Tips and tricks for successful implicit analyses with LS-DYNA

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Introduction

Explicit vs. Implicit

Explicit: $\mathbf{x}_{n+1} = \mathbf{f}(\mathbf{x}_n, \ldots)$

$$\mathbf{M}\mathbf{a}_n = \mathbf{f}_n^{ext} - \mathbf{f}_n^{\text{int}}$$

+ solution: directly
+ decoupled: efficient, fast
- many small time steps
- conditionally stable (Courant)

equilibrium? energy balance!

short time dynamics:
high frequency response,
wave propagation

➡ impact, crash, ...

Implicit: $\mathbf{f}(\mathbf{x}_{n+1}, \mathbf{x}_n, \ldots) = \mathbf{0}$

$$\mathbf{M}\Delta\mathbf{a}_{n+1} + \mathbf{K}\Delta\mathbf{u}_{n+1} = \mathbf{f}_{n+1}^{ext} - \mathbf{f}_n^{\text{int}} - \mathbf{M}\mathbf{a}_n$$

- solution: iteratively
- linearization necessary
+ few large time/load steps
+ unconditionally stable

equilibrium! **convergence?**

structural dynamics:
low frequency response,
vibration, oscillation

➡ earthquake, machines, ...

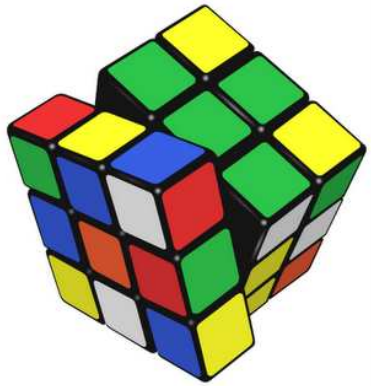
Explicit vs. Implicit

- Explicit inevitably includes inertial effects and resolves high frequencies whether you want it or not
- Implicit can neglect inertial effects and the selected time step size determines the resolved frequency spectrum

Consequences for FE models

- "cleaner" models in implicit for the sake of convergence,
  e.g. no initial penetrations, smooth material curves, contact, accuracy, …
- expensive features are not so expensive anymore
- no resctriction on element size (time step size) in implicit
- often more work to get "normal termination" in implicit

"Explicit is handcraft - implicit is skill"



Troubleshooting convergence problems

Convergence behavior is depending on the physics of the problem

- difference in physics → different method(s) for solving convergence issues

Possible reasons for convergence problems

Mesh

- Coarse meshes may result in poor element geometry and bad contact behavior

Time/load step size

- The applied load/displacement etc. in a single step may be too large or small

Rigid body motions

- Unconstrained d.o.f. due to missing BC/SPC, initial contact gaps, beams, …

Contact

- Initial penetrations, too large step sizes, large forces, …

Material properties

- “rough“ data, softening properties, discontinuities in curves, incompressibility, …

Recommendations

Use double precision of the code (_d_ in the name)

- required for accurate linear analysis
- improved convergence behavior in nonlinear analysis

Use the most recent LS-DYNA version possible (e.g. R9 beta)

implicit functionality is rapidly improving

Use command line option "memory=" to run job in-core

Verify using LPRINT=1 on *CONTROL_IMPLICIT_SOLVER or "<ctrl-c> lprint". The CPU penalty for out-of-core can be as high as 100 times the in-core simulation!!

Read Appendix P in the User’s manual and Chapter 37 of the latest draft version of the Theory Manual

Nice summary about LS-DYNA‘s Implicit Solver

Recommendations

Element types

- for solids use type 1, -1, -2, 13, or 16 elements for non-linear analysis
- for shells use type 6, 16, or -16 elements for non-linear analysis
- try to avoid pentahedral solid elements

Contact

- try to avoid initial penetrations or try IGNORE=1
- use press-fit option (IGNORE=3/4) for intended initial penetrations
- switch contacts to tied (temporarily) in order to identify problems
- use Mortar contacts or try IGAP=2
- decrease contact stiffnesses, observe penetrations
- contact often requires small time steps in implicit, too
- make sure that finer mesh is slave side
- turn off viscous damping with **VDC=0.0**

Recommendations

General

- apply 2nd order stress update by setting **OSU=1** (*CONTROL_ACCURACY)
- try to model displacement driven simulation instead of force driven simulation
- try to use IGS=1 (not default) on *CONTROL_IMPLICIT_GENERAL in case of convergence problems
- set **DNORM=1** on *CONTROL_IMPLICIT_SOLUTION,
  displacement tolerance can often be increased in that case, e.g. DCTOL=0.005
- try ABSTOL=1.e-20 on *CONTROL_SOLUTION to improve accuracy
- Sometimes Full Newton (ILIMIT=1) improves convergence
- often dynamic solution more robust than static solution

  → if static implicit fails to converge, try dynamic implicit
- try to avoid discontinuities, e.g. in material curves, geometry, ...
- use new accuracy option **IACC=1** on*CONTROL_ACCURACY (R9)

Guidelines

*CONTROL_ACCURACY

Card 1	1	2	3	4	5	6	7	8
Variable	OSU	INN	PIDOSU	IACC				
Type	I	I	I	I				
Default	1	2	0	0				

Implicit accuracy option IACC=1

- Higher accuracy in selected material models
  - Fully iterative plasticity, tightened tolerances
- Strong objectivity and consistency in selected tied contacts
  - Physical (only ties to degrees of freedoms that are ”real”)
  - Finite rotation
- Strong objectivity and increased accuracy in selected elements
  - Finite rotation support for hypoelasticity

In line with the general philospophy ”Increased accuracy implies better convergence”

