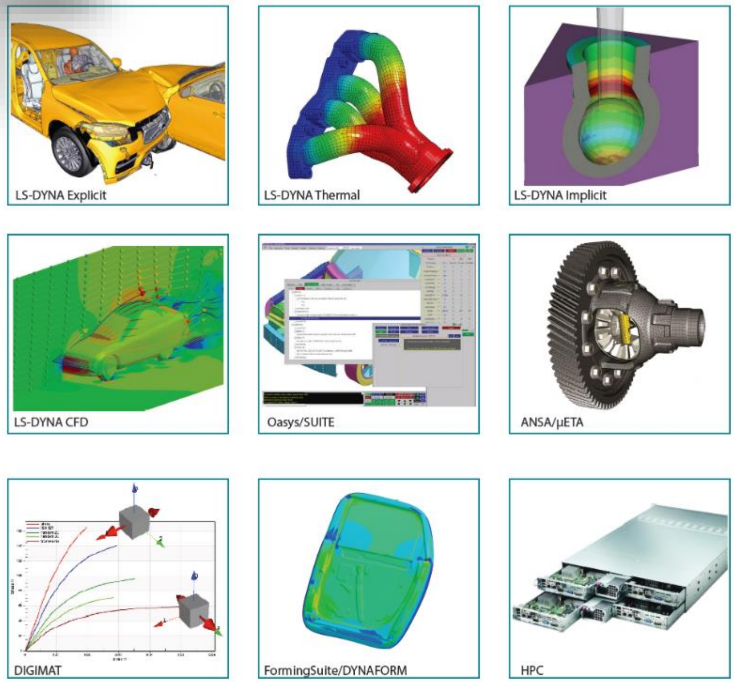
Webinar, 2022-12-01, 10:00 CET

Pre-Tensioning and Dynamic Relaxation

Axel Hallén, DYNAmore Nordic AB

Contact – DYNAmore Nordic

- Support
  - Sales: sales@dynamore.se
  - E-mail: support@dynamore.se
    - Target to answer in 4 hours
    - Call: +46 13 236680
- Training & seminars including on-line & on-site: www.dynamore.se
- Secure file server: files.dynamore.se
  - Software and license download, client area with guidelines and more
- www.dynamore.se - information on LS-DYNA, Seminars, Conferences
- 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



Introduction

- Prestressing can be done by various techniques depending on solver and modelling approach.

- Depending on which mechanical solver is used, different solutions can be preferable:

- Explicit solver: Prestressing can cause dynamics. Possibly combine with damping.

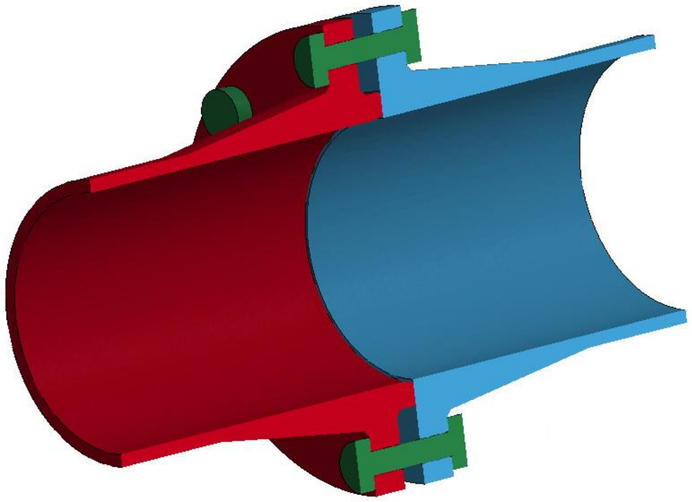
- Implicit solver: Static solution, but initial convergence can be a problem. Possibly allow for dynamics.

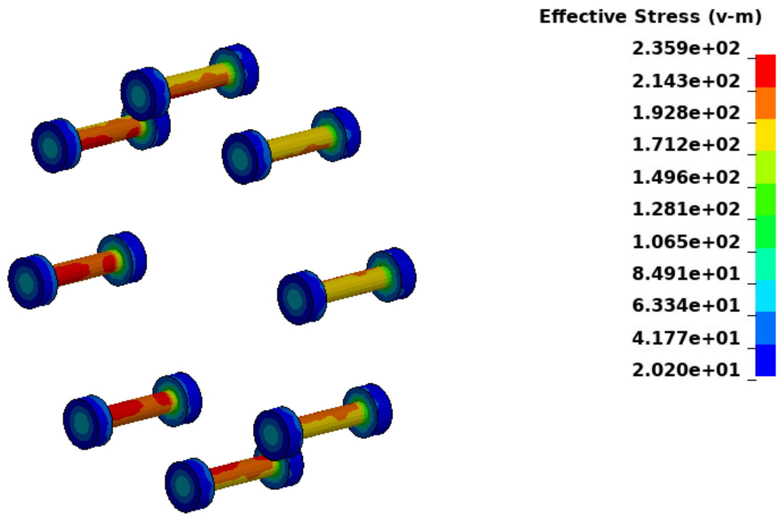
- Dynamic Relaxation: Prestressing is done in “pseudo time” with numerical damping applied.

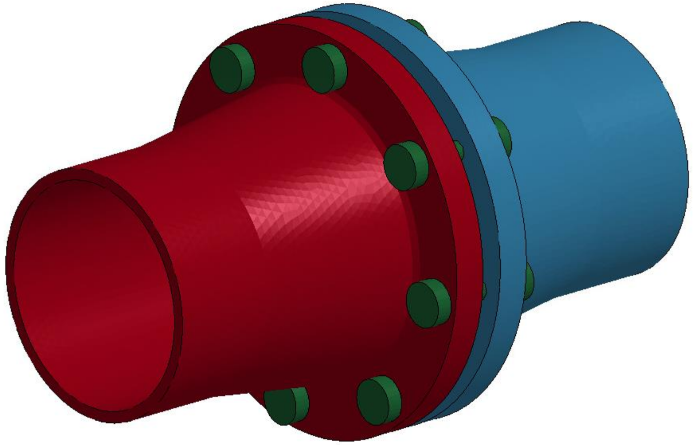
Agenda

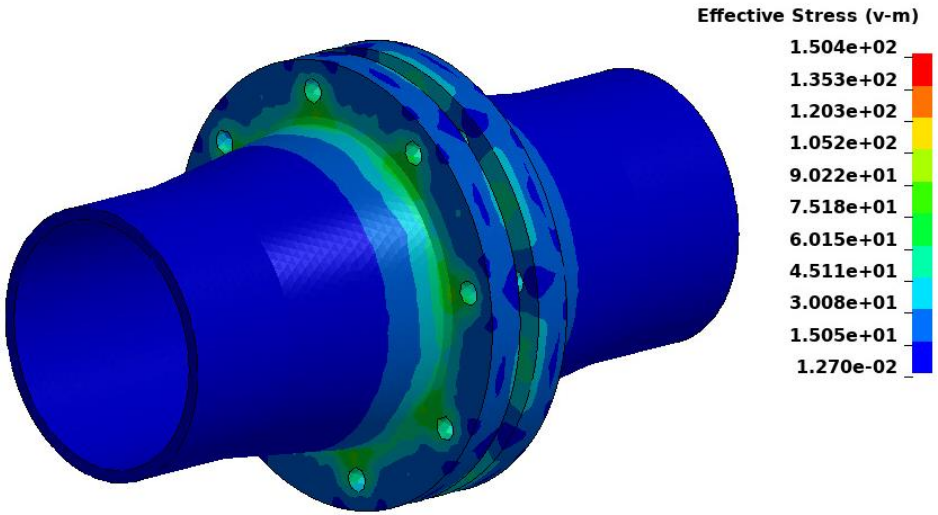
- Various techniques for pre-stressing of bolts
  - Initial strain
  - Initial force (beams)
  - Initial stress (solids)
- Compensation for bending stresses
  - Beams
  - Solids
- Press fit pre-tensioning
- Dynamic relaxation
  - Background
  - *CONTROL_DYNAMIC_RELAXATION
  - Curve control
  - Output
  - Restart

