Ultimate capacity analyses in LS-DYNA

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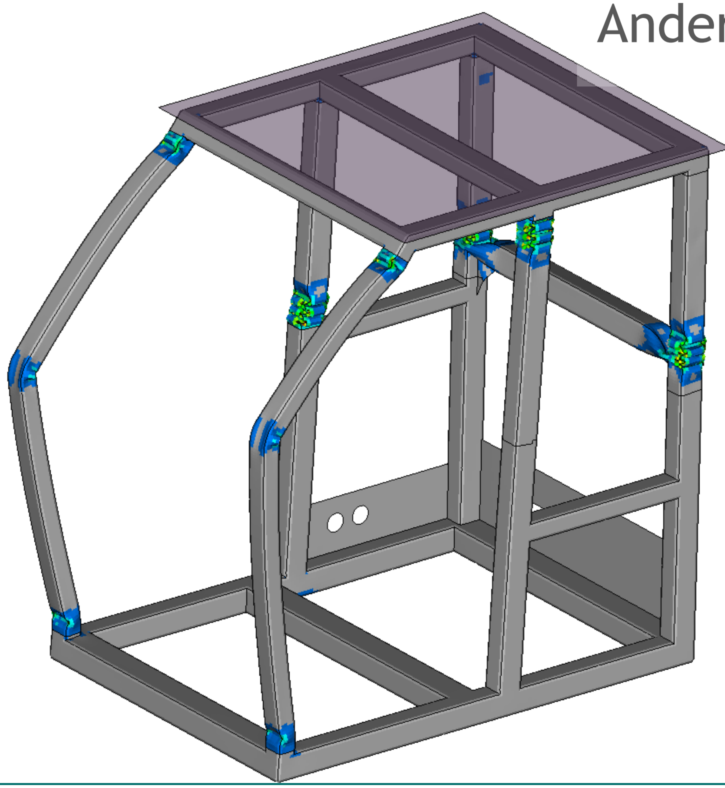
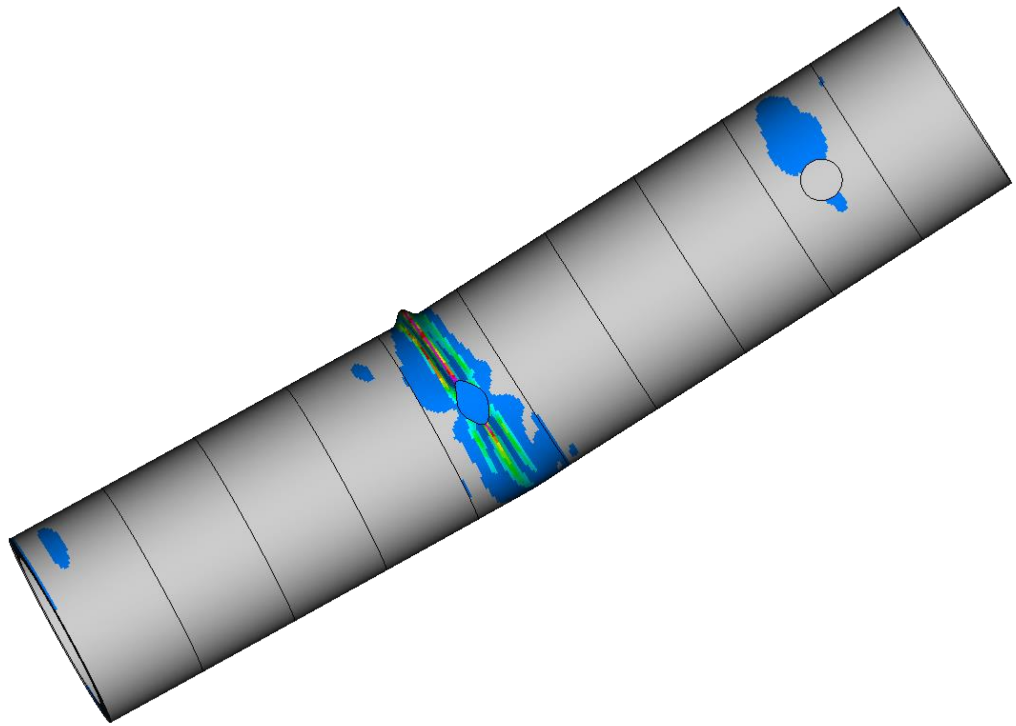


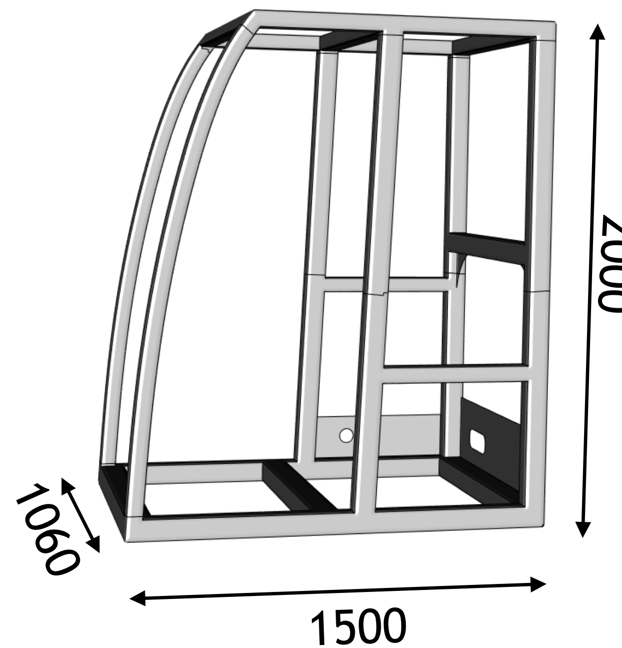


Ultimate capacity analyses in LS-DYNA

- A simplified cab frame – roof crush load case
  - Dimensions and model data
  - Roof crush load case
  - Contacts
  - Prescribed force vs. prescribed displacement
- Brief background to the arc-length method in implicit
  - Analysis set-up
- A large-scale tube structure
  - Implicit arc-length method
  - Automatic Implicit → Explicit switching
- Comments and conclusions

A simple cab frame

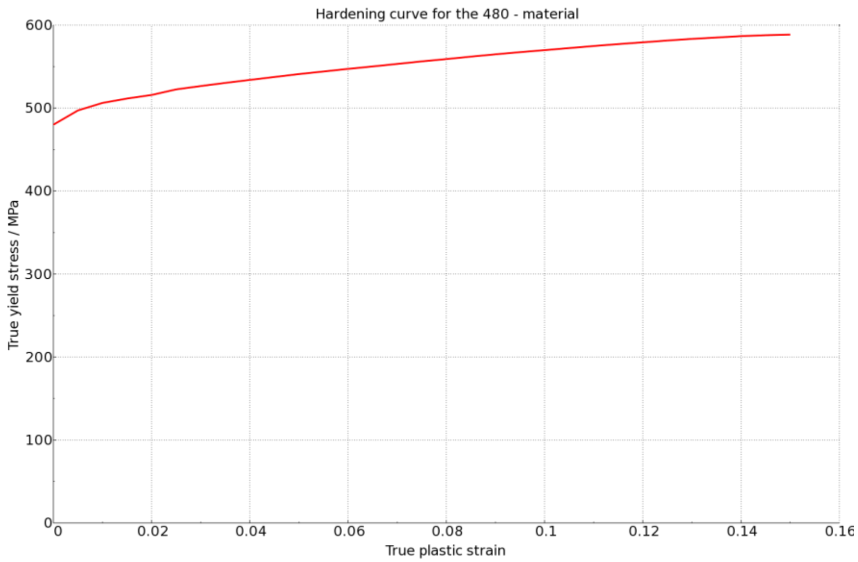
- This example is inspired by the ISO requirement 3471 for Roll Over Protective Systems of Earth moving machinery.



