METHOD DEVELOPMENT FOR FULL AIRCRAFT CRASH SIMULATION

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DLR Institute of Structures and Design

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Overview

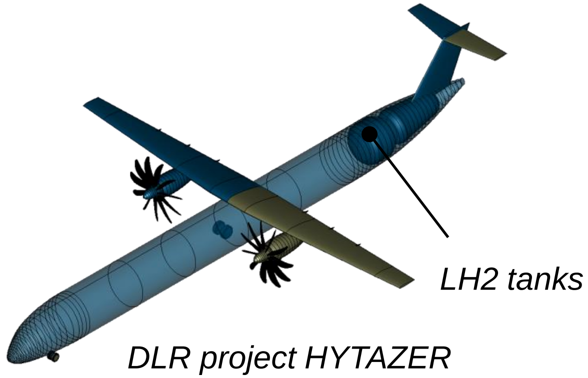
- **Motivation**
- **1 Method development**
- **2 Method validation**
- **3 Method application**
- **Summary**

Motivation

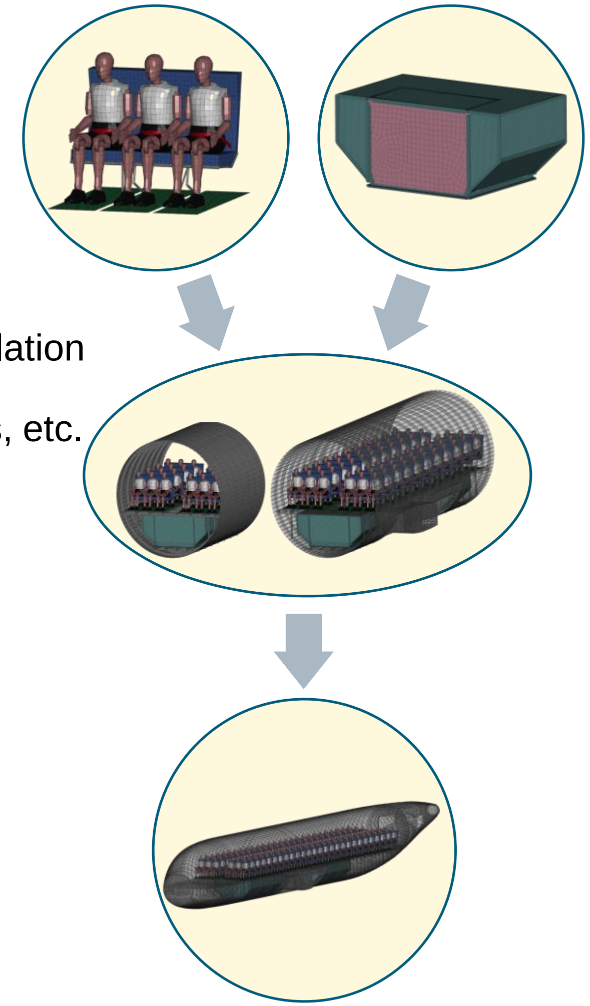
Full aircraft crash simulation as a research goal at DLR

Development of numerical methods for full aircraft crash simulation

- Understanding the aircraft response and crash performance during a crash landing
  - How is the aircraft crash performance affected by
    - Impact conditions, impact surface, occupant and cargo loading
  - Derivation of local loads from full aircraft crash simulation to be applied on a fuselage section simulation
    - Including effects such as pre-loading from aircraft rotation, combined horizontal/vertical loads, etc.
- Analysis and evaluation of future aircraft configurations
  - Need to consider full aircraft to understand and assess crash effects
  - E.g. hydrogen propulsion and LH2 tank integration



DLR project HYTAZER

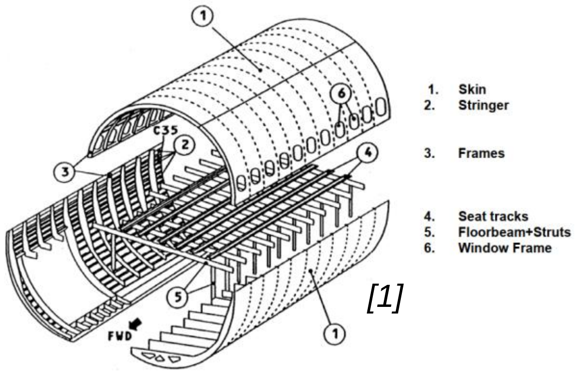


1 Method development

Generic single-aisle aircraft design

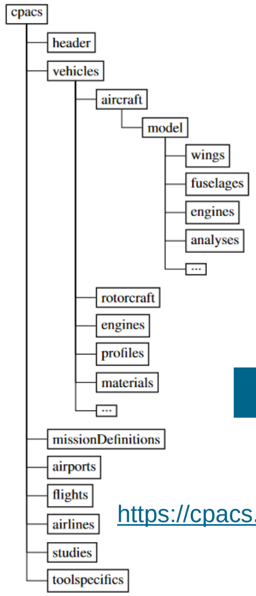
1 Method development
Approach

Process chain tool for full aircraft crash simulation



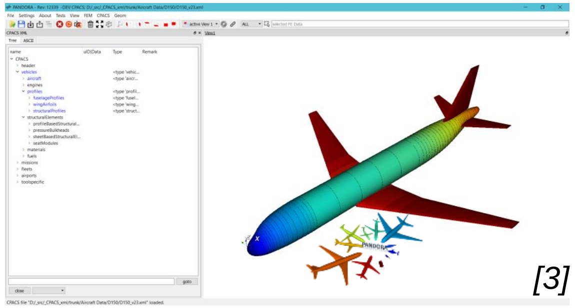
[1]

Aircraft design data



https://cpacs.de/ [2]

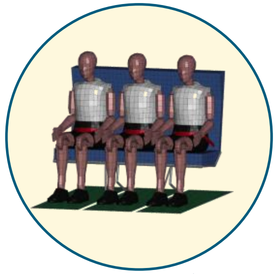
A) CPACS



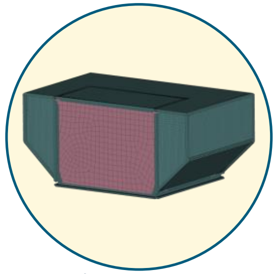
[3]

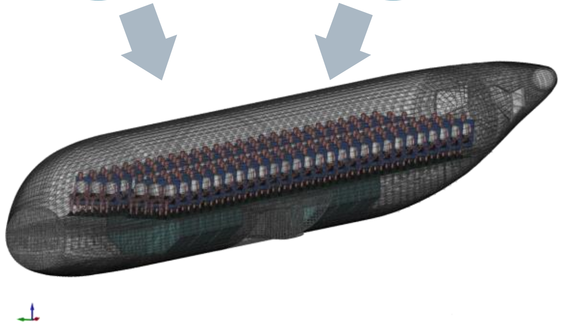
B) PANDORA

C) Occupants



D) Cargo





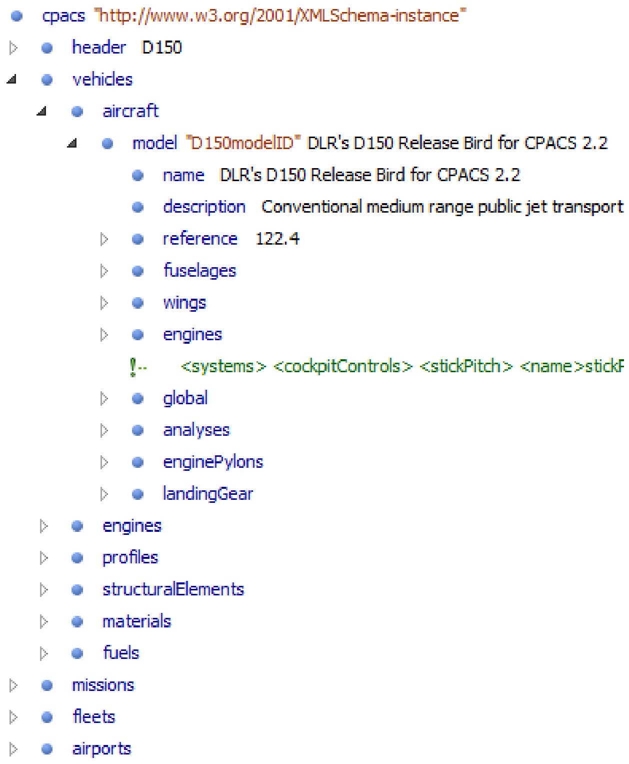
Aircraft FE model

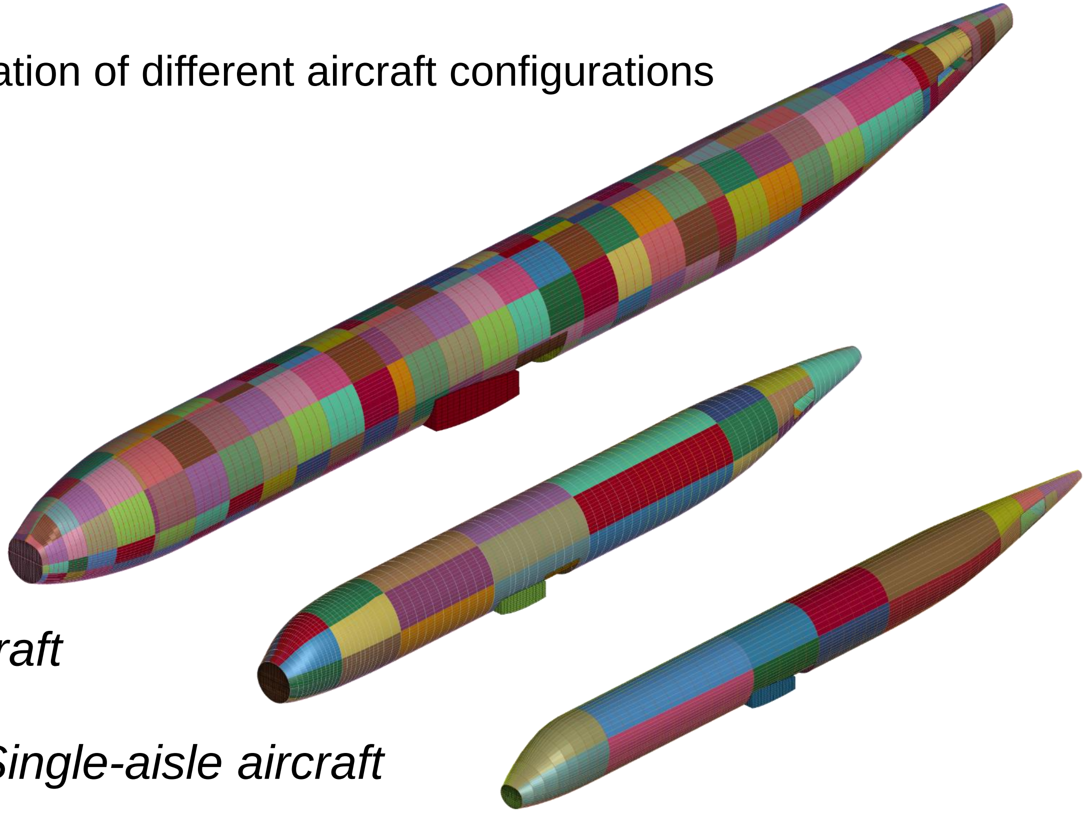
[1] K. Drechsler, P. Eyerer, and H. Dörner, "Fertigungstechnik und Bauweisen für Leichtbaukonstruktionen," Lecture material WS05/06, 2005.
[2] M. Alder, E. Moerland, J. Jepsen, and B. Nagel, "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," presented at the Aerospace Europe Conference 2020, Bordeaux, Frankreich, 2020. Available: https://elib.dlr.de/134341/
[3] M. Petsch, D. Kohlgrüber, and J. Heubischl, "PANDORA - A python based framework for modelling and structural sizing of transport aircraft," presented at the 8th EASN-CEAS International Workshop, Glasgow, Schottland, 2018. Available: https://elib.dlr.de/124181/

1 Method development
Approach

A) Aircraft structure description by CPACS [2]

- CPACS: Common Parametric Aircraft Configuration Schema (https://cpacs.de/)
- Enables parameterized and automated FE mesh generation of different aircraft configurations





Wide-body aircraft

Single-aisle aircraft

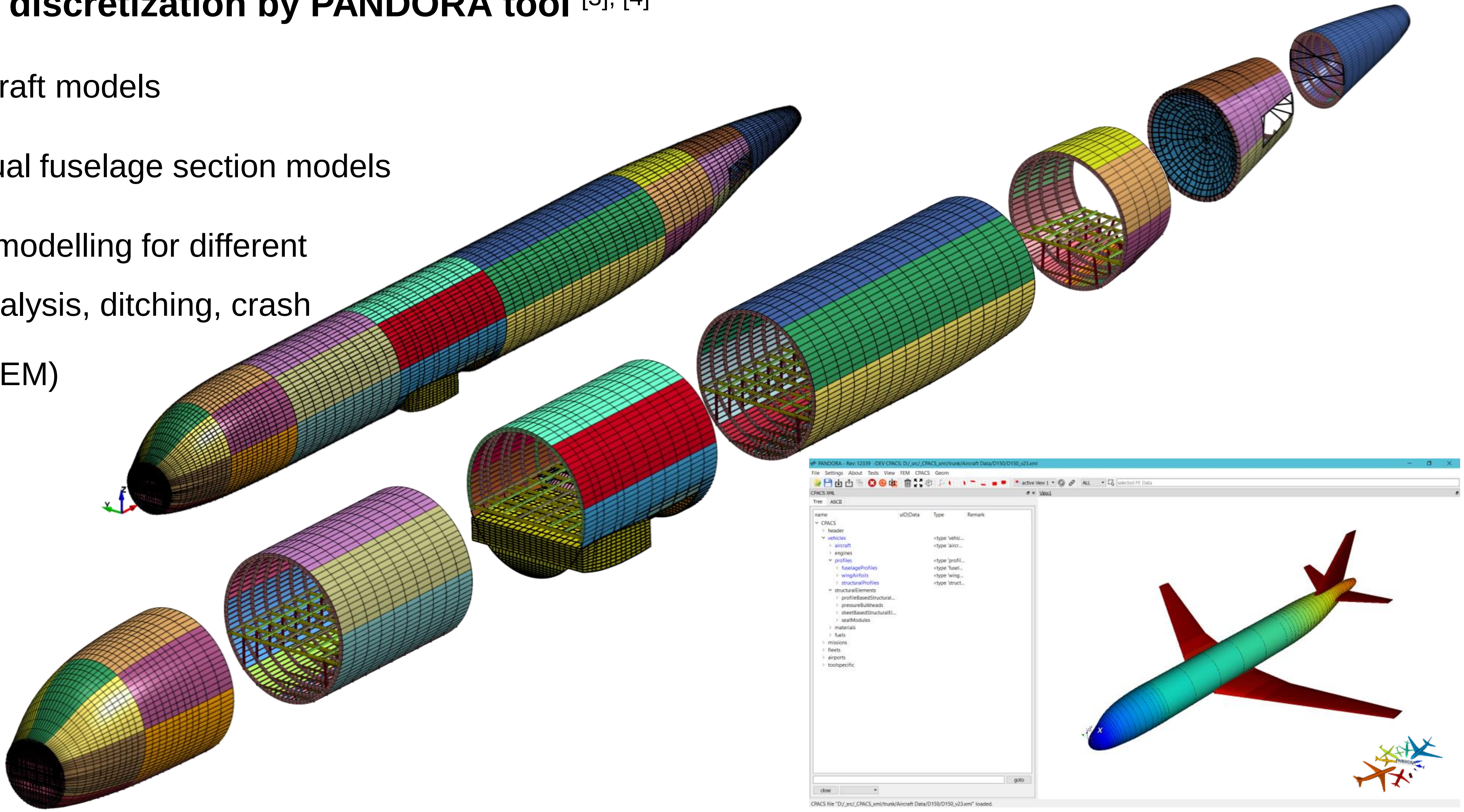
Regional aircraft

[2] M. Alder, E. Moerland, J. Jepsen, and B. Nagel, "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," presented at the Aerospace Europe Conference 2020, Bordeaux, Frankreich, 2020. Available: https://elib.dlr.de/134341/

1 Method development
Approach

B) Aircraft structure discretization by PANDORA tool [3], [4]

- Generation of full aircraft models
- Generation of individual fuselage section models
- Low and high fidelity modelling for different applications: static analysis, ditching, crash
    - Global FEM (GFEM)
    - Detailed FEM



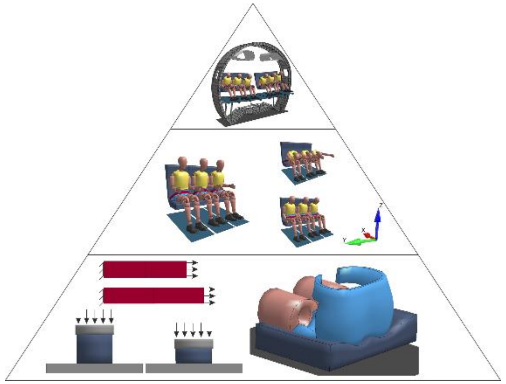
[3] M. Petsch, D. Kohlgrüber, and J. Heubischl, "PANDORA - A python based framework for modelling and structural sizing of transport aircraft," presented at the 8th EASN-CEAS International Workshop, Glasgow, Schottland, 2018. Available: https://elib.dlr.de/124181/
[4] C. Leon Muñoz and D. Kohlgrüber, "High Fidelity Simulations of Flexible Aircraft Structures Under Ditching Loads," presented at the Dynamic Modeling and Simulation (M&S) in Aircraft Ditching and Cabin Evacuation, FAA Virtual Workshop, 2022.

1 Method development

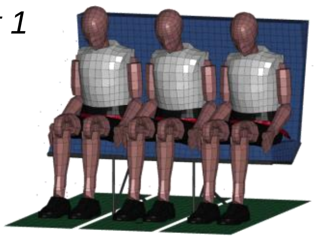
Approach

C) Occupant module [5], [6]

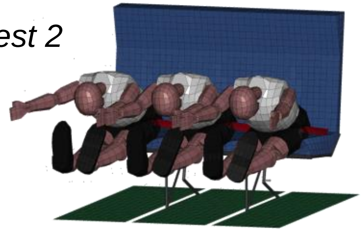
- Development according to the building block approach



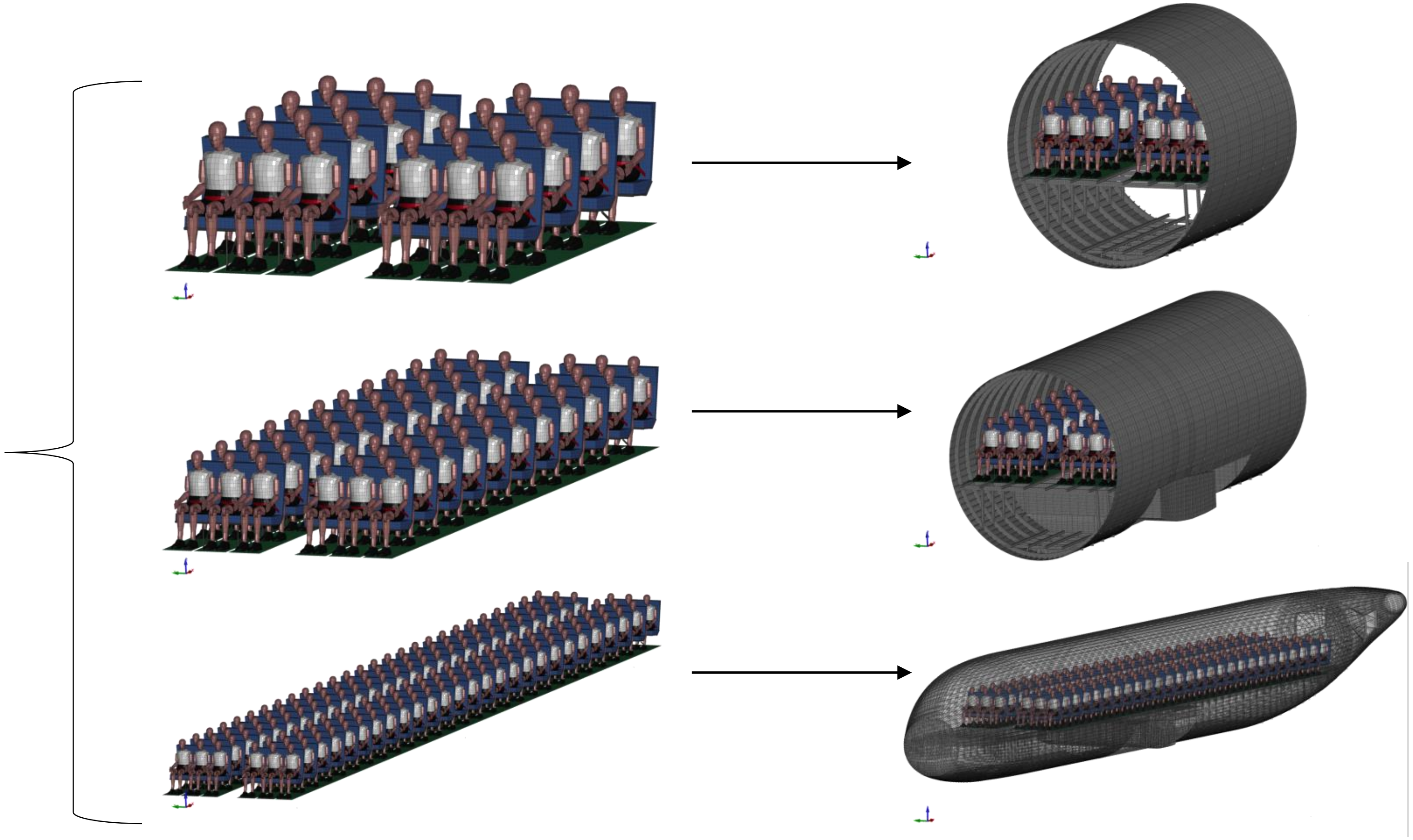
Test 1



Test 2



LSTC Hybrid 3 ATD FAST model



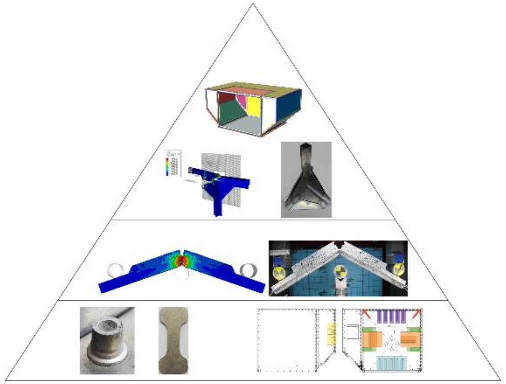
[5] T. Lehmann, "Entwicklung von Passagier-Sitz-Modellen für die Simulation von Flugzeugbruchlandungen," DLR-IB-BT-ST-2018-159, 2018

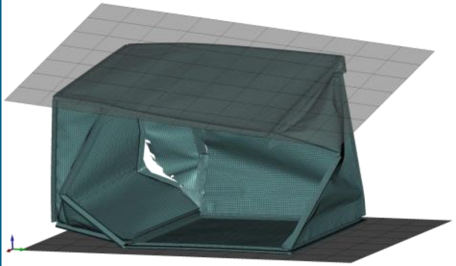
[6] N. Wegener, P. Schatrow, and M. Waimer, "Development of occupant-seat models for Fokker F28 crash test simulations," DLR-IB-BT-ST-2021-176, 2021.

1 Method development
Approach

D) Cargo module [7], [8]

- Development according to the building block approach

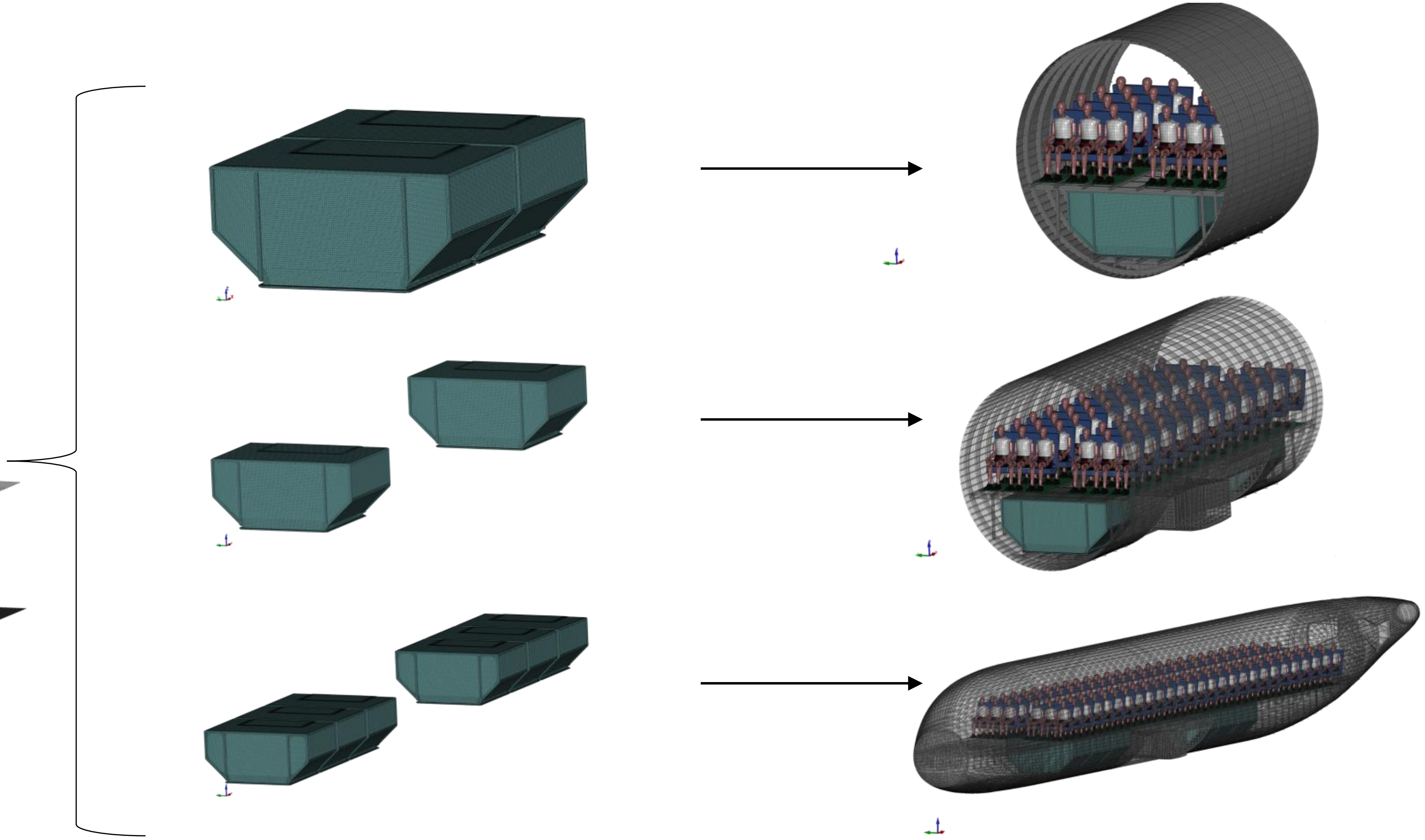




AKE without cargo (Wide-body)

AKH with cargo (Single-aisle)

Container model validation in progress

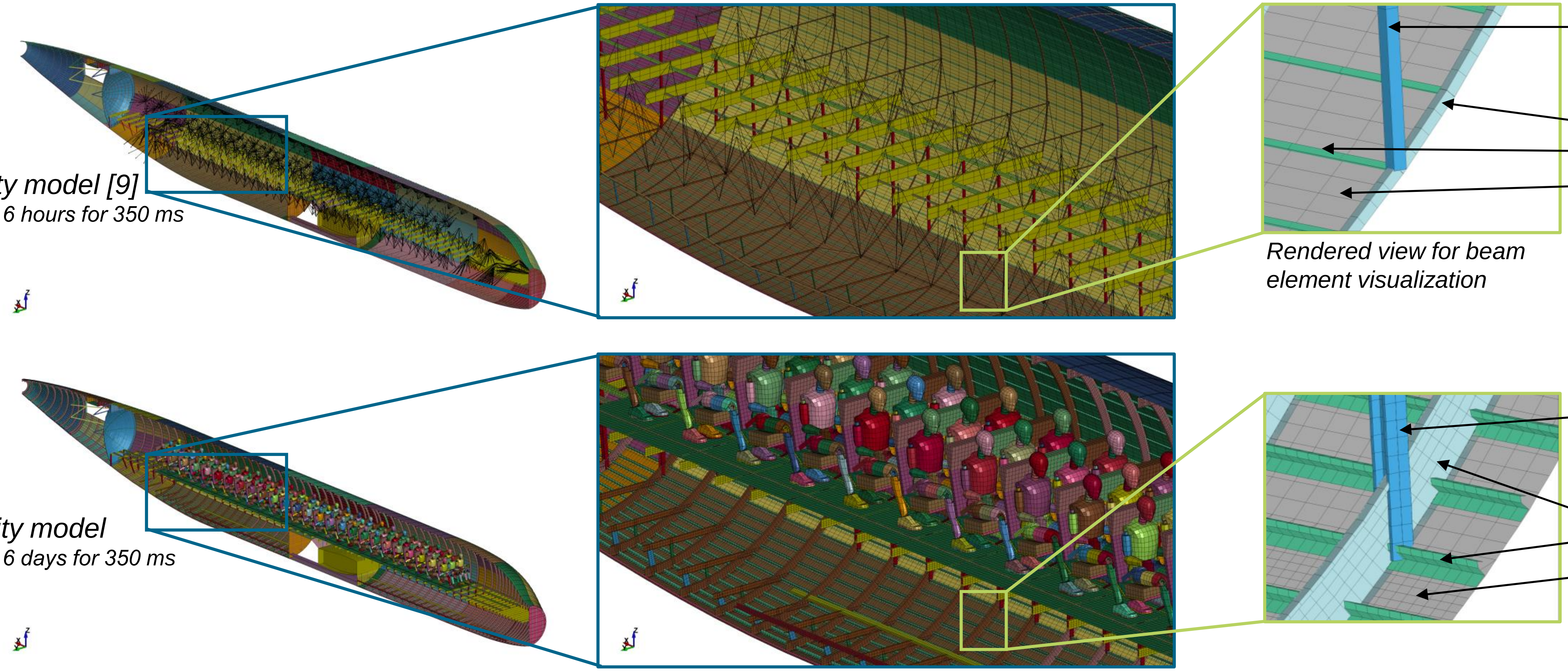


[7] M. Waimer and P. Schatrow, "Cargo Container Characterization for Airplane Crash Applications – Experimental Tests and Validation of Simulation Models," in Aerospace Structural Impact Dynamics International Conference, Madrid, Spain, 2019.
[8] M. Waimer and P. Schatrow, "Full-Scale Crash Testing of Cargo Containers - Experimental Characterization for Transport Airplane Crash Applications," in The Tenth Triennial International Fire & Cabin Safety Research Conference, Atlantic City, New Jersey, USA, 2022.

