Implementation of u-P Elements for Incompressible Hyperelastic Materials

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Background

- LS-DYNA is historically renowned as an explicit code, primarily intended for dynamic analyses
- For explicit, constraints are either
  - Sequentially applied; imposes restrictions in situations of dependency
  - Penalty enforced; accuracy and robustness is sensitive to the choice of scale factors
- With the advent of implicit, many constraints are simultaneously treated as part of an elimination strategy
  - Chain dependencies are treated properly, as long as not over constraining the system
  - Inequalities and some other constraints remain as penalty; in particular incompressibility

Incompressibility

- Incompressibility by means of a mixed element (u-P) formulation could be incorporated into the direct elimination framework, but
  - Awkward implementation – code for elements and constraints are “out-of-sync”
  - Potential overhead for treating the constraints
- Lagrangian multipliers seem to be the preferred method in this context
  - Framework for incorporating these degrees of freedom into the solution variables
- So why even do it?
  - Occasionally customers ask for it
  - Integral part of a generic implicit finite element software
  - Could it provide advantages in favor of “nearly” incompressible materials?
  - Given an existing Lagrangian multiplier framework, most of the work is already done

Discrete setting

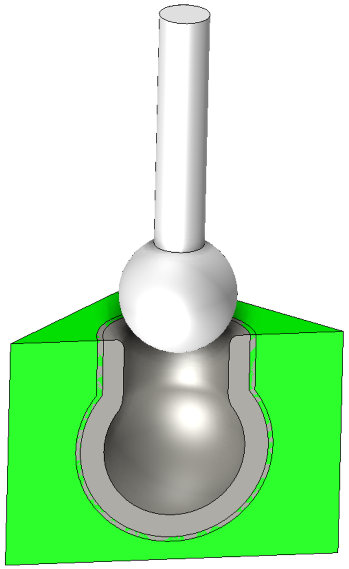
- Consider an arbitrary simulation model kinematically represented by the solution field $\boldsymbol{x}$, for which the solution is implicitly determined by an equilibrium equation $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{0}$
- An incompressibility constraint can be enforced by adding auxiliary equations $\boldsymbol{v}(\boldsymbol{x}) = \boldsymbol{0}$
  - $\boldsymbol{v}$ is a vector of whatever length required to establish the appropriate constraint
    - Number of elements in question, or number of integration points
    - Any unwanted locking phenomena must be carefully considered when designing the constraint
    - Each equation has local support, depending only on the coordinates in the vicinity of the element considered
- Derived from an energy principle, the resulting equations become $\boldsymbol{f} + \left(\frac{\partial \boldsymbol{v}}{\partial \boldsymbol{x}}\right)^T \boldsymbol{\lambda} = \boldsymbol{0}$ in addition to $\boldsymbol{v} = \boldsymbol{0}$
  - System increases by the number of extra constraints added
  - Linearized system is symmetric but indefinite, requirements on linear solver

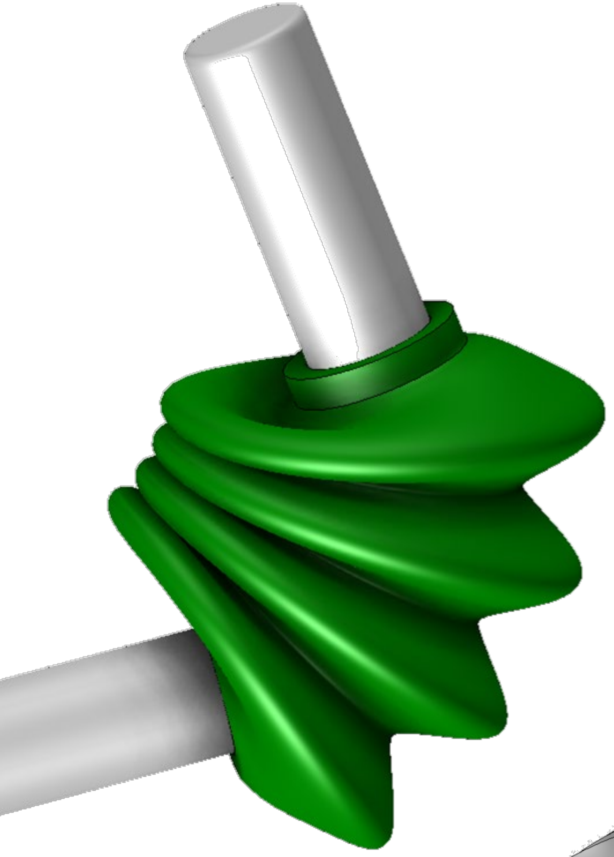
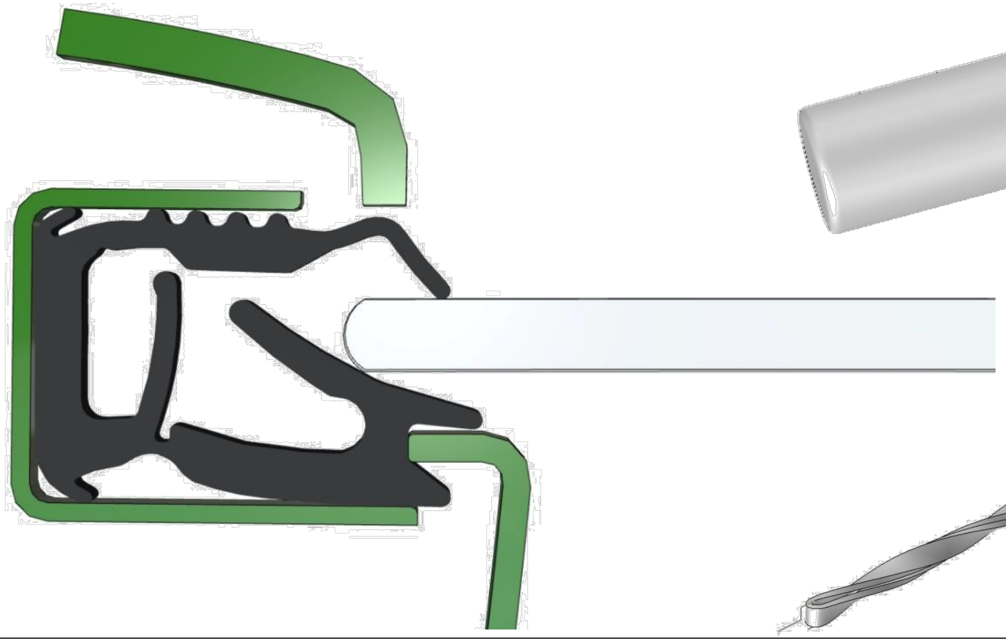
Implementation and Usage

- To activate the u-P elements
  - Use `MAT_027` or `MAT_077` with `PR = 0.5`
  - Use solid elements 2, 15, 10, 16
- What solution method to chose for implicit simulations involving Lagrange multipliers in general?
  - First recommendation, use JFNK
  - Set `NSOLVR` = 13 on `*CONTROL_IMPLICIT_SOLUTION`
  - Use default line search method
  - Should poor convergence occur, try
    - Standard BFGS
    - Full Newton
- The u-P elements may work better with the MUMPS linear solver
  - Set `LSOLVR`= 30 on `*CONTROL_IMPLICIT_SOLVER`

Examples - overview

- Mechanism
- Rubber donut
- Rubber bellow
  - Bending
  - Pull-out
  - Translate
- Twisting a rubber band
- Window sealing

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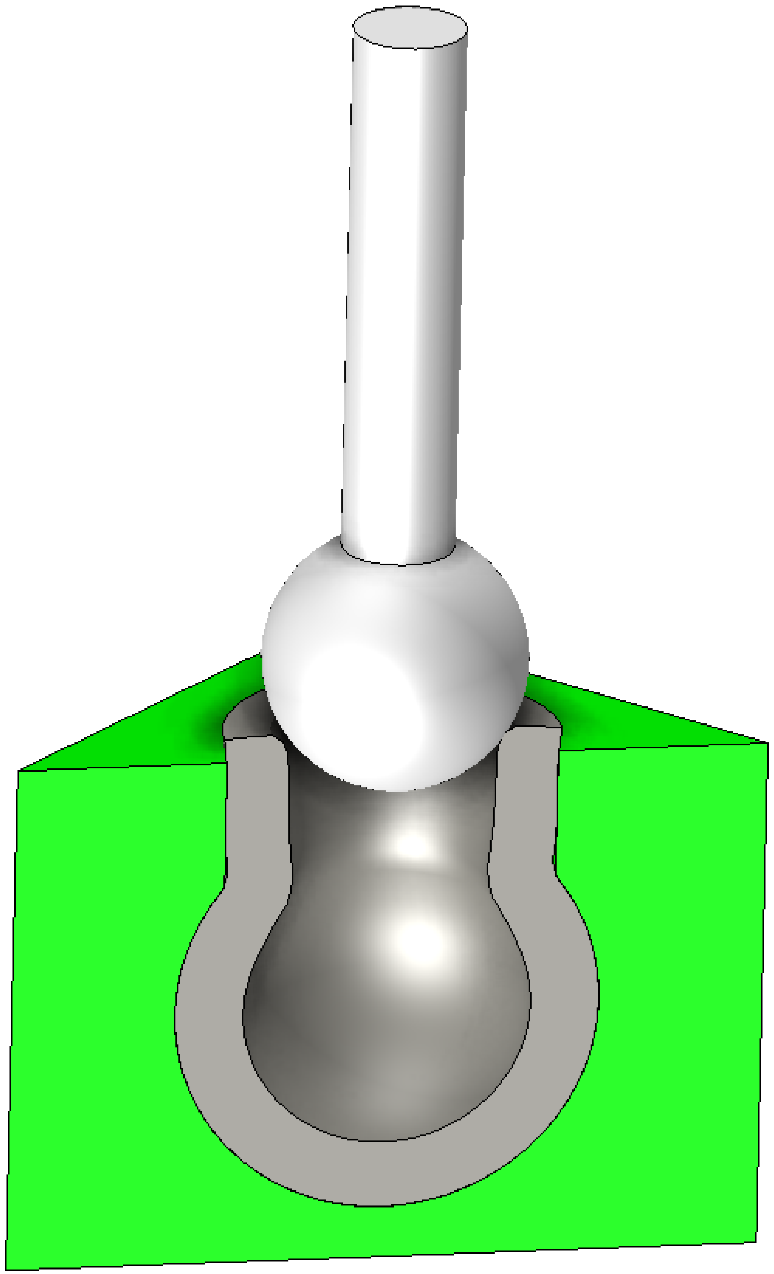
Mechanism

- Rubber, using MAT77, `*MAT_HYPERELASTIC_RUBBER`
  - Approximately corresponding to shore-A 63
- Three stages
  - Press fit of rubber
  - Insert
  - Pull-out



