Webinar, 2023-02-09, 10:00 CET

Simulation of FOPS and ROPS: an LS-DYNA Application Demonstration

Axel Hallén, DYNAmore Nordic, an Ansys company

Contact – DYNAmore Nordic, an Ansys company

- Support
  - Sales: sales@dynamore.se
  - E-mail: support@dynamore.se
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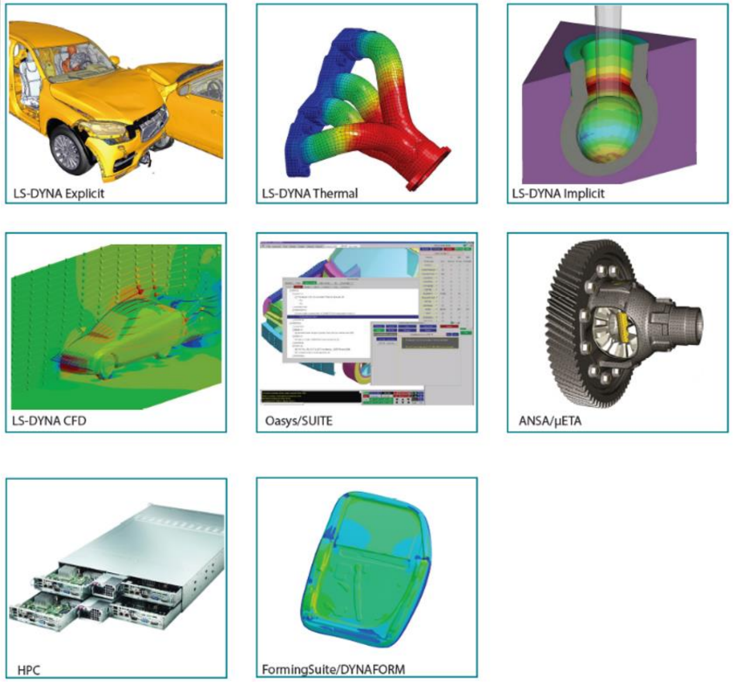
- www.dynalook.com – Papers from international LS-DYNA conferences
- www.dynasupport.com – General support for LS-DYNA
- www.dynaexamples.com – LS-DYNA example models from crash to DEM



Agenda

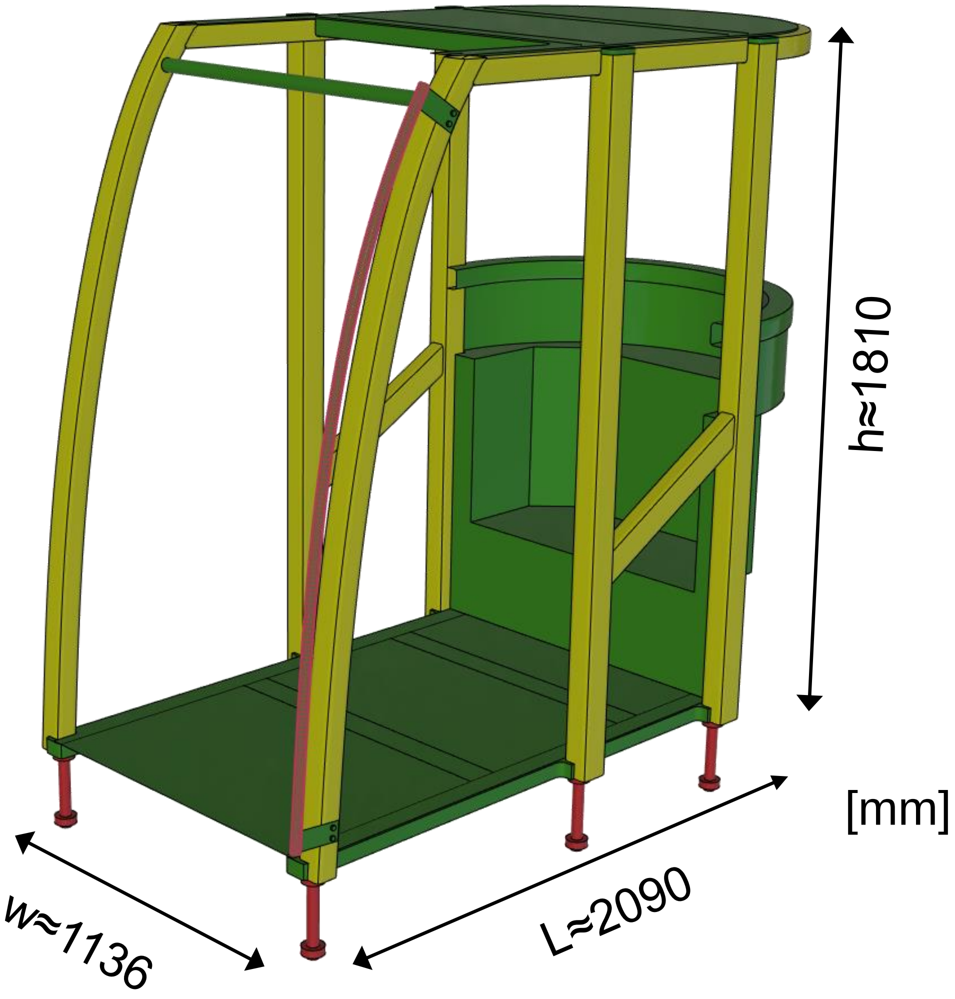
- Introduction to falling object and roll-over protective structures (FOPS and ROPS) for earth-moving machinery and testing thereof.
- Setting up an FE-simulation of FOPS testing.
- Setting up an FE-simulation of ROPS testing.
- Displaying our supporting resources in the form of webinars and guidelines in the process of discussing the above mentioned FE-modeling.

Introduction

- Testing of FOPS and ROPS is crucial to ensuring operator safety in a wide range of vehicles and machinery.
- These tests are expensive and complicated to perform physically. It is therefore desirable to reduce the amount of physical testing by using numerical simulation instead.
- This example is inspired by the standards for earth-moving machinery,
  - SS-EN ISO 3449:2008 (FOPS laboratory tests and performance requirements).
  - SS-EN ISO 3471:2008 (ROPS laboratory tests and performance requirements).
- For Integral FOPS/ROPS, where the same structure is used for the evaluation against both standards, the FOPS test precedes the ROPS test such that the latter is performed on an already deformed structure.
- The simulation of this example will thus be performed in three stages.
  - 1) Bolt pre-tensioning in a dynamic relaxation phase.
  - 2) FOPS test using explicit time integration.
  - 3) ROPS test on pre-deformed structure using implicit time integration.

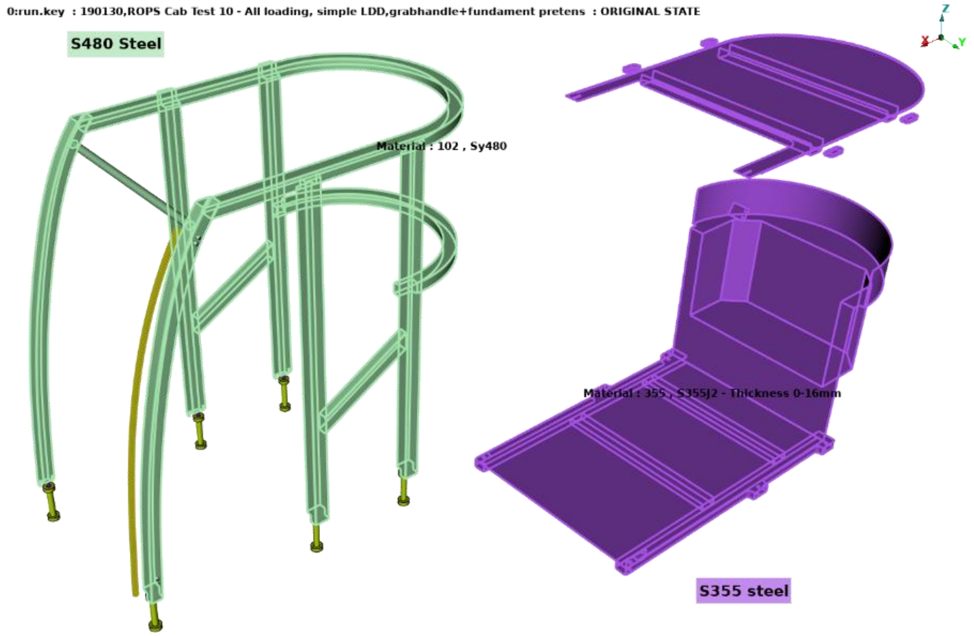
Protective Cab Geometry

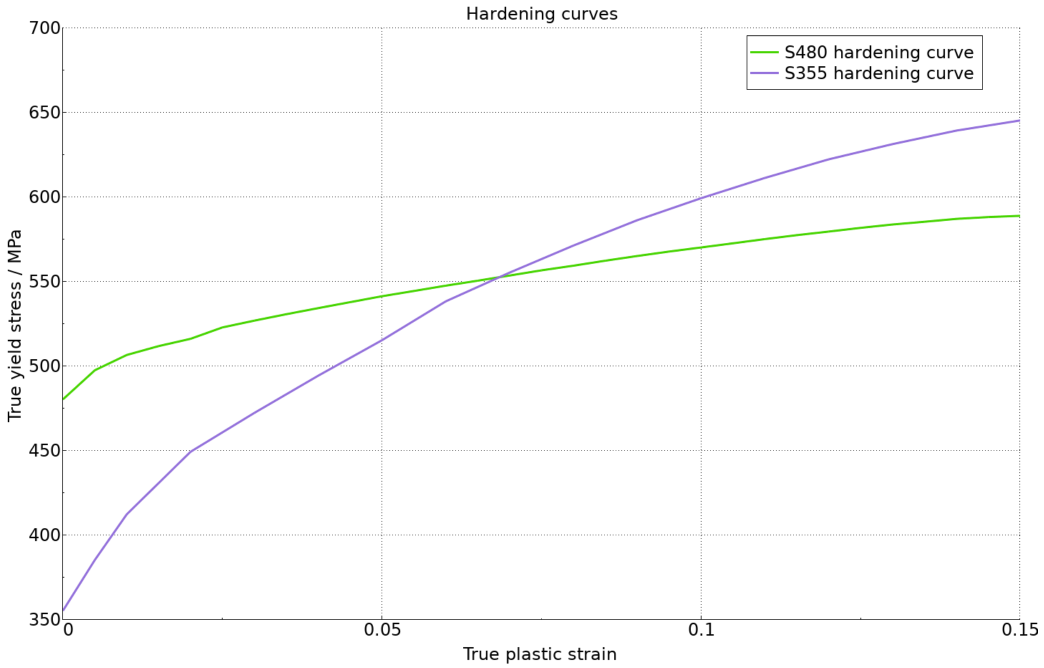
- The cab structure is inspired by images of present and past designs of earth moving machinery.
- It is assumed that the mass of the machine is 15 tonnes.
- The purpose of a FOPS is to provide the operator with reasonable protection from falling objects such as trees, rocks, small concrete blocks, hand tools, et cetera.
- A FOPS is classified as having either level 1 or level 2 impact protection.
  - Level 1: small falling objects
  - Level 2: heavy falling objects
- The purpose of a ROPS is to reduce the possibility of an (seat-belted) operator being crushed in the event of machine roll-over.



Protective Cab Geometry – Materials

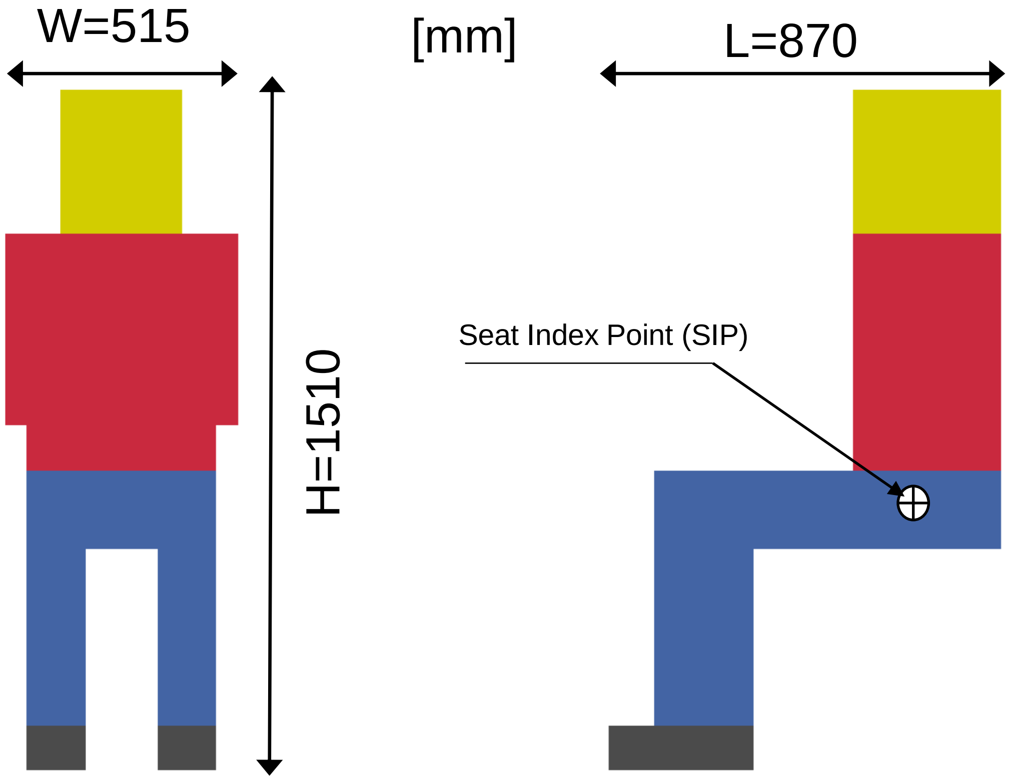
- S480 steel was used for the tubular structural members in green.
- S355 steel was used for the sheet metal and solid parts in purple.
- Steel with 10.9 strength was used for solid bolts.

