Analyses of rubber parts in LS-DYNA implicit

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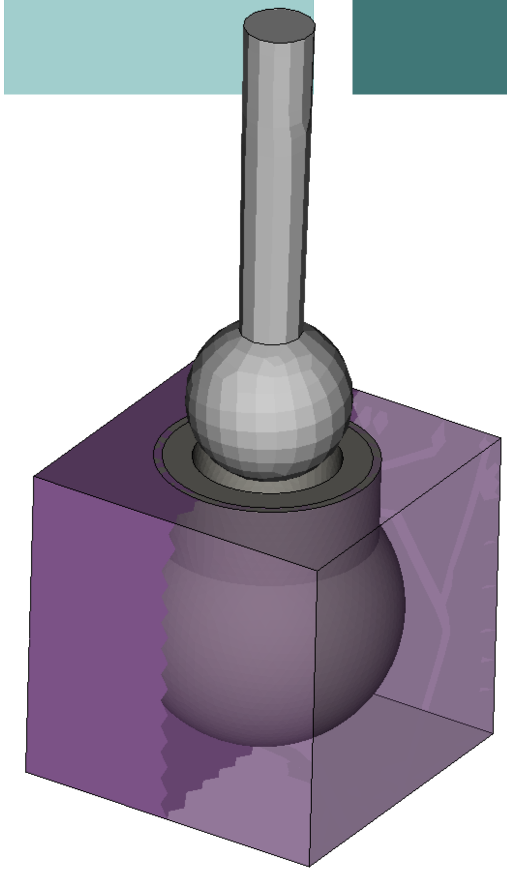
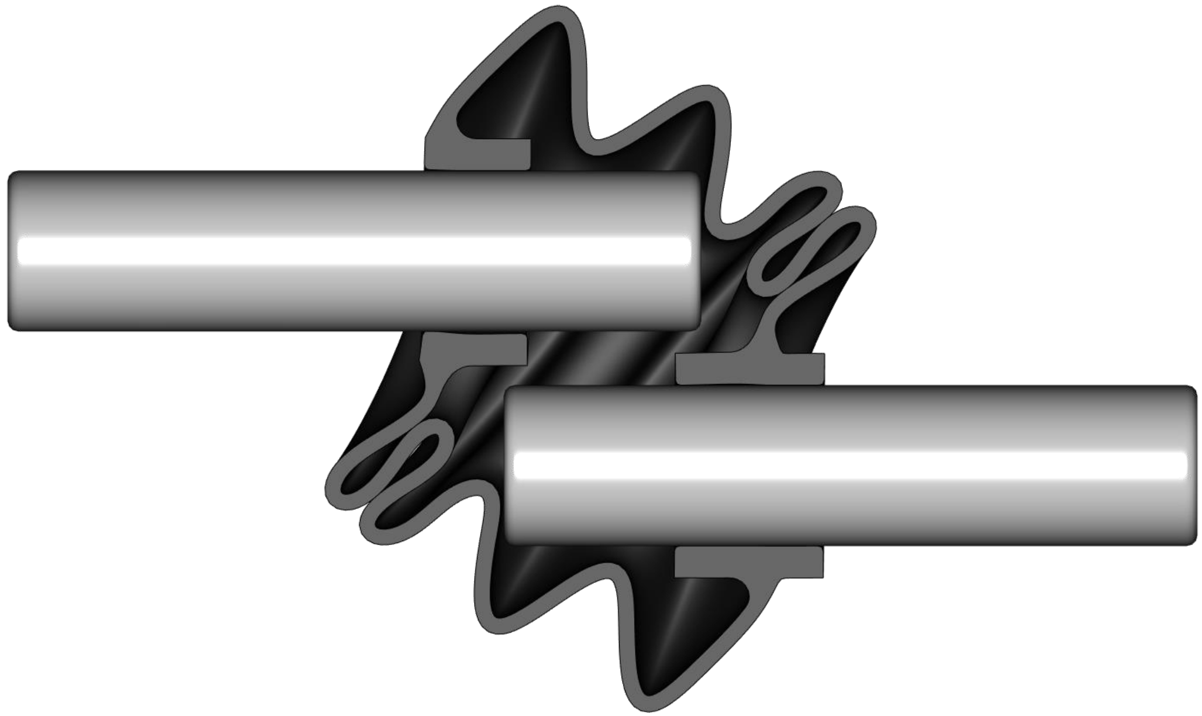




Overview

- Rubber
  - Appendix A of the Guideline for implicit analyses
  - Background / theory
  - LS-DYNA material models
- Recommended
  - solver settings,
  - element formulations and
  - contacts
- Examples
- Summary

Guideline for implicit analyses in LS-DYNA

- A good starting point for setting up an implicit analysis in LS-DYNA is the Guideline for implicit analyses
- Download it from http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna
- Contains recommended control card settings for different analysis types, recommendations regarding element types, contacts. etc. Also some small examples are included.
- Appendix A of the Guideline is dedicated to analyses of rubber
- Appendix C gives a brief guide to troubleshooting convergence problems

Rubber – background / theory

- Rubber is commonly assumed to be an Incompressible Hyperelastic material. It is able to sustain finite strains.
- Many different material models have been proposed:
  - Ogden, Neo-Hooke, Mooney-Rivlin, Aruda-Boyce, etc.
- Material models almost always formulated using some kind of strain energy potential as a function of strain invariants, like principal stretches.
  - For example Ogden (penalty formulation of incompressibility condition)

$$W = \sum_{m=1}^{n} \frac{\mu_m}{\alpha_m} (\tilde{\lambda}_1^{\alpha_m} + \tilde{\lambda}_2^{\alpha_m} + \tilde{\lambda}_3^{\alpha_m} - 3) + \frac{1}{2} K (J-1)^2 \qquad \tilde{\lambda}_i = \frac{\lambda_i}{J^{1/3}},$$

- It's always recommended to perform material identification (Testing and calibration of the material model) using a physical material sample, rather than using material data from the Internet.
  - Many LS-DYNA material models allows for automatic determination of material parameters from test curves

Rubber material models in LS-DYNA

MAT_	Name	Comment
7	*MAT_BLATZ-KO_RUBBER	
27	*MAT_MOONEY-RIVLIN_RUBBER	
31	*MAT_FRAZER_NASH_RUBBER_MODEL	
77	***MAT_HYPERELASTIC_RUBBER**	Recommended! Can account for Mullins effect.
77	*MAT_OGDEN_RUBBER	
87	*MAT_CELLULAR_RUBBER	Rubber with confined air. $0 < \nu < 0.2$
127	*MAT_ARRUDA_BOYCE_RUBBER	Hyperelastic with optional viscoelasticity
181	***MAT_SIMPLIFIED_RUBBER/FOAM**	Defined via load curves. Also recommended!
218	*MAT_MOONEY-RIVLIN_RUBBER_PHASE_CHANGE	
269	*MAT_BERGSTROM_BOYCE_RUBBER	

Rubber material models in LS-DYNA

- `*MAT_HYPERELASTIC_RUBBER` is recommended.

```
*MAT_HYPERELASTIC_RUBBER_TITLE
MAT_77 Example with constants
$#      mid         ro         pr          n         nv          g       sigf        ref
        100 1.000E-10      0.495          0          0        0.0        0.0        0.0
$#      c10        c01        c11        c20        c02        c30     therml
     0.0333        0.0        0.0        0.0        0.0 5.0500E-4        0.0
```

- Set $N > 0$ to modify input for calibration to uniaxial testing data. Card 3 is used to specify test data.

```
*MAT_HYPERELASTIC_RUBBER_TITLE
MAT_77 Example with test data
$#      mid         ro         pr          n         nv          g       sigf        ref
        1001.0000E-10      0.495          3          0        0.0        0.0        0.0
$#      sgl         sw         st     lcid1       data      lcid2     bstart      tramp
      100.0       10.0        5.0       1001        0.0          0        0.0        0.0
```

(n = 1 ➔ Fit using C10 and C01
n = 2 ➔ Fit using C10, C01, C11, C20, and C02
n = 3 ➔ Fit using C10, C01, C11, C20, C02, and C30)

Rubber material models in LS-DYNA

- *MAT_HYPERELASTIC_RUBBER is recommended.
  - Specifying only C10 gives a Neo-Hooke material
  - Specifying C10 and C01 gives a Mooney-Rivlin material
  - Specifying C10, C20 and C30 gives a Yeoh material
  - Initial guess for Poisson's ratio: 0.4995
- In LS-DYNA, the incompressibility constraint is given by Poisson's ratio (denoted as PR or ν). Alternatively, the parameter $D = 2/K_0$ may be applied