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- Rubber, using MAT77, *MAT_HYPERELASTIC_RUBBER
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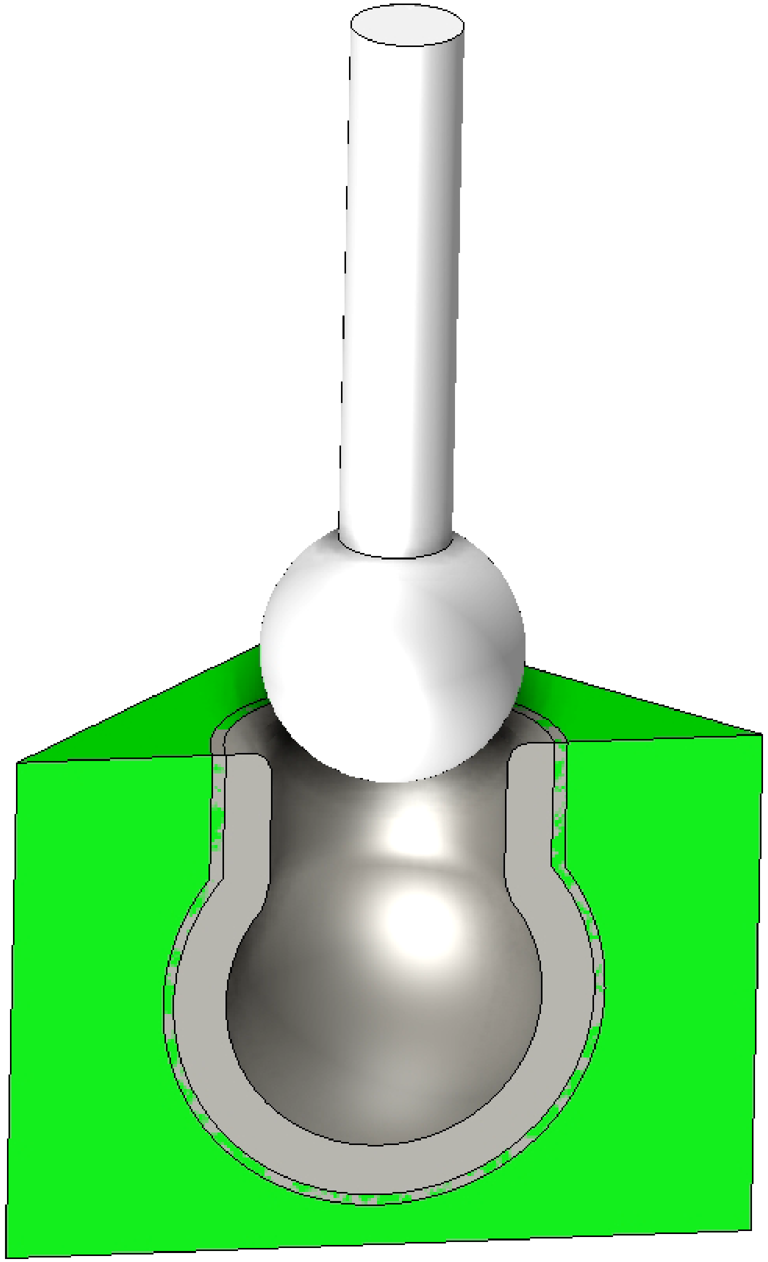
  - Insert
  - Pull-out
- Test of
  - Element formulations, contacts

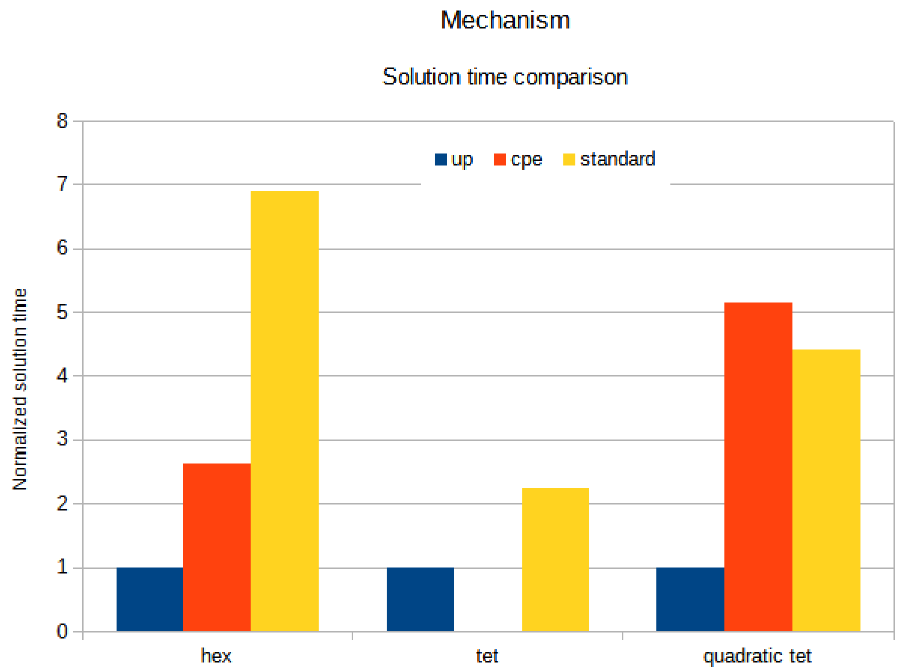


Mechanism

- Study of different element formulations
  - Linear and Quadratic tet and Linear hexa
  - Standard FE, vs. CPE and u-P
- In this case, the u-P elements are more efficient
- Using JFNK for the quadratic tet and u-P element reduces the simulation time by 77%

Relative solution times using MUMPS solver and full Newton

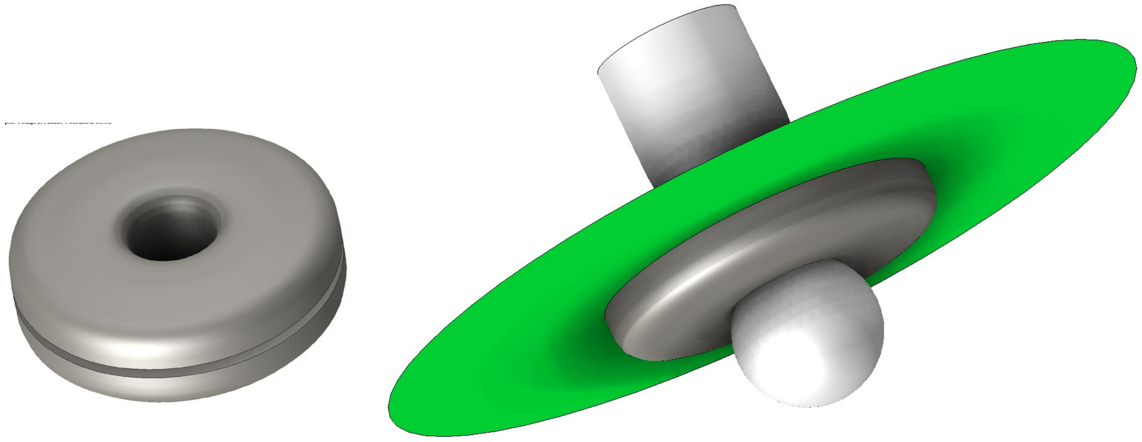
	Standard	CPE	U-P
Linear nodal avg. tet (ef 13)	3.53	N/A	N/A
Linear hex	6.91	2.65	1
Quadratic tet	153	177	35



Rubber donut

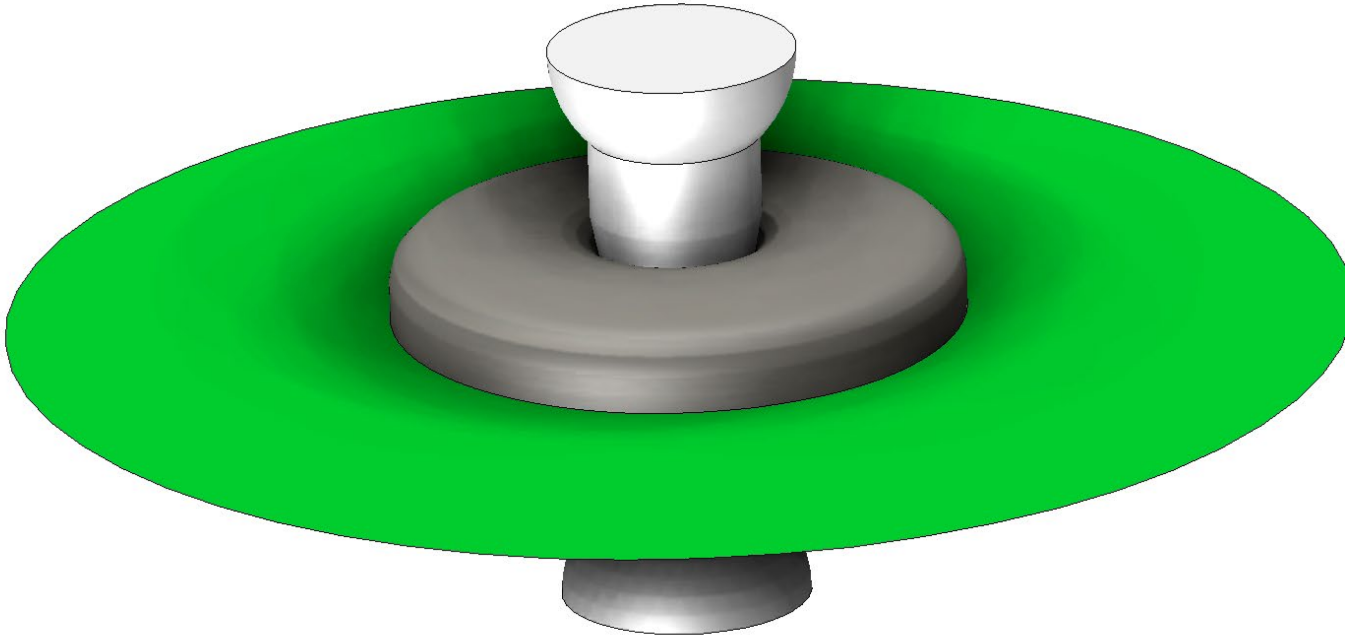
- Rubber, using MAT77, *MAT_HYPERELASTIC_RUBBER
  - C10=0.162, C01=0.041 (“soft”)
  - C10 = 0.427, C01=0.107 (“hard”)
- 10-noded tet u-P elements
- Two stages
  - Pre-loading
  - Pull-out of pin

