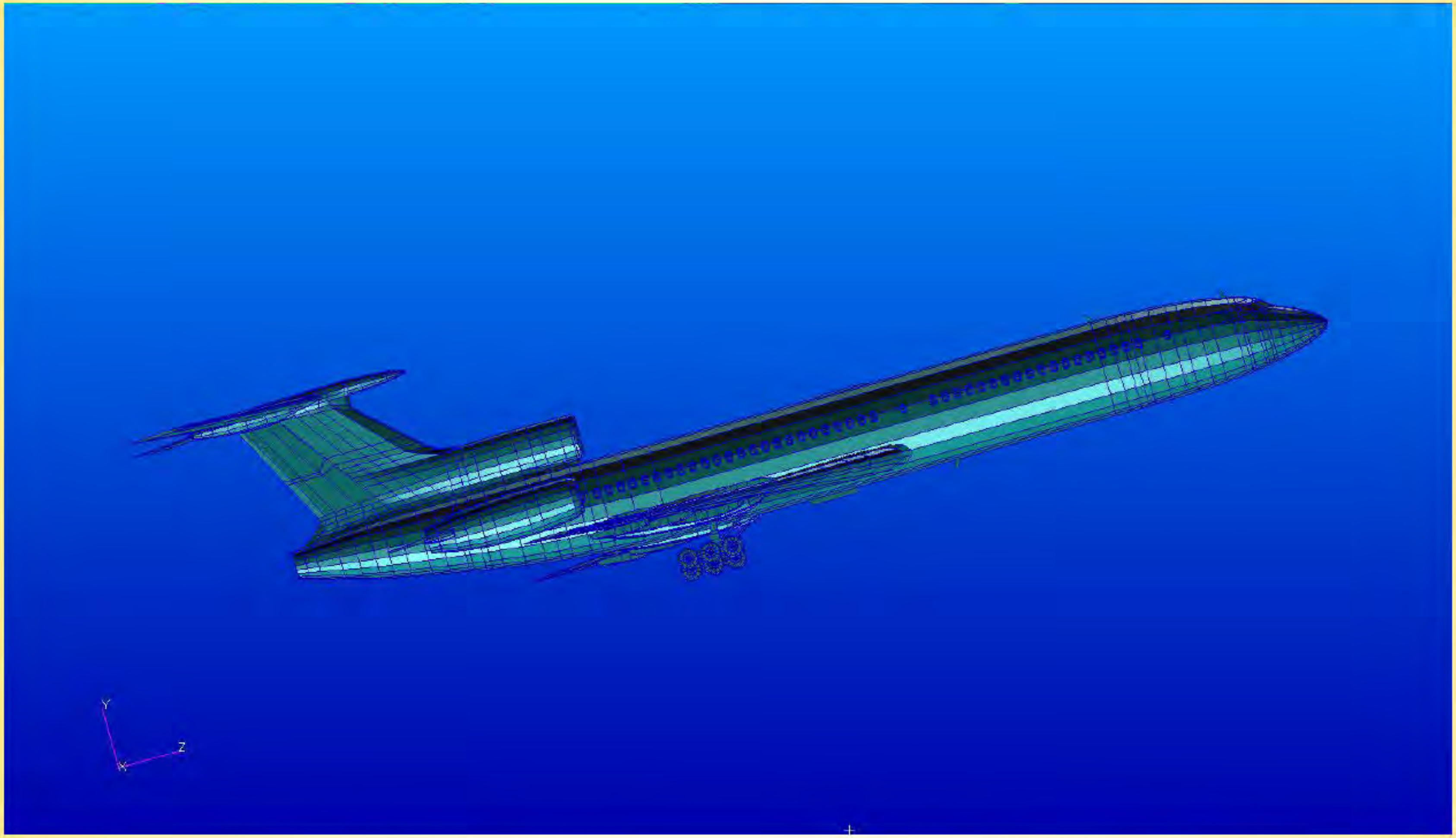
- Plane velocity: **77 m/s horizontal, 19.2m/s vertical up**
- Plane mass: **78600 kg**
- Distance from the base to the tree cut : **6m - 6.5m**
- Birch diameter at the cut section: **40cm - 44 cm**
- **Birch density: 550, 850, 1000 kg/m$^3$**
- Location of the impact on the wing from its tip: **3m - 7m**
- Several plane orientations:
  - Horizontal,
  - Climbing pitch: 5° – 20°
  - Roll -5° horizontal
  - Roll -5° and pitch 5° – 20°



## Material Models

- **Birch**- elastic, cylindrically orthotropic;
- **Aluminum**: isotropic, elasto-plastic hardened, or J-C with strain-rate dependent parameters;

# Model Tu-154M



# Internal structure of the wing Tu-154M

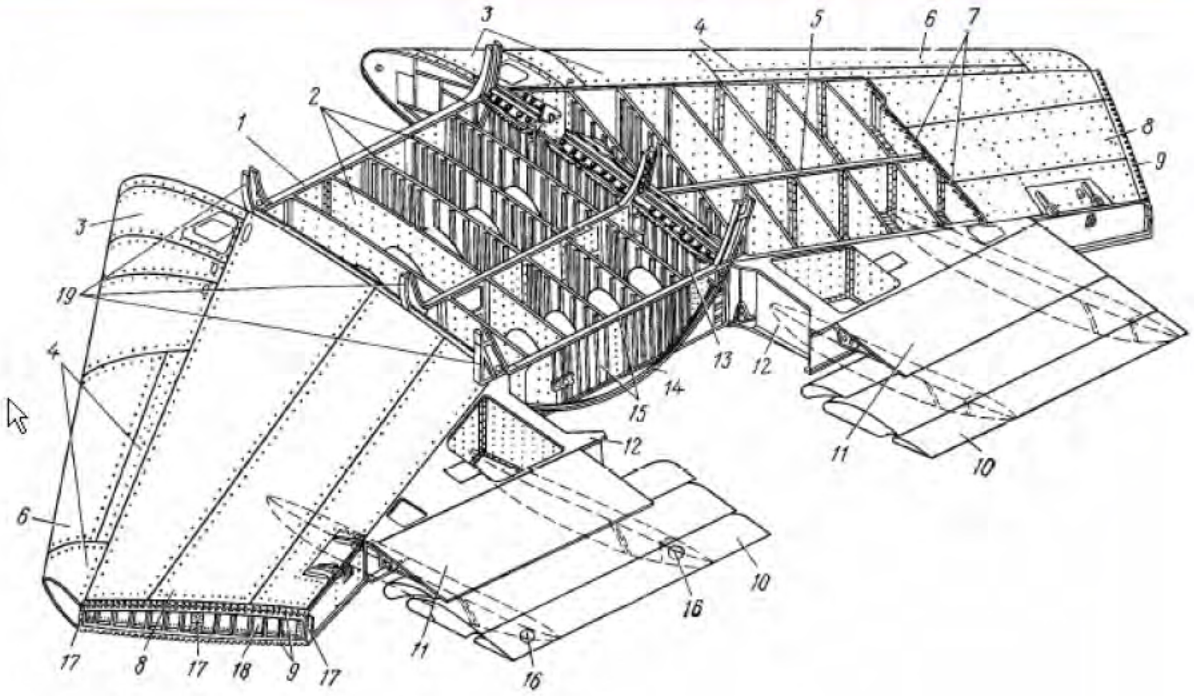



*Рис. 2.33. Центроплан крыла:*

*1—передний лонжерон; 2—нервюры; 3—съемный носок (первый); 4— съемный носок (второй); 5—средний лонжерон; 6—внутренний предкрылок; 7—стрингеры; 8— съемная панель; 9—профили разъема; 10— внутренний закрылок; 11—внутренний интерцептор; 12—хвостовая часть; 13—нервюра № 3; 14—профиль; 15—задний лонжерон; 16—балка механизма закрылка; 17—стыковая стойка; 18—нервюра № 14; 19—узлы крепления центроплана к фюзеляжу*