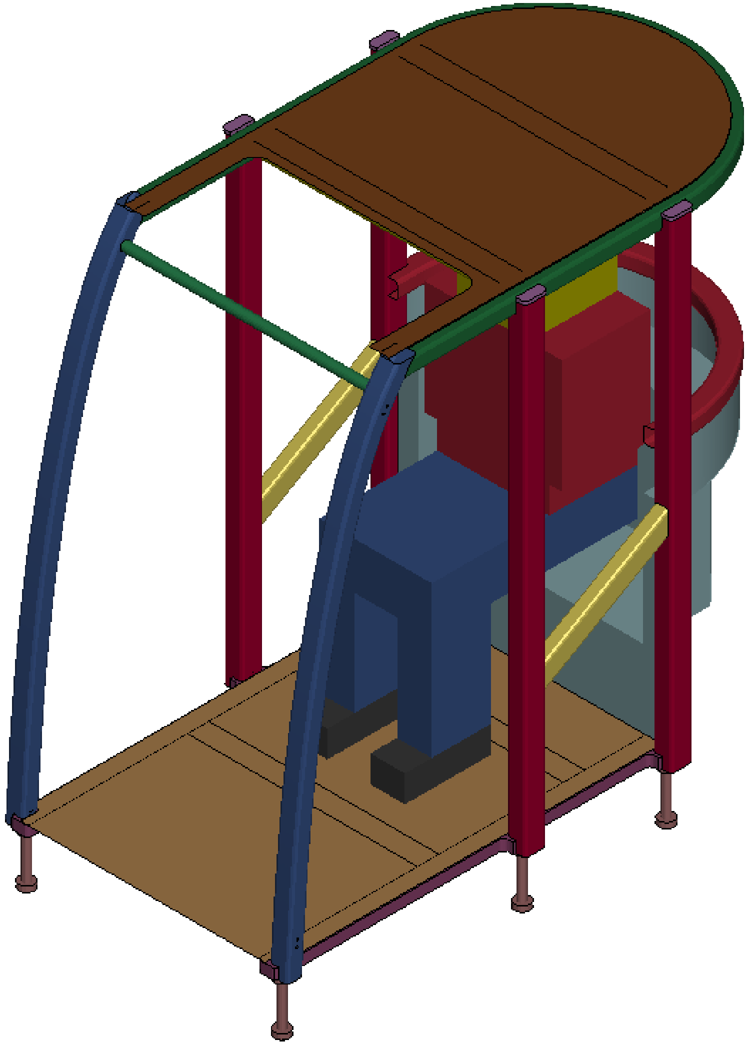




Deflection Limiting Volume (DLV)

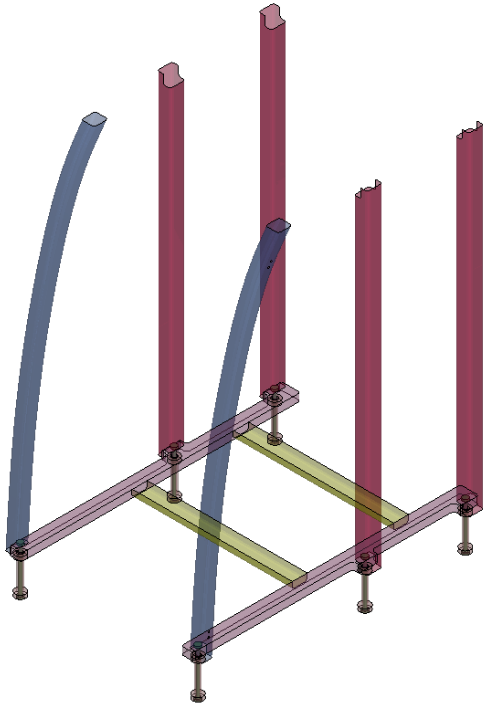
- The DLV is based on ISO 3164:1995(E) and represents ‘A large, seated, male operator wearing normal clothing and a protective helmet.

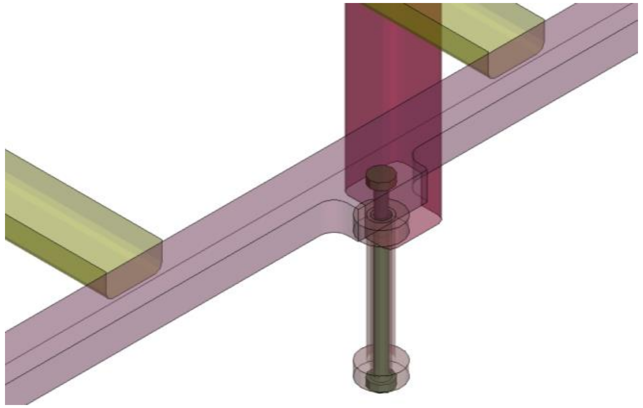




Mounting to a Testbed

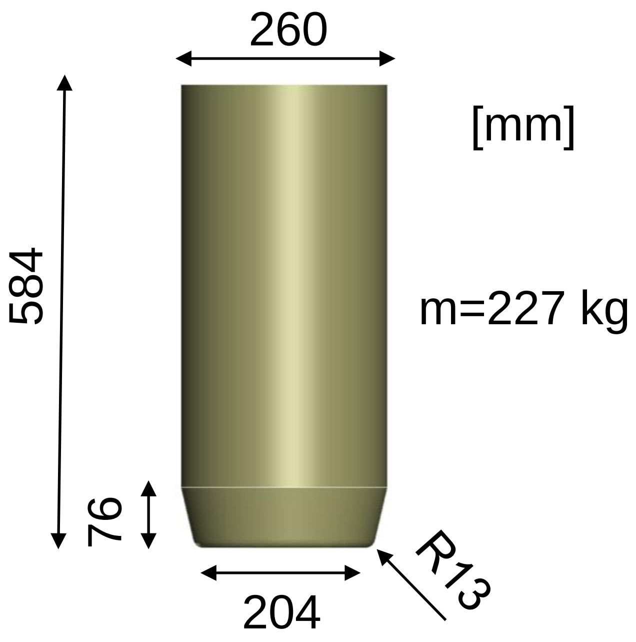
- The mounting of the test specimen to a test bed should be the same as when mounted on the machine, and the test bed shall represent the stiffness of the machine.
- The pillars are mounted to the floor of the structure through six long bolts which also connect the structure to the testbed, represented by six rigid fundaments because of the high machine mass.

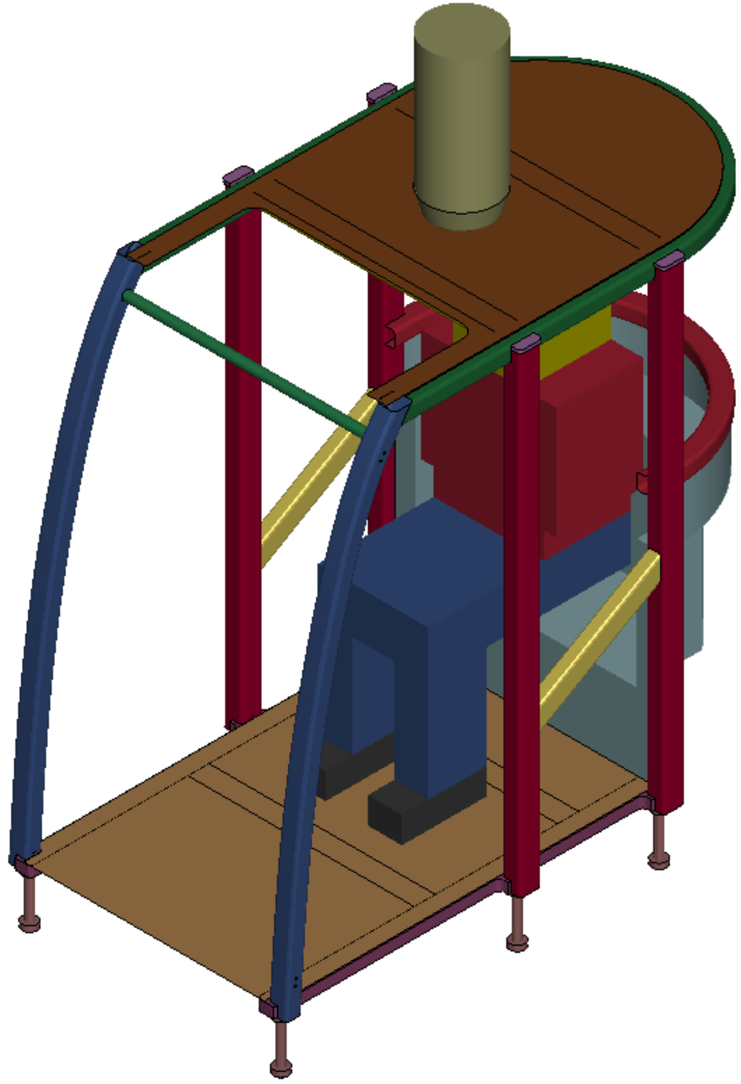




FOPS Test

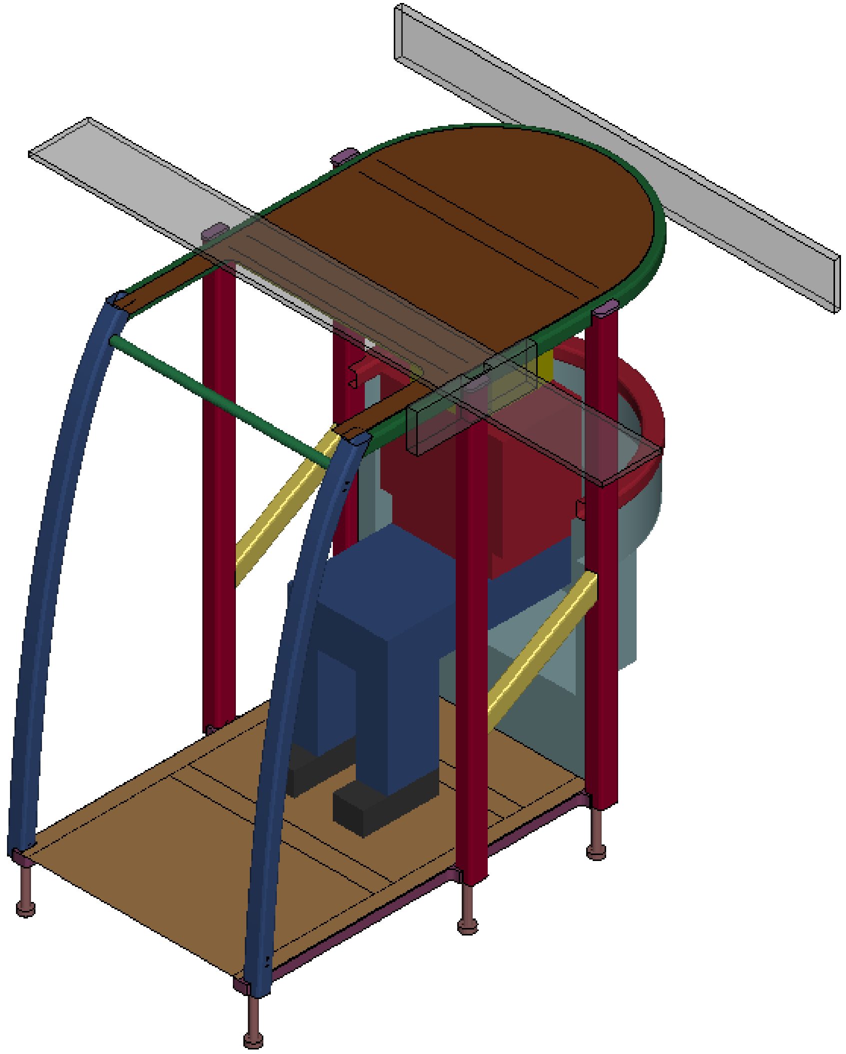
- Level 2 test object is a solid steel or ductile iron cylinder.
- The mass of the test object determines drop height such that an impact energy of 11 600 J is achieved.
- The typical mass is 227 kg, which results in a drop height of 5.22 m (g=9.807 m/s^2).
- DLV must not be penetrated.





ROPS Test

- Loads are applied to the ROPS laterally, vertically, and longitudinally, in sequence, and in a quasi-static manner. Loads are applied through load distribution devices (LDD).
  - 1. Lateral loading and unloading.
  - 2. Vertical loading and unloading.
  - 3. Longitudinal loading and unloading.
- There are force resistance requirements in all three directions as well as an energy absorption requirement in the lateral direction.
- The mass of the machine that the ROPS is mounted on determines the magnitude of force and energy requirements.
- No part of the ROPS is allowed to penetrate the DLV.

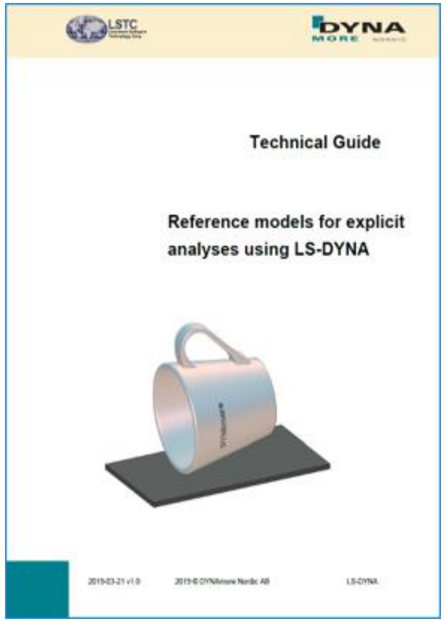


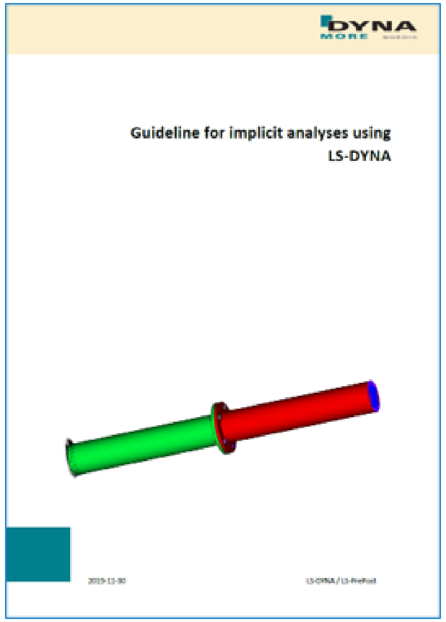
Simulation Strategy

- The simulation consists of three stages.
  - 1) Bolt pre-tensioning using dynamic relaxation
  - 2) FOPS test using explicit time integration.
    - Interface springback to save the deformed structure to use in the ROPS test.
  - 3) ROPS test using implicit time integration, set up using cases.

Simulation Strategy – Guidelines

- We at DYNAmore Nordic provide an explicit and an implicit guideline with recommendations, examples, and lots of good information to help you when using the different solvers.
- Together with the guidelines, we provide recommended Control and Database keywords.
- All of this and more is found on our Client Area.

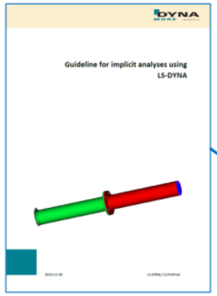


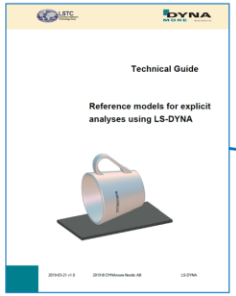


Suggested Modeling Structure

- If you are new to LS-DYNA, consider watching the webinar *“Explicit Model Breakdown”* for a good introduction.
- When modeling a large and complex problem, it is important to have a structured approach.
  - Make use of the keyword *INCLUDE to lift out parts of the model into separate keyword files for improved workability and easier overview.
  - Employ a logical numbering of ID:s by letting imported parts start with distinct numbers, e.g., the element and node ID:s of the test object in the FOPS model start at 1 000 001, and other keywords pertaining to the test object also have the ID 1 000 001.
  - Take the time to document changes that you do, and the effect they have, e.g., changing settings in a contact keyword or changing element formulation.