- Test of
  - Contacts with shells
  - Multistage analysis



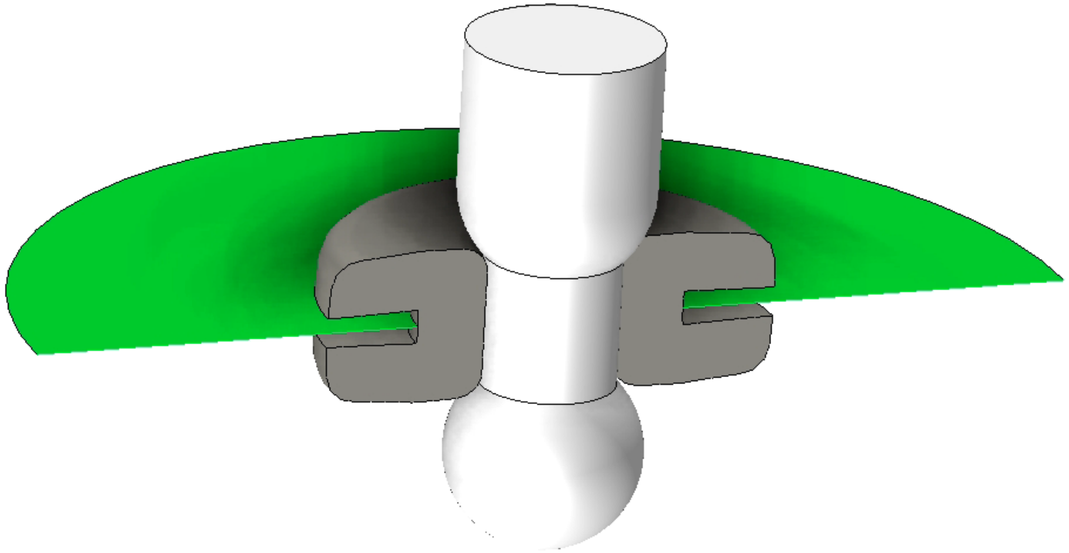
Rubber donut

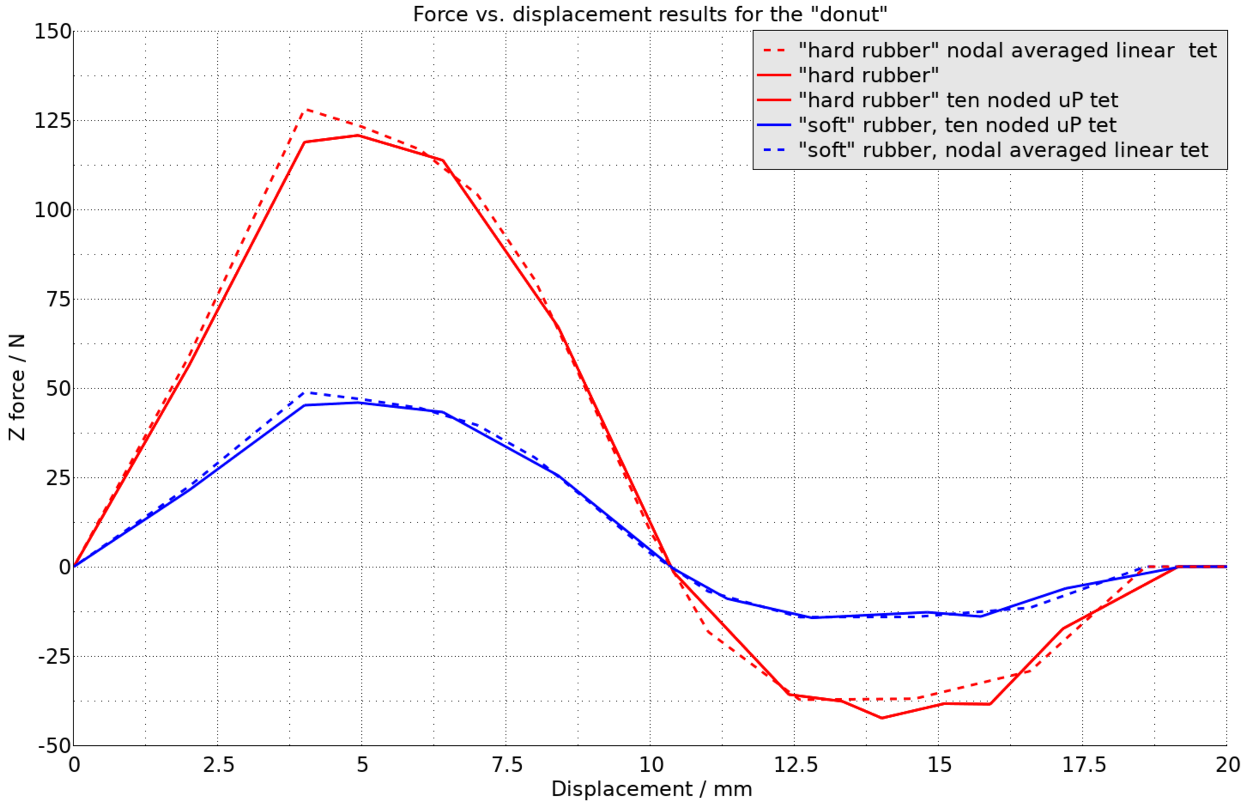
- Stage 1: Pre-load



Rubber donut

- Stage 2: Pullout





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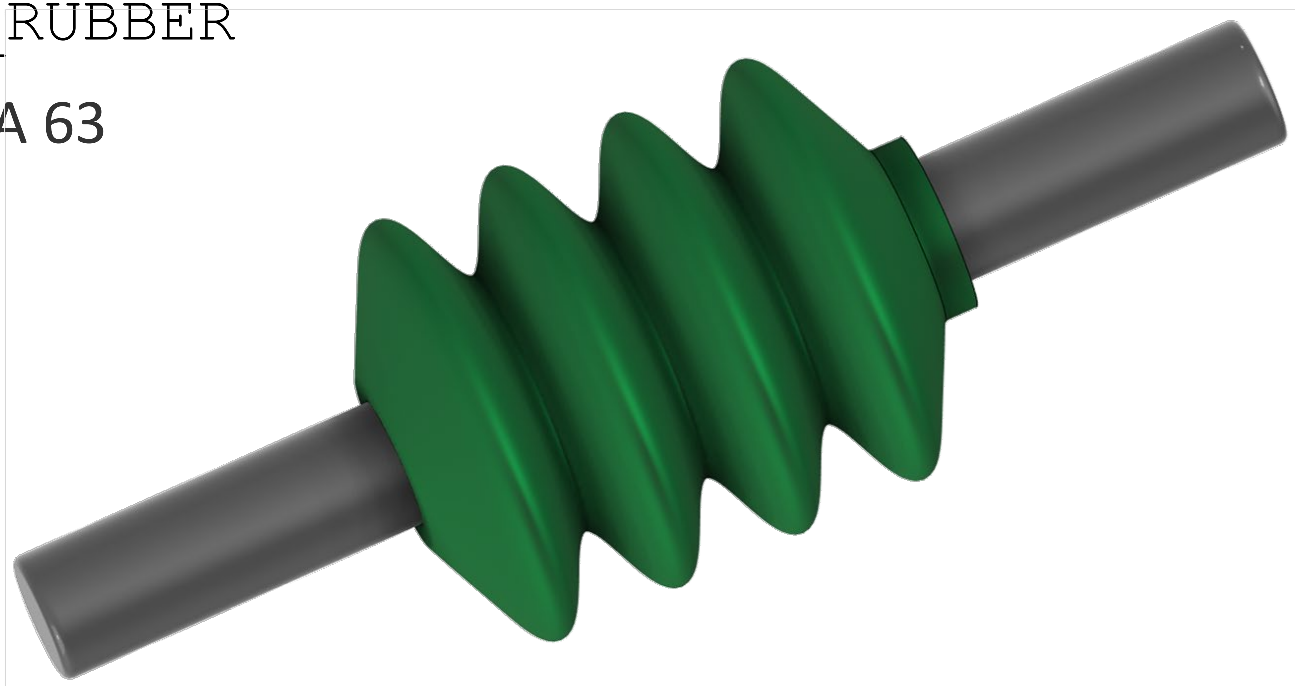
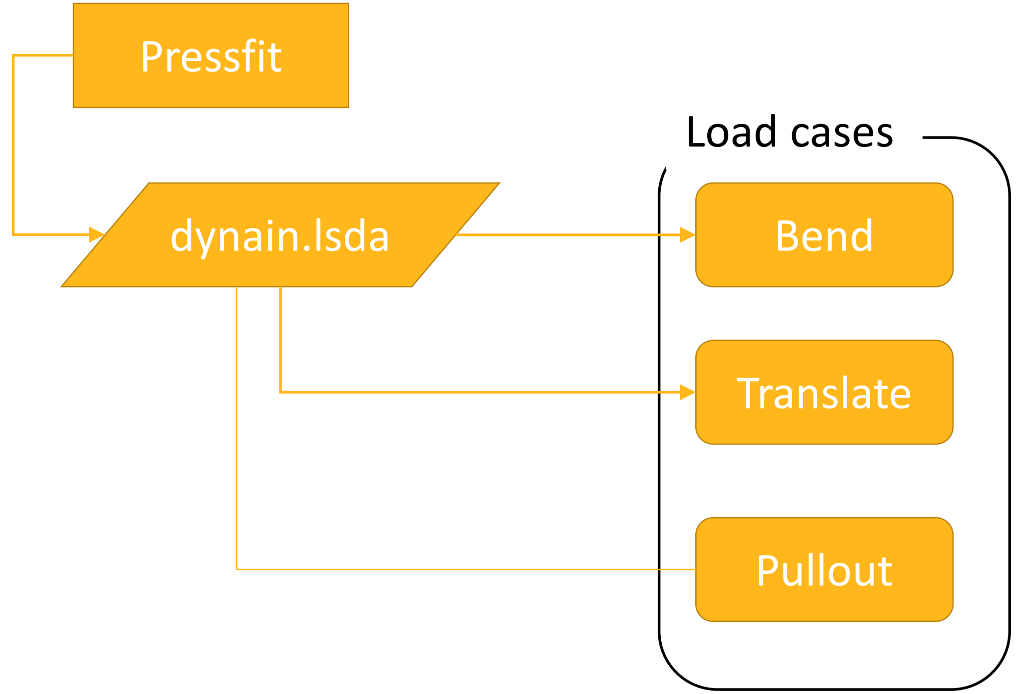
Rubber bellow

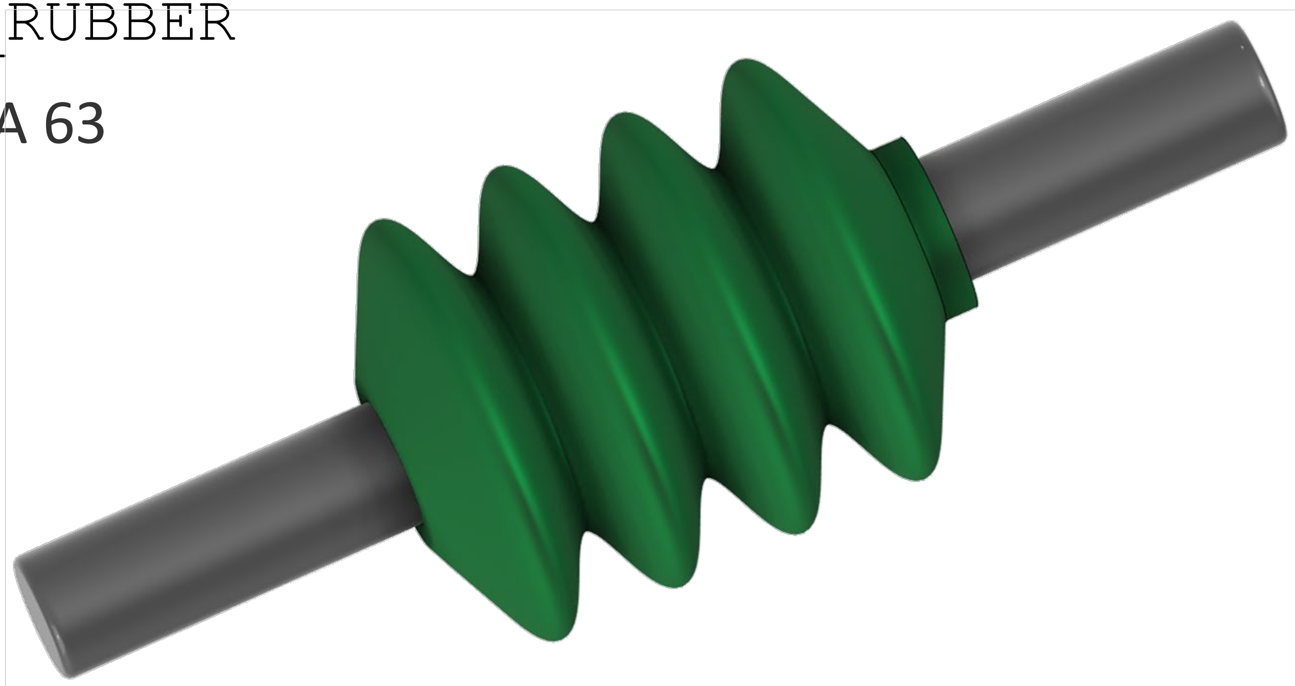
- Using MAT77, *MAT_HYPERELASTIC_RUBBER
  - Approximately corresponding to shore-A 63
- Test of press-fit and large deformation
  - Single surface contact
  - Multistage analysis
- The different load cases
  - Bend
  - Translate
  - Pull-out