Test Model




Effective Stress (v-m)
2.359e+02
2.143e+02
1.928e+02
1.712e+02
1.496e+02
1.281e+02
1.065e+02
8.491e+01
6.334e+01
4.177e+01
2.020e+01




Effective Stress (v-m)
1.504e+02
1.353e+02
1.203e+02
1.052e+02
9.022e+01
7.518e+01
6.015e+01
4.511e+01
3.008e+01
1.505e+01
1.270e-02

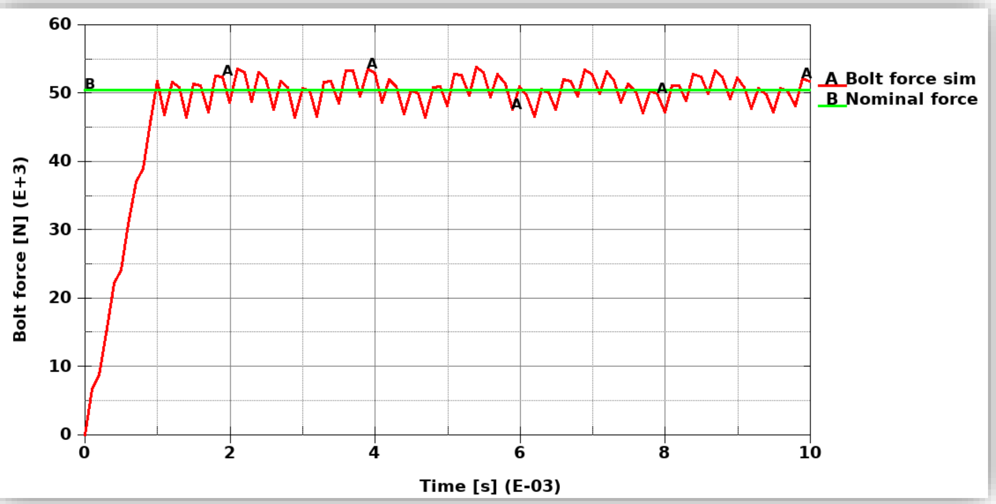
Prestressing Bolts by Initial "Thermal" Strain

- The idea is to shrink the length of the bolts.
- This is usually done using a *LOAD_THERMAL_VARIABLE keyword.
- Thermal expansion can be added to any material model by using *MAT_ADD_THERMAL_EXPANSION
- Solution is fairly quasi-static since it is a prescribed displacement.
- Iterative process to determine the thermal strain.

```
*MAT_ADD_THERMAL_EXPANSION
$#     pid      lcid      mult      lcid     multy      lcid     multz
         4         0-1.0000E-4         0       0.0         0       0.0
```

```
*LOAD_THERMAL_VARIABLE
$#    nsid    nsidex     boxid
        95         0         0
$#      ts        tb      lcid       tse       tbe     lcide     lcidr   lcidedr
      26.0       0.0         2       0.0       0.0         0         0         0
```

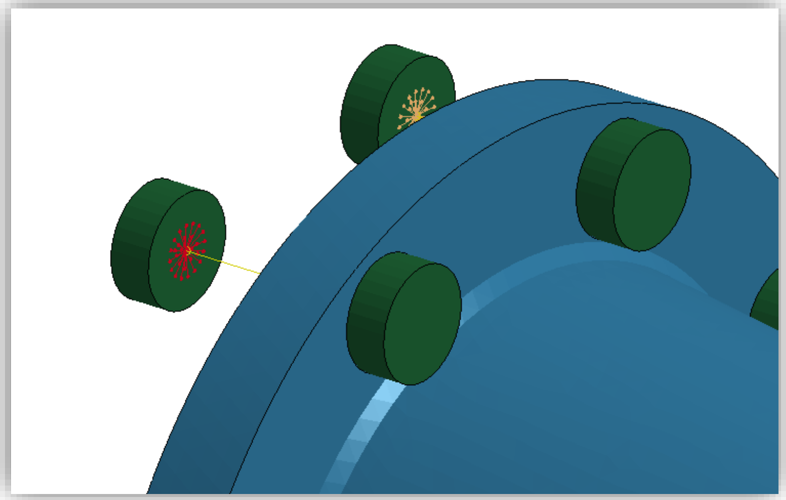
Prestressing Bolts by Initial “Thermal” Strain

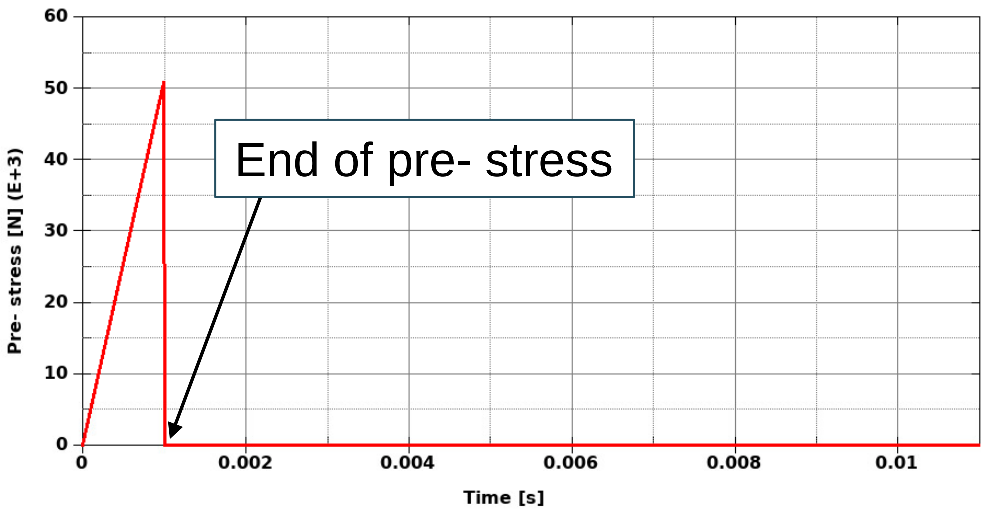


Prestressing Bolts by Initial Force

- Use *INITIAL_AXIAL_FORCE_BEAM keyword.
- From R12, one can use element type 9 with *MAT_SPOTWELD, as well as type 1 with any material.
- The forces are applied on a *SET_BEAM.
- Pre-load curve has to be reduced to 0 after pre-tension or the force will be constant throughout the simulation.

