Drop test

April 15, 2019

1 Model

The model consists of 9 parts, fuselage skin, ribs, stringers, floor, struts, seats, passengers, seatbelts, and a pad (see Figure 1). General information about the model is collected in Box 1.

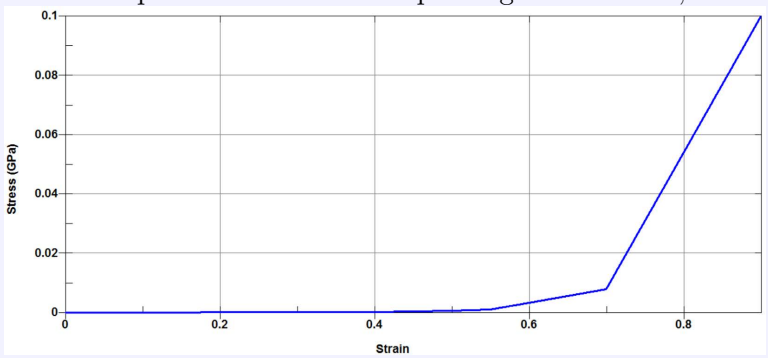
Box 1. Mathematical model for the fuselage drop test

Software
LS-DYNA. Version: R10.1.0 (R10.123355), MPP (Message Passing Parallel), single-precision arithmetic. Sometimes we use a double-precision version too.

Spatial domain
Three-dimensional space.

Governing equations
Mechanical equations of motion, including Newton's equations.

Empirical relations Hookes law of elasticity, $\sigma = E\epsilon$, for the aluminum, where ϵ is the strain, σ is stress, and E is Young's modulus. Nonlinear stress vs. strain relationship for the materials of passengers and seats, see a figure below.



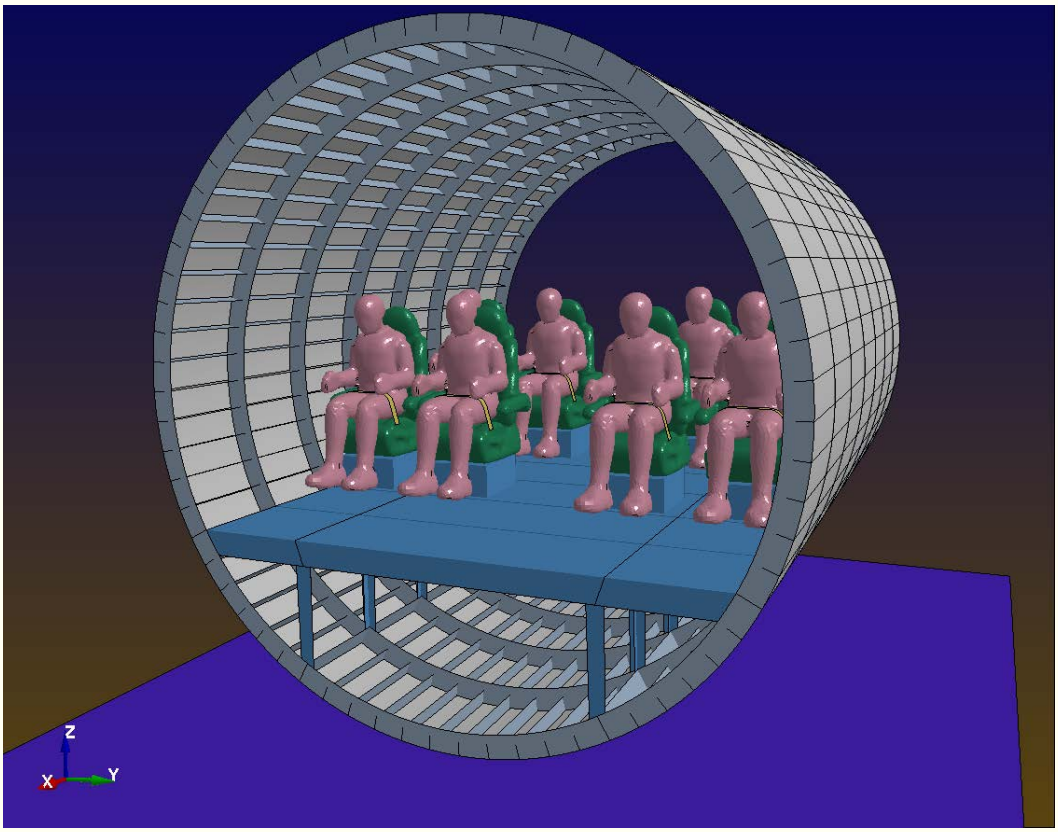


Figure 1. Parts of the fuselage section: fuselage skin (white), ribs and stringers (light blue), floor and struts (blue), seats (green), passengers (pink), seatbelts (yellow), and a pad (violet).

Mathematical methods for discretization
Finite element method for shell and solid body.

Contact conditions
Interactions are modelled by `*CONTACT_ERODING_SINGLE_SURFACE` [LS-DYNA R10.0 Keyword Manual Vol. I, p. 11-51] with static coefficient of friction (FS), dynamic coefficient of friction (FD), exponentional decay coefficient (DC), coefficient for viscous friction (VC) and viscous damping coefficient (VDC) all equal to 0.2.

Fracture criteria
The parameter "Failure strain for eroding elements" (FS) in the card `*MAT_PLASTIC_KINEMATIC` was set to 0.03. In the card `*MAT_ADD_EROSION`, the parameter "Volumetric strain at falure" (VOLEPS) is set to 0.1, and "Share strain at failure" (EPSSH) is set to 0.1.

2 Fuselage skin

Fuselage has cylindrical shape, see Figure 2. Its diameter is 2.88 m, the length 3.36 m. More properties are given in Table 2. Fuselage skin as well as other parts except passengers has shell type. The material of the skin as well as the material of ribs, stringers, floor, struts and seats is aluminum. Properties of aluminum are given in Table 2.

Table 1. Properties of fuselage skin.

Property	Value
Radius	$1.44\,m$
Length	$3.36\,m$
Thickness	$1.2\,mm$
Density	$3000\,kg/m^3$
Area	$30.40\,m^2$
Mass	$109.44\,kg$
Number of finite elements	77 616

3 Ribs

Ribs have shape of annulus, see Figure 3. The diameter is 2.88 m, and the width is 0.115 m. More properties are given in Table 3.

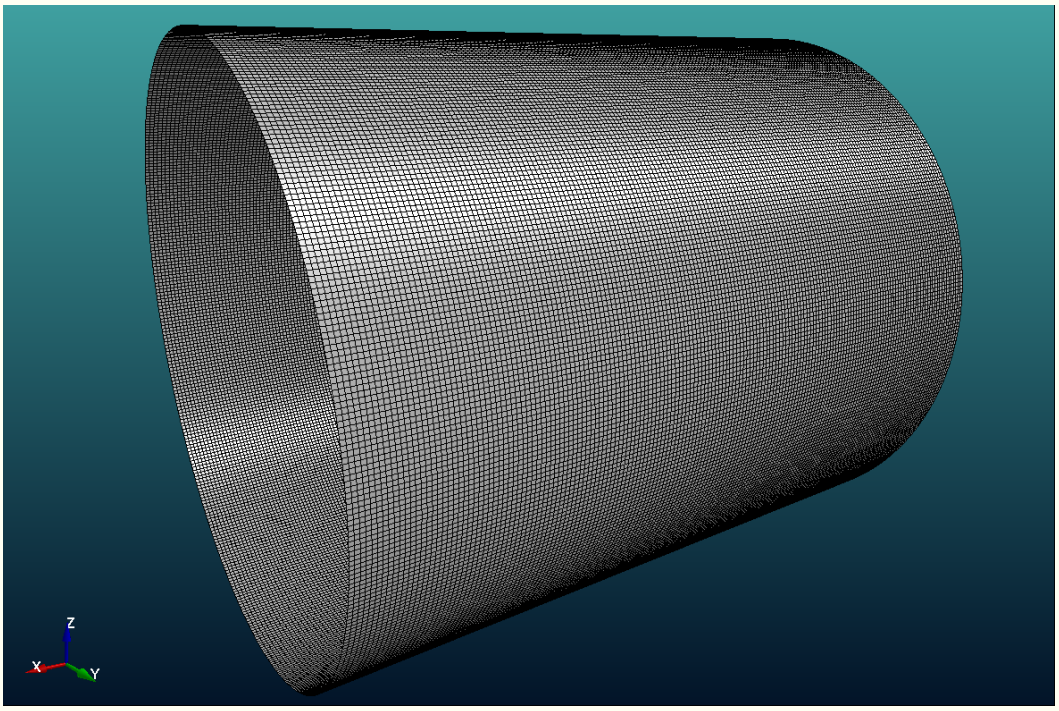


Figure 2. Cylindrical skin of the fuselage section.

Table 2. Properties of aluminum, as defined in the card `*MAT_PLASTIC_KINEMATIC`. Units are based on $mm/ms/kg$.

