# Modeling and Simulation of Pulverizing Aircraft Crashes

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On March 24, 2015, Germanwings Flight 9525 Crashed into the French Alps mountains near Prads-Haute-Bléone. All 150 passengers and crew perished. The crash was a deliberate suicide by co-pilot Andreas Lubitz. What is found as the wreckage is the totally *pulverized* remains.

**Figure 1:** `http://goo.gl/y18bPC`

# Crashes of cars and airplanes

**Figure 2:** `http://goo.gl/M76d1C`


**Figure 3:** `http://goo.gl/gTlcNu`

In this project, our objective is to perform computer simulation of a mountain-crash of an aircrash in order to understand the physical mechanisms at work.

The airplane is an Airbus A320-211 aircraft. How does it look likes? Its exterior takes the following form:

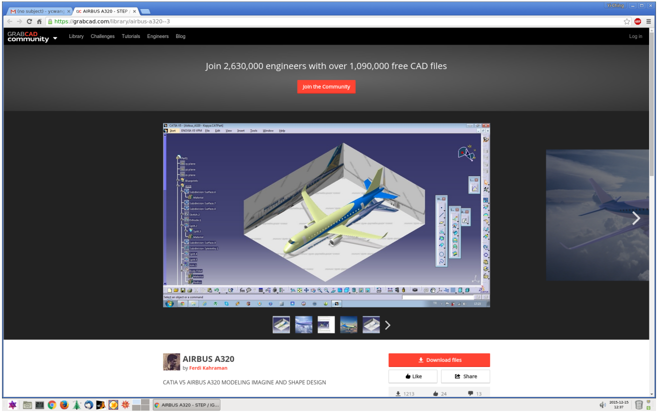
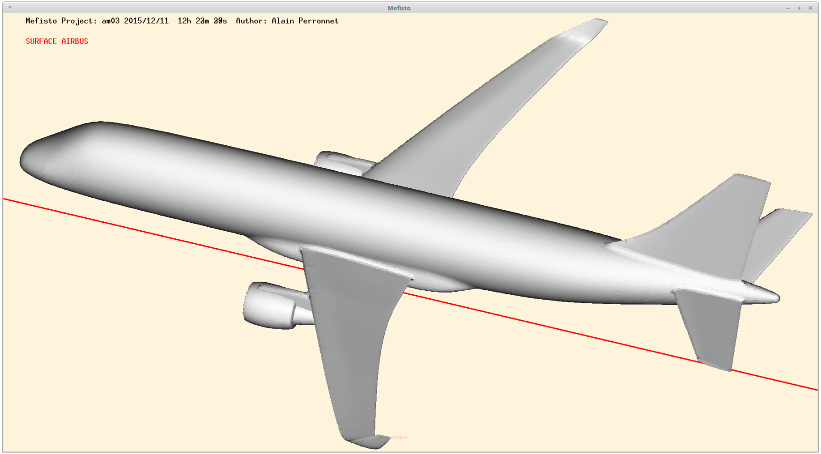



**Figure 4:** `https://grabcad.com/library/airbus-a320--3`


Mefisto
Mefisto Project: am03 2015/12/11 12h 23m 29s Author: Alain Perronnet
SURFACE AIRBUS

The following is how the interior of an Airbus A320 looks like and is organized.

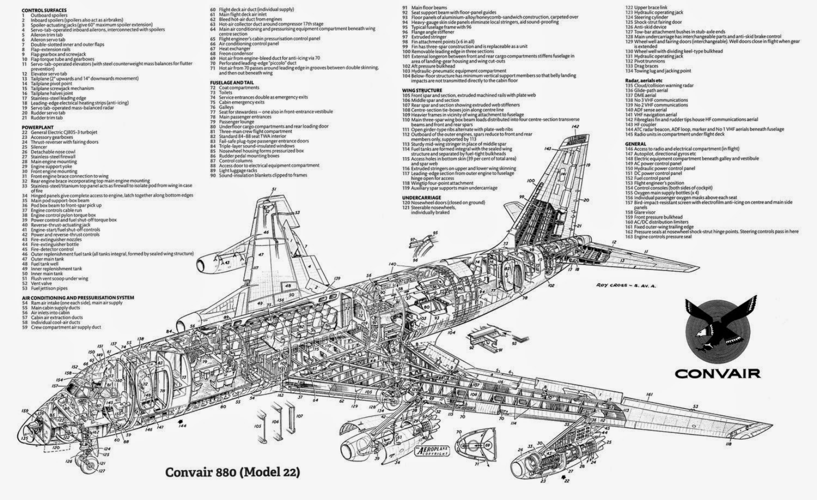
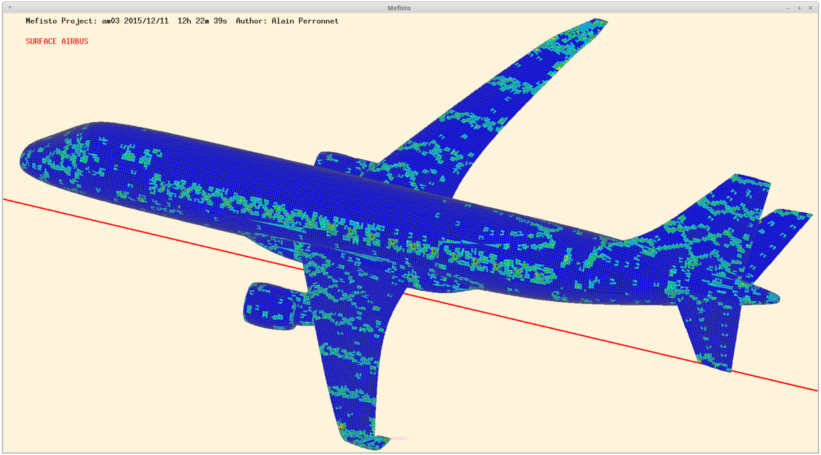
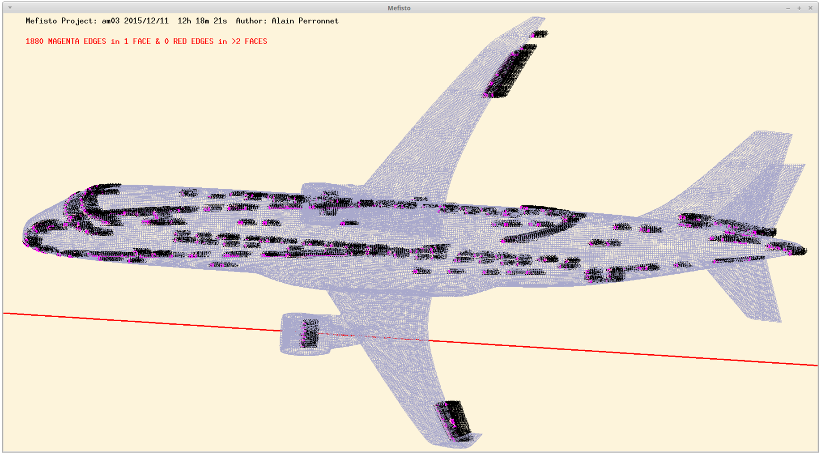