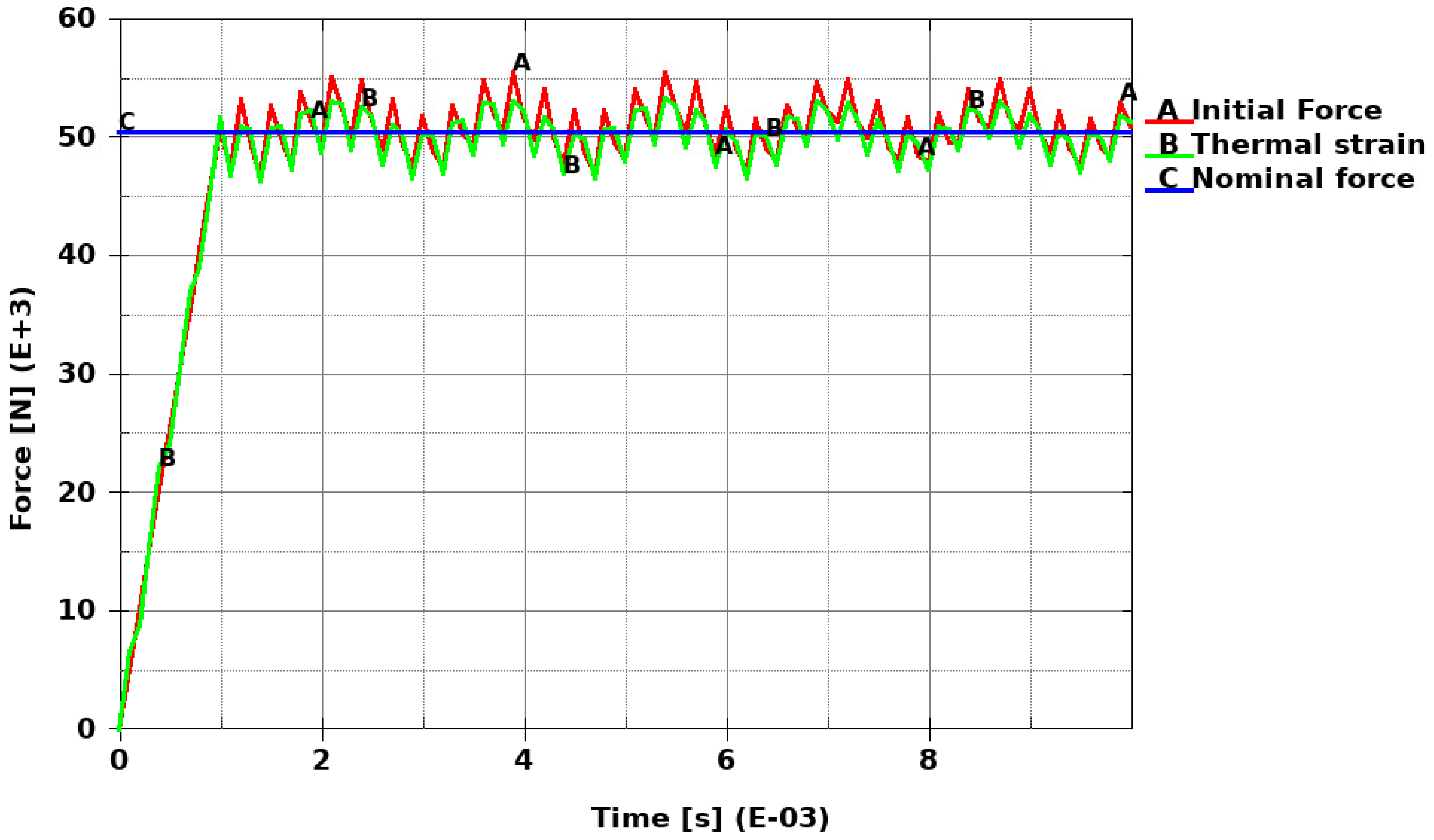
```
*INITIAL_AXIAL_FORCE_BEAM
$#    bsid      lcid     scale     kbend
         1         1       1.0         0
```





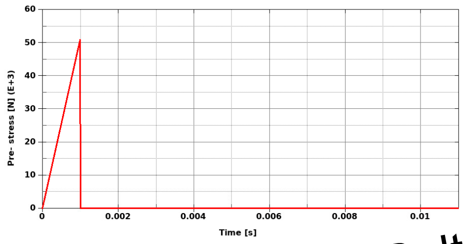
Prestressing Bolts by Initial Force

- Dynamics is similar to using thermal strains.



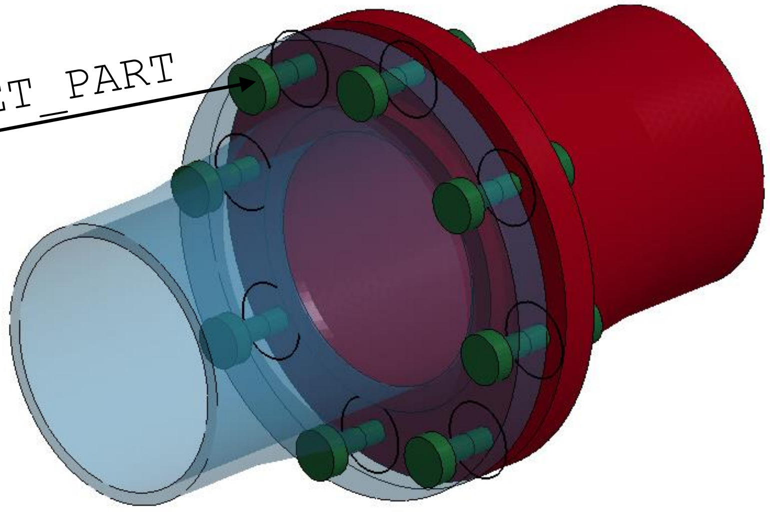
Prestressing Bolts by Initial Stress

- Use *INITIAL_STRESS_SECTION keyword.
- The initial stress is applied to a set of solid elements defined by *DATABASE_CROSS_SECTION_..
- Letting the load curve be reduced to 0 after pre-tension signals that pre-tensioning is over, otherwise the stress will be constant throughout the simulation.




```
*INITIAL_STRESS_SECTION
$#    issid       csid       lcid       psid        vid    izshear
          1          1          1          1          0          0
```

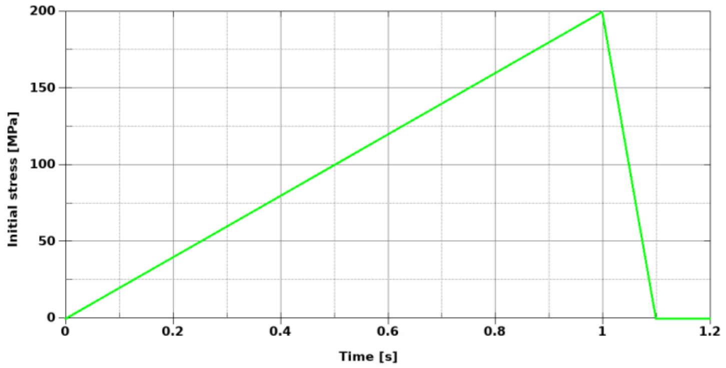
Bolt *SET_PART

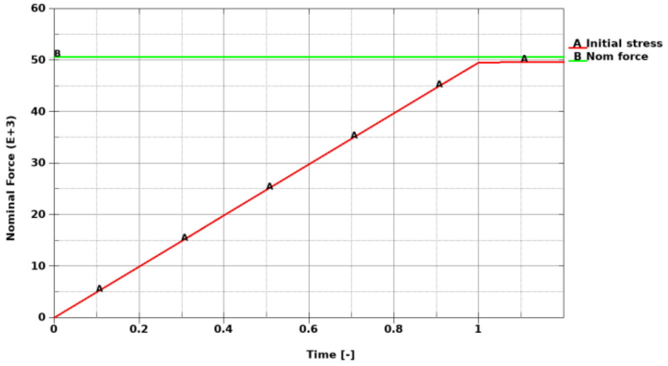


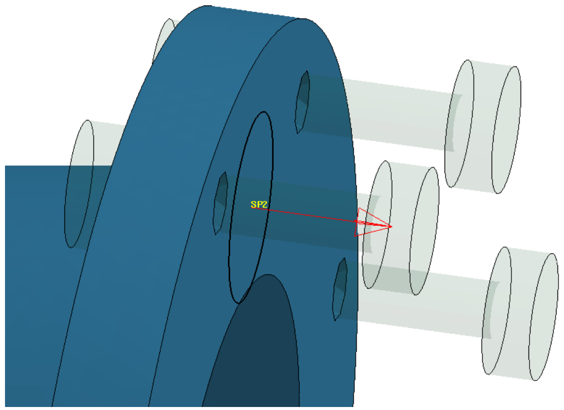
```
*DATABASE_CROSS_SECTION_PLANE_ID
$#    csid                                                       title
         1
$#    psid       xct       yct       zct       xch       ych       zch    radius
         1      12.0  -110.845    109.48      20.0  -110.845    109.48      30.0
$#    xhev      yhev      zhev      lenl      lenm        id     itype
       0.0       0.0       0.0       0.0       0.0         0         0
```