Property	Variable	Value
Title	TITLE	Aluminium Alloy 7075-T6
Mass density	RO	$3.0 \cdot 10^{-6}$
Young's modulus	E	70.0
Poisson's ratio	PR	0.35
Yield stress	SIGY	0.47
Tangent modulus	ETAN	0.70
Hardening parameter	BETA	0.11

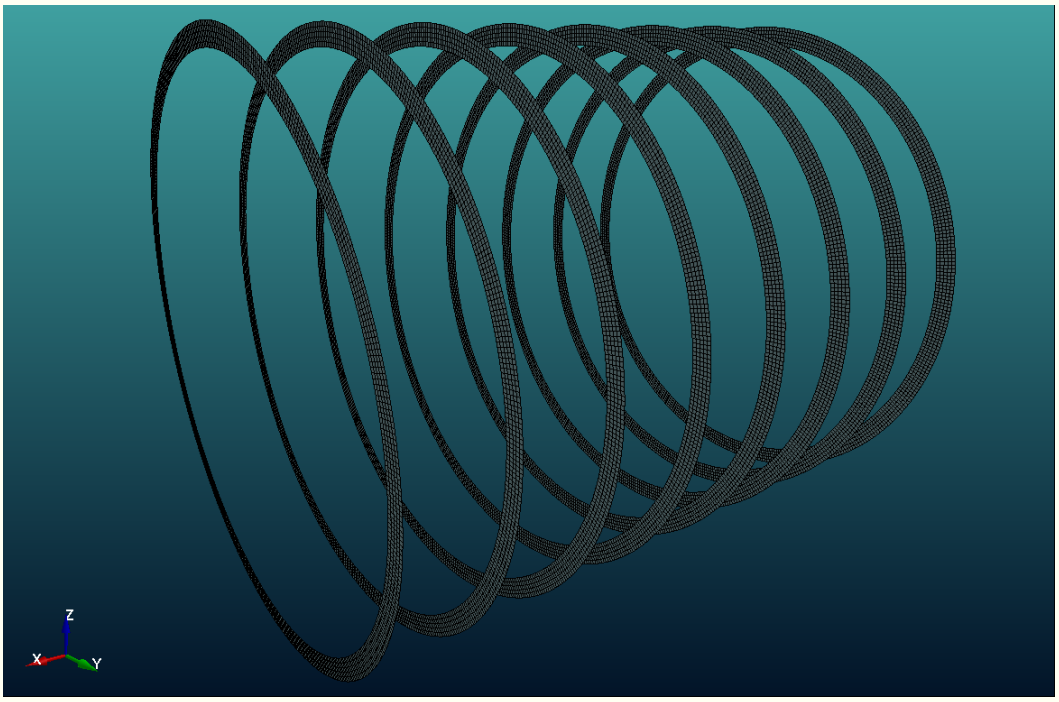


Figure 3. Ribs of the fuselage section designed to improve its stiffness.

Table 3. Properties of ribs.

Property	Value
Inner radius	$1.339\,m$
Outer radius	$1.440\,m$
Width	$100.8\,mm$
Thickness	$2.0\,mm$
Density	$3000\,kg/m^3$
Number of ribs	8
Area	$7.04\,m^2$
Mass	$42.24\,kg$
Number of finite elements	18 480

4 Stringers

Stringers have a rectangular shape. Their length is 3.36 m. There are 62 stringers of width 57.6 mm and 4 wider stringers of width 115 mm that are connected with a floor and struts, see Figure 4. More properties are given in Table 4.

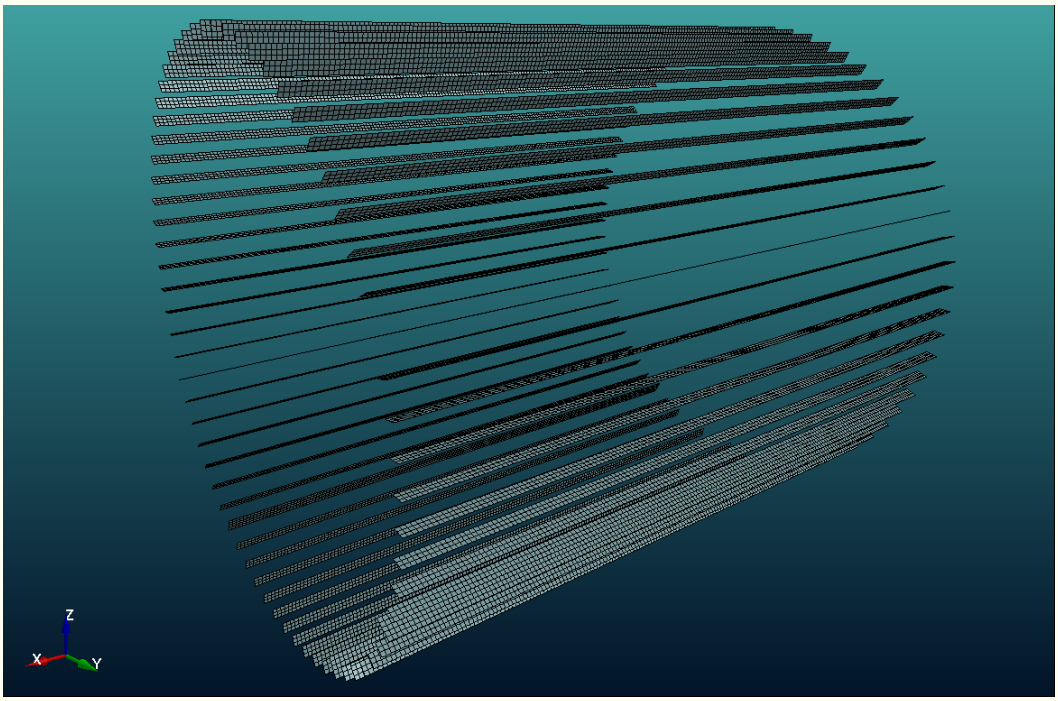


Figure 4. Stringers of the fuselage section designed to gain additional stiffness of the fuselage.

5 Floor

The floor has approximately shape of a rectangle 2.63×3.36 m. It is supported by 8 almost rectangular beams of size approximately 2.44×0.11 m, see Figure 5. More properties are given in Table 5.

6 Struts

Struts are the beam-like supporting elements that prevent sagging of the floor under weight of passengers. Their length is 0.44 m. There are 12 approximately X-shaped struts of size 80×80 mm and 4 T-shaped struts 40×80 mm at the front and the rear of the section, see Figure 6. More properties of struts are given in Table 6.

Table 4. Properties of stringers.

Property	Value
Length	$3.36\,m$
Width	$60.48\,mm$ or $100.8\,mm$
Thickness	$2.0\,mm$
Density	$3000\,kg/m^3$
Number of stringers	66
Number of stringers of width $60.48\,mm$	62
Number of stringers of width $100.8\,mm$	4
Stringer No. corresponding to $phi = 0$	17
Wider stringers connected to floor	38 and 61
Wider stringers connected to struts	44 and 55
Area	$13.95\,m^2$
Mass	$83.72\,kg$
Number of finite elements	34 608

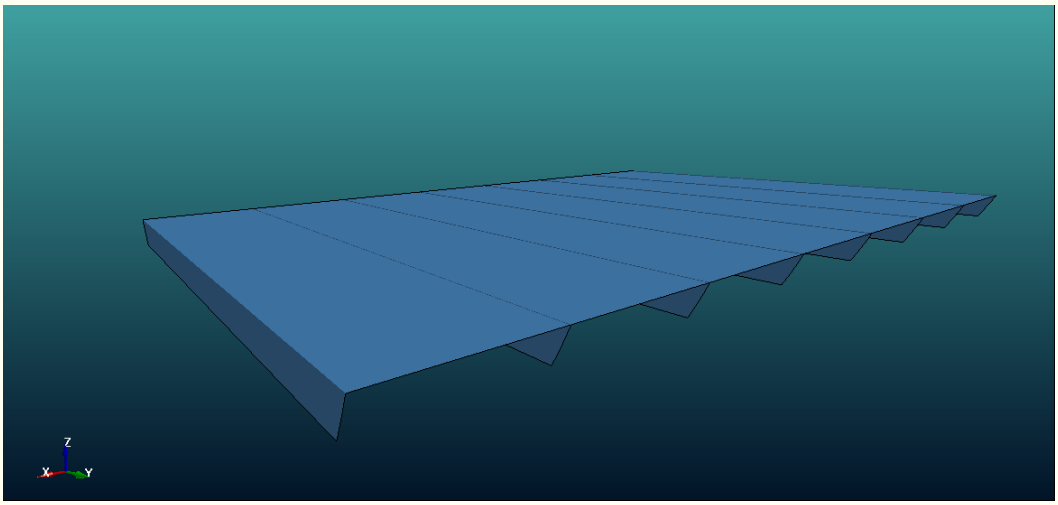


Figure 5. Floor with supporting beams.

Table 5. Properties of floor.