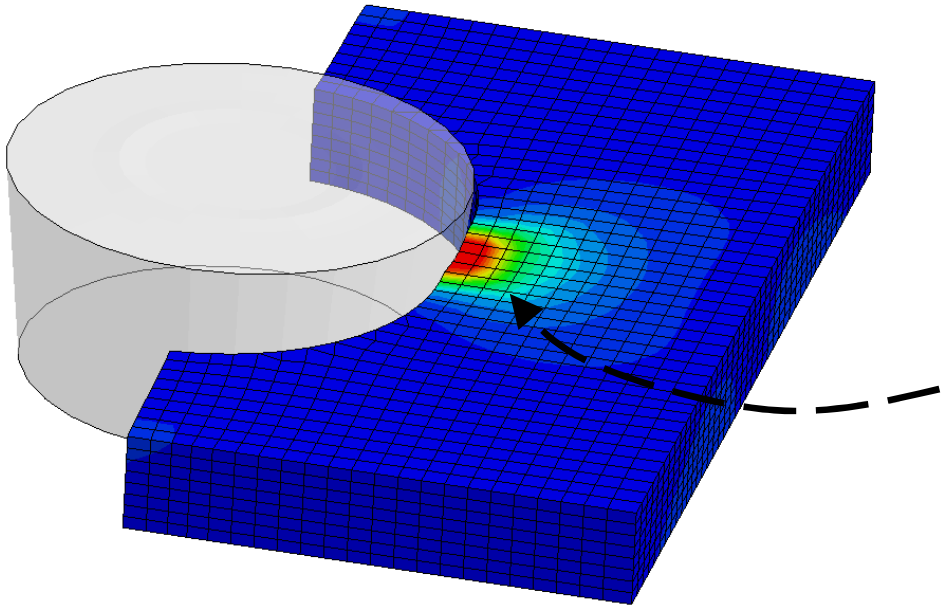
Guidelines

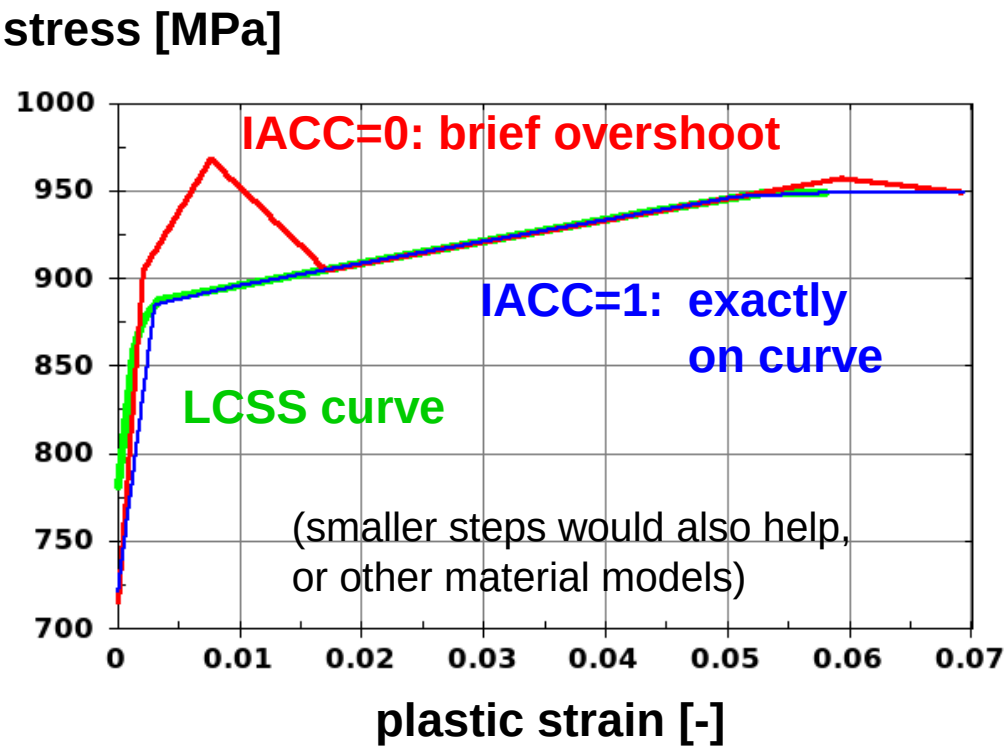
“Use new accuracy option IACC=1 on *CONTROL_ACCURACY”

Example: Plastic deformation of metal part

```
*MAT_024 with LCSS, DNORM=1, ENDTIM=0.014, DTMAX=0.001
```

New implicit accuracy flag for *MAT_024, *MAT_123, tied contacts, shell elements, … starting from release R9, see draft version of Keyword Manual



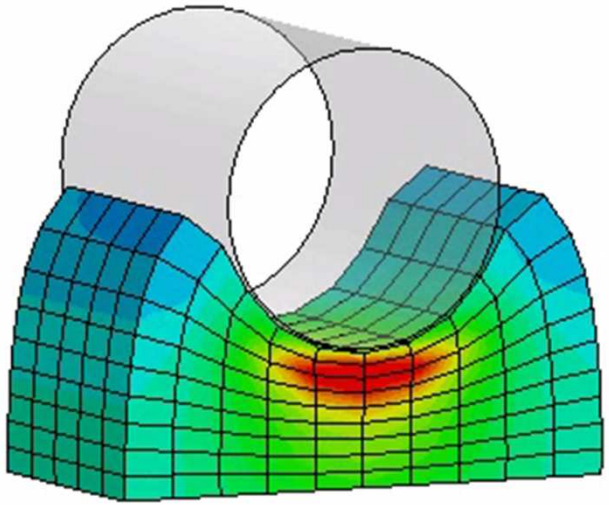


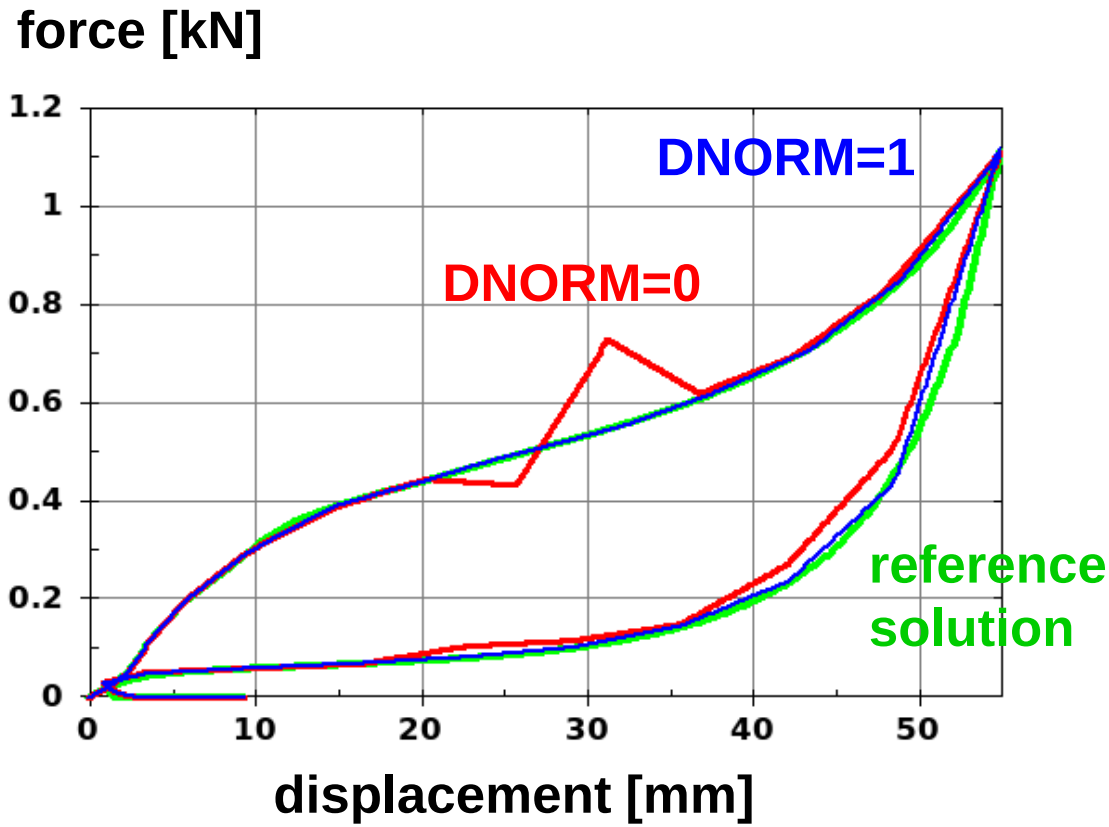
Guidelines

“Set DNORM=1 on *CONTROL_IMPLICIT_SOLUTION”