Rubber bellow

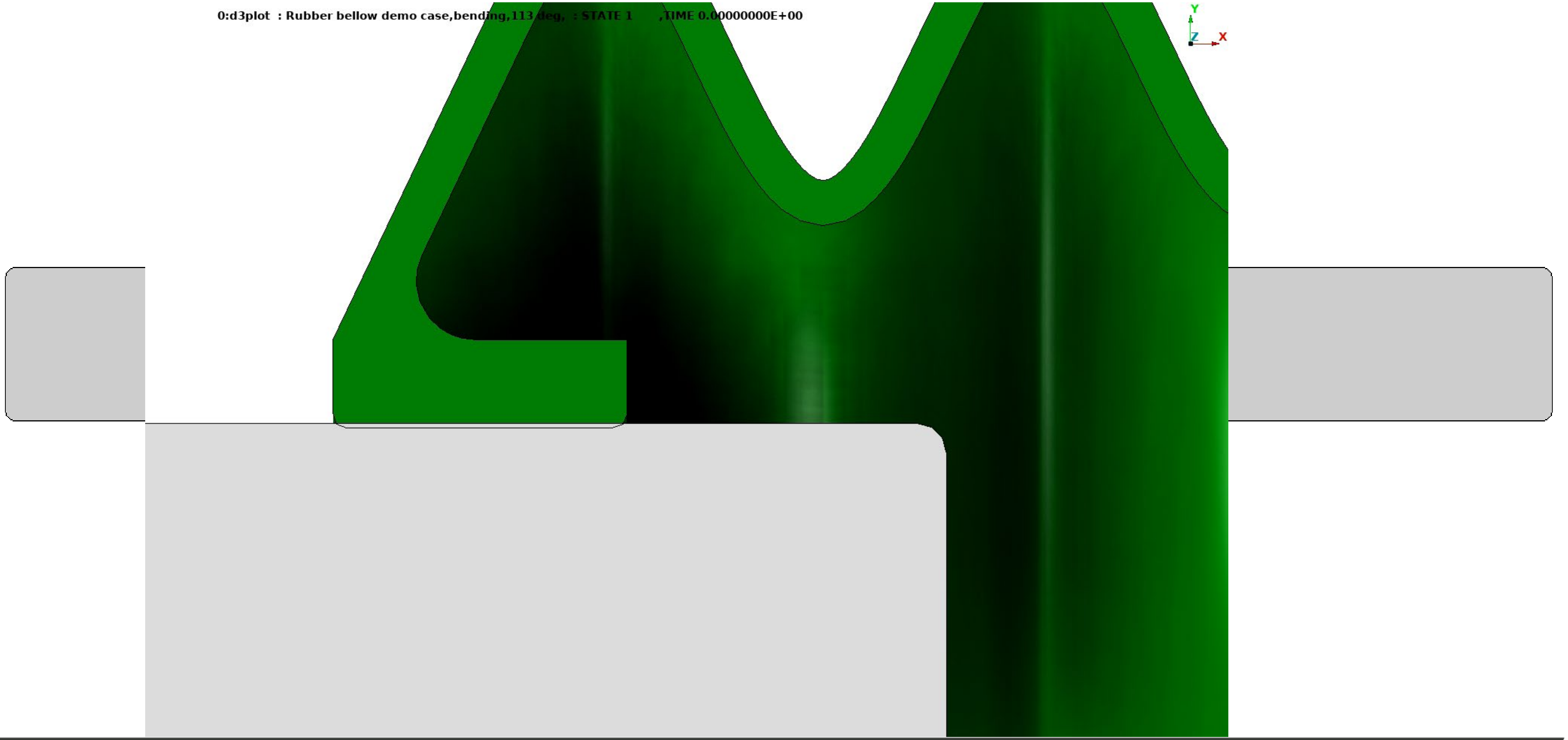
- Using MAT77, *MAT_HYPERELASTIC_RUBBER
  - Approximately corresponding to shore-A 63