Property	Value
Length	$3.36\,m$
Width	$2.63\,m$
Thickness	$3.0\,mm$
Density	$3000\,kg/m^3$
Number of support beams	8
Hight of support beam	$110.4\,mm$
Length of support beam on mid-level	$2.44\,m$
Area	$10.04\,m^2$
Mass	$90.40\,kg$
Number of finite elements	27 328

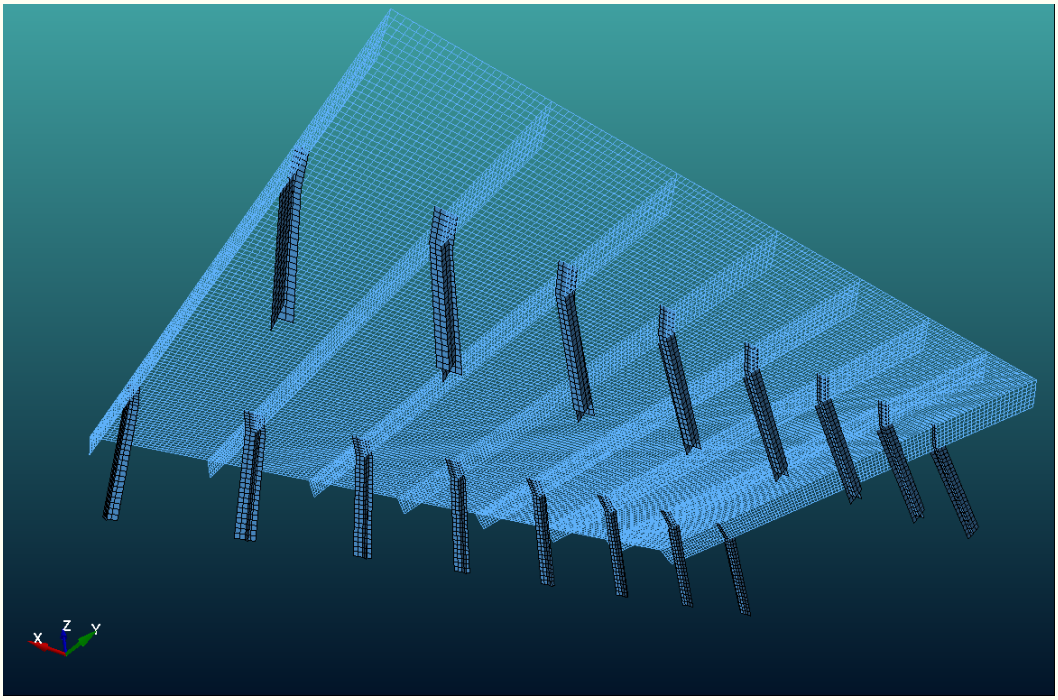


Figure 6. Struts supporting the floor.

Table 6. Properties of struts.

Property	Value
Half-width	$36.9\,mm$
Hight	$435.8\,mm$
Thickness	$3.0\,mm$
Density	$3000\,kg/m^3$
Distance between struts in pairs	$1.34\,m$
Number of struts	16
Number of X-shaped struts	12
Number of T-shaped struts	4
Area	$1.10\,m^2$
Mass	$9.88\,kg$
Number of finite elements	3 032

7 Seats

The seats consist of rectangular standing holders attached to the floor and rectangular seat cushions attached to the holder approximately in the middle. The seats are arranged in two rows of 4 seats, 8 seats in total, see Figure 7. More properties of seats are given in Table 7.

8 Seatbelts

The seatbelts have rectangular shapes and they are attached to the seats as shown on Figure 8. More properties of seatbelts are given in Table 8. Properties of material of seatbelts are given in Table 8.

9 Passengers

The passengers are modelled by human figures in sitting position, 8 in total, see Figure 7. Passengers have solid type. Number of finite elemets is 108 312 and the total mass is $1007.23\,kg$.

Properties of material of passengers are given in Table 9.

10 Pad

The pad on the ground is considered as a rectangle $3.60 \times 4.22\,m$, see Figure 11. The initial

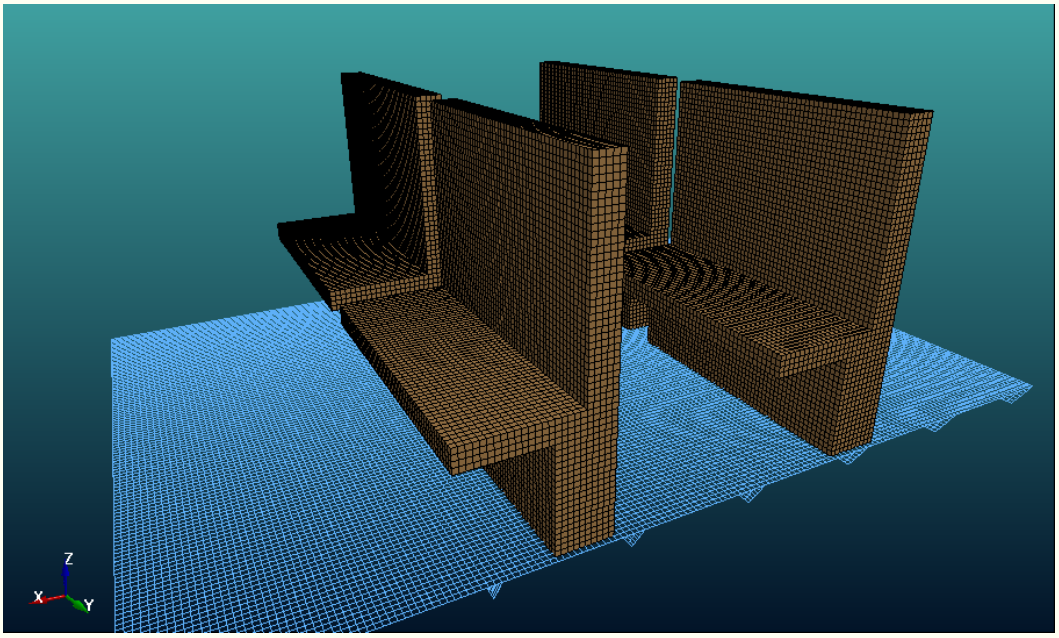


Figure 7. Seats attached to the floor.

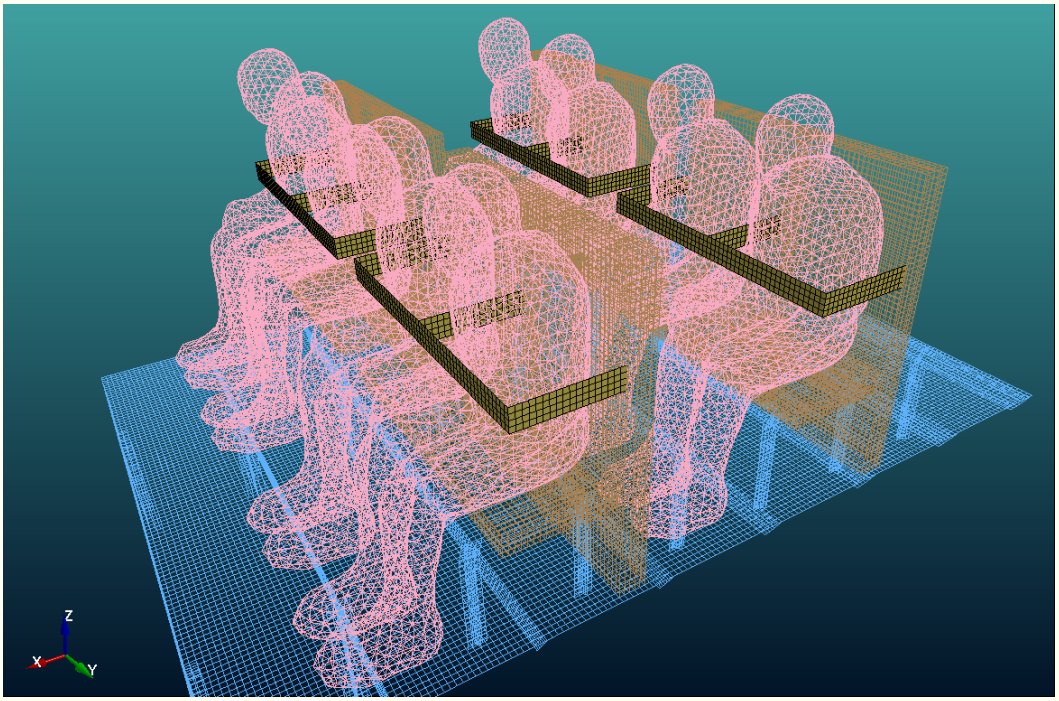


Figure 8. Seatbelts attached to the seats.

Table 7. Properties of seats.