Example: Compression of a foam block (*MAT_FU_CHANG_FOAM)

```
ENDTIM=20.0, DTMAX=1.0, DCTOL=0.005, ELFORM=1, IHQ=6, QM=1.0
```





Recommendations

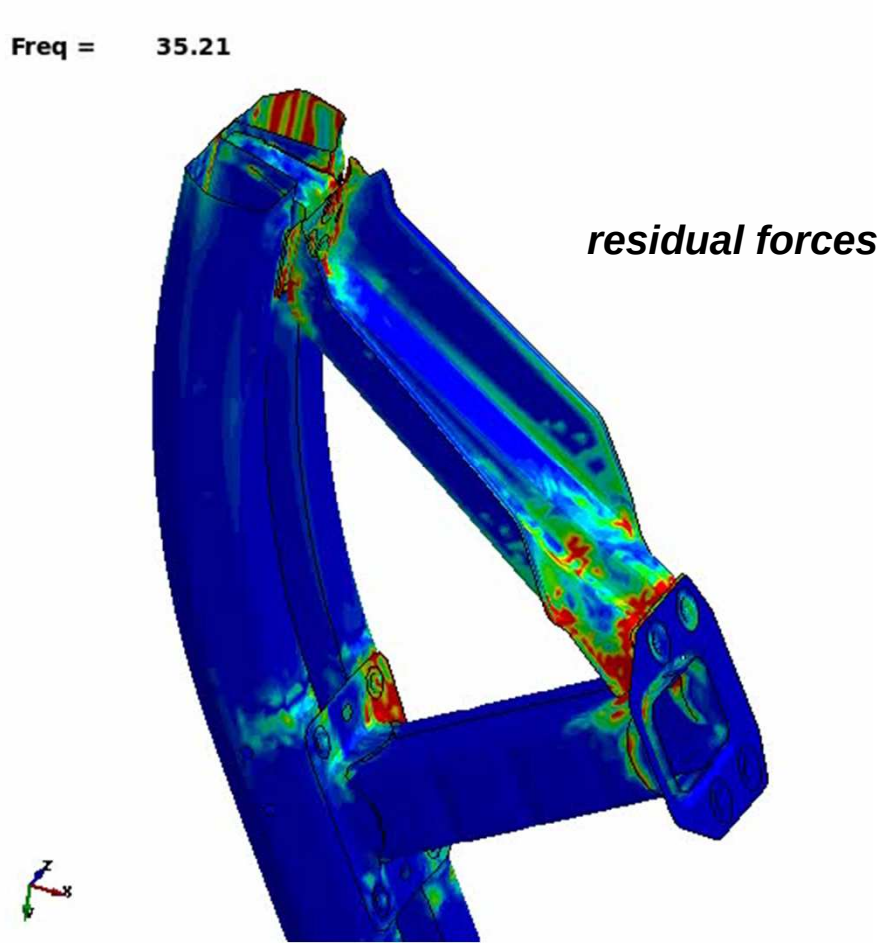
Output / “Debugging“

- activate print flags (LPRINT/NLPRINT) to get more information
- check ouput in d3hsp / messag files
- in general, if problems occur when running an implicit model, then try to check the model using *CONTROL_IMPLICIT_EIGENVALUE
- Set MINFO=1 on *CONTROL_OUTPUT to get more informations about the mortar contact: penetrations, release, …
- in case of convergence problems, dump iteration states via "<ctrl-c> iter" (residual forces in d3iter via **RESPLT=1** on *DATABASE_EXTENT_BINARY)

Output of non-converged steps

With **D3ITCTL=1**, search directions for the nonlinear implicit solution are written to the **d3iter** database. If used together with **RESPLT=1** on *DATABASE_EXTENT_BINARY, residual values can be fringed (Version R7):

deformation



residual forces

Recommendations

For “typical” nonlinear analysis, start with the following keyword settings:

```
*CONTROL_ACCURACY
$      osu       inn
         1         4
*CONTROL_IMPLICIT_GENERAL
$   imflag       dt0    imform      nsbs       igs
         1       ...                           (1)
*CONTROL_IMPLICIT_SOLUTION
$   nsolvr    ilimit    maxref     dctol     ectol     rctol  lstol  abstol
        12         6                                                (1.e-20)
$    dnorm    diverg     istif   nlprint    nlnorm   d3itctl
         1                             1       (4)       (1)
$

$    lsmtd
       (5)
*CONTROL_IMPLICIT_AUTO
$    iauto    iteopt    itewin     dtmin     dtmax
         1        30        10           (term/20)
*CONTROL_IMPLICIT_DYNAMICS
$    imass
       (1)
```

References

Guidelines and Examples

New package on www.dynasupport.com:

http://www.dynasupport.com/howtos/implicit/some-guidelines-for-implicit-analyses-using-ls-dyna/ImplicitPackage.zip

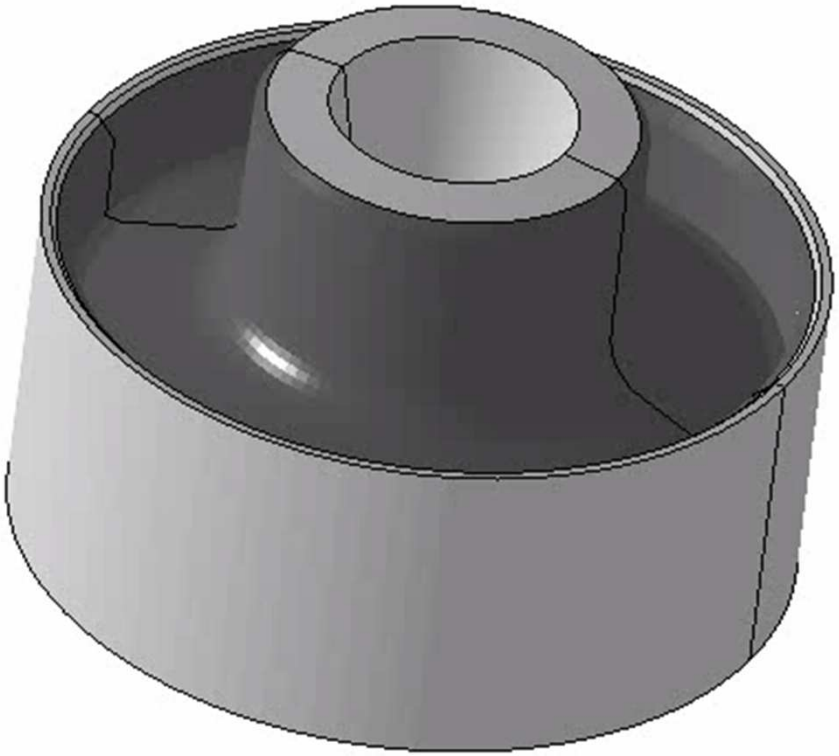
… provided by Dynamore Nordic.