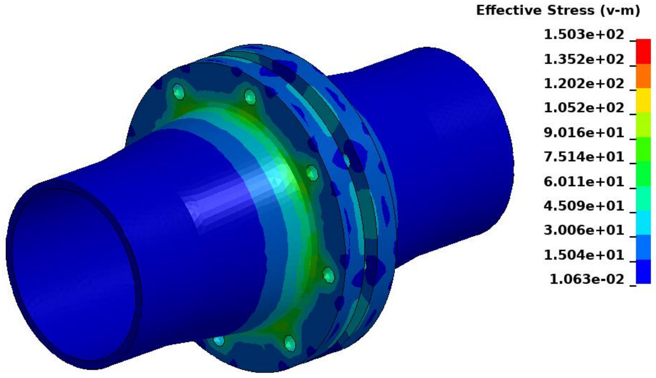
Prestressing Bolts by Initial Stress

- The example is solved using the implicit solver, thus static.
- SECFORC ASCII-file can be used to evaluate the applied force. NOTE! Could be less than expected due to discretization.



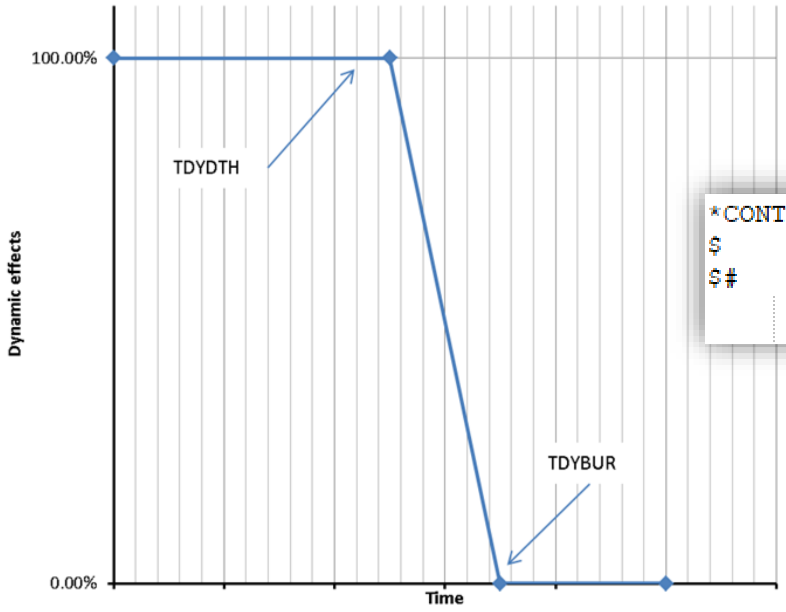






Adding Implicit Dynamics During Pre-Tension

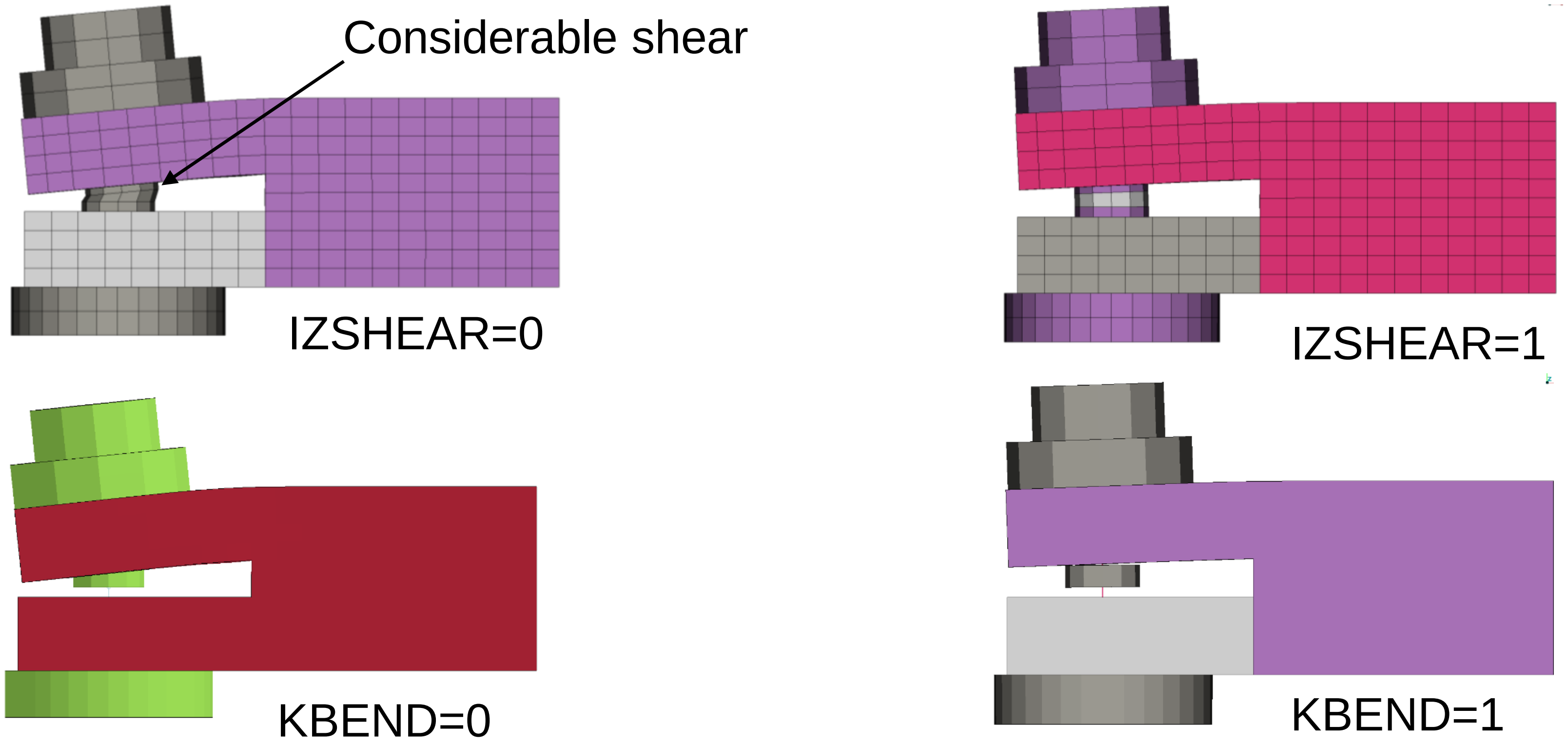
- During pre-tension, the model can be a bit “loose”, which generates negative eigenvalues.
- By adding the influence from the inertia, the problem becomes positive definite.
- The dynamics is scaled down at the end of the pre-tension by TDYDTH (Death) and TDYBUR (Burial).




```
*CONTROL_IMPLICIT_DYNAMICS
$     IMASS     GAMMA      BETA                                      IRATE
$#    imass     gamma      beta    tdybir    tdydth    tdybur    irate     alpha
          1       0.6      0.38       0.0       0.5       1.0        1       0.0
```

Accounting for Bending Deformation

- By default, LS-DYNA applies the pre-tensioning only in the axial direction. Stress gradients are not considered.
- Use IZSHEAR=1 for solids and KBEND=1 for beams to account for shear stresses.