Property	Value
Width	$546.4\,mm$
Hight	$1160\,mm$
Depth	$400\,mm$
Hight on the level of seat surface	$460\,mm$
Thickness of stander on top level	$100\,mm$
Thickness of stander on bottom level	$200\,mm$
Thickness of cushion	$80\,mm$
Distance between seats in rows	$600\,mm$
Spacing between double seats in a row	$156.1\,mm$
Distance between the last row of seats and the rear edge of the floor	$920\,mm$
Distance between the window seats and the edge of the floor	$19.5\,mm$
Number of rows	2
Number of seats in a row	4
Total number of seats	8
Thickness of material	$2.0\,mm$
Density	$3000\,kg/m^3$
Area	$17.93\,m^2$
Mass	$107.55\,kg$
Number of finite elements	45 744

Table 8. Properties of seatbelts.

Property	Value
Distance from bottom edge to the seat	$320\,mm$
Distance from top edge to the seat	$400\,mm$
Ribbon width	$80\,mm$
Lateral width	$351.2\,mm$
Width in forward direction	$360\,mm$
Total number of seatbelts	8
Thickness	$2.0\,mm$
Density	$7830\,kg/m^2$
Area	$0.81\,m^2$
Mass	$12.69\,kg$
Number of finite elements	2 048

Table 9. Properties of material of seatbelts, as defined in the card `*MAT_PIECEWISE_LINEAR_PLASTISITY`. Units are based on $mm/ms/kg$.

Property	Variable	Value
Title	TITLE	Shell belt material
Mass density	RO	$7.83 \cdot 10^{-6}$
Young's modulus	E	200.0
Poisson's ratio	PR	0.3
Yield stress	SIGY	0.15
Tangent modulus	ETAN	2.0

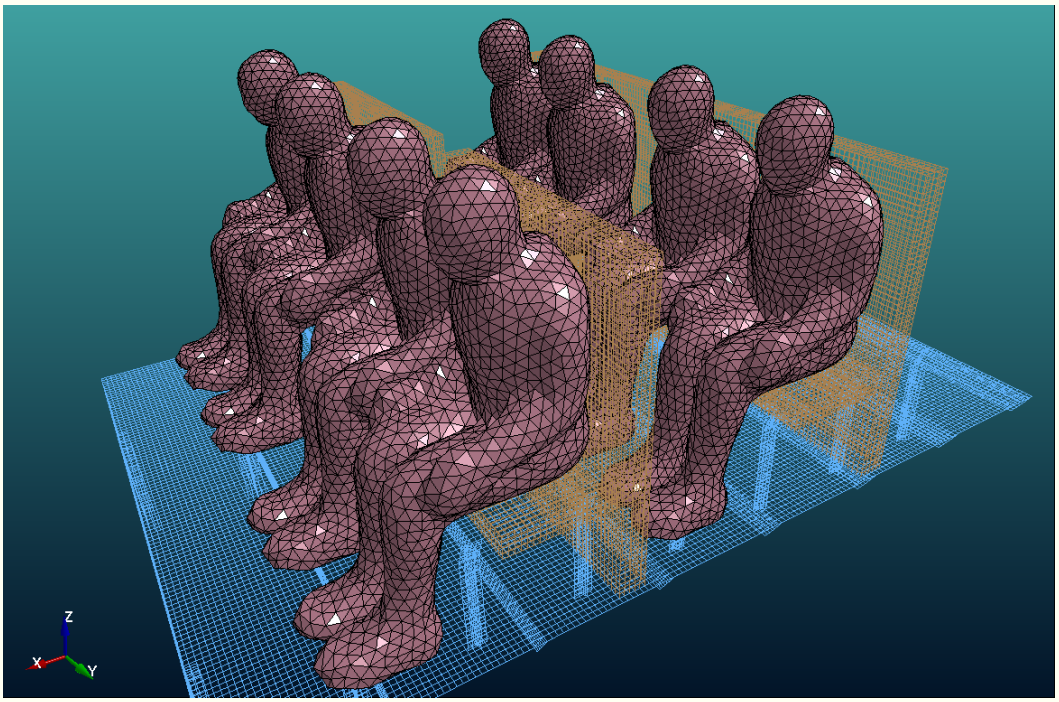


Figure 9. Passengers placed on seats.

Table 10. Properties of material of passengers, as defined in the card `*MAT_LOW_DENSITY_FOAM`. Units are based on $mm/ms/kg$. BETA, DAMP and other unspecified variables are assigned to default values.

Property	Variable	Value
Mass density	RO	$0.95 \cdot 10^{-6}$
Young's modulus	E	0.005
Nominal stress versus strain	Loaded curve	See Figure 10
Tension cut-off stress	TC	10.0
Hysteretic unloading factor	HU	1.0

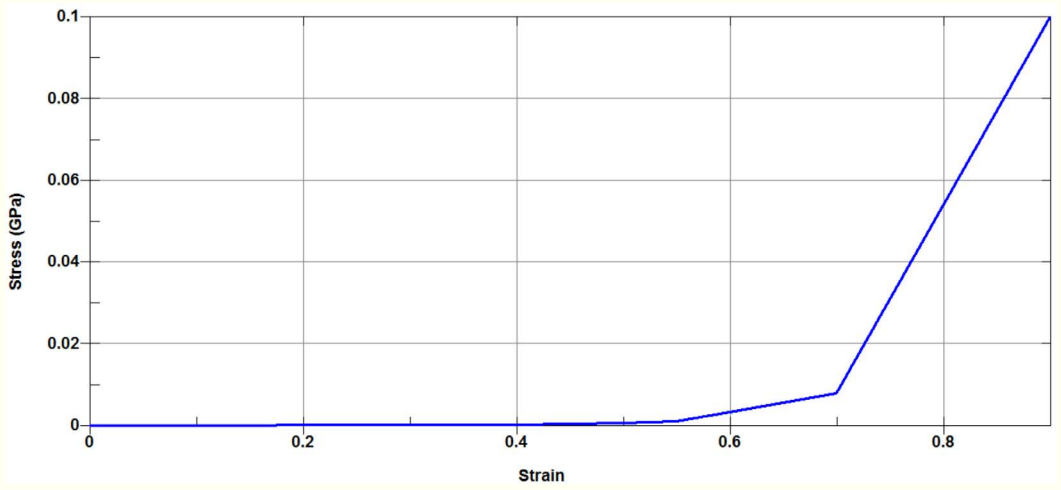


Figure 10. The curve that gives nominal stress versus strain for the material of passengers, see loaded curve definition in Table 9.

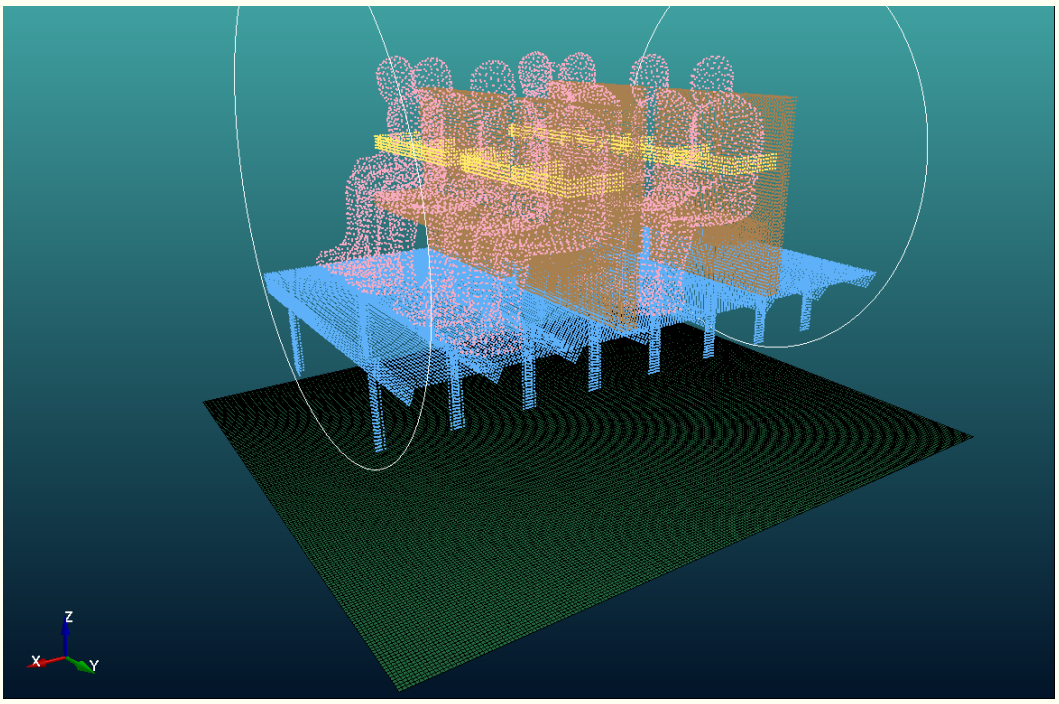


Figure 11. Pad on the ground which the fuselage hits when it is dropped to the ground

distance from the pad to the fuselage is $0.25\,m$. The material is Rigid, i.e. deformations are not allowed. The number of finite elements is 37980.