In this document, some basic control card settings suitable for different implicit analysis types are presented. The analysis types are also accompanied by some basic examples. The purpose is to reduce the effort of getting started with implicit analysis in LS-DYNA.

The package also includes a document about Implicit Mortar Contact Problems.

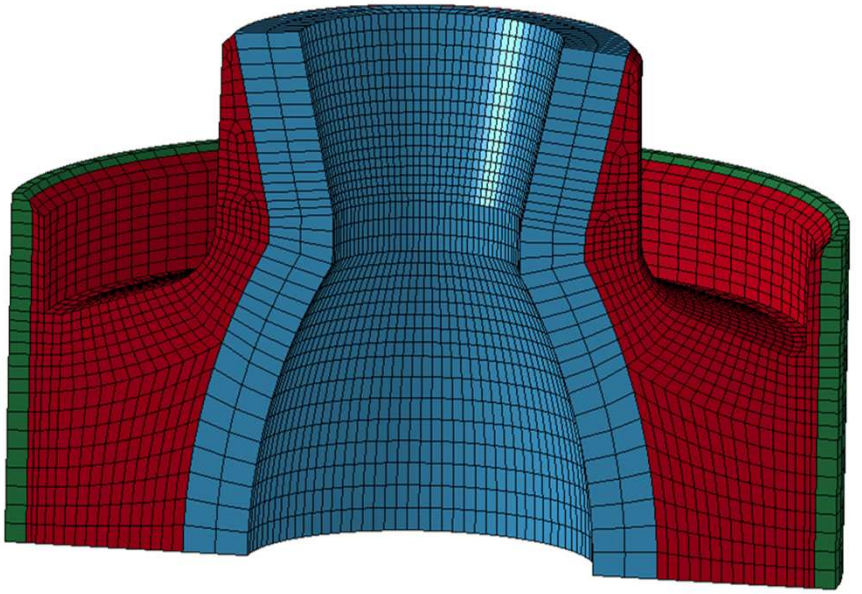
Examples

Rubber bearing



- Rubber confined by steel parts (diameter: 63mm, height: 40 mm)
- 1st phase: outer ring flanging
- 2nd phase: core shift by 2mm

- *MAT_027 for rubber ($\nu = 0.495$)
- Hexahedral elements (half model)

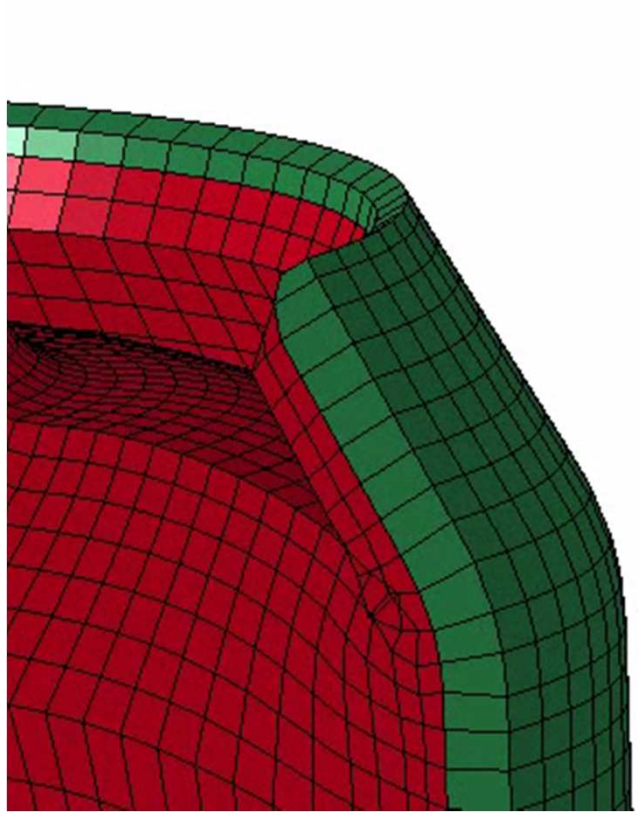


[LS-DYNA Version R9 beta MPP, double precision]

Examples

Rubber bearing: 1st run

```
*CONTROL_TERMINATION
$   endtim
       2.0
*CONTROL_IMPLICIT_GENERAL
$   imflag       dt0
         1      0.05
*SECTION_SOLID
$    secid    elform
         1         1
*HOURLGASS
$     hgid       ihq        qm
         1         6       1.0
*CONTACT_AUTOMATIC_SINGLE_SURFACE
$     ssid      msid     sstyp     mstyp
         1                  3
$       fs
       0.4
```



Nice convergence, but contact does not work at all!

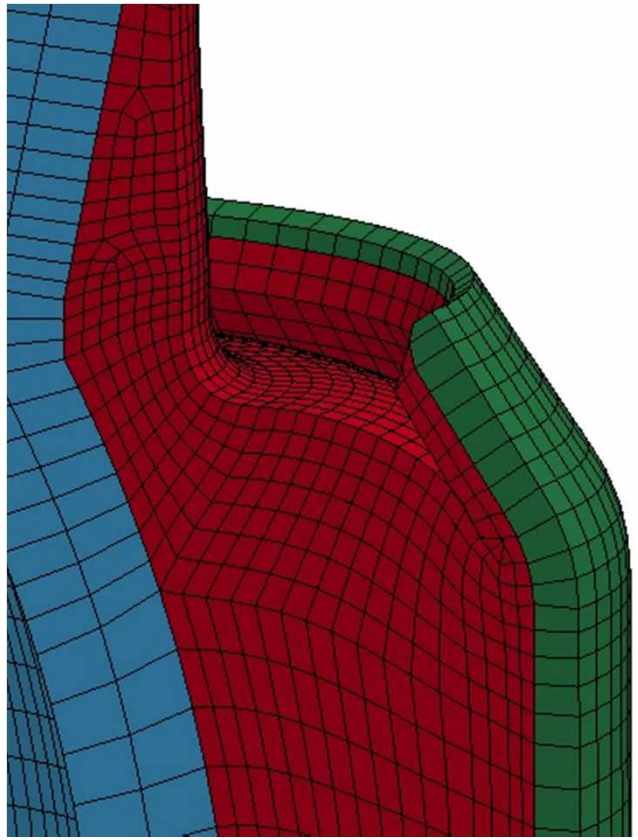
Examples

Rubber bearing: 2nd run

```
*CONTACT_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp
         2         1         0         0
$       fs
        0.4
```

- Old contact with segment sets
- Maybe better suited for solid contact with nearly incompressible material

→ Contact works better now, but solver fails to find equilibrium at t=0.9 (near the end of flanging phase)



```
*** Warning 60124 (IMP+124)
    6 negative eigenvalues detected
```