Suggested Modeling Structure





Main.k

```
*INCLUDE *CONTACT
*LOAD    *BOUNDARY
*INITIAL *SET_…_ADD
…
```

Control_cards.k

```
*CONTROL_ACCURACY
*CONTROL_BULK_VISCOSITY
*CONTROL_CONTACT
*CONTROL_ENERGY
*CONTROL_HOURGLASS
*CONTROL_OUTPUT
*CONTROL_SHELL
*CONTROL_SOLID
*CONTROL_SOLUTION
…
```

Database_cards.k

```
*DATABASE_…
*DATABASE_BINARY_D3PLOT
*DATABASE_BINARY_INTFOR
*DATABASE_EXTENT_BINARY
*DATABASE_HISTORY…
…
```

Often Combined

Materials.k

```
*MAT_020/RIGID
*MAT_024/PIECEWISE…
…
```

Geometry.k

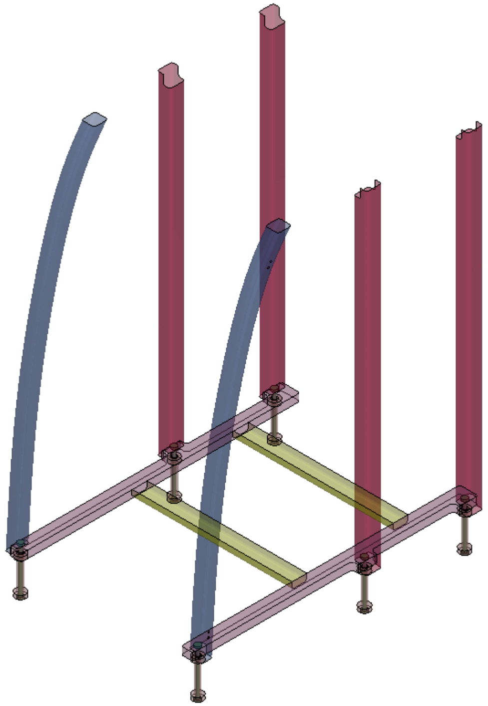
```
*NODE
*ELEMENT…
*PART
*SECTION…
*SET_NODE
*SET_ELEMENT
*SET_PART
*DATABASE_HISTORY_NODE
```

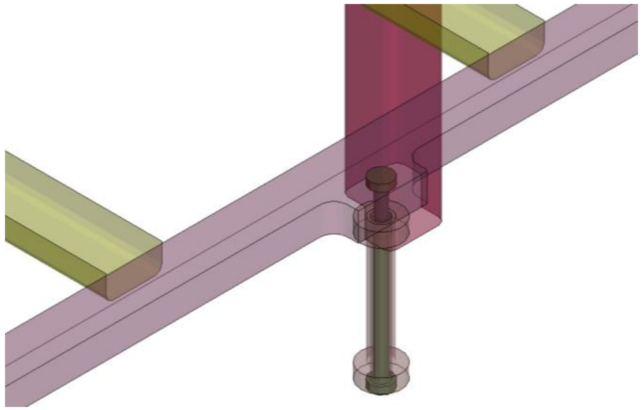
Rarely changed ⟹

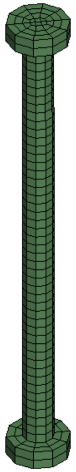
- Few errors are introduced.
- All normal results are always available.
- Prepare settings for different types of analyses.

Bolt Pre-Tensioning – Dynamic Relaxation

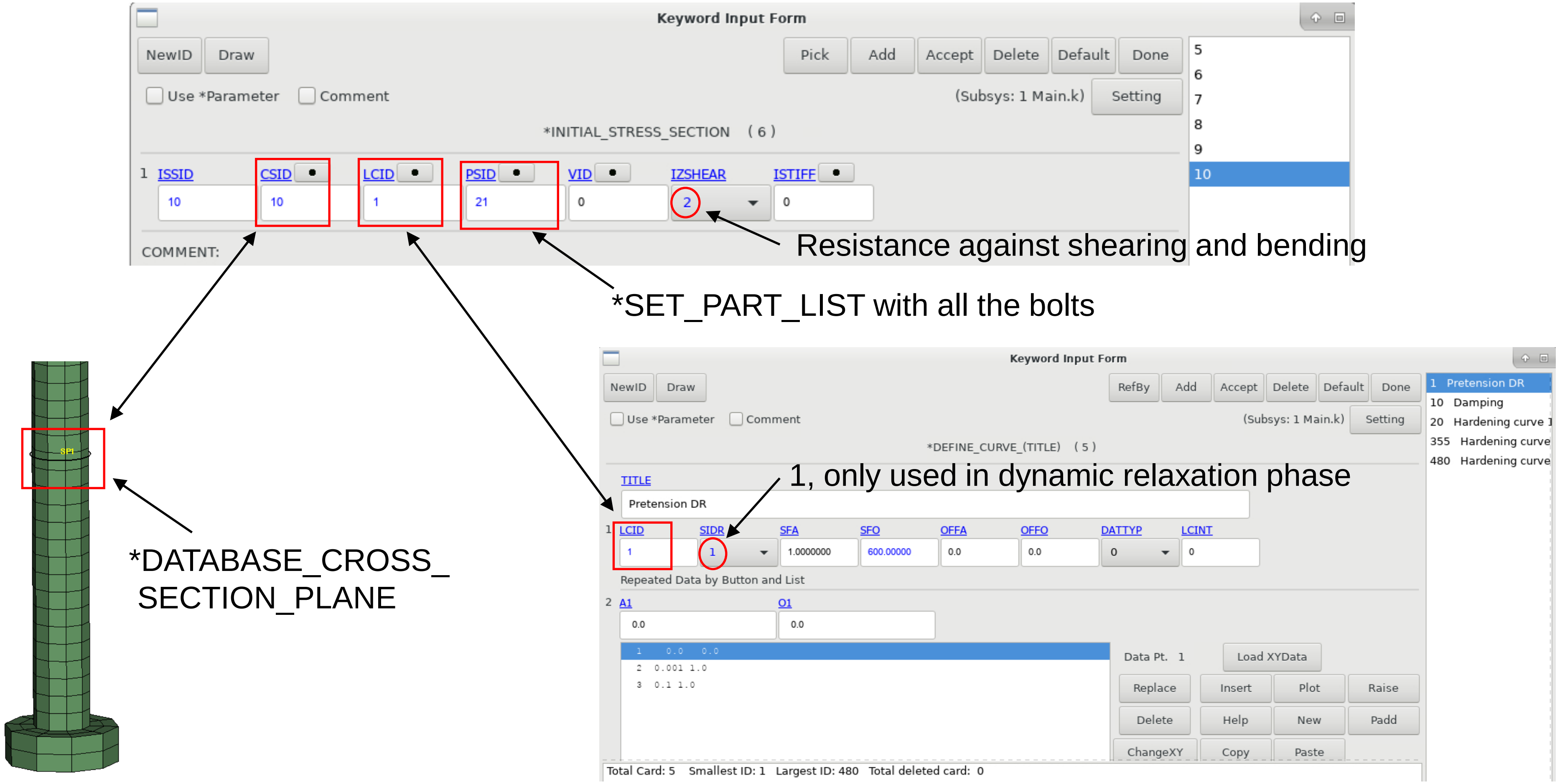
- The model contains six long bolts for mounting the structure to the testbed.
- Pre-tensioning takes place in a dynamic relaxation phase preceding the FOPS test.
- See our related webinar “*Pre-Tensioning and Dynamic Relaxation”* on our Client Area.



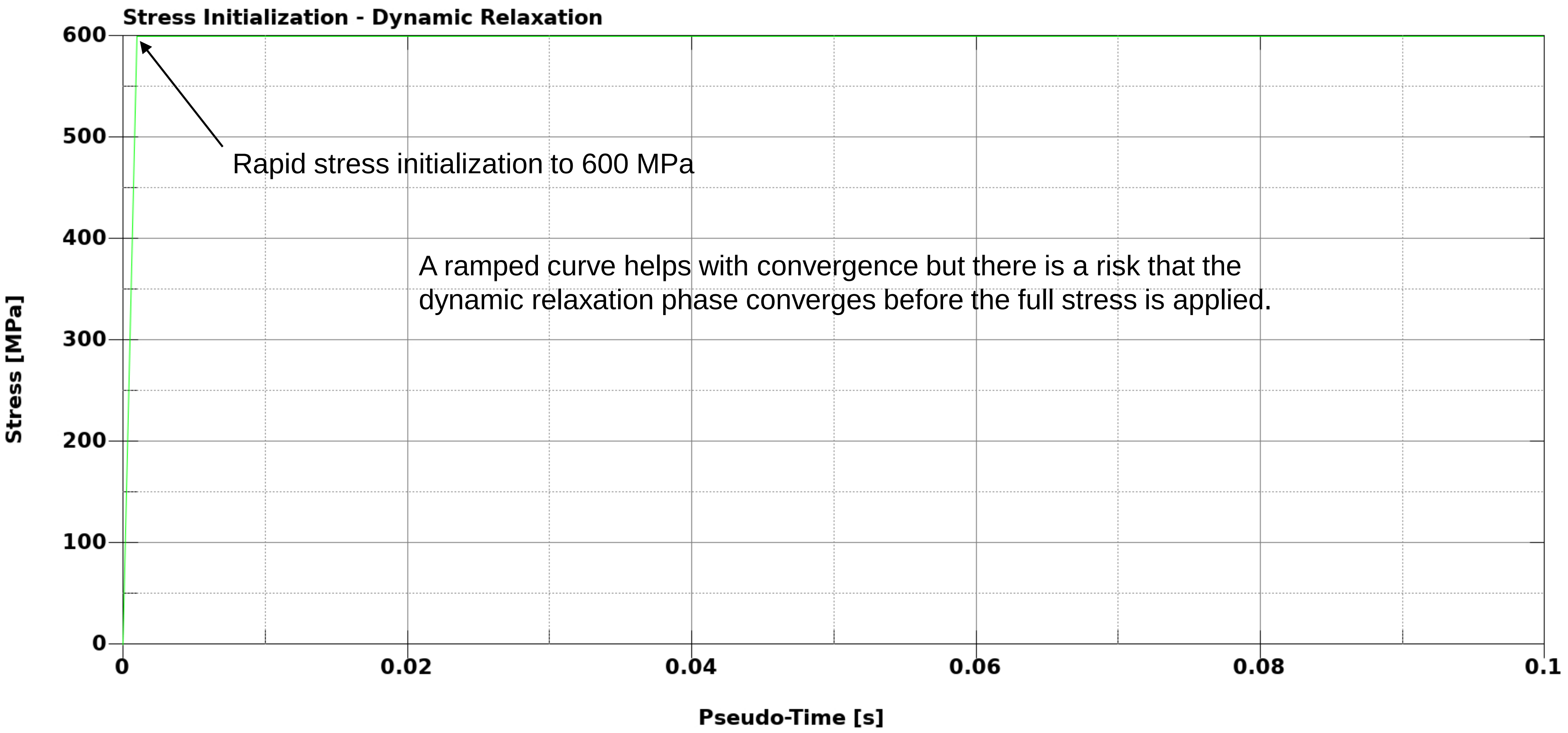




Bolt Pre-Tensioning – Dynamic Relaxation

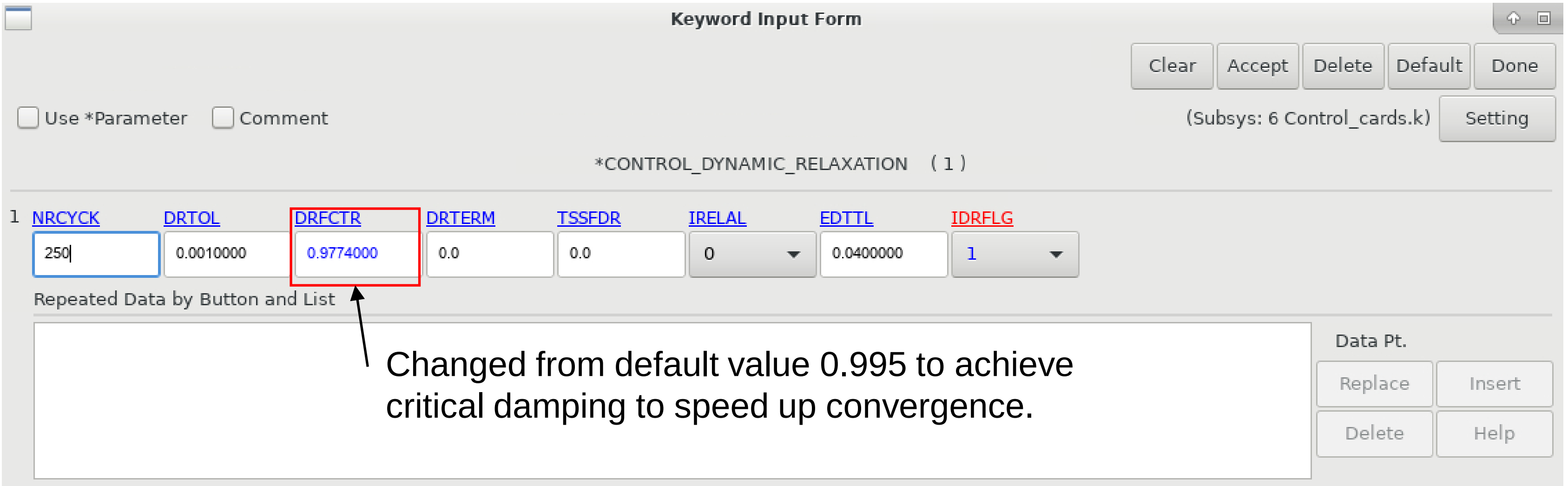


Bolt Pre-Tensioning – Dynamic Relaxation



Bolt Pre-Tensioning – Dynamic Relaxation

- *DATABASE_BINARY_D3DRLF to receive output during a dynamic relaxation phase in the same way as a normal D3PLOT-file. The user specifies the number of calculation cycles between output states.