11 Initial conditions

The initial velocity is $-5.684\,m/sec$ and it is directed vertically. The free fall acceleration is $9.81\,m/sec^2$. The velocity reaches $-6.1\,m/sec$ when the fuselage hits the ground, or approximately 20 feet per second.

11.1 Results

Calculations were done up to maximal time 0.5 sec, with an output interval of 1 msec, on 8 processors, with double precision. The calculation time is around 20 hours. The results are shown on Figure 12.

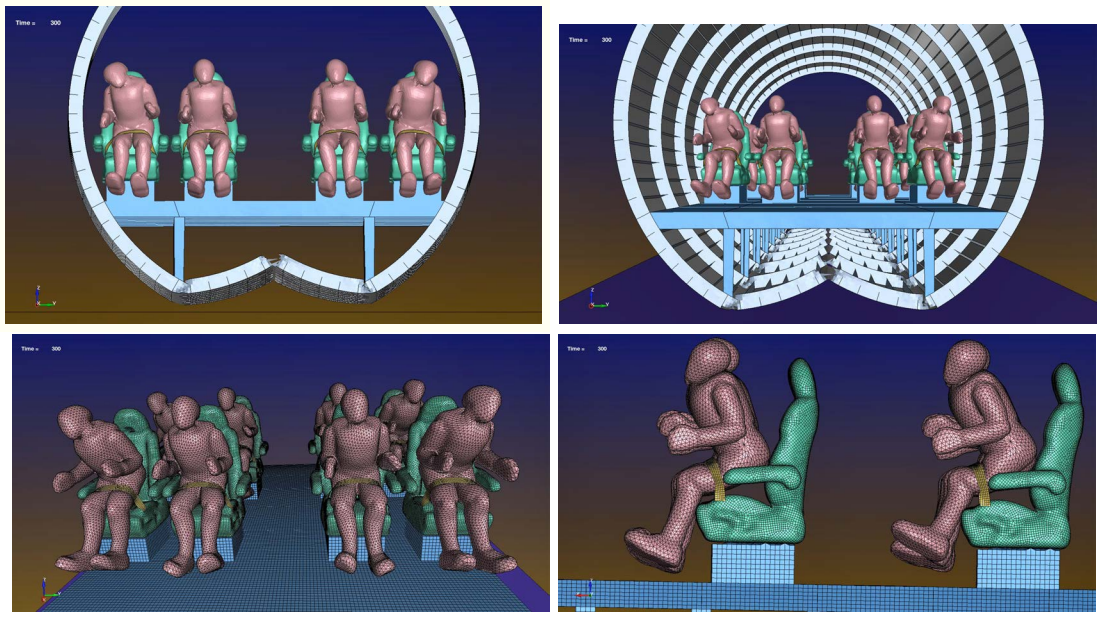


Figure 12. Results of calculations at $t = 0.3\,sec$: front view, isometric projection (top left), perspective projection (top right), passengers (bottom left), and side view (bottom right). Links to the movies:
`http://www.asergeev.com/files/lsdyna/01/index.htm` (front view, isometric projection),
`http://www.asergeev.com/files/lsdyna/02/index.htm` (perspective projection),
`http://www.asergeev.com/files/lsdyna/03/index.htm` (passengers),
`http://www.asergeev.com/files/lsdyna/04/index.htm` (side view).

12 Dropping a tilted fuselage section

Here, we consider dropping a fuselage section with a large roll angle. By definition, the roll angle corresponds to rotation in respect to the longitudinal axis which points out of the nose of the aircraft. In our case, the roll angle was set to 135°. The calculations show completely different structural damage in comparison with the untilted case, see Figure 13.

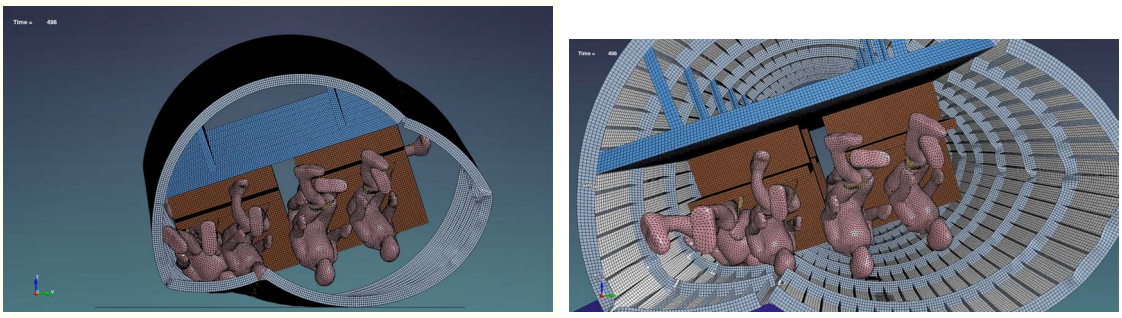


Figure 13. Results of calculations of the fuselage tilted by by 135°: front view, isometric projection (left), perspective projection (right). Links to the movies:
`http://www.asergeev.com/temp/droptest/02-04.avi` (front view, isometric projection),
`http://www.asergeev.com/temp/droptest/02-06.avi` (perspective projection).

13 Dropping a fuselage section of double length

We performed a drop test with a section of double length of 6.72 m. The number of dummies was increased from 8 to 24. The section is tilted by the pitch angle of 20° in respect to the horizon. The initial distance from the fuselage to the ground is 0.25 m. The vertical speed is 10 m/sec. Maximum time is 0.12 sec. The results are shown on Figure 14.

14 Testing the seatbelts

Here, we consider dropping a dummy with a chair tight together by a seatbelt. It allows to see clearly deformations of the dummy, the seat, and reliability of the seatbelt. The results are shown on Figure 15 for two vertical velocities, 10 and 15 m/sec.

15 Dropping test on natural terrain

Appearance of natural terrain could be mimicked on a computer with a *fractal landscape*, see `https://en.wikipedia.org/wiki/Fractal_landscape`. To produce the fractal land-

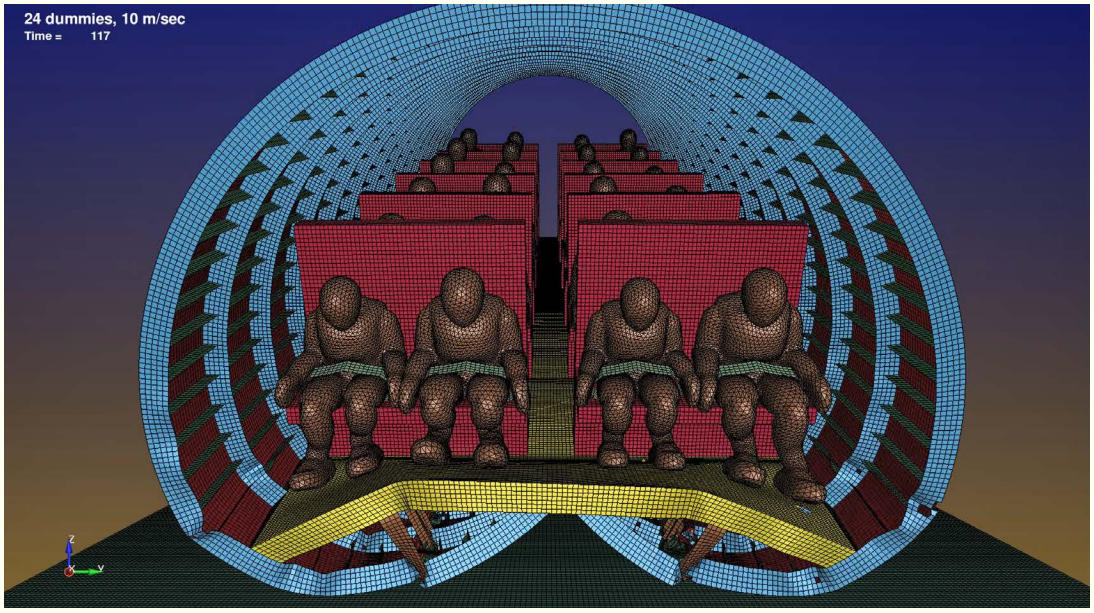


Figure 14. Drop test of the fuselage section of double length (6.72 m) with 24 dummies, front view. Links to the movie:
http://www.asergeev.com/temp/droptest/08-99.avi

scape, we use a freely available mesh editing software MeshLab. We start from flat surface of the grounding pad that was used in our previous simulations. A fractal terrain perturbation was generated by *Fractal Displacement* filter using the algorithm "Ridged multifractal terrain". Detailed algorithm description could be found in a book Texturing and Modeling: A Procedural Approach, edited by David S. Ebert, http://bookfi.net/dl/1427441/ed4a86.

Parameters of the filter are listed in Table 15.

The vertical velocity was set to 15 m/sec. We increased the velocity because natural terrain is softer than the solid flat ground. Calculations were done up to maximal time 0.3 sec, with an output interval of 0.5 msec, on 8 processors, with double precision. The calculation time is around 10 hours. The results are shown on Figure 16.