- Generic dimensions, not from any existing or planned design of any manufacturer.

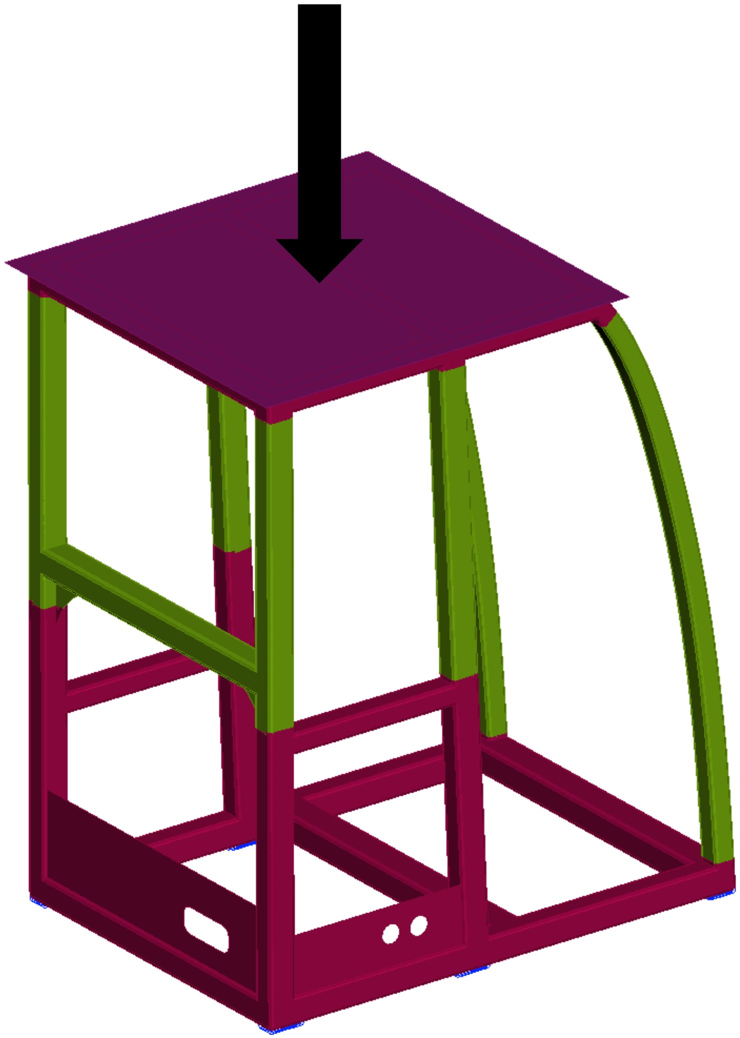
A simple cab frame – model data

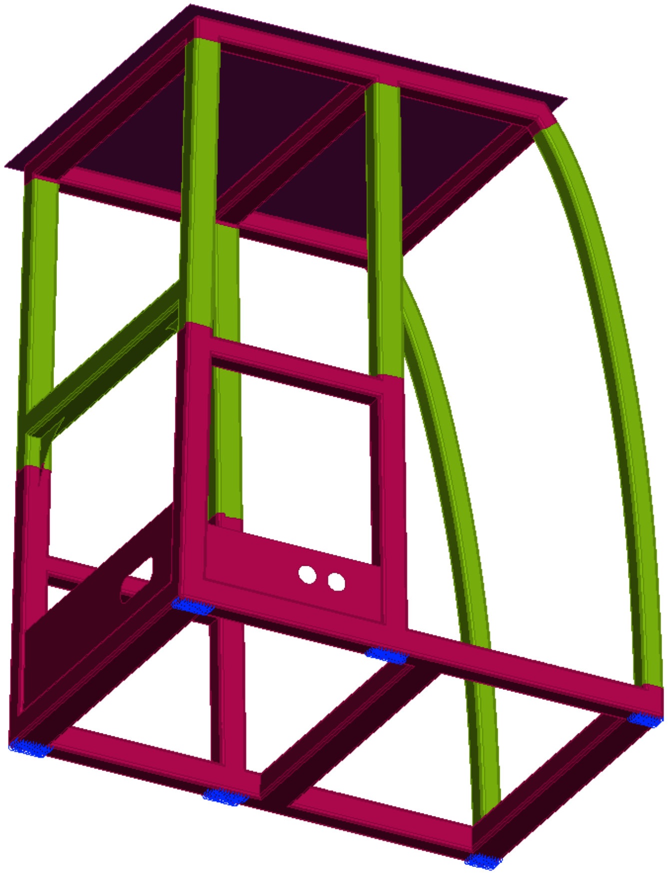
- Generic dimensions, not from any existing or planned design of any manufacturer.
- About 100 000 shell elements (elform 16). Typical element size is 10 mm.
- Square tubes, simplified weld modelling.
- Steel with a yield strength of 480 MPa was assumed.



- The bottom of the frame is fully constrained at 6 supports.
- A rigid loading device was used (`*MAT_RIGID` in LS-DYNA)