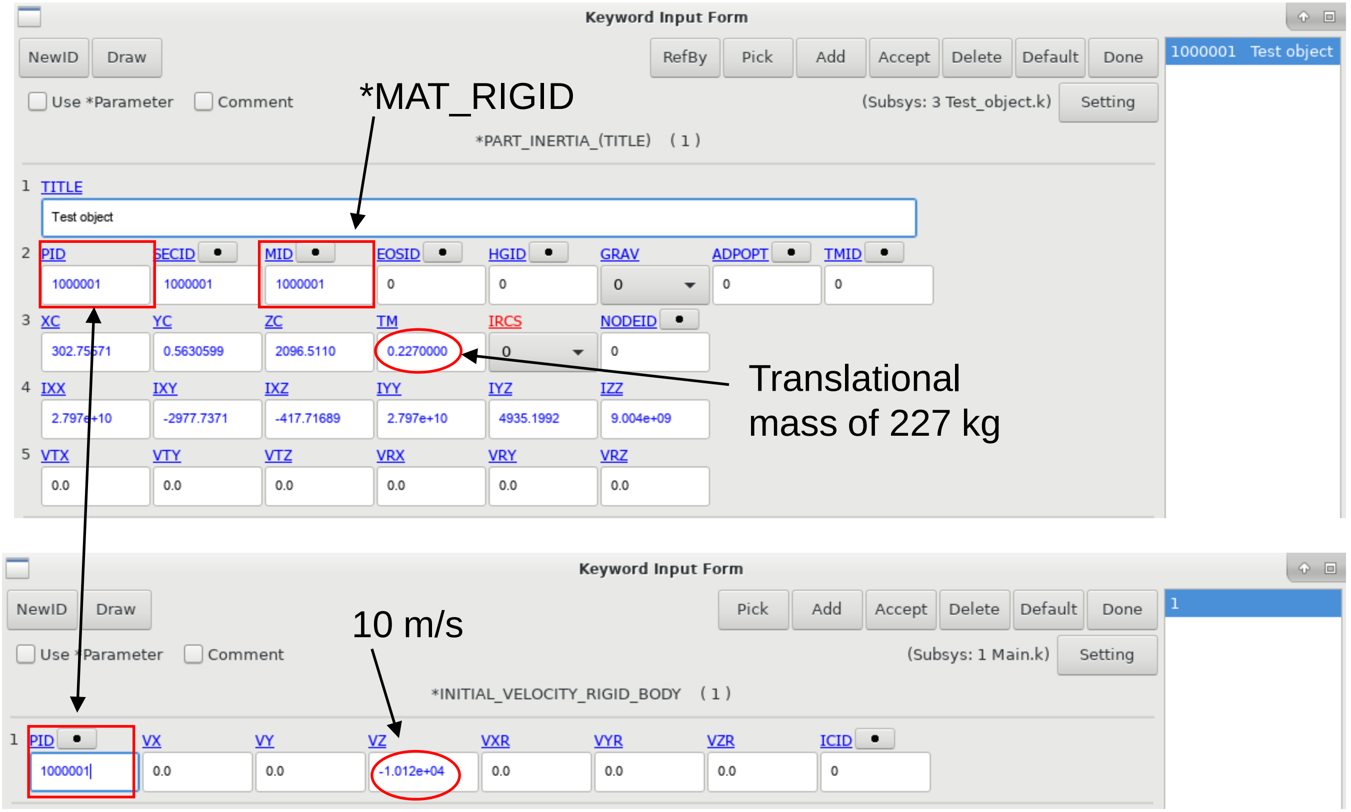


Simulation of FOPS Test – Overview

- High-speed, dynamic event → Explicit analysis is suitable.
- First order, under-integrated elements.
- R13.1.1 version of LS-DYNA. Run with single precision.
- The test object is placed close to the point of impact and given an initial velocity rather than simulating free fall.
- The initial velocity of the 227 kg test object dropped from a height of 5.22 m is 10.12 m/s.
- Contact between test object and roof as well as other contacts to hold the structure together.
- Selective mass-scaling to decrease computational cost
- Damping is applied to make the structure still after impact quicker
- Upon termination, the deformed structure is saved by using springback.

Simulation of FOPS Test – Test Object

- The test object is modeled as a rigid body for simplicity and to reduce computational cost.
- For information about how rigid bodies work in LS-DYNA, there is the webinar “*Rigid Bodies in LS-DYNA*”.

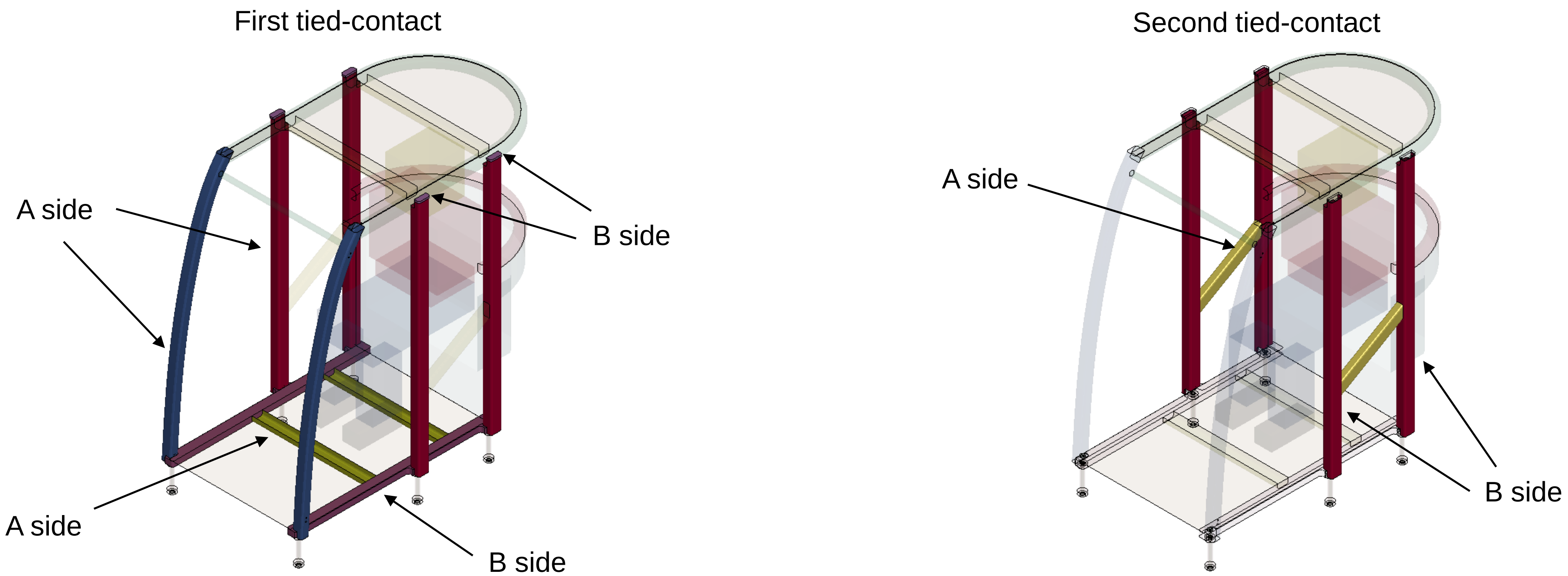


Simulation of FOPS Test – Contacts

- Without any contact algorithms, the test object would just pass through the cab, and it would be difficult to get achieve connectivity for the whole structure.
- We have a webinar on "*Tied and Tiebreak Contacts in Explicit Simulation".*
- Additionally, the upcoming webinar in two weeks by Jimmy Forsberg will be about contacts in explicit analyses.

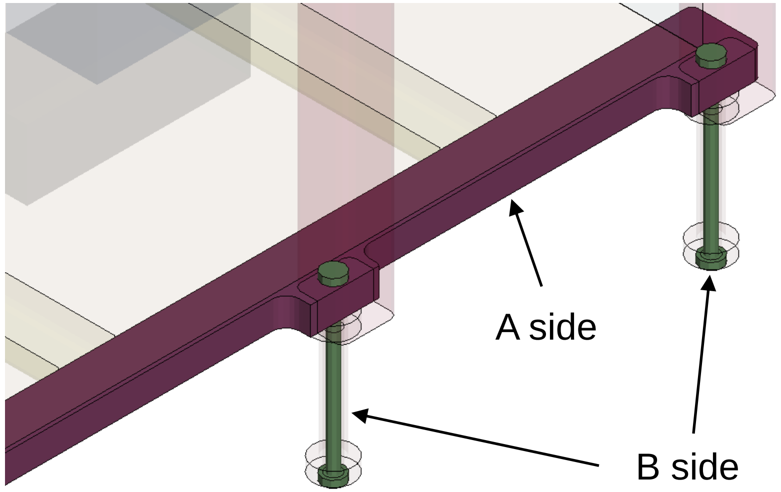
Simulation of FOPS Test – Contacts

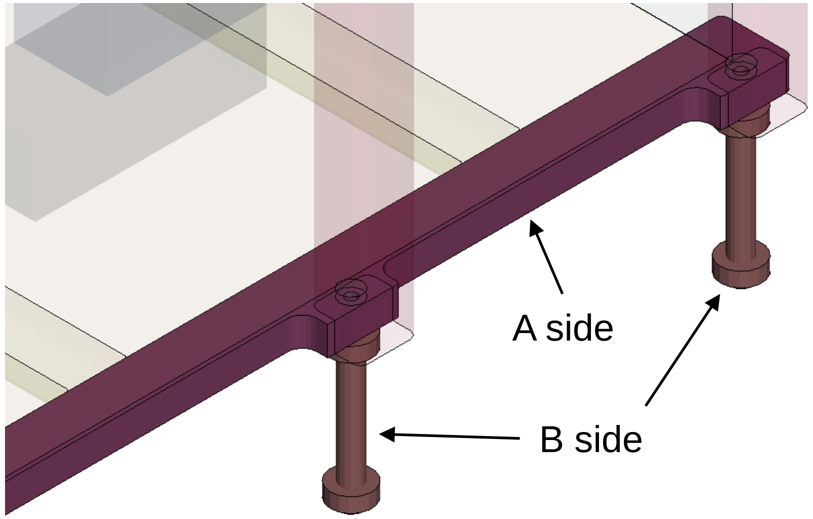
- *CONTACT_TIED_SHELL_EDGE_TO_SURFACE_OFFSET is used for the tied contacts. The addition of OFFSET changes from a constraint formulation to a penalty formulation.

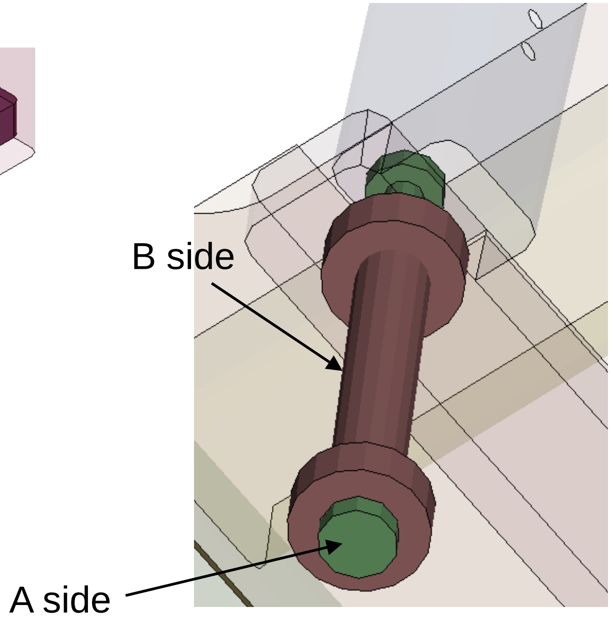


Simulation of FOPS Test – Contacts

- *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is used for standard contacts. Settings are taken from the Explicit Guideline.
- One contact between test object and the rest of the model. Another contact between DLV and the cab to check for penetration of the DLV.
- In addition, there are three contacts involving the floor, bolts, and fundaments.





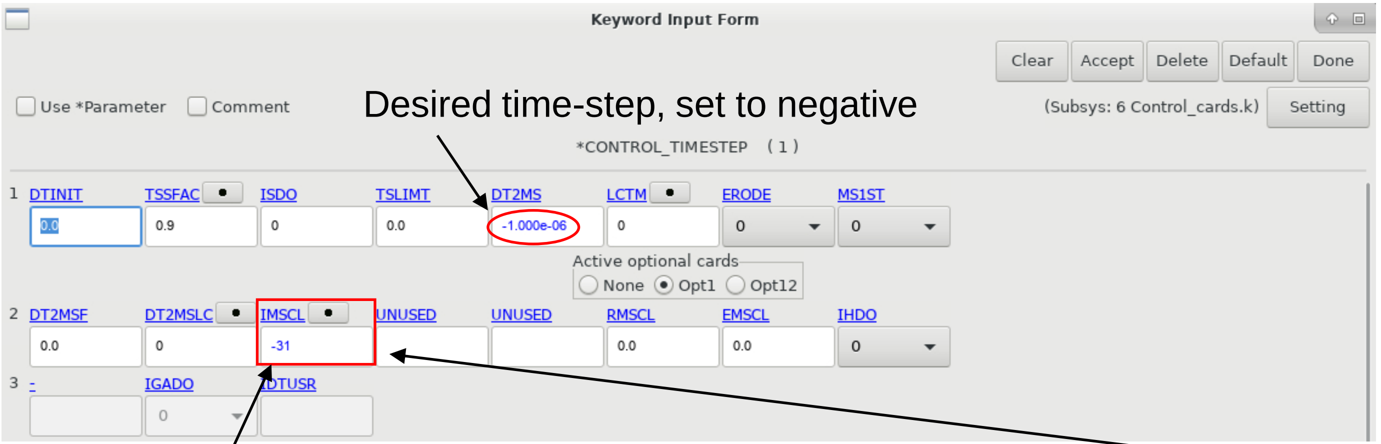


Simulation of FOPS Test – Mass Scaling

- There are parts in the model with solid elements which results in a low critical time-step. To reduce computational cost, one can use mass-scaling.
- There is information about mass-scaling in the webinar “*Mass-Scaling and Subcycling in LS-DYNA*”*.*

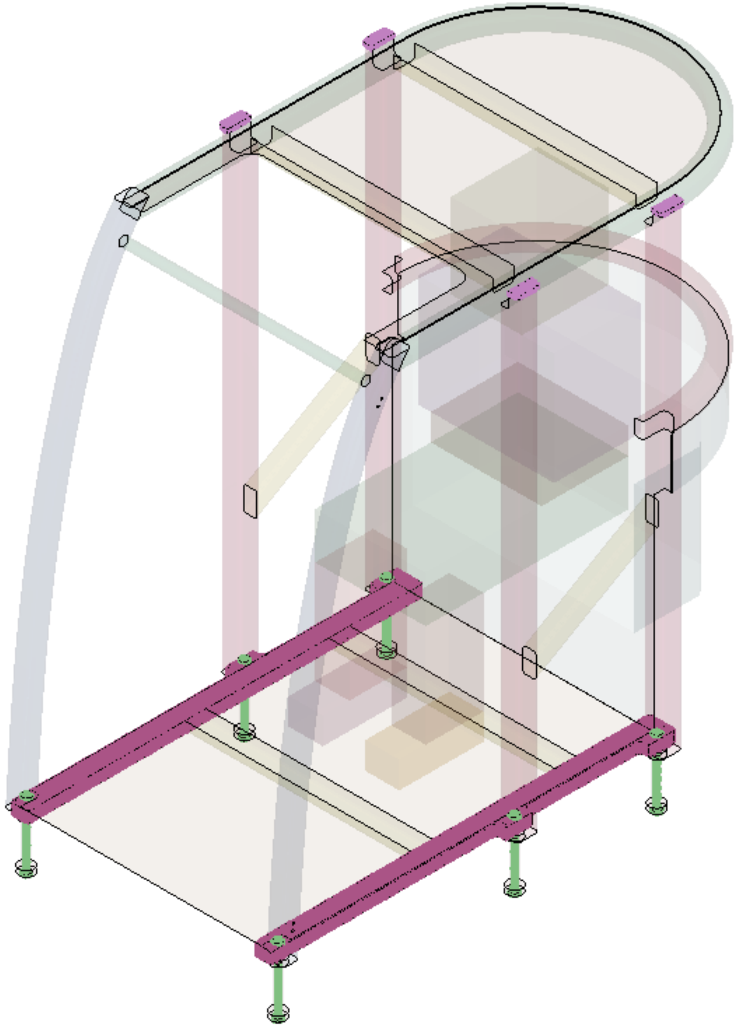
Simulation of FOPS Test – Mass Scaling

Desired time-step, set to negative



Activates selective mass-scaling.
Negative value indicates part set.