1 Method development
Approach

Process chain output

- Application-driven: suitable model fidelity for given application (global FEM, detailed FEM)



Low fidelity model [9]
CPU time: ≈ 6 hours for 350 ms

Rendered view for beam element visualization

High fidelity model
CPU time: ≈ 6 days for 350 ms

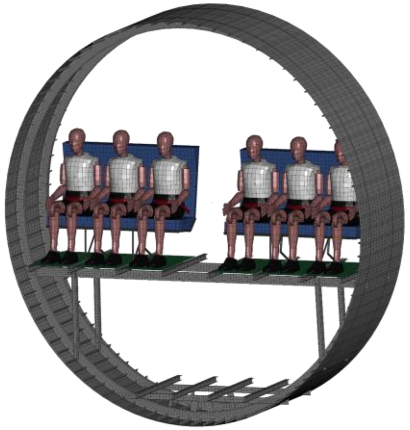
[9] P. Schatrow, M. Waimer, M. Petsch, C. Leon Muñoz, and D. Kohlgrüber, "Method development for full aircraft crash simulation at different levels of modeling detail," presented at the The Ninth Triennial International Fire & Cabin Safety Research Conference, Atlantic City, New Jersey, USA, 2019. Available: https://elib.dlr.de/130176/

1 Method development

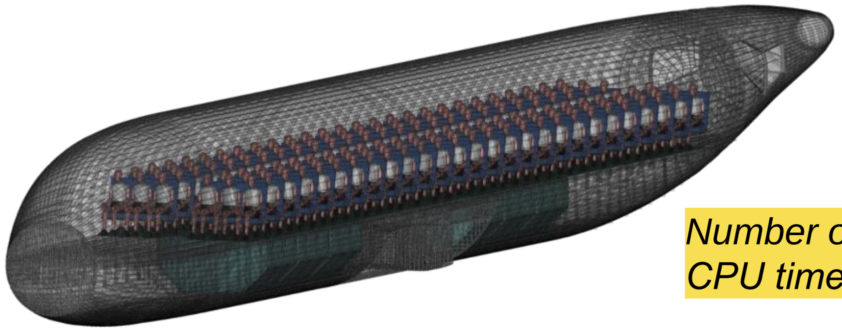
Current status of high fidelity full aircraft crash simulation

FE model overview (exemplary)

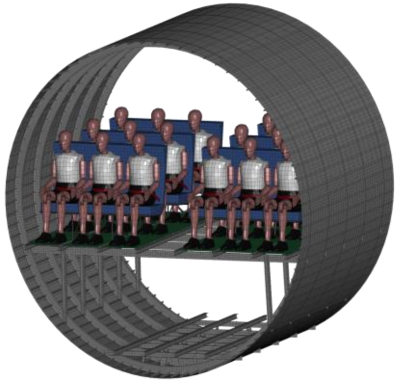
- Potential applications: configuration assessment, conceptual & preliminary design, determination of local loads, etc.

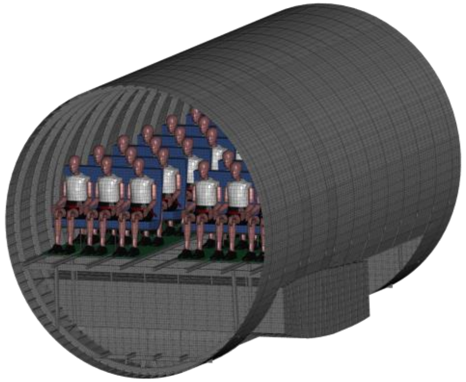


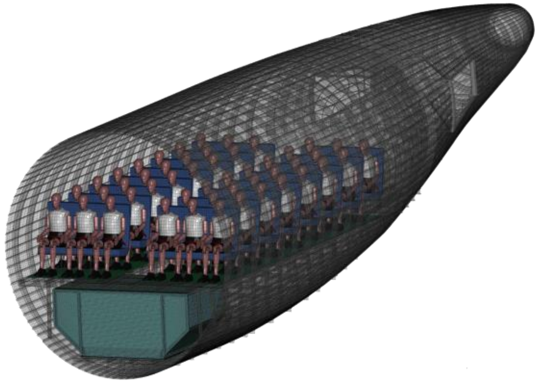
Number of nodes: 95,000
CPU time: ≈ 50 min for 250 ms



Number of nodes: 3.3 M
CPU time: ≈ 8 days for 350 ms







Linux cluster
LS-Dyna 13.1.0
16 core processor

2 Method validation

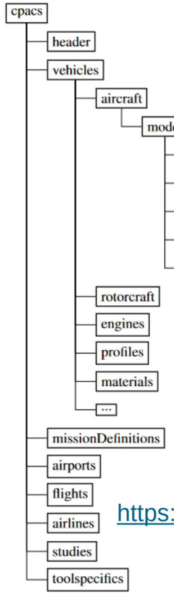
Specific aircraft design Fokker F28

2 Method validation
Current status

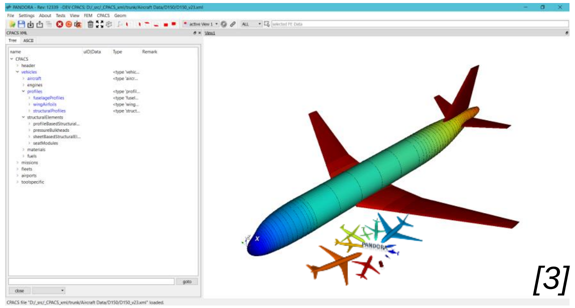
FE model generation

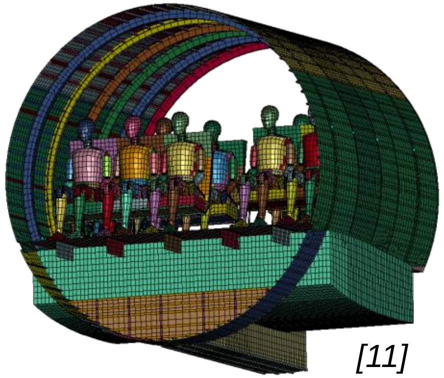
Design data provided by Fokker Services


[10]



https://cpacs.de/ [2]


[3]


[11]

Aircraft design data | *CPACS* | *PANDORA* | *Aircraft FE model*

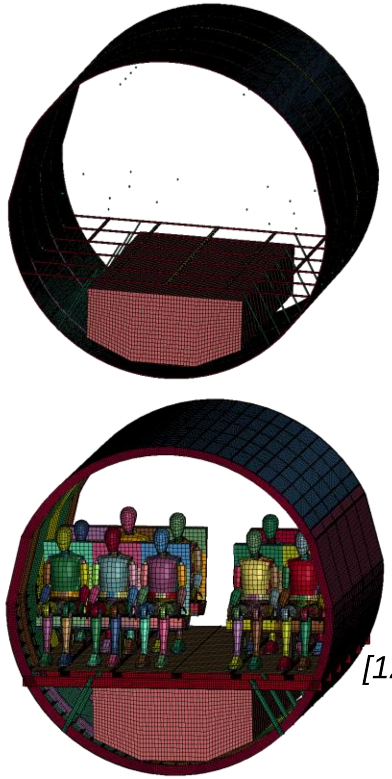
[10] J. D. Littell, "A summary of results from two full-scale Fokker F28 fuselage section drop tests," NASA/TM–2018-219829, 2018.
[11] E. Wegener, "Numerical Simulation of a Crash Test on a Fokker F28 Center Fuselage Section with Wing Box and Oblique Impact Surface," DLR-IB-BT-ST-2021-148, 2021.

2 Method validation
Current status

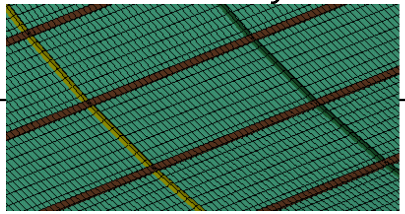
Definition of F28 CPACS data set and generation of two fuselage section models with PANDORA

FAA/NASA Test 1:
F28 fuselage section with cargo door and luggage

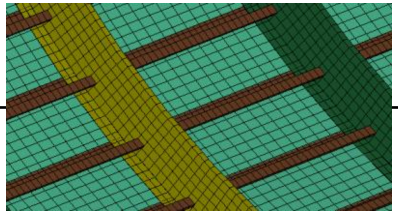
[10]


[12]

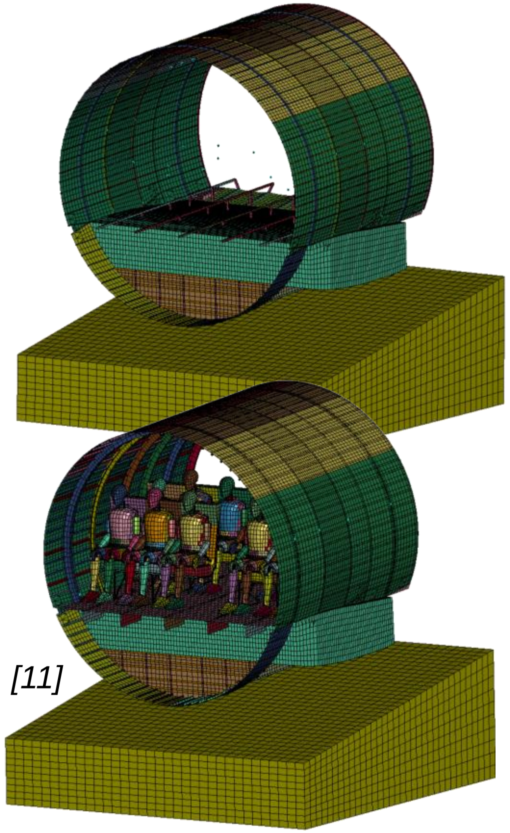
Low-Fidelity



High-Fidelity



FAA/NASA Test 2:
F28 fuselage section with wingbox

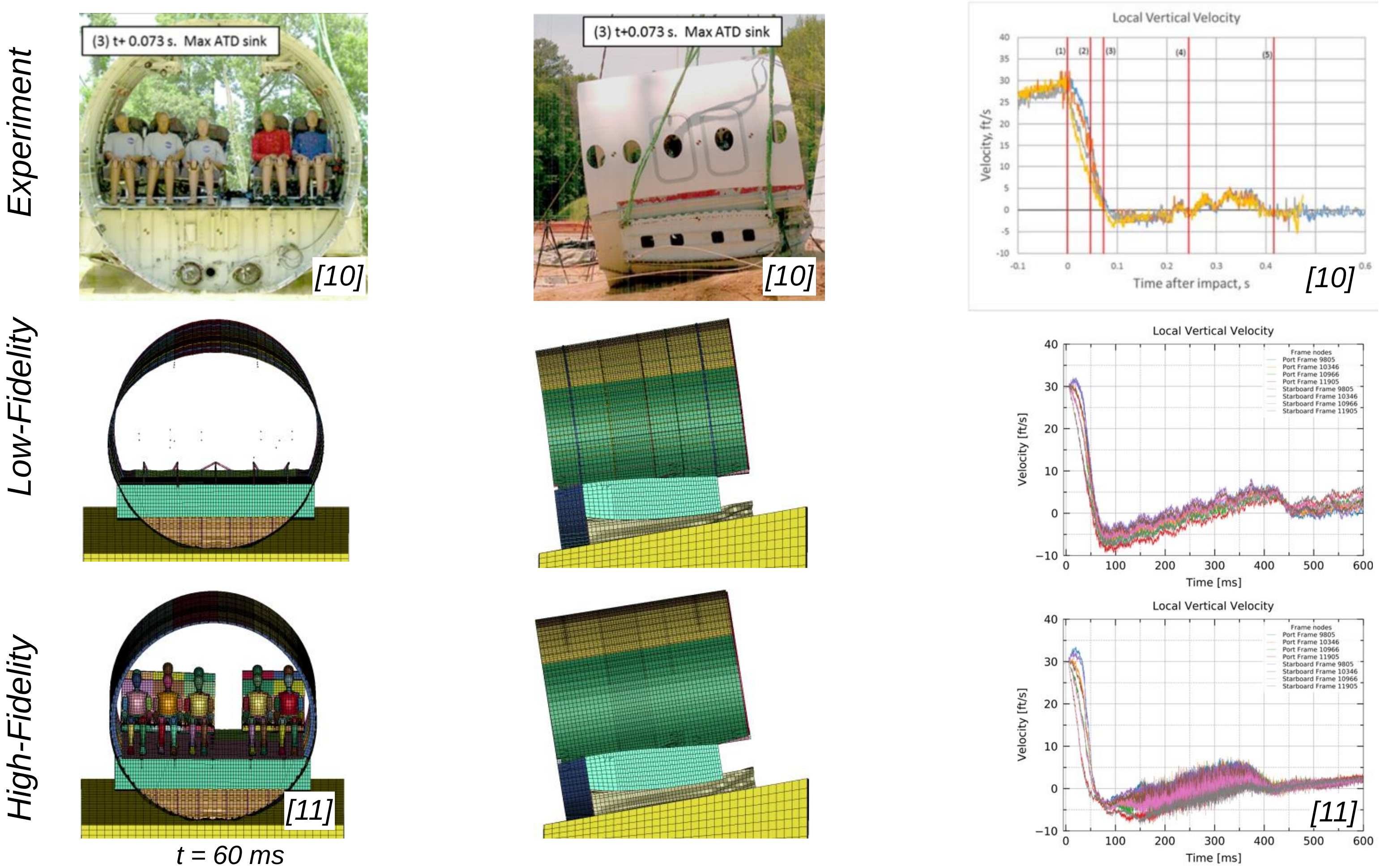

[11]


[10]

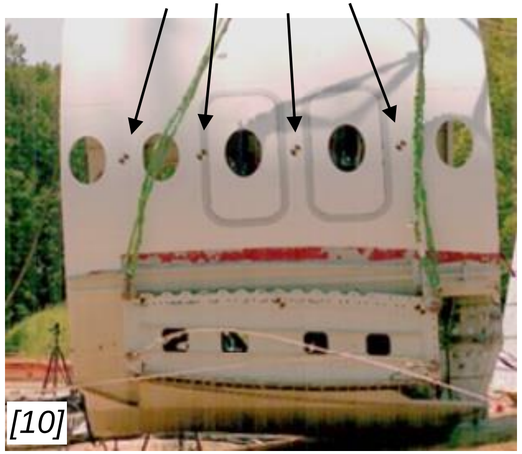
[12] J. Birk, "Numerical Simulation of a Crash Test on a Fokker F28 Typical Fuselage Section with Cargo Door and Bulk Loading," DLR-IB-BT-ST-2021-147, 2021.

2 Method validation
Current status

Partial validation of simulation methods on the basis Fokker F28 full scale crash test data



t = 60 ms
ATD maximum sink position



3 Method application

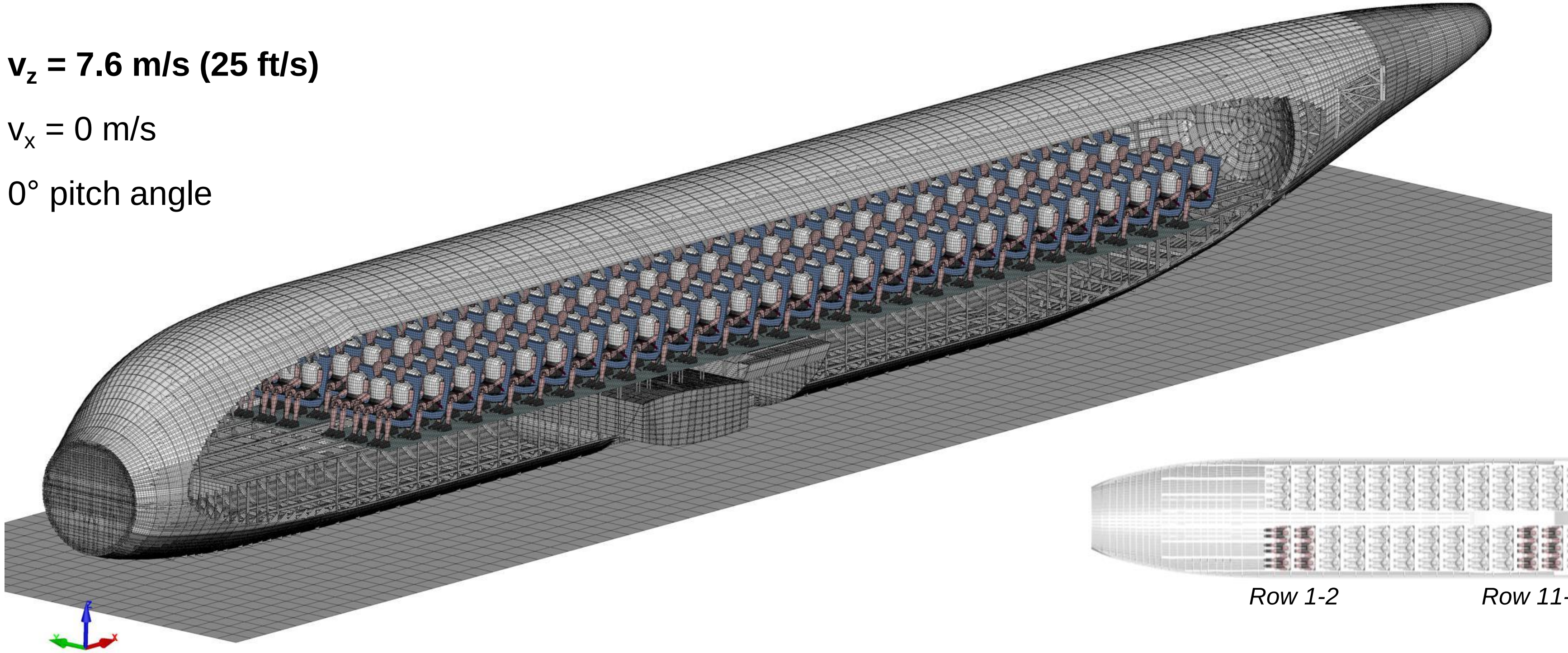
Examples (generic single-aisle aircraft)

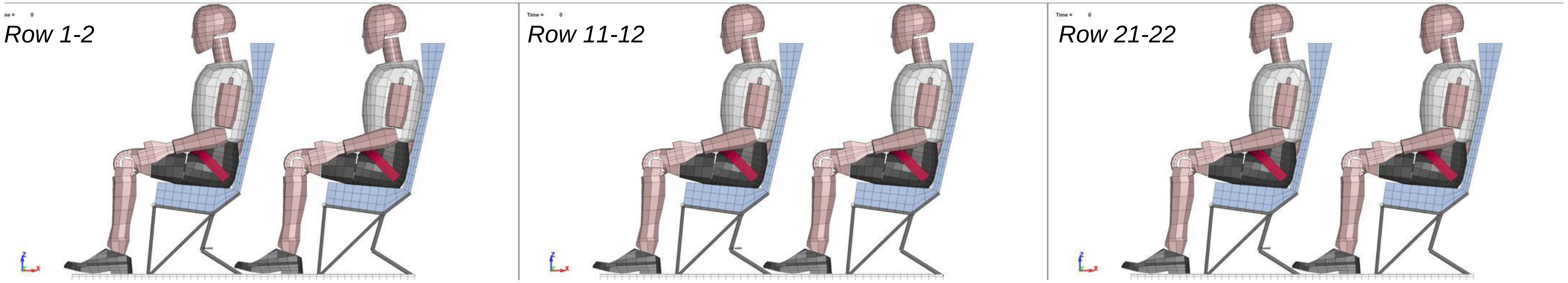
3 Method application (examples)

I) Vertical drop of full aircraft model

Crash kinematics

- **v_z = 7.6 m/s (25 ft/s)**
- v_x = 0 m/s
- 0° pitch angle





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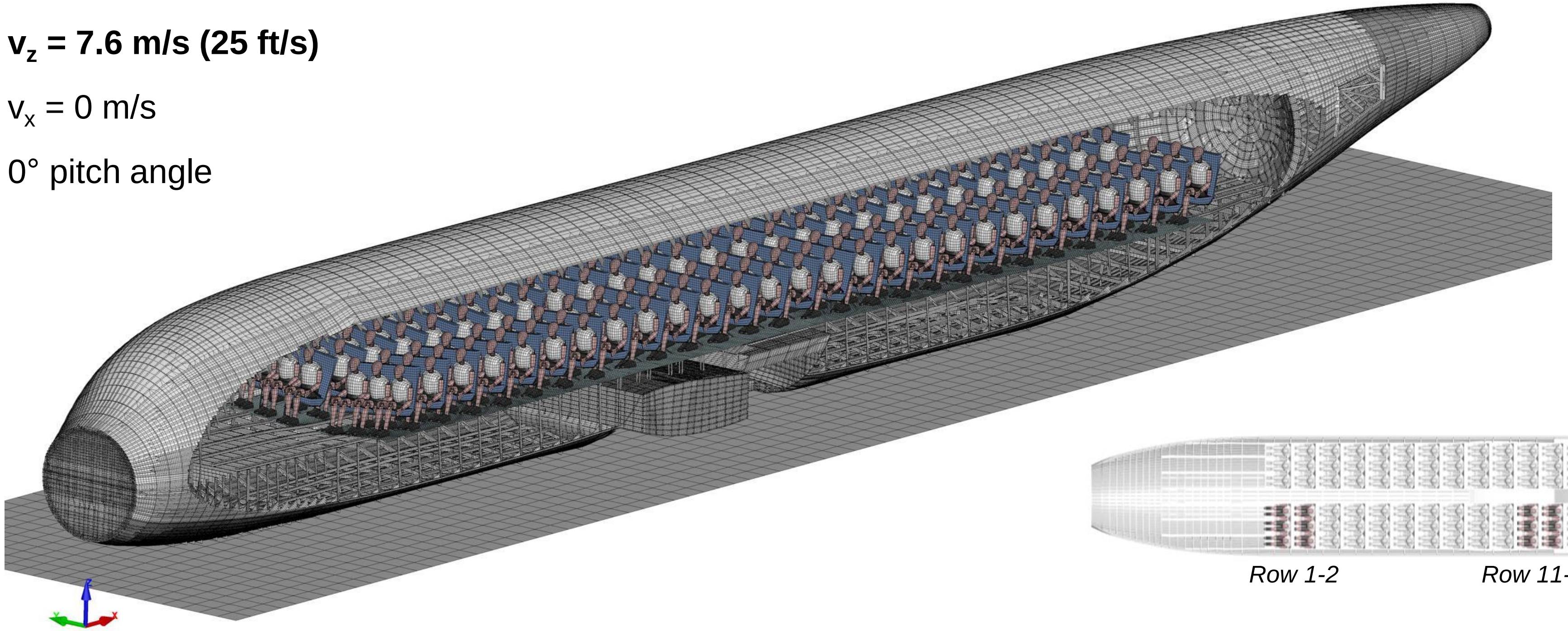

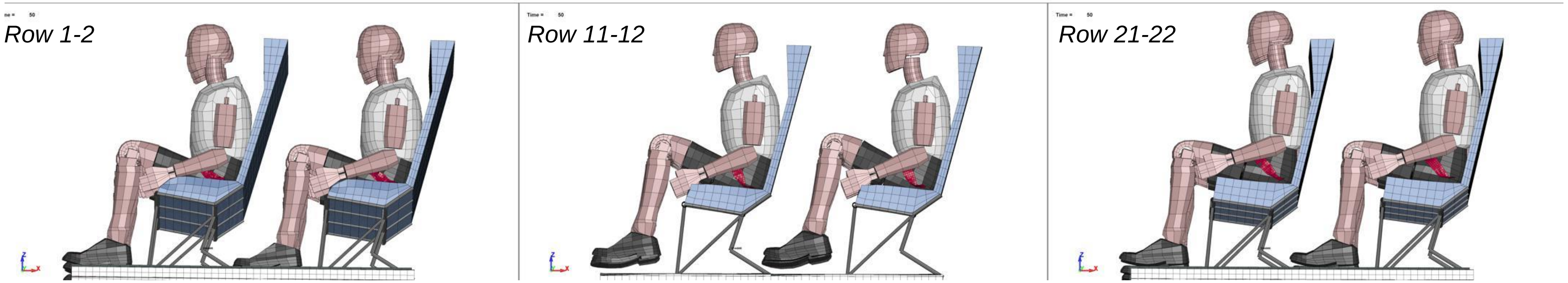

3 Method application (examples)
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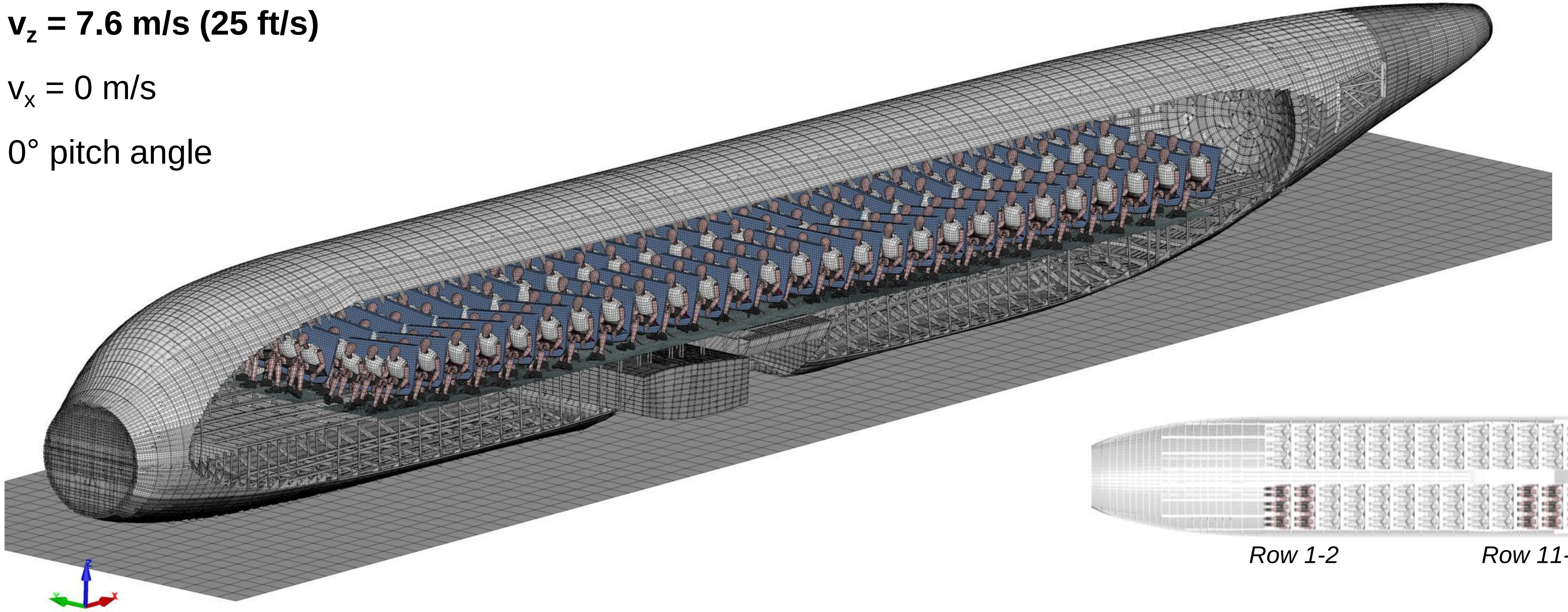