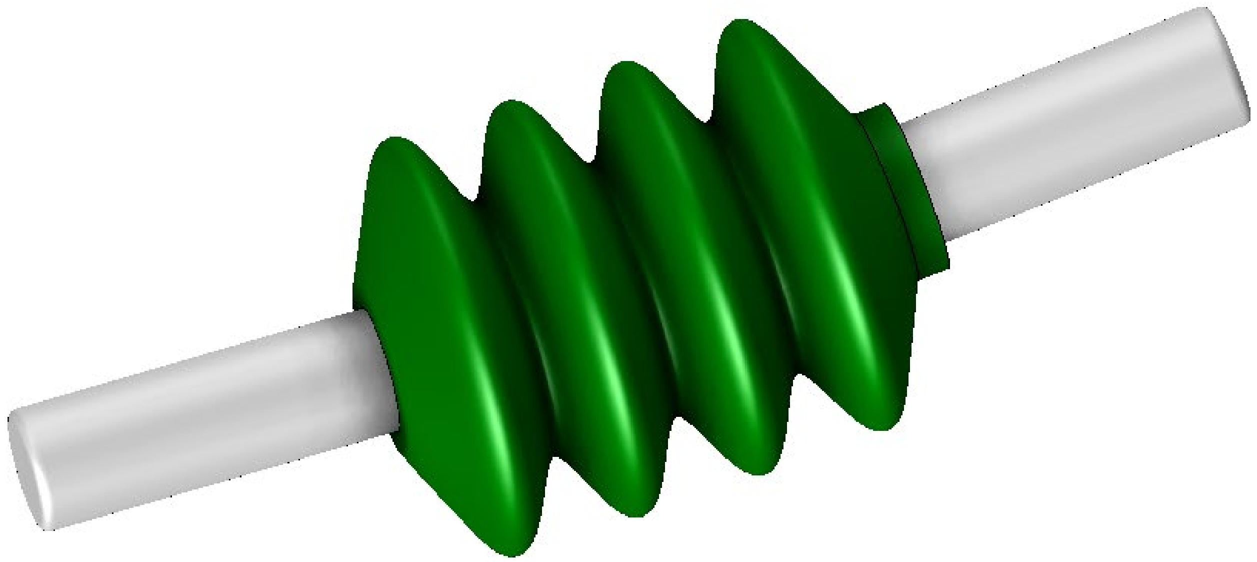
Rubber bellow

- Stage 1: Press-fit



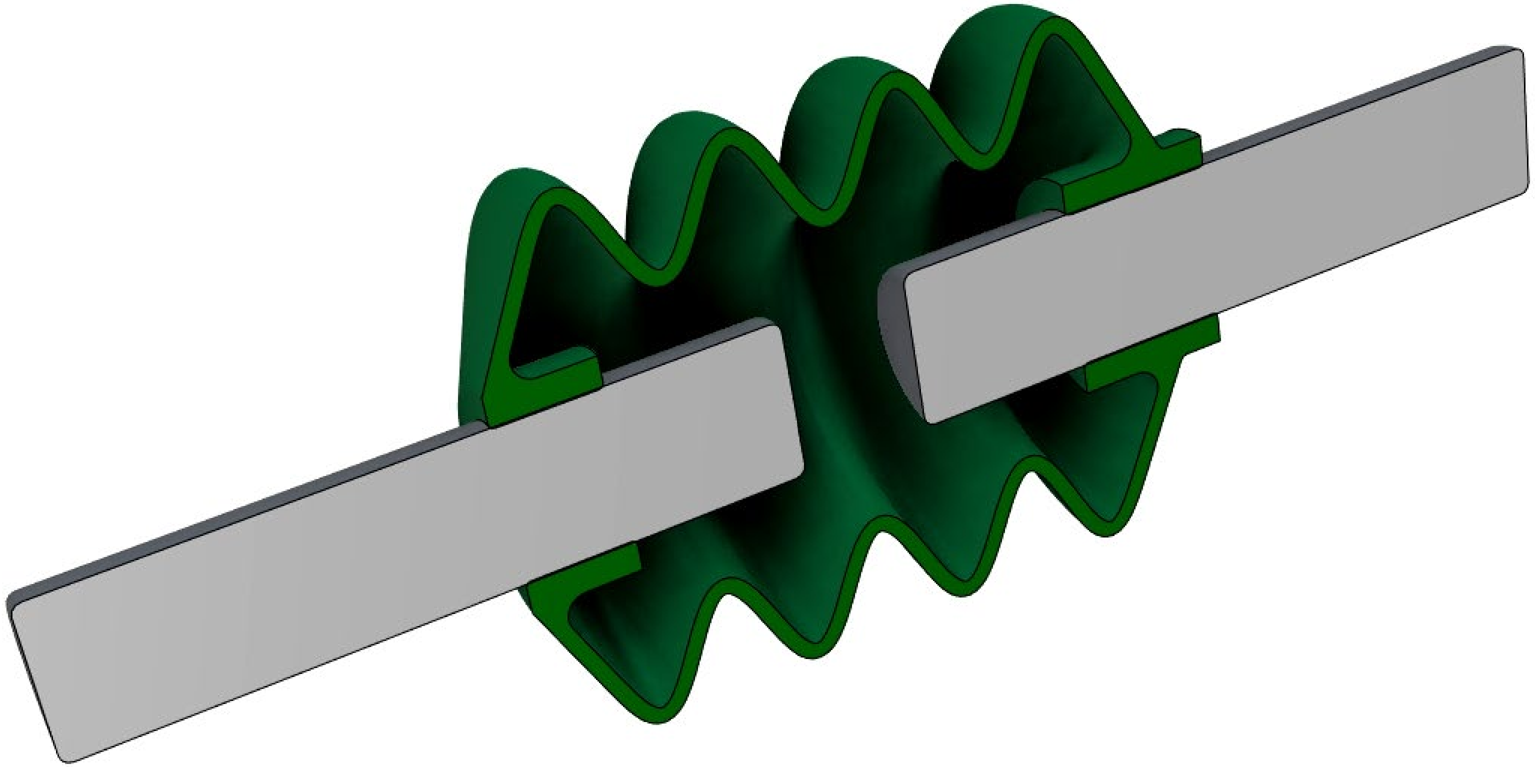
Rubber bellow

- Load case: bend



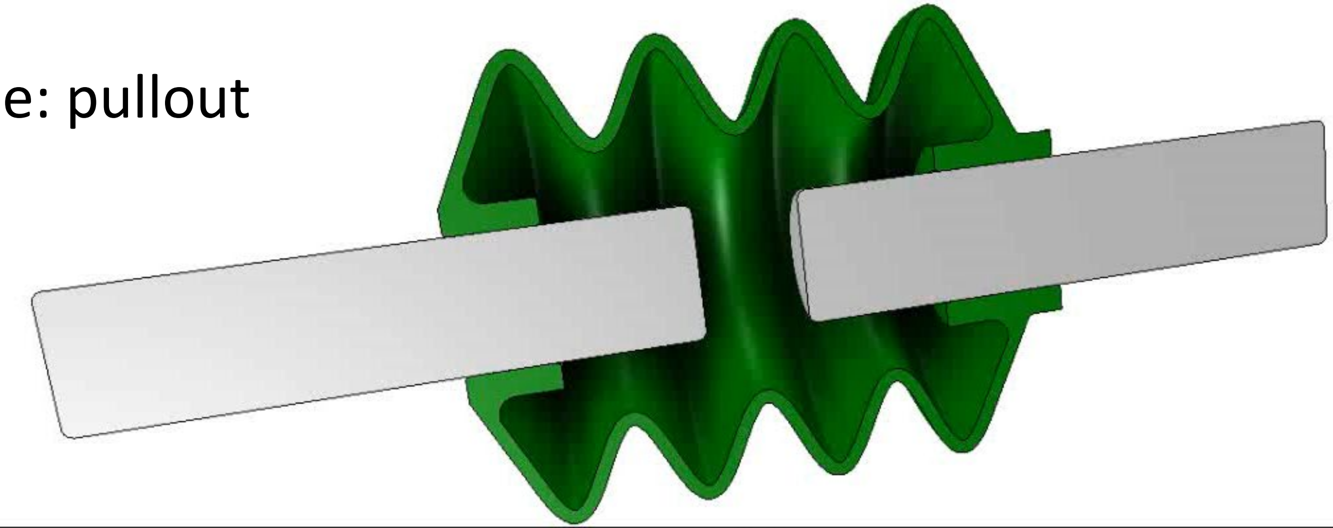
Rubber bellow

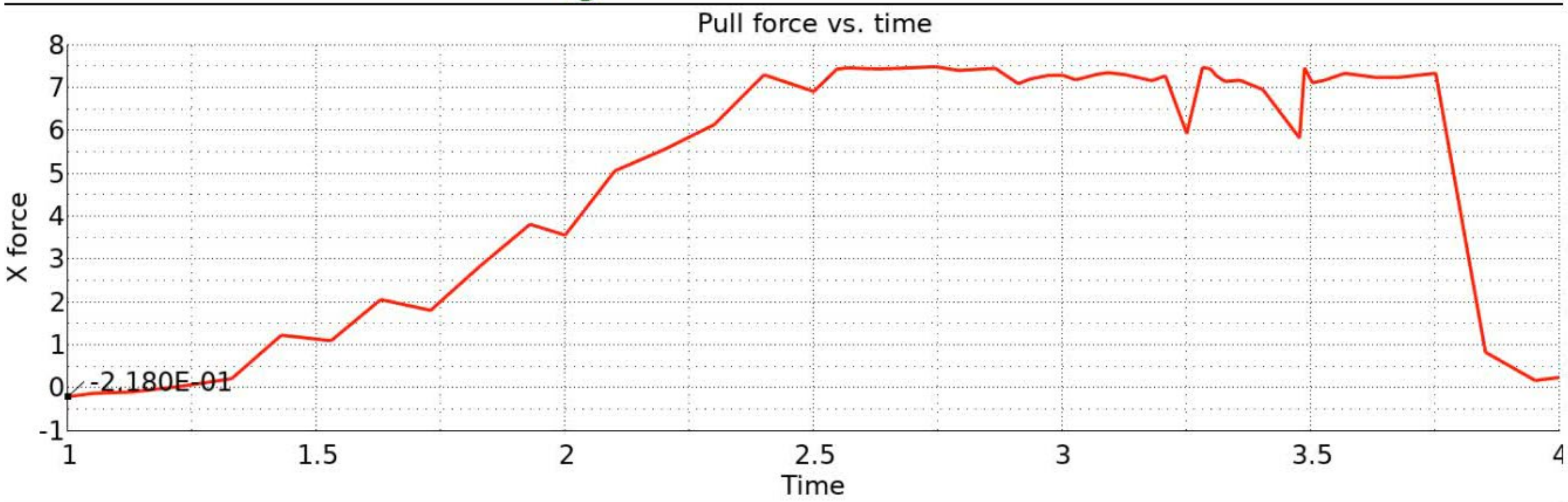
- Load case: translate



Rubber bellow

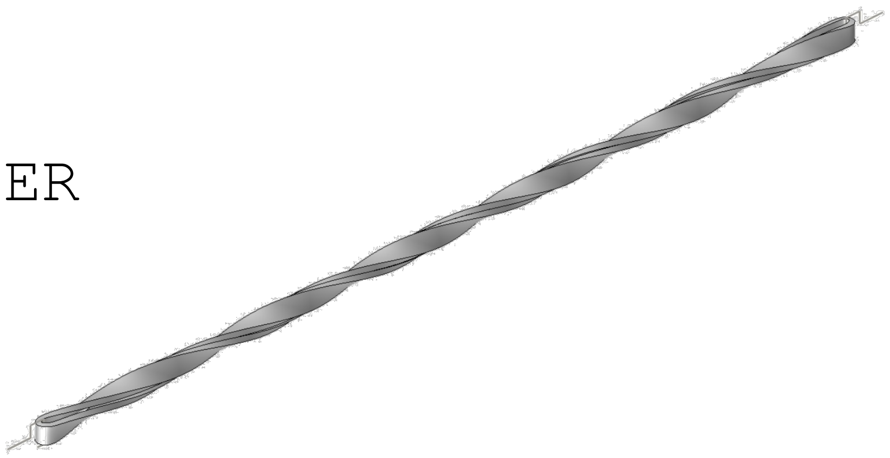
- Load case: pullout

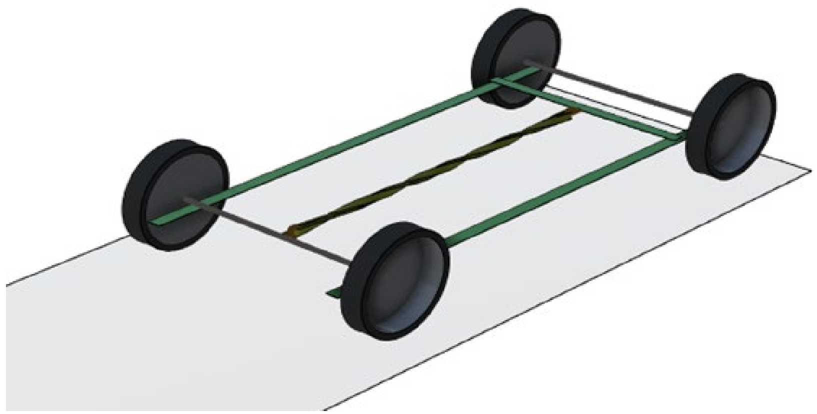




Rubber band

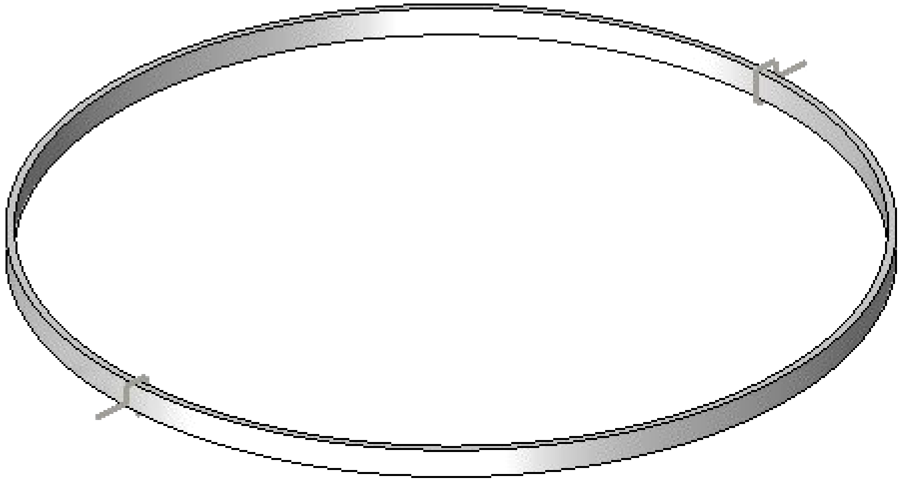
- Using MAT77, *MAT_HYPERELASTIC_RUBBER
- Test of
  - Single surface contact
  - Multistage analysis
- Two different load cases
  - Twist the band
  - Roll a car





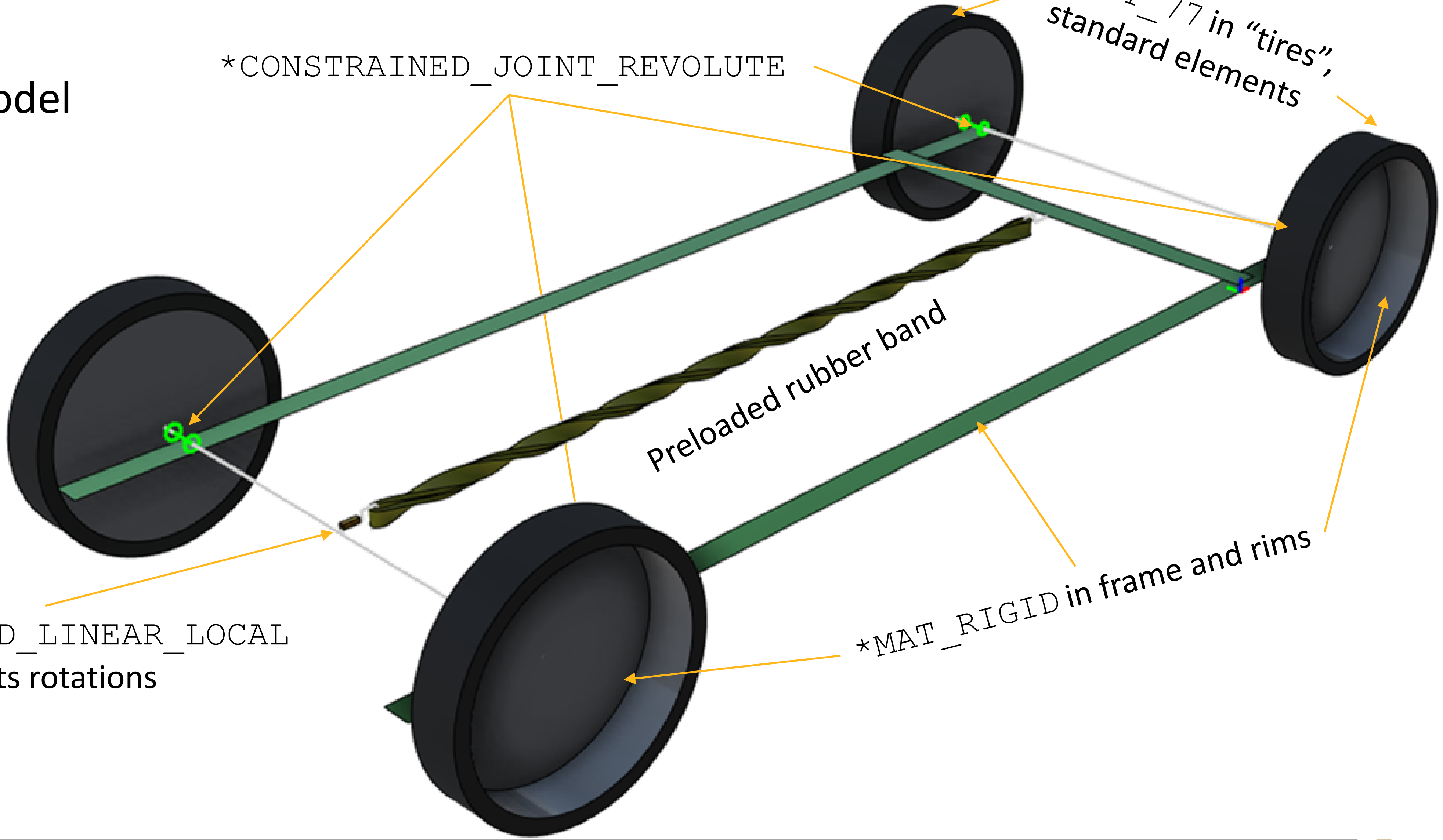
Rubber band

- Twisting of the band
  - Multistage analysis
  - One revolution at a time
  - Final state passed on as dynain.lsda
- Using standard BFGS settings
- Manages 8.5 twists before convergence failure