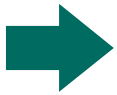
Examples

Rubber bearing: 3rd run

```
*CONTROL_IMPLICIT_SOLUTION
$   nsolvr    ilimit
        12         6
$    dnorm                        nlprint
         1                              1

$    lsmtd
         4
*CONTROL_IMPLICIT_AUTO
$    iauto    iteopt    itewin     dtmin     dtmax
         1        30        10    0.0001     -1234
*DEFINE_CURVE
      1234
                 0.0                0.05
                 1.0                0.05
                 2.0                0.05
*CONTACT_AUTOMATIC_SINGLE_SURFACE_MORTAR
$     ssid      msid     sstyp     mstyp
         2         1         0         0
$       fs
       0.4
```

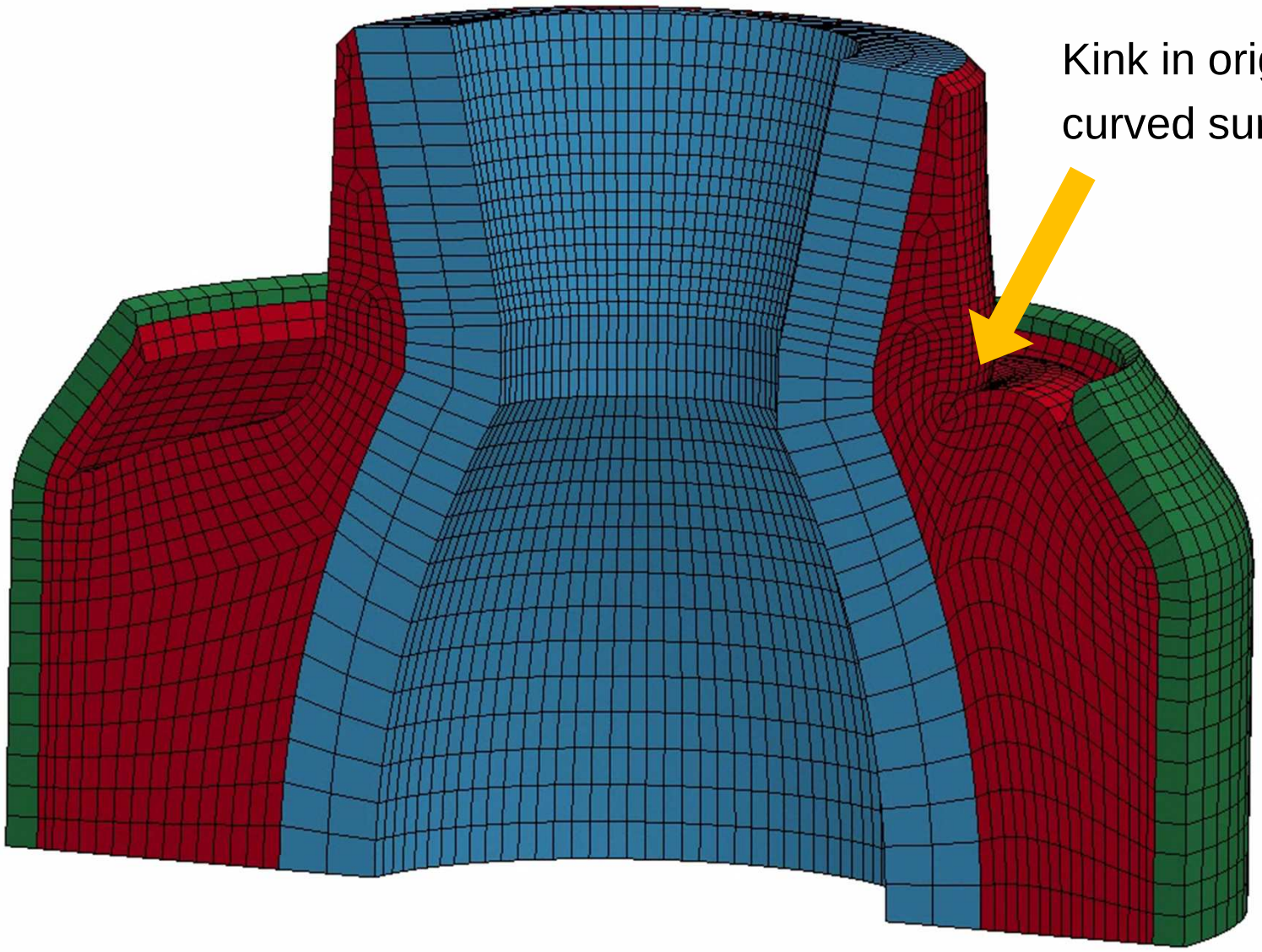
- Use all recommended implicit settings
- DNORM = 1
- Automatic time stepping
- Mortar contact



Contact works correctly, good convergence, even manages large element distorsions

Examples

Rubber bearing: 3rd run



Rubber bearing: 4th run

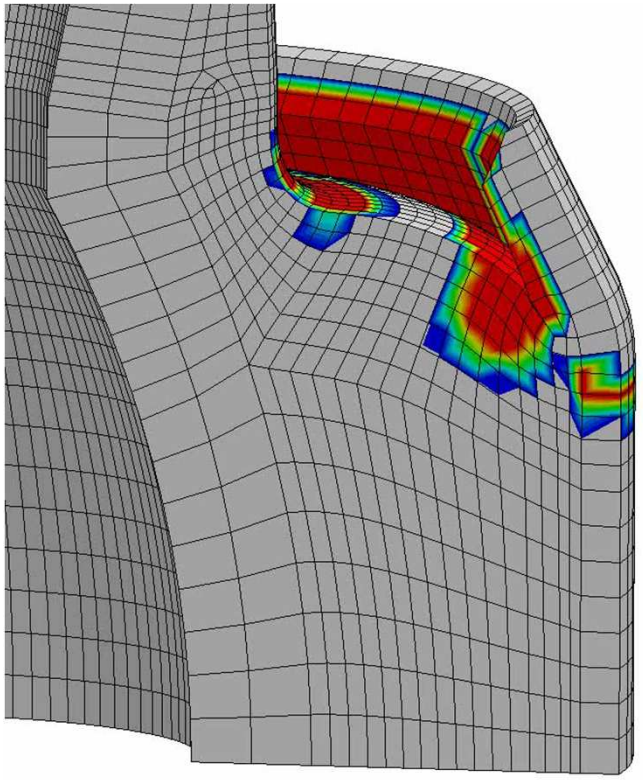
- Make it more difficult: increase Poisson‘s ratio from 0.495 to 0.499

```
*MAT_MOONEY-RIVLIN_RUBBER
$      mid        ro         pr          a          b
         1   1.85E-9      0.499       0.31      0.031
```