# Internal structure of the wing Tu-154M

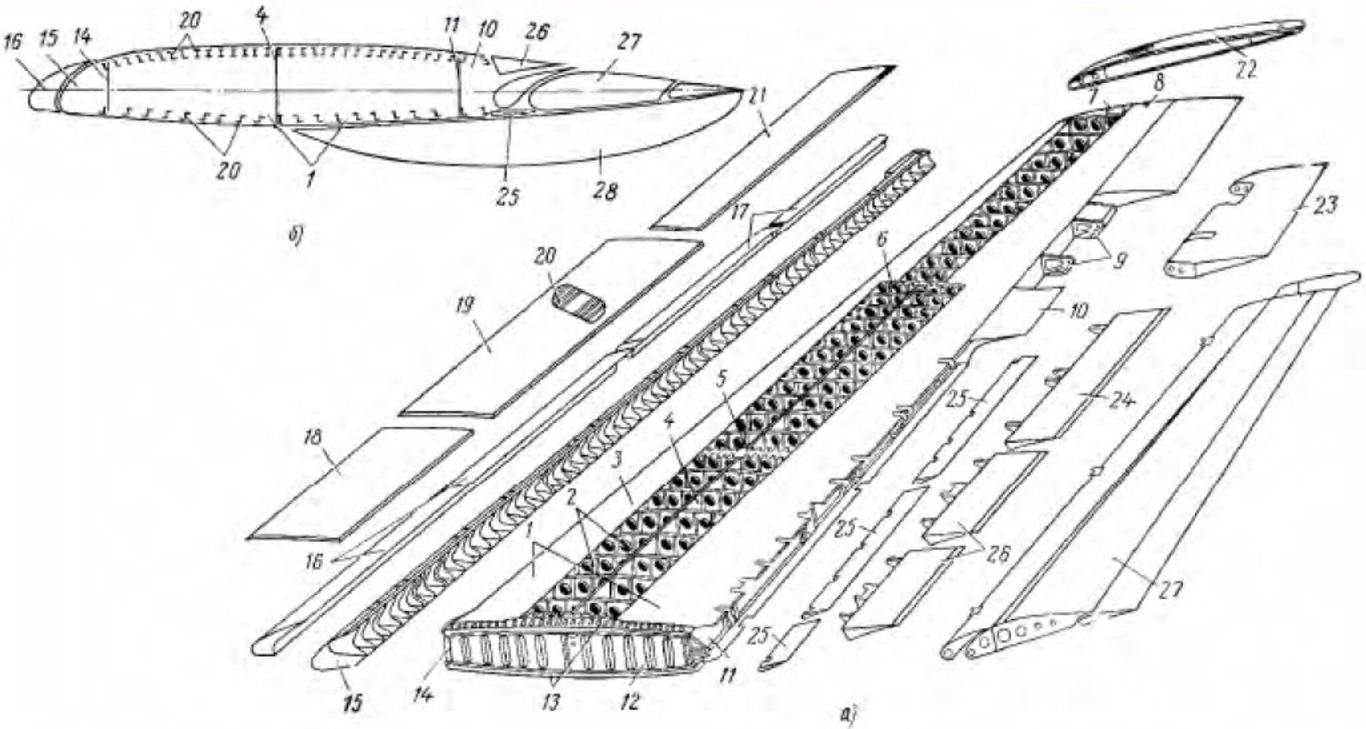



*Рис. 2.37. Отъемная часть крыла (аэродинамические перегородки не показаны): а—общий вид; б—сечение ОЧК по нервюре № 18; 1—кессон; 2—нервюры; 3—первая технологическая панель; 4—средний лонжерон; 5, 6—стыковочные профили; 7—нервюра №. 45; 8—вторая технологическая панель; 9—кронштейны подвески элерона; 10—*

# Internal structure of the wing Tu-154M

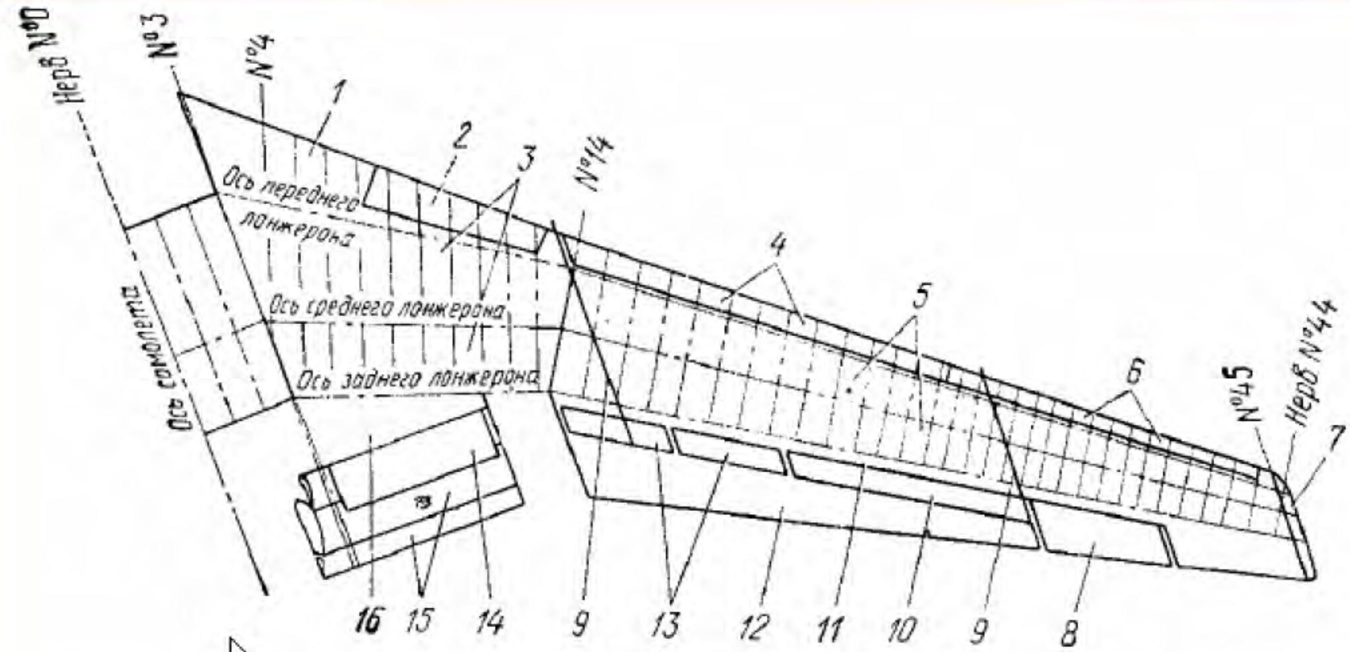



*Рис. 2.31. Схема крыла:*

*1—носовая часть (носок) центроплана; 2—внутренний предкрылок; 3—кессон центроплана; 4—средний предкрылок; 5—кессон ОЧК; 6—внешний предкрылок; 7—концевой обтекатель; 8—элерон; 9—аэродинамическая перегородка; 10—элерон-интерцептор; 11—хвостовая часть ОЧК;12—внешний закрылок; 13—средний интерцептор; 14—внутренний интерцептор; 15—внутренний закрылок; 16—хвостовая часть центроплана*

# Material parameters of the birch tree

| | | | | | | |
|---|---|---|---|---|---|---|
| Density($Kg/m^3$) | Longitudinal modulus, Eb(Pa) | Radius Modulus, Ea(Pa) | Transverse Modulus, Ec (Pa) | Poisson Ratio, Vba | Poisson Ratio, Vca | Poisson Ratio, Vcb |
| 1000 | 1.60E+10 | 11.0E+8 | 6.000E+8 | 0.451 | 0.397 | 0.043 |
| Shear Modulus, Gab (Pa) | Shear Modulus, Gbc (Pa) | Shear Modulus, Gca (Pa) | Maximum Effective Strain | | | |
| 7.04E+8 | 7.622E+8 | 1.751E+8 | 0.05 | | | |

# Parameters of the Aluminum Tu-154

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

| Density($Kg/m^3$) | Young's modulus, E(Pa) | Yield Stress(Pa) | Tangent Modulus, Ec (Pa) | Poisson Ratio, ν | Failure Strain |
|---|---|---|---|---|---|
| 2850 | 7.4E+10 | 4.44E+8 | 5.738E+8 | 0.33 | 0.14 |

# Computer System and Results

- 18 CPU parallel system
- Transient explicit calculations with time step of the order $10^{-9}$ sec.
- Total time for each simulation 7-10 days.