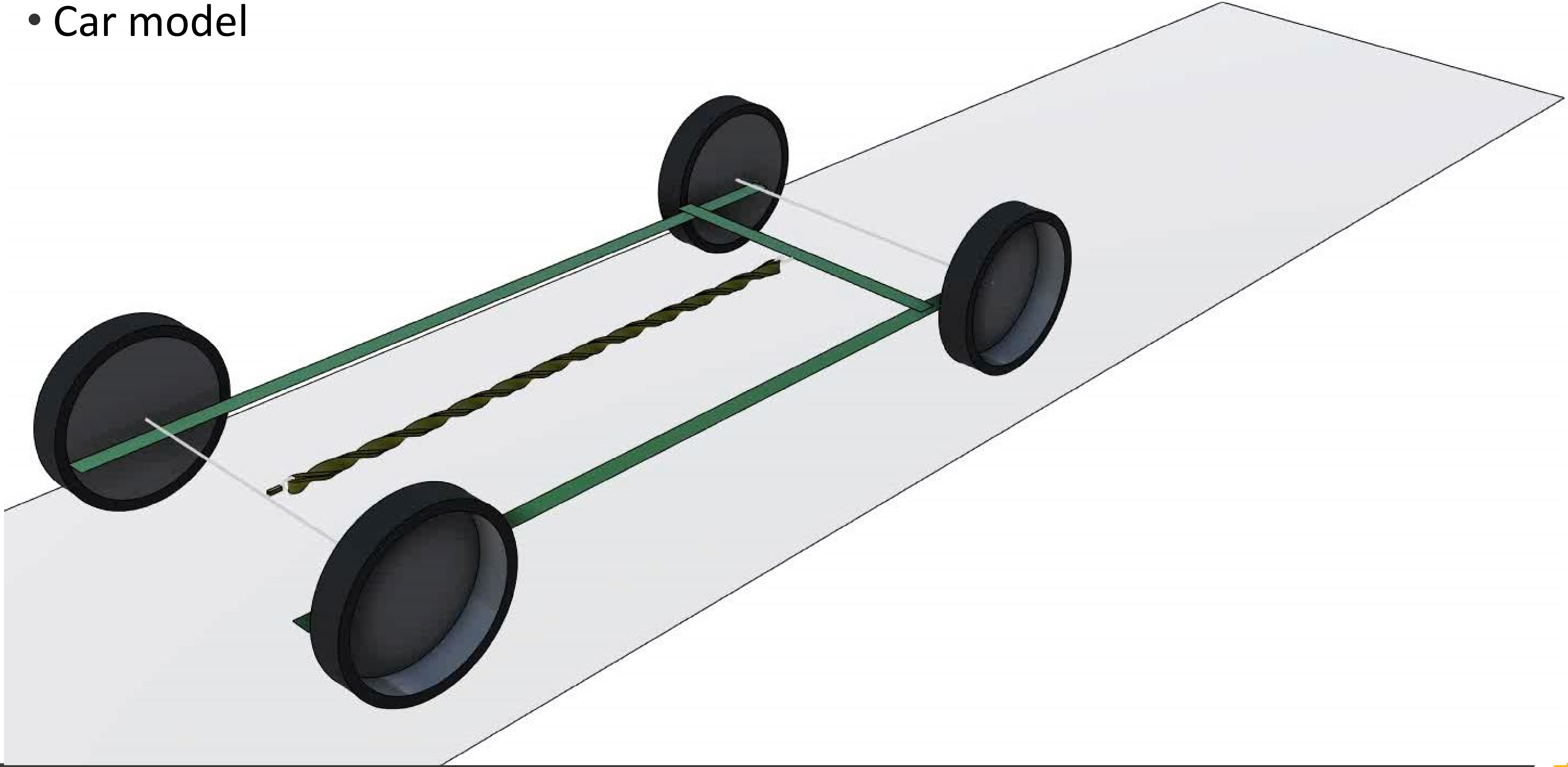
Rubber band

- Car model



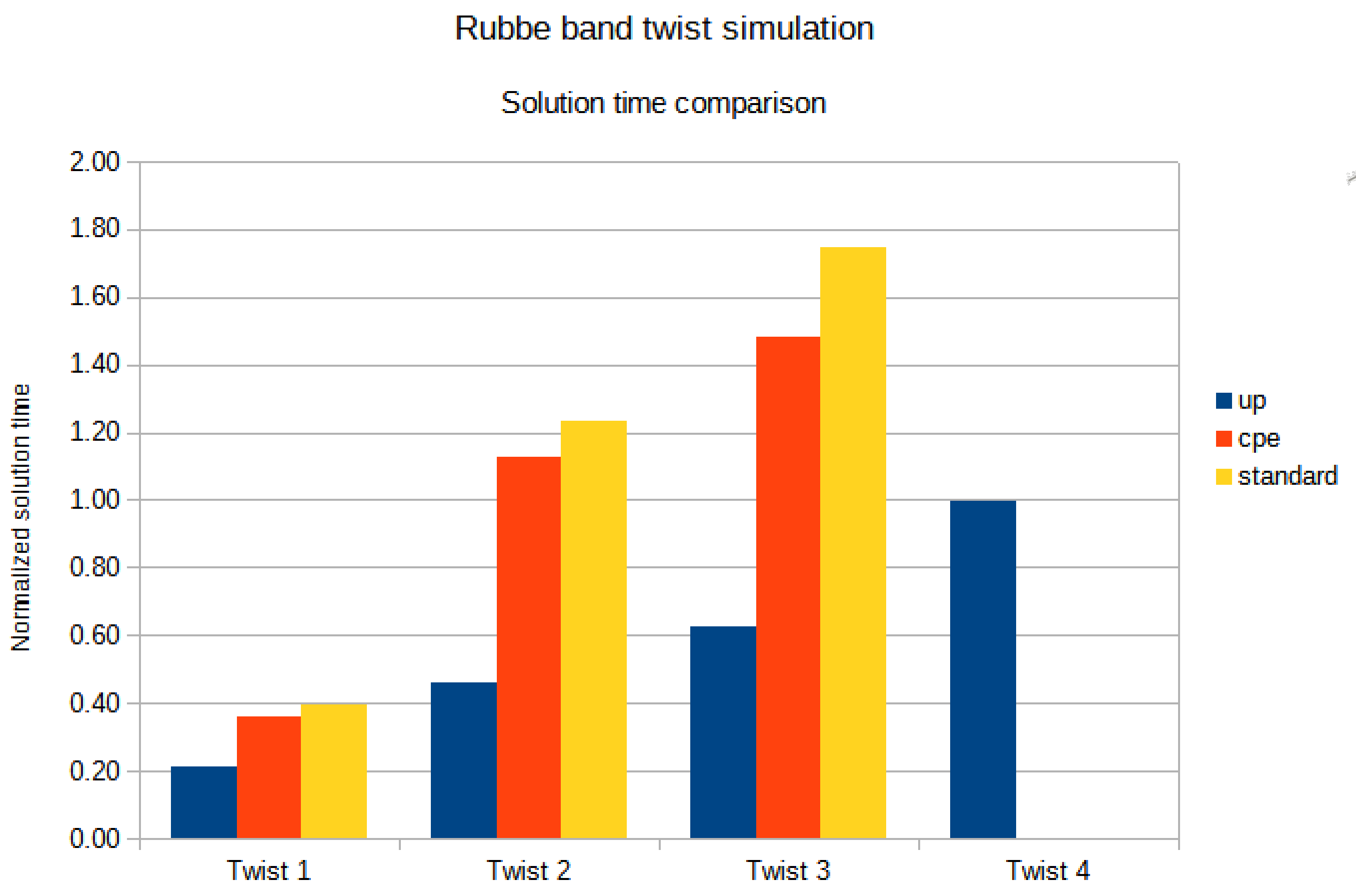
Rubber band

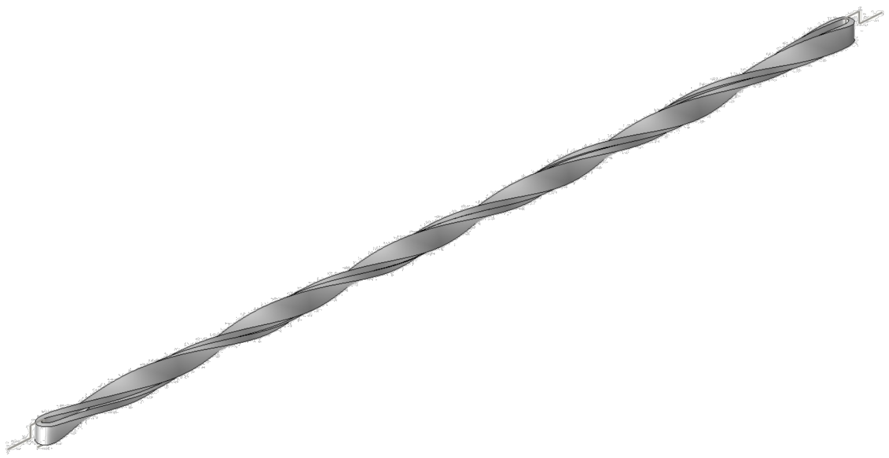
- Car model

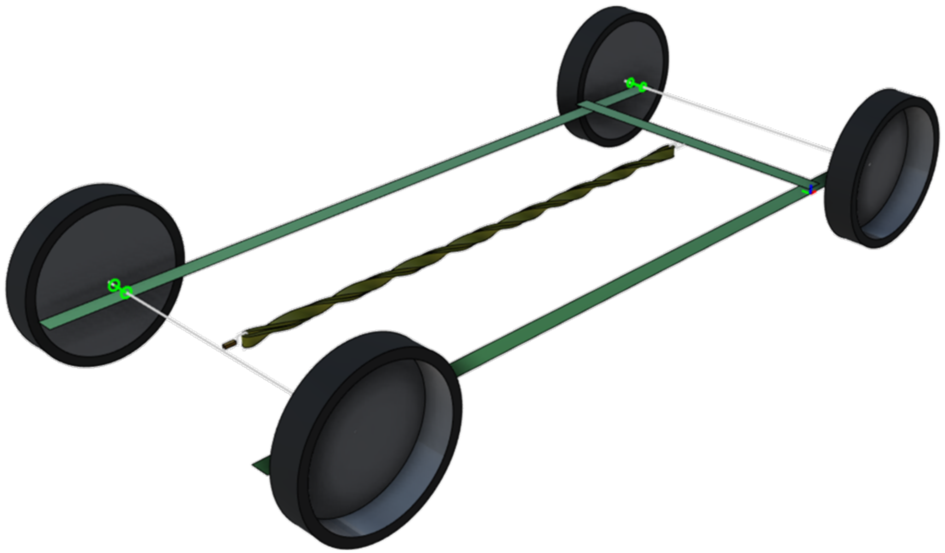


Rubber band

- Performance comparison