A simple cab frame – model data

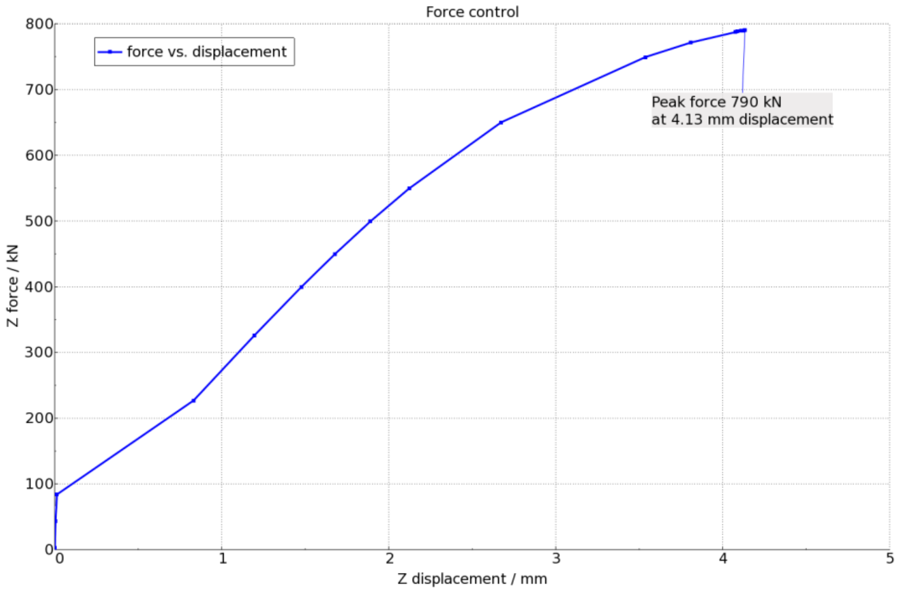




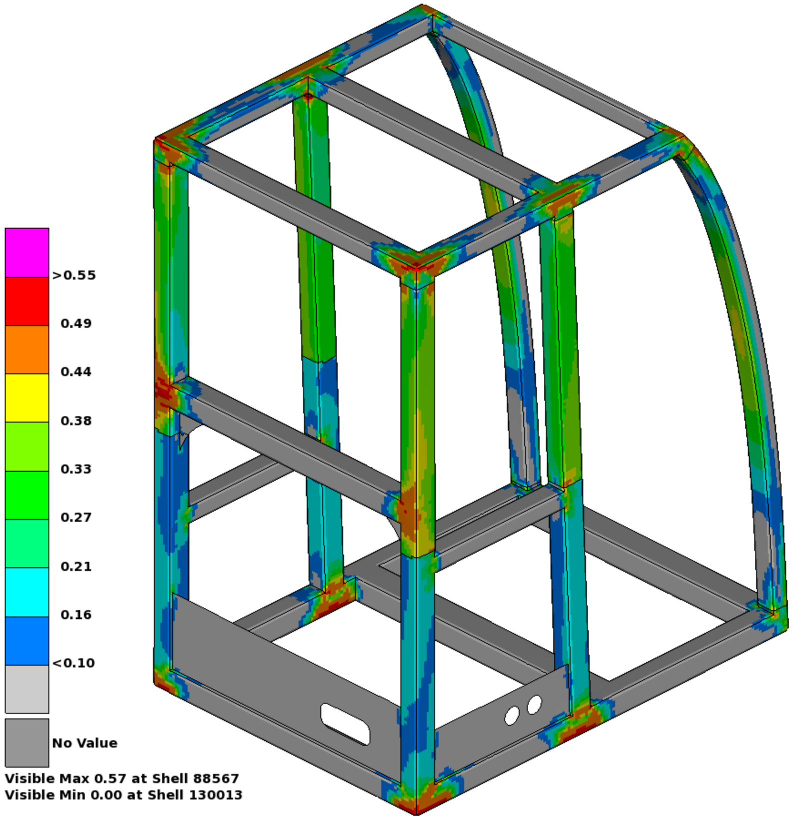
The frame is fully constrained at 6 patches (blue). Thickness of red parts is 4 mm, while the green parts are 2 mm.

A simple cab frame – prescribed force

- A first guess of the peak force is required. 1000 kN is taken in this case.
- Error termination due to non-convergence is obtained at 79 % of this loading.



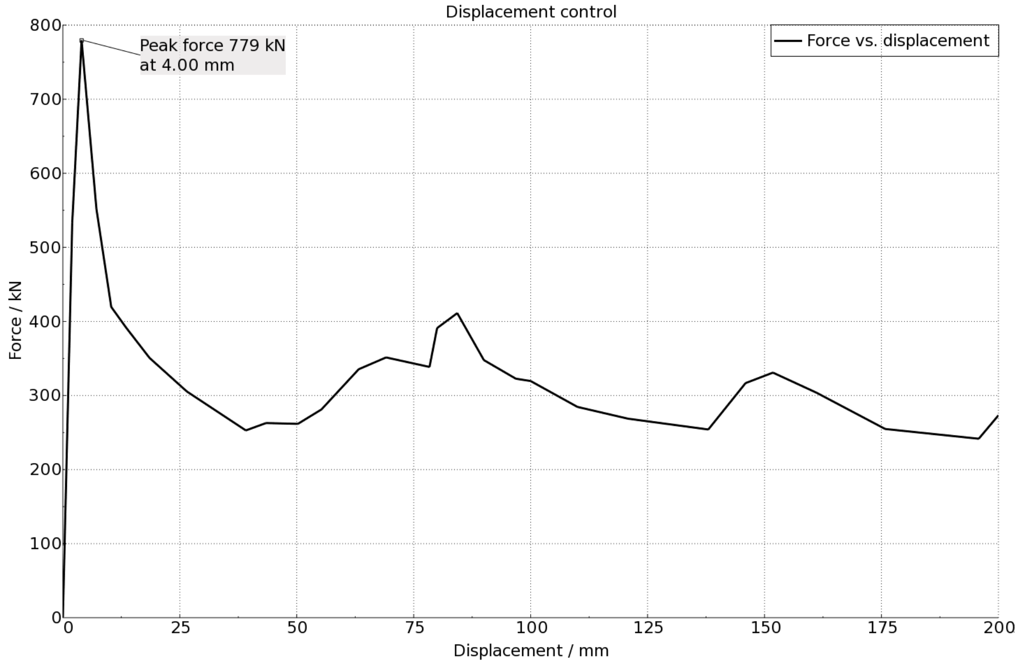
Force vs. displacement curve



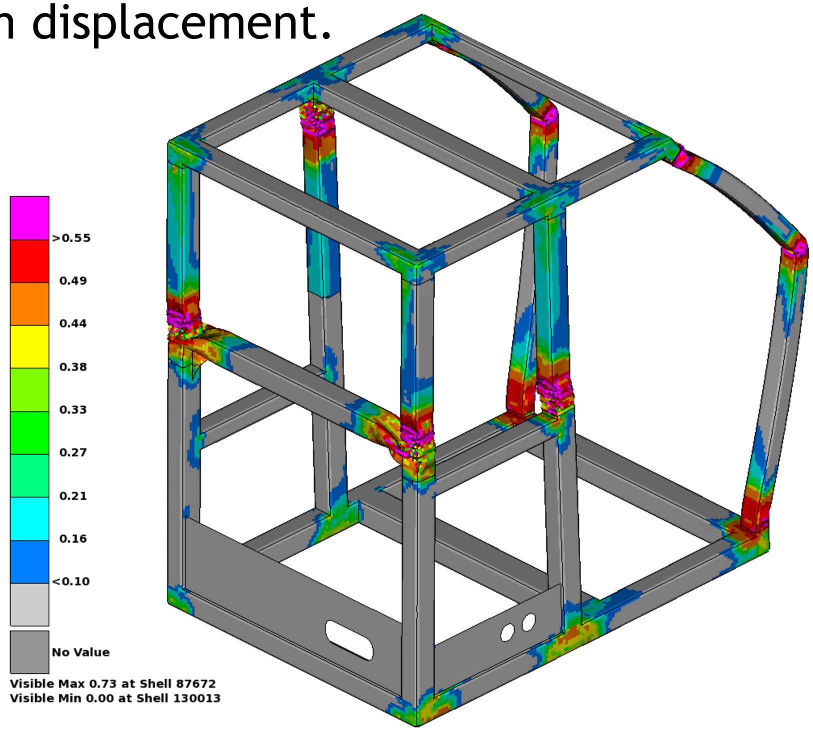
Effective stress at final state

A simple cab frame – prescribed displacement

- A "large" final displacement (200 mm) is prescribed. Note:
  - Small initial steps required to capture the peak force (at ~ 4 mm) correctly!
  - Since this is a "large" displacement, `dnorm` = 1 on `*CONTROL_IMPLICIT_SOLUTION` was used.
- Normal termination is obtained after 200 mm displacement.