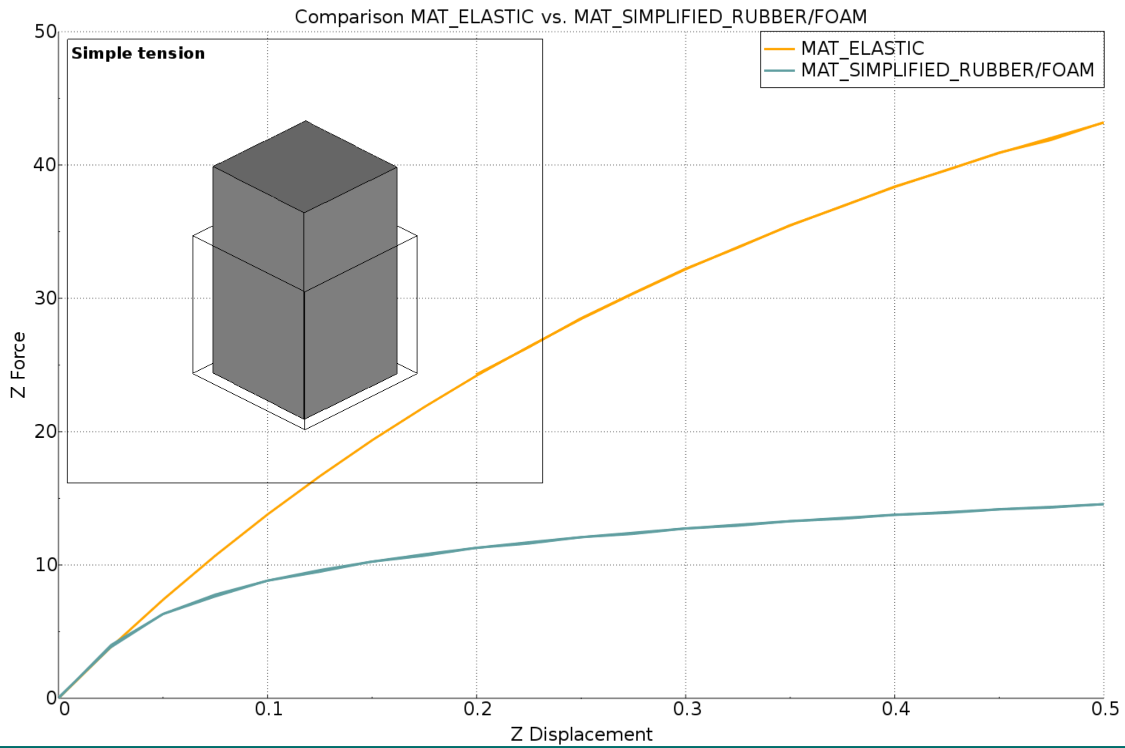
Yeoh: $$\nu = \frac{3 - 2DC_{10}}{6 + 2DC_{10}}$$

Mooney-Rivlin: $$\nu = \frac{3 - 2D(C_{10} + C_{01})}{6 + 2D(C_{10} + C_{01})}$$

- *MAT_SIMPLIFIED_RUBBER/FOAM is an alternative. Requires tabulated input, from testing. Has pre-defined Poisson's ratio to account for incompressibility.

Rubber material models in LS-DYNA

- **NOTE!** `*MAT_ELASTIC` is not a rubber material model!
- It is **NOT** at all suited for modelling an incompressible material subjected to finite strains.
- The main application of `*MAT_ELASTIC` is to model metallic materials ($\nu \approx 0.3$) subjected to small (< 1 %) strains.



Peak force overestimated by a factor 3 by use of `*MAT_ELASTIC` in this simple case

Possible solver settings modifications

- Start out with the settings from the Guideline for implicit analyses (see http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna)
- In many cases, using a tighter tolerance can be beneficial for convergence, since accepting an initial step which is not converged enough may lead to instabilities later on.
  For example, set *DCTOL* = 5.E-4 on `*CONTROL_IMPLICIT_SOLUTION`:

```
*CONTROL_IMPLICIT_SOLUTION
$#  nsolvr    ilimit    maxref     dctol     ectol     rctol     lstol    abstol
        12        11        15     5.E-4     1.E-2                       1.E-20
$#   dnorm    diverg     istif   nlprint    nlnorm   d3itctl
         2         1         1         3         2        10
$#  arcctl    arcdir    arclen    arcmth    arcdmp

$#   lsmtd
         5
```

Possible solver settings modifications

- Start out with the settings from the Guideline for implicit analyses (see http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna)
- In many cases, using a tighter tolerance than default can be beneficial for convergence, since accepting an initial step which is not converged enough may lead to instabilities later on. In cases with large displacements, set *DNROM* = 1 on `*CONTROL_IMPLICIT_SOLUTION`:

```
*CONTROL_IMPLICIT_SOLUTION
$#  nsolvr    ilimit    maxref     dctol     ectol     rctol     lstol    abstol
        12        11        15     1.E-3     1.E-2                       1.E-20
$#   dnorm    diverg     istif   nlprint    nlnorm   d3itctl
         1         1         1         3         2        10
$#  arcctl    arcdir    arclen    arcmth    arcdmp

$#   lsmtd
         5
```

Possible solver settings modifications

- Start out with the settings from the Guideline for implicit analyses (see http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna)
- Ignoring the geometric stiffness effect is often beneficial for convergence, when (nearly) incompressible behavior is studied. Set *IGS* = 2 on `*CONTROL_IMPLICIT_GENERAL`.

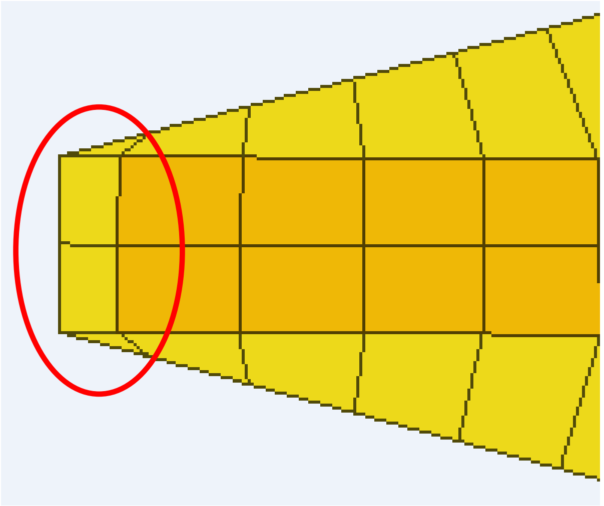
```
*CONTROL_IMPLICIT_GENERAL
$#   imflag       dt0    imform      nsbs       igs     cnstn      form    zero_v
          1       0.1         2         0         2         0         0         0
```

- If high coefficients of friction (approx. μ > 0.3) are used, activating the non-symmetric equation solver may be beneficial for convergence. For such cases, set *LCPACK* = 3 on `*CONTROL_IMPLICIT_SOLVER`.

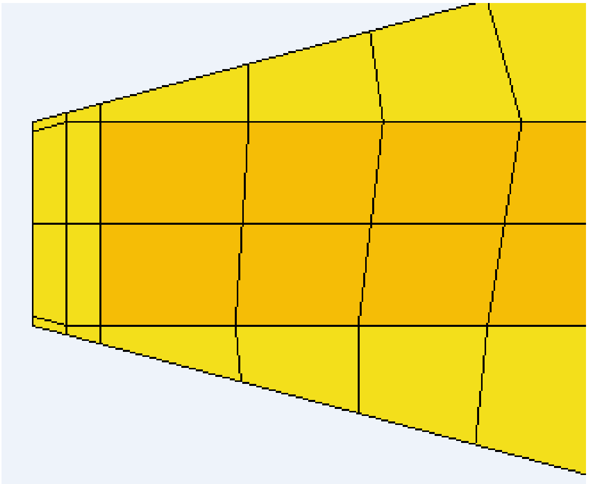
```
*CONTROL_IMPLICIT_SOLVER
$#   lsolvr    lprint

$#   lcpack
          3
```

Recommended element formulations

- A minimum of 2 element layers through the thickness is recommended to avoid locking up the mesh.
- Avoid penta elements if possible



Penta + single layer hex at the edge/tip

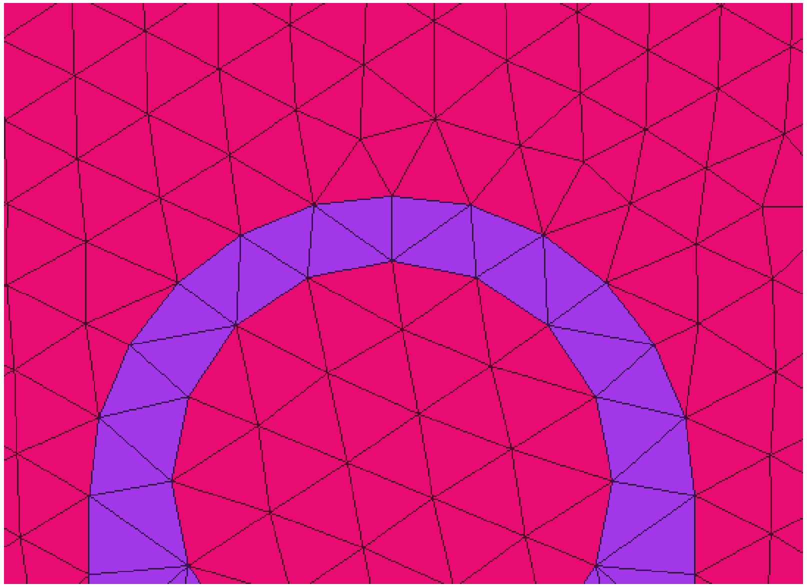


Recommended: Try to avoid pentas

Recommended element formulations

- A minimum of 2 element layers through the thickness is recommended to avoid locking the mesh.
- Avoid penta elements if possible
- For implicit analyses: solid hex -2 or -1, tet 13
  - Manual sorting required if a part contains both hex and tet
- Beware of node-to-node couplings of tet elform 13 between different materials, for example steel / `*MAT_RIGID` and rubber