➡ Convergence troubles at t=0.75:

```
…
Iteration:   8     *|du|/|u| =  4.1805309E-01     *Ei/E0 =  1.6741033E-03
ITERATION LIMIT reached, automatically REFORMING stiffness matrix...
 *** Warning 60124 (IMP+124)      74 negative eigenvalues detected
Iteration:   9     *|du|/|u| =  1.0000000E+00     *Ei/E0 =  1.4155968E-03
Iteration:  10     *|du|/|u| =  1.0000000E+00     *Ei/E0 =  5.9733603E-04
Negative initial energy from quasi-Newton step,
automatically REFORMING stiffness matrix...
 *** Warning 60124 (IMP+124)      49 negative eigenvalues detected
Iteration:  11     *|du|/|u| =  3.7395361E-01     *Ei/E0 =  5.4974565E-04
Iteration:  12     *|du|/|u| =  1.0000000E+00     *Ei/E0 =  5.7415020E-04
…
```

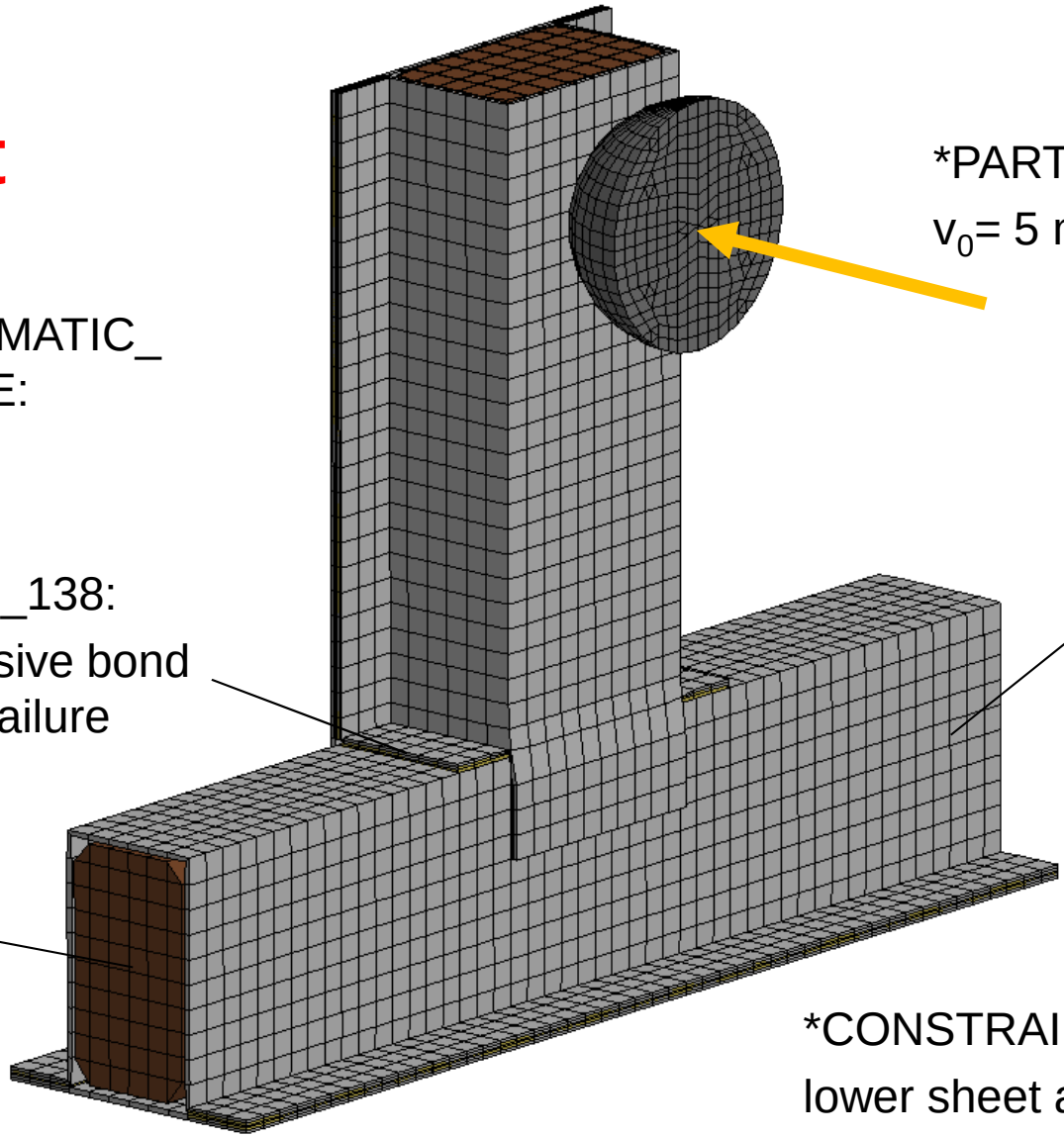
➡ That situation improves by changing LSMTD from 4 (default) to 6 (most robust)



d3iter: deformations and residual forces

Examples

T-joint component



*PART_INERTIA:
v_0= 5 m/s

*CONTACT_AUTOMATIC_
SINGLE_SURFACE:
overall contact

*MAT_024:
DP 800

*MAT_138:
adhesive bond
with failure

5 mm mesh
for steel parts

*MAT_024:
wooden blocks

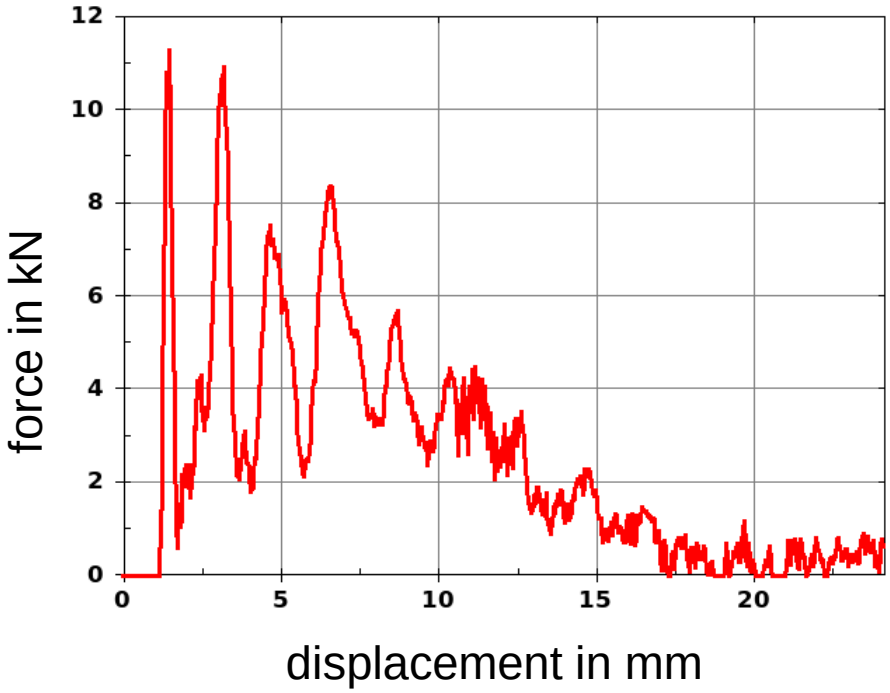
*CONSTRAINED_RIGID_BODY:
lower sheet and wooden block

[LS-DYNA Version R7.1.1 MPP, single and double precision]