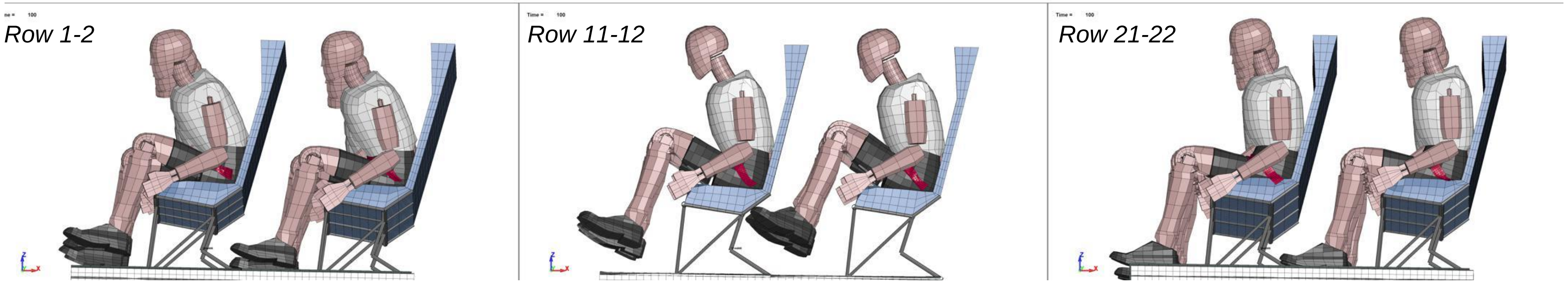

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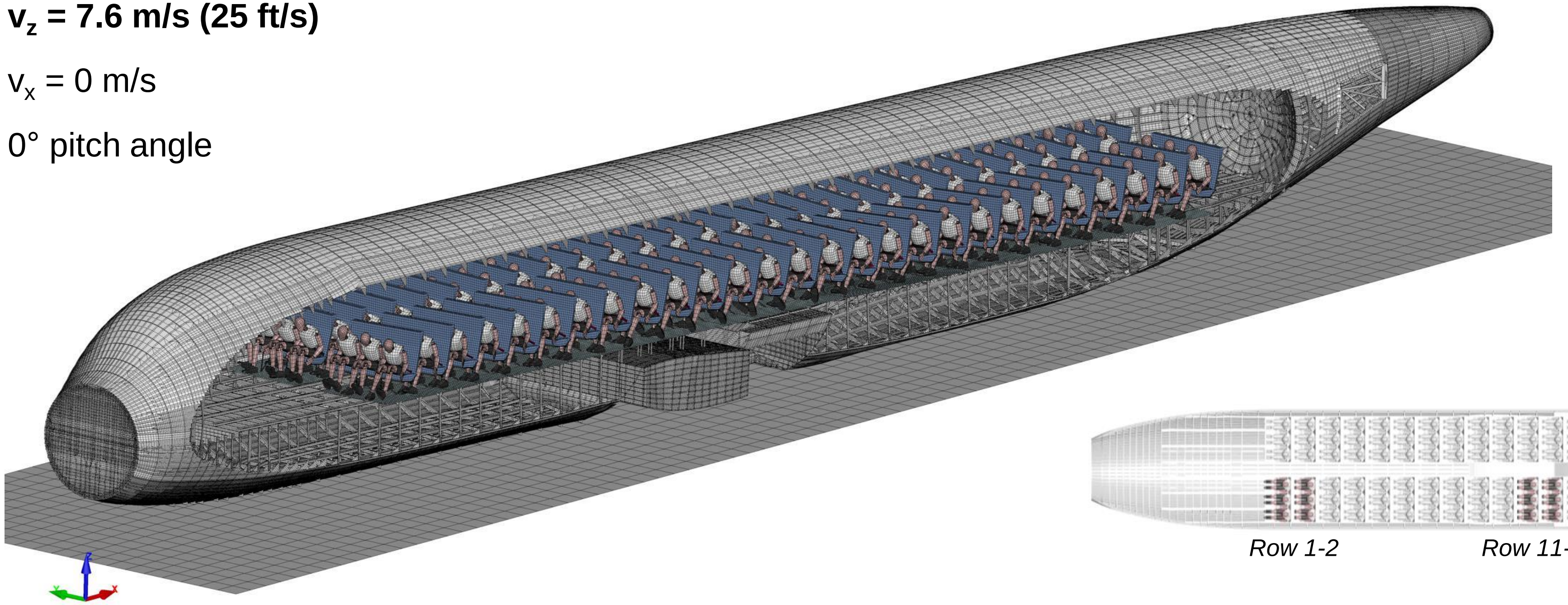

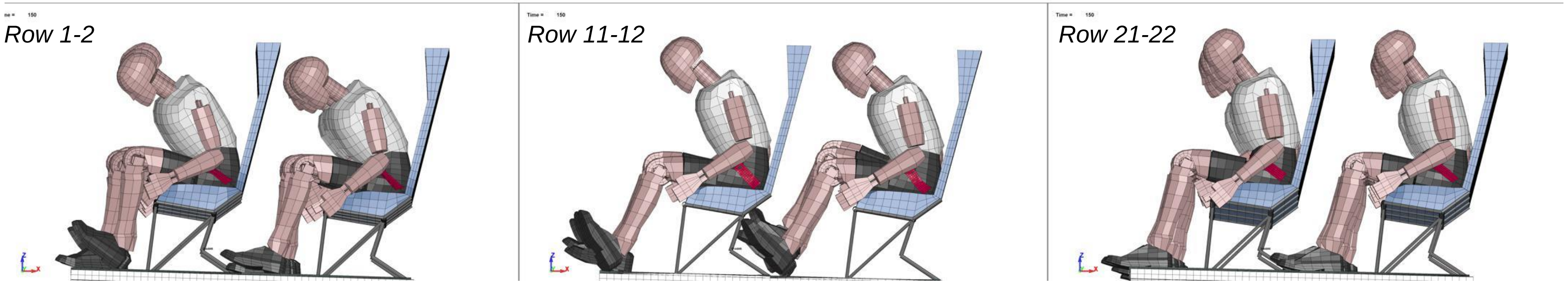

3 Method application (examples)

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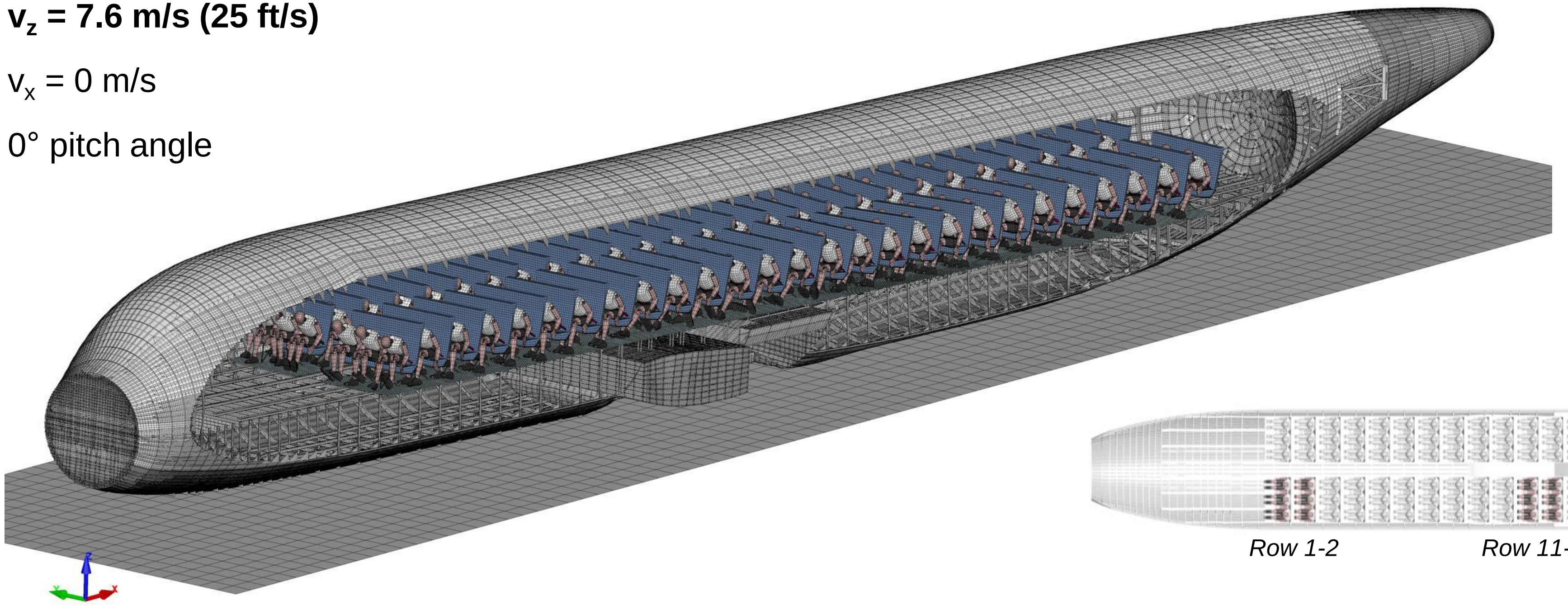

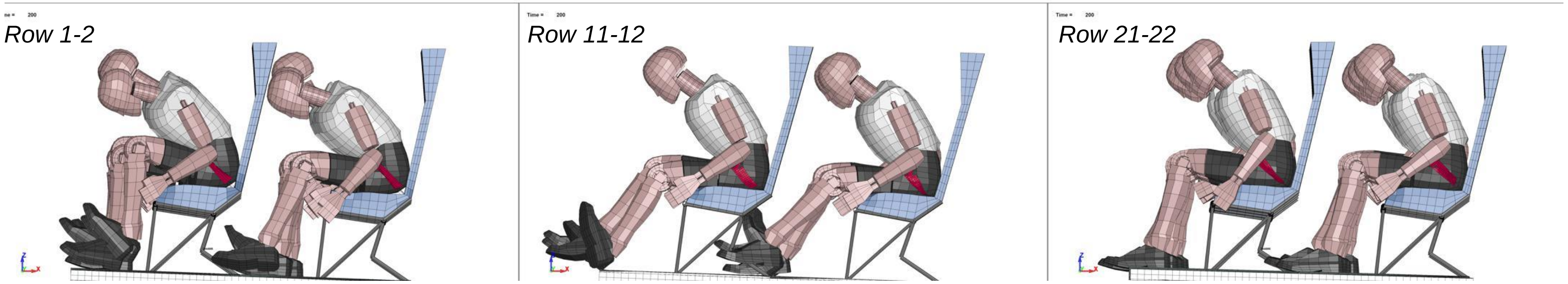

3 Method application (examples)
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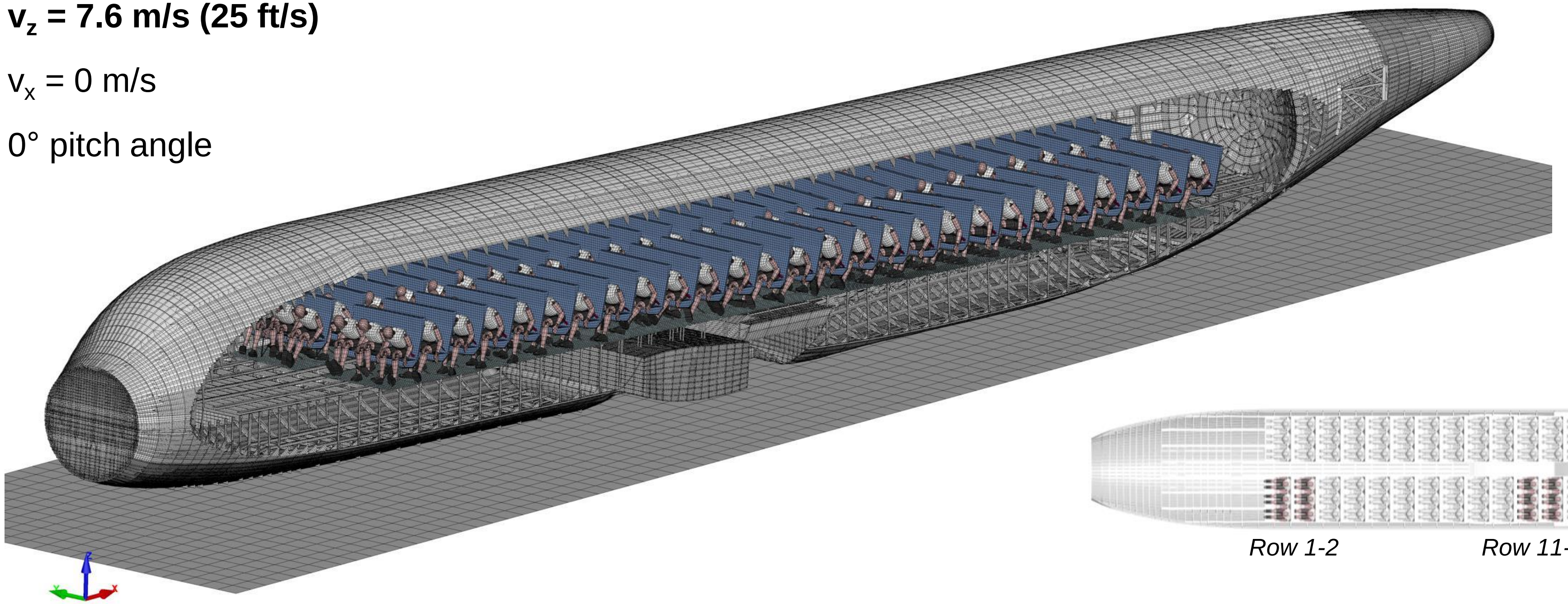

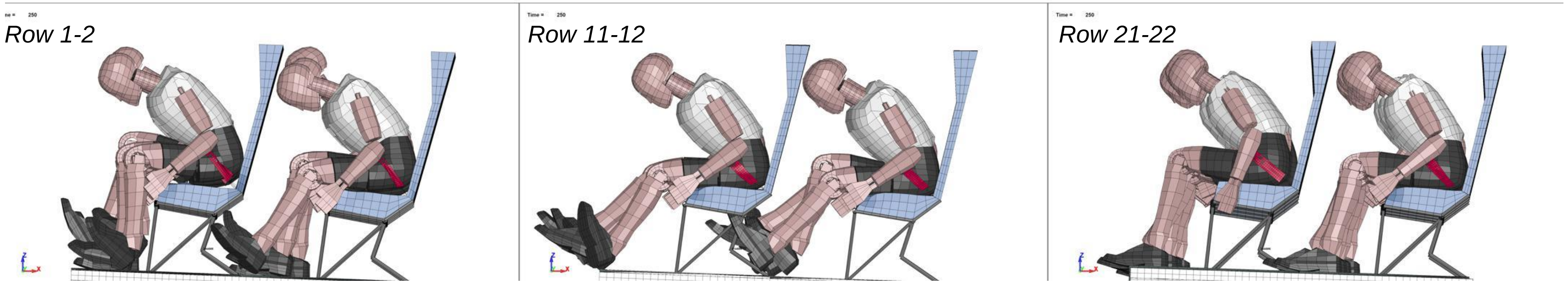

3 Method application (examples)

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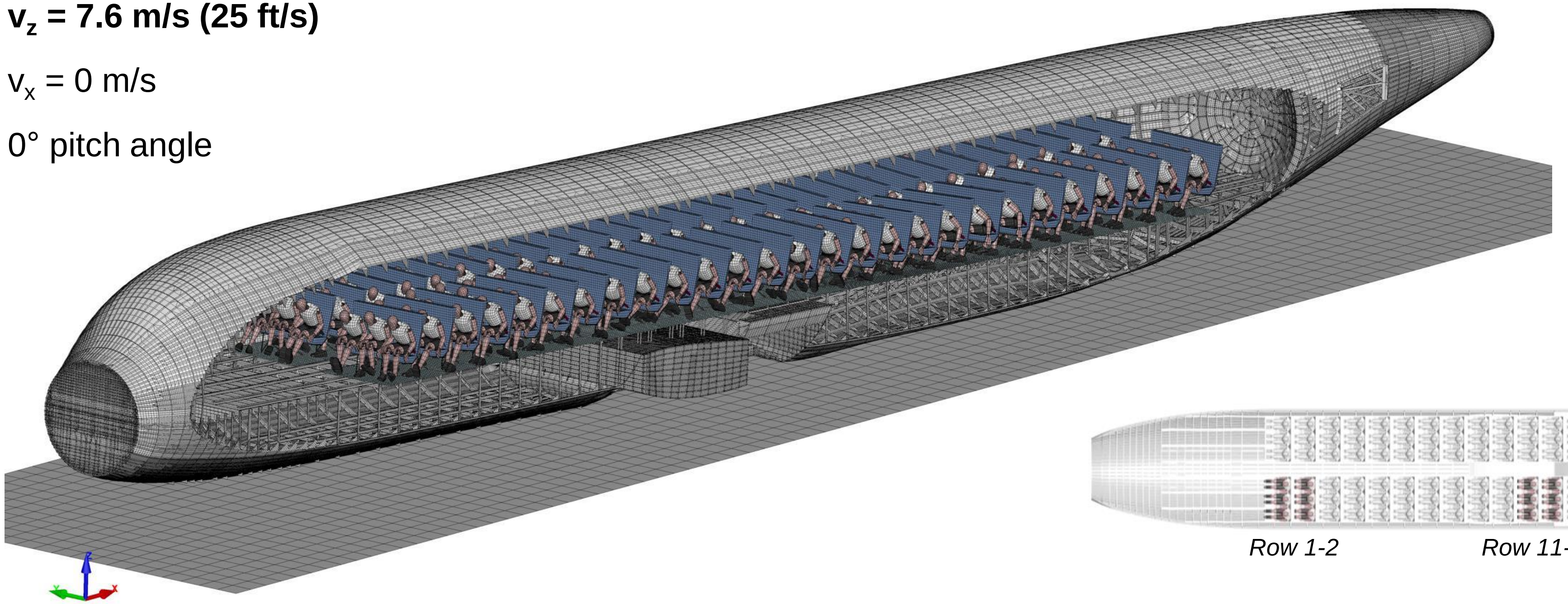
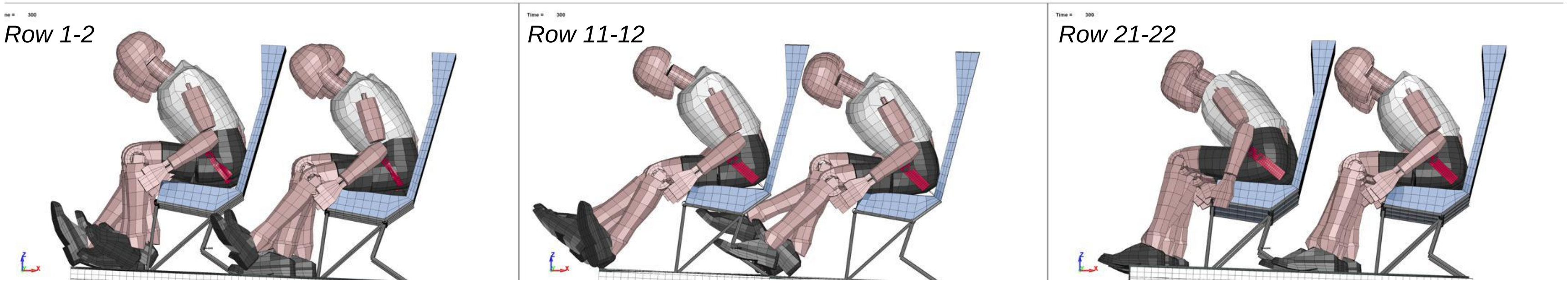
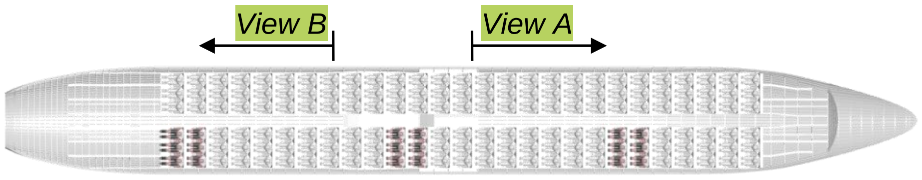




3 Method application (examples)

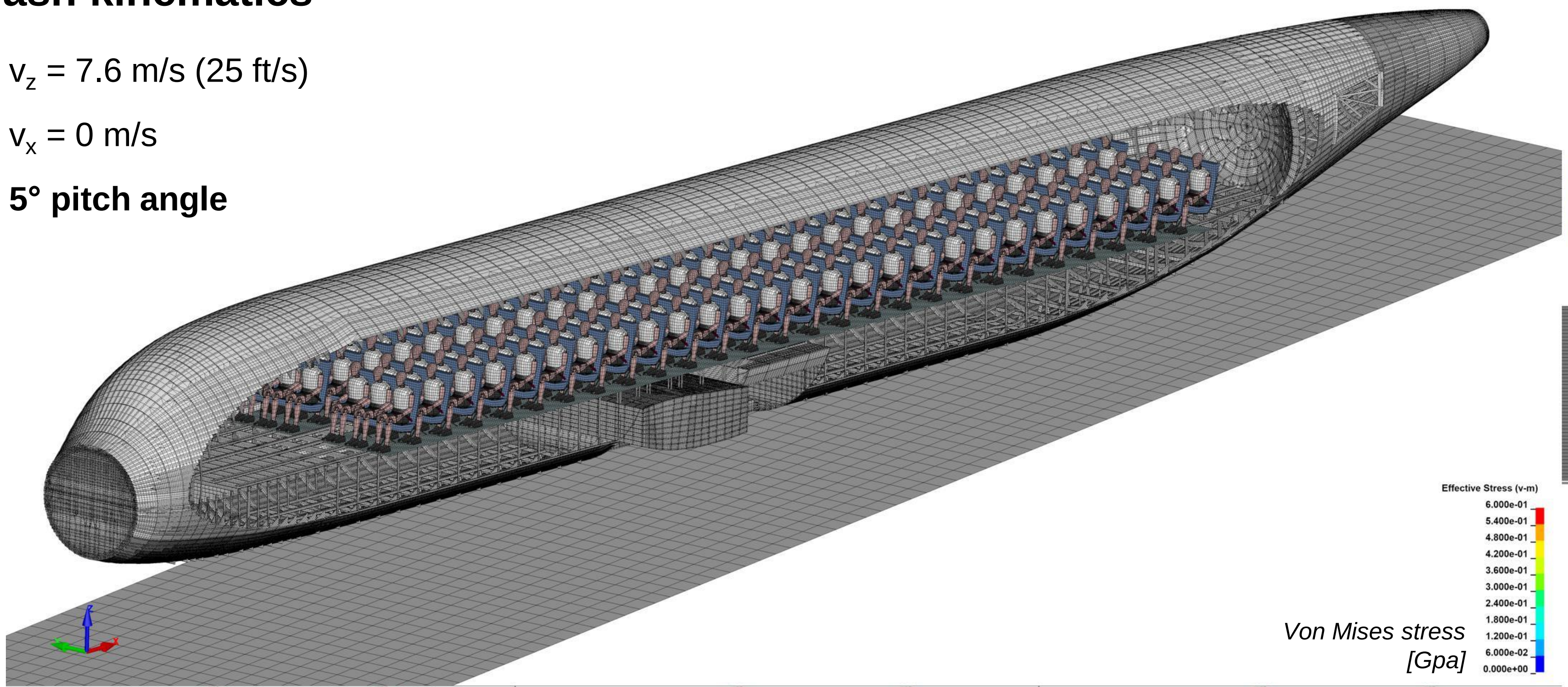
II) Vertical drop with pitch angle

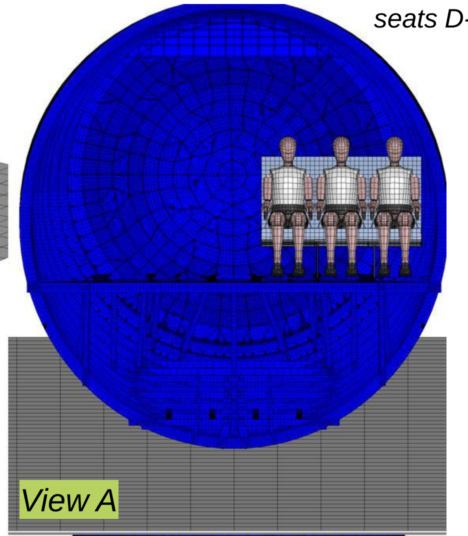


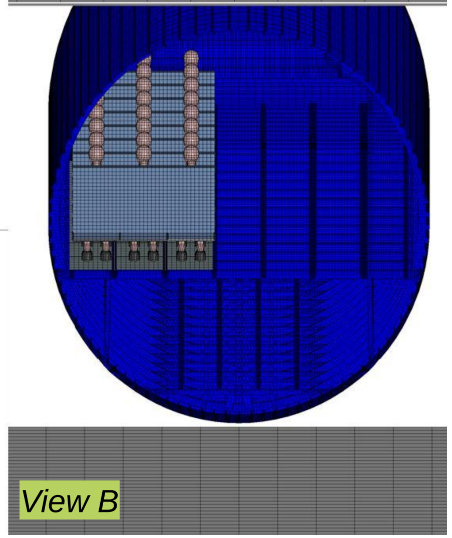
Crash kinematics

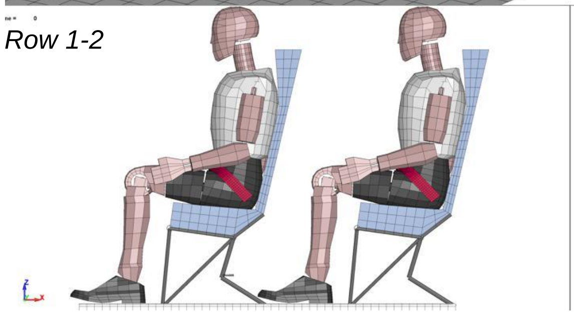
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**

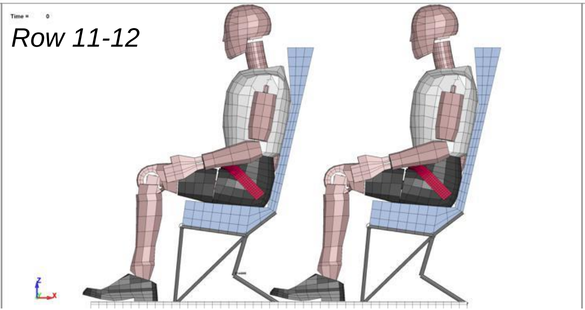
In view A and view B seats A-C displayed, seats D-F hidden

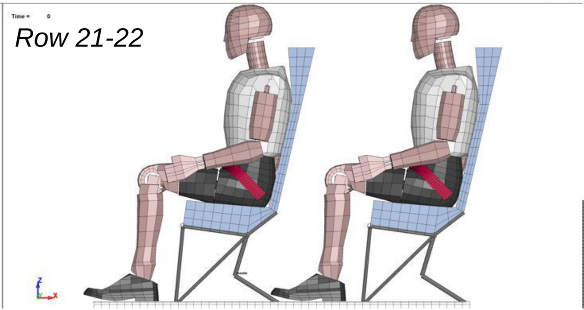






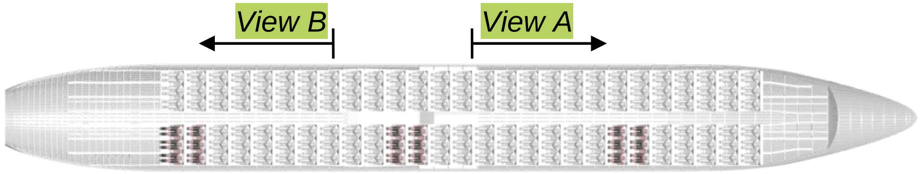






3 Method application (examples)

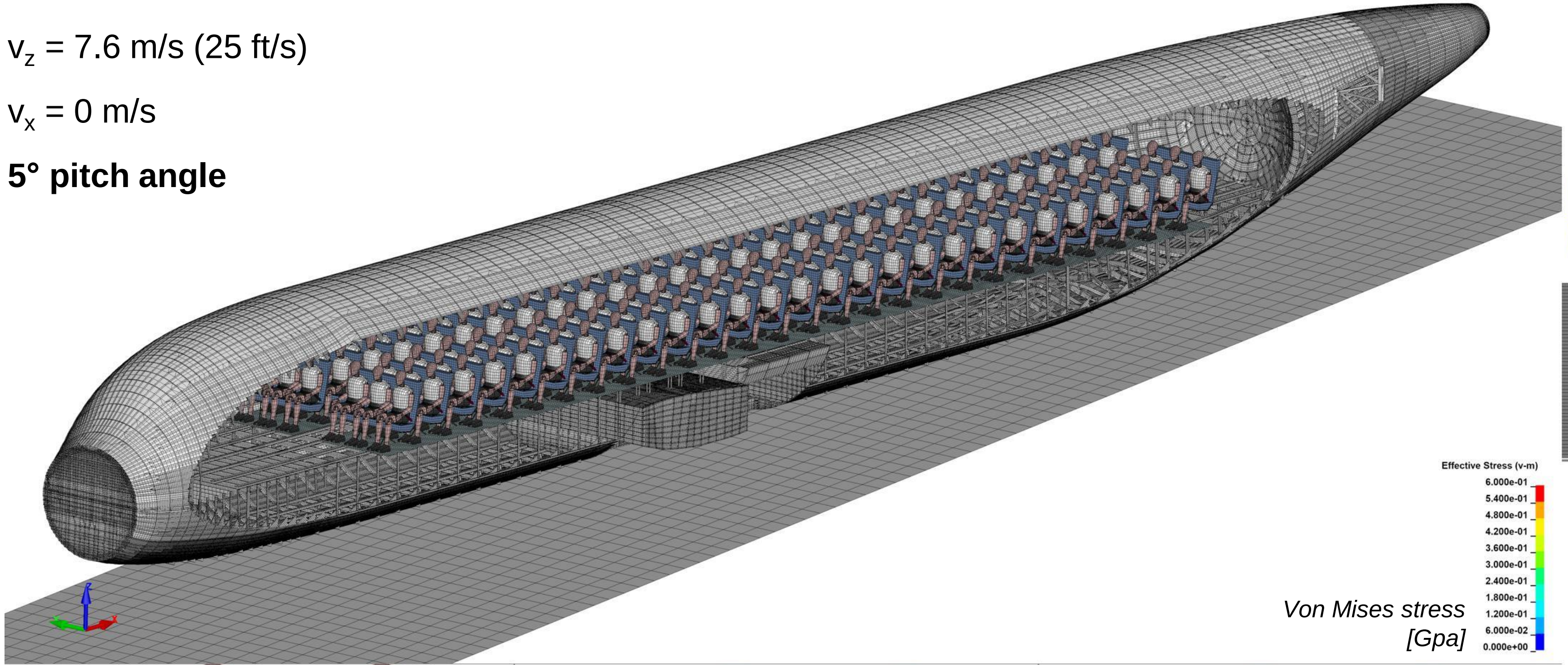
II) Vertical drop with pitch angle

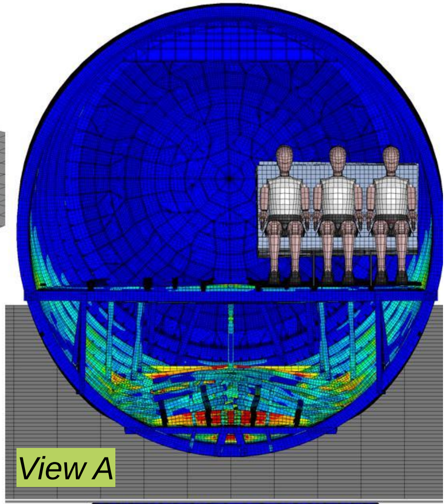


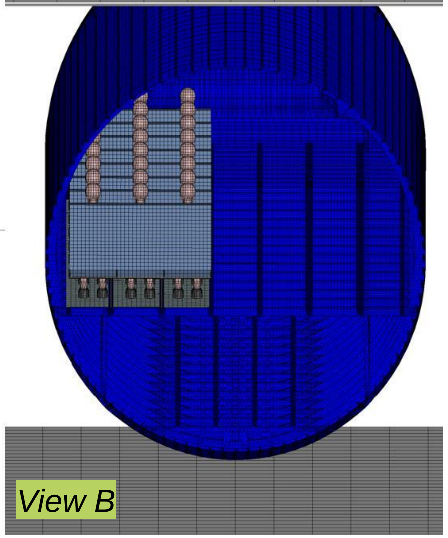
In view A and view B seats A-C displayed, seats D-F hidden