Elastic Steel. Use tet elform 10 in this case



Rubber. Use tet elform 13. (Should ideally be at least two layers)

Recommended element formulations

- A minimum of 2 element layers through the thickness is recommended to avoid locking the mesh.
- Avoid penta elements if possible
  For implicit analyses: solid hex -2 or -1, tet 13
- Beware of node-to-node couplings of tet elform 13 between different materials, for example steel / `*MAT_RIGID` and rubber
- (Element Free Galerkin (EFG) may also be an option for implicit analyses. If you'd like to test this, use tets for the background mesh and solid elform 42

```
*SECTION_SOLID_EFG_TITLE
RUBBER EFG TET
$#   secid    elform       aet
         1        42         0
$#      dx        dy        dz   ispline     idila      iebt      idim    toldef
       1.1       1.1       1.1         0         0         3         2      0.01
$#     ips     stime      iken        sf      cmid       ibr        ds      ecut
         1
```

)

Recommended contacts

- For implicit analyses, Mortar contact is strongly recommended
  - For single surface contacts, contact forces can be requested using `*CONTACT_FORCE_TRANSDUCER_PENALTY_ID`

```
*CONTACT_AUTOMATIC_SINGLE_SURFACE_MORTAR_ID
  19000001Global contact
  19000111                               2
       0.1



                   -2
```

Title

Contact based on part set

Coefficient of friction

(Blank lines → Default values)

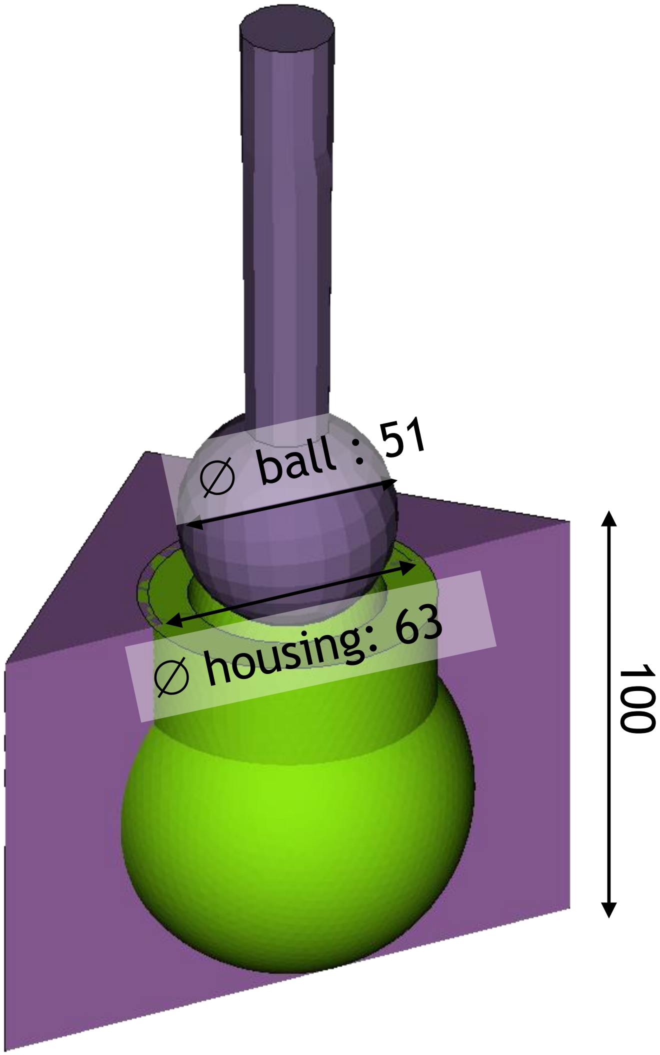
Ignore = -2 ➔ Self-contact within a part is not considered in this case

- When rubber is involved, high coefficients of friction may arise. As always, a physical friction measurement increases the confidence in the analyses (compared to using values found in the Internet).

Analyses of rubber components in LS-DYNA implicit

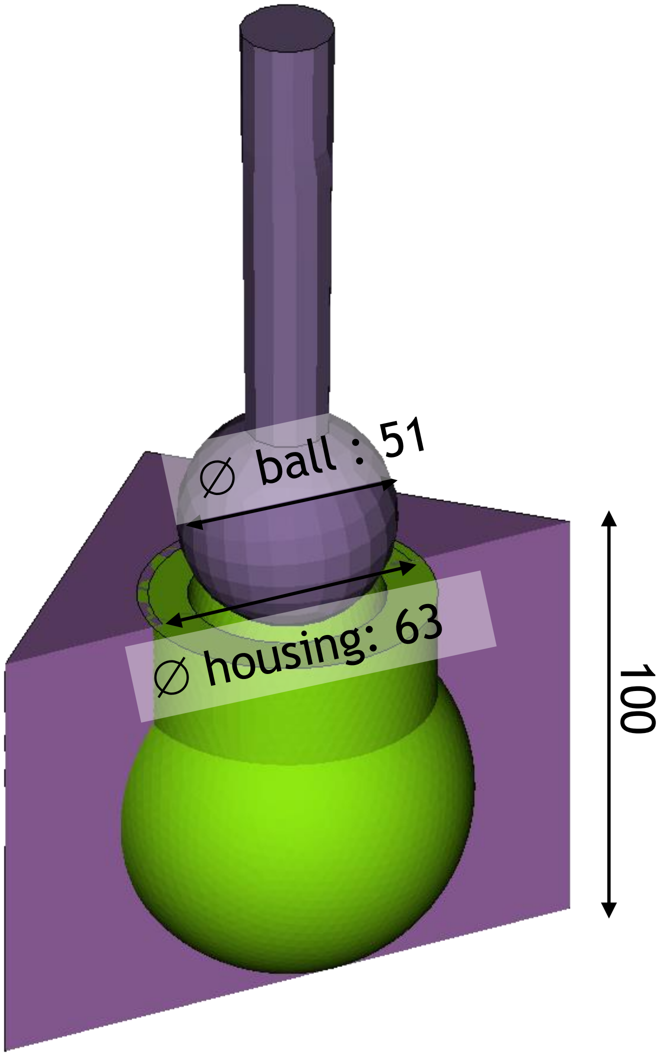
- Some examples
  - ball-joint interference and insert
  - Accounting for pre-loading
  - bellow: pull-out, compression, bending.

Interference and insert example



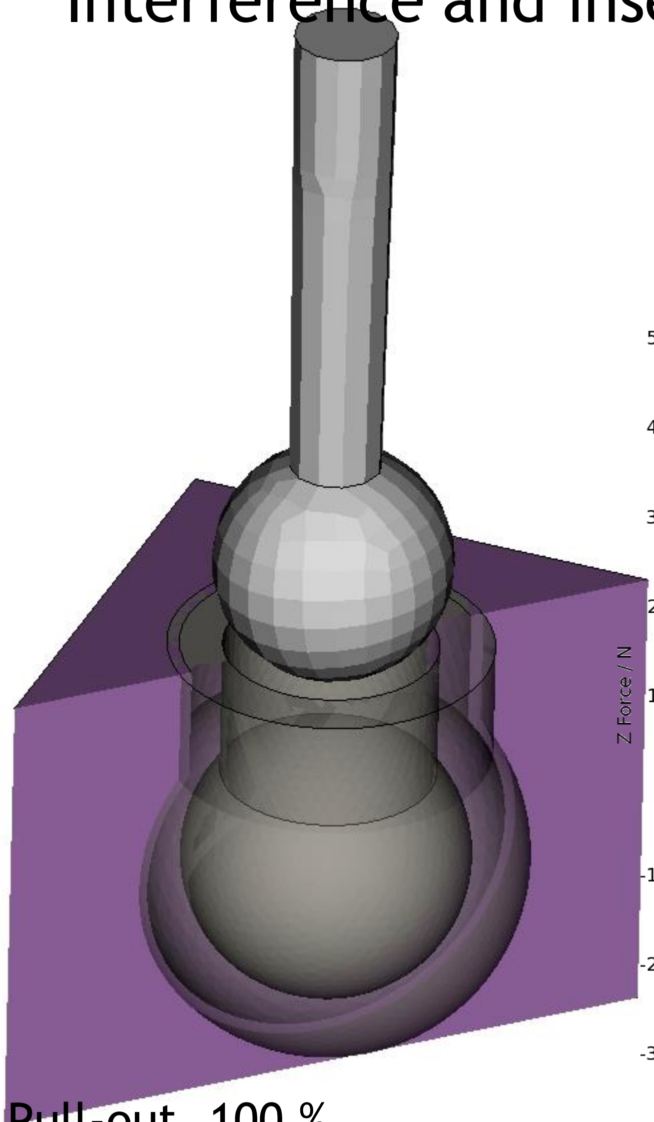
- About 100 000 deformable elements (Tet ef. 13)
- Inner diameter of the rubber before press-fit is 44.7mm
- A rubber sleeve (green in the image) is press-fit in a steel housing (modelled as rigid). The grip is 2.4 mm. The hole diameter in the rubber sleeve is 39.2 mm after completed press-fit.
- Then a steel ball with diameter 50 mm (modelled as rigid) is inserted.
- Coefficient of friction: 0.1 (well lubricated surfaces)
- Rubber material approximately corresponding to 62 Shore-A. Parameters for `*MAT_HYPERELASTIC_RUBBER` (`*MAT_77`): C10 = 0.5508, C01=0.1377, ν = 0.4995.