**Figure 5:** `http://goo.gl/vTFqmt`

**Figure 6:** `http://goo.gl/S0KmnR`

# Finite element mesh generation for the LS-DYNA computations

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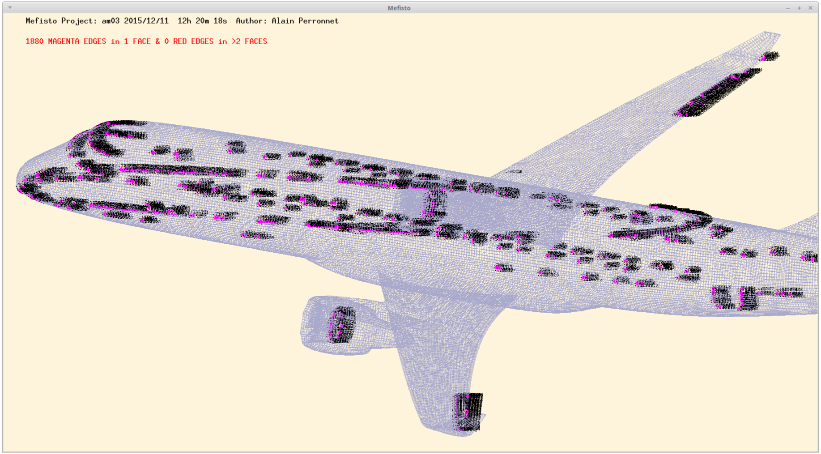
Mefisto Project: am03 2015/12/11 12h 18m 21s Author: Alain Perronnet
1880 MAGENTA EDGES in 1 FACE & 0 RED EDGES in >2 FACES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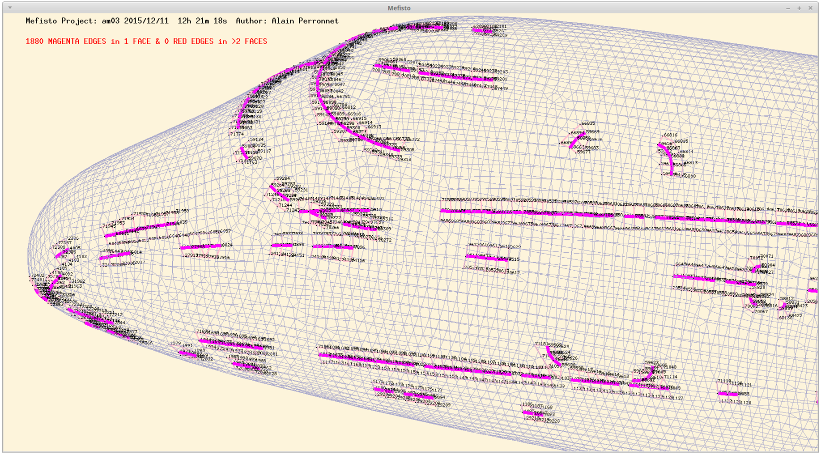
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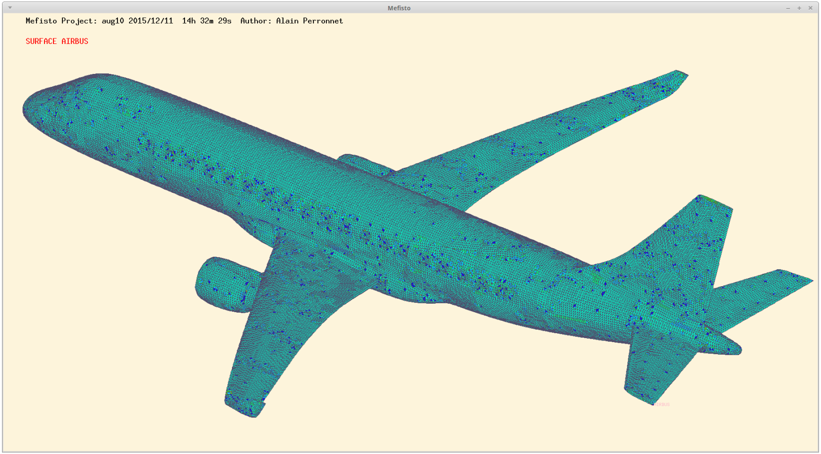
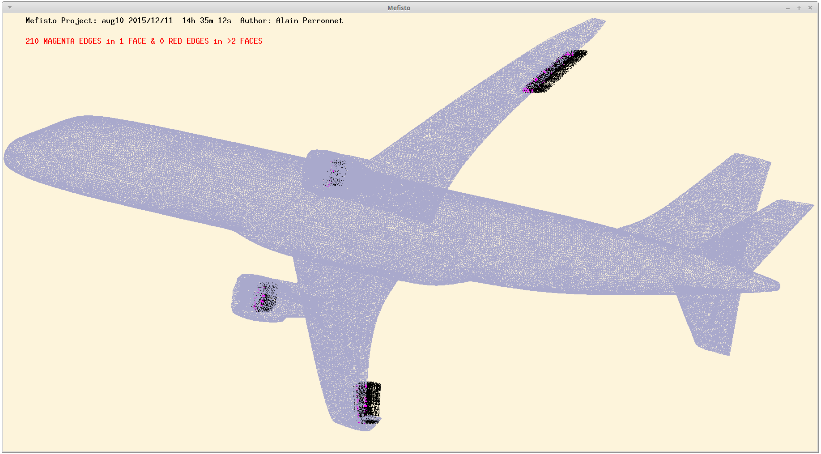

Mefisto
Mefisto Project: aug10 2015/12/11 14h 32m 29s Author: Alain Perronnet
SURFACE AIRBUS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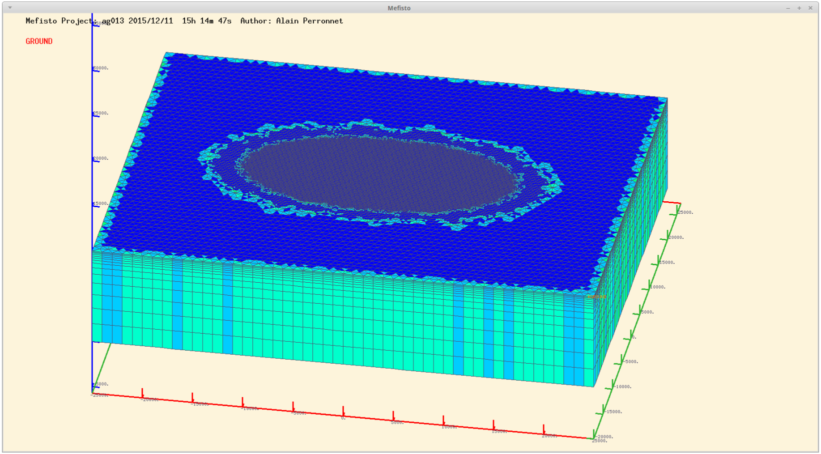
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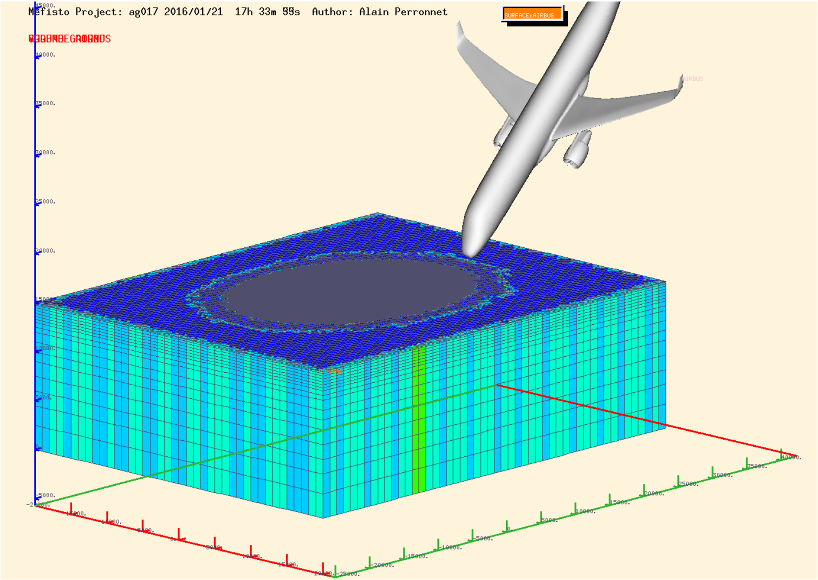
GROUND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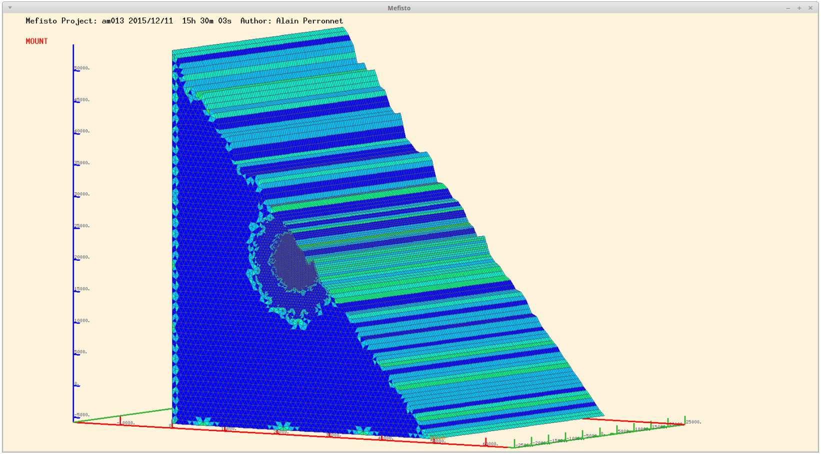
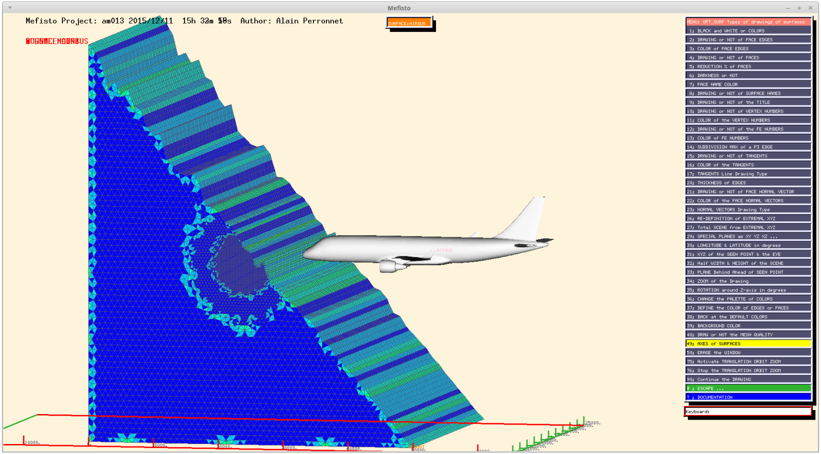
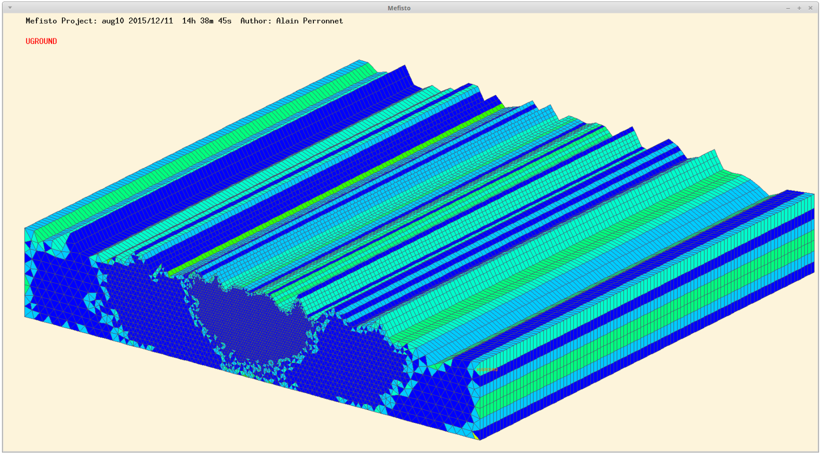
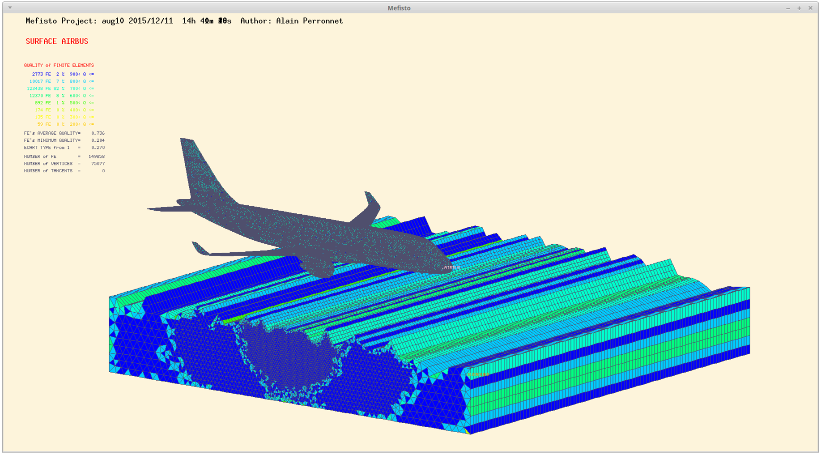
SURFACE:AIRBUS