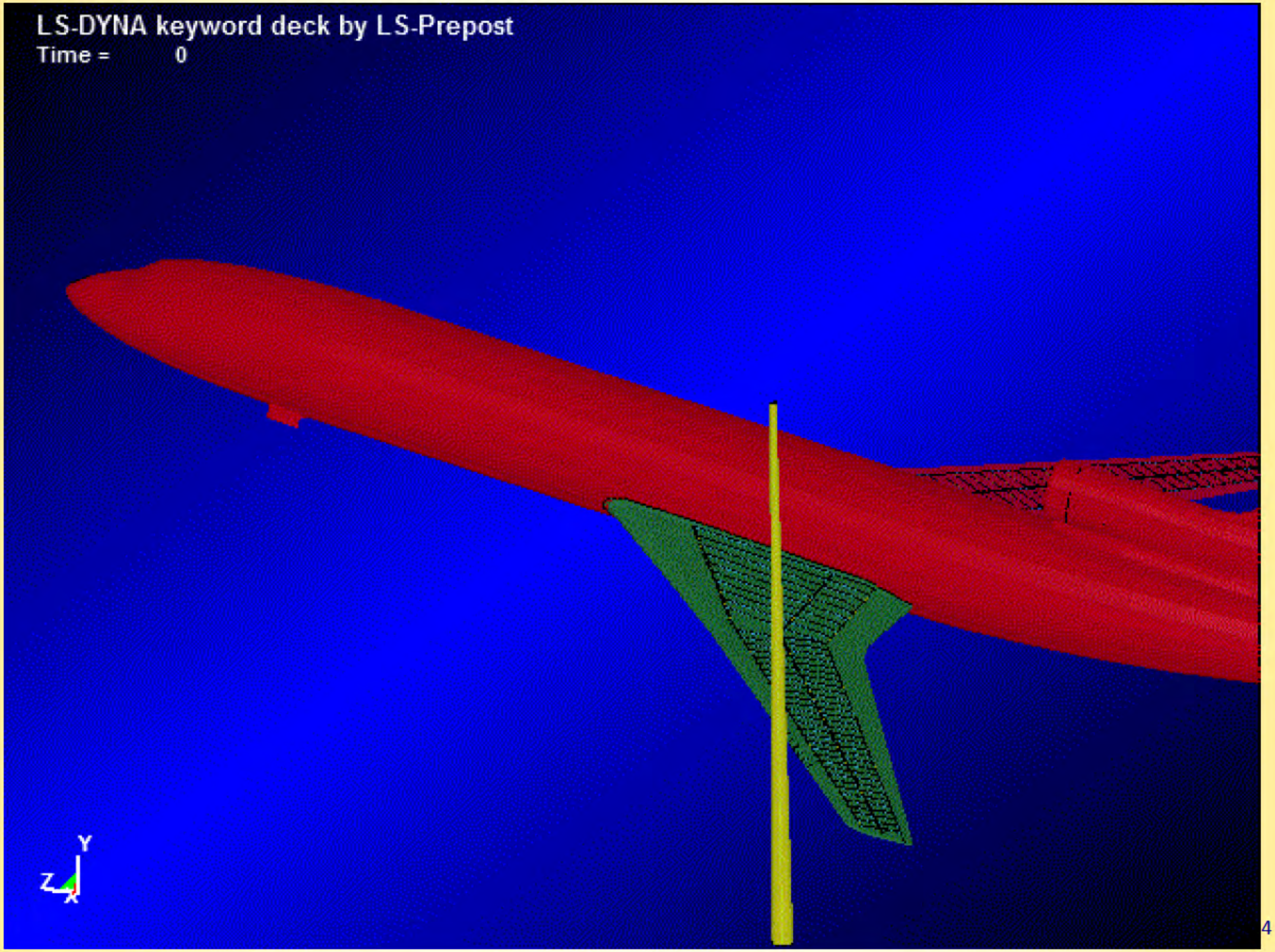
Simulations demonstrated using LsPost

Wing crashing to the tree,

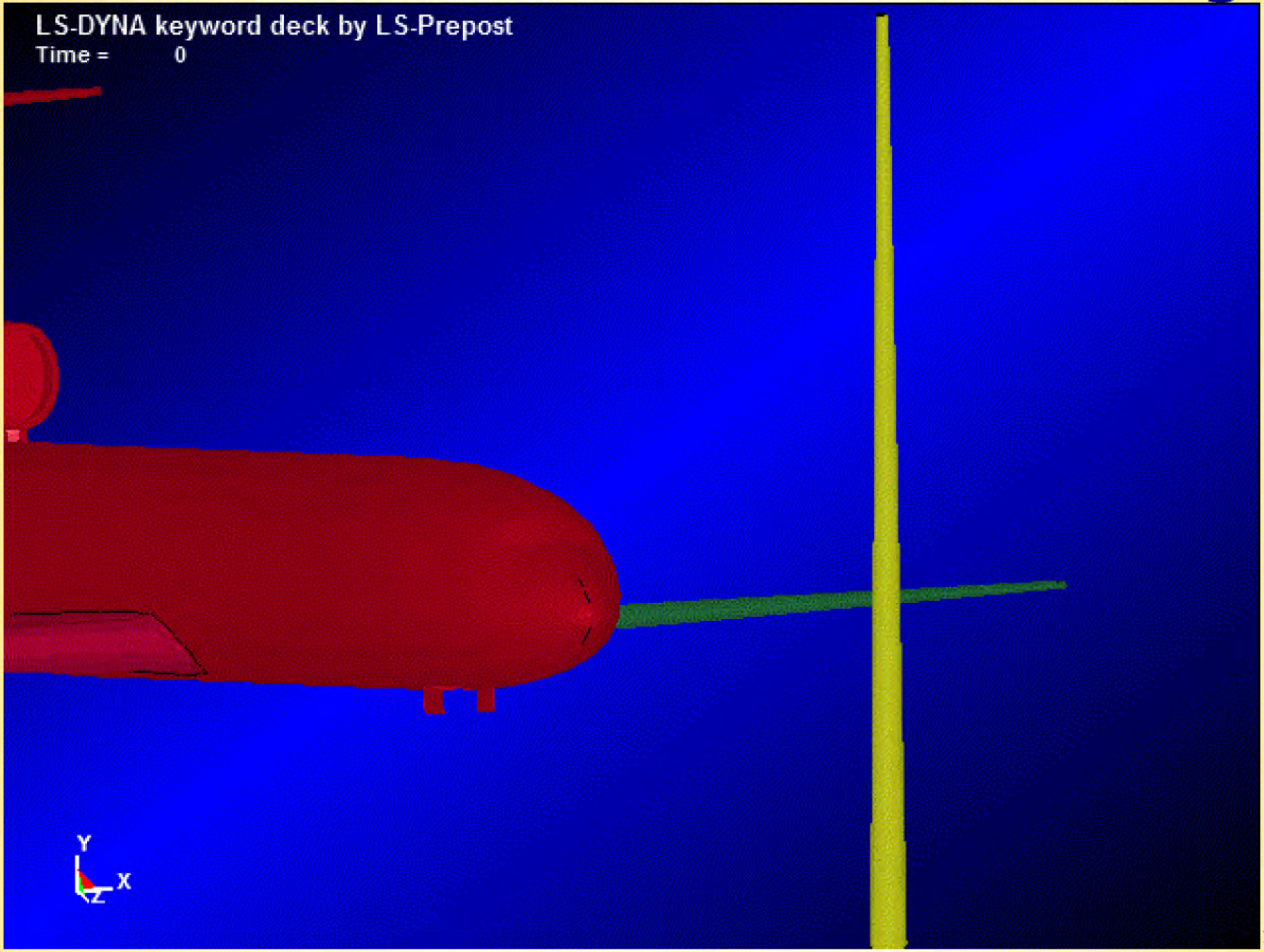
Local tree behavior,