Interference and insert example – model set-up



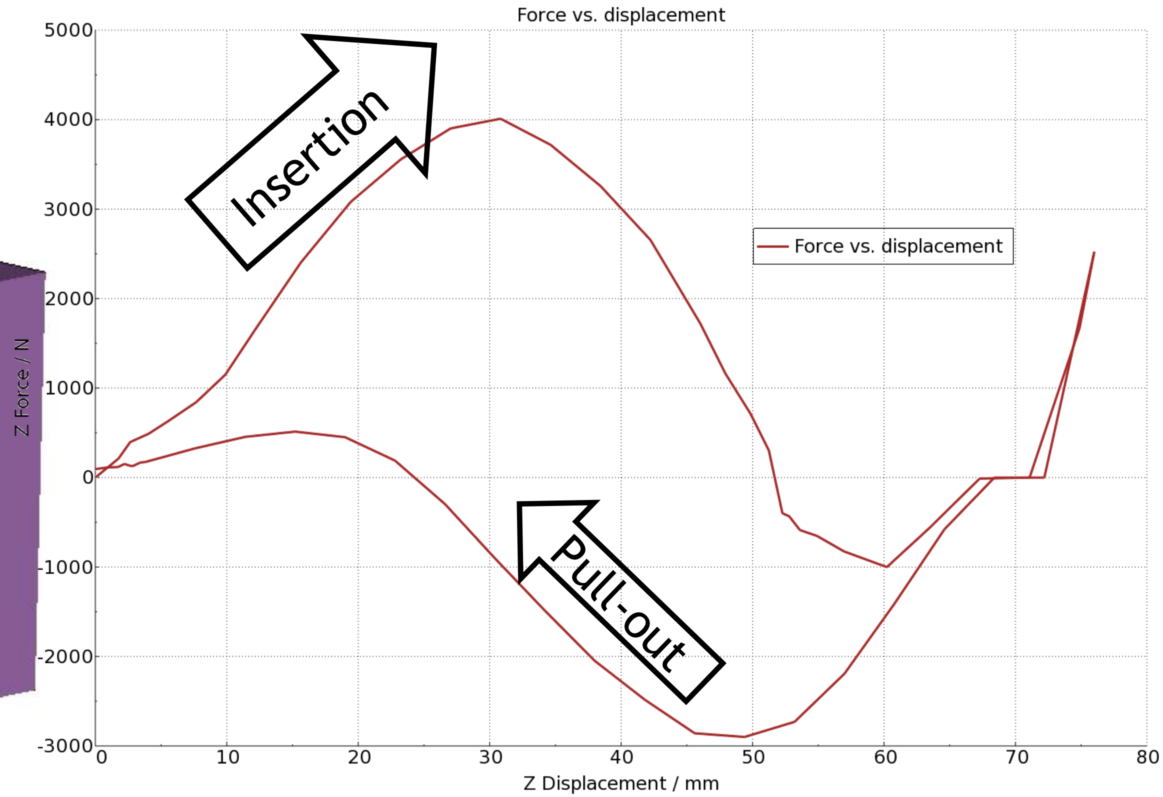
- Control cards for non-linear implicit analysis from the Guideline for implicit analysis
- Implicit dynamics is used, with settings for quasi-static dynamics.
- Effect of geometric stiffness is switched off(IGS=2 on `*CONTROL_IMPLICIT_GENERAL`)
- Solid element formulation 13 (also hex elform -2 for reference) was used for the rubber, with a typical element size of 3 mm.

Interference and insert example

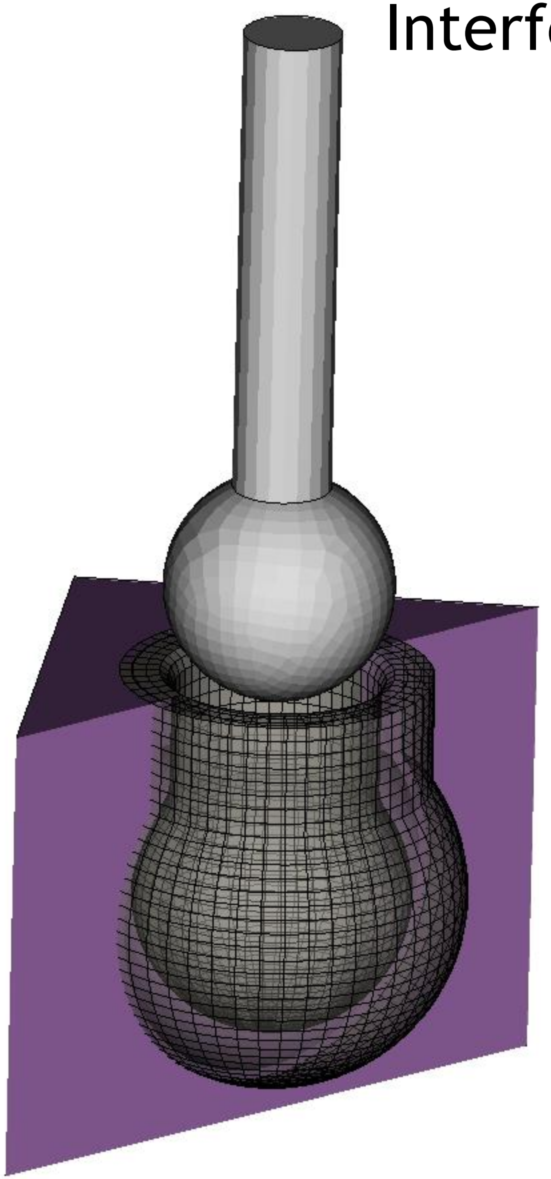


Pull-out, 100 %

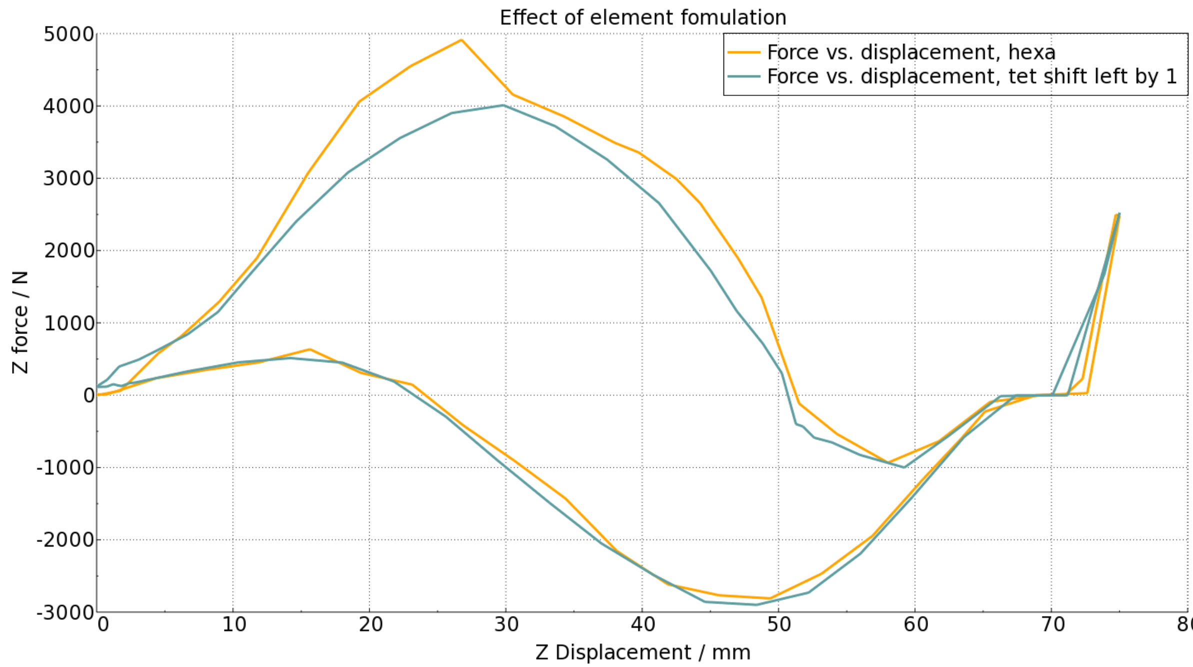
- Normal termination after 2h 10min, using mpp-LS-DYNA R10.0 on 4 cores.
- Force vs. displacement curve



Interference and insert example, effect of elform



- Force vs. displacement comparison – tet elform 13 vs. solid hex elform -2 in the rubber.