16 Improvements of the model

16.1 Dummies

To model a dummy, we used LSTC Hybrid III 50th Percentile model, see Figure 17

Firstly, the model was positioned as it is shown on Figure 17. Then, we used a mesh processing software MeshLab to make a more uniform mesh. For this purpose, the mesh

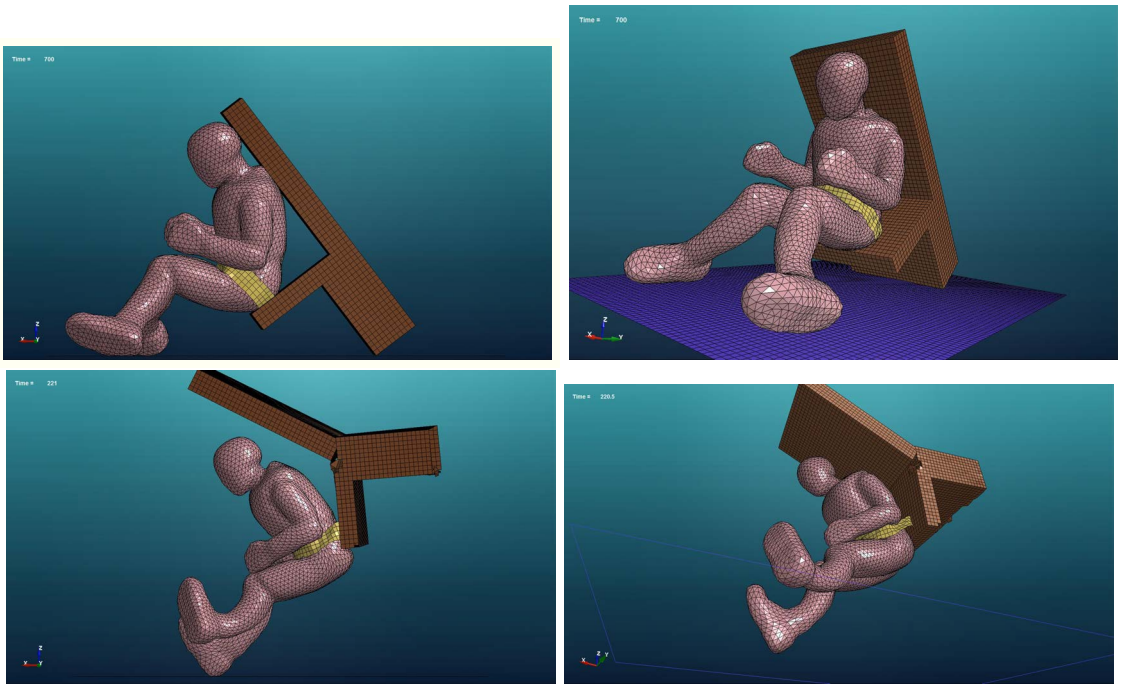


Figure 15. Seatbelt test for two dropping velocities, 10 m/sec (top) and 15 m/sec (bottom). Side view, isometric projection are shown to the left, ans perspective projection to the right. Links to the movies:
`http://www.asergeev.com/temp/droptest/05-00.avi` (10 m/sec, isometric projection),
`http://www.asergeev.com/temp/droptest/05-02.avi` (10 m/sec, perspective projection),
`http://www.asergeev.com/temp/droptest/06-00.avi` (15 m/sec, isometric projection),
`http://www.asergeev.com/temp/droptest/06-04.avi` (15 m/sec, perspective projection).

Table 11. Parameters of the *Fractal Displacement* filter in MeshLab. Asterisk marks the parameters changed from their default values.

Property	Value
Max height	4.0%
Scale factor	1
Normal smoothing steps	5
Seed	2
Algorithm	Ridged multifractal terrain
Octaves	8
Lacunarity	4
Fractal increment	0.2
Offset*	0.75
Gain	2.5

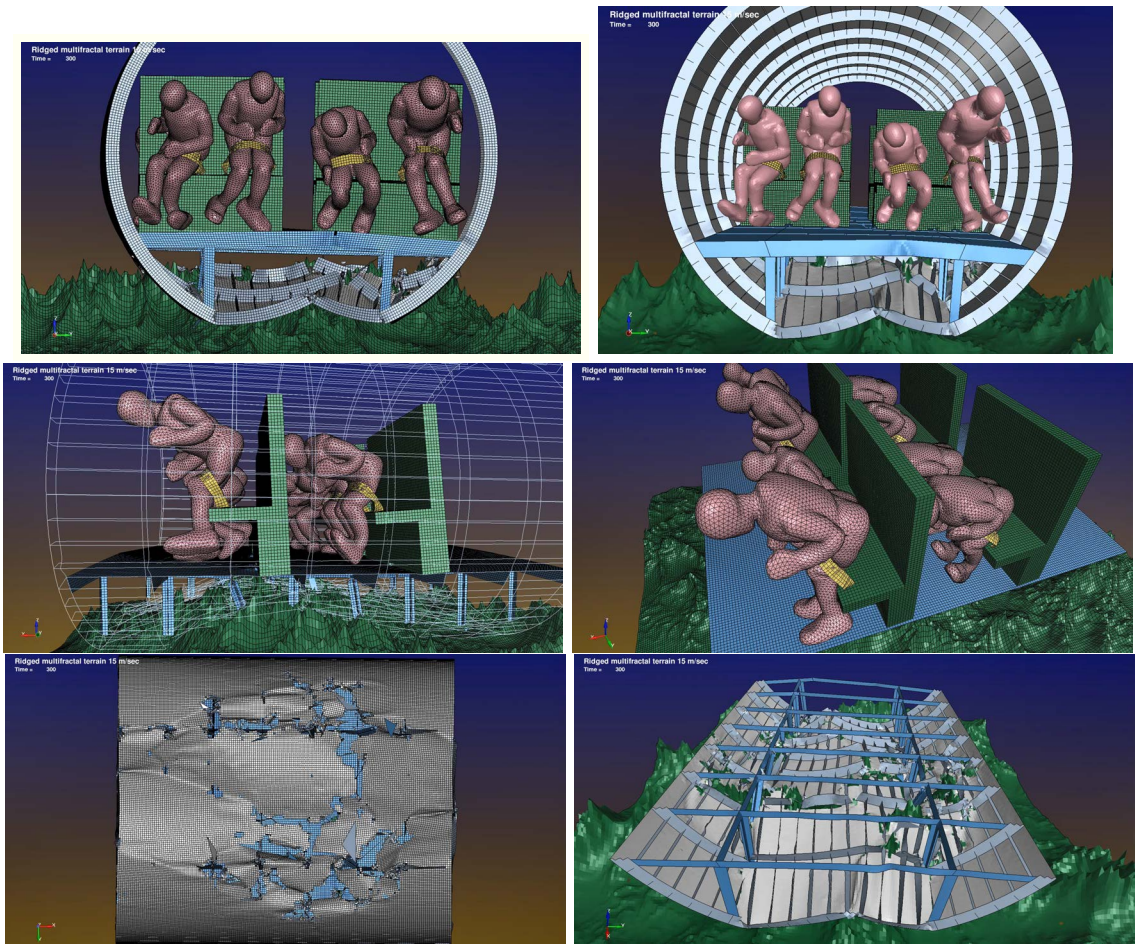


Figure 16. Drop test on natural terrain at $t = 0.3\,sec$: front view, isometric projection (top left), perspective projection (top right), side view (middle left), passengers (middle right), bottom view (bottom left), and bottom section (bottom right). Links to the movies:
`http://www.asergeev.com/temp/droptest/08-01.avi` (front view, isometric projection),
`http://www.asergeev.com/temp/droptest/08-02.avi` (perspective projection),
`http://www.asergeev.com/temp/droptest/08-03.avi` (side view),
`http://www.asergeev.com/temp/droptest/08-05.avi` (passengers),
`http://www.asergeev.com/temp/droptest/08-06.avi` (bottom view),
`http://www.asergeev.com/temp/droptest/08-07.avi` (bottom section).