Mefisto
Mefisto Project: am013 2015/12/11 15h 30m 03s Author: Alain Perronnet
MOUNT


Mefisto
Mefisto Project: am013 2015/12/11 15h 32m 58s Author: Alain Perronnet
SURFACE:AIRBUS
MENU: OPT_SURF Types of drawings of surfaces
1; BLACK and WHITE or COLORS
2; DRAWING or NOT of FACE EDGES
3; COLOR of FACE EDGES
4; DRAWING or NOT of FACES
5; REDUCTION % of FACES
6; DARKNESS or NOT
7; FACE NAME COLOR
8; DRAWING or NOT of SURFACE NAMES
9; DRAWING or NOT of the TITLE
10; DRAWING or NOT of VERTEX NUMBERS
11; COLOR of the VERTEX NUMBERS
12; DRAWING or NOT of the FE NUMBERS
13; COLOR of FE NUMBERS
14; SUBDIVISION MAX of a P3 EDGE
15; DRAWING or NOT of TANGENTS
16; COLOR of the TANGENTS
17; TANGENTS Line Drawing Type
20; THICKNESS of EDGES
21; DRAWING or NOT of FACE NORMAL VECTOR
22; COLOR of the FACE NORMAL VECTORS
23; NORMAL VECTORS Drawing Type
26; RE-DEFINITION of EXTREMAL XYZ
27; Total SCENE from EXTREMAL XYZ
29; SPECIAL PLANES as XY YZ XZ ...
30; LONGITUDE & LATITUDE in degrees
31; XYZ of the SEEN POINT & the EYE
32; Half WIDTH & HEIGHT of the SCENE
33; PLANE Behind Ahead of SEEN POINT
34; ZOOM of the Drawing
35; ROTATION around Z-axis in degrees
36; CHANGE the PALETTE of COLORS
37; DEFINE the COLOR of EDGES or FACES
38; BACK at the DEFAULT COLORS
39; BACKGROUND COLOR
40; DRAW or NOT the MESH QUALITY
49; AXES of SURFACES
50; ERASE the WINDOW
75; Activate TRANSLATION ORBIT ZOOM
76; Stop the TRANSLATION ORBIT ZOOM
90; Continue the DRAWING
@ ; ESCAPE ...
? ; DOCUMENTATION
Keyboard:


Mefisto
Mefisto Project: aug10 2015/12/11 14h 38m 45s Author: Alain Perronnet
UGROUND


Mefisto
Mefisto Project: aug10 2015/12/11
Author: Alain Perronnet
SURFACE AIRBUS
QUALITY of FINITE ELEMENTS
2773 FE 2 % 900< Q <=
10017 FE 7 % 800< Q <=
123438 FE 82 % 700< Q <=
12370 FE 8 % 600< Q <=
892 FE 1 % 500< Q <=
174 FE 0 % 400< Q <=
135 FE 0 % 300< Q <=
59 FE 0 % 200< Q <=
FE's AVERAGE QUALITY= 0.736
FE's MINIMUM QUALITY= 0.204
ECART TYPE from 1 = 0.270
NUMBER of FE = 149858
NUMBER of VERTICES = 75077
NUMBER of TANGENTS = 0

## Construction of FE meshes for the surface of Airbus320

From LS-PrePost software, many quad-triangulations are done with the option Auto Mesher and different sizes of edge lengths. The case with a 100mm of edge size minimum is saved in the file airbusA320.k.

QUALITY of the MESH : SURFACE AIRBUS0

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$$\begin{aligned} \text{NUMBER of VERTICES} &= 75721 \\ \text{NUMBER of FINITE ELEMENTS} &= 76016 \\ \text{AVERAGE QUALITY of FE} &= 0.921 \\ \text{MINIMUM QUALITY of FE} &= 0.485E-03 \;\; \text{for the FE} \;\; 42627 \\ \text{ECART TYPE / 1 of FE} &= 0.134 \\ \text{NUMBER of TRIANGLES} &= 2044 \\ \text{NUMBER of QUADRANGLES} &= 73972 \\ 0.900 = 2 \;\; &\text{QTANGLES} \end{aligned}$$

## Software

(1) LS-DYNA

LS-DYNA is an advanced general-purpose multiphysics simulation software package developed by the Livermore Software Technology Corporation (LSTC). It first originated from the 3D FEA program DYNA3D, developed by Dr. John O. Hallquist at Lawrence Livermore National Laboratory (LLNL) in 1976. The package's development is being continued to contain more and more possibilities for the calculation of many complex, real world problems, its core-applications lie in highly nonlinear transient dynamic finite element analysis (FEA) using explicit time integration. LS-DYNA is used by the automobile, aerospace, construction, military, manufacturing, and bioengineering industries.

For more details, see

`https://en.wikipedia.org/wiki/LS-DYNA`

(2) ANSYS Explicit Dynamics

ANSYS Explic Dynamics, a software product of ANSYS, Inc., aims to simulate and study impacts or short-duration high-pressure loadings so that the designs of products' survivals can be facilitated. Advanced FEA tools are developed in order to accurately predict and understand the effect of design considerations on product response to severe loadings. (The real physical testing of complex impact phenomena is too expensive or even impossible.)

For more details, see

`http://www.ansys.com/Products/Simulation+Technology/Structural+Analysis/Explicit+Dynamics`

# Selection of models and materials for LS-DYNA applications



***MAT_PLASTIC_KINEMATIC**

This is Material Type 3. This model is suited to model isotropic and kinematic hardening plasticity with the option of including rate effects. It is a very cost effective model and is available for beam (Hughes-Liu and Truss), shell, and solid elements.

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | RO | E | PR | SIGY | ETAN | BETA | |
| Type | A8 | F | F | F | F | F | F | |
| Default | none | none | none | none | none | 0.0 | 0.0 | |

| Card 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | SRC | SRP | FS | VP | | | | |
| Type | F | F | F | F | | | | |
| Default | not used | not used | not used | 0.0 | | | | |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material identification. A unique number or label not exceeding 8 characters must be specified. |
| RO | Mass density. |
| E | Young's modulus. |
| PR | Poisson's ratio. |
| SIGY | Yield stress. |
| ETAN | Tangent modulus, see Figure 3.1. |
| BETA | Hardening parameter, $0 < \beta' < 1$. See comments below. |
| SRC | Strain rate parameter, C, for Cowper Symonds strain rate model, see below. If zero, rate effects are not considered. |

| VARIABLE | DESCRIPTION |
|---|---|
| SRP | Strain rate parameter, P, for Cowper Symonds strain rate model, see below. If zero, rate effects are not considered. |
| FS | Failure strain for eroding elements. |
| VP | Formulation for rate effects:<br>EQ.0.0: Scale yield stress (default),<br>EQ.1.0: Viscoplastic formulation |

**Remarks**:

Strain rate is accounted for using the Cowper and Symonds model which scales the yield stress with the factor

$$1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}$$

where $\dot{\varepsilon}$ is the strain rate. A fully viscoplastic formulation is optional which incorporates the Cowper and Symonds formulation within the yield surface. An additional cost is incurred but the improvement allows for dramatic results. To ignore strain rate effects set both SRC and SRP to zero.