Rubber band

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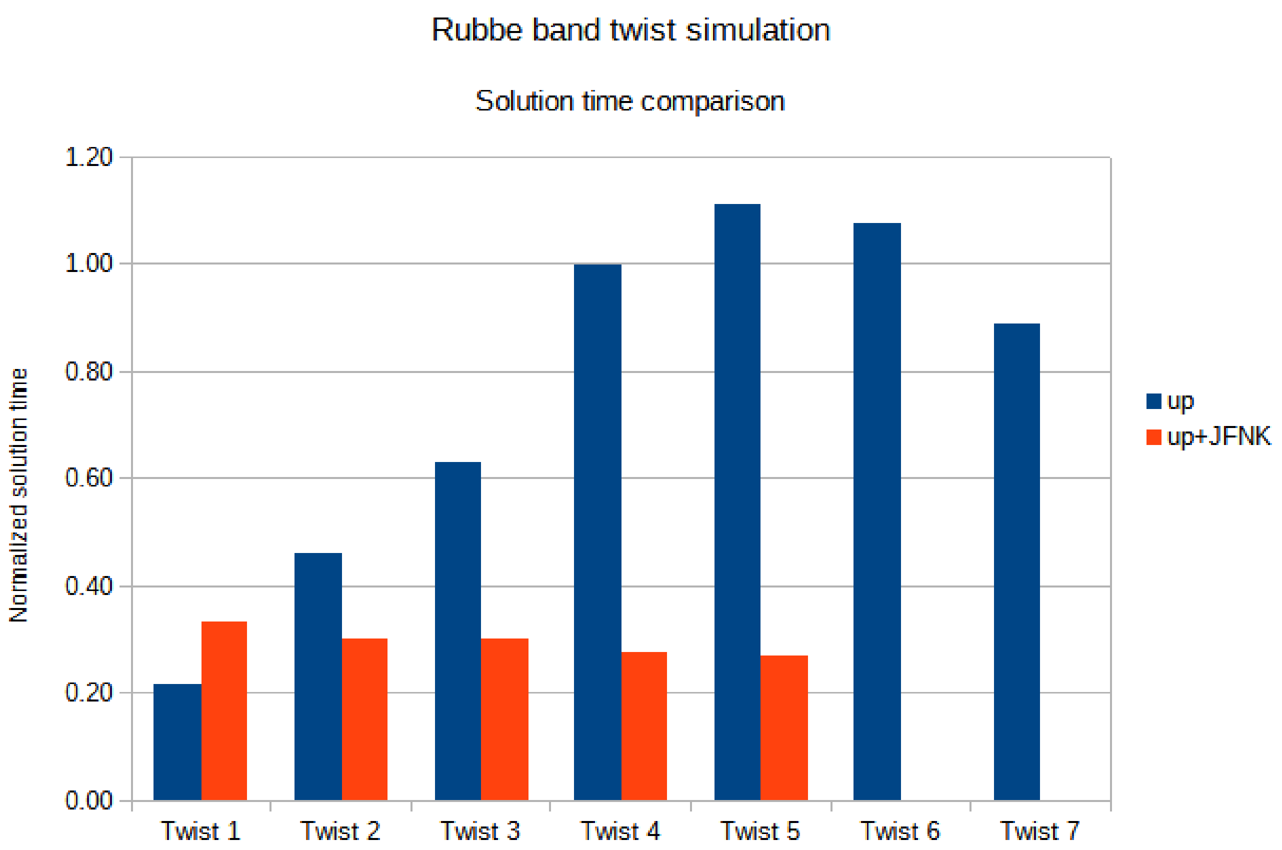
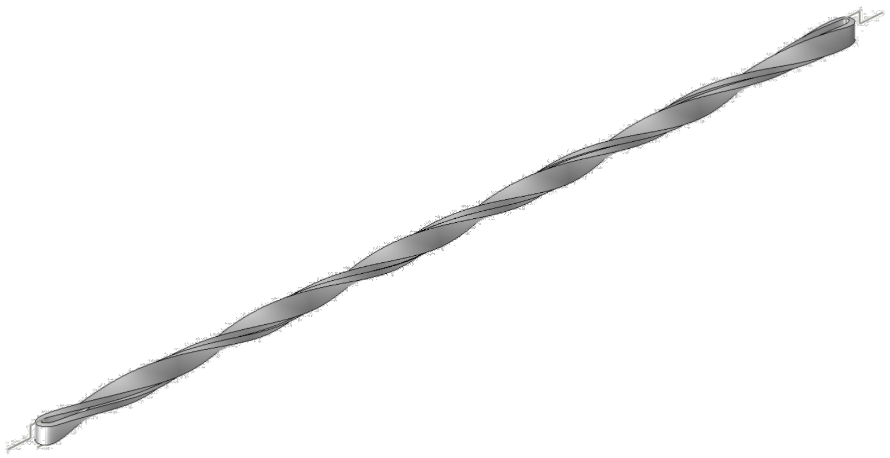
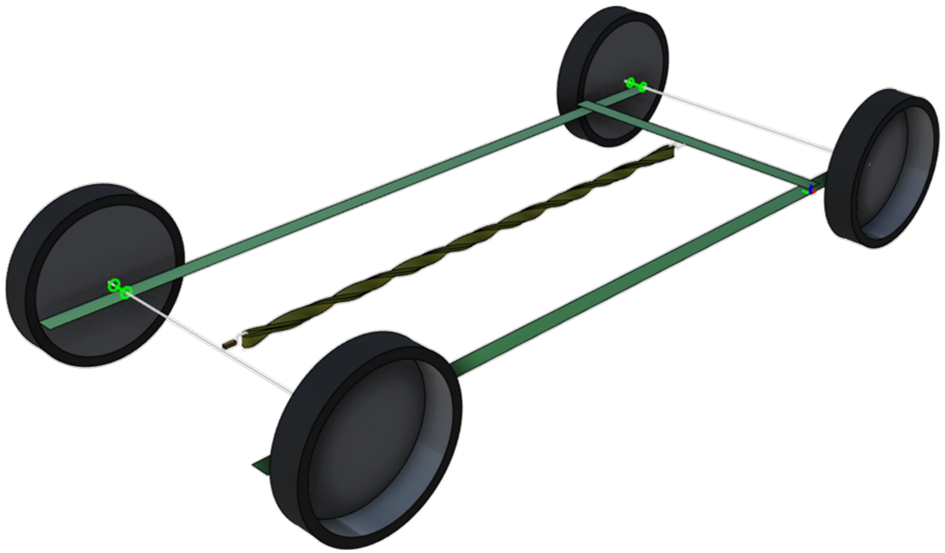
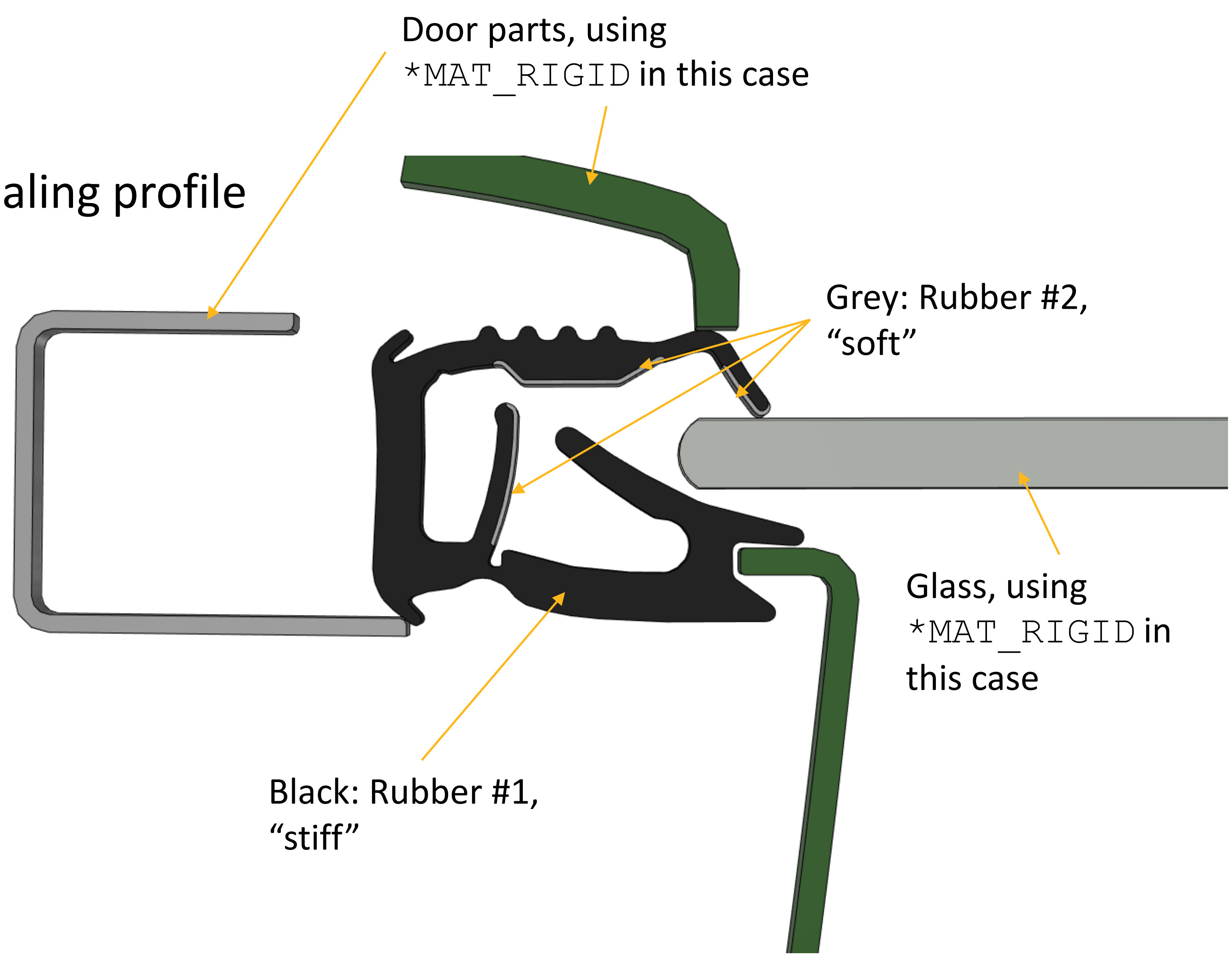