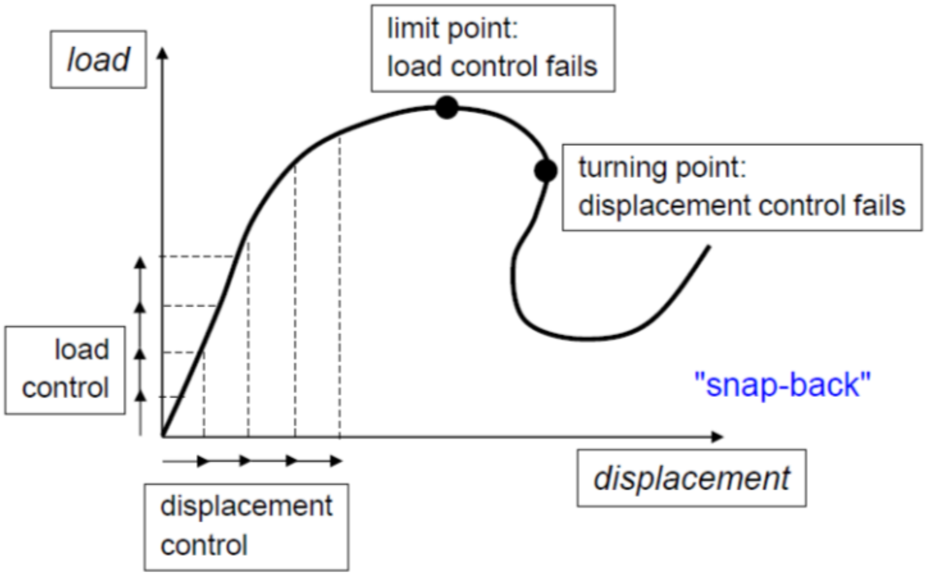
Force vs. displacement curve



Effective stress at final state

Limit load analyses in LS-DYNA: The arc length method

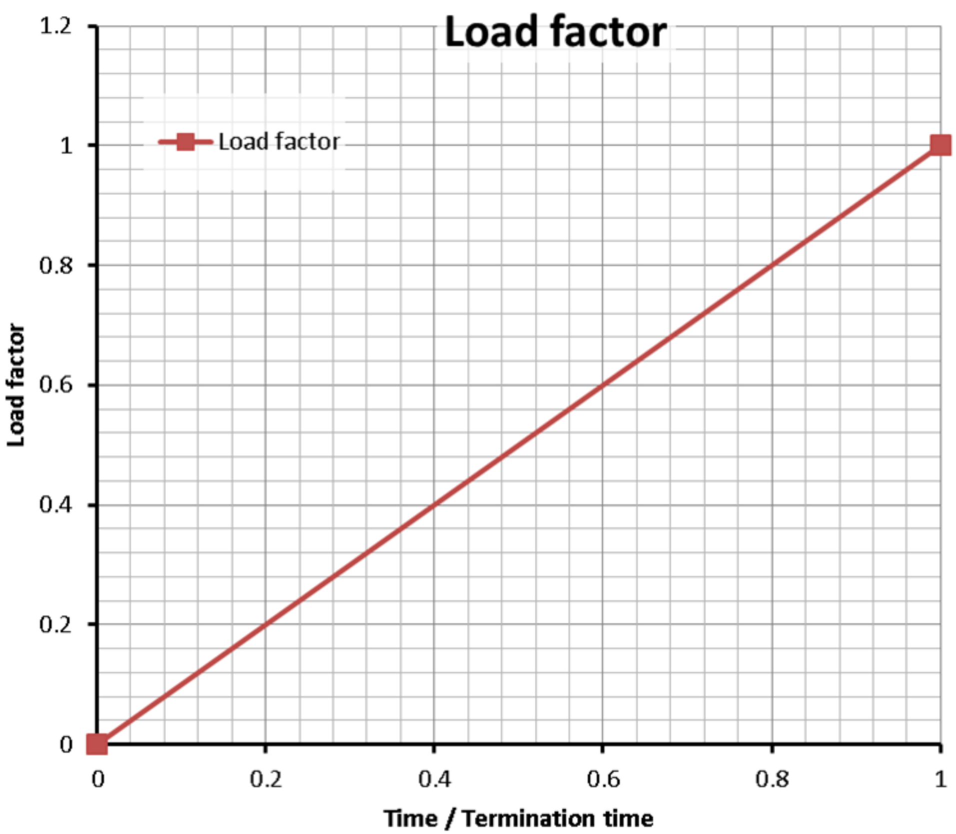
- The arc length method can be applied to follow an “arbitrary” load-displacement path. It can be seen as a mixed load and displacement controlled loading with a highly advanced control system. Situations of load reversal, snap-through and snap-back can be handled.



- The arc-length method is activated by setting `arcmth` = 3 on `*CONTROL_IMPLICIT_SOLUTION`.
- A pre-defined control card include file, `control_cards_arc.key`, is supplied with the Guideline for implicit analyses using LS-DYNA.

Limit load analyses in implicit

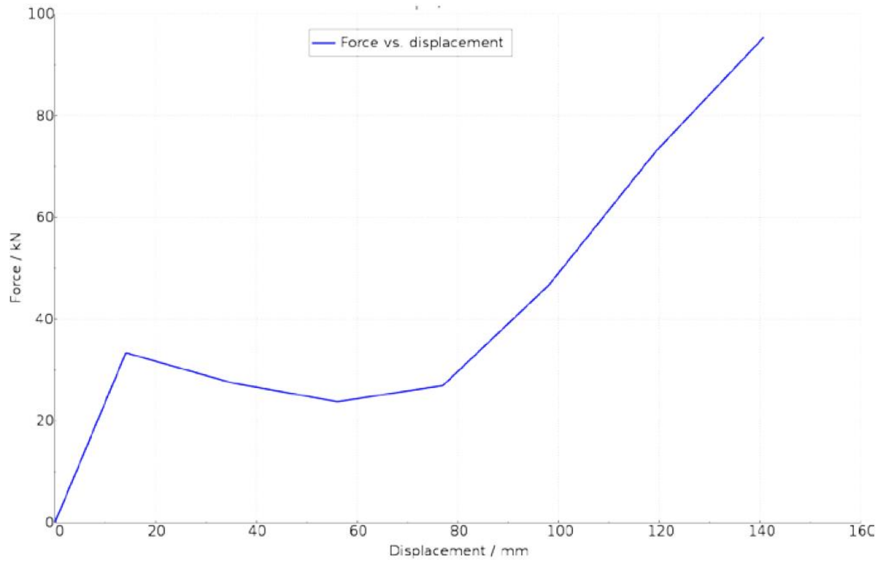
- Using the arc-length method, the loading must be applied using linear ramps, starting at (0,0).



- The time will determine the load factor. This means that time can go back and forth (dt < 0 when the loading must decrease) and even negative times can be reached, indicating complete load reversal.
- This means that `*CONTROL_TERMINATION` may be an insufficient stopping criterion.
- `*TERMINATION_NODE` or `*TERMINATION_BODY` can be used to specify displacement-based termination criteria. For example, to terminate the analysis when the loaded node has moved 1000 mm.