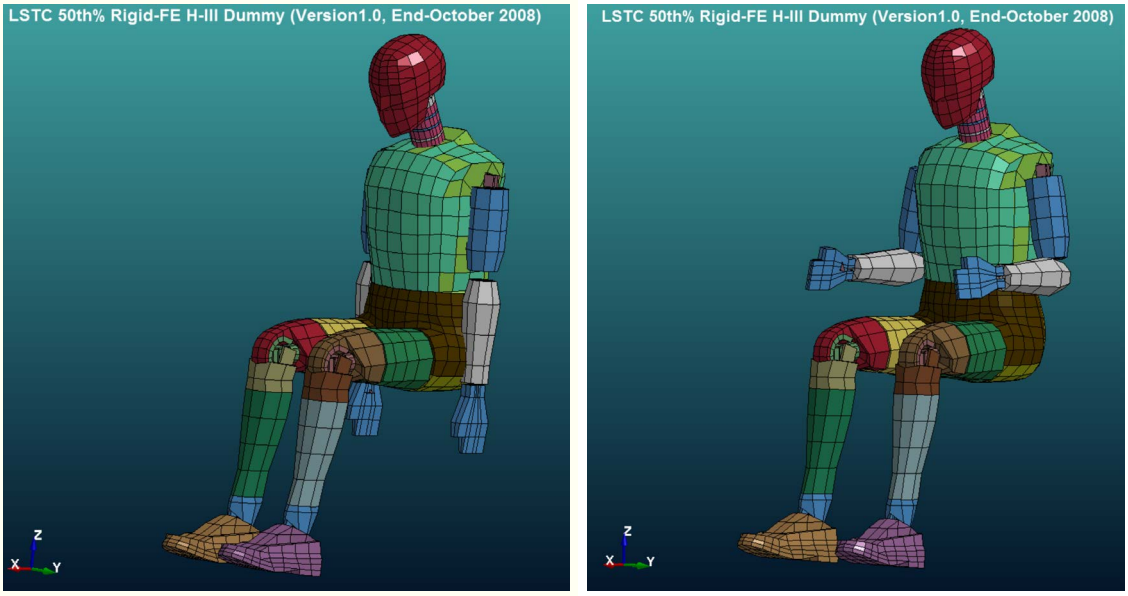


Figure 17. LSTC Hybrid III 50th Percentile dummy model used as a prototype for our model. Left panel is the original dummy, right panel is the positioned dummy.

was uniformly resampled, see Figure 18. Note that arms are not fused with the body in the new model. Finally, we tried to apply several mesh transformations, or filters, see Figures 19 and 20. We found that the filter "ISO parametrization remeshing" gives the most uniform mesh, and this mesh was used to construct a three-dimensional tetrahedral mesh in LS-PREPOST. Number of solid elements in the new dummy model was increased from 13539 to 78930 in comparison with an earlier version.

16.2 Seats

A model of an airplane seat was downloaded from Sketchfab Store website `https://sketchfab.com/3d-models/plane-seat-a4b5b9692a904dee8236a1e7e79f80fc`. It was uniformly remeshed as it is shown on Figure 21.

As it was in earlier calculations, seats were modelled by shell elements with thickness 2 mm. The number of shell element was increased from 5718 to 14200 in comparison with an earlier rectangular model.

16.3 Seatbelts

In the new model, seatbelts are placed around laps and attached to seat cushions, see Figure 22.

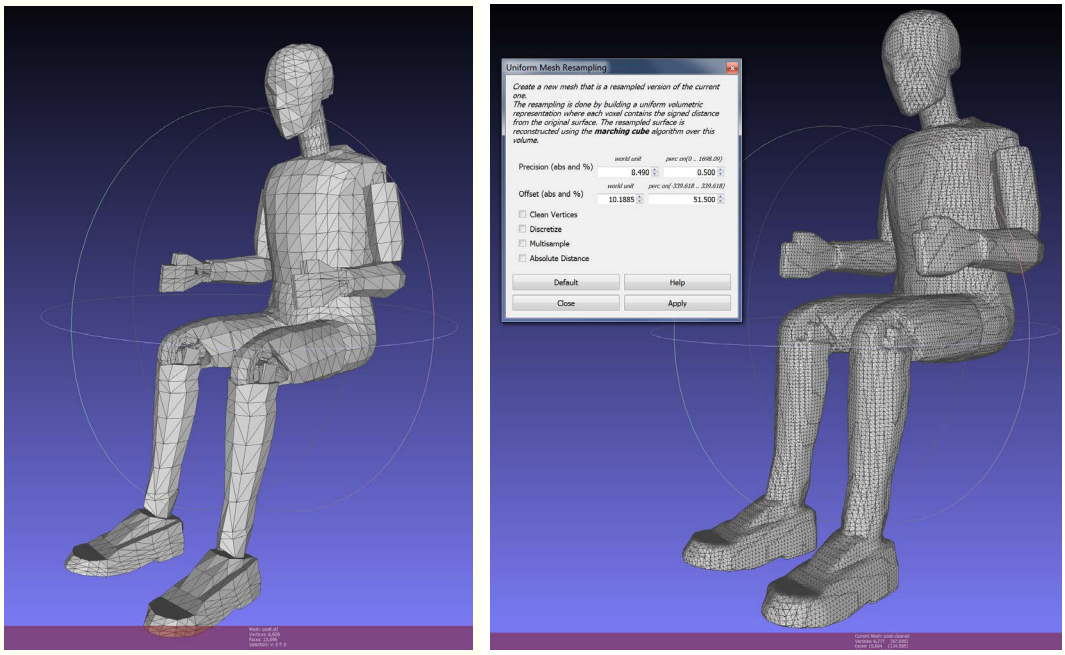


Figure 18. Resampling mesh of a dummy. Left panel is the original mesh, right panel is the uniformly resampled mesh.

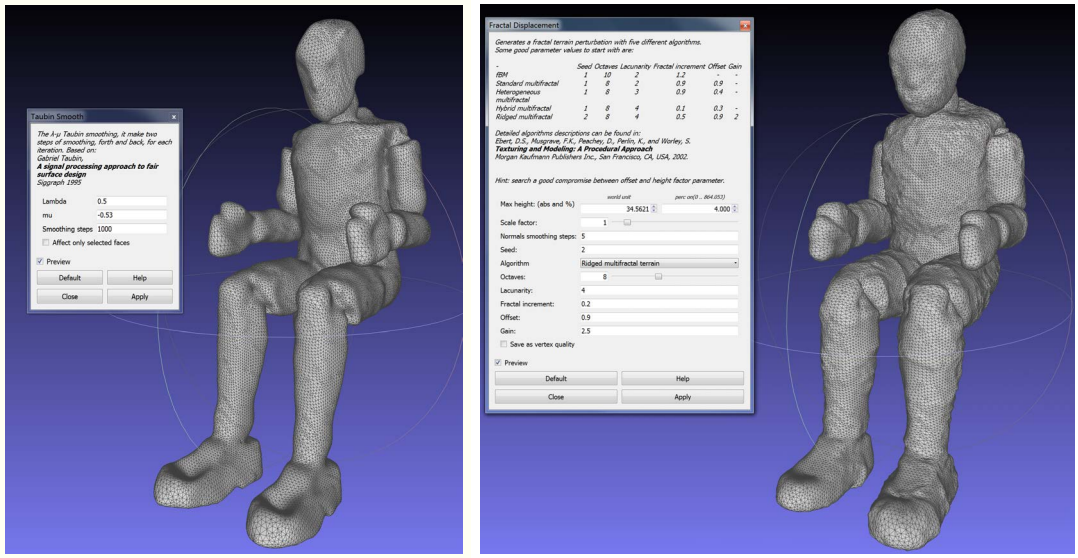


Figure 19. Trying mesh transformations to make it more smooth. Left panel is Taubin smoothing, right panel is fractal displacement.

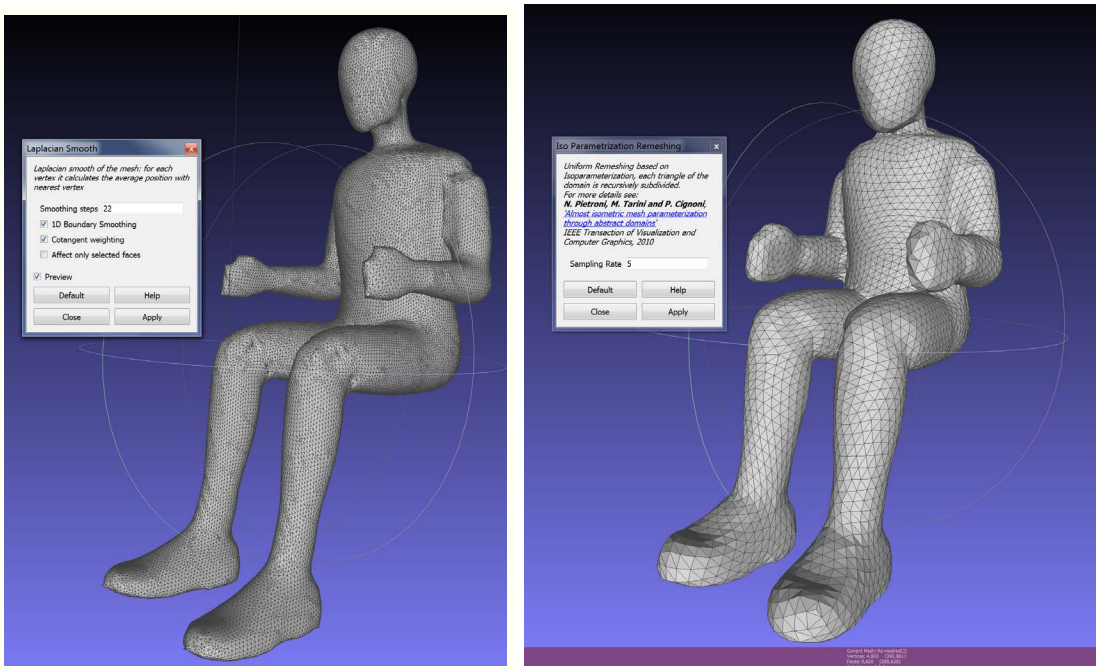


Figure 20. Trying mesh transformations to make it more smooth. Left panel is Laplacian smoothing, right panel is ISO parametrization remeshing.