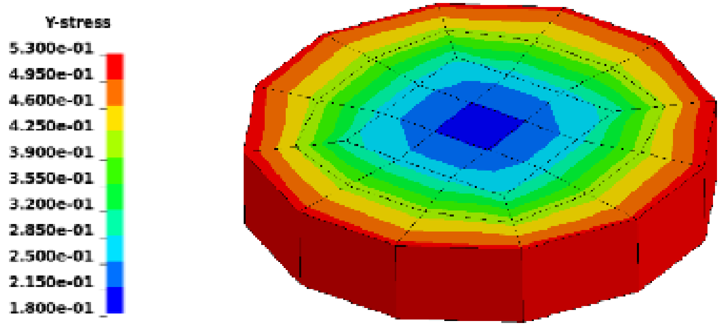


Accounting for Bending Deformation

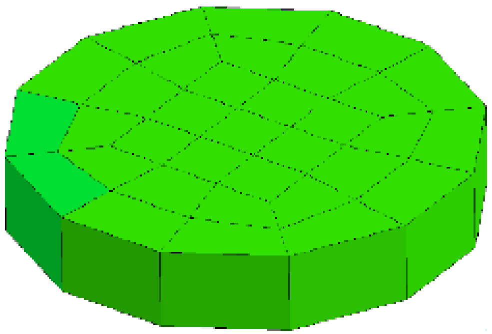
- The IZSHEAR option differs between explicit and implicit analyses.
- Implicit: IZSHEAR=1 and IZSHEAR=2 are the same, and radial stress gradient is obtained.
- Explicit:
  - IZSHEAR=1 yields homogenous normal stress over the cross-section.
  - IZSHEAR=2 yields heterogenous normal stress over the cross-section.

Implicit

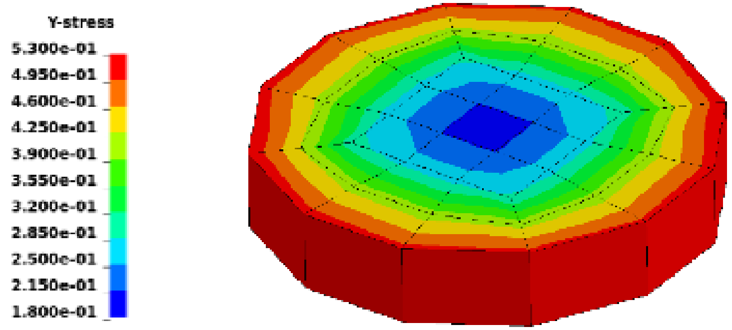
Explicit



IZSHEAR=1,2



IZSHEAR=1



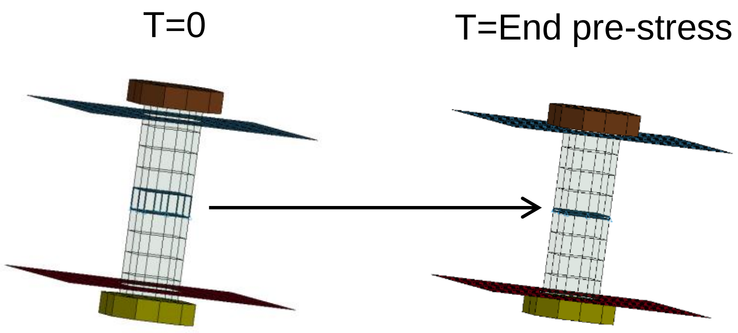
IZSHEAR=2

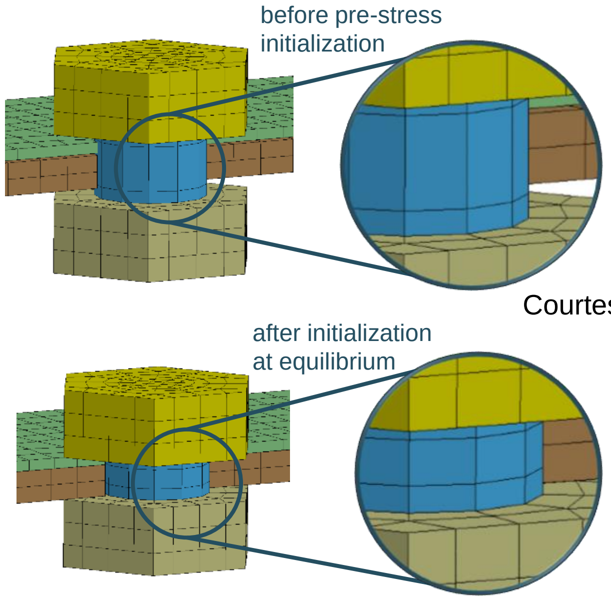
*INITIAL_STRESS_SECTION – Mesh Deformation

- One element row will be distorted in order to induce requested stress state. Problems occur if:
  - High stress-state wanted.
  - Plastic deformation of bolt shanks.
  - Small element sizes.
  - Gaps in model.

- Manually account for the deformation in advance.

- Distribute the deformation along the shank using “ghost” elements.
  - ISTIFF parameter to add artificial stiffness to distribute the straining.
  - Webinar 20-10-07 by J. Forsberg on Client Area.
  - Under development.



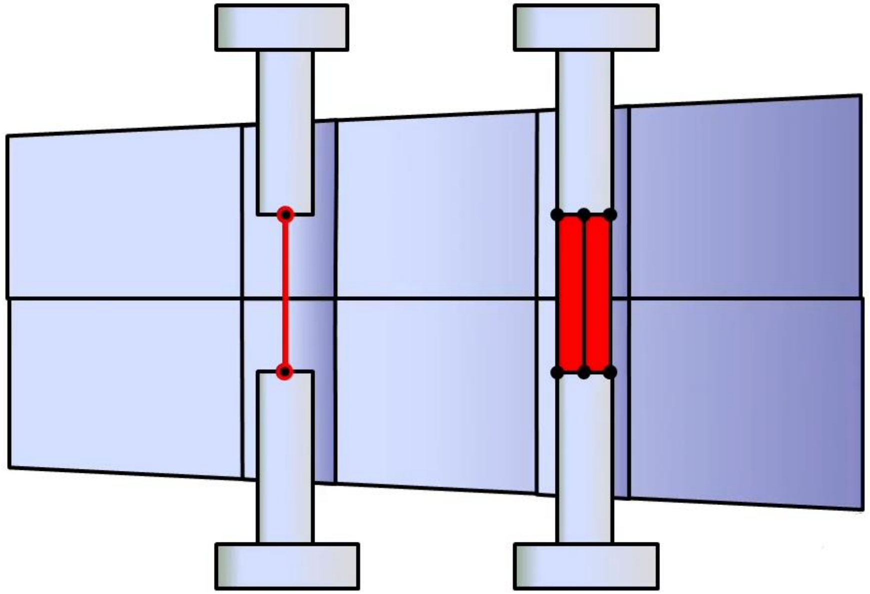


Courtesy Karajan et al.