Further motivations for use of the arc length method

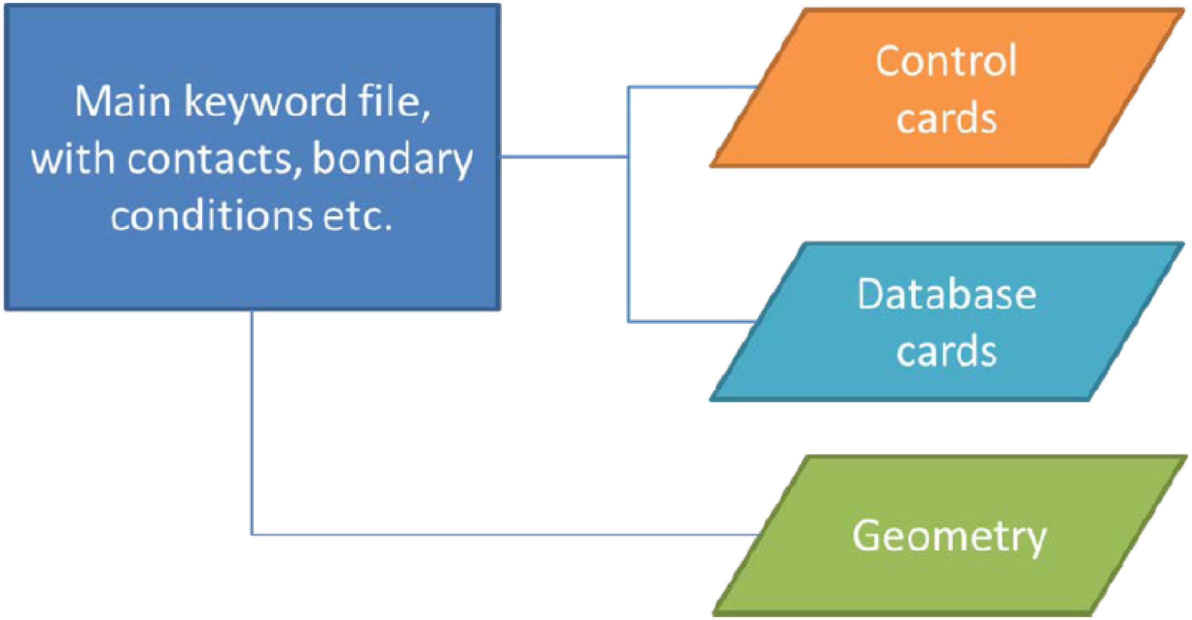
- By prescribed displacement, there may be a risk that the actual peak force is missed.



- It may not always be possible to switch a desired applied force to a prescribed displacement. Loading by force may be the only way to obtain the desired loading direction.
- A coarse (beam) model may be applied to find the load distribution. Then section forces and moments can be applied to a detailed sub-model to estimate the ultimate capacity of the design.

Set-up using the arc-length method

- Setting up a limit-load / ultimate capacity analysis is described in the Guideline for implicit analyses
  - Download it from http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna
- Using an include-file structure, separating control cards, geometry, and load case, might be convenient



- Use the provided control cards include file `control_cards_arc.key` to start with (modifications may be required in some special cases)

Set-up using the arc-length method

```
*KEYWORD
*INCLUDE
Include file defining geometry, materials etc.
*PERTURBATION_NODE
Define parameters for creating geometrical imperfections
*LOAD_...
Define nodal loads etc.
*BOUNDARY_...
Data line to prescribe boundary conditions
*CONTACT_AUTOMATIC_...MORTAR_ID
Define contacts etc.
*INCLUDE
control_cards_nonlin_arc.key
*DEFINE_CURVE_TITLE
Implicit time incrementation
700,
0., dt0 (first timestep)
Additional lines to define time incrementation
*CONTROL_TERMINATION
Define end time of the simulation
*TERMINATION_NODE
Define termination criteria based on displacement
*INCLUDE
database_cards_static.key
*TITLE
Simulation title
*END
```

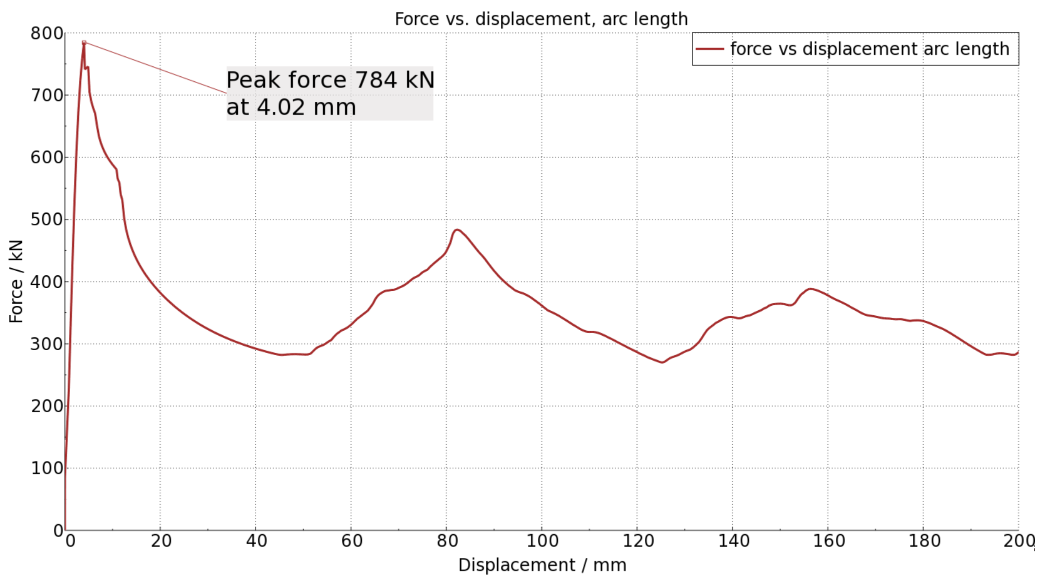
Geometry

Main file / loads and boundary conditions

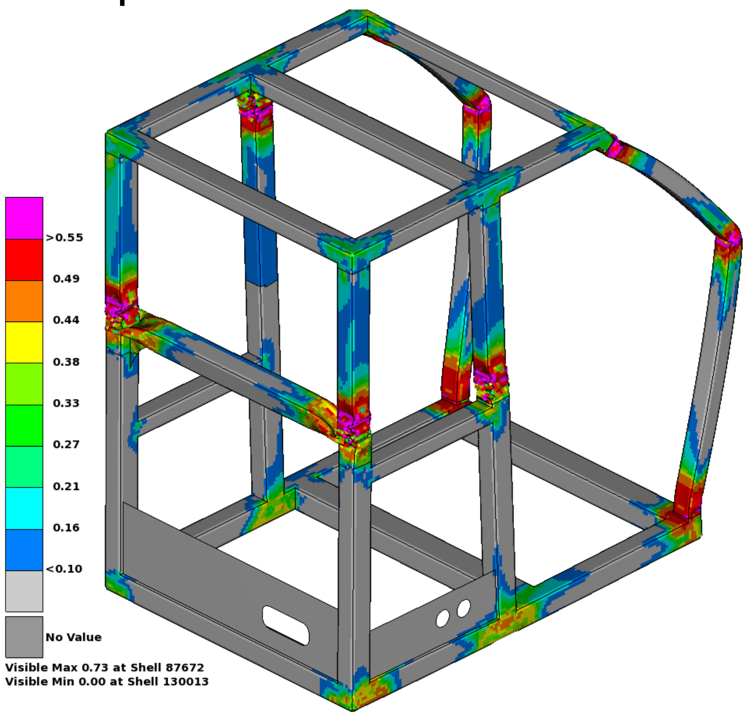
Control cards and Main file / control card modifications

A simple cab frame – loading by the arc length method

- As in the case with pure force control, a peak load of1000 kN was applied.
  - `*TERMINATION_BODY` was used to terminate the simulation after 200 mm displacement
  - Since this is a “large” displacement is expected, `dnorm` = 1 on `*CONTROL_IMPLICIT_SOLUTION` was used.
- Normal termination is obtained after 200 mm displacement.