Local wing damage

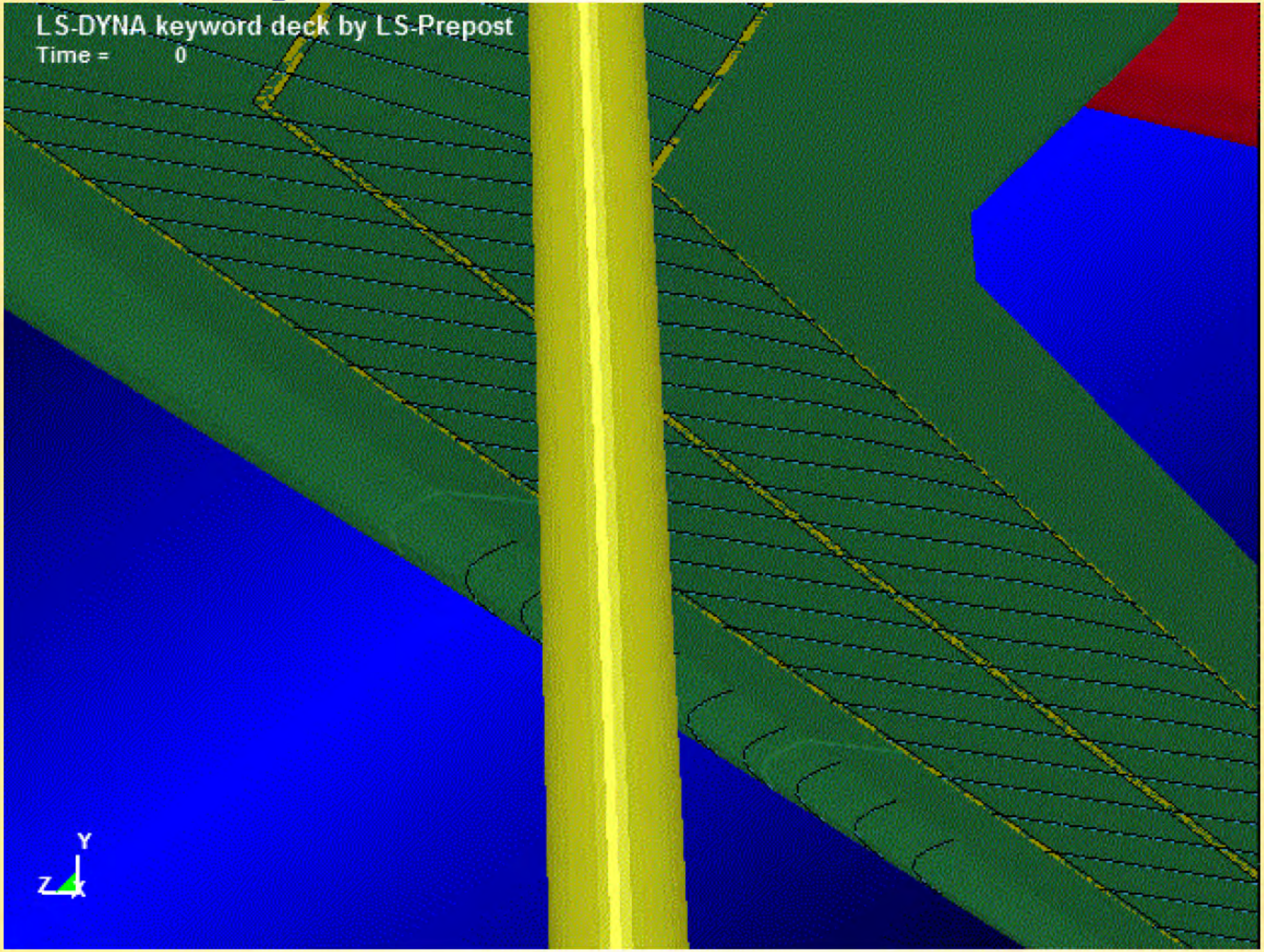
# Simulation – view from the left side



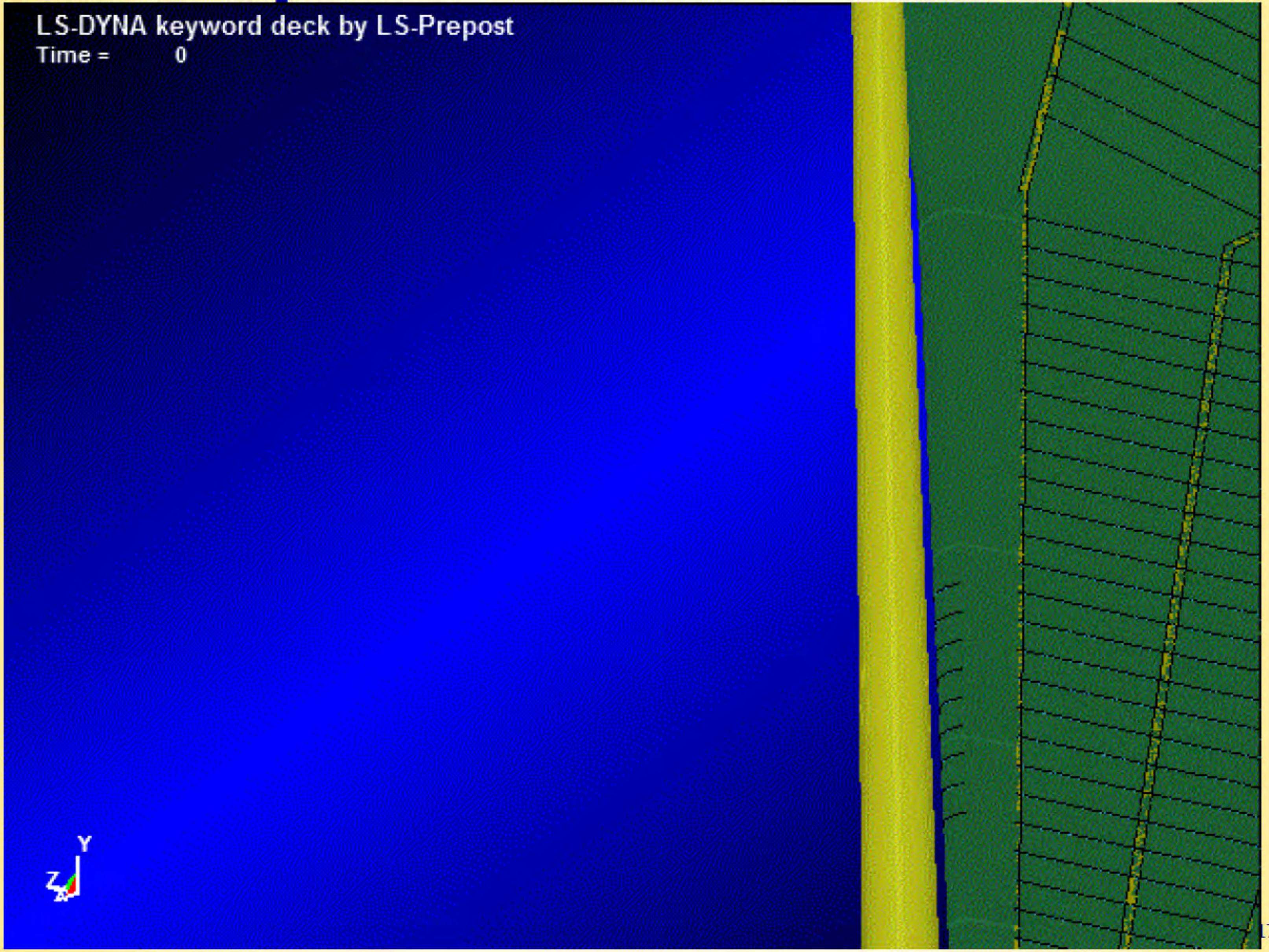
# Simulation – view from the front/right