(Hexa geometry is slightly modified)

Accounting for pre-loading

- In many cases, the rubber component is compressed initially (by a press-fit or initial loading) and then subjected to a series of load cases.
- In order to avoid performing the initial pre-loading step in each analysis, two different techniques can be applied:
  - Restart, or
  - the use of `*INITIAL_FOAM_REFERENCE_GEOMETRY`

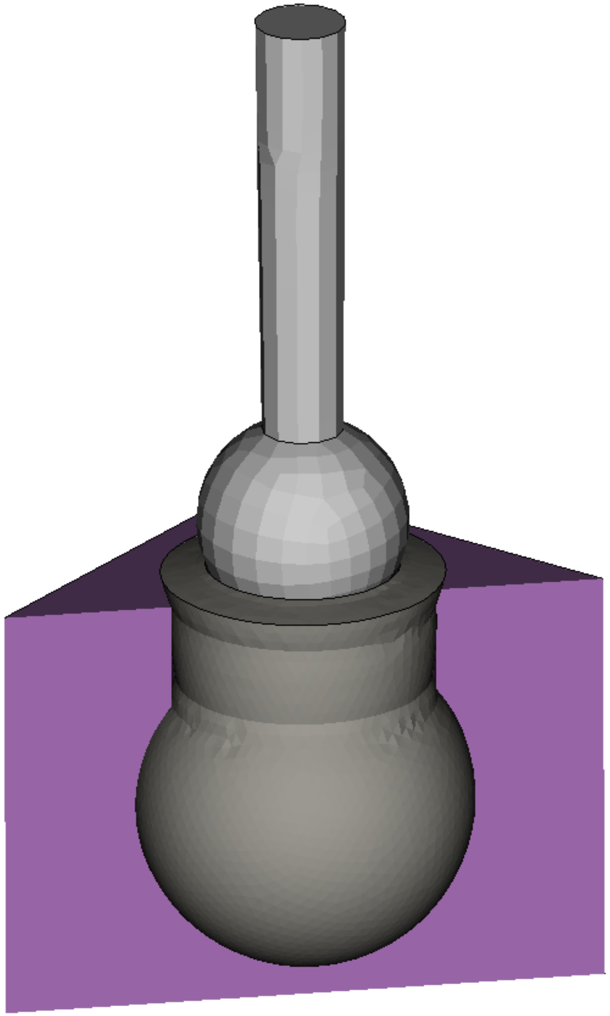
Accounting for pre-loading

- Pre-loading of rubber component can be accounted for using `*INITIAL_FOAM_REFERENCE_GEOMETRY`. The procedure follows:

1. Simulate the compression in a pre-simulation. Export the deformed nodal coordinates.
2. Import the deformed nodal coordinates into the main simulation. This means that the main simulation will start out with the deformed rubber geometry.
3. Export the original geometry (nodal coordinates) of the rubber part. Change `*NODE` to `*INITIAL_FOAM_REFERENCE_GEOMETRY`. Include this file in the main run file.
4. Set *REF*=1.0 on `*MAT_HYPERELASTIC_RUBBER`. By this, the initial stresses due to the deformation/pre-loading of the rubber will be accounted for.

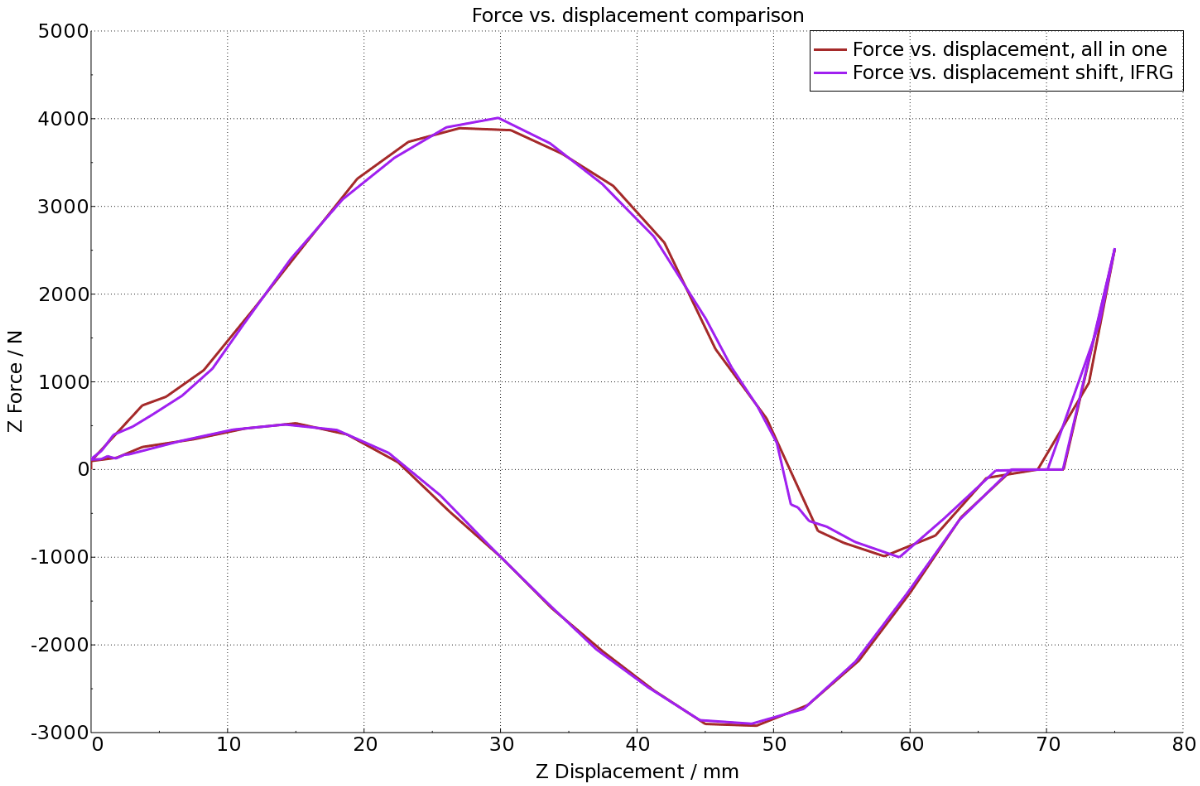
- This procedure can be applied also for many other hyperelastic materials.

Interference and insert example, separate pre-loading



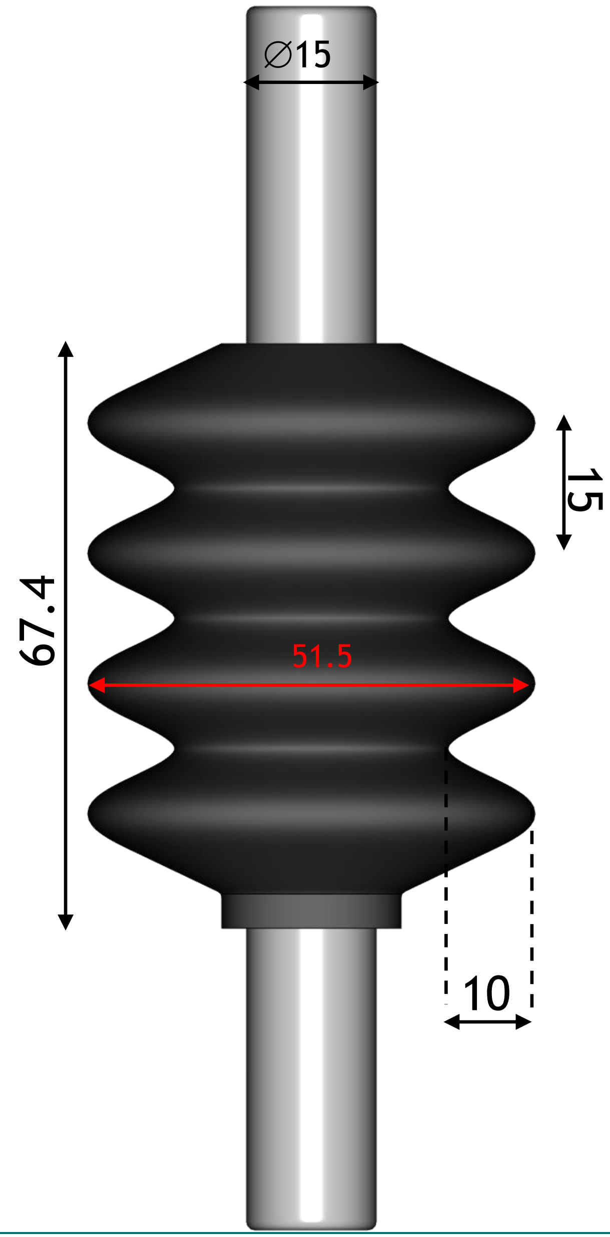
Pull-out, 100 %

- Force vs. displacement comparison – complete simulation vs. loading only combined with `*INITIAL_FOAM_REFERENCE_GEOMETRY`.