Kinematic, isotropic, or a combination of kinematic and isotropic hardening may be specified by varying $\beta'$ between 0 and 1. For $\beta'$ equal to 0 and 1, respectively, kinematic and isotropic hardening are obtained as shown in Figure 3.1. For isotropic hardening, $\beta' = 1$, Material Model 12, *MAT_ISOTROPIC_ELASTIC_PLASTIC, requires less storage and is more efficient. Whenever possible, Material 12 is recommended for solid elements, but for shell elements it is less accurate and thus Material 12 is not recommended in this case.

***MAT_ADD_EROSION**

Many of the constitutive models in LS-DYNA do not allow failure and erosion. The ADD_EROSION option provides a way of including failure in these models although the option can also be applied to constitutive models with other failure/erosion criterion. Each of the criterion defined here are applied independently, and once any one of them is satisfied, the element is deleted from the calculation. NOTE: THIS OPTION CURRENTLY APPLIES TO THE 2D CONTINUUM AND 3D SOLID ELEMENTS WITH ONE POINT INTEGRATION.

**Define the following two cards:**

| Card 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MID | EXCL | MXPRES | MNEPS | | | | |
| Type | A8 | F | F | F | | | | |
| Default | none | none | none | none | | | | |

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | MNPRES | SIGP1 | SIGVM | MXEPS | EPSSH | SIGTH | IMPULSE | FAILTM |
| Type | F | F | F | F | F | F | F | F |
| Default | none | none | none | none | none | none | none | none |

| VARIABLE | DESCRIPTION |
|---|---|
| MID | Material identification for which this erosion definition applies. A unique number or label not exceeding 8 characters must be specified. |
| EXCL | The exclusion number. When any of the failure constants are set to the exclusion number, the associated failure criteria calculations are bypassed (which reduces the cost of the failure model). For example, to prevent a material from going into tension, the user should specify an unusual value for the exclusion number, e.g., 1234., set $P_{min}$ to 0.0 and all the remaining constants to 1234. The default value is 0.0, which eliminates all criteria from consideration that have their constants set to 0.0 or left blank in the input file. |

| VARIABLE | DESCRIPTION |
|---|---|
| MXPRES | Maximum pressure at failure, $P_{max}$. If the value is exactly zero, it is automatically excluded to maintain compatibility with old input files. |
| MNEPS | Minimum principal strain at failure, $\varepsilon_{min}$. If the value is exactly zero, it is automatically excluded to maintain compatibility with old input files. |
| MNPRES | Minimum pressure at failure, $P_{min}$. |
| SIGP1 | Principal stress at failure, $\sigma_{max}$. |
| SIGVM | Equivalent stress at failure, $\bar{\sigma}_{max}$. |
| MXEPS | Maximum principal strain at failure, $\varepsilon_{max}$. |
| EPSSH | Shear strain at failure, $\gamma_{max}$. |
| SIGTH | Threshold stress, $\sigma_0$. |
| IMPULSE | Stress impulse for failure, $K_f$. |
| FAILTM | Failure time. When the problem time exceeds the failure time, the material is removed. |

The criteria for failure besides failure time are:

1. $P \geq P_{max}$, where $P$ is the pressure (positive in compression), and $P_{max}$ is the maximum pressure at failure.
2. $\varepsilon_3 \leq \varepsilon_{min}$, where $\varepsilon_3$ is the minimum principal strain, and $\varepsilon_{min}$ is the minimum principal strain at failure.
3. $P \leq P_{min}$, where $P$ is the pressure (positive in compression), and $P_{min}$ is the minimum pressure at failure.
4. $\sigma_1 \geq \sigma_{max}$, where $\sigma_1$ is the maximum principal stress, and $\sigma_{max}$ is the maximum principal stress at failure.
5. $\sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}} \geq \bar{\sigma}_{max}$, where $\sigma'_{ij}$ are the deviatoric stress components, and $\bar{\sigma}_{max}$ is the equivalent stress at failure.
6. $\varepsilon_1 \geq \varepsilon_{max}$, where $\varepsilon_1$ is the maximum principal strain, and $\varepsilon_{max}$ is the maximum principal strain at failure.

7. $\gamma_1 \ge \gamma_{max}$, where $\gamma_1$ is the maximum shear strain = $(\varepsilon_1 - \varepsilon_3)/2$, and $\gamma_{max}$ is the shear strain at failure.

8. The Tuler-Butcher criterion,

$$\int_0^t [\max(0, \sigma_1 - \sigma_0)]^2 dt \ge K_f,$$

where $\sigma_1$ is the maximum principal stress, $\sigma_0$ is a specified threshold stress, $\sigma_1 \ge \sigma_0 \ge 0$, and $K_f$ is the stress impulse for failure. Stress values below the threshold value are too low to cause fracture even for very long duration loadings.

These failure models apply only to solid elements with one point integration in 2 and 3 dimensions.

## System of dynamic PDEs to model impact and damage

Remark: The material here is quoted directly from Wikipedia.

### Flow stress models

The quantity $f(\sigma, q)$ represents the evolution of the yield surface. The yield function $f$ is often expressed as an equation consisting of some invariant of stress and a model for the yield stress (or plastic flow stress). An example is von Mises or $J_2$ plasticity. In those situations the plastic strain rate is calculated in the same manner as in rate-independent plasticity. In other situations, the yield stress model provides a direct means of computing the plastic strain rate.

Numerous empirical and semi-empirical flow stress models are used the computational plasticity. The following temperature and strain-rate dependent models provide a sampling of the models in current use:

1. the Johnson-Cook model
2. the Steinberg-Cochran-Guinan-Lund model
3. the Zerilli-Armstrong model
4. the Mechanical threshold stress model
5. the Preston-Tonks-Wallace model

## Johnson-Cook flow stress mode

The Johnson-Cook (JC) model is purely empirical and gives the following relation for the flow stress $\sigma_y$

$$\sigma_y(\varepsilon_p, \dot{\varepsilon_p}, T) = [A + B(\varepsilon_p)^n]\,[1 + C\ln(\dot{\varepsilon_p}^*)]\,[1 - (T^*)^m] \qquad (1)$$

where $\varepsilon_p$ is the equivalent plastic strain, $\dot{\varepsilon_p}$ is the plastic strain-rate, and A,B,C,n,m are material constants.
The normalized strain-rate and temperature in equation (1) are defined as

$$\dot{\varepsilon_p}^* := \frac{\dot{\varepsilon_p}}{\dot{\varepsilon_{p0}}} \qquad \text{and} \qquad T^* := \frac{(T - T_0)}{(T_m - T_0)}$$

where $\dot{\varepsilon_{p0}}$ is the effective plastic strain-rate of the quasi-static test used to determine the yield and hardening parameters A,B and n. This is not as it is often thought just a parameter to make $\dot{\varepsilon_p}^*$ non-dimensional. $T_0$ is a reference temperature, and $T_m$ is a reference melt temperature. For conditions where $T^* < 0$, we assume that $m = 1$.

## Rheological models of viscoplasticity

### Perfectly viscoplastic solid (Norton-Hoff model)

This model is for metals and alloys at temperatures higher than one third of their absolute melting point (in kelvins) and polymers/asphalt at elevated temperature. In a perfectly viscoplastic solid, also called the Norton-Hoff model of viscoplasticity, the stress (as for viscous fluids) is a function of the rate of permanent strain. he hypothesis of partitioning the strains by decoupling the elastic and plastic parts is still applicable where the strains are small, i.e.,

$$\varepsilon = \varepsilon_{\rm e} + \varepsilon_{\rm vp} \ , \tag{2}$$

where $\varepsilon_{\rm e}$ is the elastic strain and $\varepsilon_{\rm vp}$ is the viscoplastic strain.

The effect of elasticity is neglected in the model, i.e., $\varepsilon_e = 0$ and hence there is no initial yield stress, i.e., $\sigma_y = 0$. The viscous dashpot has a response given by

$$\boldsymbol{\sigma} = \eta\,\dot{\varepsilon}_{\mathrm{vp}} \implies \dot{\varepsilon}_{\mathrm{vp}} = \frac{\boldsymbol{\sigma}}{\eta}\,, \tag{3}$$

where $\boldsymbol{\sigma}$ is stress, $\eta$ is the viscosity of the dashpot, and $\dot{\varepsilon}_{\mathrm{vp}}$ is the viscoplastic strain rate. In the Norton-Hoff model the viscosity $\eta$ is a nonlinear function of the applied stress and is given by

$$\eta = \lambda\left[\frac{\lambda}{||\boldsymbol{\sigma}||}\right]^{N-1}\,. \tag{4}$$

where N is a fitting parameter, Îż is the kinematic viscosity of the material and $||\boldsymbol{\sigma}|| = \sqrt{\boldsymbol{\sigma} : \boldsymbol{\sigma}} = \sqrt{\sigma_{ij}\sigma_{ij}}$. Then the viscoplastic strain rate is given by the relation

$$\dot{\varepsilon}_{\mathrm{vp}} = \frac{\boldsymbol{\sigma}}{\lambda}\left[\frac{||\boldsymbol{\sigma}||}{\lambda}\right]^{N-1}\,. \tag{5}$$

In one-dimensional form, the Norton-Hoff model can be expressed as

$$\sigma = \lambda \left(\dot{\varepsilon}_{\rm vp}\right)^{1/N} , \tag{6}$$

When $N = 1.0$ the solid is viscoelastic.