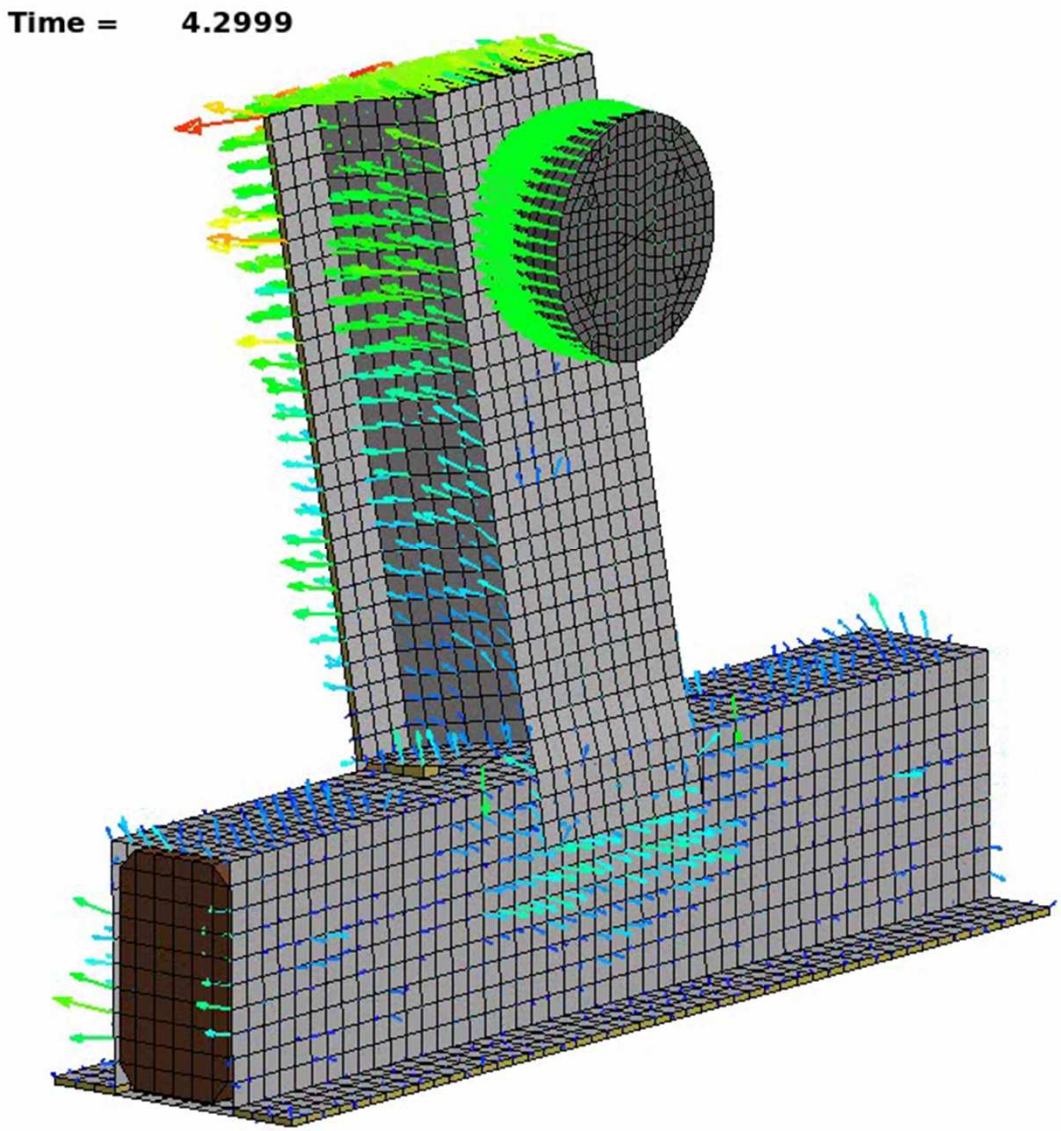
Examples

Dynamic explicit

- Process time = 5 ms
- ~10,000 time steps
- 52 cohesive elements fail
- Low-frequency vibration and high-frequency response (wave propagation)



velocity [0 - 10 m/s]



Examples

Now, we want to do a static analysis of that process:

1. Start with explicit using a larger time period (“slow“ loading)

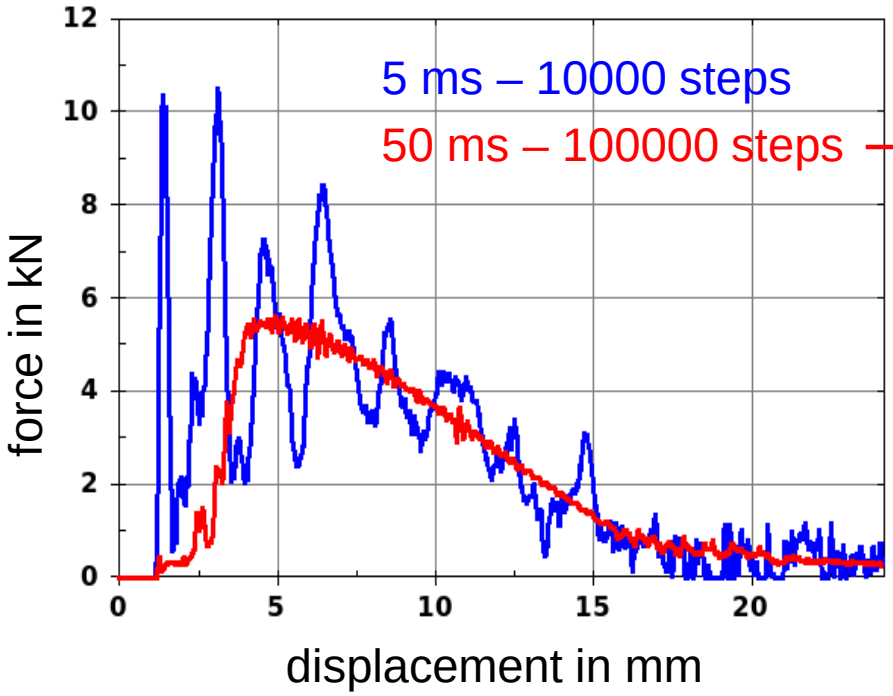
2. Add implicit cards needed for dynamic implicit analysis (“slow“ loading)