Force vs. displacement curve



Effective stress at final state

A simple cab frame – loading by the arc length method

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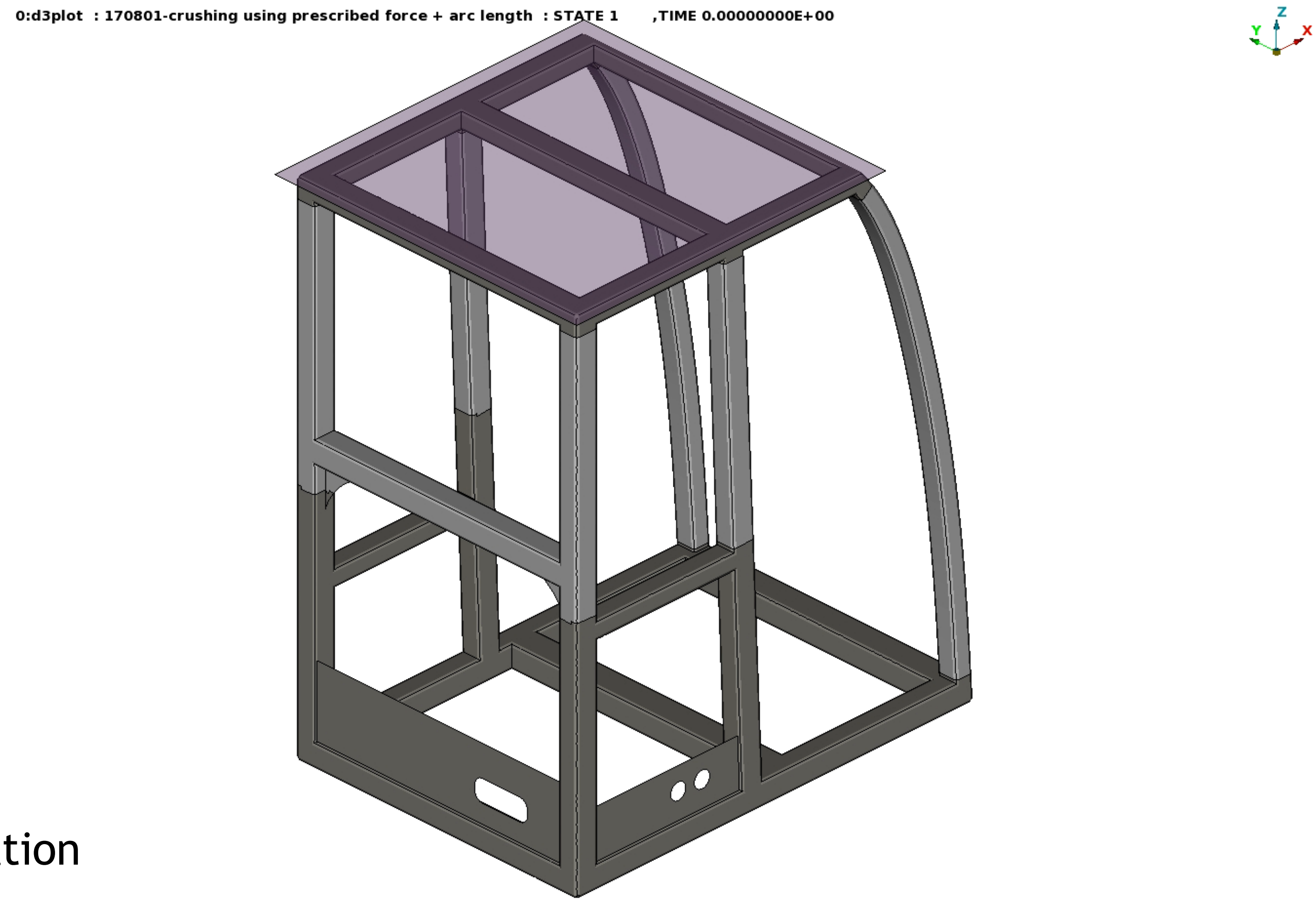


Animated deformation

Performance comparison

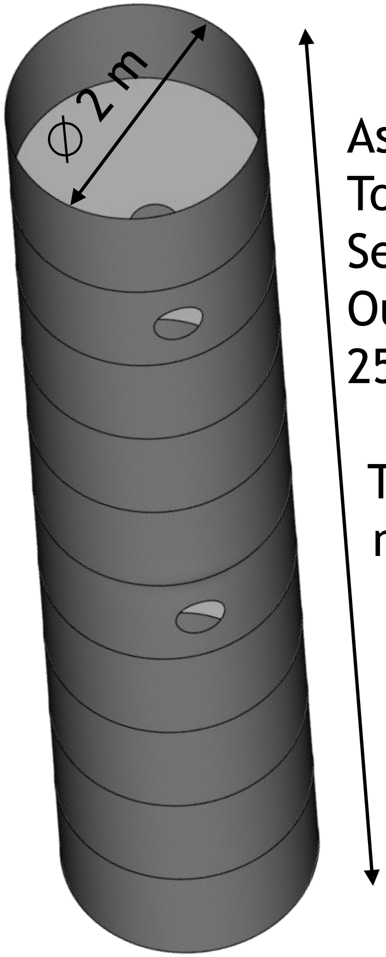
- Using 8 cores, mpp-LS-DYNA R9.1, the following results were obtained.

Version	Solution time	Max displacement	Peak force	Comment
Force control	1 h 44 mm	4.13 mm	790 kN	Fails to converge beyond peak force
Displacement control	4 h 48 min	200 mm	779 kN	
Arc length	5 h 25 min	200 mm	784 kN	

A reinforced tubular member

- This example is inspired by an ultimate capacity analysis of an offshore rig.

Image by Chad Teer, Coquitlam, France (Flickr.com)



Assumed dimensions:
Total length 10 m.
Section length 1m.
Outer tube thickness 25 mm.

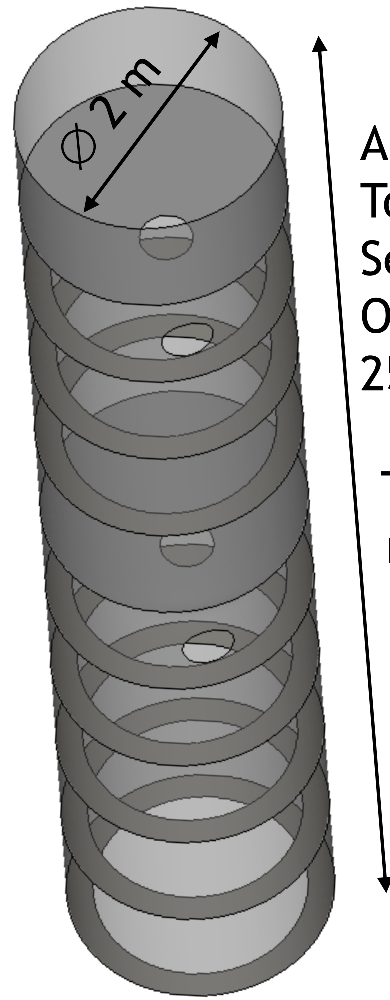
The same 480 – steel material model as in the cab frame was used.

Mesh size 25 mm, 125 000 elements.

A reinforced tubular member

- This example is inspired by an ultimate capacity analysis of an offshore rig.

Image by Chad Teer, Coquitlam, France (Flickr.com)



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Section length 1m.
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The same 480 – steel material model as in the cab frame was used.

Mesh size 25 mm, 125 000 elements.

A reinforced tubular member

- This example is inspired by an ultimate capacity analysis of an offshore rig. Global, coarse model gives loads for the individual members.