If we assume that plastic flow is isochoric (volume preserving), then the above relation can be expressed in the more familiar form

$$\boldsymbol{s} = 2K \left(\sqrt{3}\dot{\varepsilon}_{\rm eq}\right)^{m-1} \dot{\boldsymbol{\varepsilon}}_{\rm vp} , \tag{7}$$

where $\boldsymbol{s}$ is the deviatoric stress tensor, $\dot{\varepsilon}_{\rm eq}$ is the von Mises equivalent strain rate, and $K$, $m$ are material parameters. The equivalent strain rate is defined as

$$\dot{\bar{\epsilon}} = \sqrt{\left( \frac{2}{3} \dot{\bar{\bar{\epsilon}}} : \dot{\bar{\bar{\epsilon}}} \right)} . \tag{8}$$

**Supercomputer simulations of air crash in mountains of an airliner**

Our numerical simulations consist of the following cases:

(Case I) Head-in first horizontally into a mountain
(Case II) Head-scraping on a horizontal plateau
(Case III) Pancake drop
(Case IV) -45°-pitch nosedive

All the computations were carried out on the Texas A & M University ADA Supercomputer using 20 processors. The execution time took about 48 96 hours.

# LS-DYNA failed cases:

Case I:

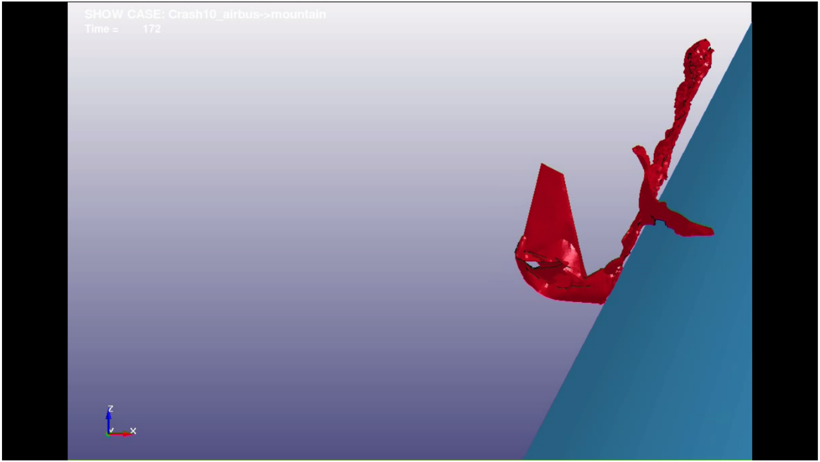



**Figure 7:** This simulation models the mountain as granite material with little erosion. The impact site does not show any cratering. The simulation did not use proper deformable properties (density, elastic modulus, yield stress) of aluminum for the fuselage of the airliner.

# Case II:


**Figure 8:** This case shows complete penetration into the mountain. The material of the mountain is modeled as "MAT_PIECEWISE_LINEAR_PLASTICITY" (instead of as AM033 "MAT_PLASTIC_KINEMATIC"). It does not have the proper yield stress.

# Case III:

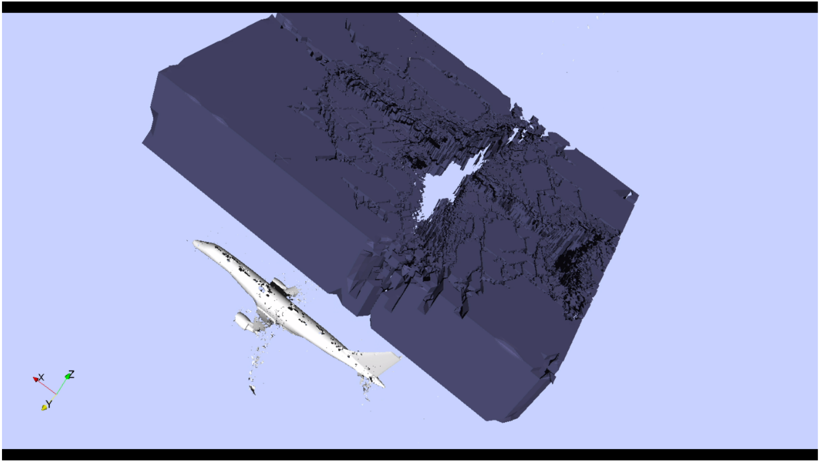



**Figure 9:** The wall (i.e., mountain) lacks proper thickness. The erosion of the mountain is not properly chosen, either.

## Case IV:

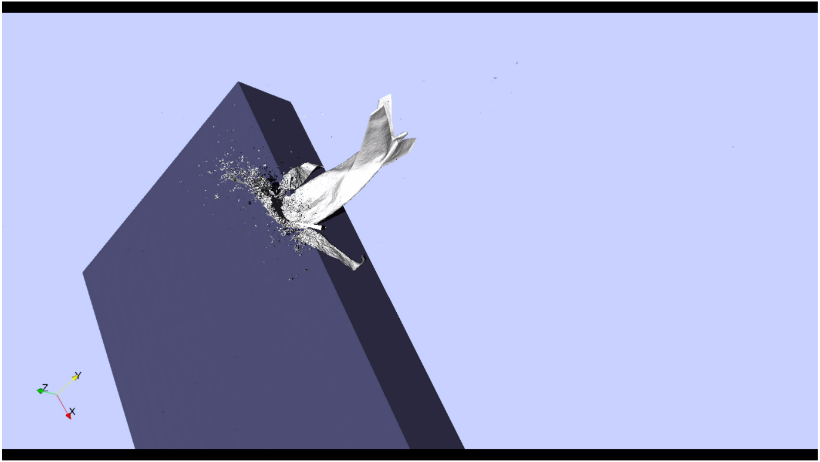



**Figure 10:** This video does show strong pulverization effects, with the additional useful damaging effect of collision on the edge of the mountain. Nevertheless, erosion of the ground (i.e., mountain) was not chosen properly and, thus, the ground shows no sign of cave-in.

# Case V:

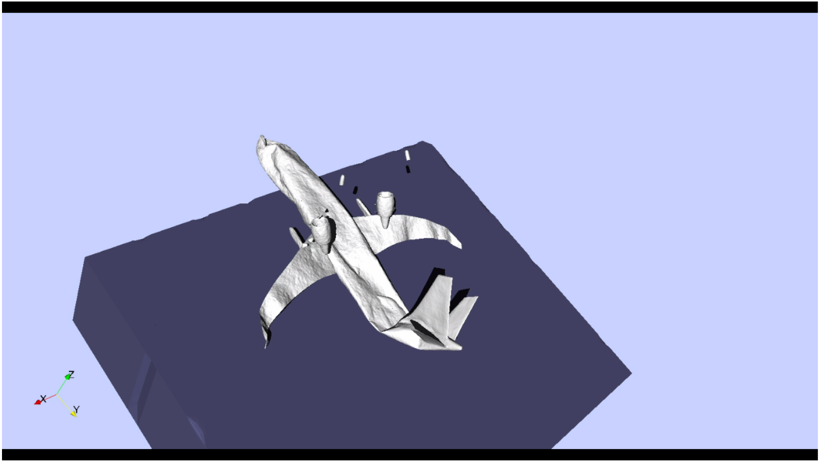
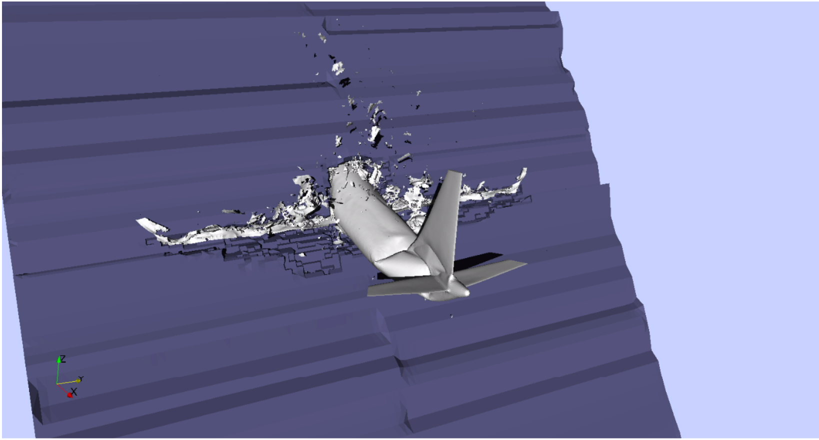
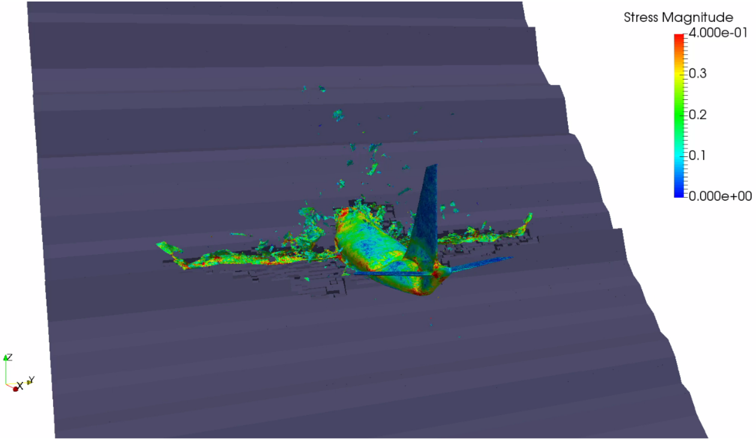