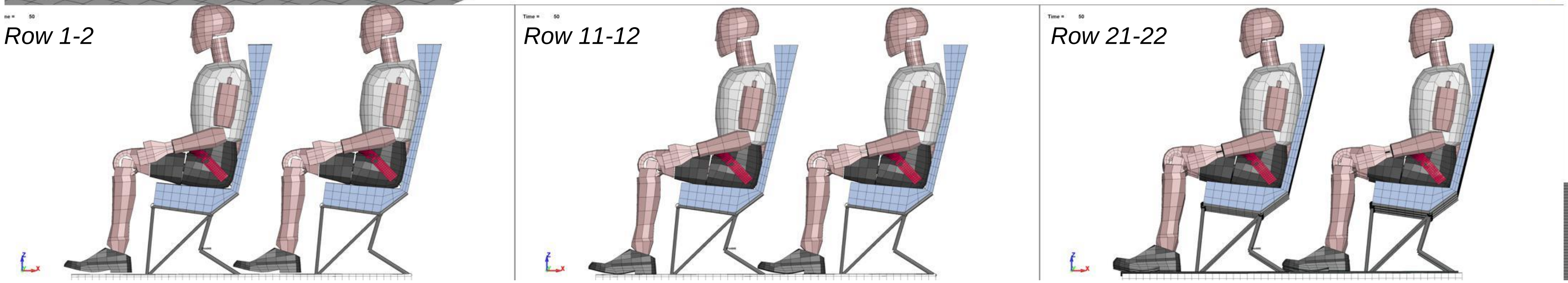
Crash kinematics

- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**









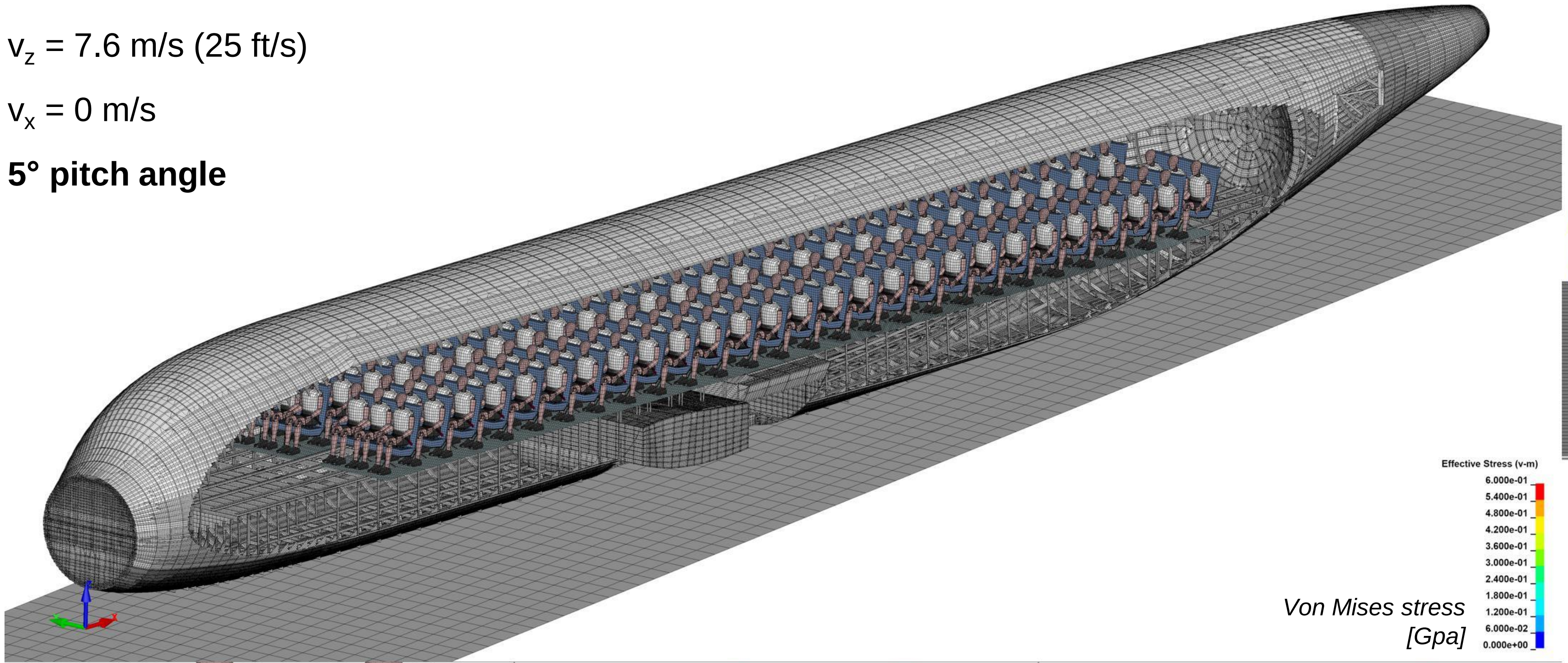
3 Method application (examples)
II) Vertical drop with pitch angle

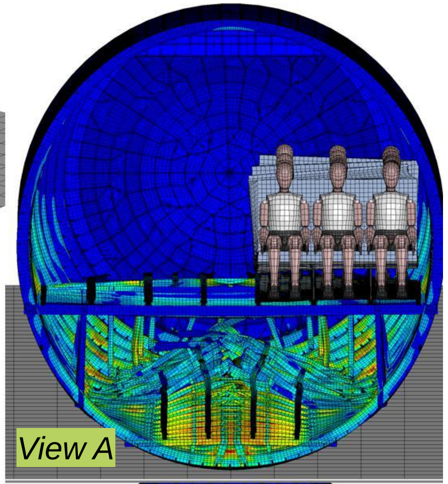
DLR

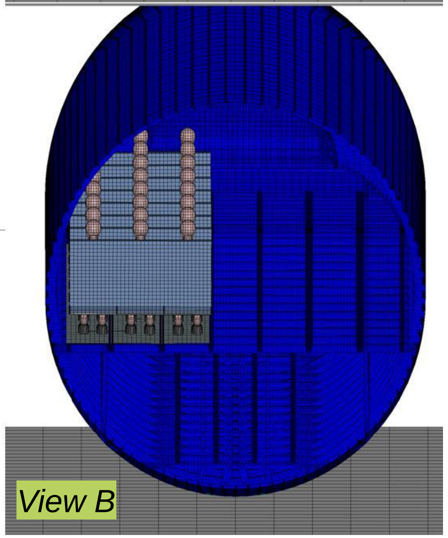
In view A and view B seats A-C displayed, seats D-F hidden

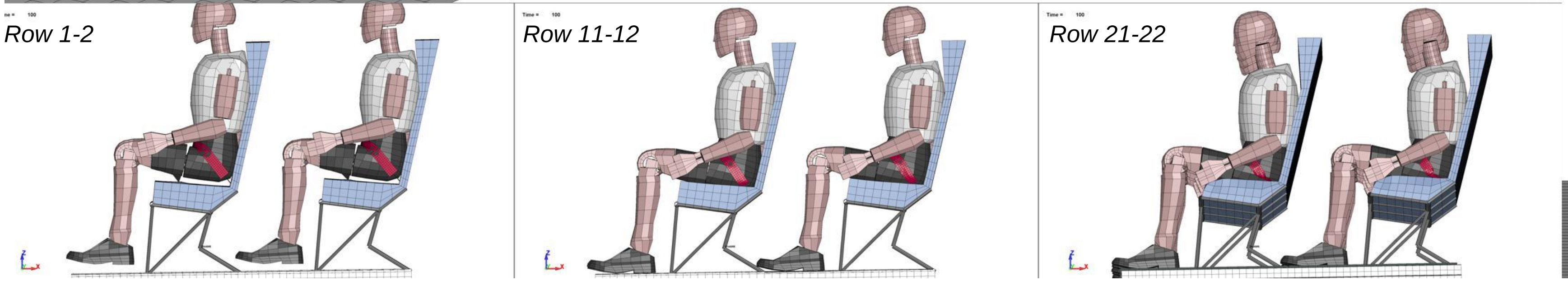
Crash kinematics

- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**









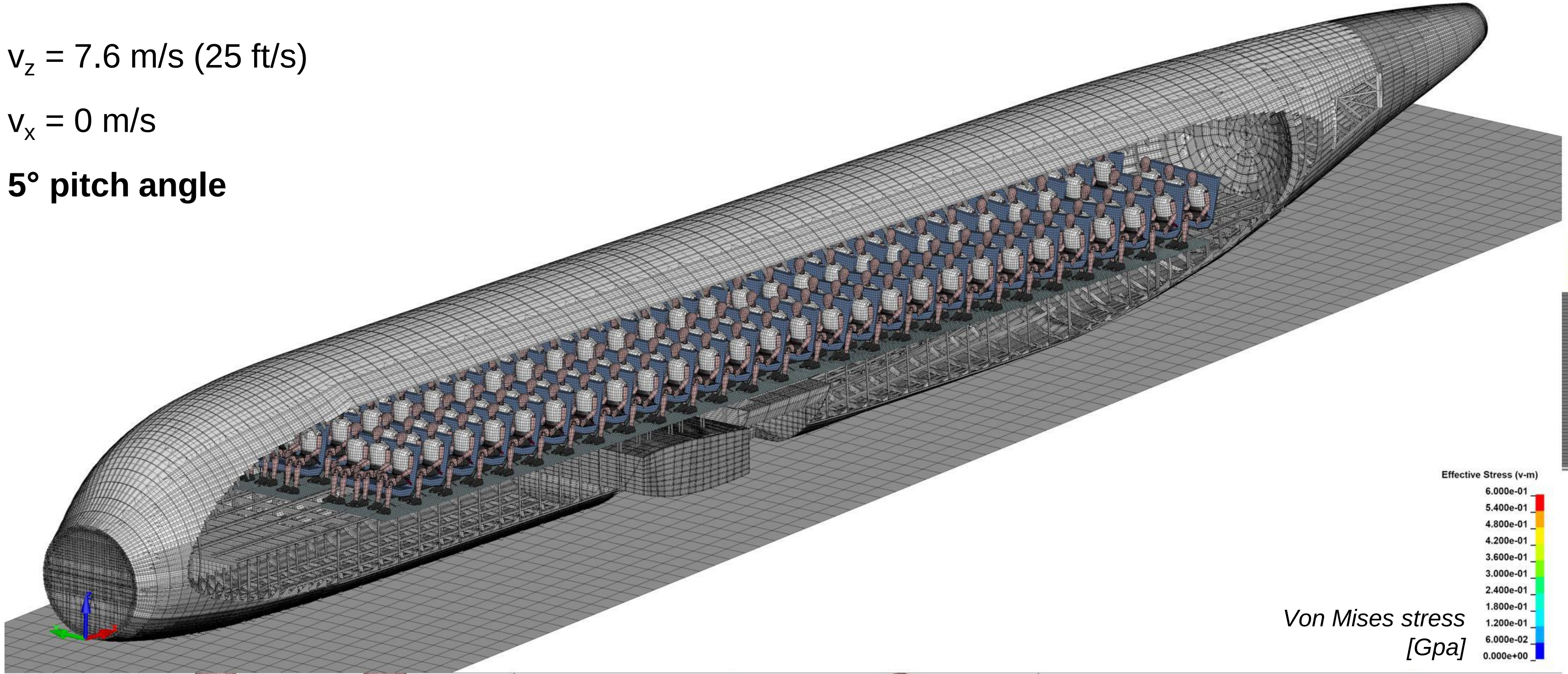
3 Method application (examples)

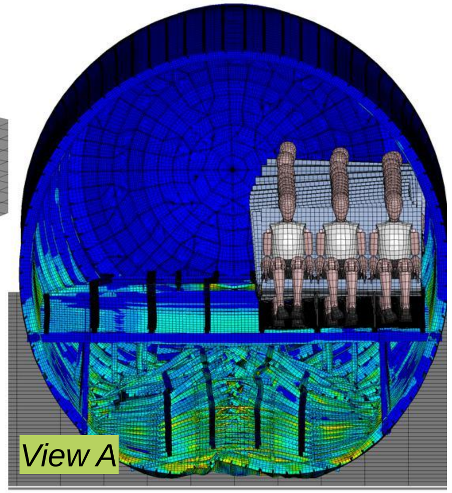
II) Vertical drop with pitch angle

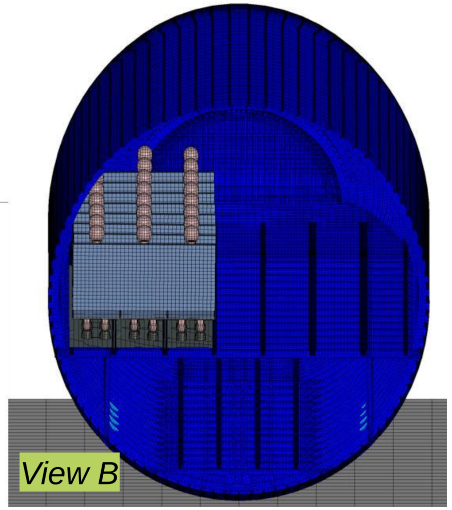
In view A and view B seats A-C displayed, seats D-F hidden

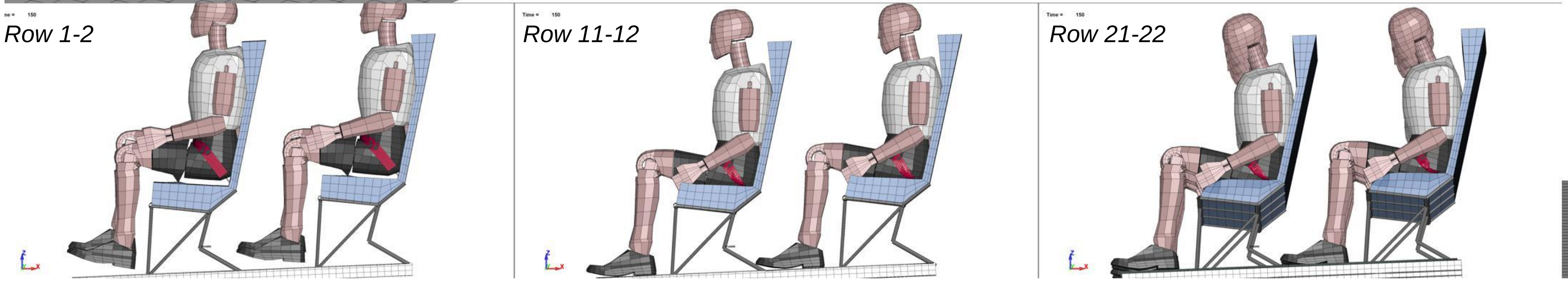
Crash kinematics

- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**



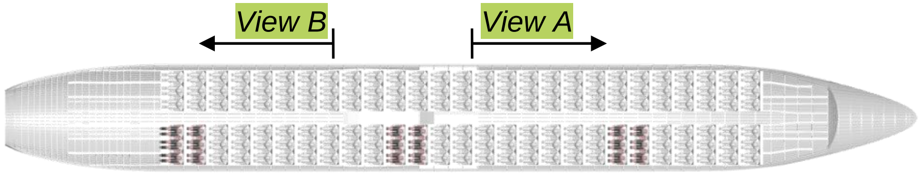






3 Method application (examples)

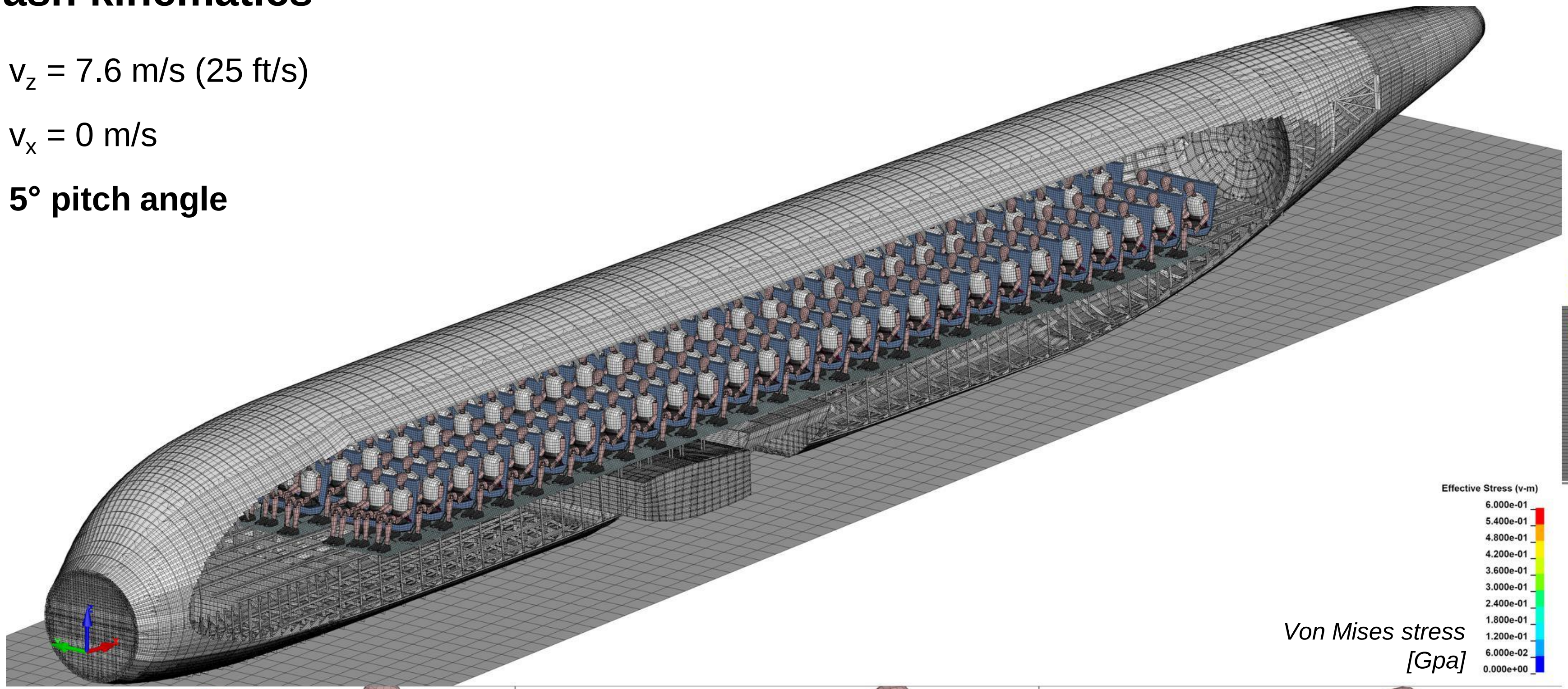
II) Vertical drop with pitch angle



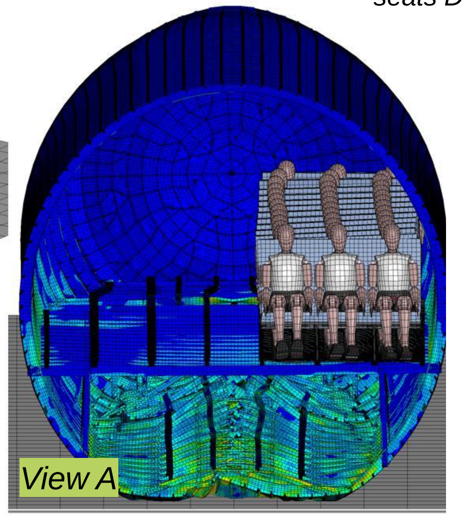
In view A and view B seats A-C displayed, seats D-F hidden

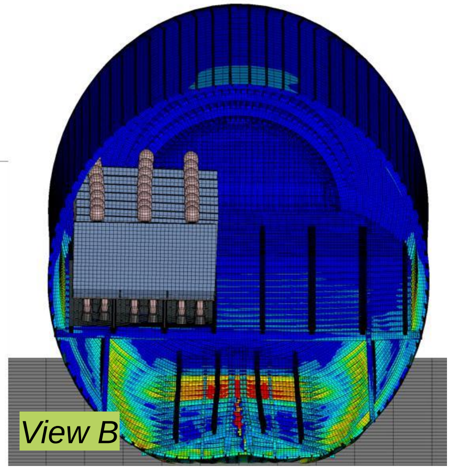
Crash kinematics

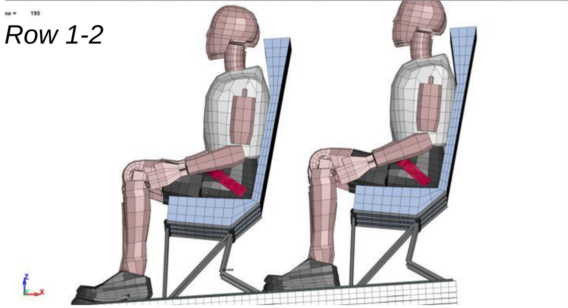
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**

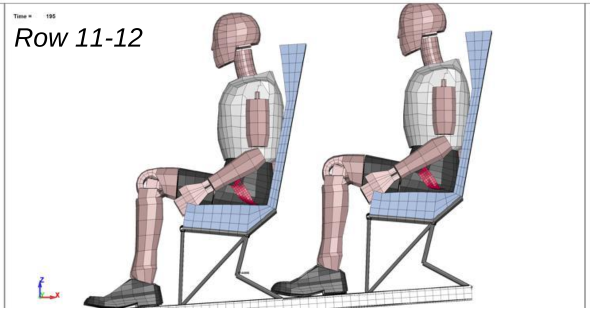


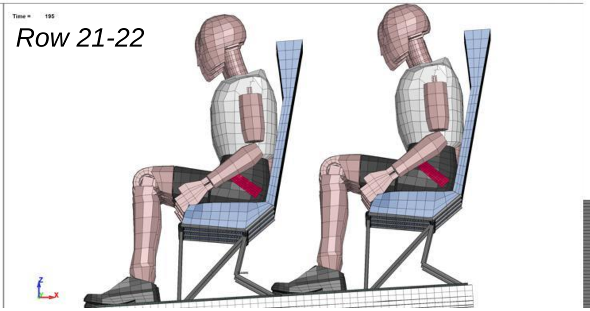
Von Mises stress [Gpa]





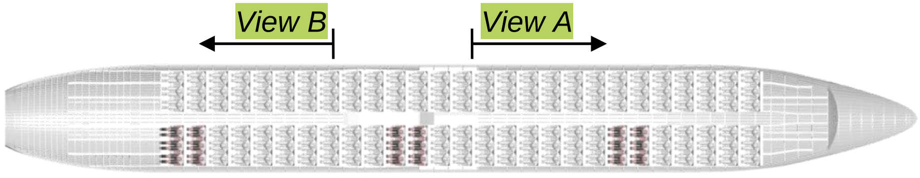






3 Method application (examples)

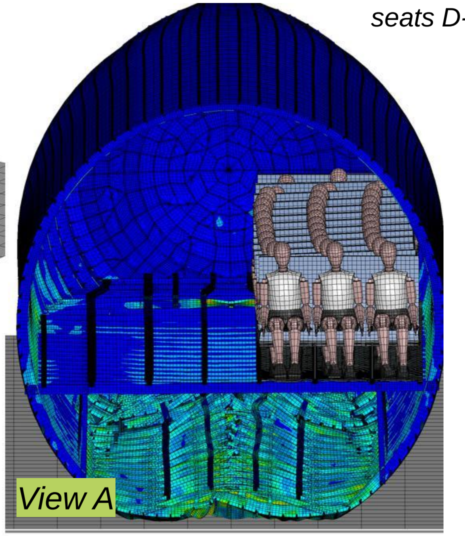
II) Vertical drop with pitch angle

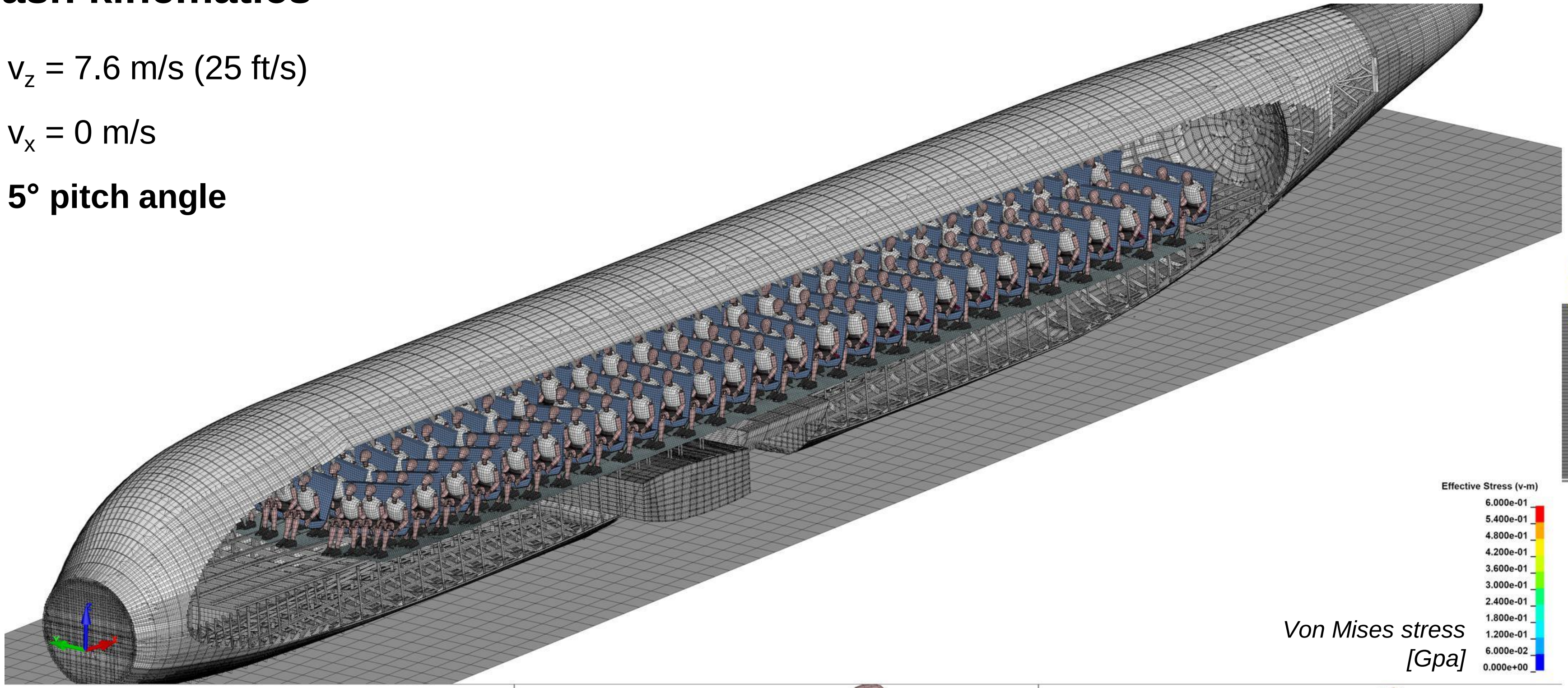


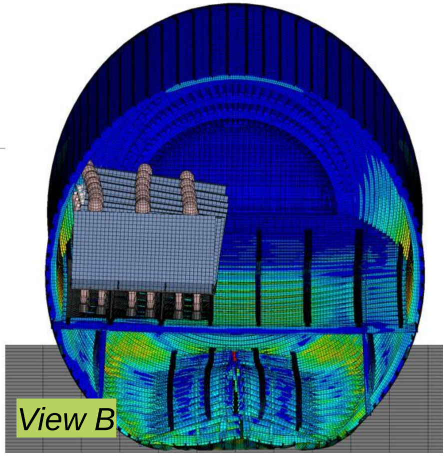
In view A and view B seats A-C displayed, seats D-F hidden