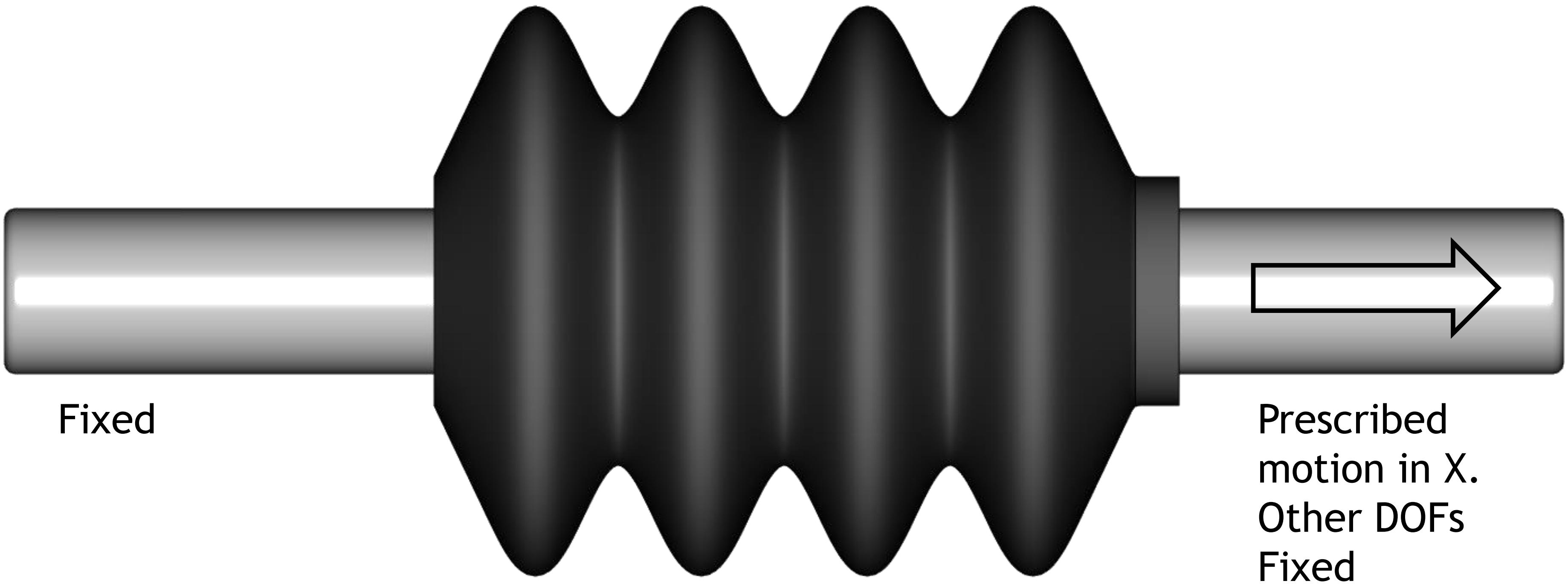
The bellow example – model data

- Main dimensions:
  - Thickness of the bellow: 1.5 mm
  - Axle diameter: 15 mm
  - Grip: 0.15 mm
  - Friction: μ = 0.7 (same for all contacts)
  - Totally 335000 elements. Hex elform -2 in the bellow, element size ~ 0.5 mm.
- Load cases: initial press-fit, followed by separate load cases:
  - pull out,
  - movement and compression, and
  - bending
- Rubber material approximately corresponding to 62 Shore-A. Parameters for `*MAT_HYPERELASTIC_RUBBER` (`*MAT_77`): C10 = 0.5508, C01=0.1377, ν = 0.4995.
- Implicit dynamics is activated after press-fit



The bellow example – axle pull out

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *IGNORE* = 3)
- Pull-out by prescribed displacement.

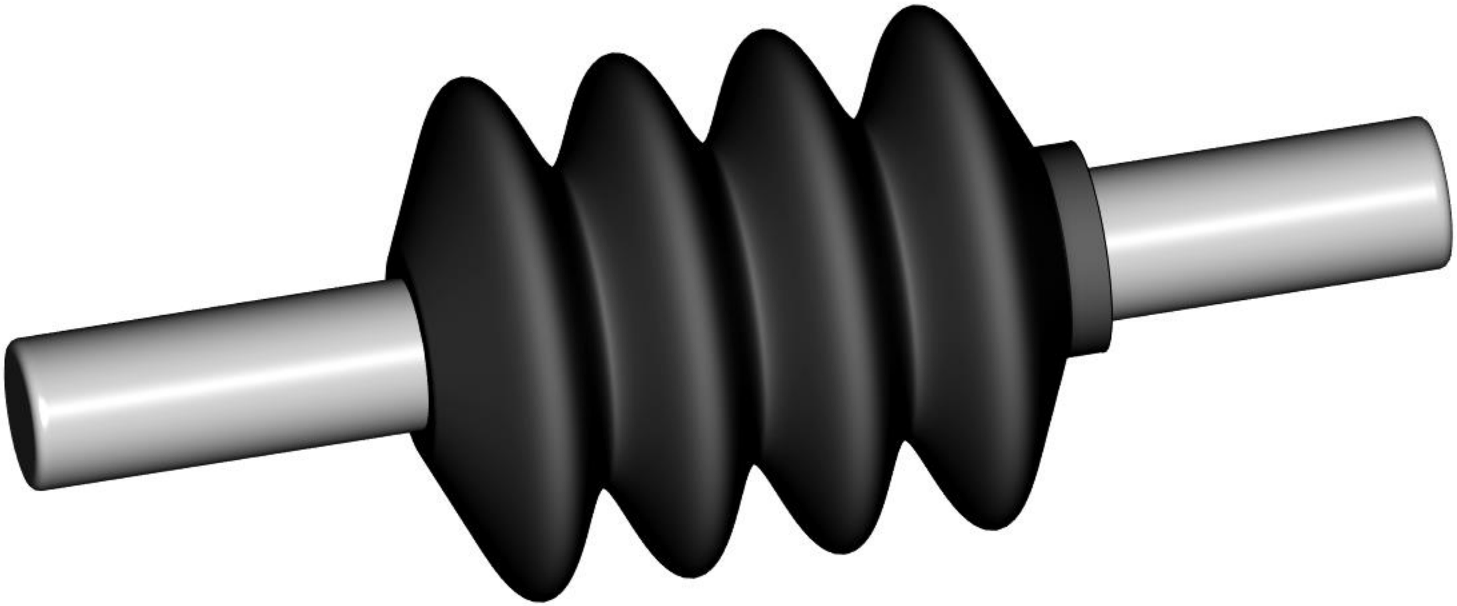


Fixed

Prescribed motion in X. Other DOFs Fixed

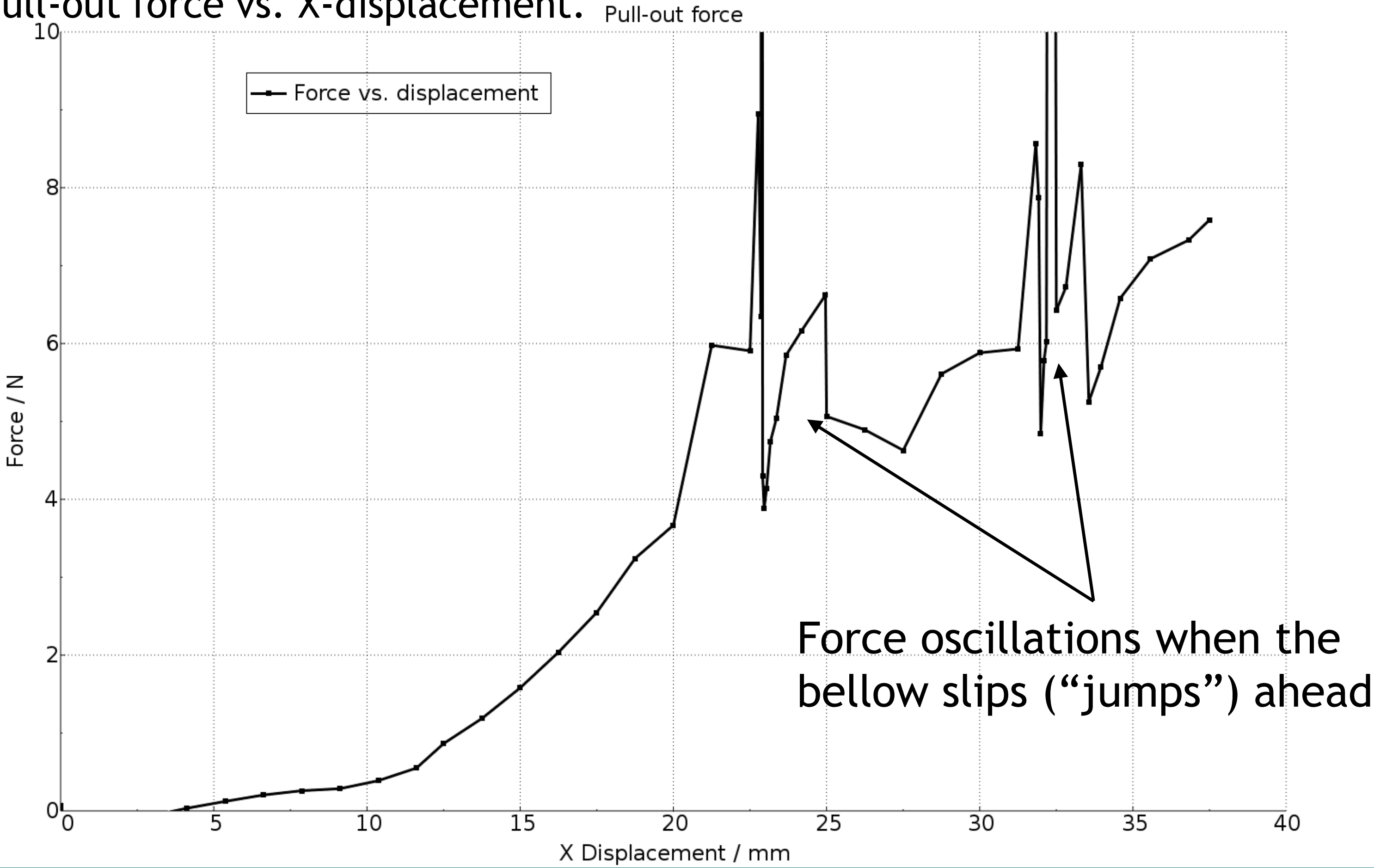
The bellow example – axle pull out

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *`IGNORE`* = 3)
- Pull-out by prescribed displacement.