**Figure 11:** The airliner behaves as an elastic body, bouncing upward after impact, which is totally unrealistic. The video animation can be viewed at `http://gucong.github.io/crash/failed`.

## LS-DYNA successful cases:
Case I



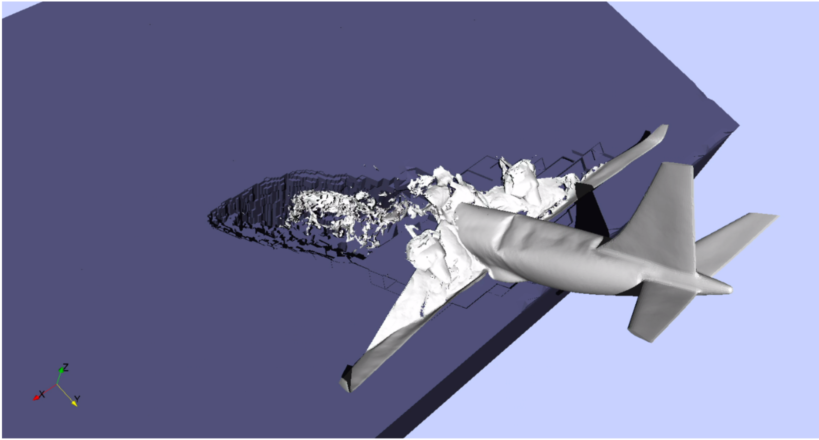

**(a)** Head-in first horizontally into a mountain



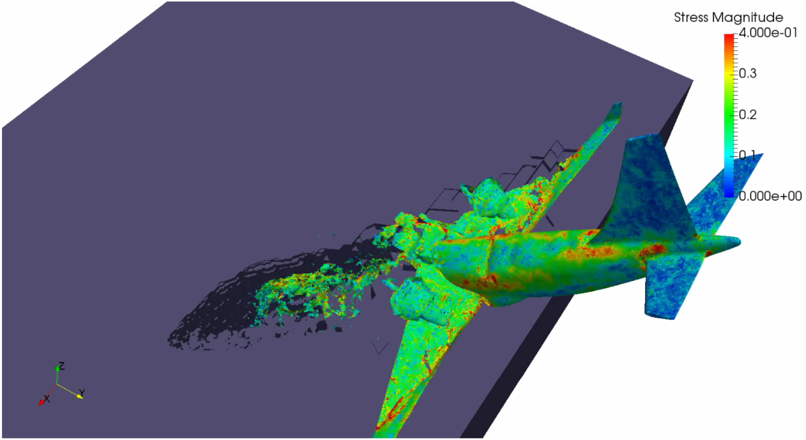

**(b)** stress distribution

**Figure 12:** The video animations can be viewed at
`https://goo.gl/90fZoK`
`https://goo.gl/bj0n4M` (slow motion)
`https://goo.gl/PkeMdX` (with stress)
`https://goo.gl/b5TUiG` (from inside of cabin).

# Case II



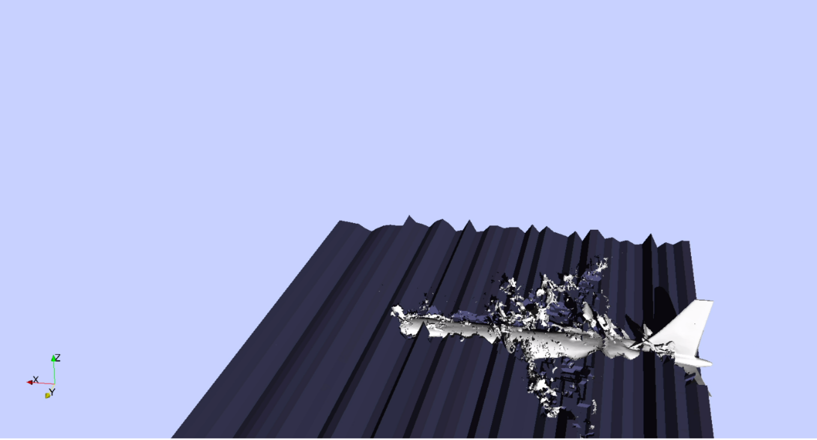

**(a)** Head-scraping on a horizontal plateau



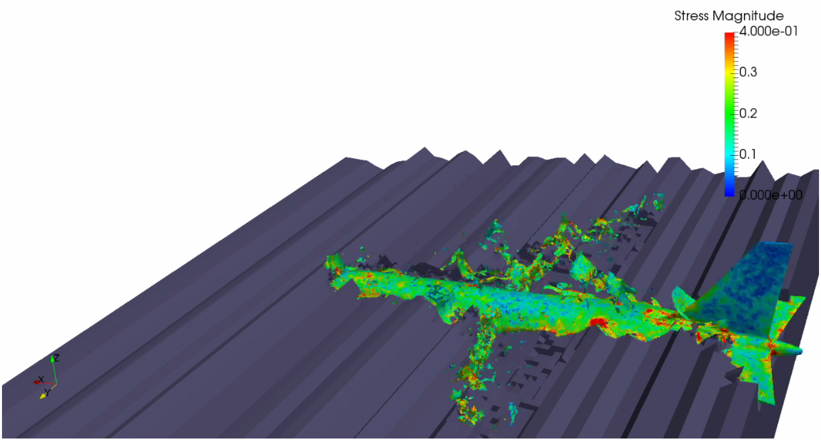

**(b)** stress distribution

**Figure 13:** The video animations can be viewed at
`https://goo.gl/gnxQKK`
`https://goo.gl/jflXTG` (slow motion)
`https://goo.gl/rwenF0` (with stress).

# Case III



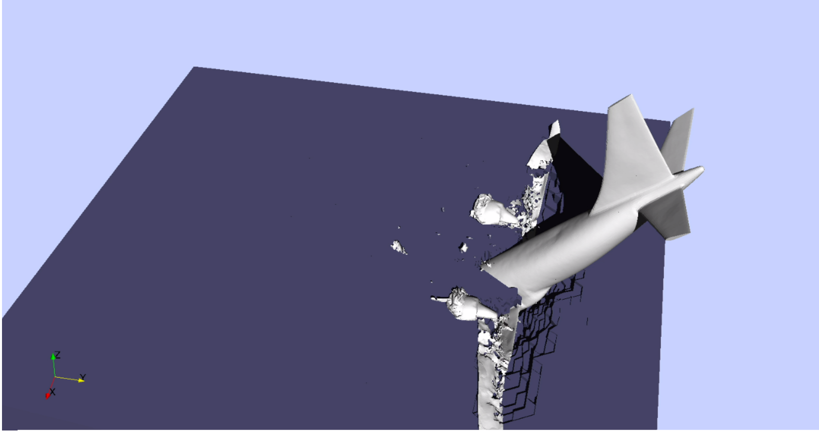

**(a)** Pancake drop



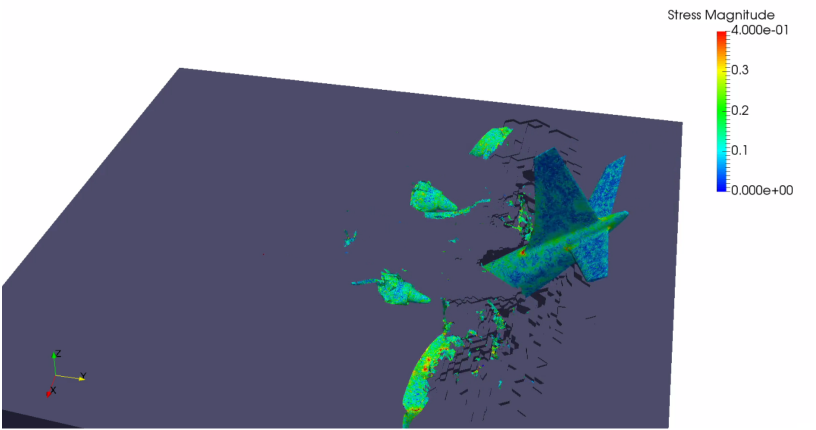

**(b)** stress distribution

**Figure 14:** The video animations can be viewed at
`https://goo.gl/hdjBNz`
`https://goo.gl/IDyfx5` (slow motion)
`https://goo.gl/glEYYm` (with stress).