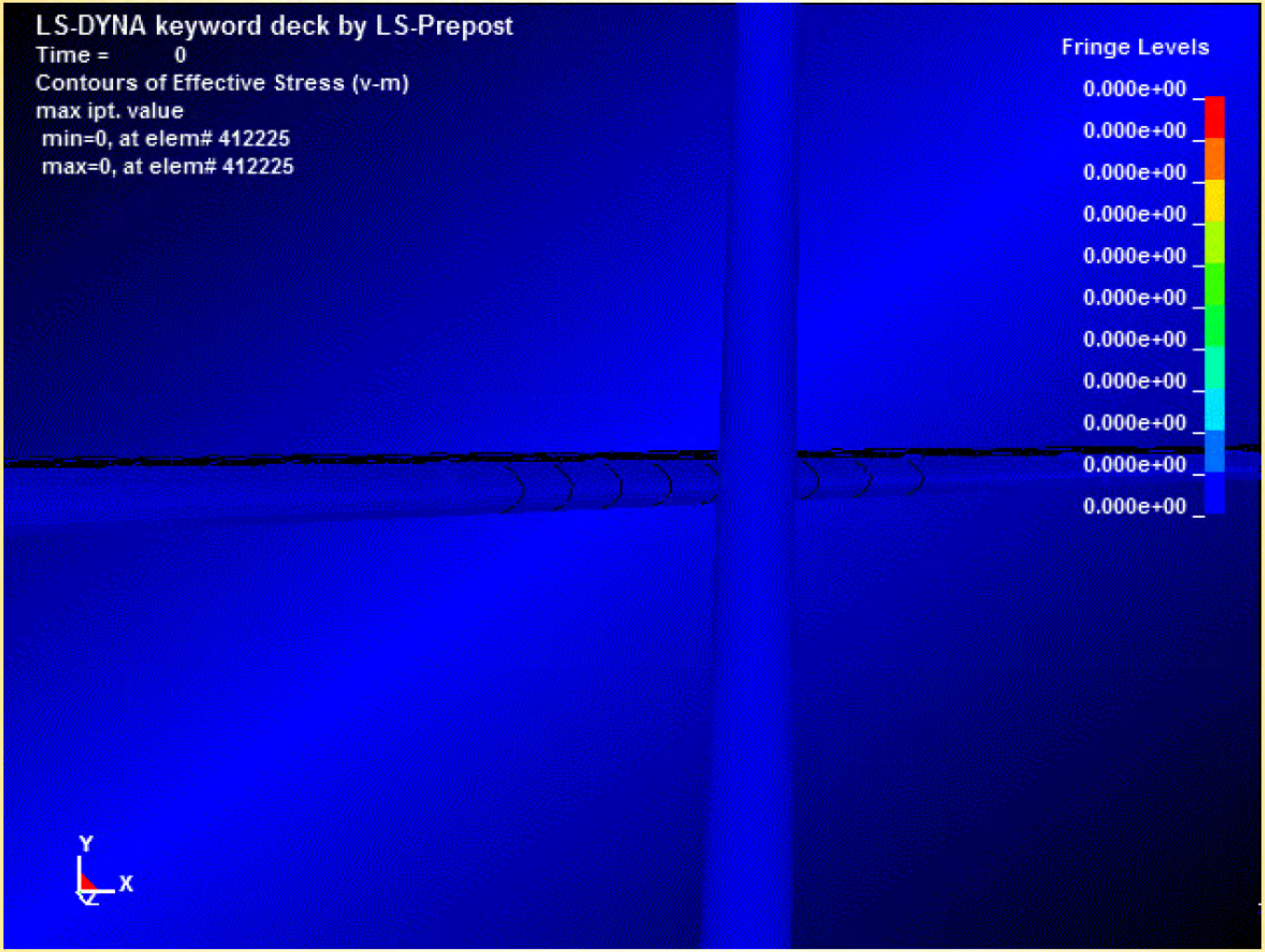
# Close-up 1



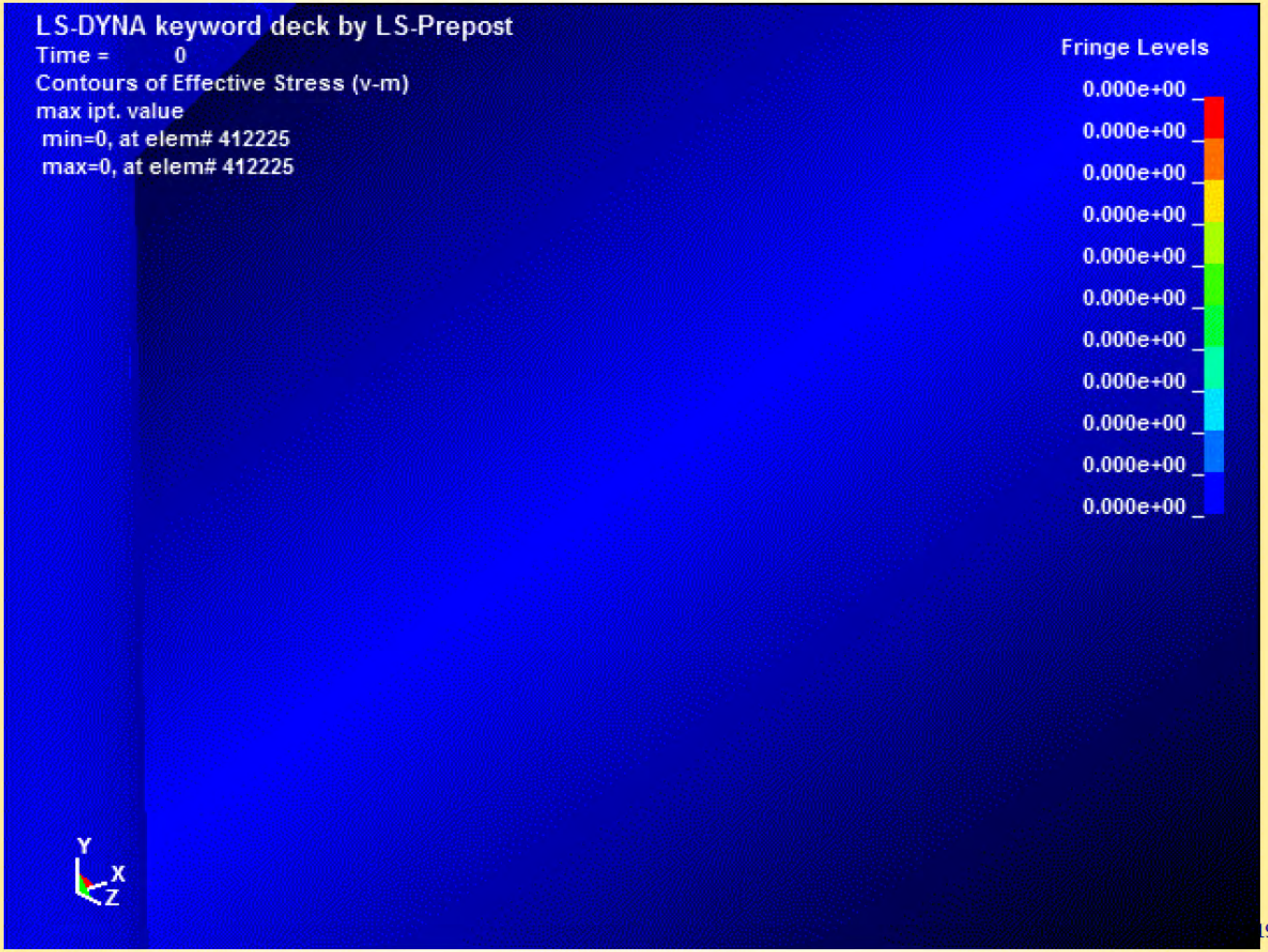
# Close-up 2



# Effective stress distribution



# Effective stress distribution



# Conclusions # 1

- Based on the parameters provided in the official reports, the model shows that the wing of the Tu-154M plane cuts through the birch for every analyzed scenario.
- 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.

# Question # 2

What is the most probable position of the Tu-154M airplane at the moment when 1/3 of the wing breaks away?

# 1/3 of the wing was found 111 meters from the birch


# Satellite View of the Airplane Path

# Methodology of the analysis

- Illustration of the air drag

  Example calculated using simple physics equations for the baseball with and without air drag.

- Simulations

  - Air streams and pressures on the fragment of the wing before and after separation calculated using Ansys CFX and LsDyna3D.
  - Plane speed: **77m/s horizontal, 19.2m/s up**
  - Length of the wing fragment: **6m.**
  - Pitch: 20°.

# Flight Equations with drag – from NASA

**Vertical Ascent**

$$F_{net} = -W - D$$

$$a = -g - \frac{Cd\ A\ \rho V^2}{2\ m}$$

$$V = V_t\ \frac{V_o - V_t \tan(t\ g / V_t)}{V_t + V_o \tan(t\ g / V_t)}$$

$$y = \frac{V_t^2}{2g}\ \ln\left(\frac{V_o^2 + V_t^2}{V^2 + V_t^2}\right)$$

$$y_{max} = \frac{V_t^2}{2g}\ \ln\left(\frac{V_o^2 + V_t^2}{V_t^2}\right)$$

$$V_t = \sqrt{\frac{2\ m\ g}{Cd\ A\ \rho}}$$

$$t_{(v=0)} = \frac{V_t}{g}\ \tan^{-1}\left(\frac{V_o}{V_t}\right)$$

**Vertical Descent**

$$F_{net} = -W + D = 0$$

$$a = 0$$

$$V = V_t$$

**Horizontal:** $F_{net} = -D$

$$a = -\frac{Cd\ A\ \rho\ U^2}{2\ m}$$

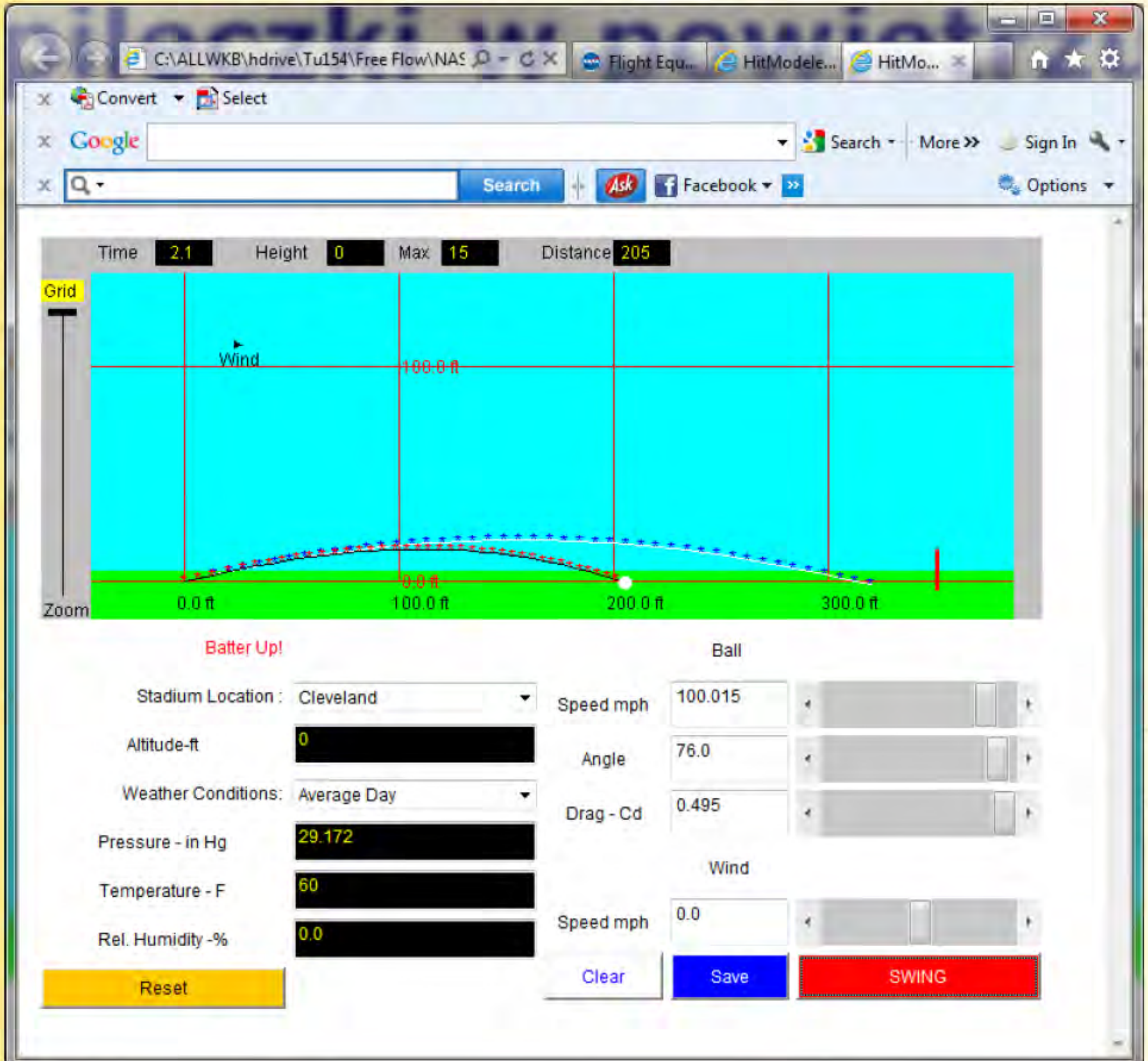
**Horizontal :**

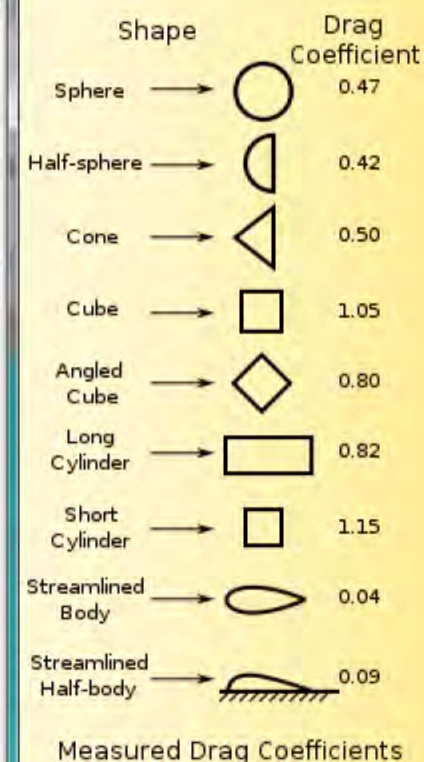
$$U = \frac{V_t^2\ U_o}{V_t^2 + g\ U_o t}$$