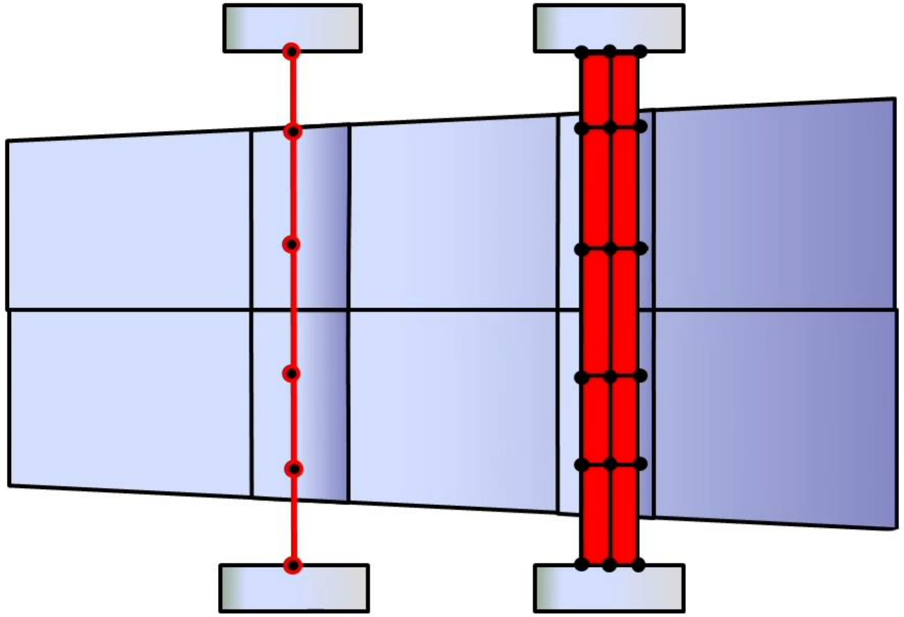
Accounting for Bending Deformation

- Upcoming feature in R14: possibility to prescribe the average force or stress along the entire shank of the bolt with the KBEND=2 and IZSHEAR=2 Options.
- The length is reduced in a controllable way, thus limiting dynamic effects of bolt head impacts.

Old way with KBEND=0,1,2 and IZSHEAR=0,1,2



New option with KBEND=2 and IZSHEAR=2

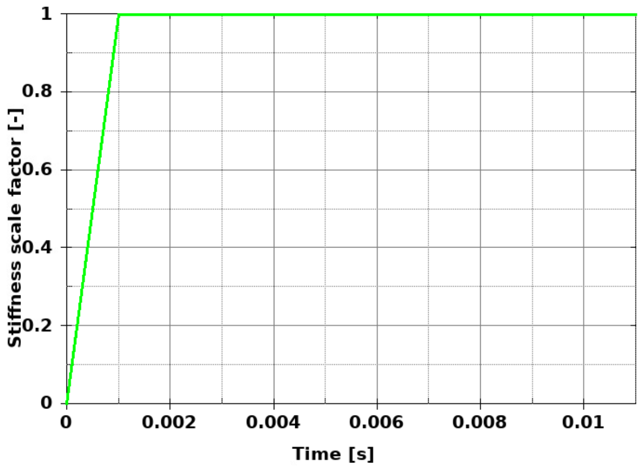


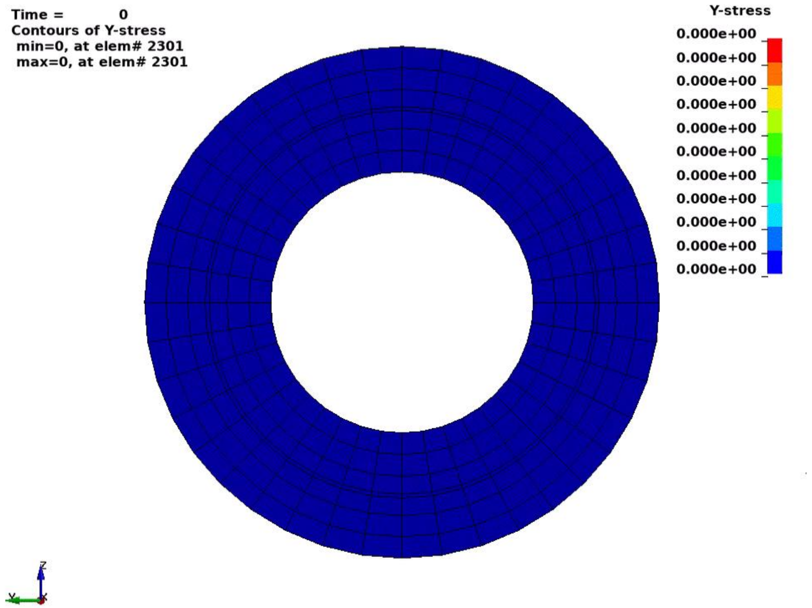
Press Fit Pre-Tensioning

- By thermal straining:
  - Shrink the part.
  - Activate the contact.
  - Expand the part.
- *CONTACT_...._INTERFERENCE
  - The parts are modelled with interference and the stiffness of the contact interface is gradually increased.
  - Input is a load curve for the dynamic relaxation phase and transient phase, respectively.
- *CONTACT_...._MORTAR
  - IGNORE=3 or 4 : Initial penetrations are eliminated between time 0 and time specified by MPAR1.
  - IGNORE=3 is intended for ”small” initial penetrations.
  - IGNORE=4 is intendend for ”large” initial penetrations where the penetration depth can be given by MPAR2, thus overriding the default search depth.
- NOTE! Discretization will be an issue if the press fit joint is supposed to rotate. *CONTACT_..._SMOOTH could remedy this.

Press Fit Pre-Tensioning

```
*CONTACT_SURFACE_TO_SURFACE_INTERFERENCE_ID
$#     cid                                                                 title
         1
$#    ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
         2         3         3         3         0         0         0         0
$#      fs        fd        dc        vc       vdc    penchk        bt        dt
       0.1       0.0       0.0       0.0       0.0         0       0.01.00000E20
$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
       1.0       1.0       0.0       0.0       1.0       1.0       1.0       1.0
$#   lcid1     lcid2
         0         2
```





Dynamic Relaxation

- Explicit DR is an optional transient analysis that takes place in ‘pseudo-time’ (precedes regular transient analysis).
- DR is typically used to preload a model before onset of transient loading.
  - Preload stresses are typically elastic, and displacements are small.
- In explicit DR, the computed nodal velocities are reduced each timestep by the dynamic relaxation factor (default = .995). Thus, the solution undergoes a form of damping during DR.
- The distortional kinetic energy is monitored. When this KE has been sufficiently reduced, i.e., the “convergence factor” has become sufficiently small, the DR phase terminates, and the solution automatically proceeds to the transient analysis phase.
- Alternately, DR can be terminated at a preset termination time.

*CONTROL_DYNAMIC_RELAXATION

Card 1	1	2	3	4	5	6	7	8
Variable	NRCYK	DRTOL	DRFCTR	DRTERM	TSSFDR	IRELAL	EDTTL	IDRFLG
Type	I	F	F	F	F	I	F	I
Default	250	0.001	0.995	T_end	TSSFAC	0	0.04	1/-1/-999

- NRCYK: Number of cycles between convergence check.
- DRTOL: Convergence tolerance (Kinetic Energy/Peak Kinetic Energy) where the “rigid body” kinetic energy is removed.
- DRFCTR: Reduction factor on nodal velocities.
- DRTERM: Optional time for dynamic relaxation finish.
- TSSFDR: Timestep scale factor during Dynamic relaxation.
- IDRFLG: Treated on separate slide.