# Case IV




**(a)** -45°-pitch nosedive




**(b)** stress distribution

**Figure 15:** The video animations can be viewed at
`https://goo.gl/AVEEJw`
`https://goo.gl/p0ZU0x` (slow motion)
`https://goo.gl/iXel5O` (with stress).

# Computer simulations by ANSYS Explicit Dynamics

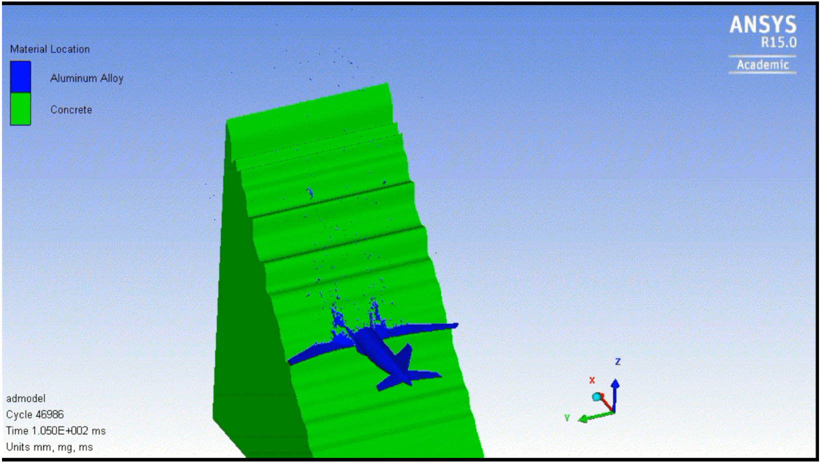



**Figure 16:** The video animation can be viewed at `https://www.dropbox.com/s/8zhozc1fqlbupmb/admodel.avi?dl=0`.

# Comparison with a “Hollywood-style” video animation (a “pancake drop”)


**Figure 17:** `https://www.youtube.com/watch?v=7IcNnUa5DQI`

## Concluding Remarks

(i) Crashes of airplanes, cars, ships, etc. are all deeply tragic events. Their research has been ongoing as an active field of impact engineering and applied physics.

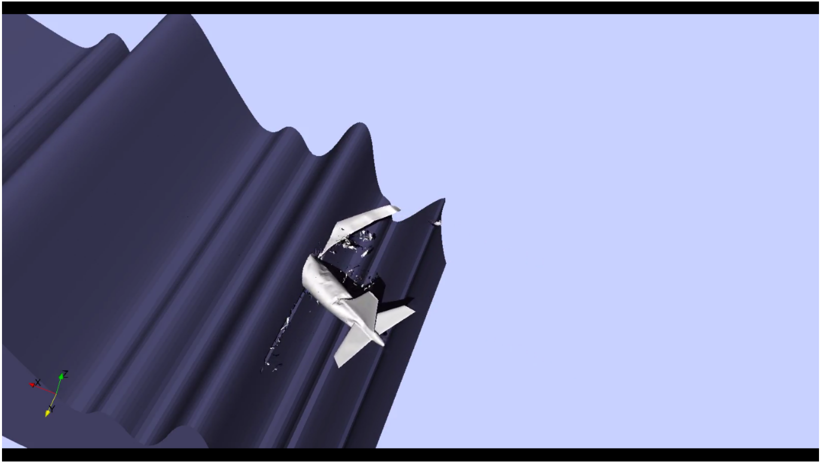
(ii) Through supercomputer simulations by using proven softwares, one can achieve a much better understanding of crash physical mechanisms to improve survivals and crashworthiness.

(iii) For the crash of the Germanwings Flight 9525, our computer simulations and visualizations support the theory that the airlines crashed into the mountain in a "pancake drop" way.

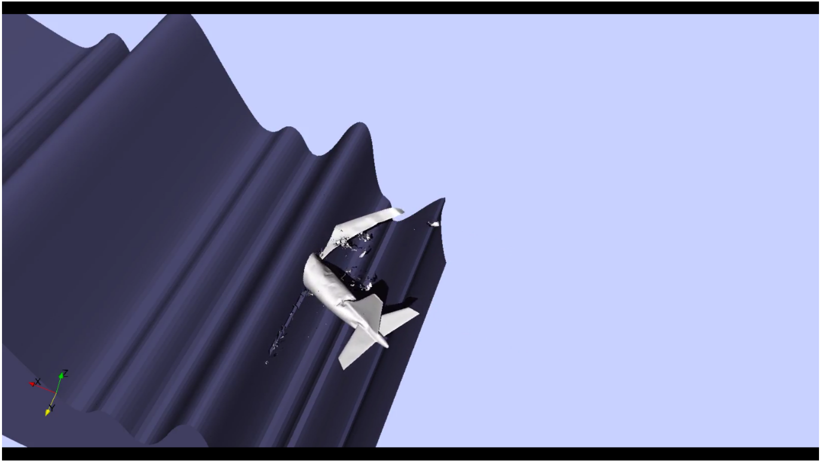
## Pulverizing crash simulations based on the recovered flight recorder data