$$x = \frac{V_t^2}{g} \ln\left(\frac{V_t^2 + g\ U_o t}{V_t^2}\right)$$

http://www.grc.nasa.gov/WWW/k-12/airplane/flteqs.html

# Baseball with and without drag



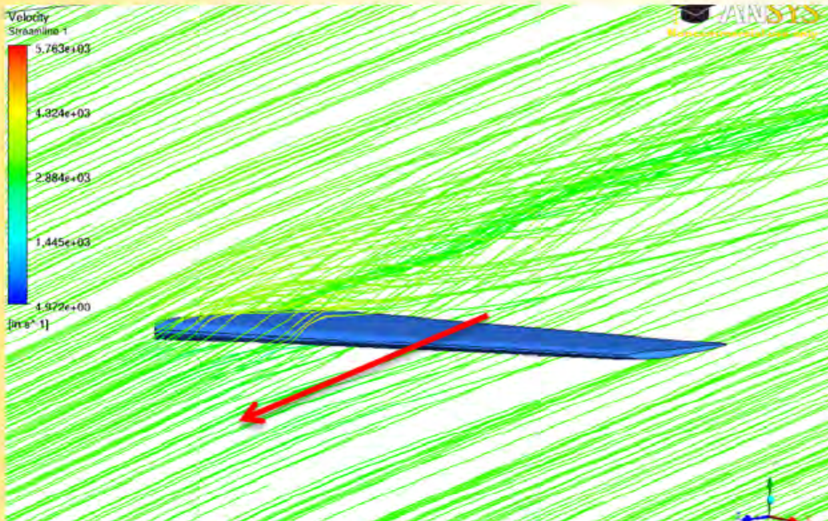
# Math and Physics Background

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

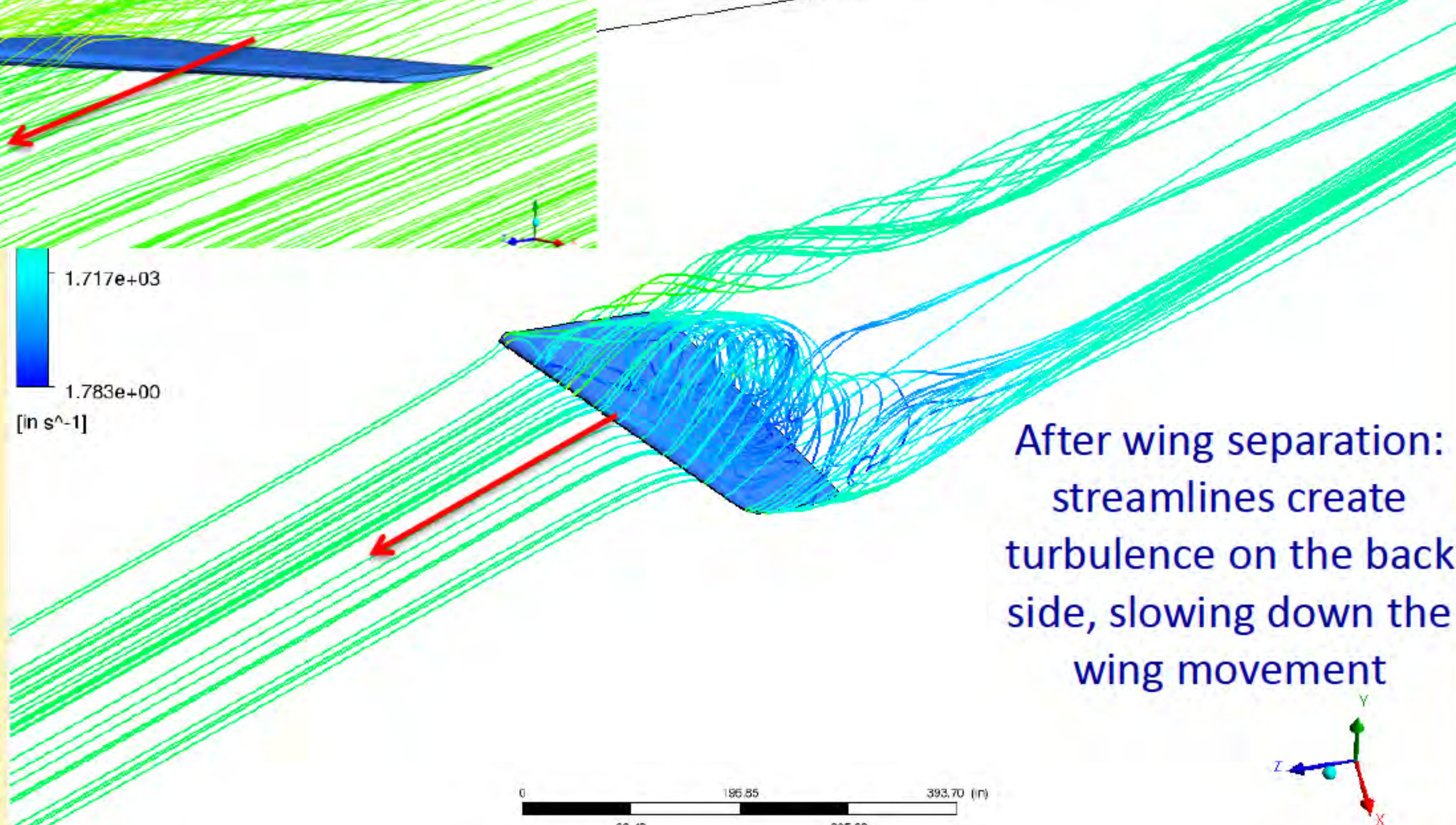
$$\frac{\partial(\rho u_i)}{\partial t} + \nabla \cdot \left(\rho \overrightarrow{V} u_i\right) = -\frac{\partial p}{\partial x_i} + \nabla \cdot (\mu \nabla u_i) + S_{Mx_i}$$

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

# Air streamlines before and after wing separation - CFX

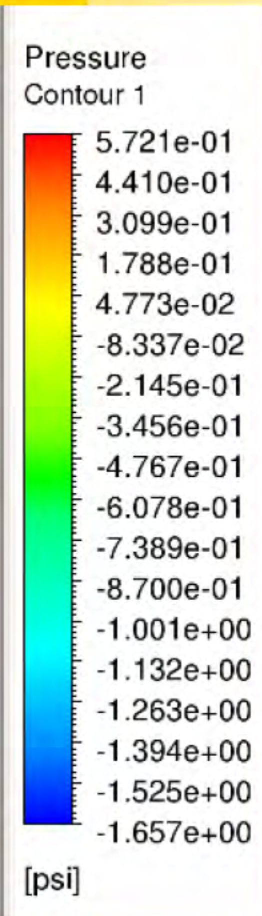



Before wing separation: streamlines follow the shape of the wing

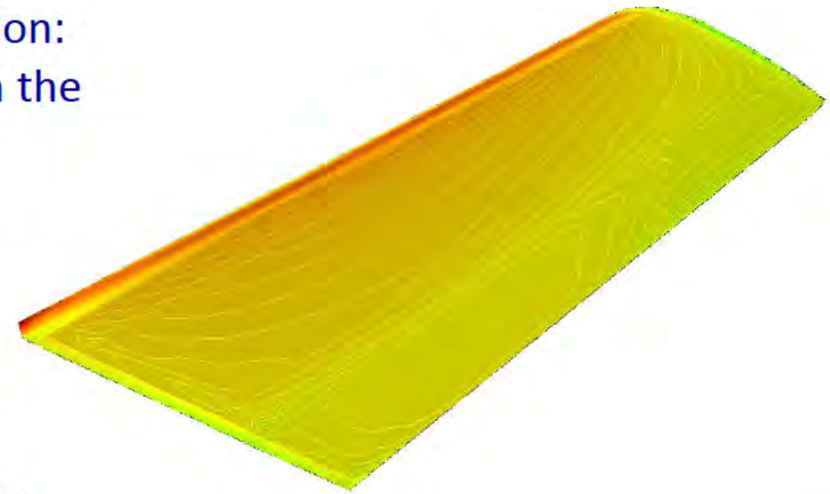



After wing separation: streamlines create turbulence on the back side, slowing down the wing movement