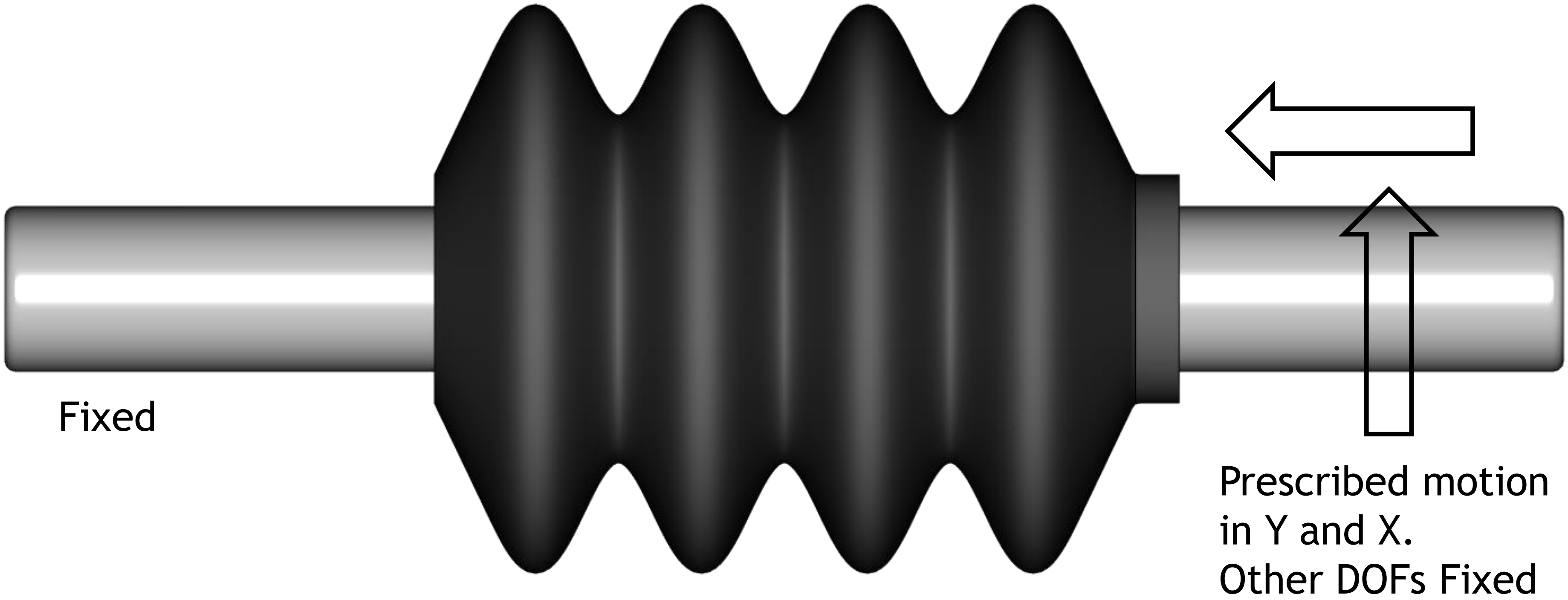
The bellow example – axle pull out

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *IGNORE* = 3)
- Pull-out force vs. X-displacement.



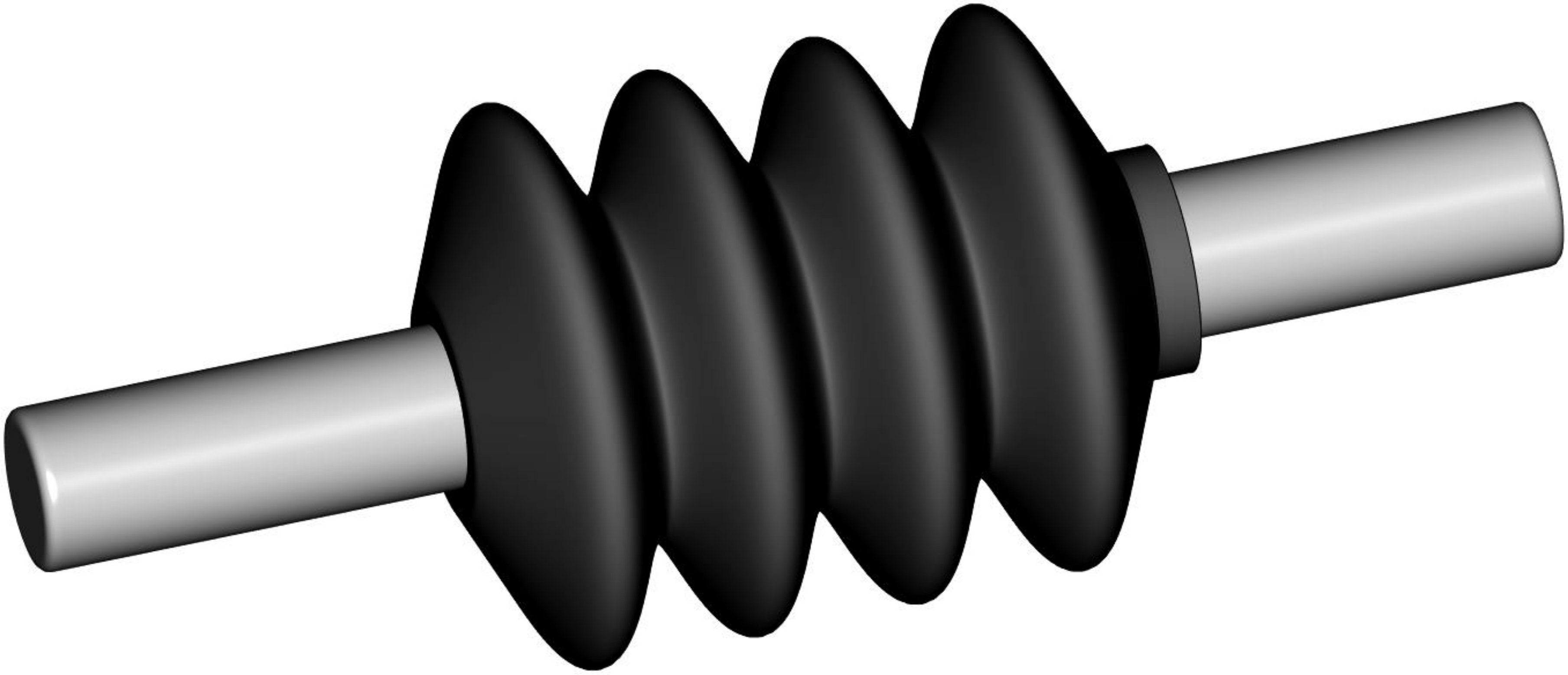
The bellow example – movement and compression

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *`IGNORE`* = 3)
- The axle is first moved in Y by 20 mm, and the by -30 mm in X