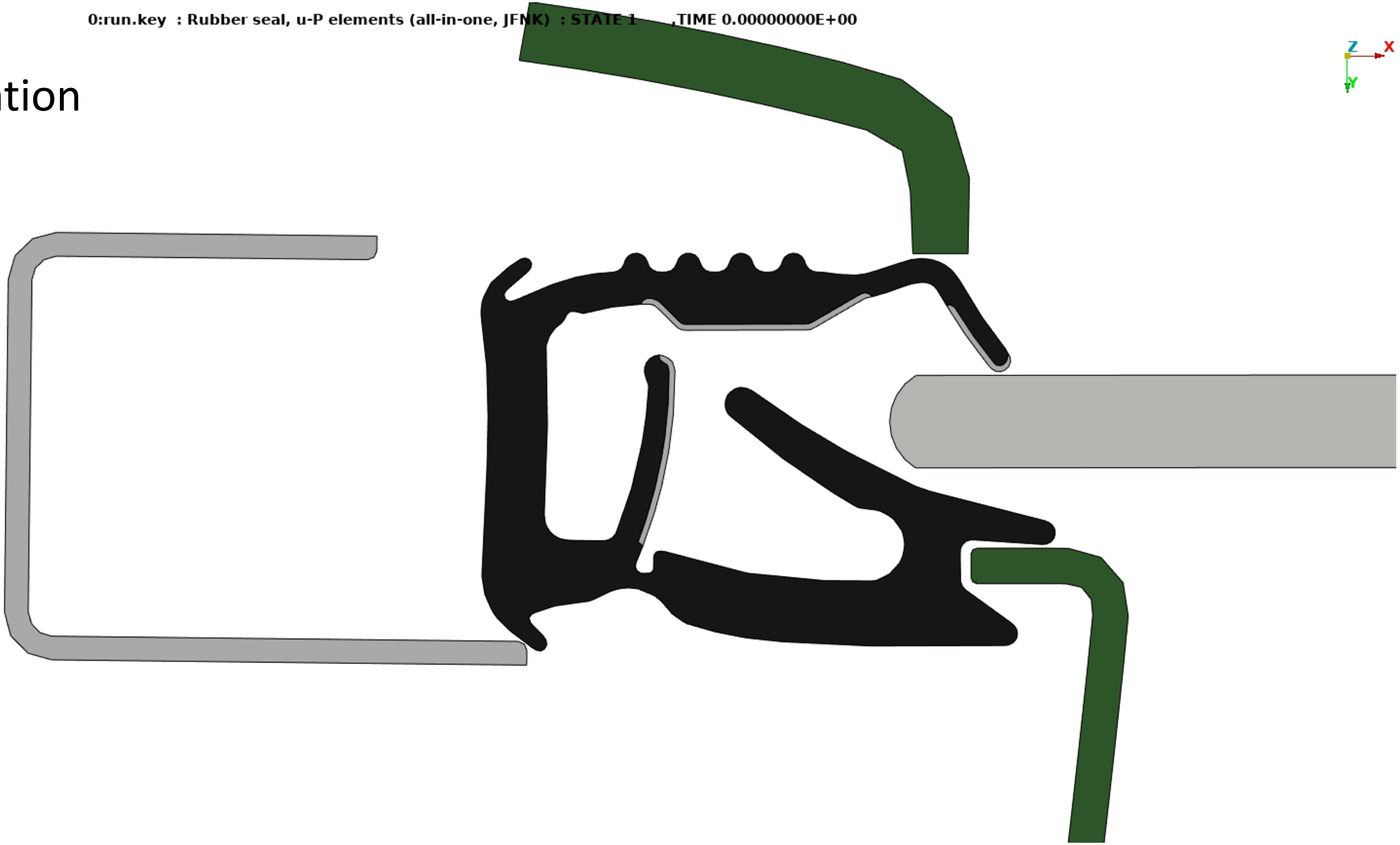
Window sealing

- Simulate testing of a window sealing profile
  - Quasi 2D - model
  - Single surface contact



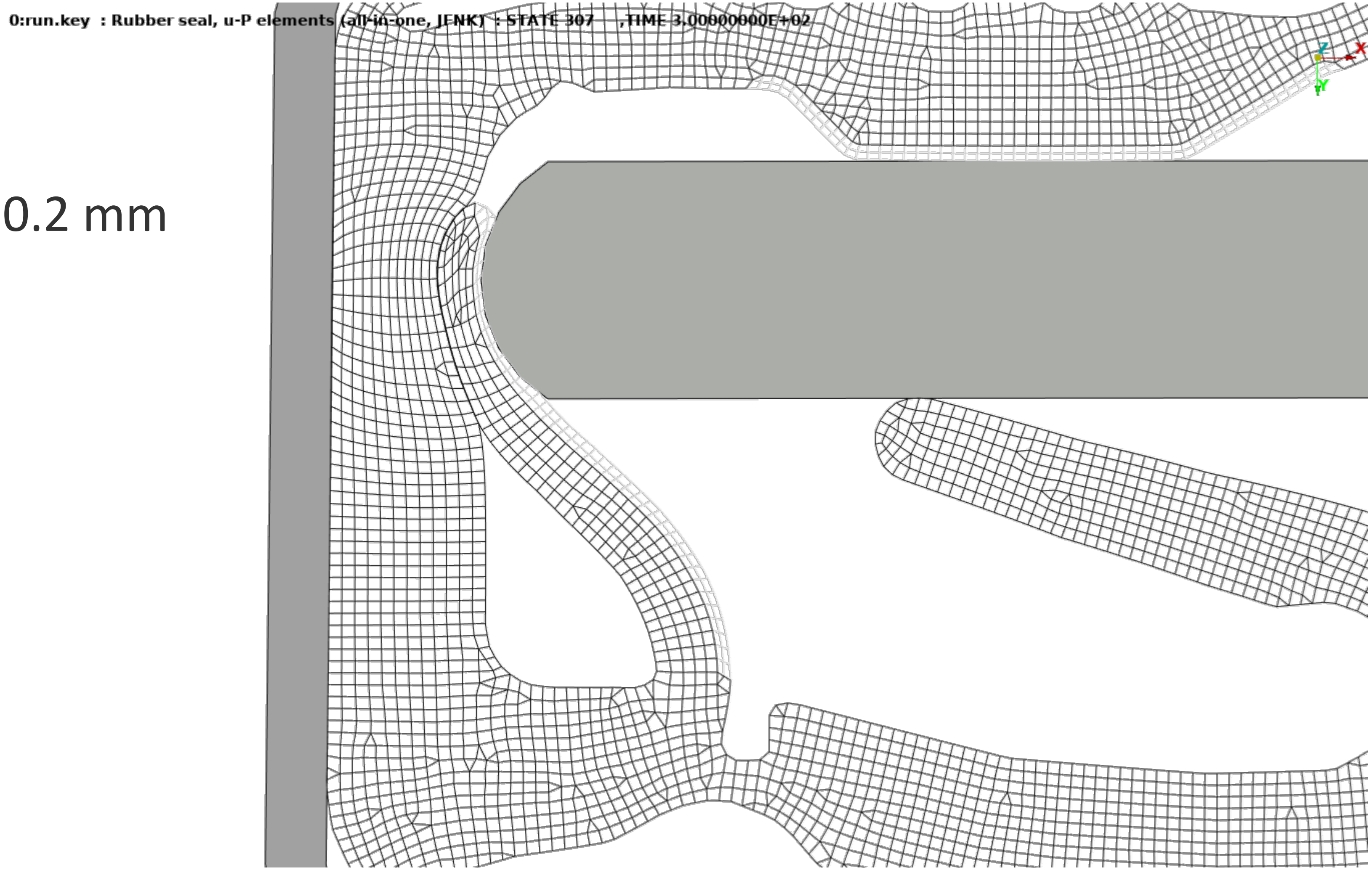
Window sealing

- Deformation



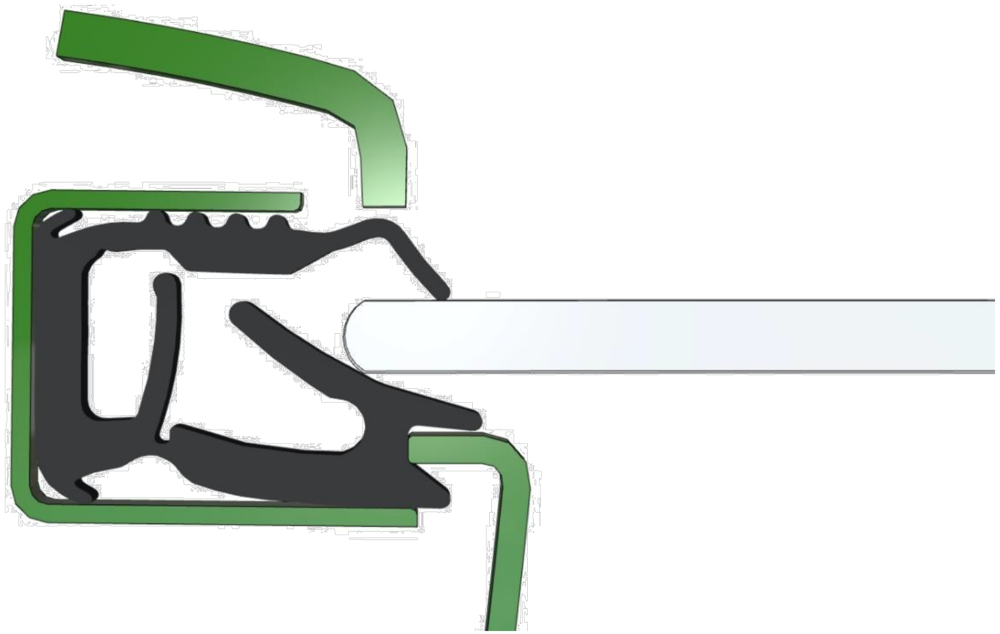
Window sealing

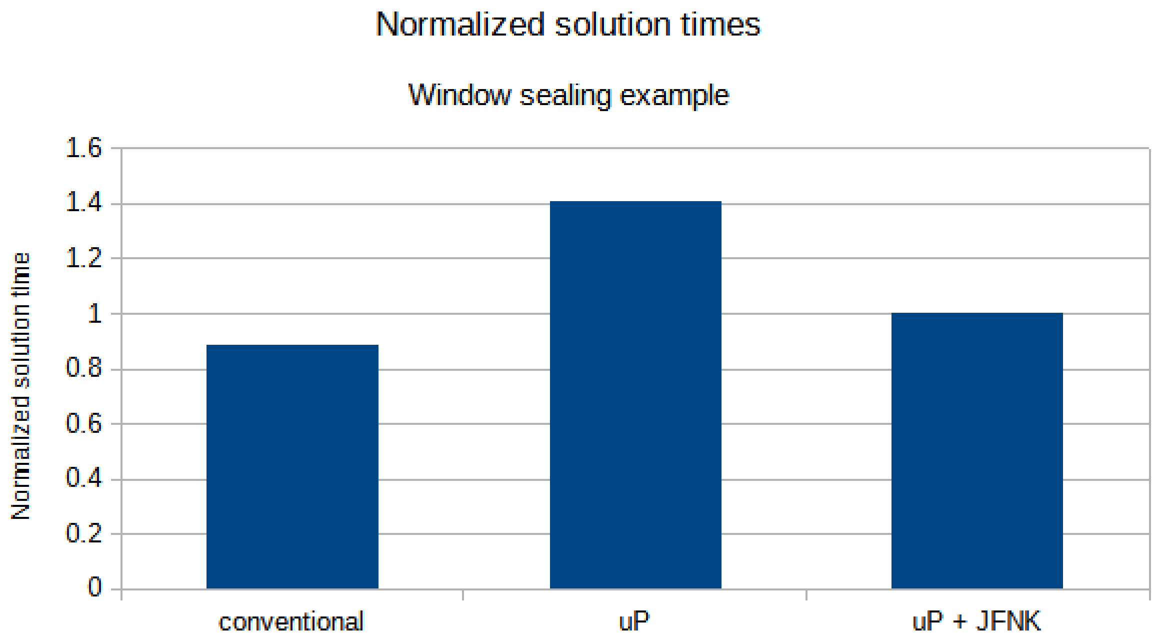
- Deformation
  - High mesh resolution,
    element length in rubber: 0.2 mm



Window sealing

- Test of a window sealing profile





Summary and outlook

- Mixed displacement – pressure elements have been implemented for incompressible hyperelastic materials.
  - Solid elforms 2, 15, 10 and 16
  - MAT27 and 77
- Tested for several non-trivial examples with promising results
- The JFNK Non-linear solution scheme shows a great potential for reducing solution time
- Further possible developments
  - Axi-symmetric solids
  - Support more materials
  - Further studies on implicit/explicit switching using u-P elements