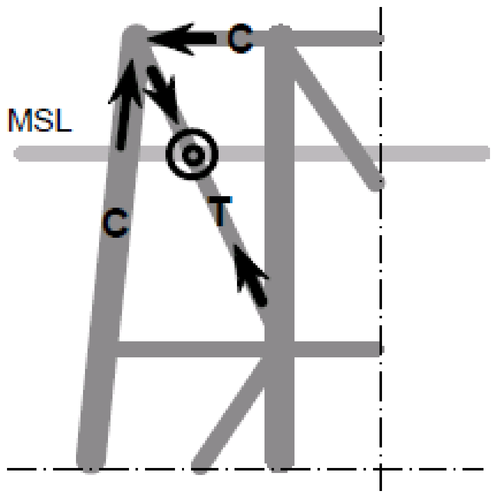
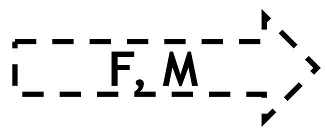
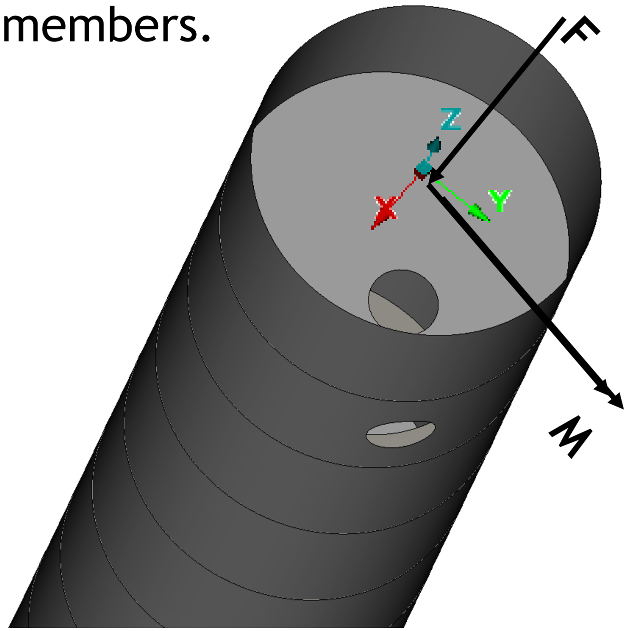


Image from HSE Research Report 220



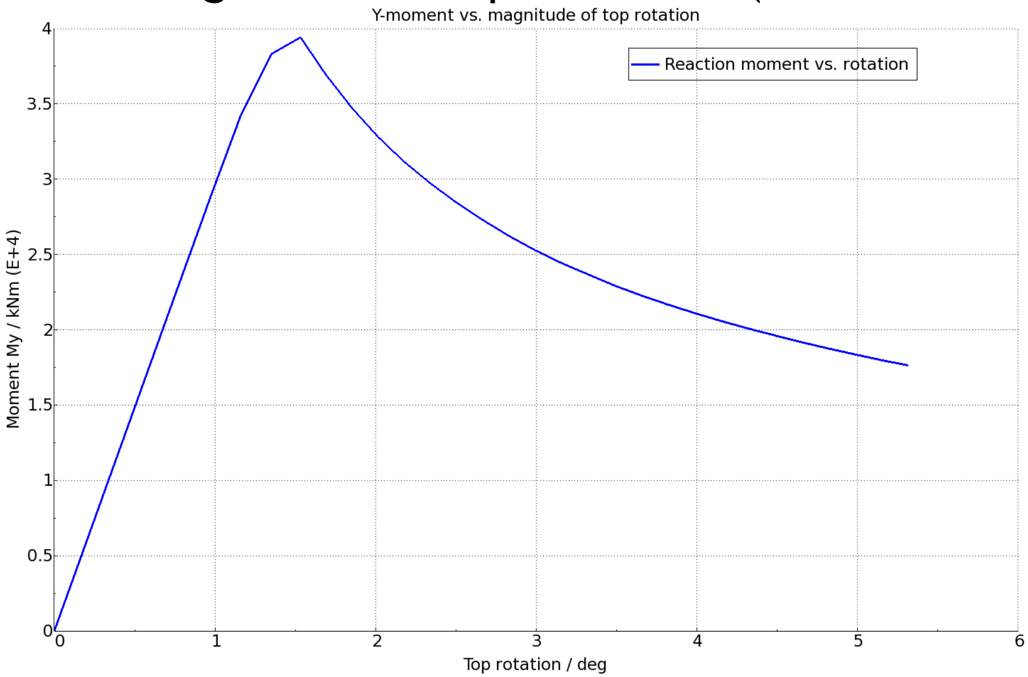


Assumed load case		
Fx	Fy	Fz
500 kN	50 kN	-5 MN
Mx	My	Mz
5 MNm	50 MNm	5 MNm

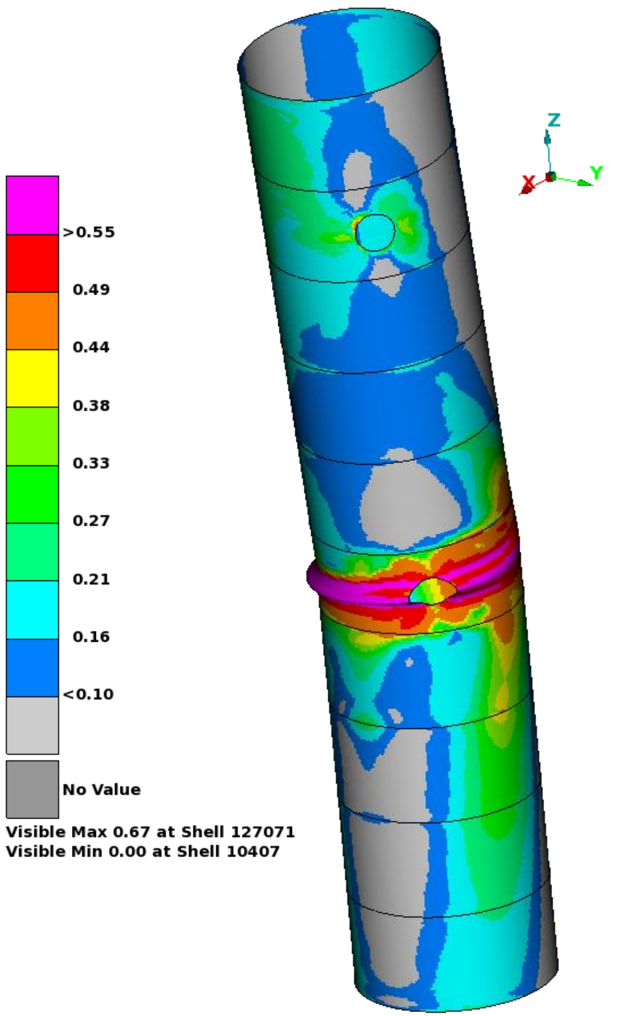
Loading applied via a rigid body at the top edge. Fully constrained boundary conditions applied at the bottom edge of the tube.