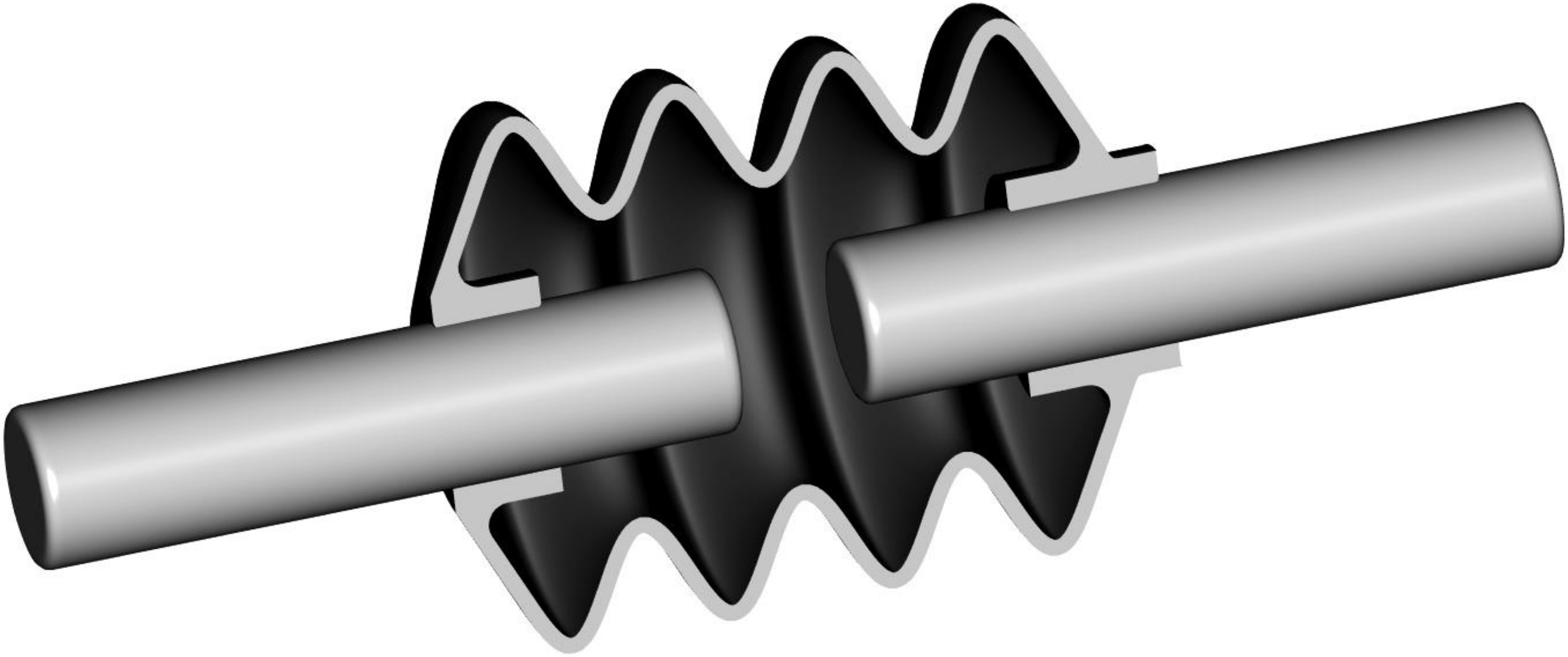
The bellow example – movement and compression

- Initial press fit (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID and *IGNORE* = 3)
- The axle is first moved in Y by 20 mm, and the by -30 mm in X



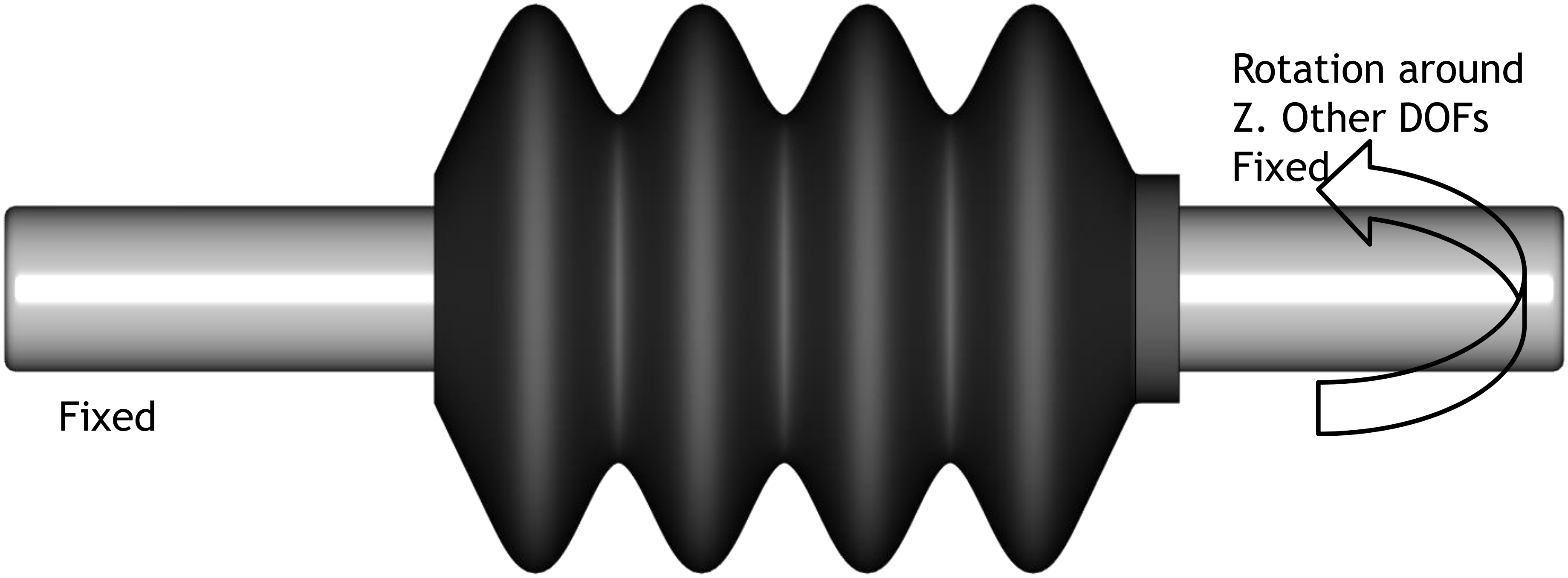
The bellow example – movement and compression

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *IGNORE* = 3)
- The axle is first moved in Y by 20 mm, and the by -30 mm in X



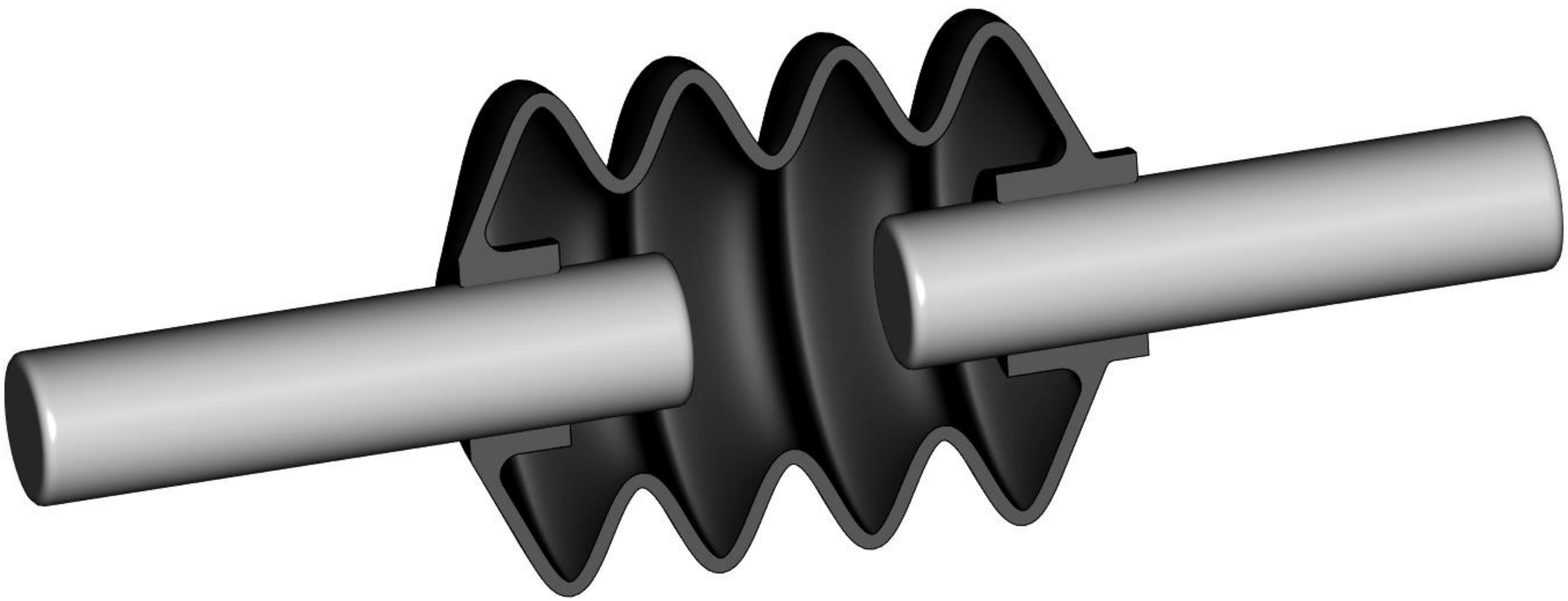
The bellow example – bending

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *`IGNORE`* = 3)
- The axle is rotated ±80° around the Z axle



The bellow example – bending

- Initial press fit (`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR_ID` and *IGNORE* = 3)
- The axle is rotated ±113° around the Z axle



Summary

- `*MAT_HYPERELASTIC_RUBBER` is recommended for modeling rubber materials
  - Poisson's ratio (PR) can be computed from Abaqus parameter D and material coefficients
- Spend some time to get a "nice" mesh.
  - Use tet elform 13, hex elform -2 in implicit.
  - Manual sorting required if tet elform 13 is desired
- For implicit, start out with the control card settings from the Guideline.
  - Set *IGS* = 2 on `*CONTROL_IMPLICIT_GENERAL`
  - Tighter convergence criteria (`*CONTROL_IMPLICIT_SOLUTION`) may be beneficial for convergence. For *DNORM* = 2, try for example *DCTOL* = 5.E-4. For *DNORM* = 1 (recommended in case of large deformations), try *DCTOL* = 1.E-3 to 5.E-3
- In implicit, use Mortar contacts

Thank you!

Your LS-DYNA distributor and more