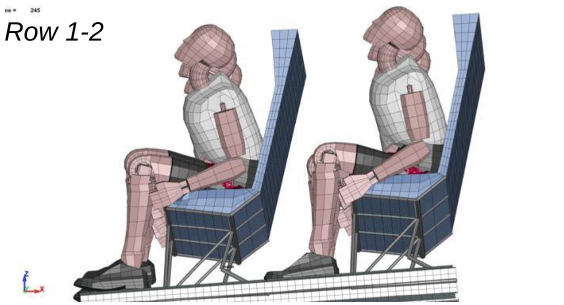
Crash kinematics

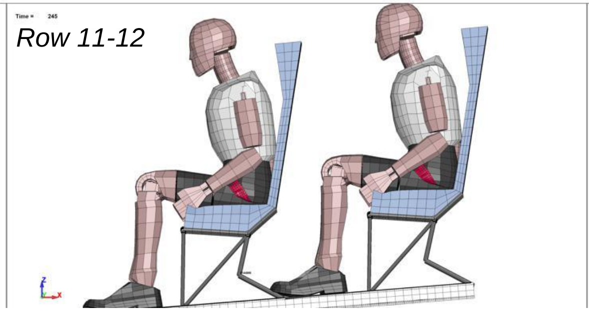
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**

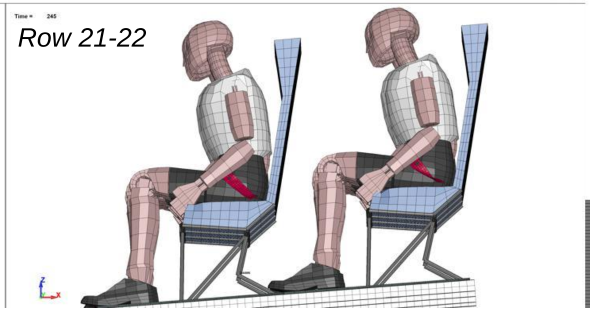






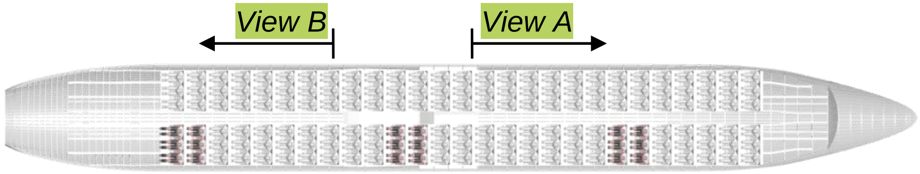






3 Method application (examples)

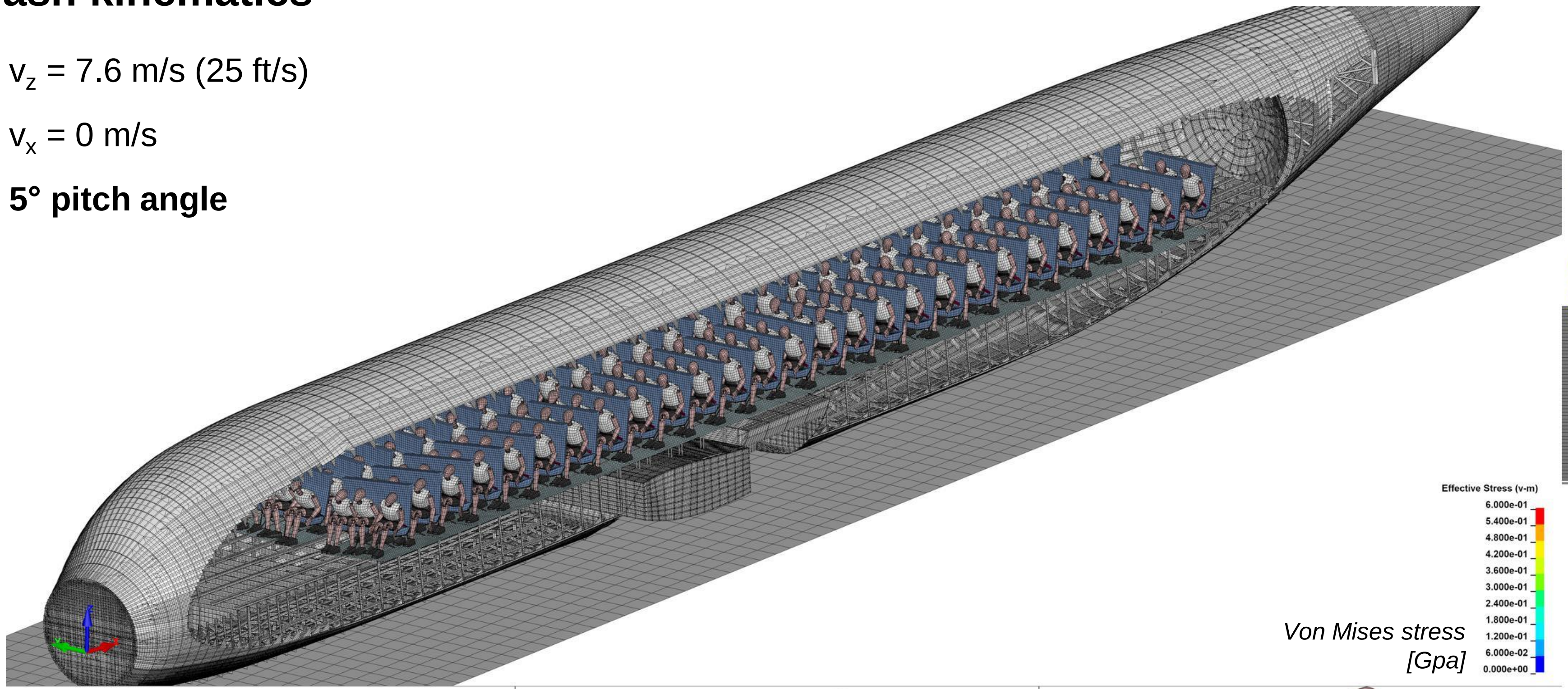
II) Vertical drop with pitch angle

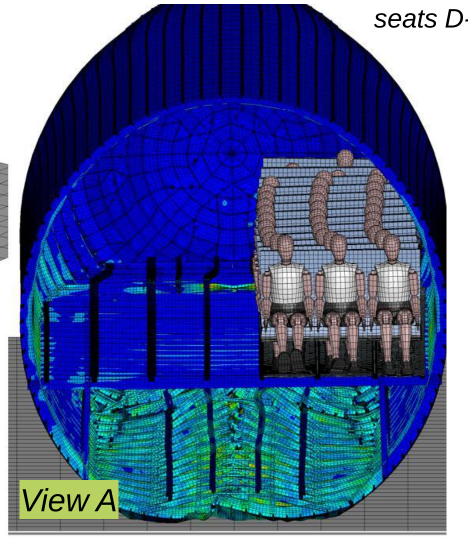


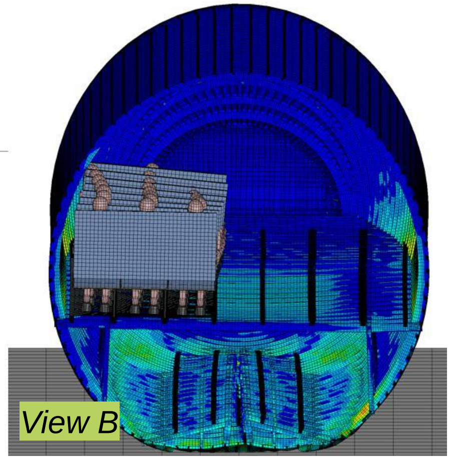
Crash kinematics

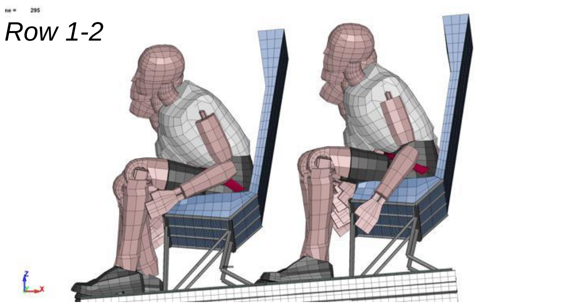
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**

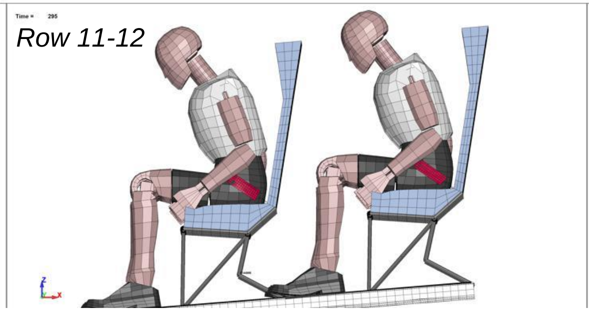
In view A and view B seats A-C displayed, seats D-F hidden

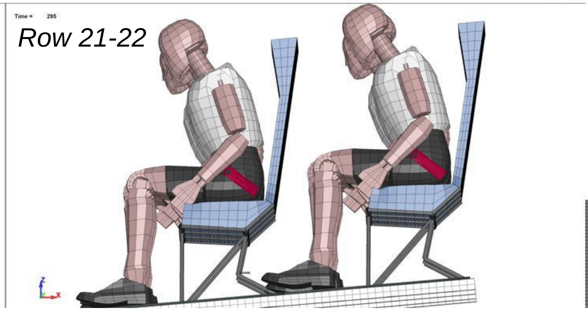






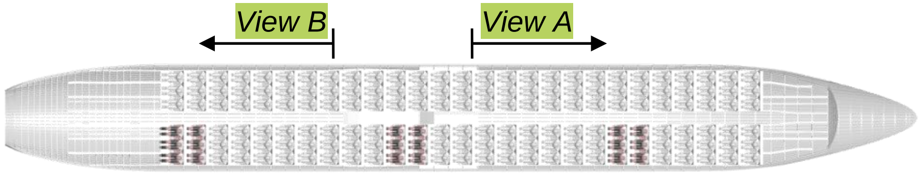






3 Method application (examples)

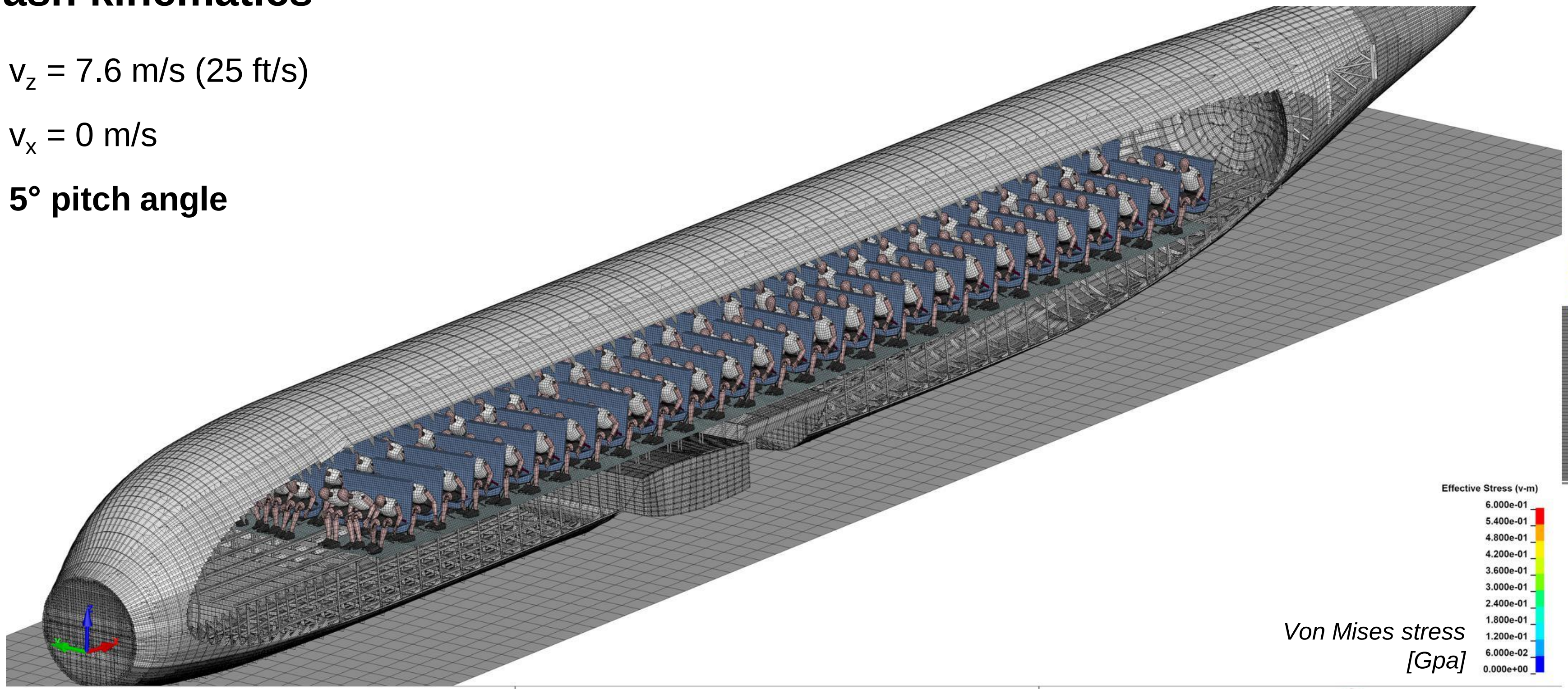
II) Vertical drop with pitch angle

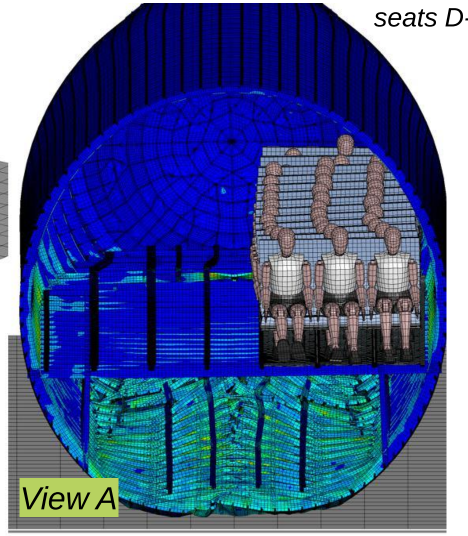


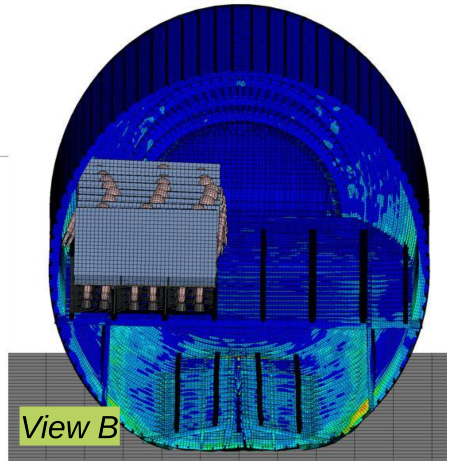
Crash kinematics

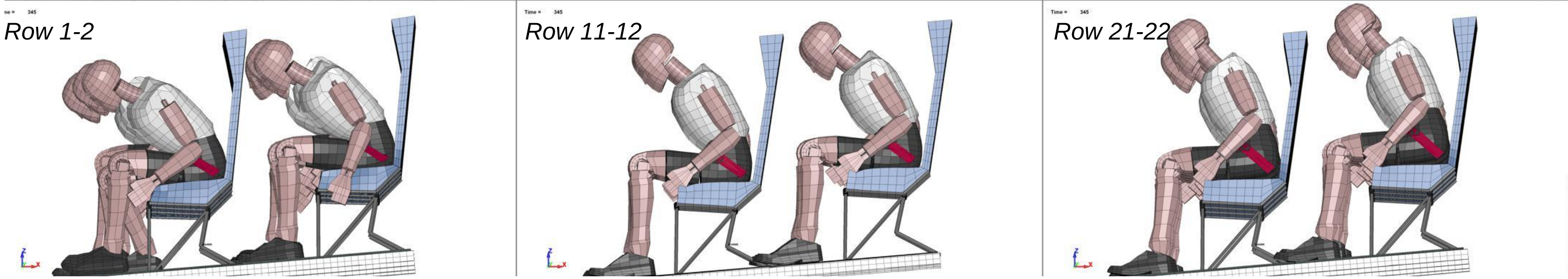
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- **5° pitch angle**

In view A and view B seats A-C displayed, seats D-F hidden



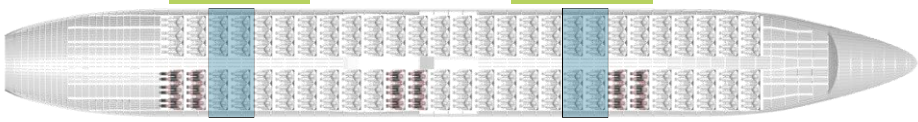






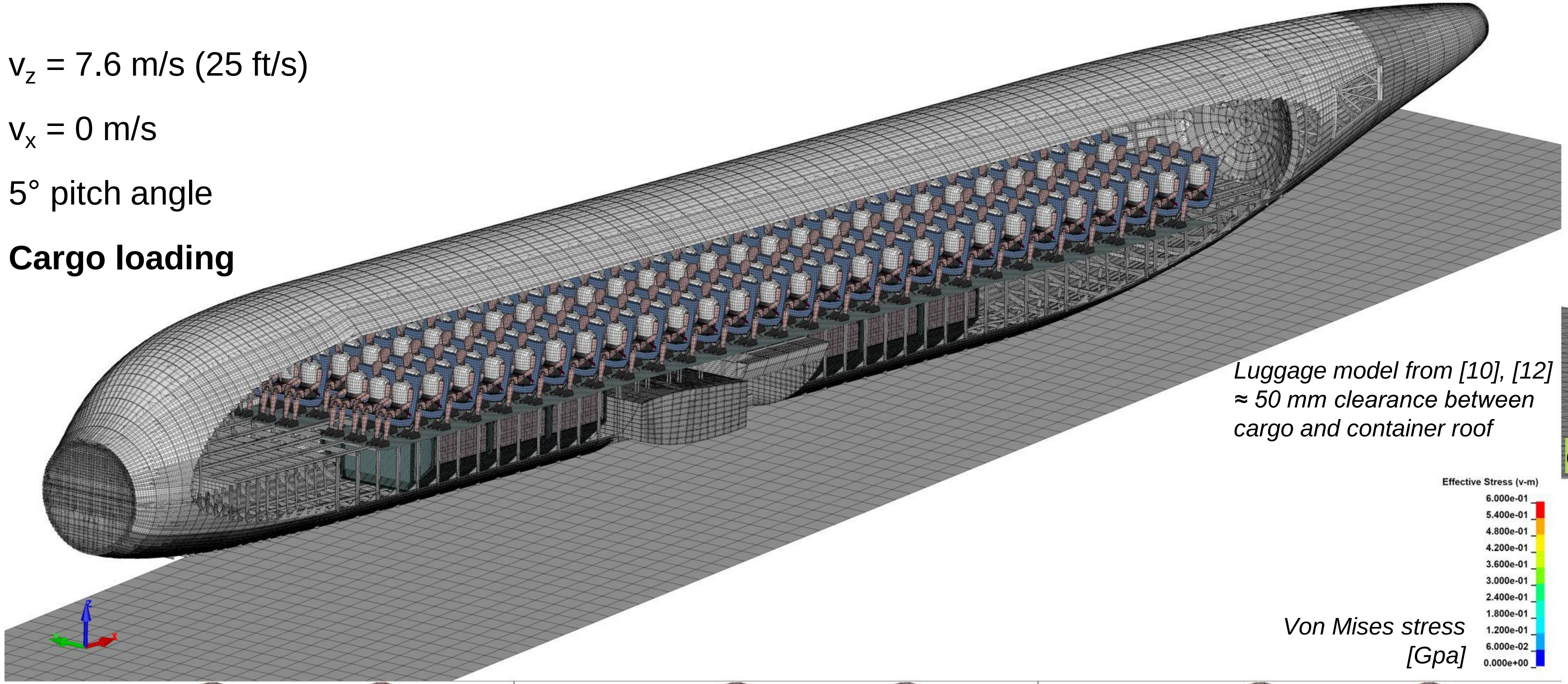
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

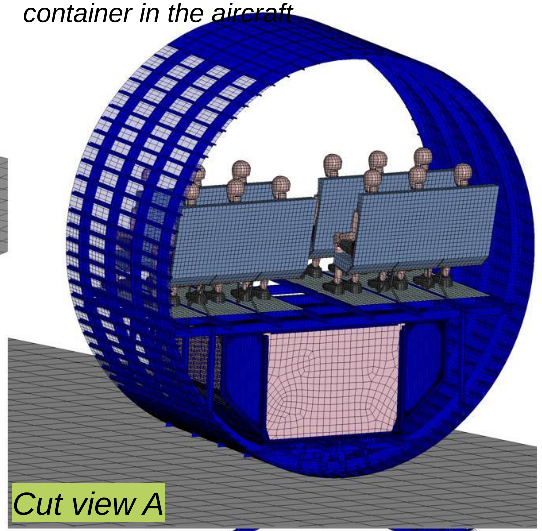


Crash kinematics

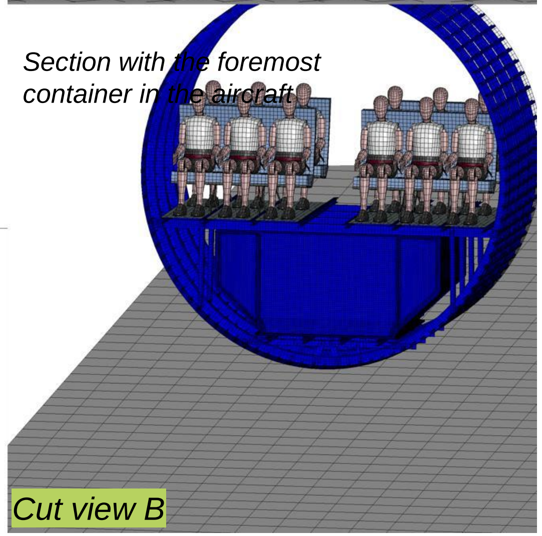
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

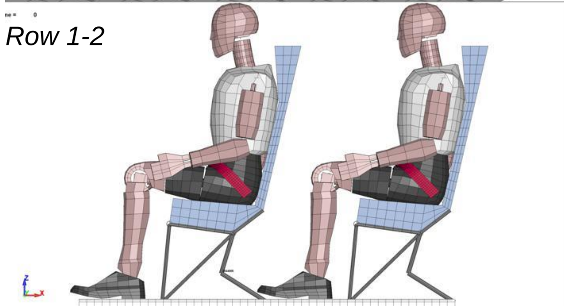


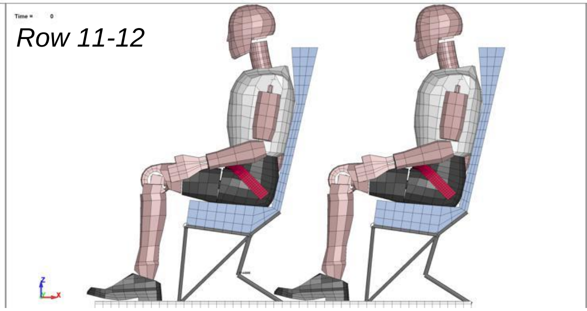
Section with the rearmost container in the aircraft

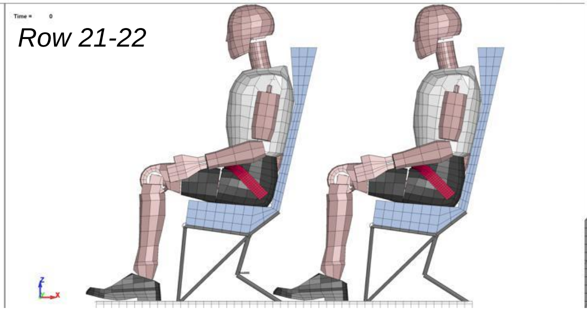


Section with the foremost container in the aircraft



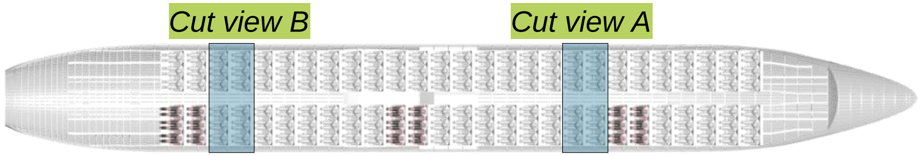






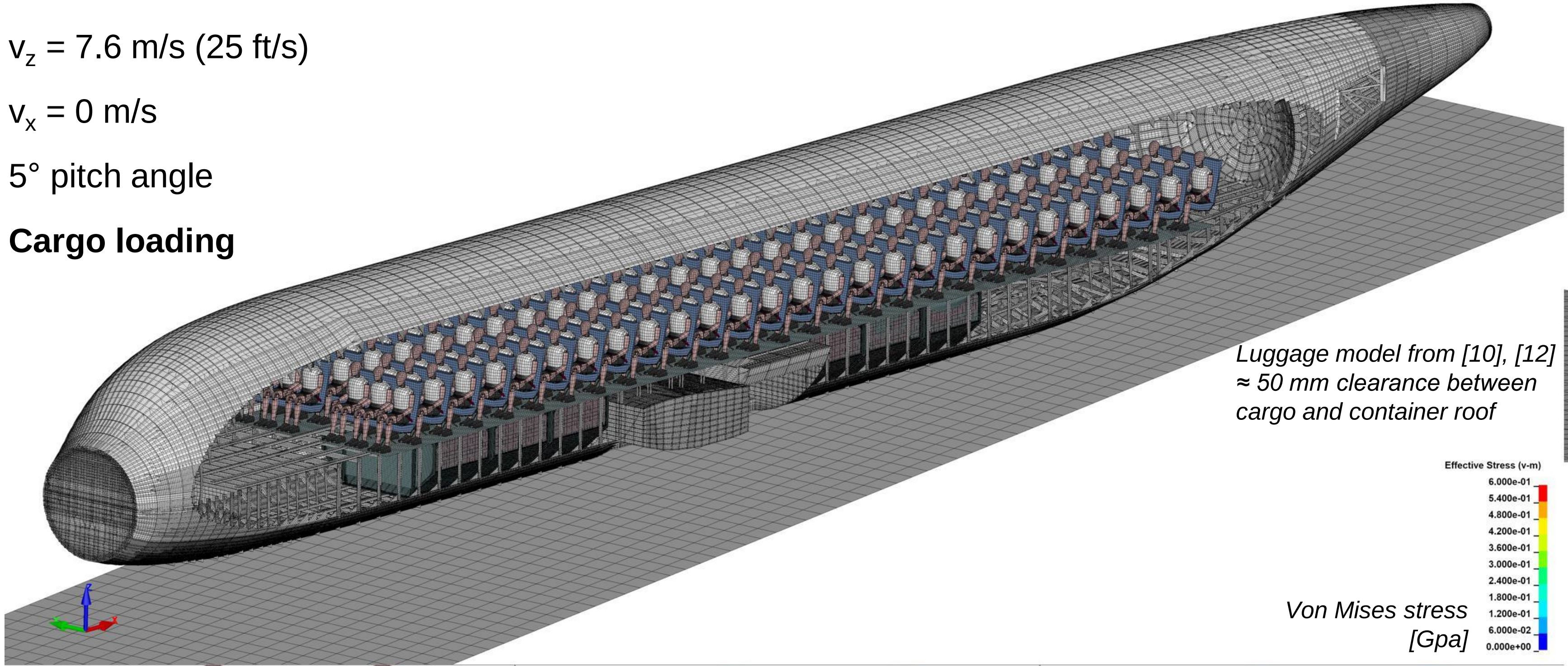
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading



Crash kinematics

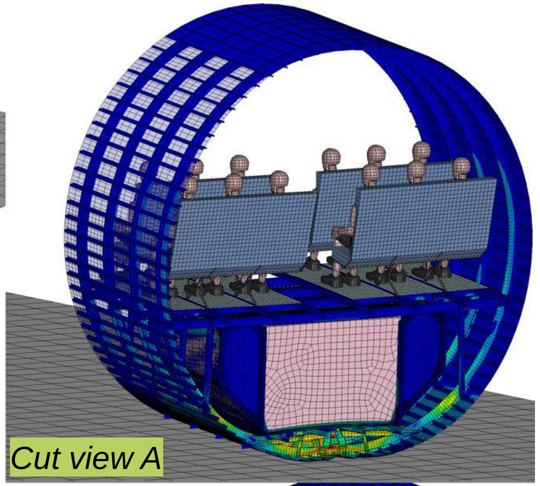
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**



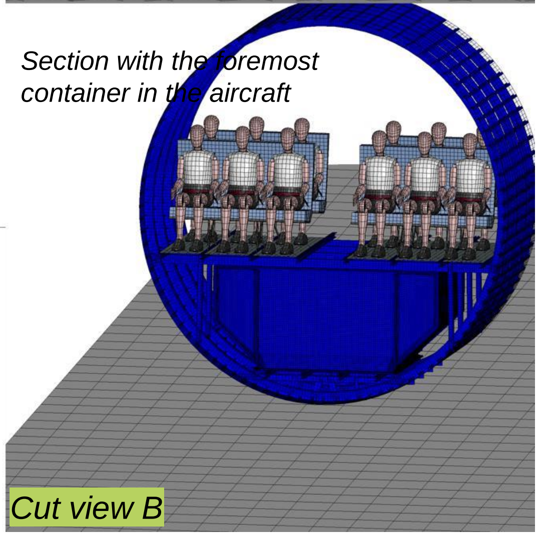
Luggage model from [10], [12]
≈ 50 mm clearance between cargo and container roof