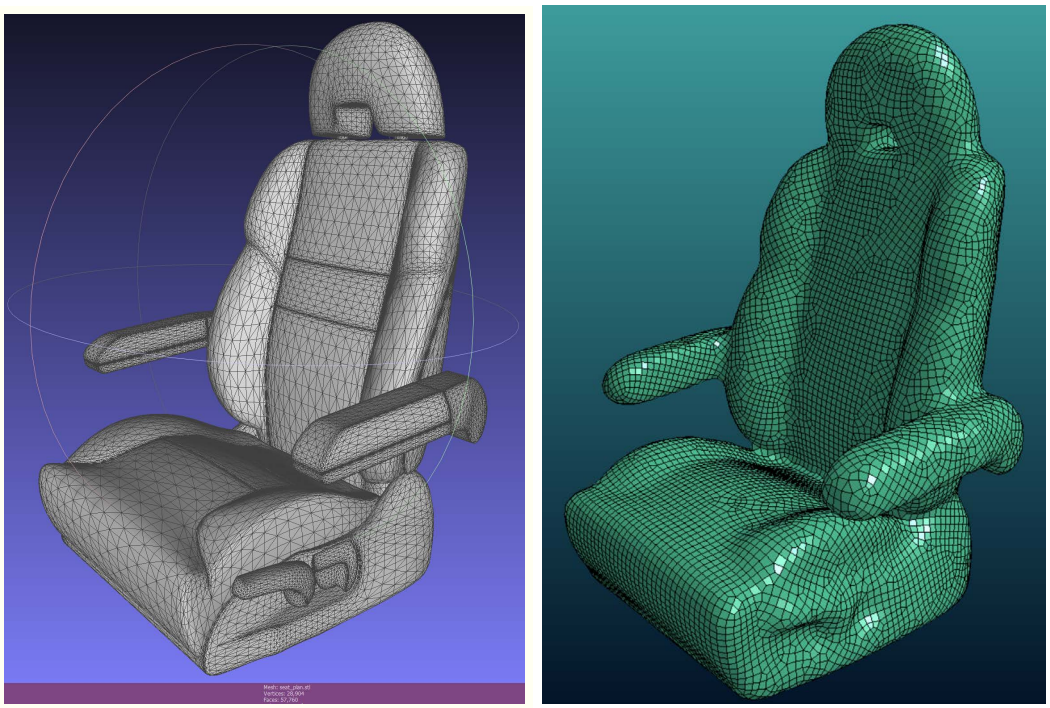


Figure 21. Remeshing the seat. Left panel is the original mesh downloaded from Sketchfab Store website, right panel is the remeshed seat.

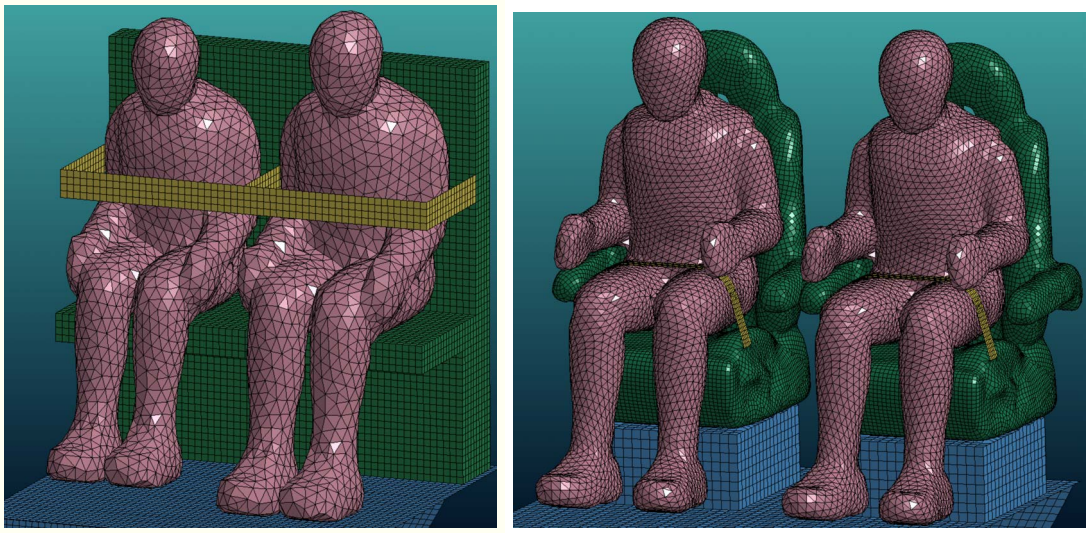


Figure 22. Comparison of the old model (left) with the new model for dummies, seats and setbelts (right)

16.4 Control of time step

In our earlier attempts, the calculations are frequently become stuck by increasingly small time step at the moment when deformations of the fuselage become large. It occurs because several mesh elements become extremely deformed, and in order to avoid negative volumes or the divergence, the time step decreases to very small values $\sim 10^{-7}\, msec$. Here, we perform several steps to avoid this phenomenon. (1) The parameter "Failure strain for eroding elements" (FS) in the card `*MAT_PLASTIC_KINEMATIC` was set to 0.03. Our previous value was often 0.01, but it seems that 0.03 is more realistic. (2) We added a card `*MAT_ADD_EROSION` with "Volumetric strain at falure" (VOLEPS) equal to 0.1 and "Share strain at failure" (EPSSH) equal to 0.1. It allows to delete very deformed elements that were somehow missed by a standard failure strain criterium for deletion. (3) In the card `*CONTROL_TERMINATION`, we set "Reduction factor for the initial time step size to determine minimum time step" (DTMIN) to 0.3. It forced the time step to be always larger than the initial time step times 0.3. (4) We added a card `*CONTROL_TIMESTEP` where we set "Shell element minimum time step assignement" (TSLIMT) to 0.0002. Theoretically, it should force to delete the elements with too small time step, but in practice it seems that it does not work.

With these changes, the calculation could be performed up to very large time of several second and for large impact velocities up to 15 m/sec.

16.5 Comparison of old and new configurations

The seats were placed inside the fuselage section in the same configuration of two rows with four seats in each row, see Figure 23. The size of the dummies was decreased to allow more space for a new version of seats. Density of dummies in the new model was increased to $3000\, kg/m^2$ in order to keep the total weight the same. Additional rectangular boxes were added under each seat to support it.

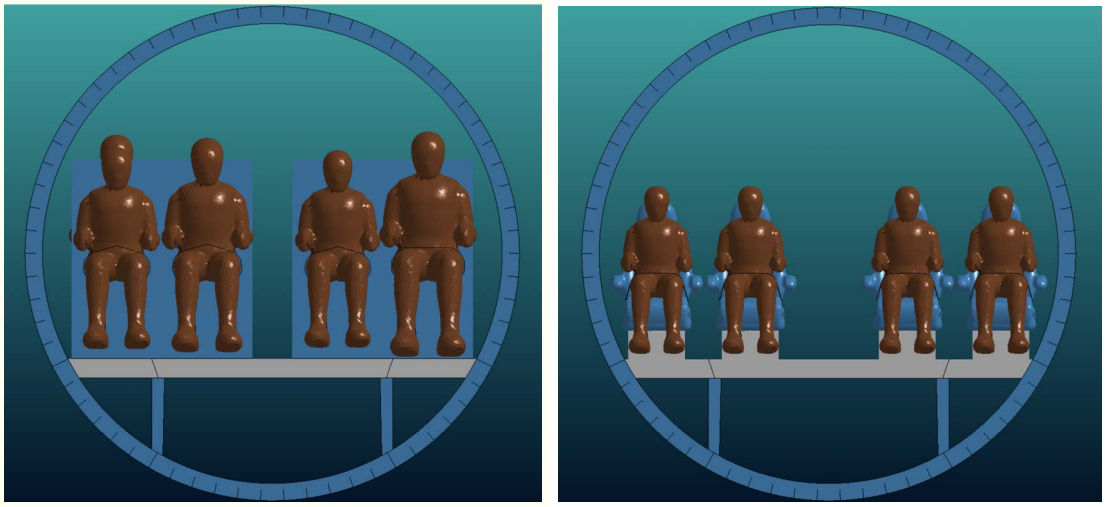


Figure 23. Comparison of the old configuration of dummies/seats (left) with the new one (right). Note that the dummy size is decreased to accomodate more space for seats and to a space between double seats.