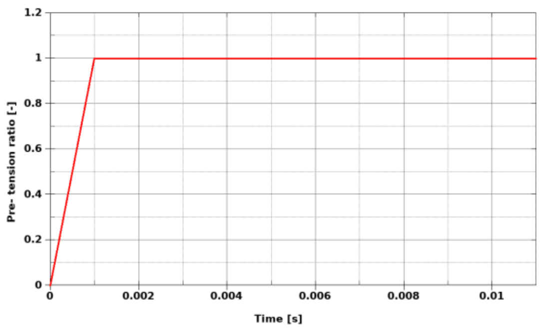
*CONTROL_DYNAMIC_RELAXATION - IDRFLG

Card 1	1	2	3	4	5	6	7	8
Variable	NRCYK	DRTOL	DRFCTR	DRTERM	TSSFDR	IRELAL	EDTTL	IDRFLG
Type	I	F	F	F	F	I	F	I
Default	250	0.001	0.995	T_end	TSSFAC	0	0.04	1/-1/-999

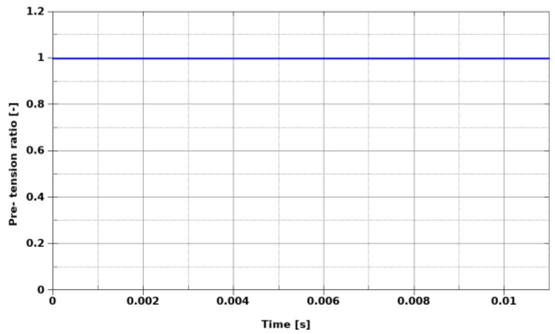
- EQ. -999: Dynamic relaxation is not activated regardless of what is specified on *DEFINE_CURVE card (SIDR).
- EQ. -3: DR for whole model but only convergence check for part set ID (DRPSET on card 2).
- EQ. -1: Activated and time history is output.
- EQ. 0: Not activated.
- EQ. 1: Activated.
- EQ. 2: Initialization to prescribed geometry.
- EQ. 3: 1 but only for part set ID (DRPSET on Card 2).
- EQ. 5: Initialize using the implicit solver.
- EQ. 6: Initialize using the implicit solver but part set ID (DRPSET on Card 2) for convergence checking.

Activating Dynamic Relaxation

- DR is activated by setting parameter SIDR in *DEFINE_CURVE to 1 or 2.
  - SIDR=0 : Load curve is only used in transient analysis.
  - SIDR=1 : Load curve is only used in dynamic relaxation analysis.
  - SIDR=2 : Load curve is used in both dynamic relaxation and transient analysis.
- Two options of loading:
  - 1. Ramp the load during DR phase and then hold load constant until solution converges.
    - NOTE! Make sure convergence occurs after 100% of preload is applied.
    - Maintain the preload in subsequent transient analysis phase (use separate load curve without the ramp).
  - 2. Apply the load directly. The load curve can be used for both analyses (SIDR=2).

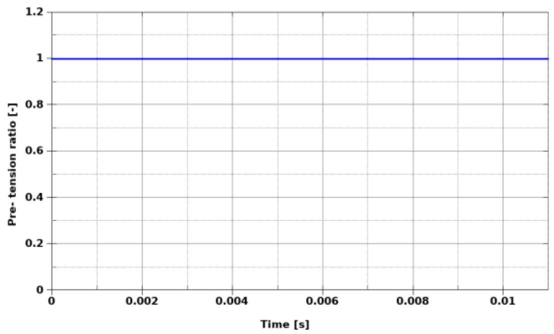


SIDR=1 for DR phase



SIDR=0 for transient phase

or

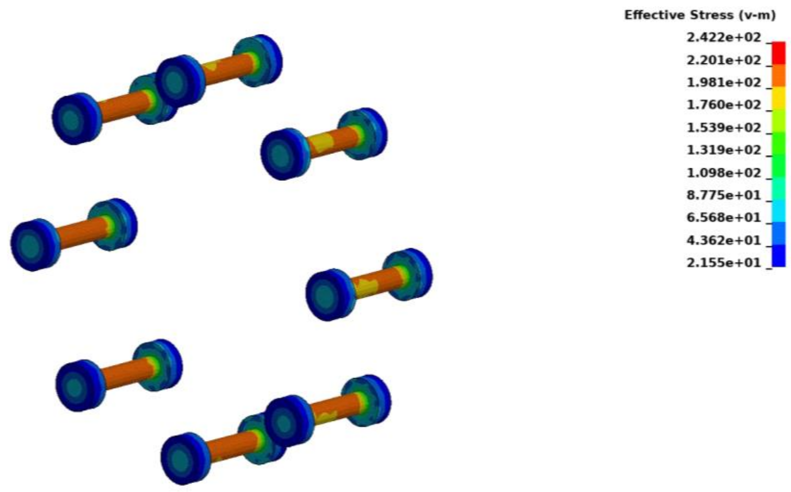


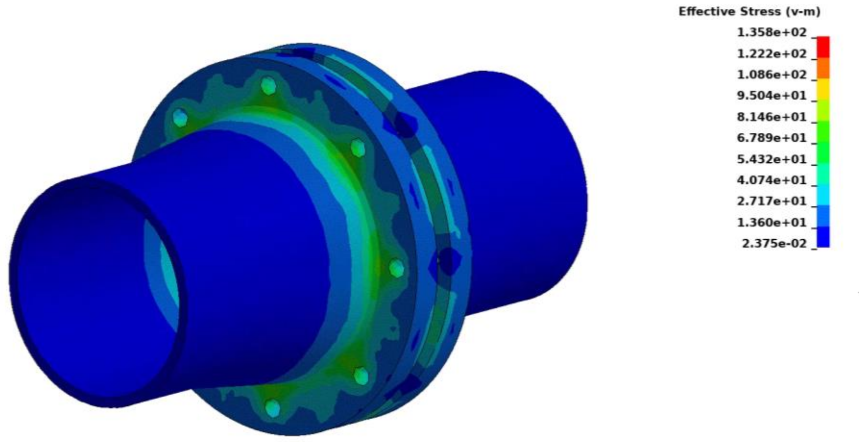
SIDR=2 for DR and transient phase

Example: Pre-Tension Using Dynamic Relaxation

- Pre-tension using *INITIAL_STRESS_SECTION and the explicit solver.
- NOTE! Use SIDR=1 to only use the curve in Dynamic Relaxation phase. Otherwise, the stress will be constant during the transient analysis.
- No pre-stress is needed during the transient analysis. Curve should be 0.