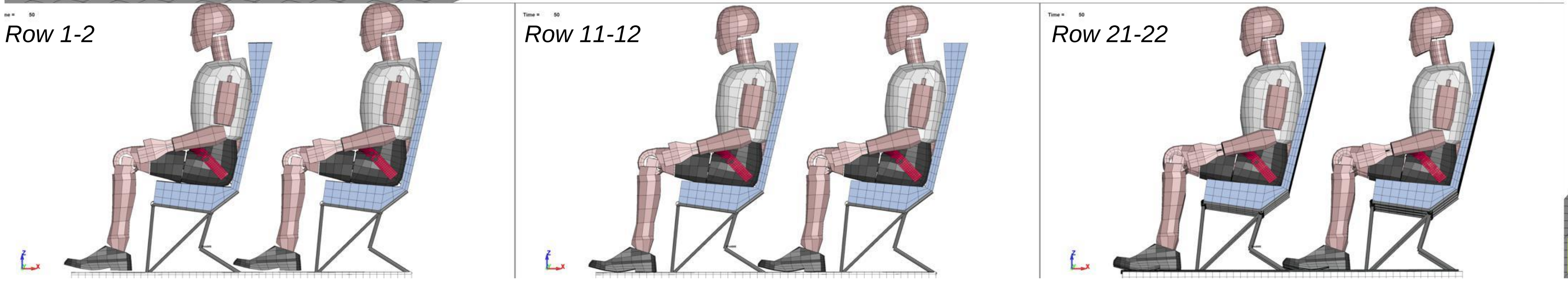
Von Mises stress [Gpa]

Section with the rearmost container in the aircraft



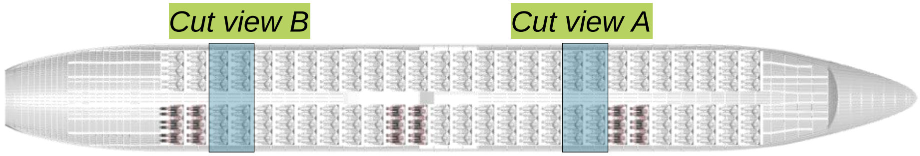
Section with the foremost container in the aircraft





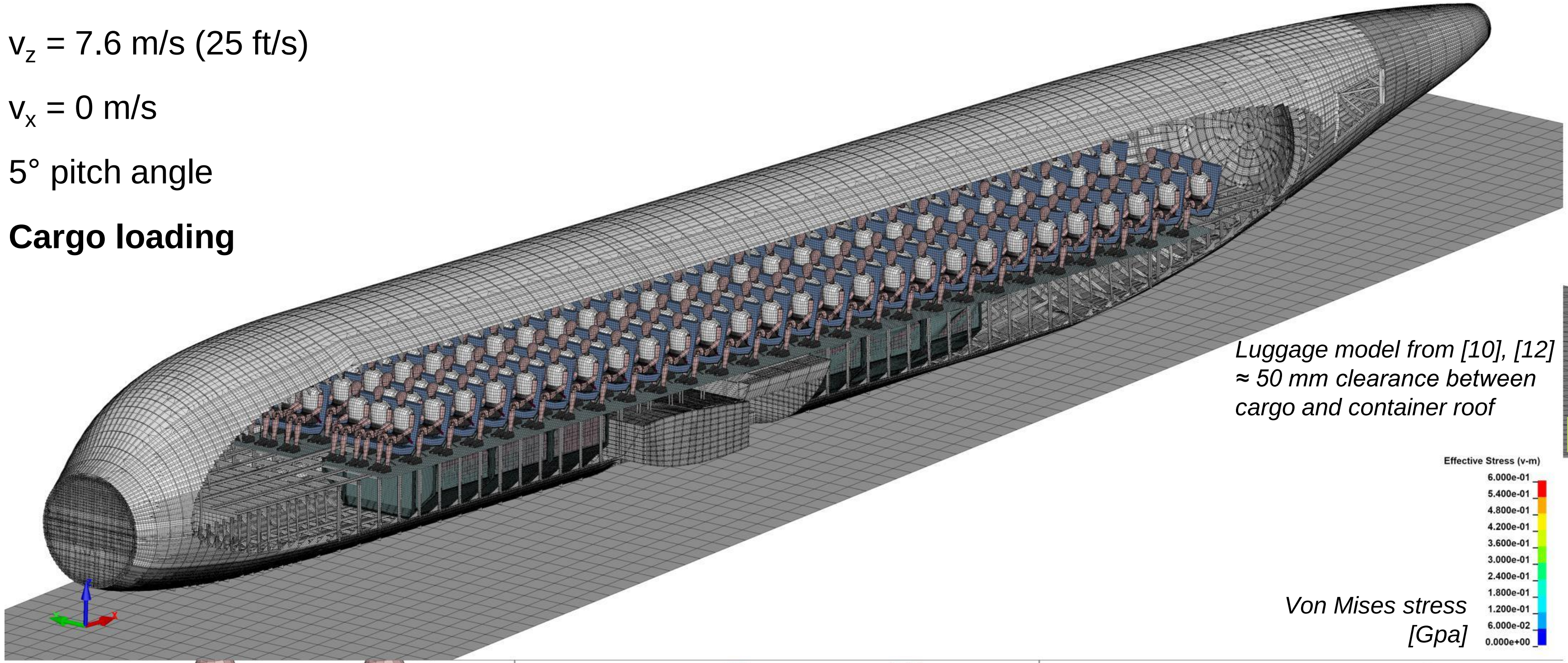
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

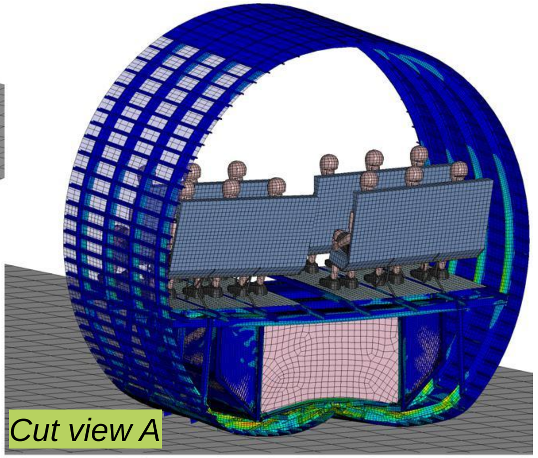


Crash kinematics

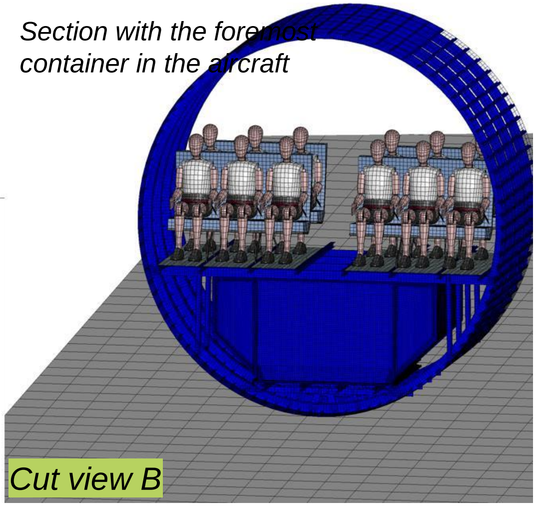
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

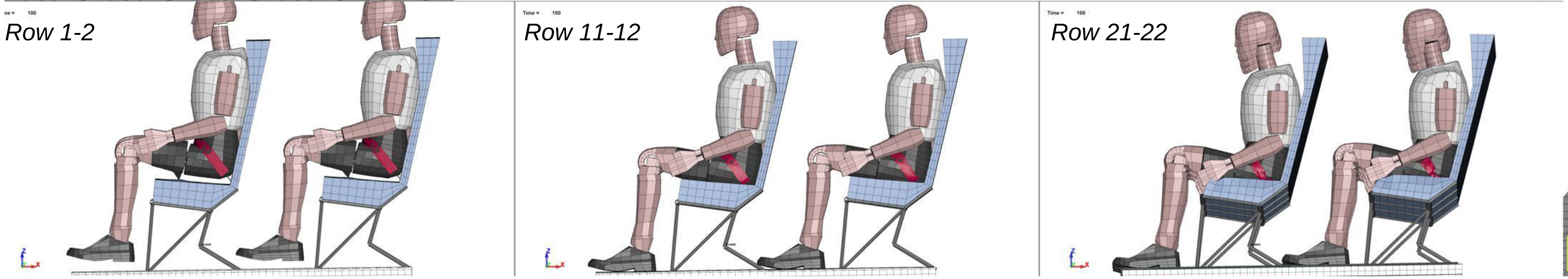


Section with the rearmost container in the aircraft



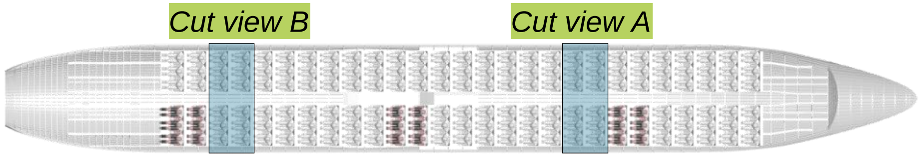
Section with the foremost container in the aircraft





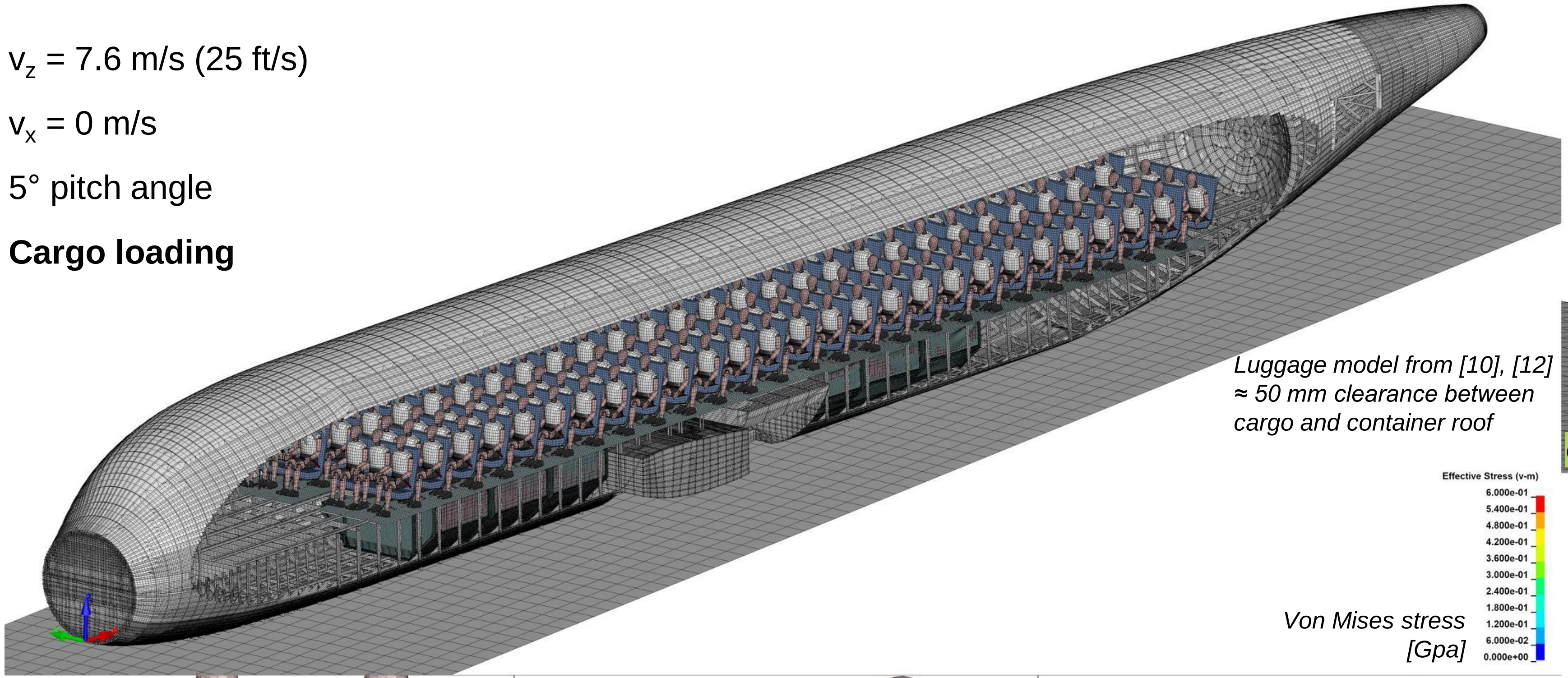
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

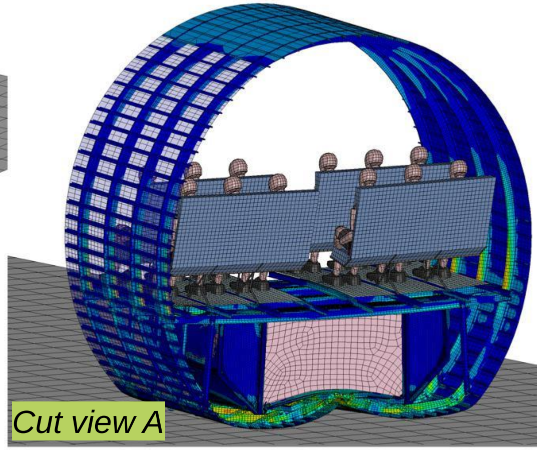


Crash kinematics

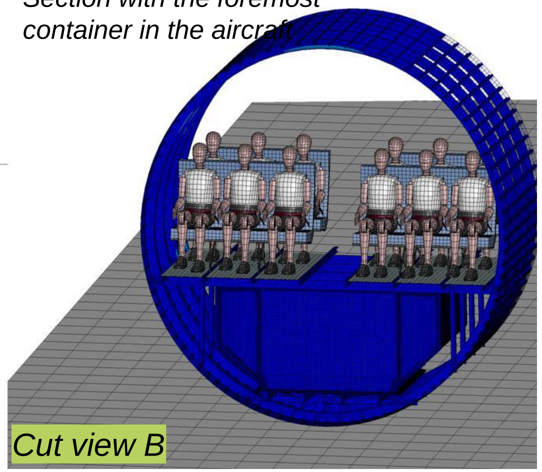
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

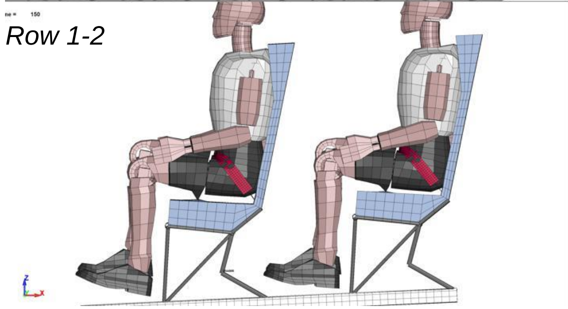


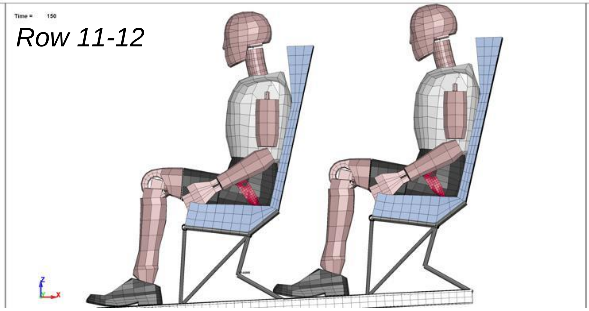
Section with the rearmost container in the aircraft

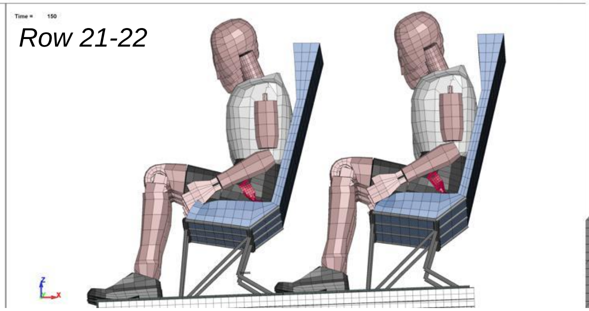


Section with the foremost container in the aircraft



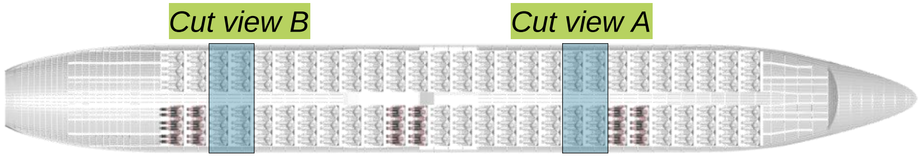






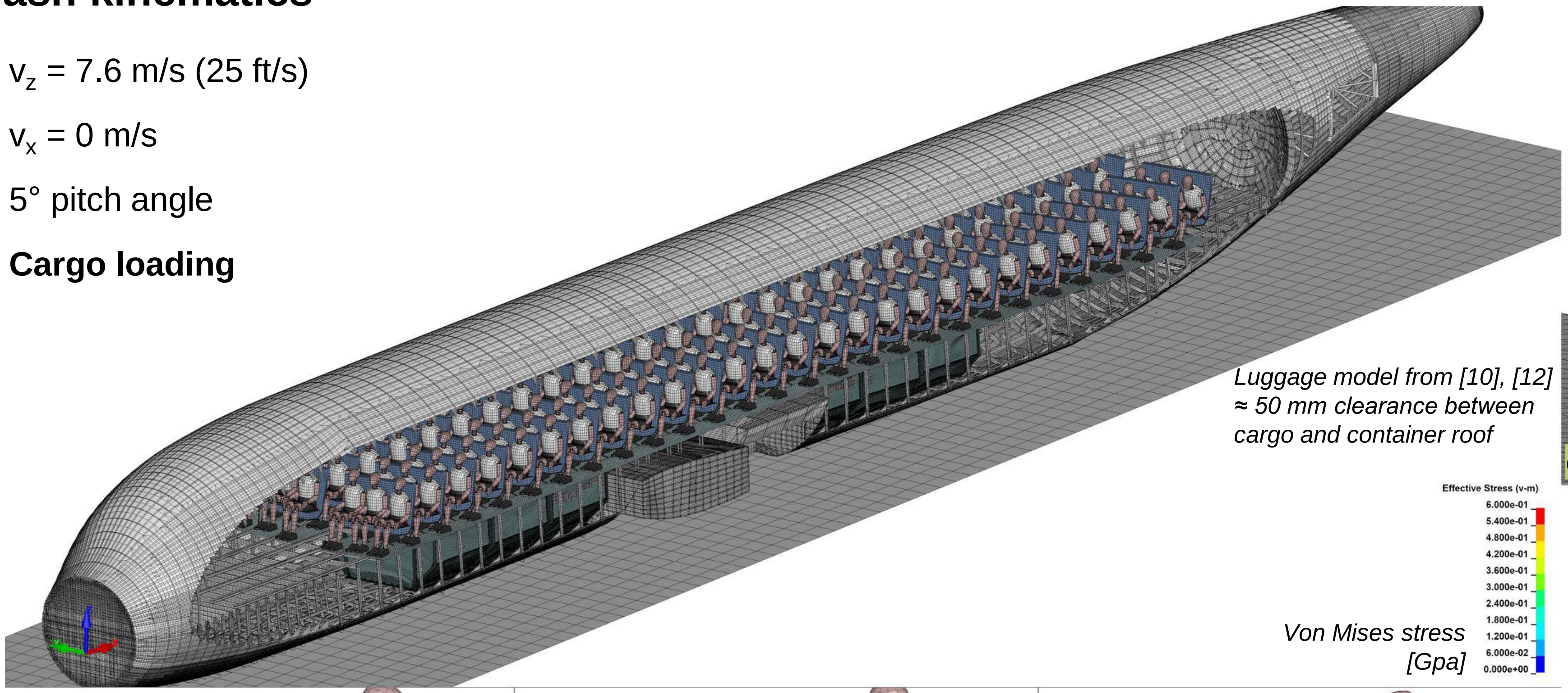
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

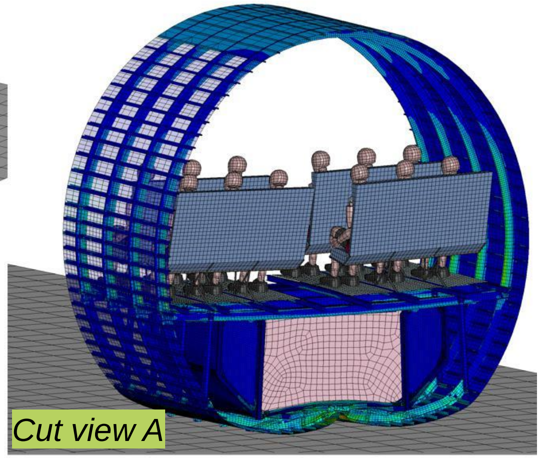


Crash kinematics

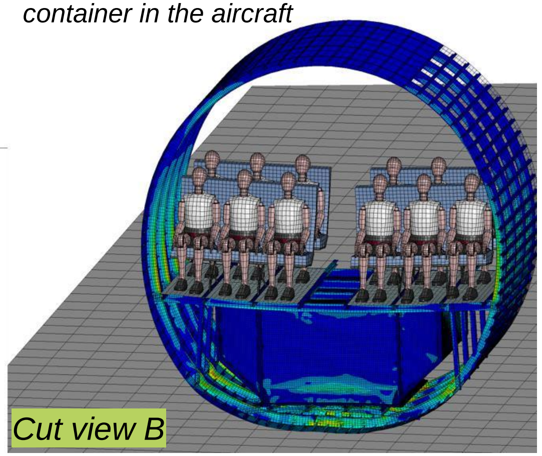
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

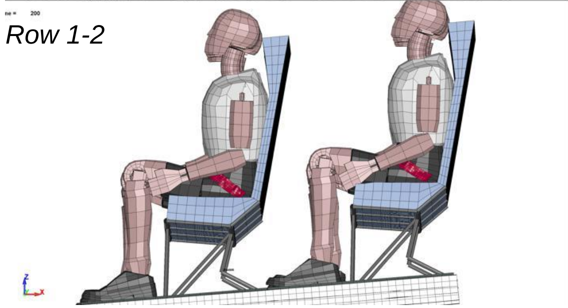


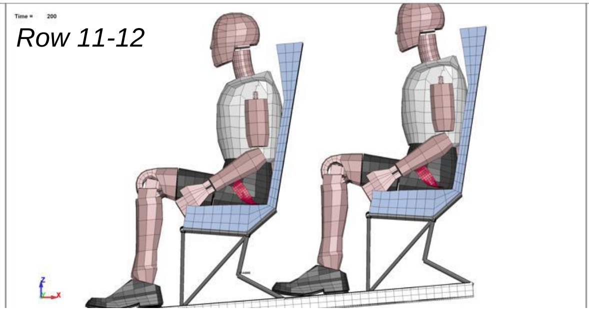
Section with the rearmost container in the aircraft

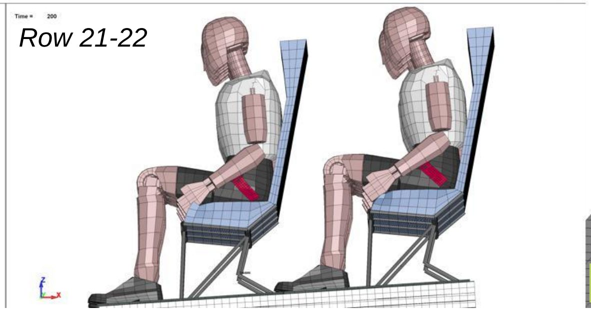


Section with the foremost container in the aircraft



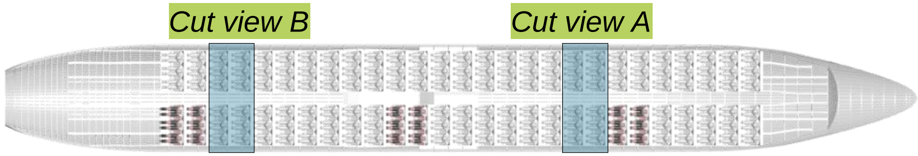






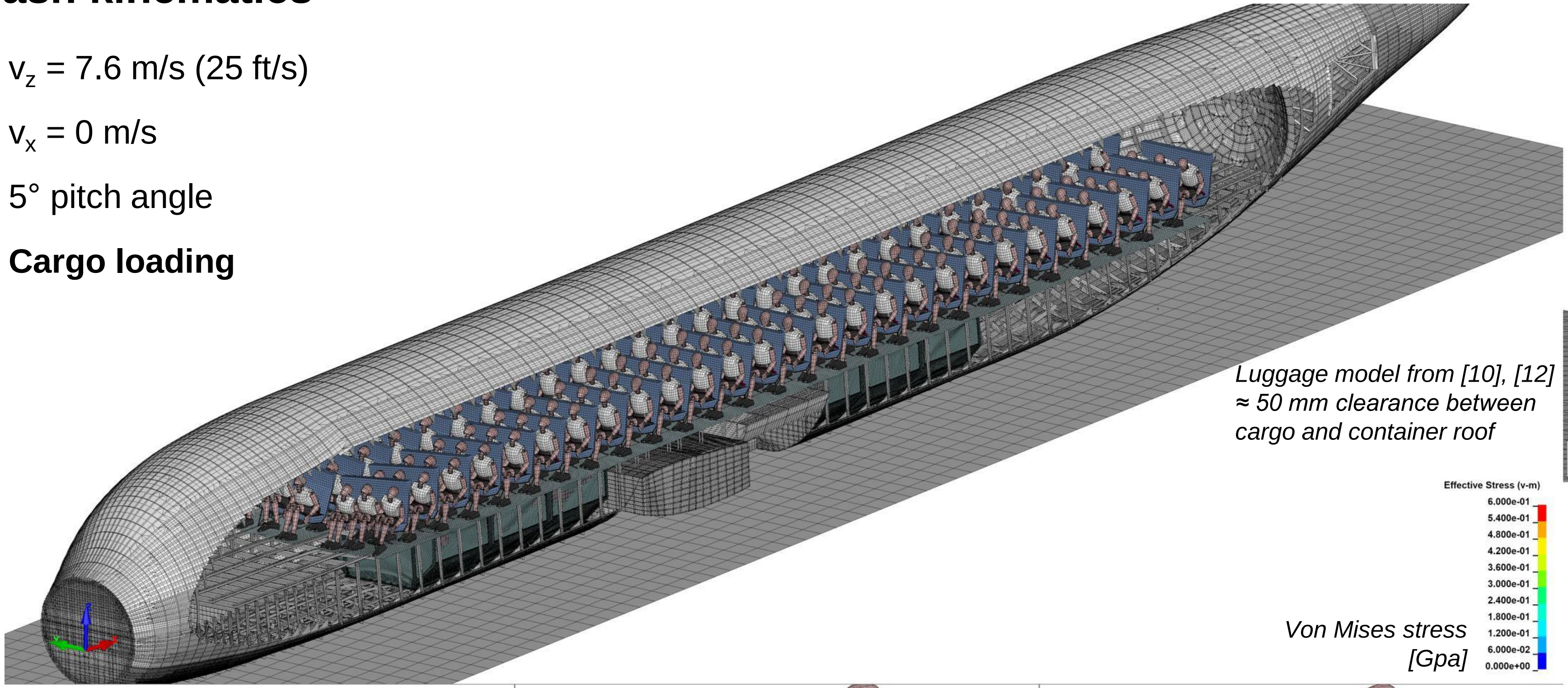
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

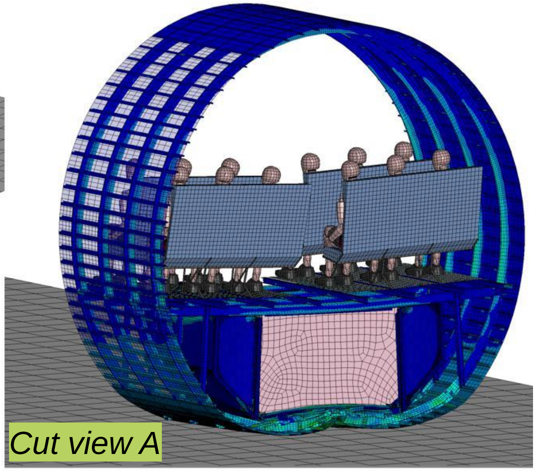


Crash kinematics

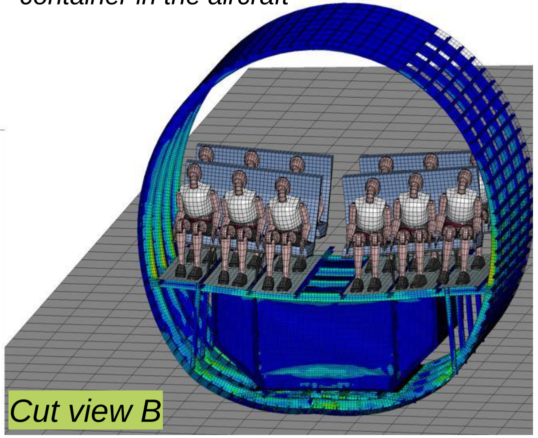
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