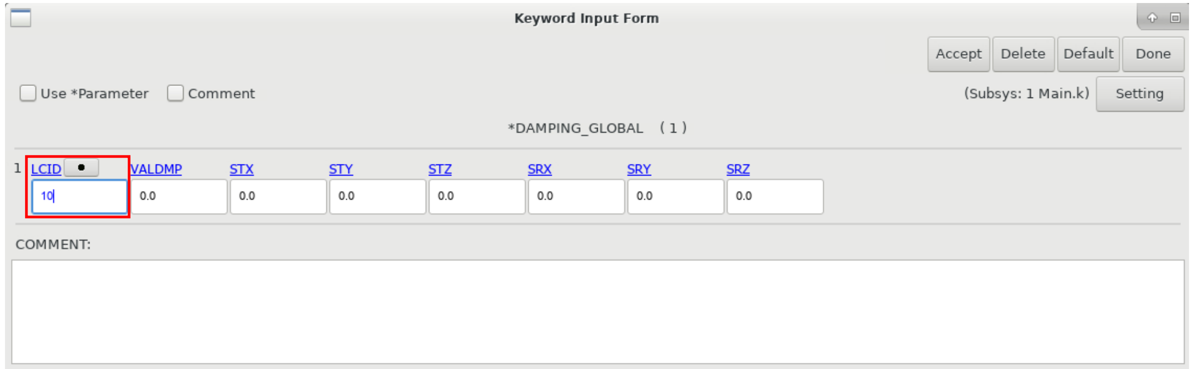
*SET_PART_LIST of solid parts that receive selective mass-scaling. Other parts receive conventional mass-scaling.

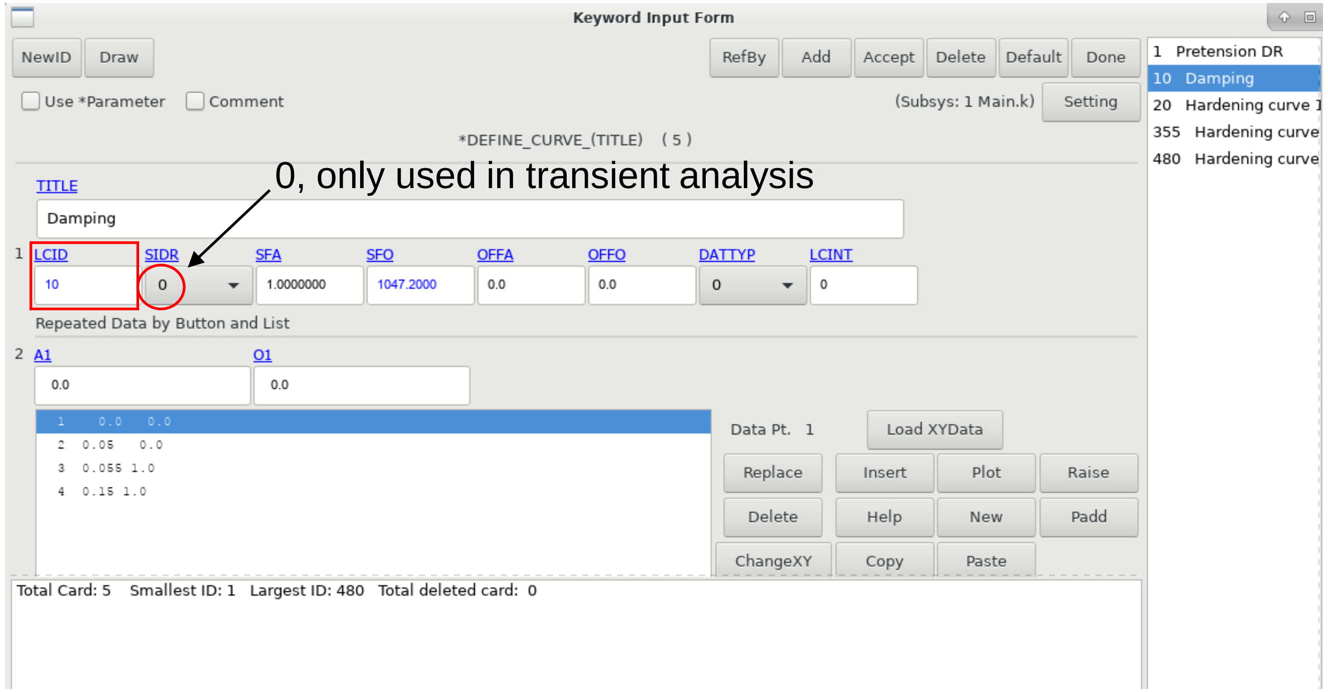


Simulation of FOPS Test – Damping

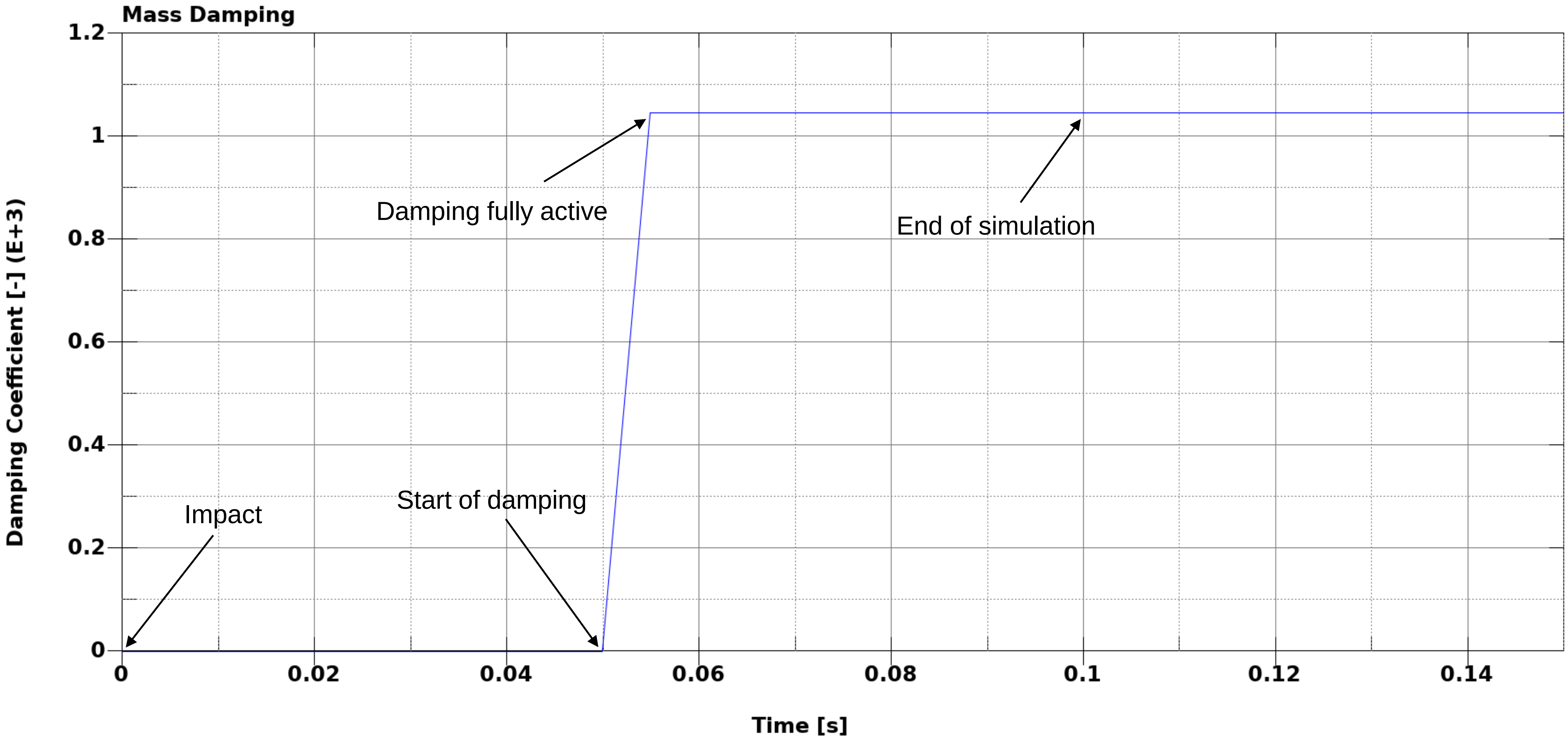
- The impact from the test object induces vibrations in the structure, and there are no natural damping effects such as surrounding air or internal losses in the material. To obtain a structure at equilibrium within a reasonable simulation time, damping is introduced.
- There is information about damping in the webinar "*Damping in Explicit LS-DYNA".*
- *DAMPING_GLOBAL is used which is mass weighted damping.
  - A load curve is used to turn the damping on at an appropriate time and to decide damping coefficient.
  - To achieve critical damping, the coefficient is set to $2\pi\omega_{min}$, where ω_{min} is the lowest angular frequency mode of interest.

Simulation of FOPS Test – Damping



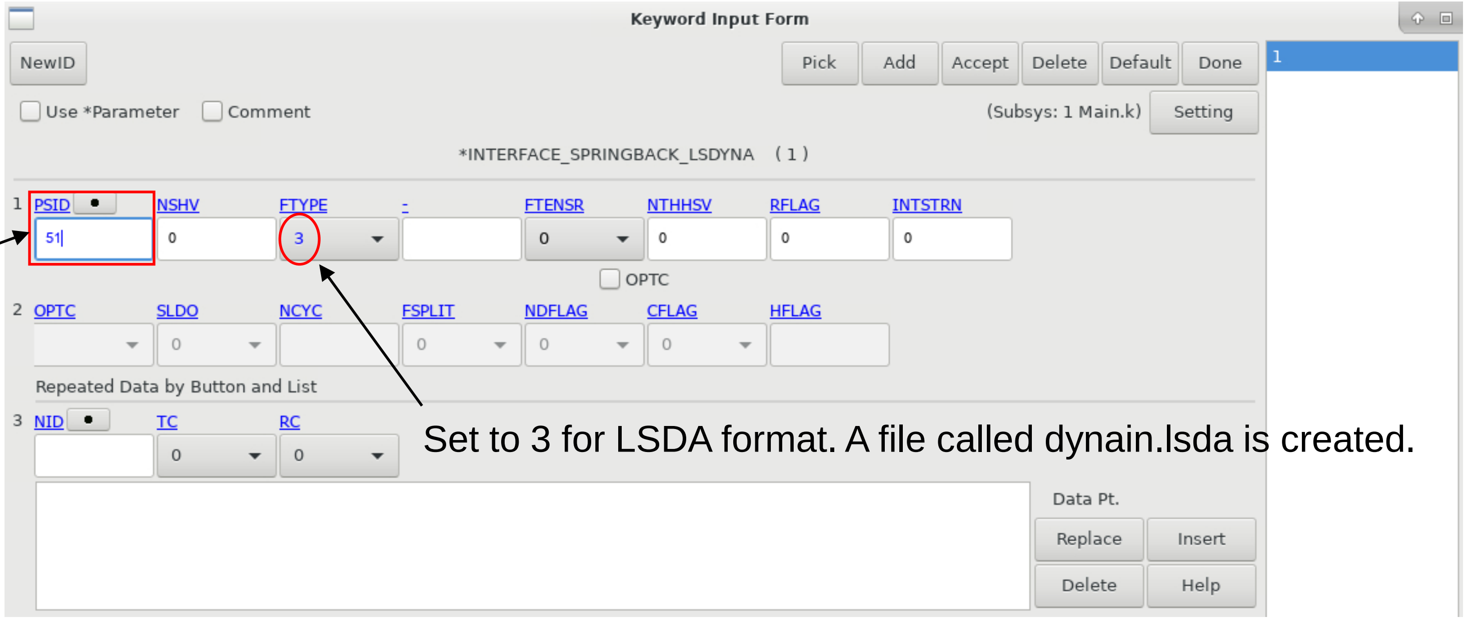


Simulation of FOPS Test – Damping



Simulation of FOPS Test – Springback

- The purpose of adding “Springback” to the simulation is that this causes LS-DYNA to, upon termination, write the final state of the system to an output file so that the results can be used as input for another subsequent analysis.
- The name springback is due to historical reasons since this was implemented in the context of metal forming but is in no way limited to such types of analyses.



*SET_PART_LIST containing all parts that are to be outputted. In this case, the test object is excluded.

Set to 3 for LSDA format. A file called dynain.lsda is created.

Simulation of ROPS Test – Overview

- Slow, quasi-static event → Implicit analysis is suitable.
- First order, fully-integrated elements.
- R13.1 version of LS-DYNA. Run with double precision.
- Load distribution devices in three directions are prescribed displacements in sequence.
- Three simulations are run in sequence using the *CASE logic.
- Contact between LDDs and cab as well as other contacts to hold the structure together.

Simulation of ROPS Test – Implicit Guideline

- The implicit guideline has already been mentioned, but there is also a webinar “*Guideline for Implicit Analysis*”, where my colleague Anders Jonsson goes through some details.