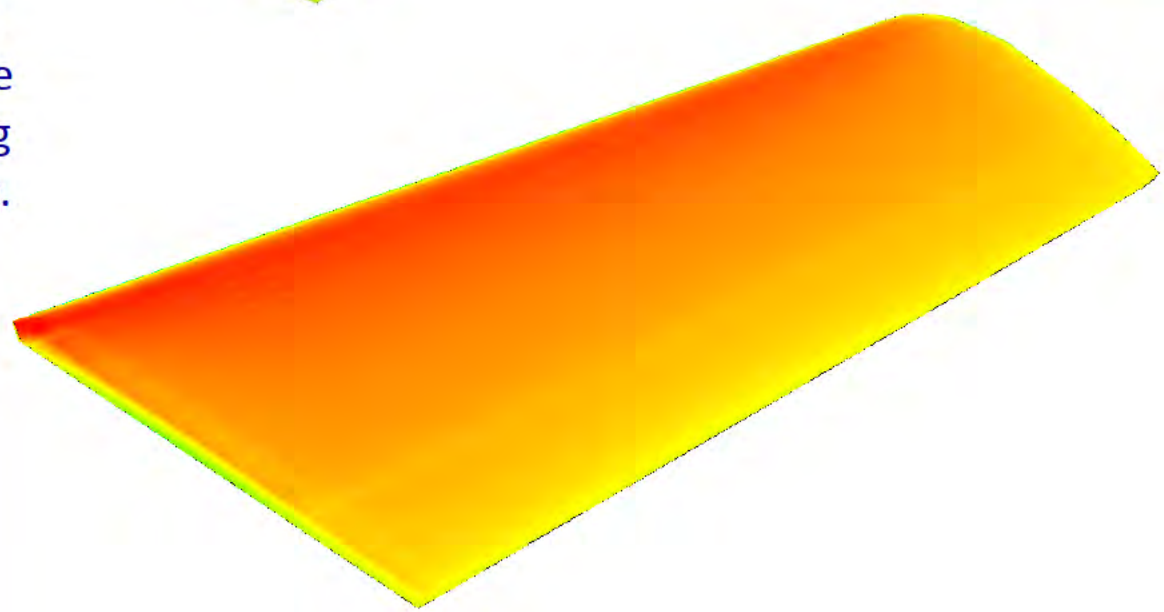
# Pressures before and after wing separation - CFX




Before wing separation: high pressure only on the front edge



After wing separation: high pressure along the entire surface, resisting movement of the wing.

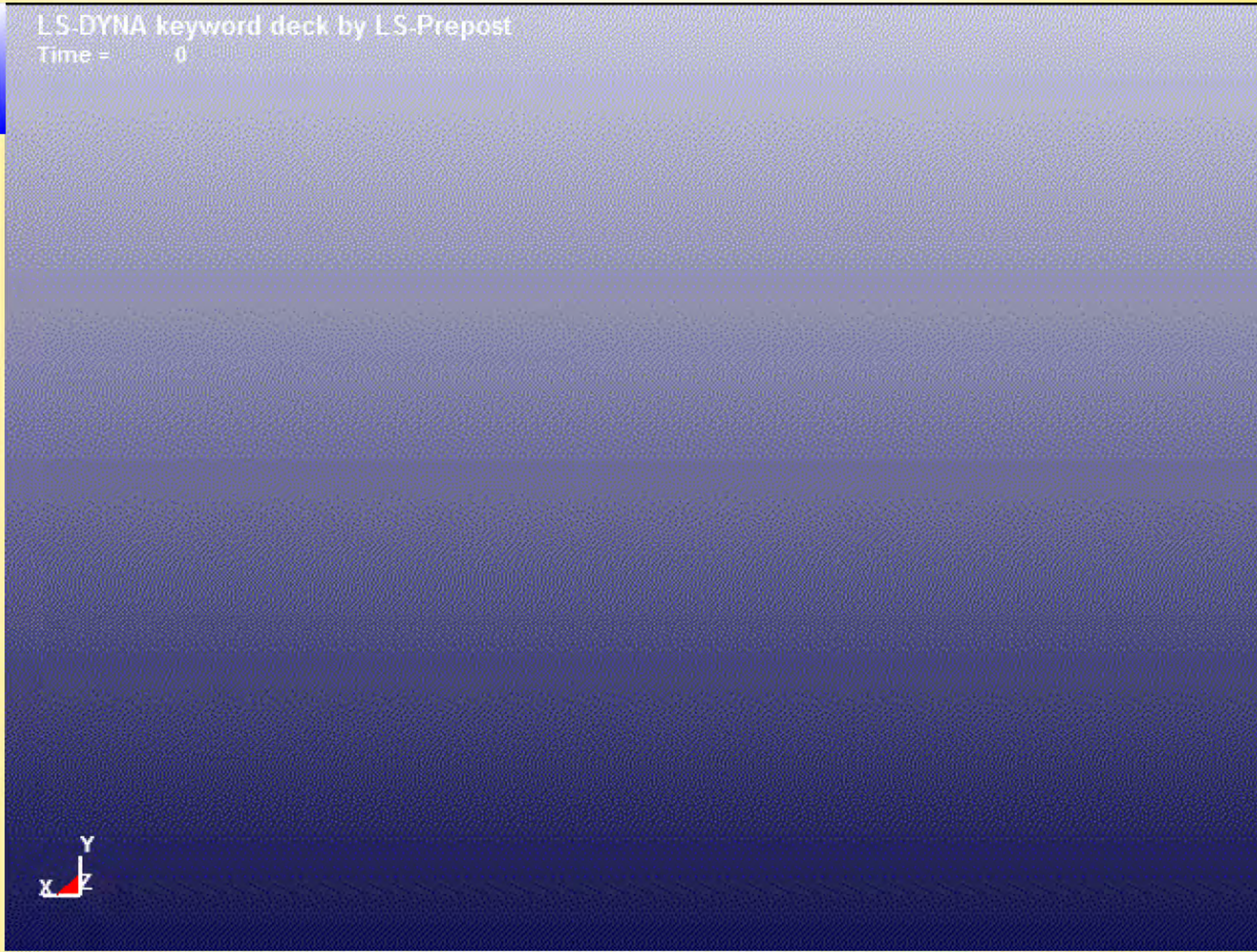


# Transient wing movement simulation calculated using LsDyna3D

- Arbitrary Lagrangian Eulerian method
- Constraint_Lagrange_in_Solid keyword
- Before separation, the fragment (in red) flies together with the wing and the airplane (which is not visible here)
- After separation, the wing fragment slows down and is falling with erratic rotations governed by air drug.

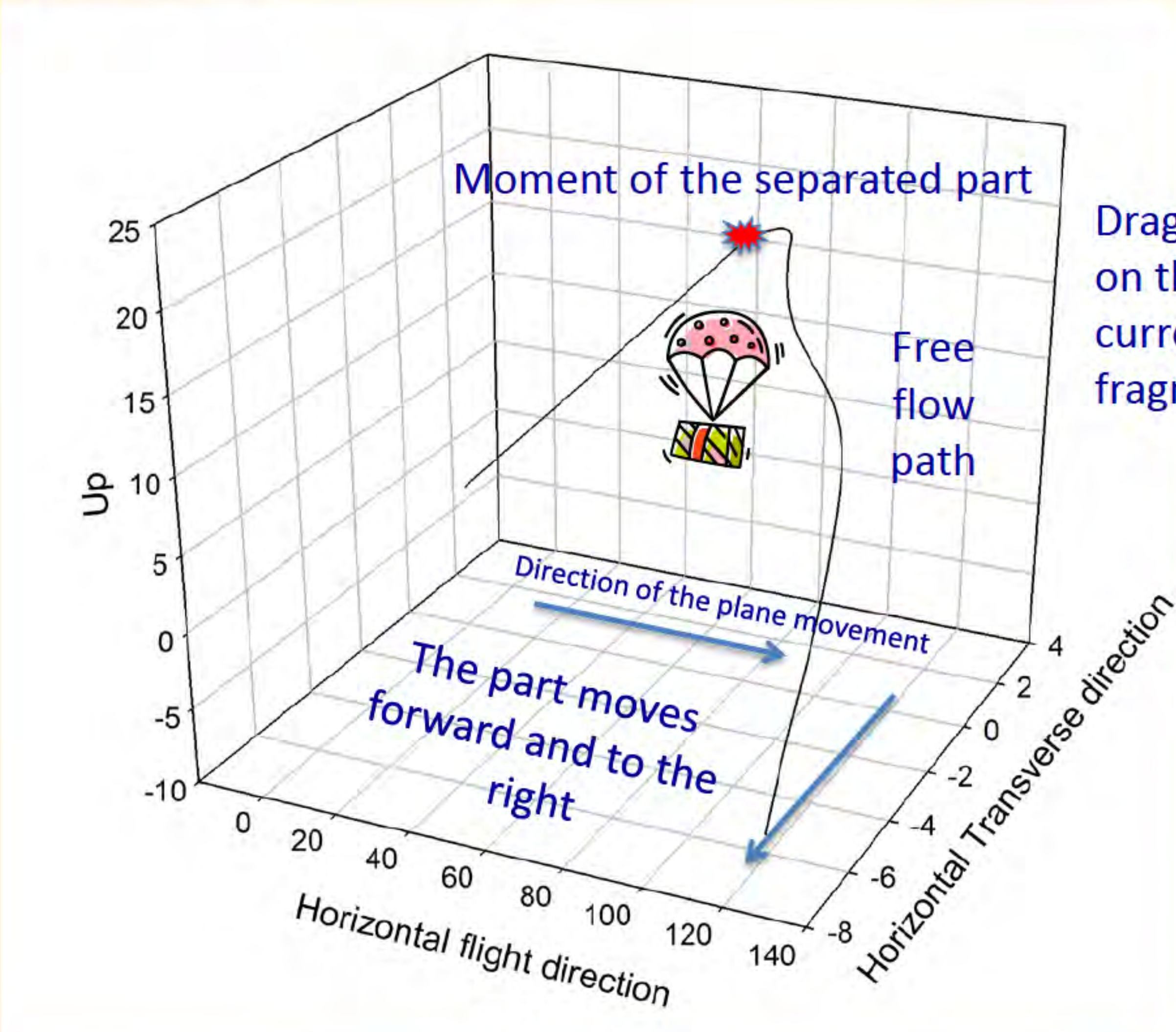
# Simulations - view from the side/back of the airplane.