$$v_x = 194.2 \ m/sec$$
$$v_y = 0 \ m/sec$$
$$v_z = -18 \ m/sec$$

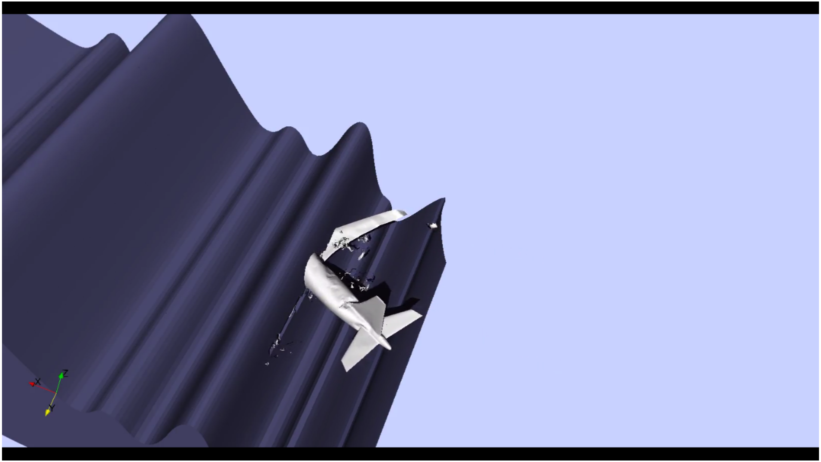
(1) **Change of** $V_z$



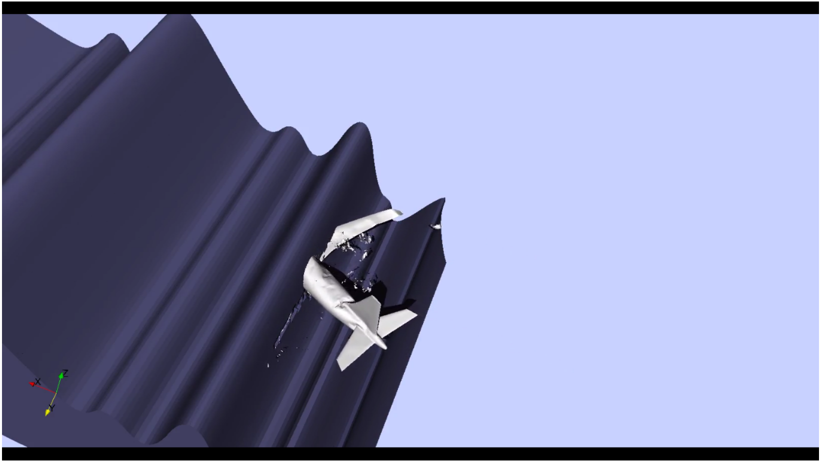

**(a)** $V_z = 14$ m/sec



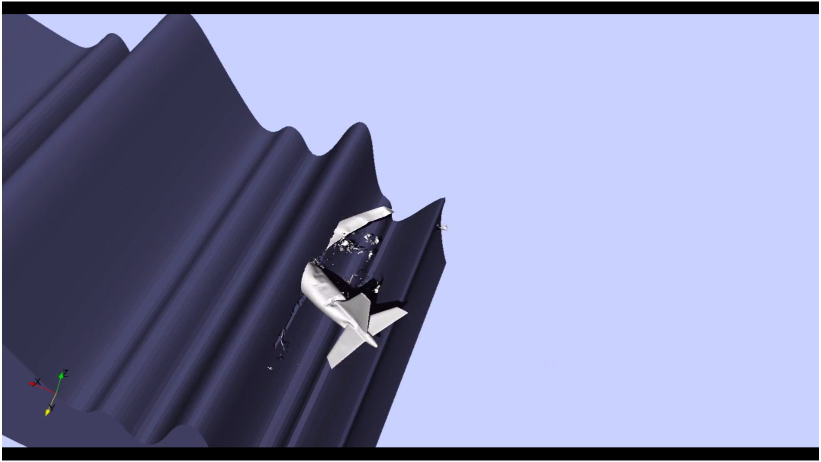

**(b)** $V_z = 16$ m/sec



**(c)** $V_z = 18$ m/sec



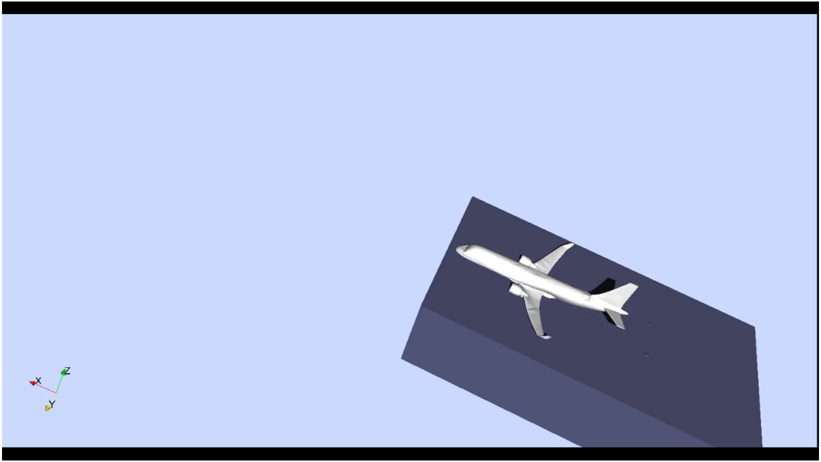

**(d)** $V_z = 20$ m/sec



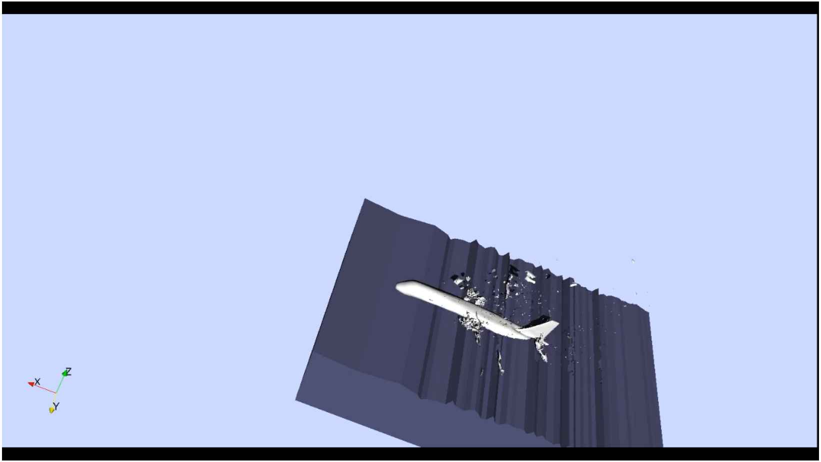

**(e)** $V_z = 22$ m/sec

**Figure 18:** The video animations can be viewed at http://gucong.org/crash/AUG30BR14/, http://gucong.org/crash/AUG30BR16/, http://gucong.org/crash/AUG30BR18/, http://gucong.org/crash/AUG30BR20/, http://gucong.org/crash/AUG30BR22/.

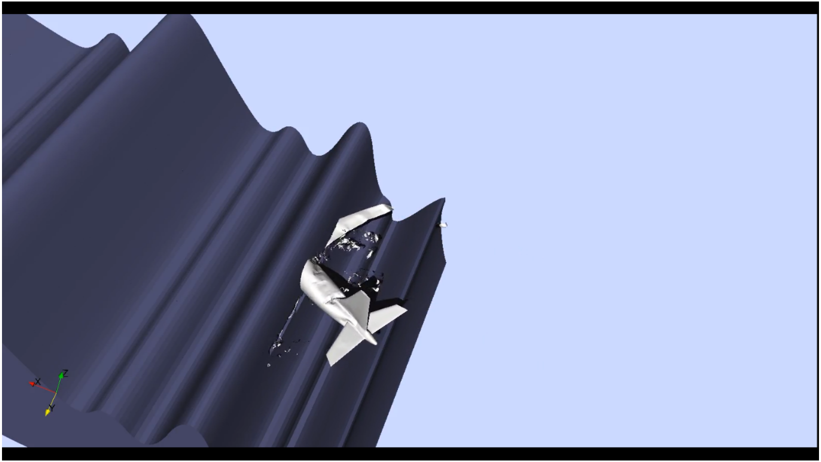
## (2) **Terrain dependence**




**(a)** even ground



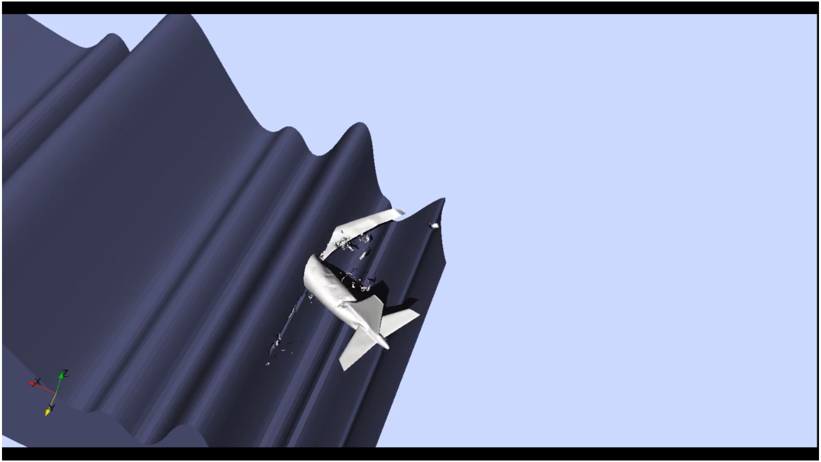

**(b)** uneven ground



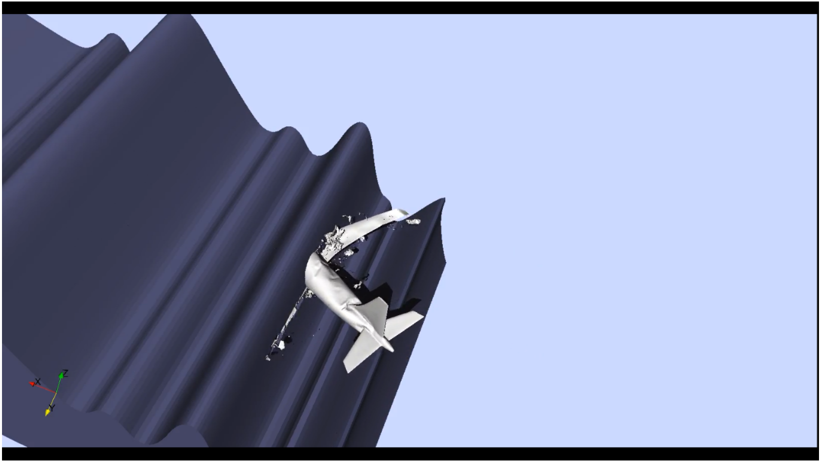

**(c)** ravine

**Figure 19:** The video animations can be viewed at
`http://gucong.org/crash/AUG30BF18/`
`http://gucong.org/crash/AUG30BA18/`
`http://gucong.org/crash/AUG30BR18/`.

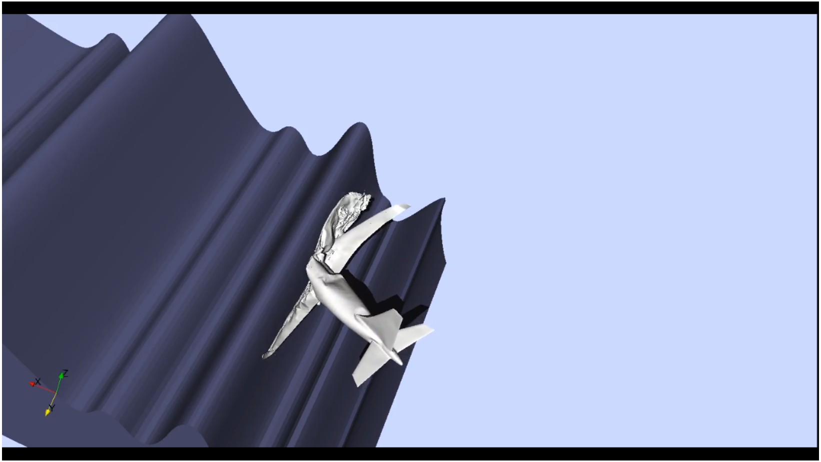
## (3) **Thickness**



**(a)** 3 mm




**(b)** 4.5 mm




**(c)** 9 mm

**Figure 20:** The video animation can be viewed at
`http://gucong.org/crash/AUG30BR18/`
`http://gucong.org/crash/AUG30B18/`
`http://gucong.org/crash/AUG30BH18/`.