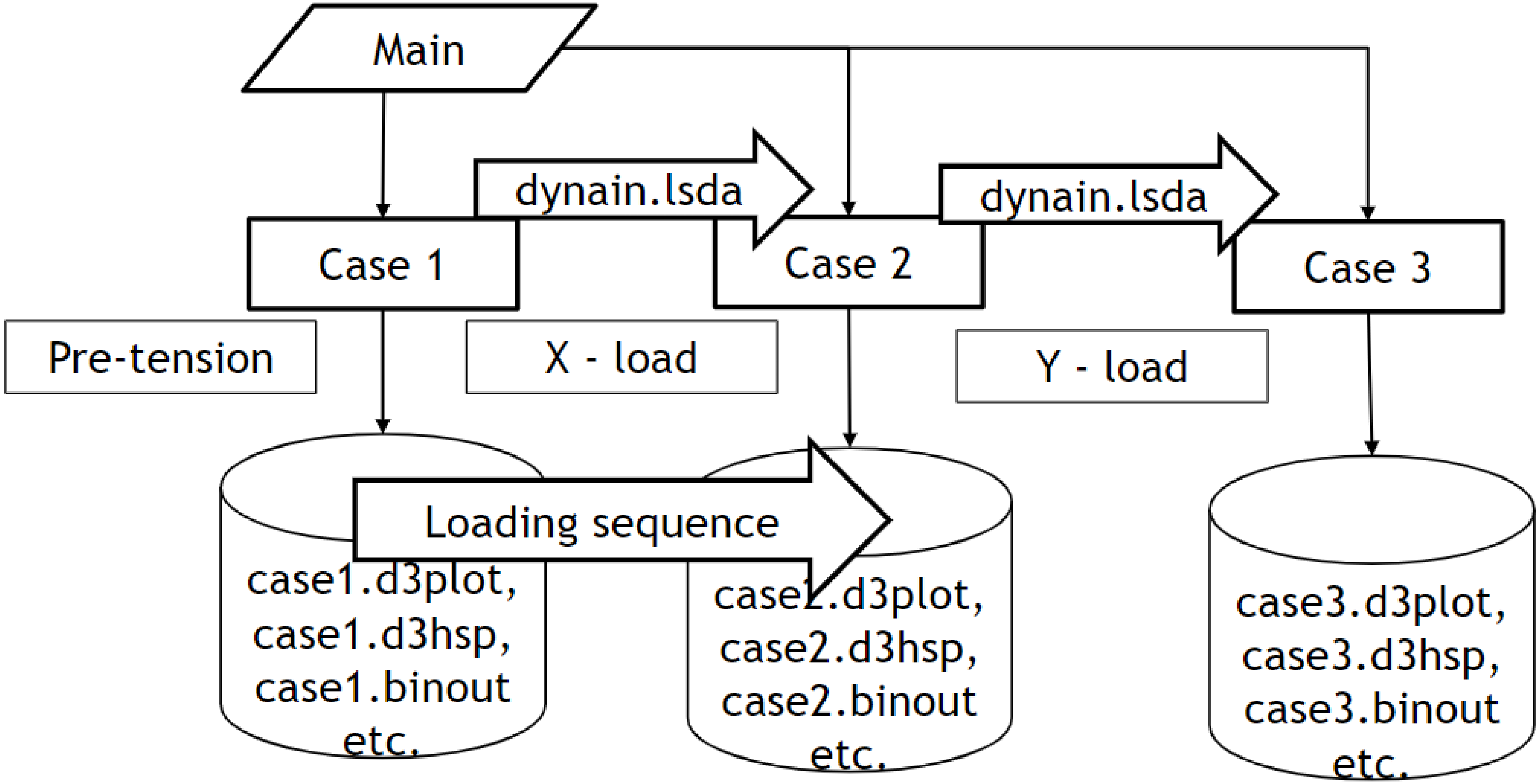
Simulation of ROPS Test – Explicit to Implicit

- There is a webinar on our Client Area titled “*From Explicit to Implicit Simulation Models”* which deals with the considerations one must take when moving between the two solvers.
- In addition, there is an upcoming webinar in four weeks which my colleague Anders Jonsson will give on the topic of Explicit/Implicit Switching.
- For this case, there was not a lot of problems associated with going from an explicit model to an implicit model, but in general there are a few things that one needs to keep in mind.
  - When doing explicit analyses, you can generally get away with modeling practices of questionable nature to a higher extent than when doing implicit analyses, i.e. explicit analysis is more forgiving.
  - Connectivity is crucial for implicit analysis. While an explicit analysis may work fine even with parts of the model hanging freely, this might hinder convergence in an implicit context.
  - For a more detailed explanation, please see the referenced webinars.

Simulation of ROPS Test – *CASE

- You can use the *CASE logic when setting up a simulation with several steps in sequence to split up the analysis into smaller parts for easier workability.
  - The *CASE concept offers an intuitive way of setting up a load history.
  - It gives a clear definition of which features that are active in each step.
  - It reduces the need for birth/death times for contacts, boundary conditions et cetera.
- Our webinar on the topic is called *“Load History Management”.*

Simulation of ROPS Test – *CASE



Simulation of ROPS Test – *CASE

DYNA MORE

Cases.k

```
$LSPrePost Multiphysics Solution CASE FILE
*KEYWORD
*CASE
                1lateral

1
*CASE
                2vertical

2
*CASE
                3longitudinal

3
*CASE_BEGIN_1
*INCLUDE
lateral.k
*CASE_END_1
*CASE_BEGIN_2
*INCLUDE
vertical.k
*CASE_END_2
*CASE_BEGIN_3
*INCLUDE
longitudinal.k
*CASE_END_3
*END
```

lateral.k

```
$# LS-DYNA Keyword file created by LS-PrePost(R) V4.10 (Beta)-30Jan2023
$# Created on Feb-7-2023 (12:56:09)
*KEYWORD
*CONTROL_TERMINATION
$#  endtim    endcyc     dtmin    endeng    endmas     nosol
      20.0         0       0.0       0.01.000000E8         0
*INTERFACE_SPRINGBACK_LSDYNA
$#    psid      nshv     ftype         -    ftensr    nthhsv     rflag   intstrn
        20      9999         3                   0         0         1         0
$#    optc      sldo      ncyc    fsplit    ndflag     cflag     hflag
OPTCARD            0         0         0         0         1         1
*INCLUDE
$#                                                                     filename
Main_lateral.k
*INCLUDE
$#                                                                     filename
FOPS.dynain.lsda
*SET_PART_LIST_TITLE
Springback
$#     sid       da1       da2       da3       da4    solver
        20       0.0       0.0       0.0       0.0MECH
$#    pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
         3         4         5         6         7         8         9        10
        11        12        14        15        16        19        20        22
   2000008   2000001   2000002   2000003   2000004   2000005   2000006   2000007
*END
```

File containing everything, geometry, materials, loads..

dynain.lsda file from previous analysis.
In this case the FOPS simulation.

Simulation of ROPS Test – *CASE

Cases.k

```
$LSPrePost Multiphysics Solution CASE FILE
*KEYWORD
*CASE
                  1lateral

1
*CASE
                  2vertical

2
*CASE
                  3longitudinal

3
*CASE_BEGIN_1
*INCLUDE
lateral.k
*CASE_END_1
*CASE_BEGIN_2
*INCLUDE
vertical.k
*CASE_END_2
*CASE_BEGIN_3
*INCLUDE
longitudinal.k
*CASE_END_3
*END
```

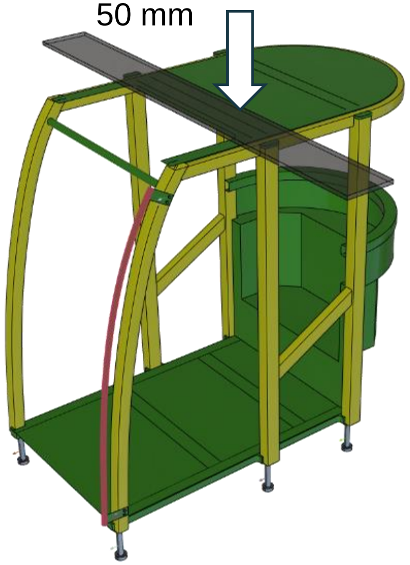
Name	Date modified	Type	Size
Cases.k	2023-02-07 13:02	K File	1 KB
lateral.k	2023-02-07 14:42	K File	2 KB
longitudinal.k	2023-02-07 14:43	K File	2 KB
Main_lateral.k	2023-02-08 08:49	K File	7 KB
Main_longitudinal.k	2023-02-08 08:50	K File	7 KB
Main_vertical.k	2023-02-08 08:50	K File	7 KB
vertical.k	2023-02-07 14:43	K File	2 KB
FOPS.dynain.lsda	2023-02-01 17:09	LSDA File	126 225 KB
lateral.dynain.lsda	2021-03-04 12:46	LSDA File	1 KB
vertical.dynain.lsda	2021-03-04 12:46	LSDA File	1 KB

Simulation of ROPS Test – Loading

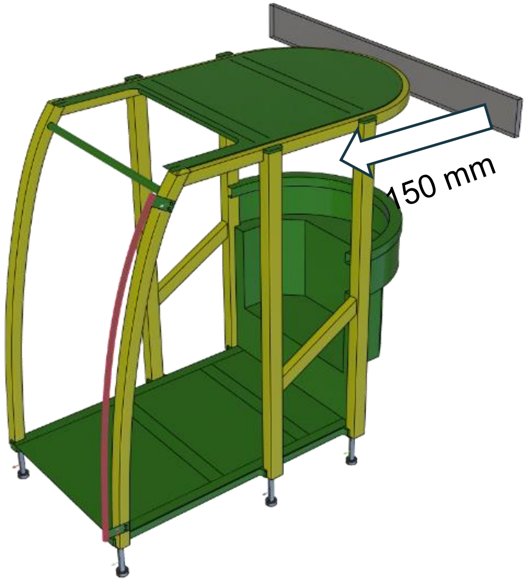
- In a ROPS test, the loading is applied in a quasi-static manner through load distribution devices.
- The LDD:s are rigid bodies and have all except one degree of freedom constrained.
- The LDD:s are given prescribed displacements of 200 mm, 50 mm, and 150 mm.