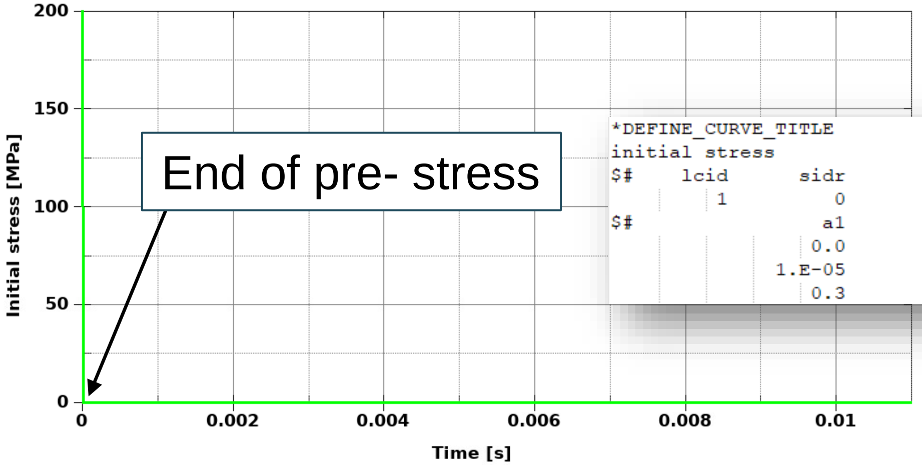
```
*DEFINE_CURVE_TITLE
initial stress
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         1         1       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0               200.0
                0.01               200.0
               0.011               200.0
```





Restart using Displacement of Pre-Loaded State

- IDRFLG=2 initiates the displacements of deformable bodies to the ASCII file specified on the execution line (m=….).
- The ASCII file (drdisp.sif) contains nodal translations, rotations and temperatures of the pre-loaded state.
- The pre-load is linearly ramped to the prescribed values over NC steps (Card 2).
- For instance, if *INITIAL_.. Keywords are used:
  - No pre- stress keywords are necessary during Dynamic Relaxation.
  - Use SIDR=0 in transient analysis and initialize the stress in the first timestep.




```
*DEFINE_CURVE_TITLE
initial stress
$#     lcid      sidr       sfa       sfo
          1         0       1.0       1.0
$#                 a1                  o1
                  0.0               200.0
               1.E-05                  0.
                  0.3                  0.
```

```
Use this restart dump if you want to restart the
dynamic relaxation and re-converge to a tighter tolerance
Use the next restart dump to restart as a transient analysis

ASCII File drdisp.sif written at end of dynamic relaxation.
This file contains nodal displacements, rotations and temperatures.
The file may be used for stress initialization - See
Dynamic relaxation option #2.

initialization complete at
   pseudo-time =  4.3309E-04
   cycle =      1500
```

Dynamic relaxation

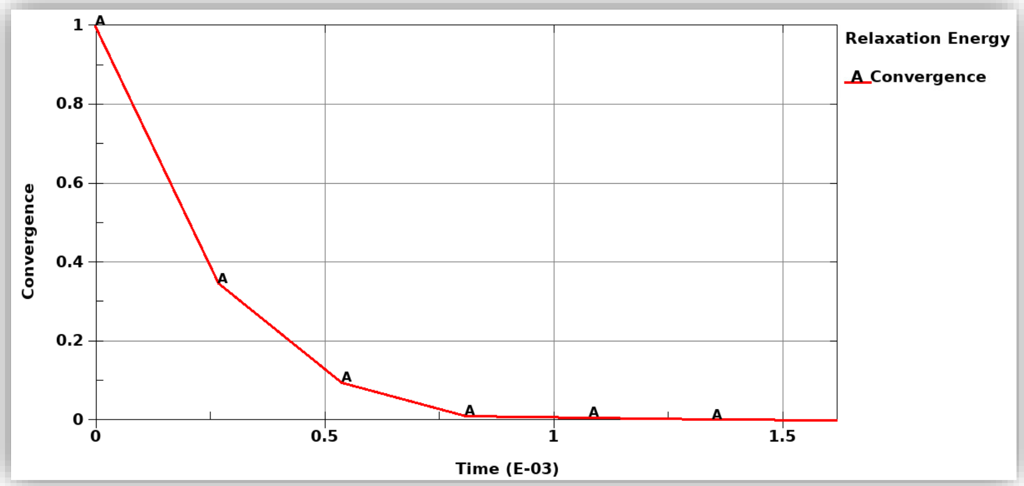
```
Use this restart dump if you want to restart the
dynamic relaxation and re-converge to a tighter tolerance
Use the next restart dump to restart as a transient analysis

initialization complete at
   pseudo-time =  2.8884E-05
   cycle =      101
```

IDRFLG=2

Output During Dynamic Relaxation

- BINARY DATABASE D3DRLF
  - Binary database to fringe plot during Dynamic Relaxation. Output is governed by *DATABASE_BINARY_D3DRLF.
- CONVERGENCE HISTORY
  - Convergence history is plotted in the file relax which can be read and plotted in LS-PrePost.
- TIME HISTORY DATA
  - Output in d3thdt file governed by *DATABASE_BINARY_D3THDT. The element and node subsets are defined in *DATABASE_HISTORY.
- CONVERGED GEOMETRY
  - d3dump can be used in a restart analysis.
  - drdisp.sif Can be used in a repeated dynamic relaxation run using IDRFLG=2.



Summary

- Pre-stressing can be done in transient simulation or in Dynamic relaxation phase.
- Pre-stressing can be either implicit or explicit.
- The pre-stressing can be done using:
  - “Thermal” straining using *MAT_ADD_THERMAL_EXPANSION.
  - *INITIAL_AXIAL_FORCE_BEAM for beam bolts.
  - *INITIAL_STRESS_SECTION for solid bolts.
  - *CONTACT_…_INTERFERENCE for interference joints.
- The benefit of using Dynamic relaxation is:
  - Damping is applied.
  - The pre-stressing phase is controlled by a convergence criterion.
  - Possibility to initialize the solution to a known pre-stressed displacement.
- SIDR on *DEFINE_CURVE activates dynamic relaxation and controls which load curves are used in dynamic relaxation and transient phase.
- When using Dynamic relaxation:
  - Make sure that the pre-stress load is fully applied at the converged state.

Further Reading..

- Karajan, N., et al., Modeling bolts in LS-DYNA using explicit and implicit time integration, 15thInt. LS-DYNA Users Conf. (https://www.dynalook.com/15th-international-ls-dyna-conference/implicit/modeling-bolts-in-ls-dyna-c-using-explicit-and-implicit-time-integration).

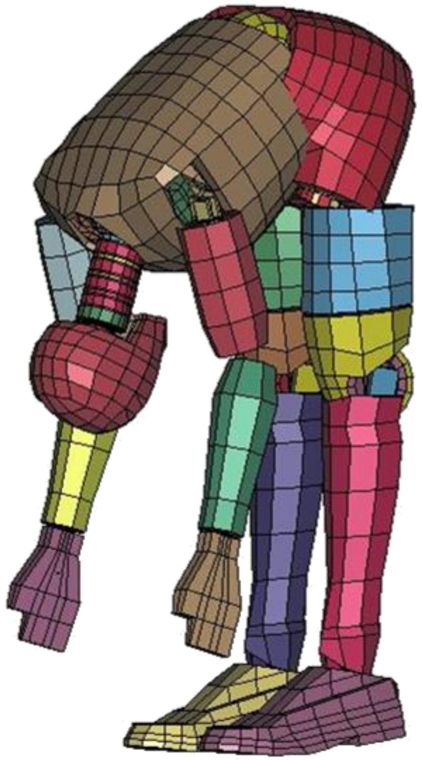
- On DYNAmore Nordic Client Area

  - Webinar by J. Forsberg, Bolt Pre-Tensioning in LS-DYNA, (2020-10-07).

  - Webinar by A. Jonsson, Pre-Tensioning Techniques in LS-DYNA-implicit, (2021-01-28).

- On DYNAmore Nordic’s website
  - Short video by T. Borrvall, Bolt Preload with Bending Resistance, (2022-03).

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

Find us on

DYNAmore worldwide
Germany ▪ France ▪ Italy ▪ Sweden ▪ Switzerland ▪ USA