A reinforced tubular member – loading by the arc-length method

- *TERMINATION_BODY was used to terminate the simulation after 500 mm displacement
- For the analysis, scaled deformations from a linear buckling analysis (*CONTROL_IMPLICIT_BUCKLE) was used to model geometric imperfections (*PERTURBATION)



Moment vs. rotation curve



Effective stress at final state

A reinforced tubular member – loading by the arc-length method

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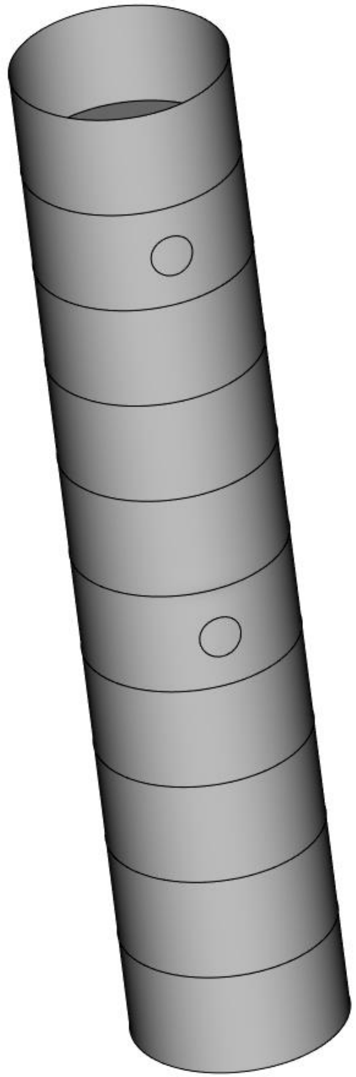


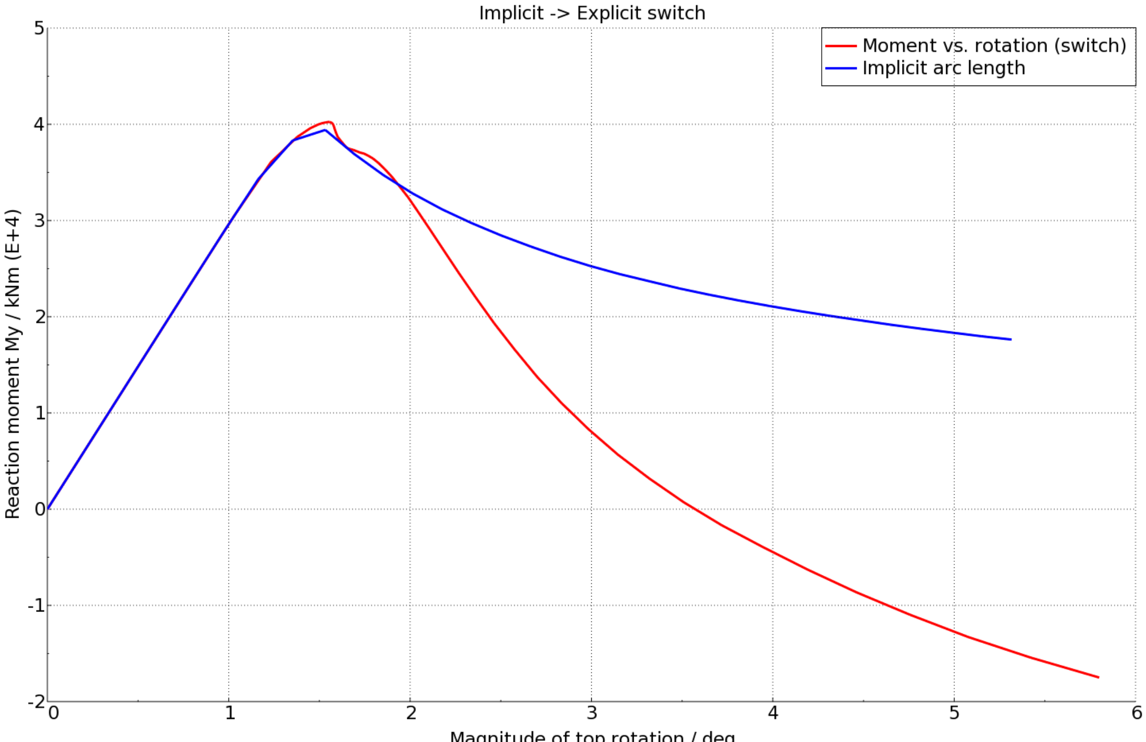
Animated deformation

Limit load analyses in LS-DYNA: Implicit → Explicit switching

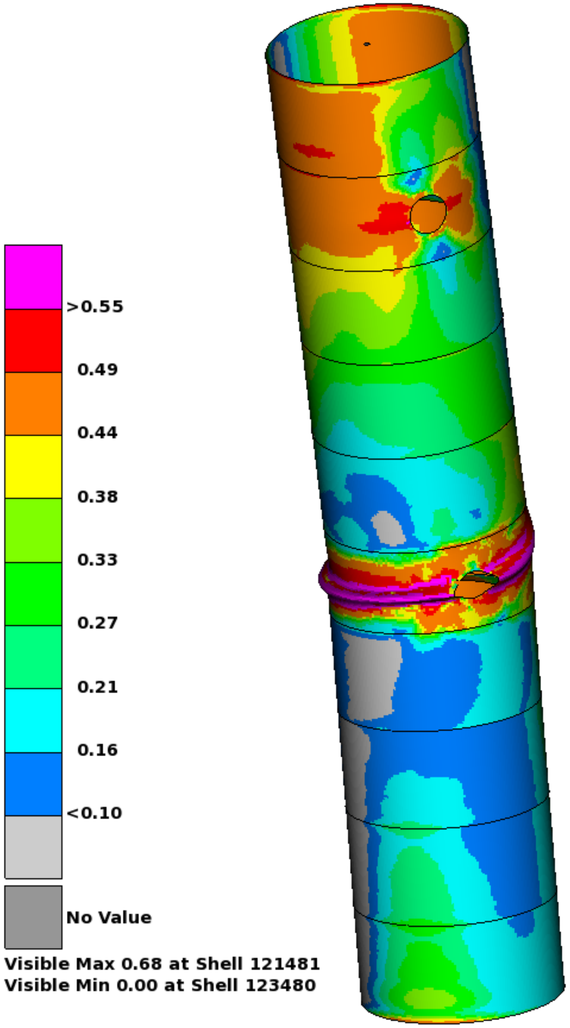
- As an alternative way to find out how the structure reacts when the loading is increased beyond the ultimate capacity, is to let LS-DYNA automatically switch to explicit when the (static) implicit solution fails to converge.
- To activate automatic implicit → Explicit switching, set
  - `imflag` = 4 or 5 on `*CONTROL_IMPLICIT_GENERAL` (5 means mandatory Implicit finish)
  - Specify time to run in explicit, by `dtexp` on `*CONTROL_IMPLICIT_AUTO`. If only one switch is desired, set `dtexp` ≈ termination time.
  - Also, set `kcfail` on `*CONTROL_IMPLICIT_AUTO`. This determines the number of failed attempts to converge implicitly before the solution switches to explicit.
  - `*CONTROL_TIMESTEP` strongly recommended! (As in any explicit analysis)
  - Note that the explicit simulation will take place in physical time! Check the loading history and unit system!
  - Also, take care to specify a reasonably output frequency for d3plot:s using `*DATABASE_BINARY_D3PLOT`

A reinforced tubular member – Implicit → Explicit switch

- *TERMINATION_BODY was used to terminate the simulation after 500 mm displacement.
- For this example, also a RTCL material failure criterion was added, with $\varepsilon_f = 0.2$.



Moment vs. rotation curve



Effective stress at final state

Comments and conclusions

- By force control, the peak load carrying capacity of a structure can be found. In statics, convergence beyond the peak load point is not possible.
- The arc-length method in implicit can be used to explore the structural behavior beyound the peak load is reached.
  - Introduce imperfections for post-buckling analyses. Use for example buckling shapes from linear buckling analyses (`*CONTROL_IMPLICIT_BUCKLE, *PERTURBATION`).
  - Note! All loads vary simultaneously!
- Automatic Implicit → Explicit switching can also be used to find out how the structure reacts when the loading is increased beyond the ultimate capacity.

Thank you!

Your LS-DYNA distributor and more