Lateral

Vertical

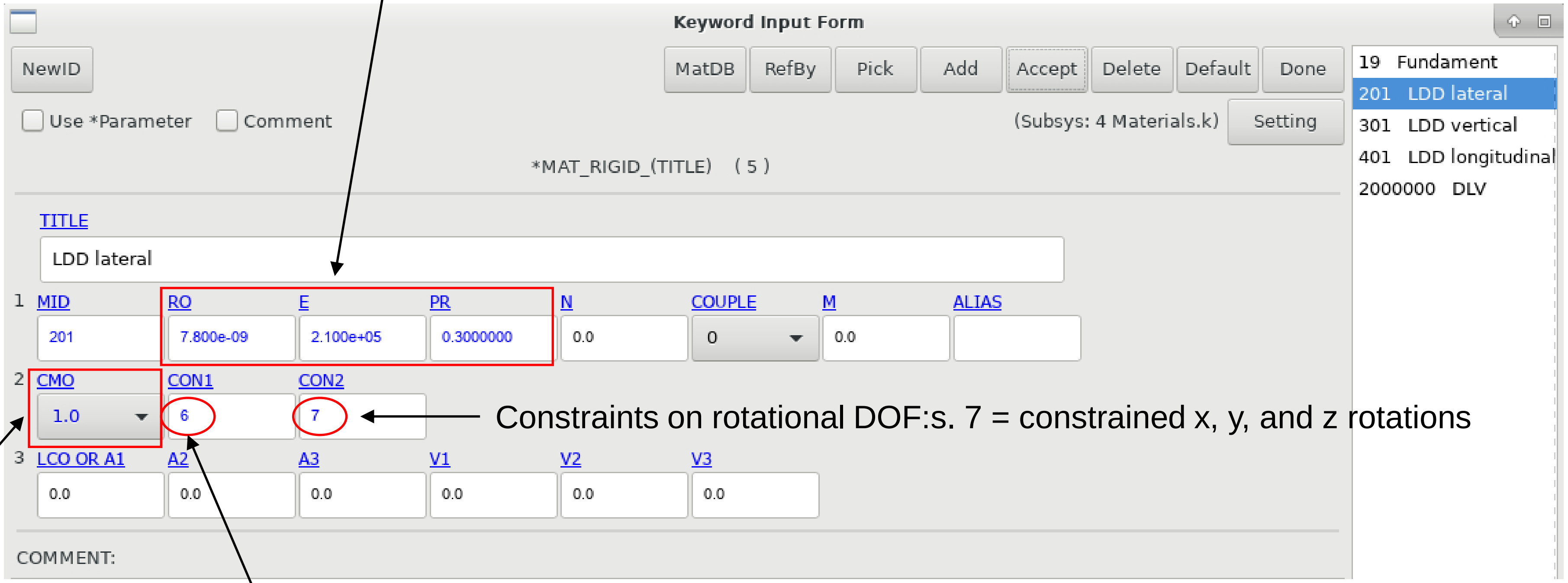


Longitudinal



Simulation of ROPS Test – Loading

Generic steel properties for reasonable contact behaviour

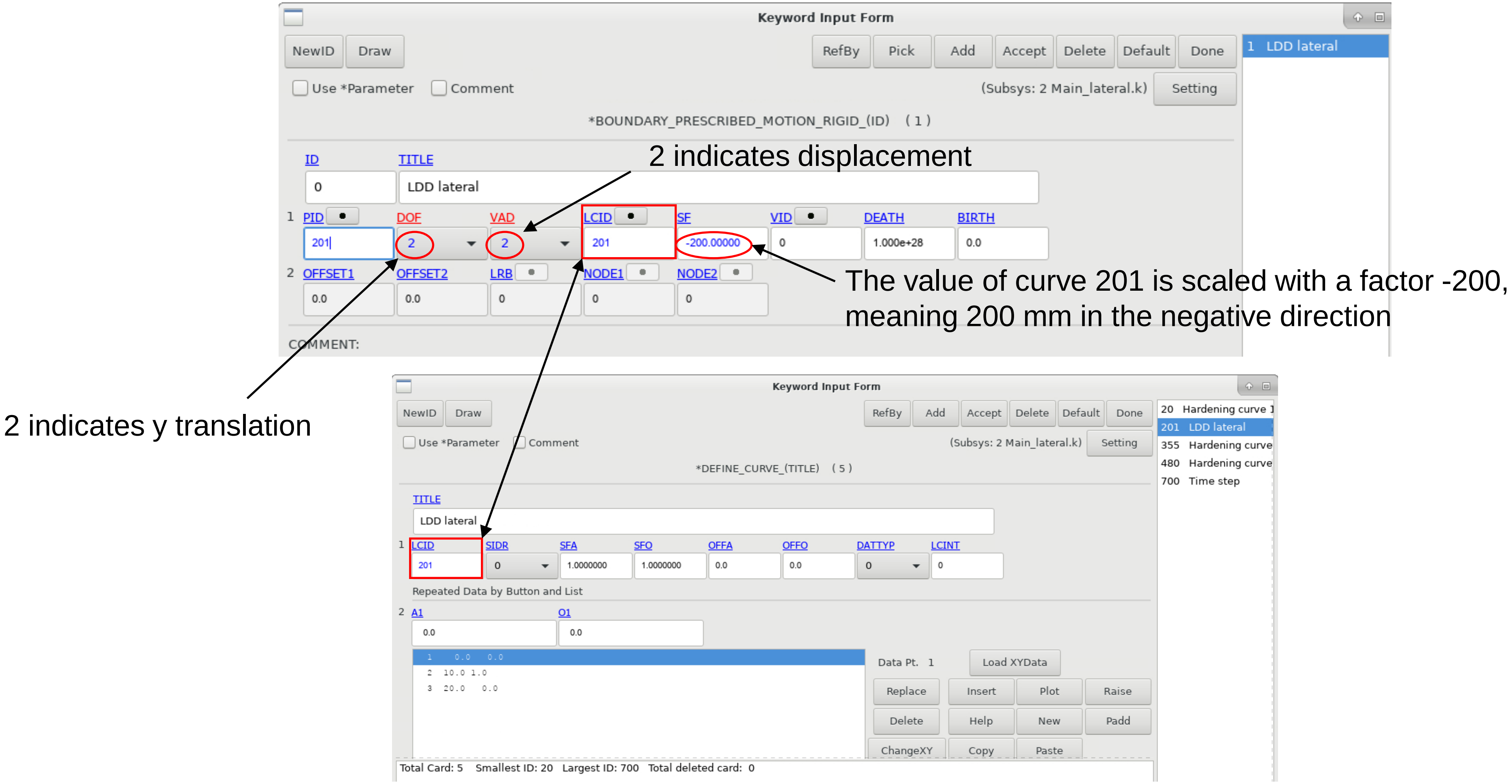


Constraints on rotational DOF:s. 7 = constrained x, y, and z rotations

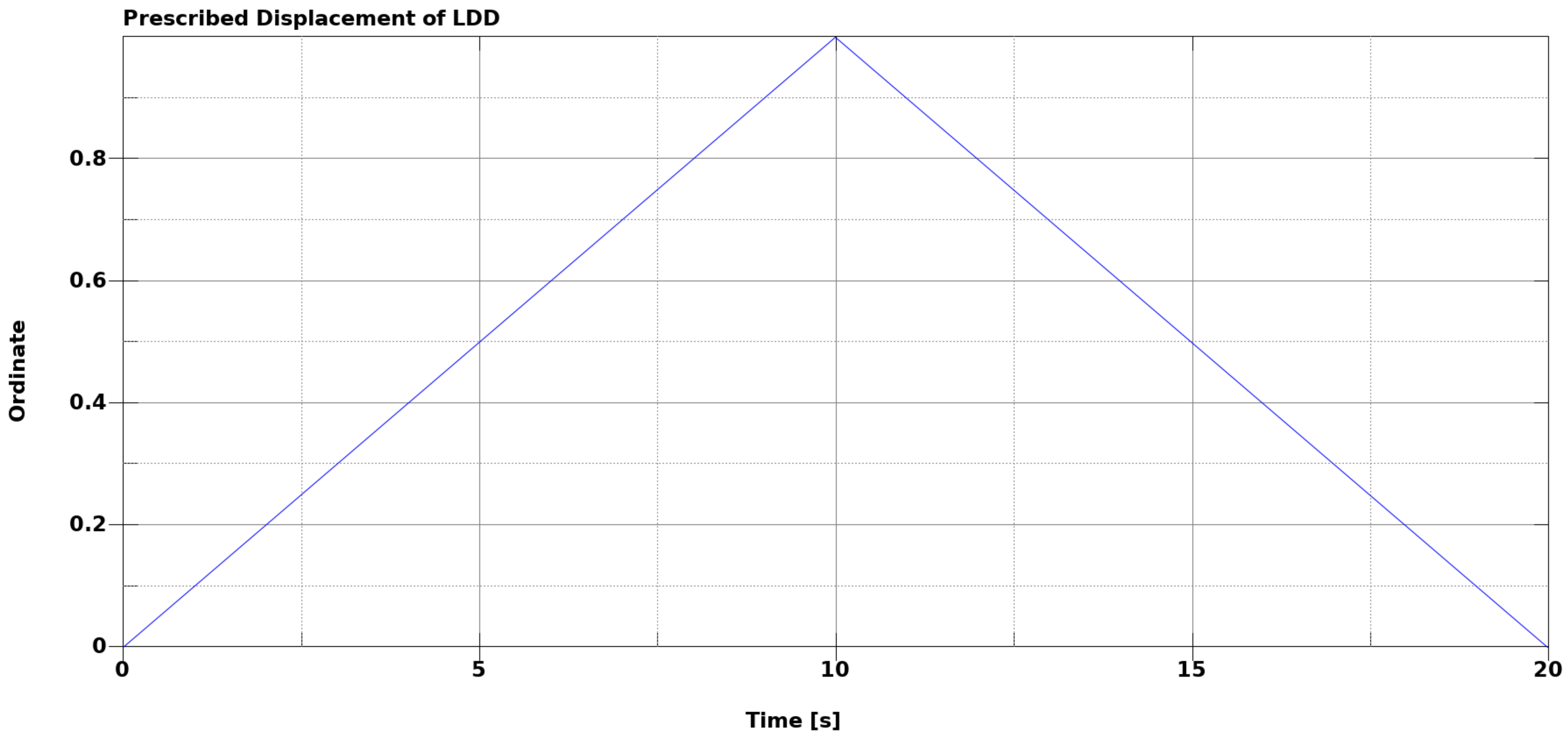
Places a constraint on the center of mass of the rigid body.

Constraints on translational DOF:s. 6 = constrained x and z displacements

Simulation of ROPS Test – Loading



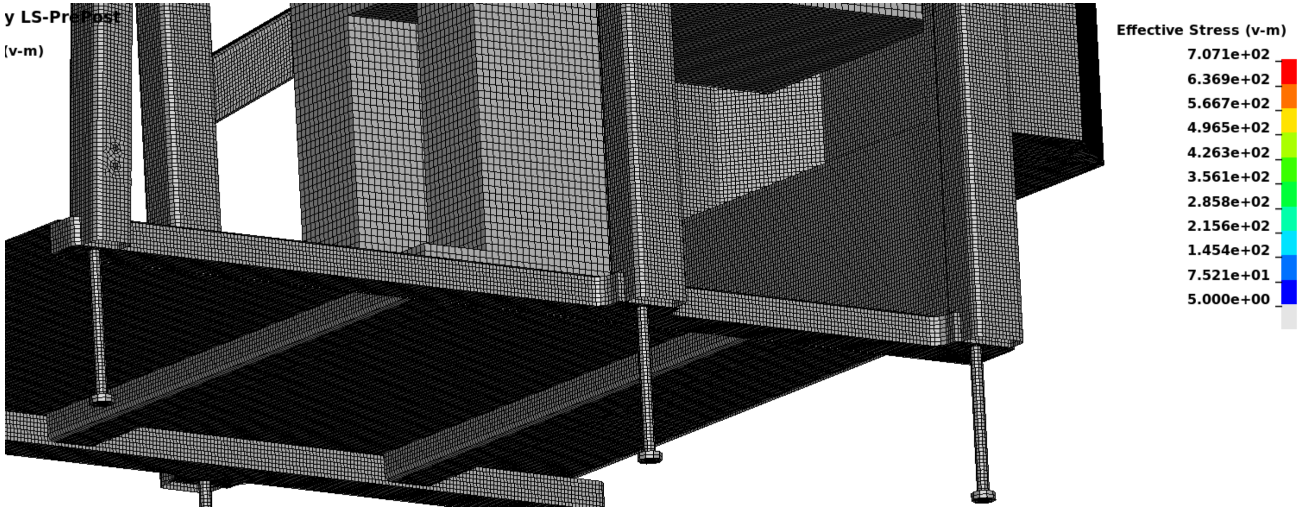
Simulation of ROPS Test – Loading

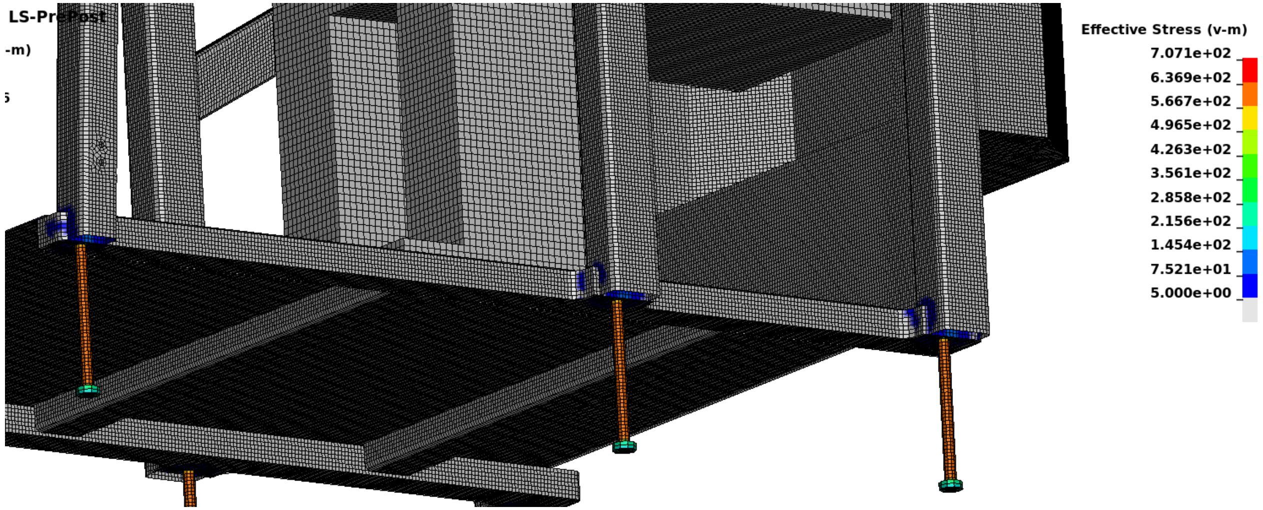


Simulation of ROPS Test – Contacts

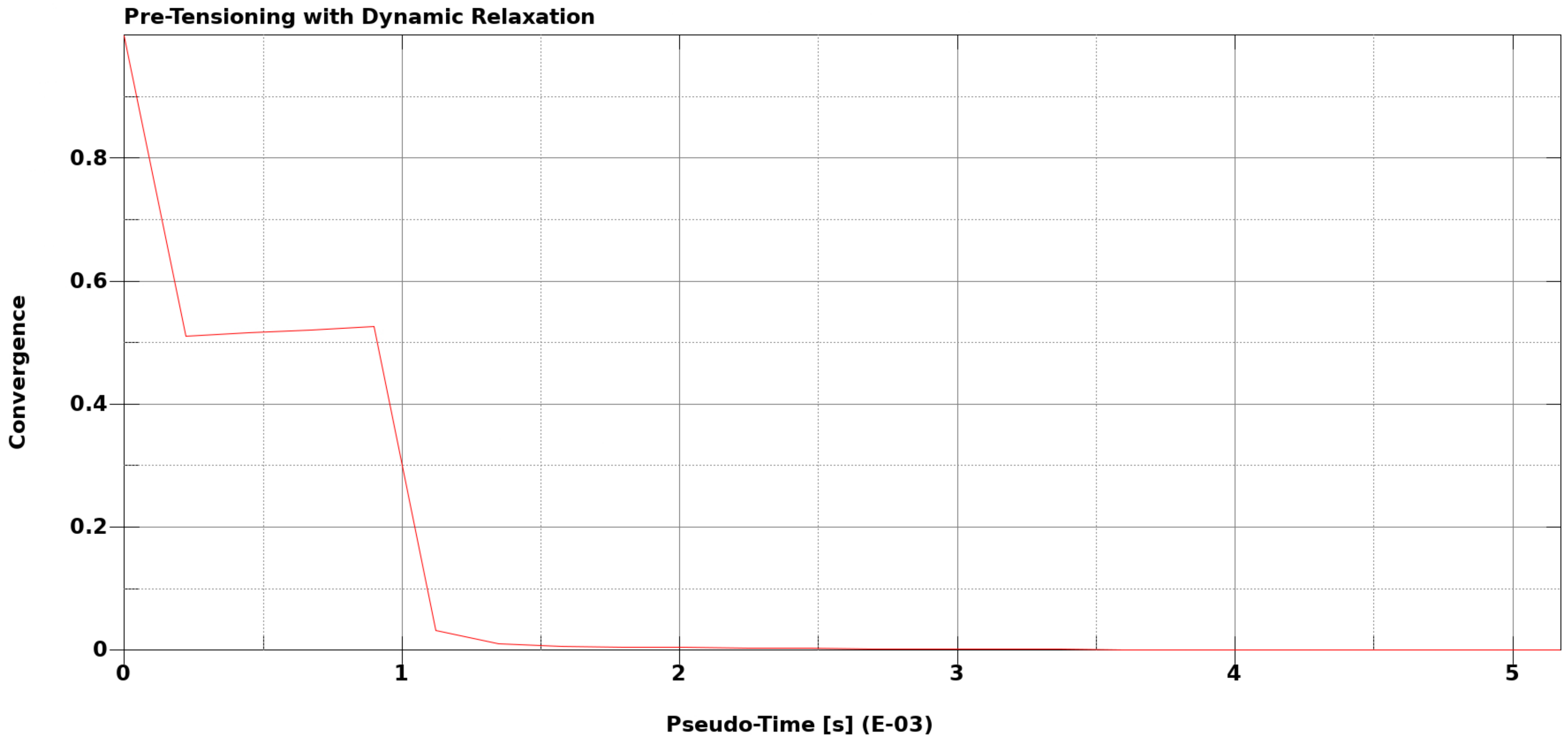
- The ROPS test has the same contacts as the FOPS test except that *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR is used.
- Additionally, there are contacts between the respective LDDs and the cab structure.
- Using Mortar type contacts allows information about contacts to be written to the dynain.lsda file between cases.