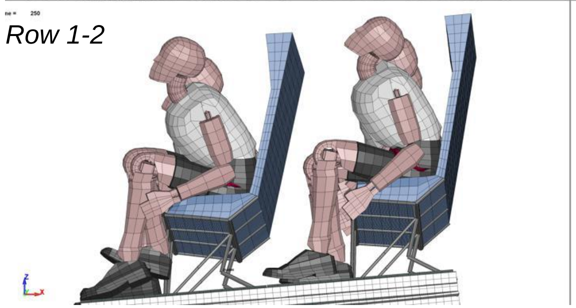


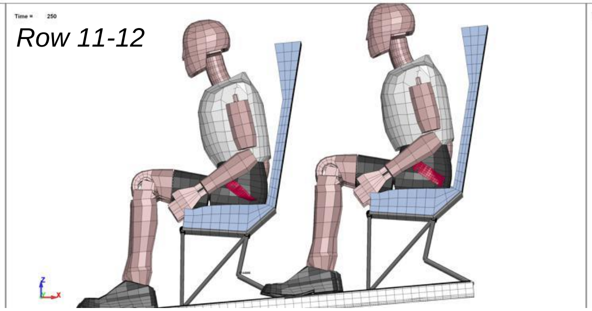
Section with the rearmost container in the aircraft

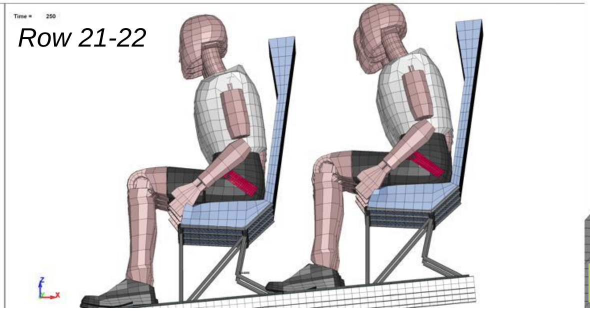


Section with the foremost container in the aircraft



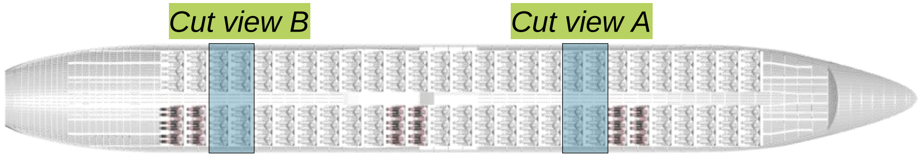






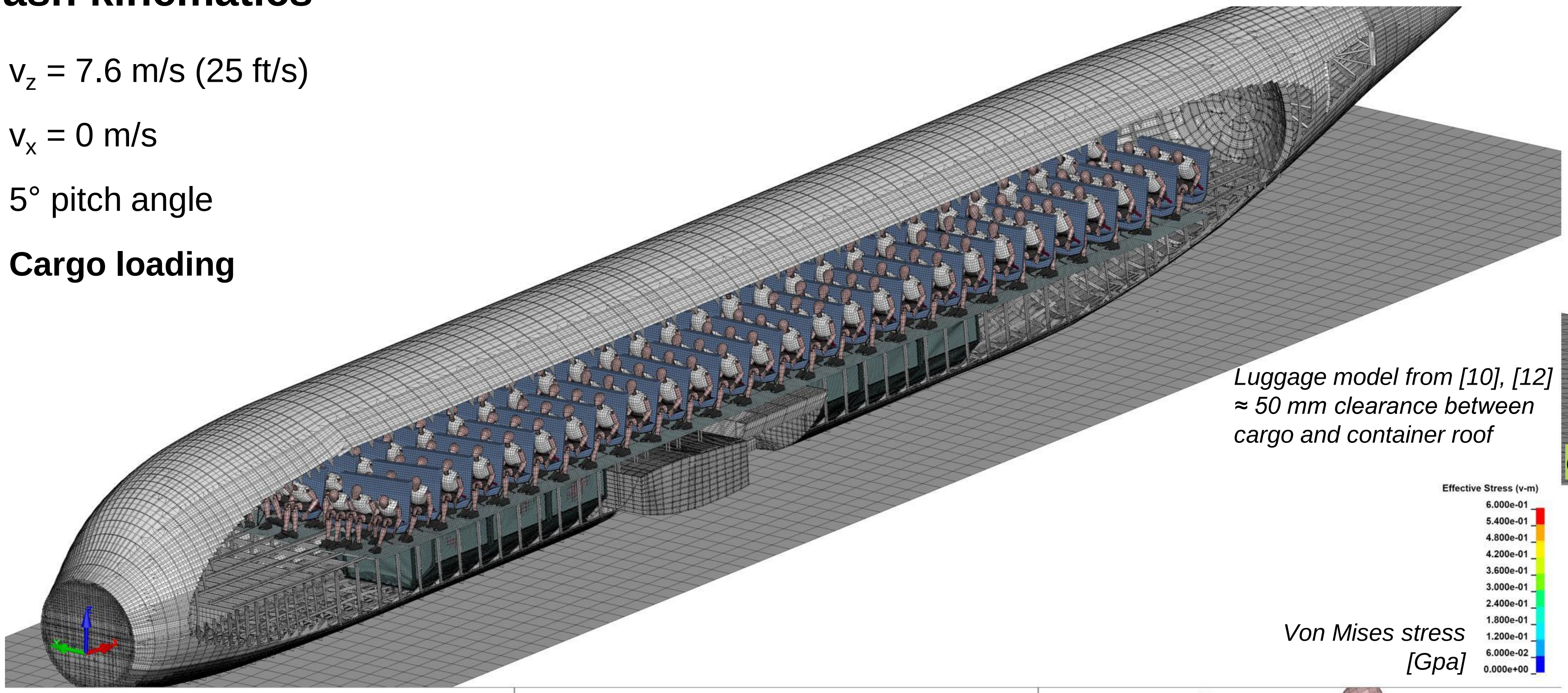
3 Method application (examples)

III) Vertical drop with pitch angle and cargo loading

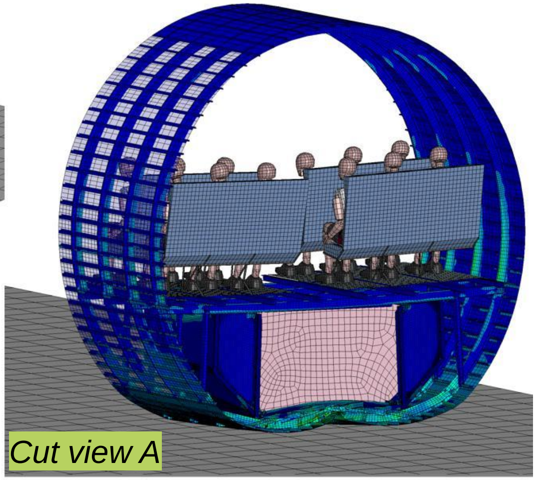


Crash kinematics

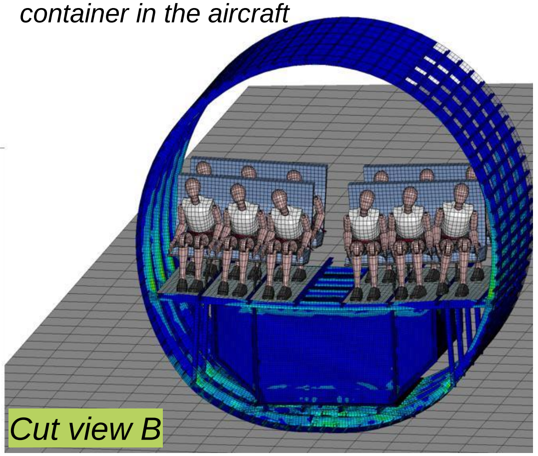
- v_z = 7.6 m/s (25 ft/s)
- v_x = 0 m/s
- 5° pitch angle
- **Cargo loading**

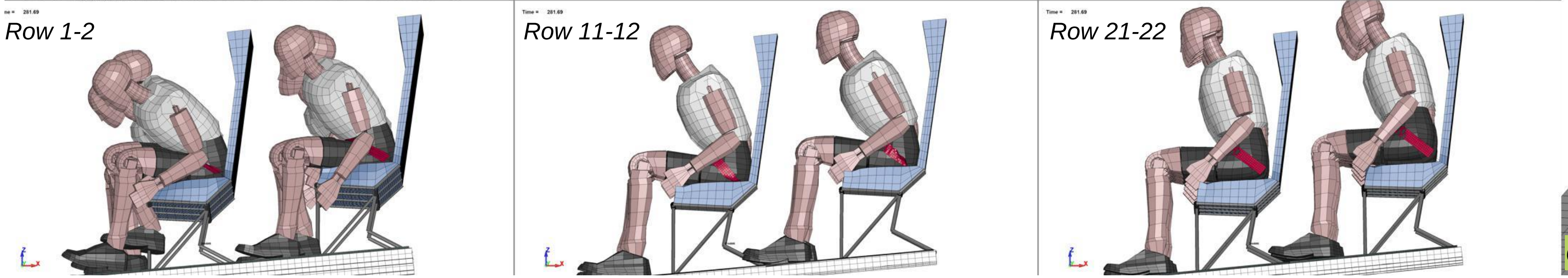


Section with the rearmost container in the aircraft



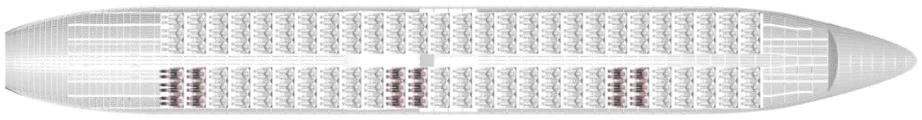
Section with the foremost container in the aircraft





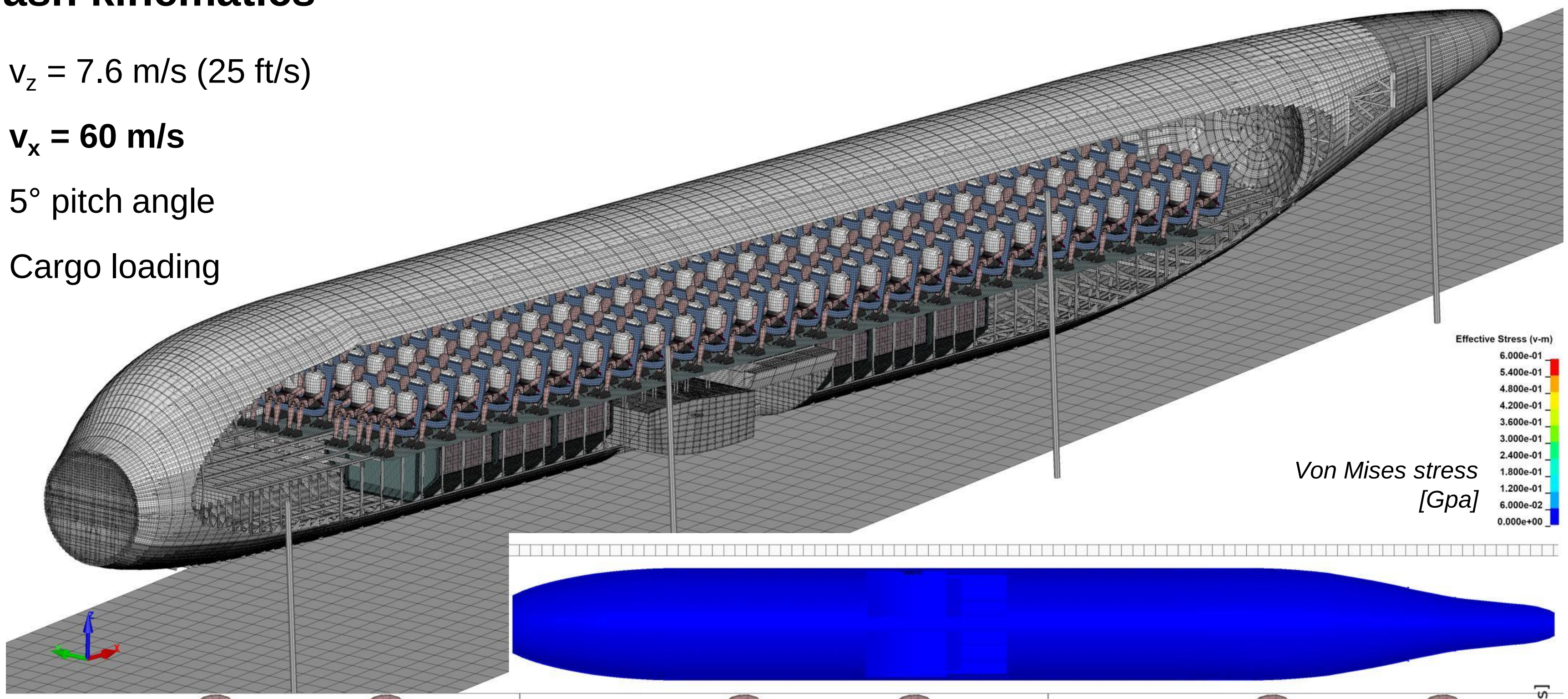
3 Method application (examples)

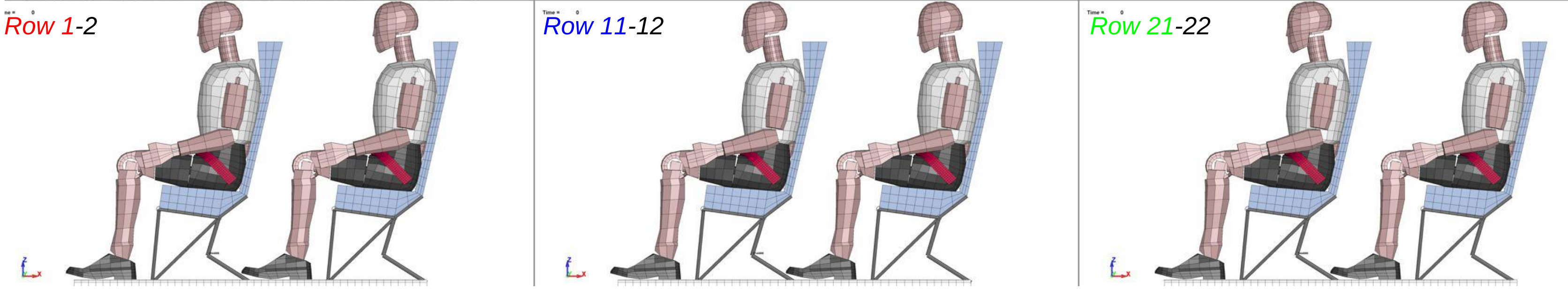
IV) Full aircraft xz-crash



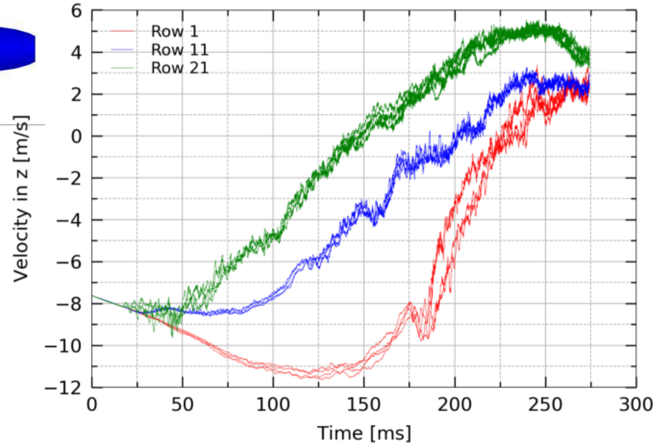
Crash kinematics

- v_z = 7.6 m/s (25 ft/s)
- **v_x = 60 m/s**
- 5° pitch angle
- Cargo loading





Seat foot local velocity
Row 1, Row 11, Row 21
Left side in flight direction



3 Method application (examples)

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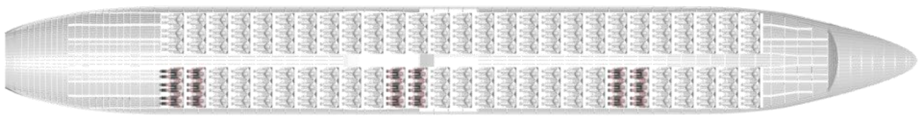

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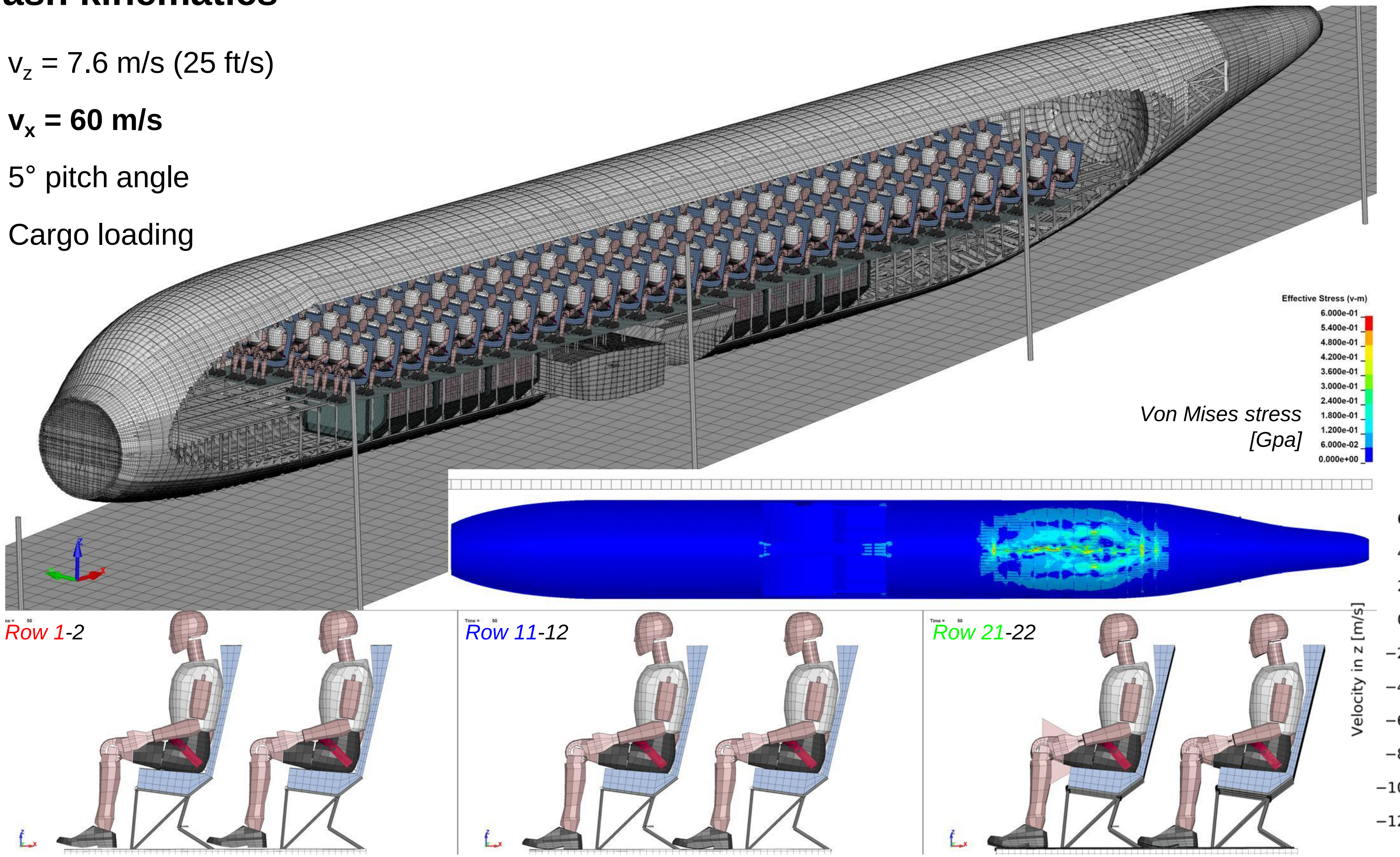
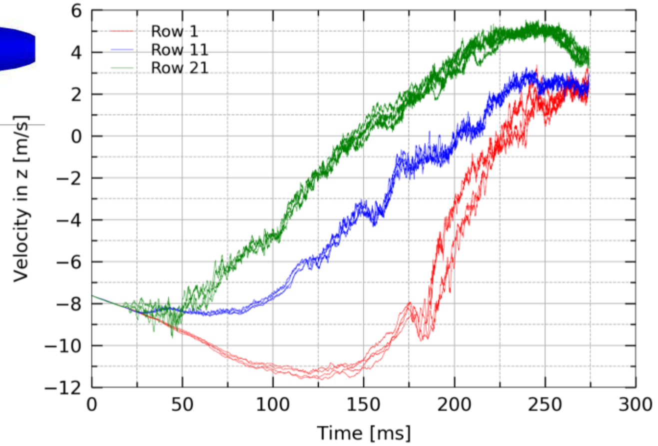
- Cargo loading



Seat foot local velocity
Row 1, Row 11, Row 21
Left side in flight direction



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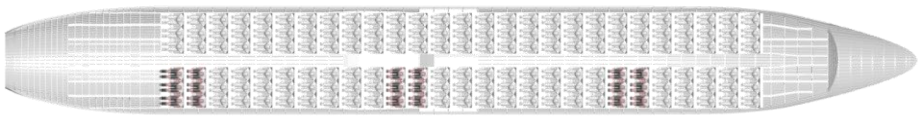

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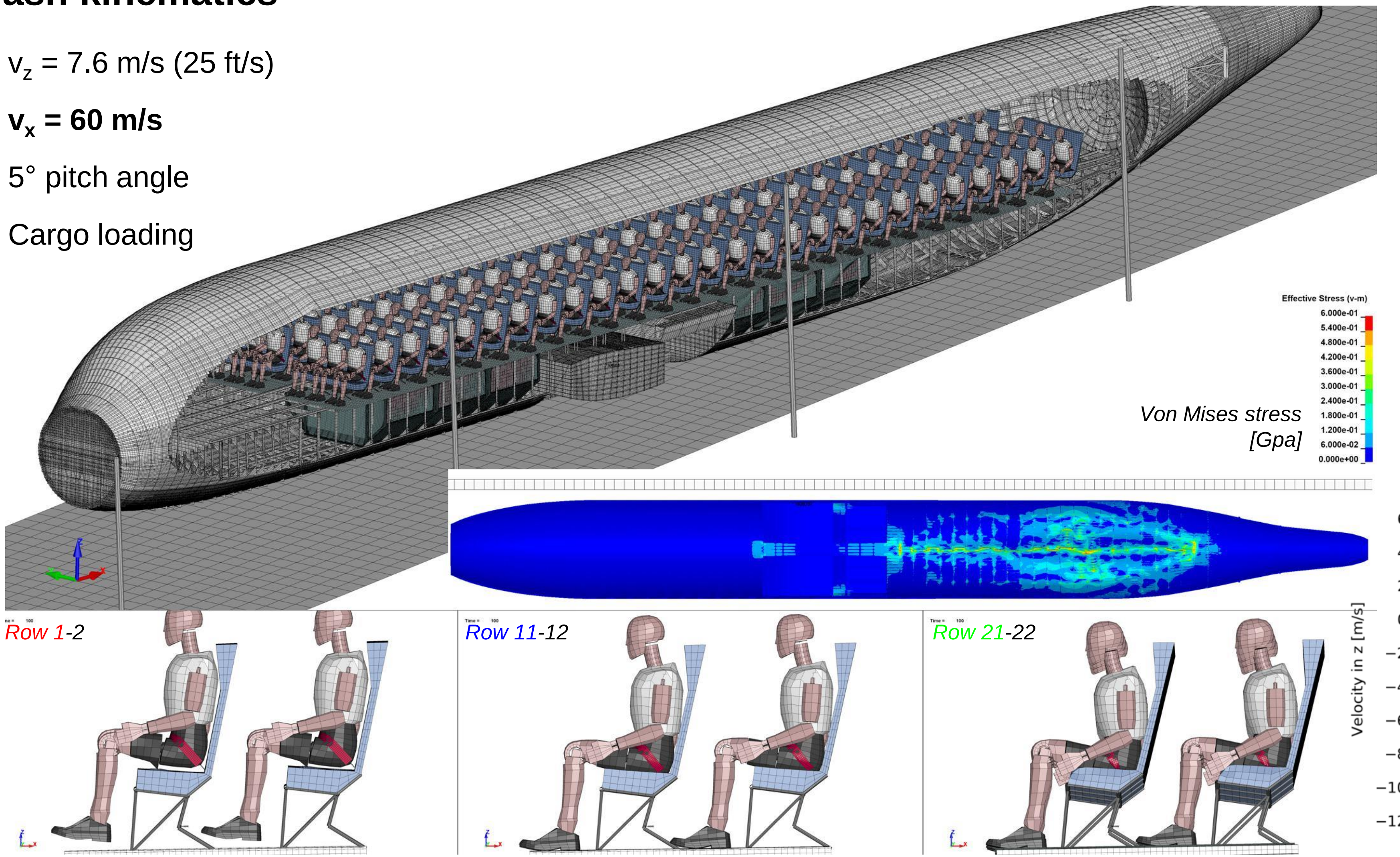

Seat foot local velocity
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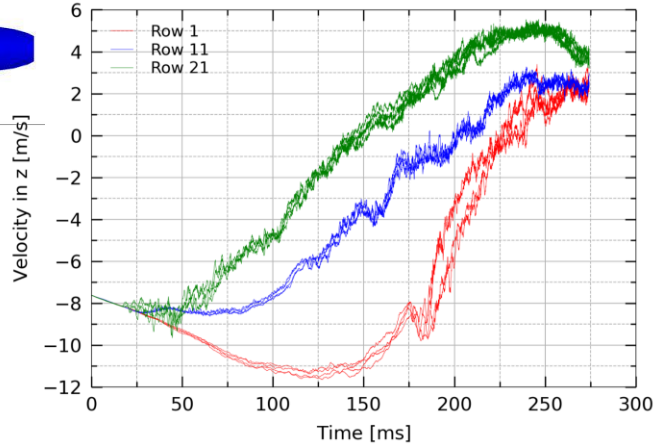

3 Method application (examples)

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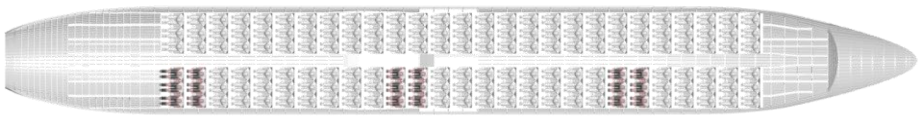

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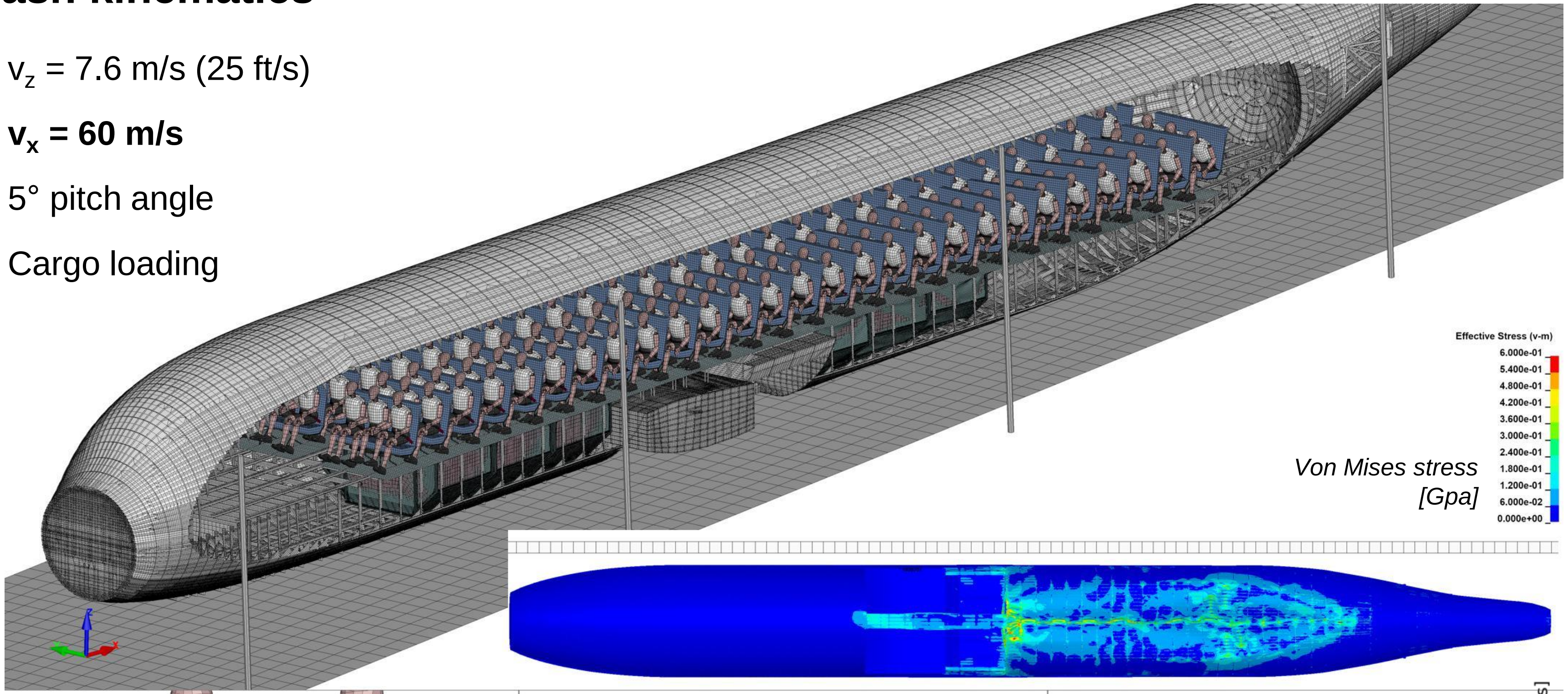
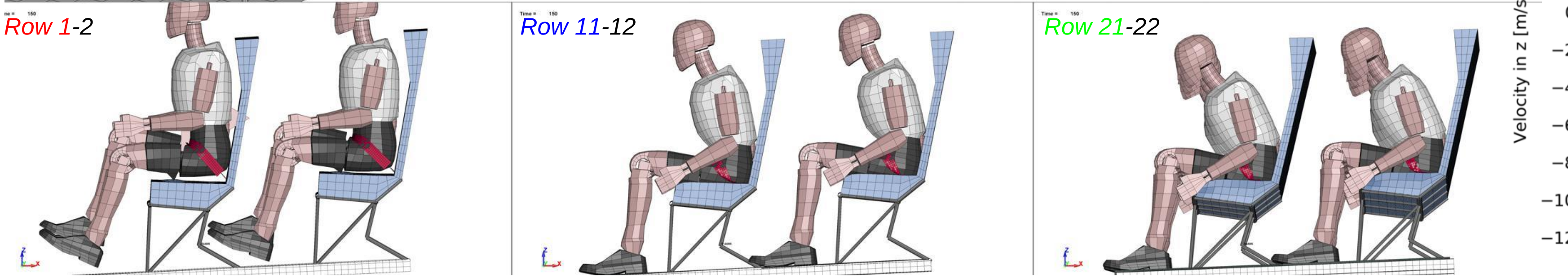