# Simulation – view from the back of the airplane



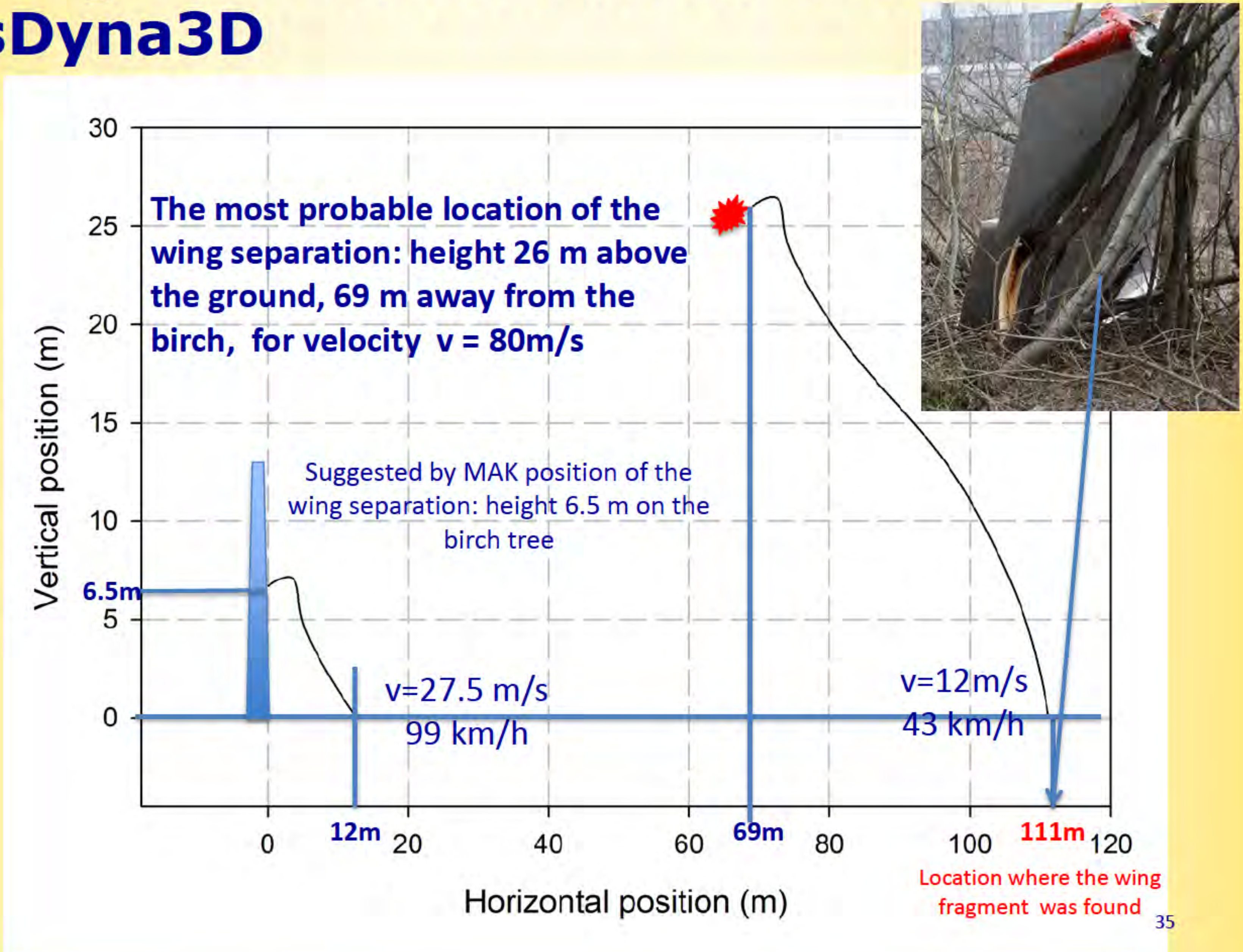
# Simulation – view from the side of the airplane.

# Center of Mass position from the LsDyna3D

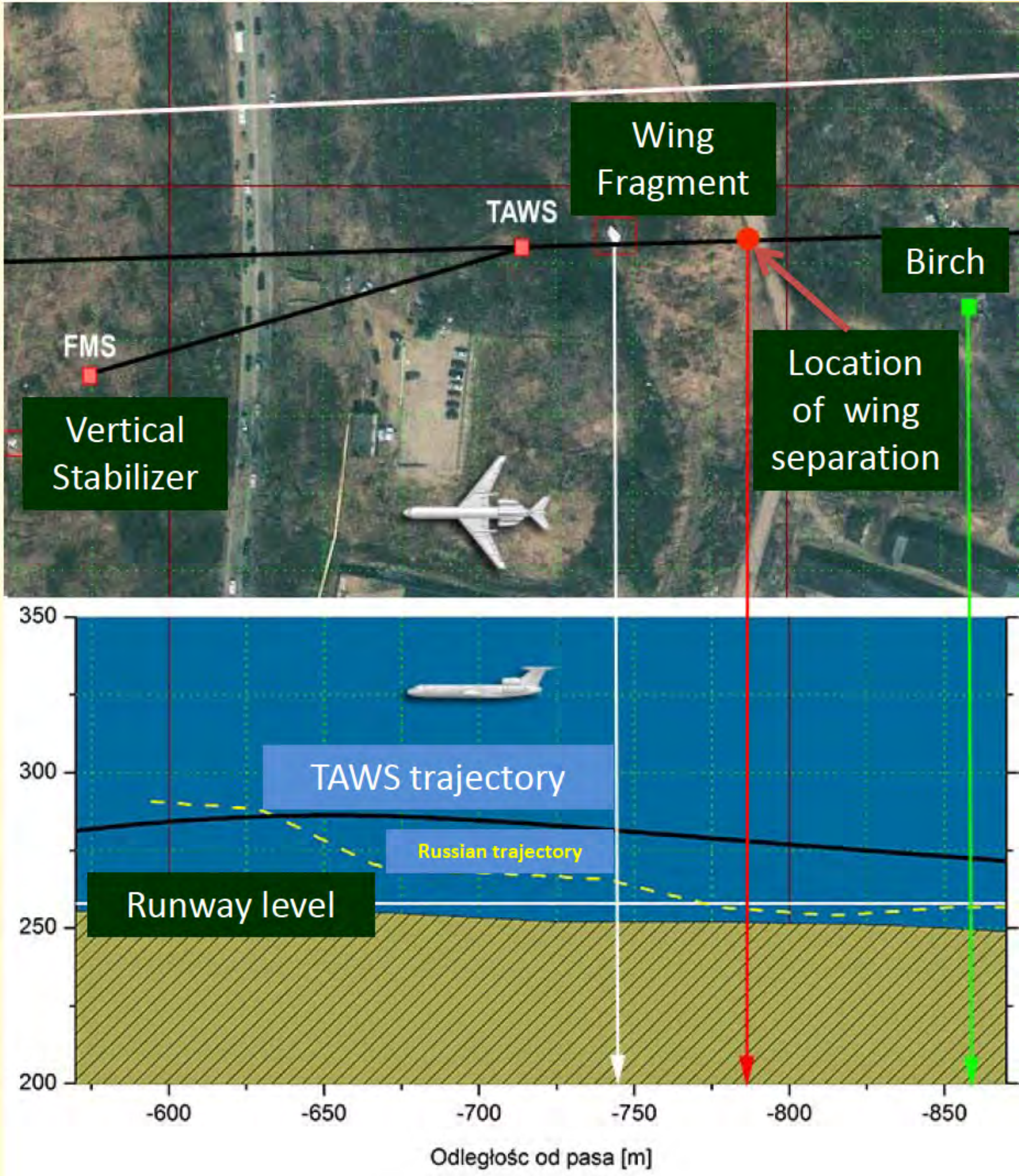



Drag force depends on the position and current velocity of the fragment of the wing.

# Using the free flow curve from LsDyna3D



# Location of the most probable separation of the wing fragment: 26m above the ground and 69 m away from the birch



# Conclusions # 2

- The wing fragment cannot separate on the birch and fly over the terrain 111 m away from the tree. From 6 m height the fragment would fly only 10-12 m away and could not have enough space to move 10-13 meters to the right.

- The most probable location of the wing separation is  the location at least 26 m above the ground and 69 meters from the tree or 42 meters from the location where the fragment was found.

- http://www.youtube.com/watch?v=LPbhQS6IljU
- http://www.youtube.com/watch?v=TBcC8zqNjKk

# Example of the wing/airplane behavior after the wing break