Results – Pre-Tensioning





Results – Pre-Tensioning



Results – FOPS Simulation

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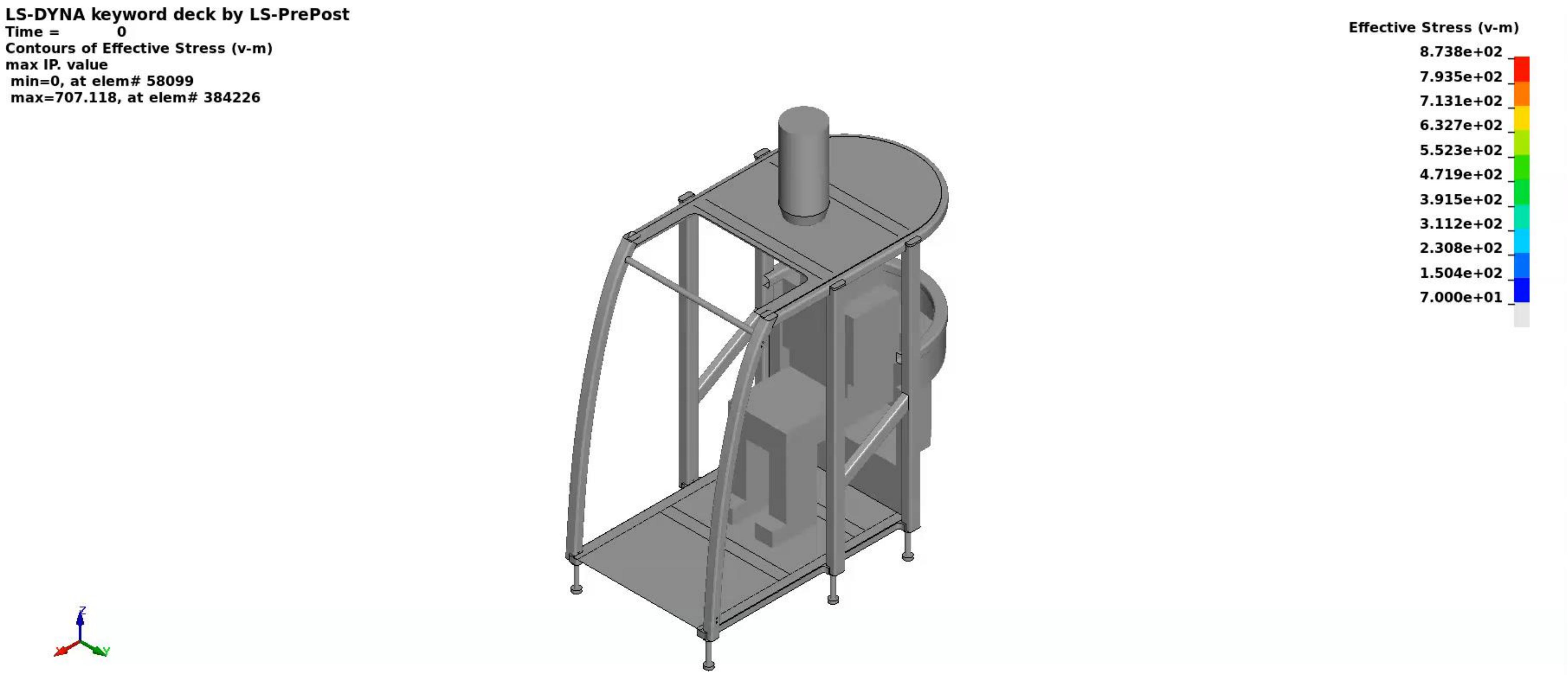
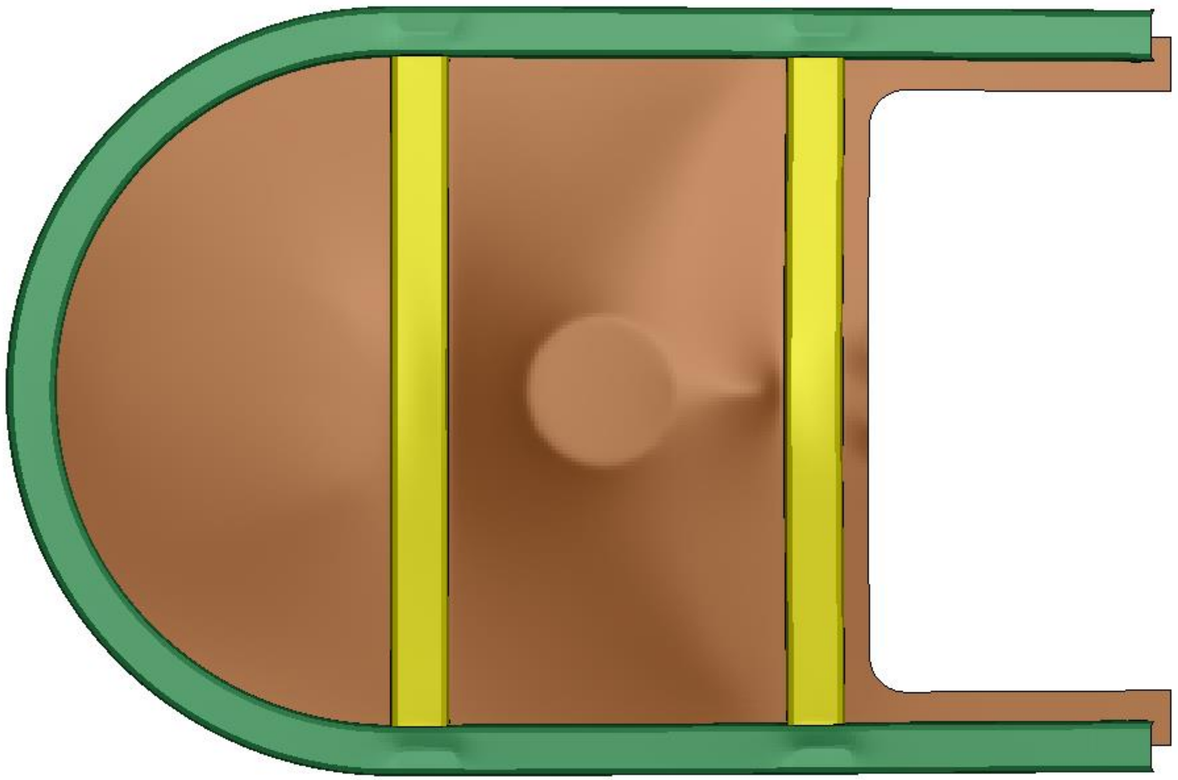
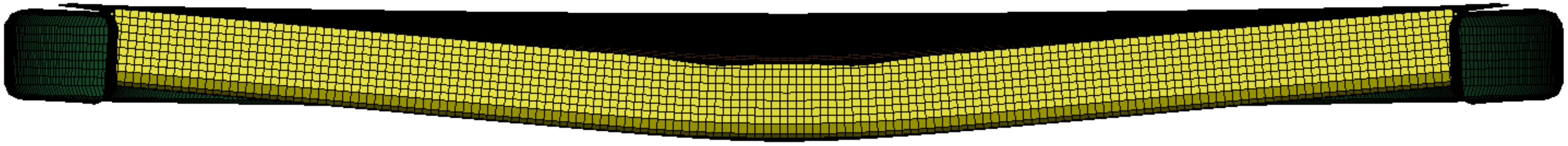
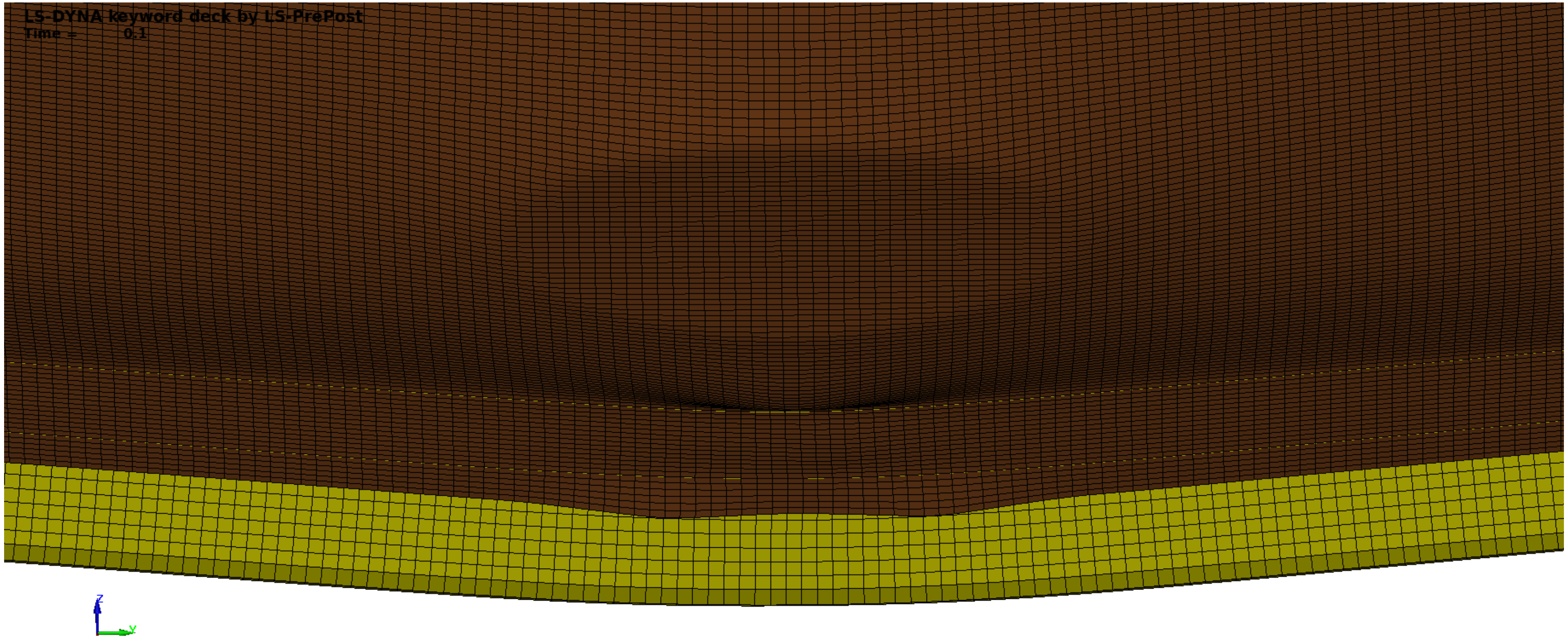


Results – FOPS Simulation

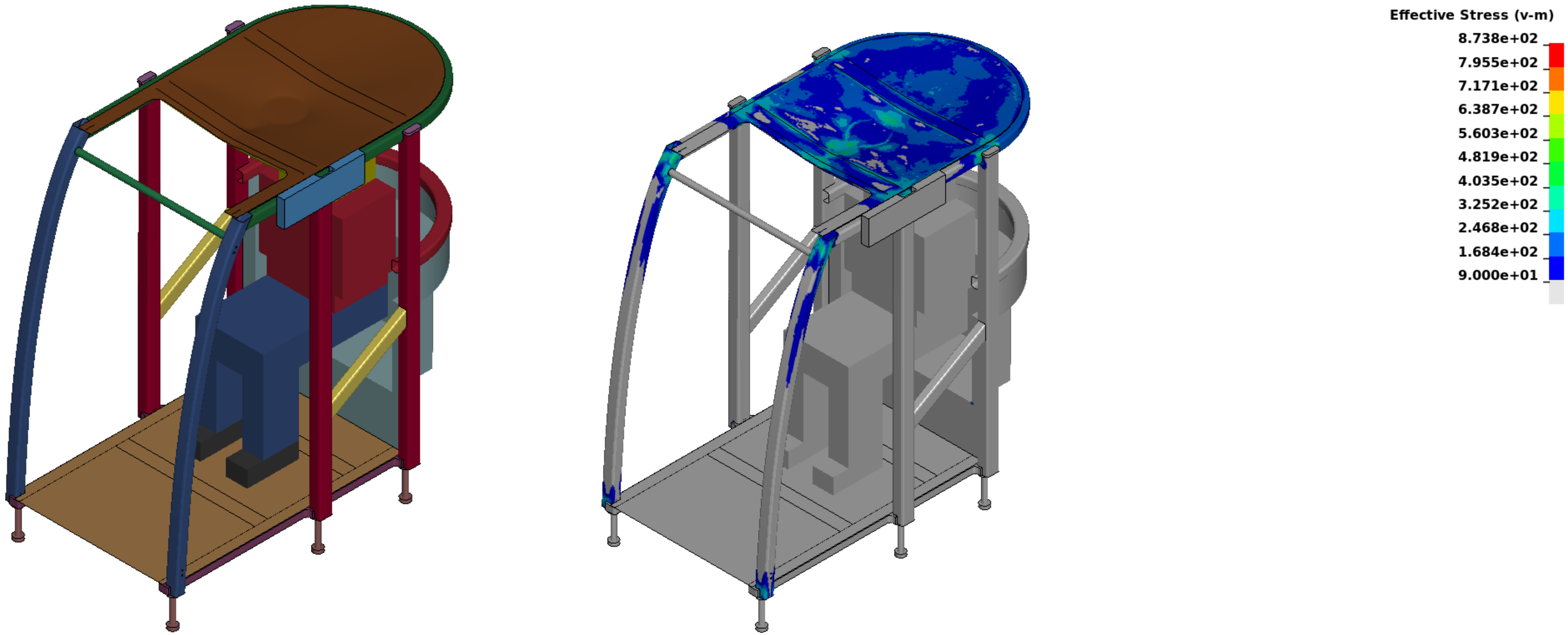


Results – FOPS Simulation



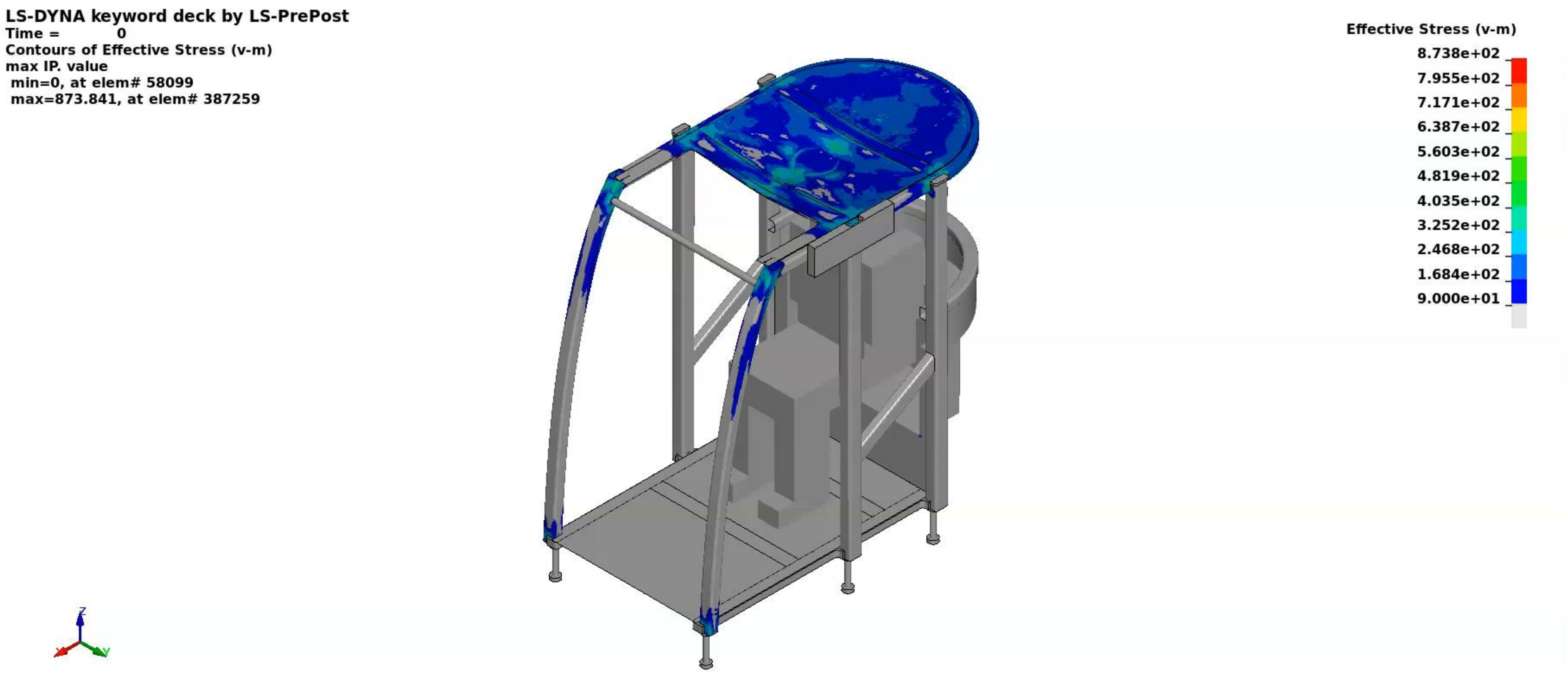


Results – ROPS Simulation



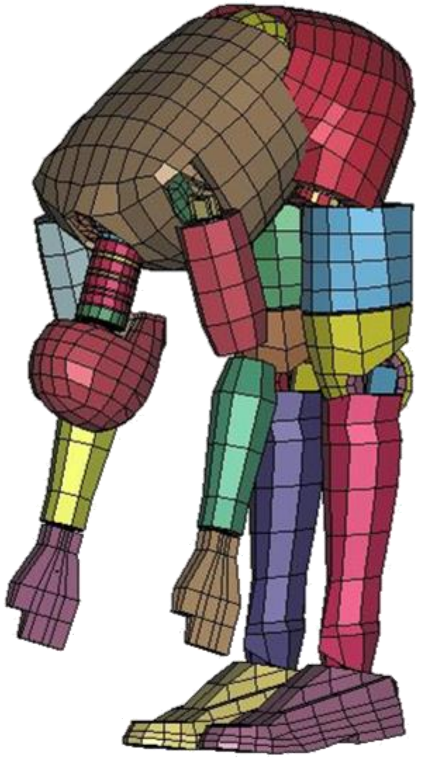
Results – ROPS Simulation

Results – ROPS Simulation



Results – ROPS Simulation

Thank You



DYNAMore Nordic AB
Brigadgatan 5
587 58 Linköping, Sweden

Tel.: +46 - (0)13 23 66 80
info@dynamore.se

www.dynamore.se
www.dynaexamples.com
www.dynasupport.com
www.dynalook.com

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