Von Mises stress [Gpa]



Seat foot local velocity
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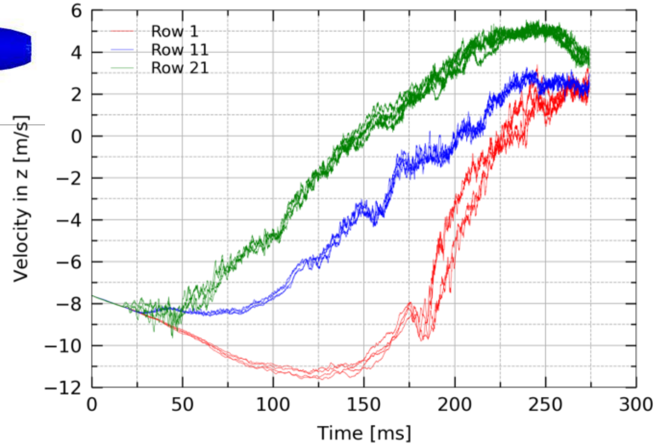
Left side in flight direction



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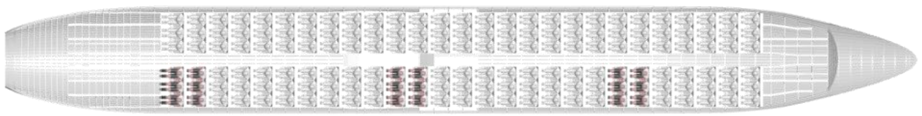

Crash kinematics

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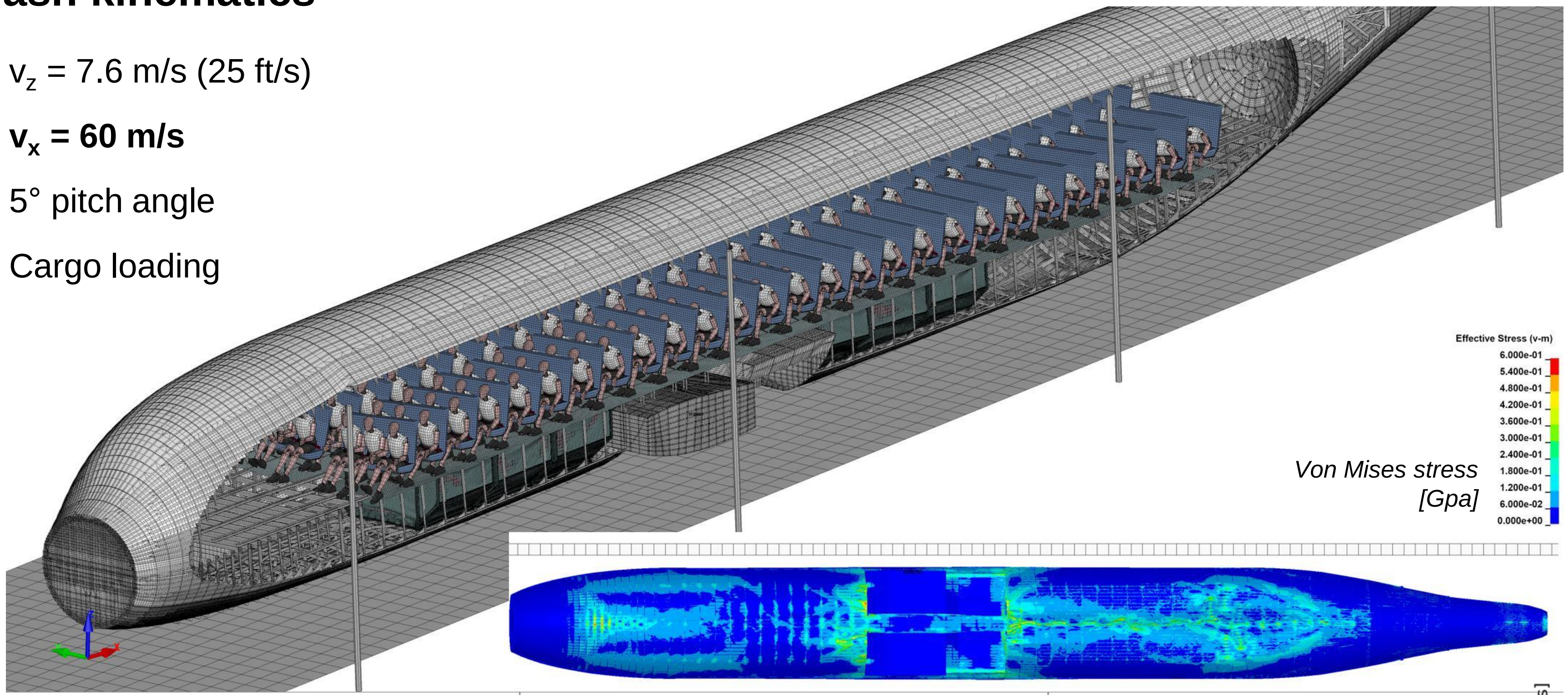
- Cargo loading



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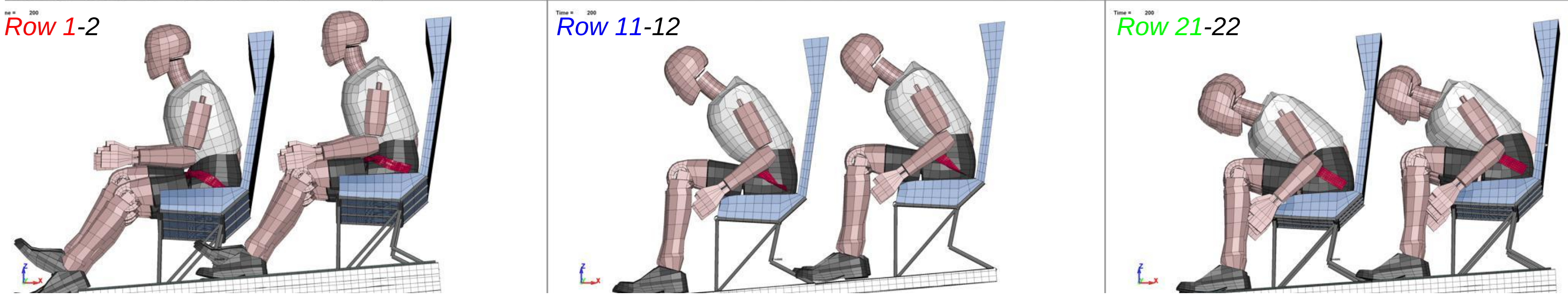

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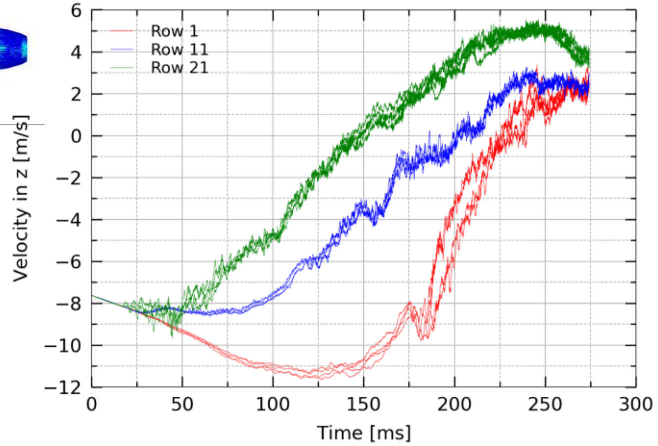

3 Method application (examples)

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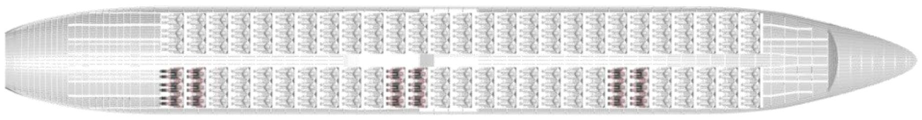

Crash kinematics

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- **v_x = 60 m/s**
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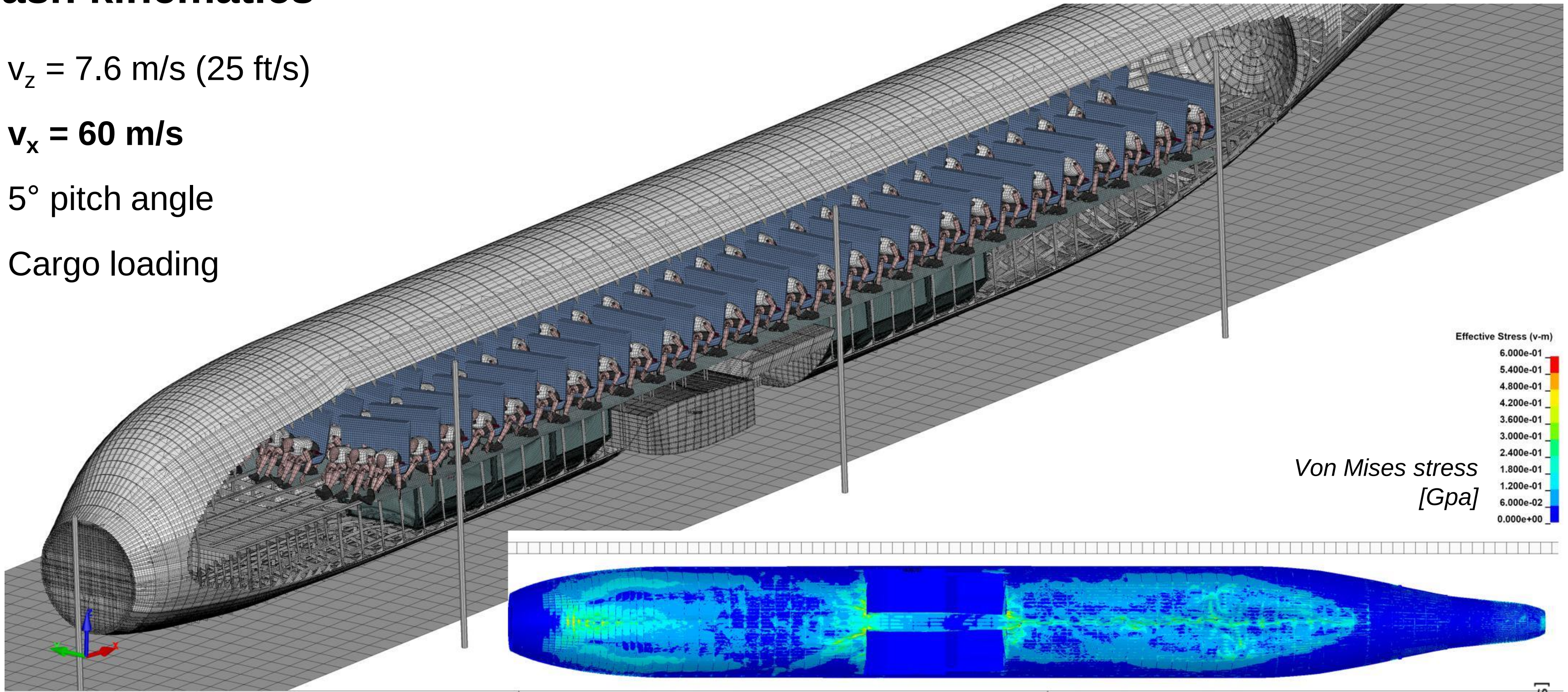
- Cargo loading



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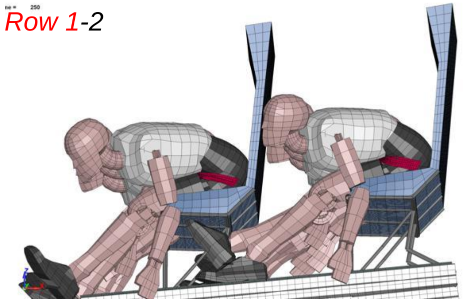
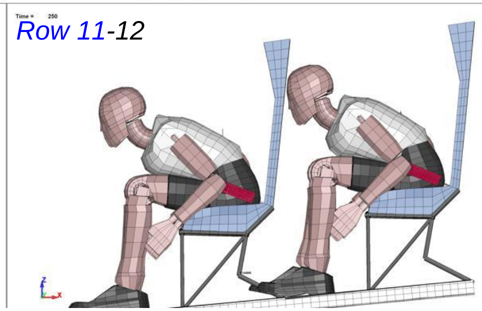
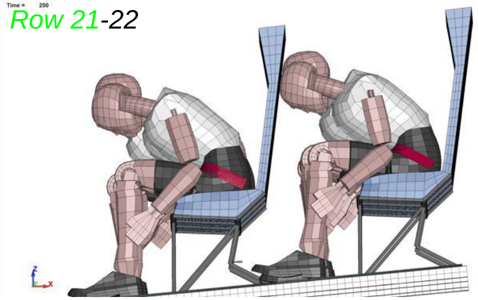
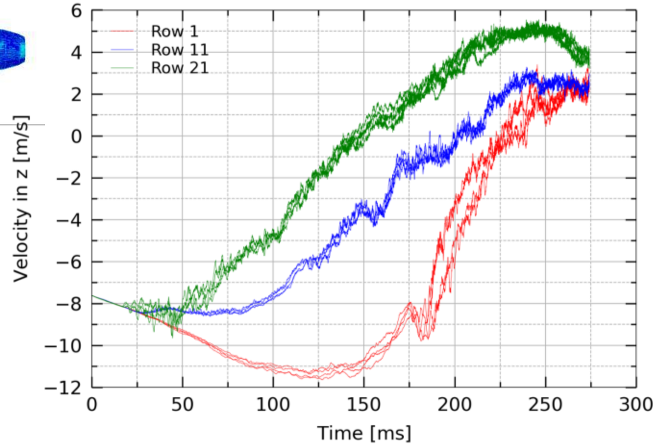




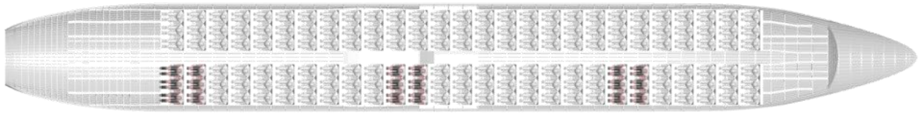


Seat foot local velocity
Row 1, Row 11, Row 21
Left side in flight direction



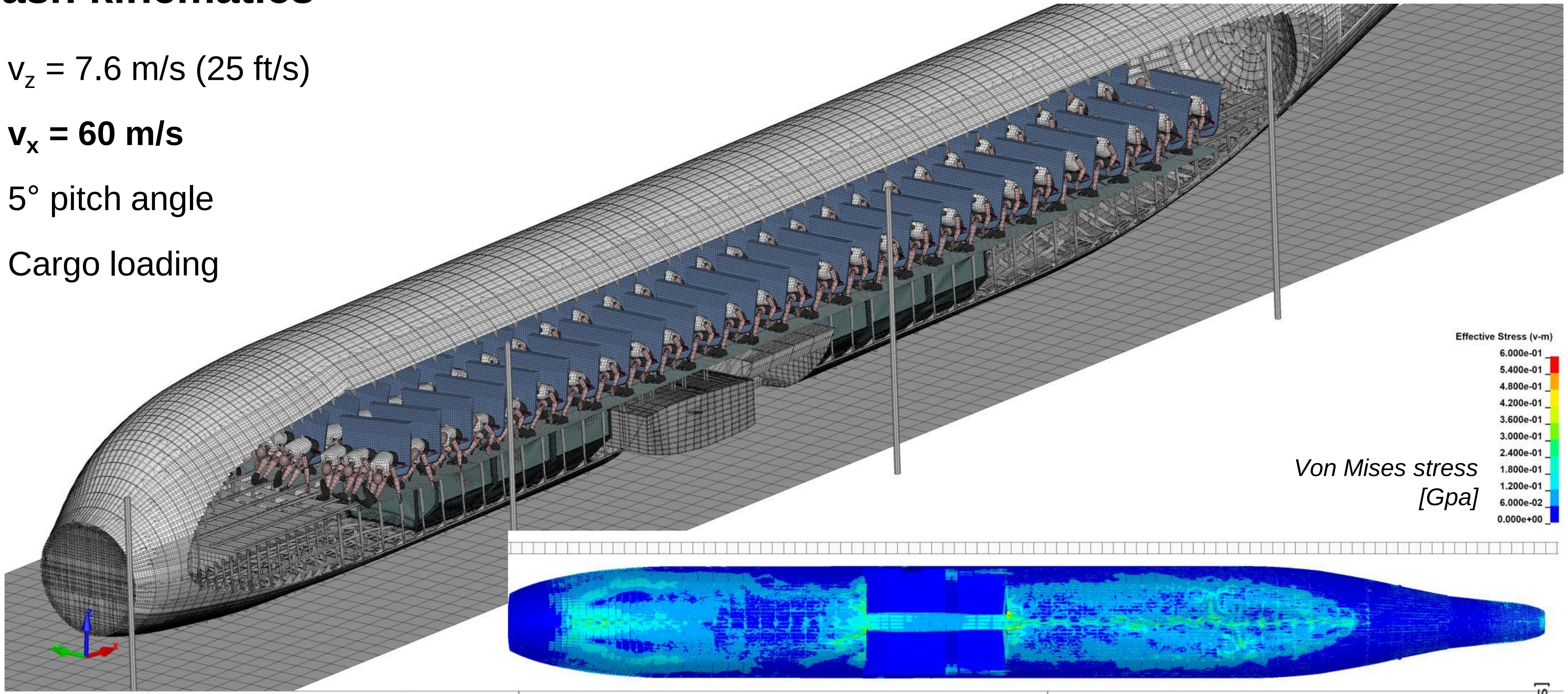
3 Method application (examples)

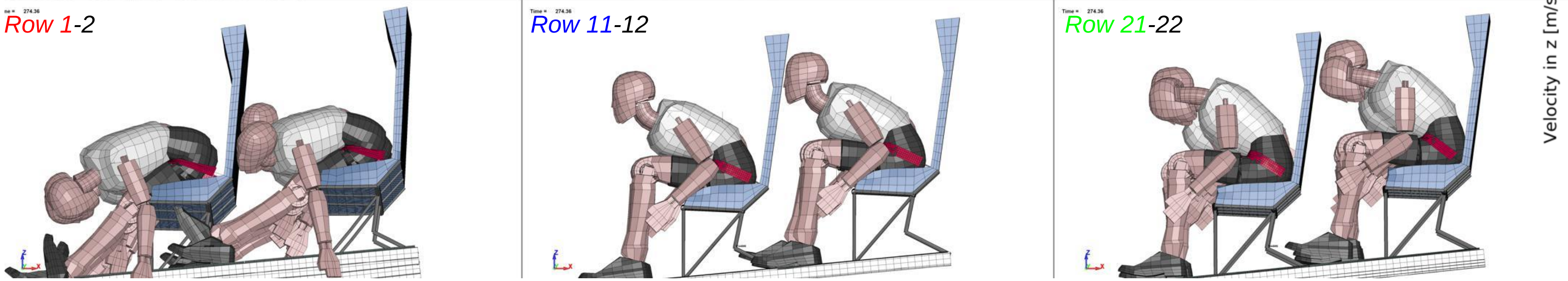
IV) Full aircraft xz-crash



Crash kinematics

- v_z = 7.6 m/s (25 ft/s)
- **v_x = 60 m/s**
- 5° pitch angle
- Cargo loading





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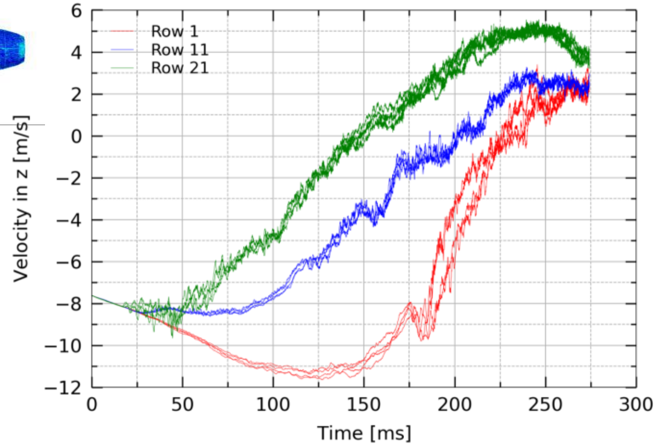
Row 1, Row 11, Row 21
Left side in flight direction

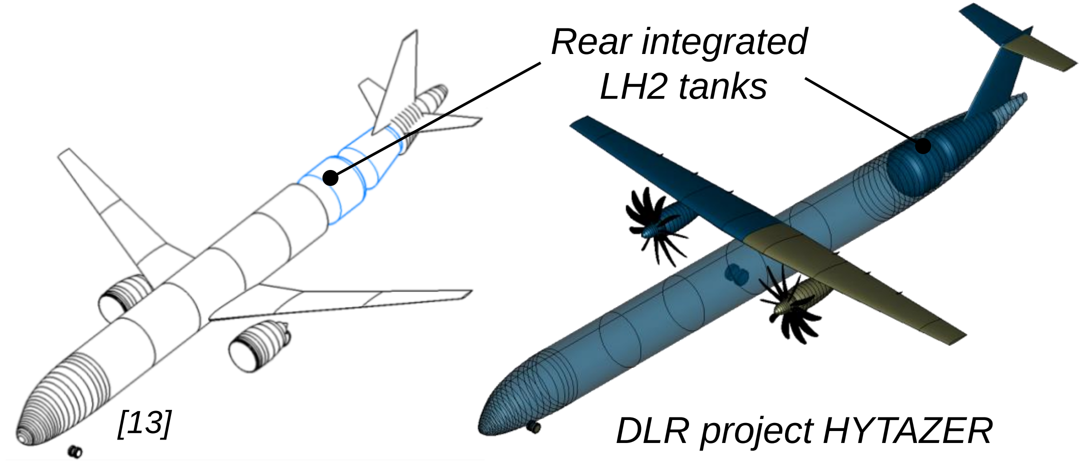


3 Method application (examples)

V) Crashworthiness assessment of novel aircraft configurations

Crashworthy LH2 tank integration

- Assessment of LH2 tank installation locations with respect to real-world crash loads and effects
  - Fuselage break
  - Retention of tank mass
- Assessment of LH2 tank integration with respect to real-world crash loads and effects
  - Crashworthy tank mounts
- Determination of local crash loads from full aircraft crash simulation
  - Detailed development of crashworthy LH2 tank integration
  - Iteration of full aircraft crash simulation and more detailed local analysis (e.g. fuselage section or structural detail)

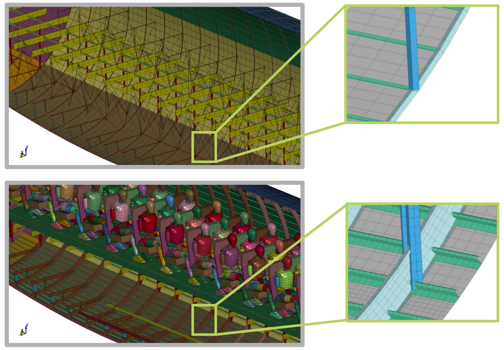


[13] D. Silberhorn, G. Atanasov, J.-N. Walther, and T. Zill, "Assessment of Hydrogen Fuel Tank Integration at Aircraft Level," presented at the Deutscher Luft- und Raumfahrtkongress 2019, Darmstadt, Deutschland, 2019. Available: https://elib.dlr.de/129643/

Summary

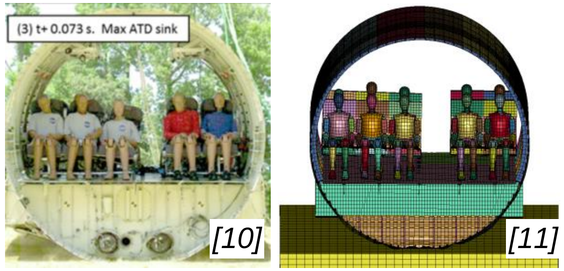
Motivation: Full aircraft crash simulation as a research goal at DLR

1 Method development



- Aircraft structure description by CPACS file format (https://cpacs.de/) [2]
- Aircraft structure generation at different levels of model fidelity by PANDORA tool [3]
- Development of individual modules for occupants [5], [6] , cargo [7], [8], masses, impact terrains, etc.

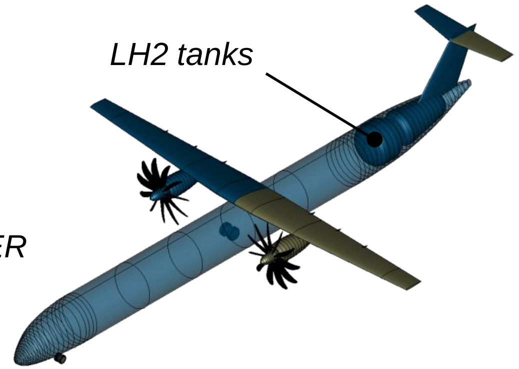
2 Method validation



- Ongoing method validation based on available experimental data [11], [12]

3 Method application

- Crash simulation of a generic single-aisle aircraft at different levels of model fidelity: low fidelity modeling [9] and high fidelity modeling
- Future work: Assessment of new aircraft configurations such as aircraft with rear integrated LH2 tanks



DLR project HYTAZER

Thank you for your attention!

Acknowledgements

The authors wish to thank Eric van Teeseling (ETaerostruct) and Daniël den Bleker (GKN Aerospace, GKN Fokker Services) for great support in providing the Fokker F28 design data.

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- [3] M. Petsch, D. Kohlgrüber, and J. Heubischl, "PANDORA - A python based framework for modelling and structural sizing of transport aircraft," presented at the 8th EASN-CEAS International Workshop, Glasgow, Schottland, 2018. Available: https://elib.dlr.de/124181/
- [4] C. Leon Muñoz and D. Kohlgrüber, "High Fidelity Simulations of Flexible Aircraft Structures Under Ditching Loads," presented at the Dynamic Modeling and Simulation (M&S) in Aircraft Ditching and Cabin Evacuation, FAA Virtual Workshop, 2022.
- [5] T. Lehmann, "Entwicklung von Passagier-Sitz-Modellen für die Simulation von Flugzeugbruchlandungen," DLR-IB-BT-ST-2018-159, 2018
- [6] N. Wegener, P. Schatrow, and M. Waimer, "Development of occupant-seat models for Fokker F28 crash test simulations," DLR-IB-BT-ST-2021-176, 2021.
- [7] M. Waimer and P. Schatrow, "Cargo Container Characterization for Airplane Crash Applications – Experimental Tests and Validation of Simulation Models," in Aerospace Structural Impact Dynamics International Conference, Madrid, Spain, 2019.
- [8] M. Waimer and P. Schatrow, "Full-Scale Crash Testing of Cargo Containers - Experimental Characterization for Transport Airplane Crash Applications," in The Tenth Triennial International Fire & Cabin Safety Research Conference, Atlantic City, New Jersey, USA, 2022.
- [9] P. Schatrow, M. Waimer, M. Petsch, C. Leon Muñoz, and D. Kohlgrüber, "Method development for full aircraft crash simulation at different levels of modeling detail," presented at the The Ninth Triennial International Fire & Cabin Safety Research Conference, Atlantic City, New Jersey, USA, 2019. Available: https://elib.dlr.de/130176/
- [10] J. D. Littell, "A summary of results from two full-scale Fokker F28 fuselage section drop tests," NASA/TM–2018-219829, 2018.
- [11] E. Wegener, "Numerical Simulation of a Crash Test on a Fokker F28 Center Fuselage Section with Wing Box and Oblique Impact Surface," DLR-IB-BT-ST-2021-148, 2021.
- [12] J. Birk, "Numerical Simulation of a Crash Test on a Fokker F28 Typical Fuselage Section with Cargo Door and Bulk Loading," DLR-IB-BT-ST-2021-147, 2021.
- [13] D. Silberhorn, G. Atanasov, J.-N. Walther, and T. Zill, "Assessment of Hydrogen Fuel Tank Integration at Aircraft Level," presented at the Deutscher Luft- und Raumfahrtkongress 2019, Darmstadt, Deutschland, 2019. Available: https://elib.dlr.de/129643/