3. Remove dynamics and perform pure static analysis

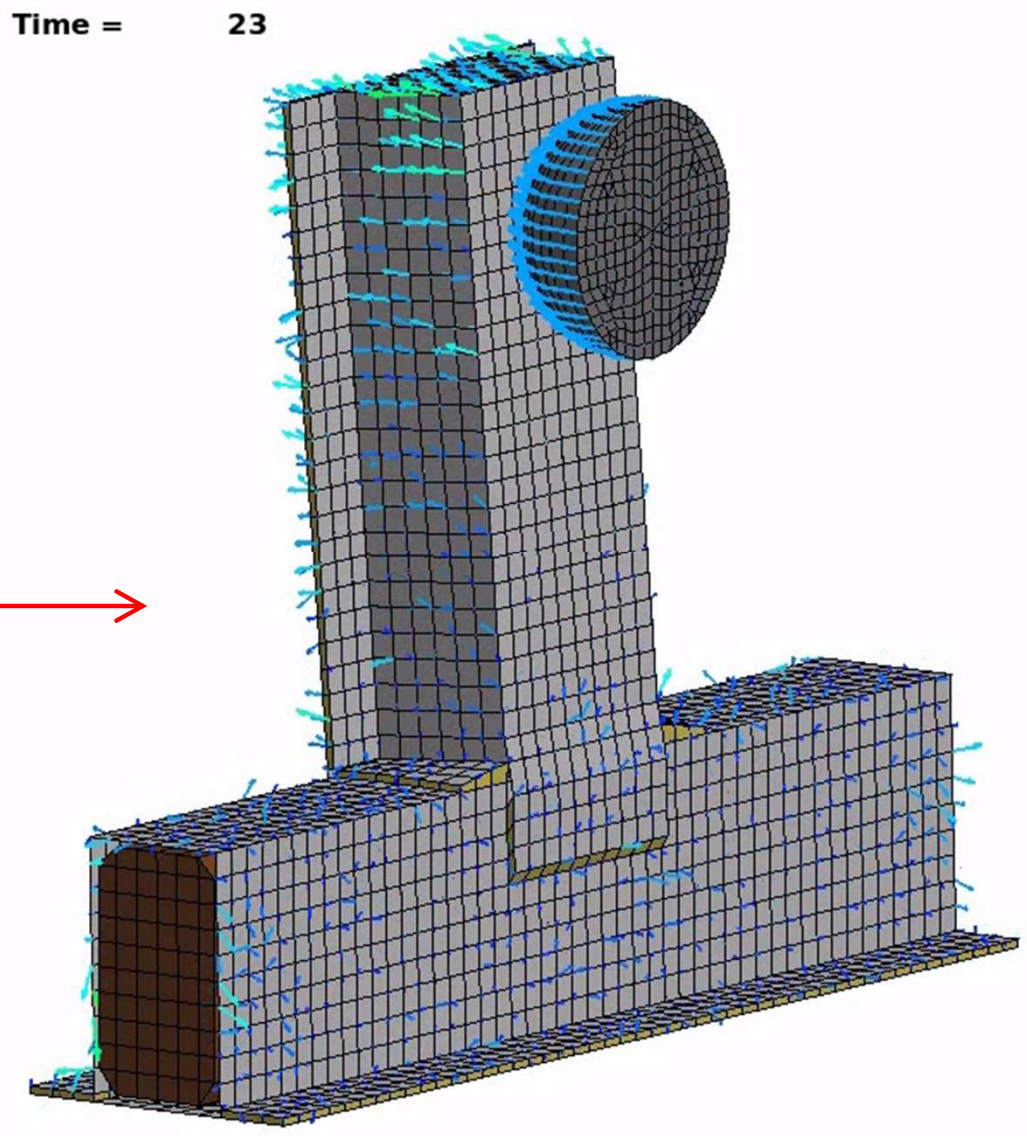
Examples

Static (??) explicit

- Process time = 5 / 50 ms
- ~ 10,000 / 100,000 time steps
- No initial velocity, but prescr. motion
- 52 cohesive elements fail
- Response still dynamic
- Damping… ??



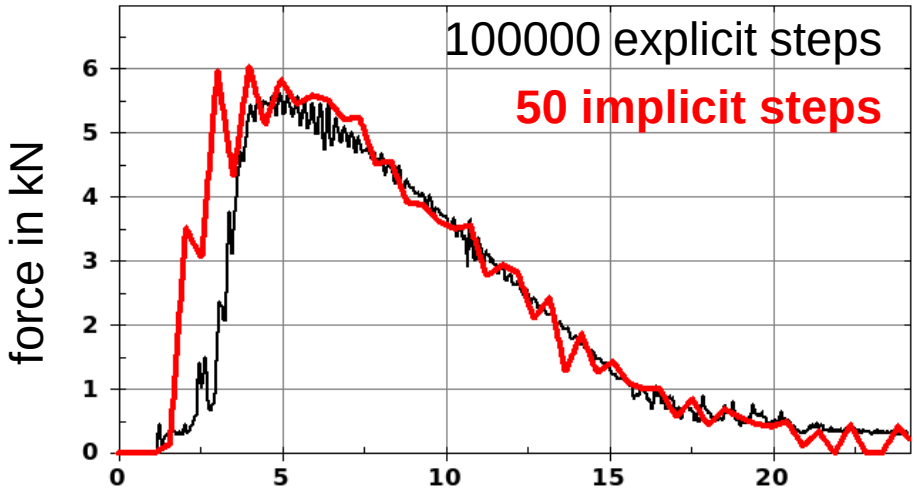
velocity [0 - 3 m/s]

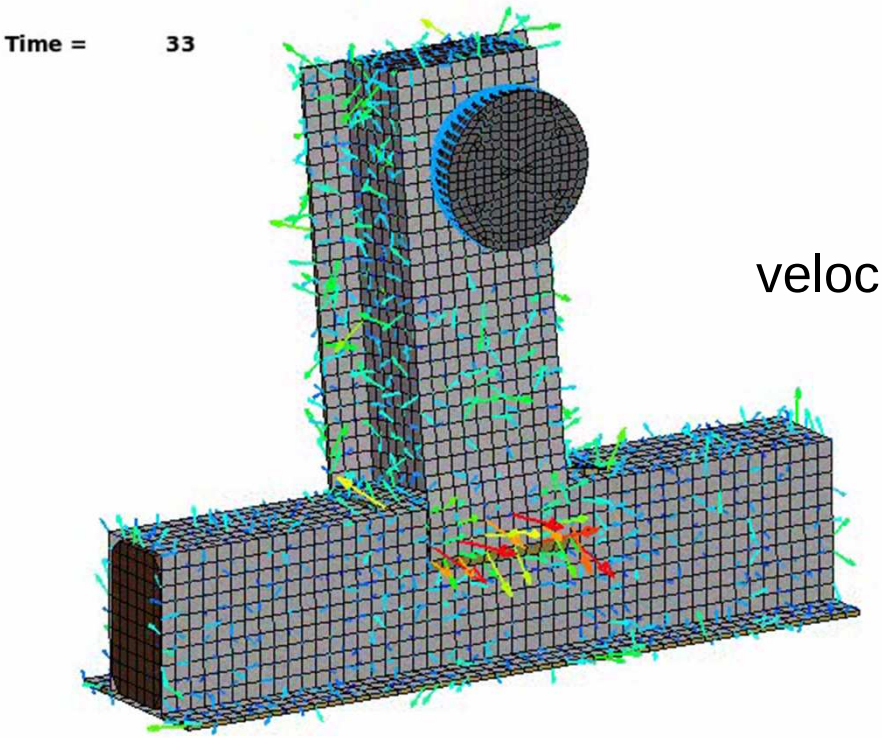


Examples

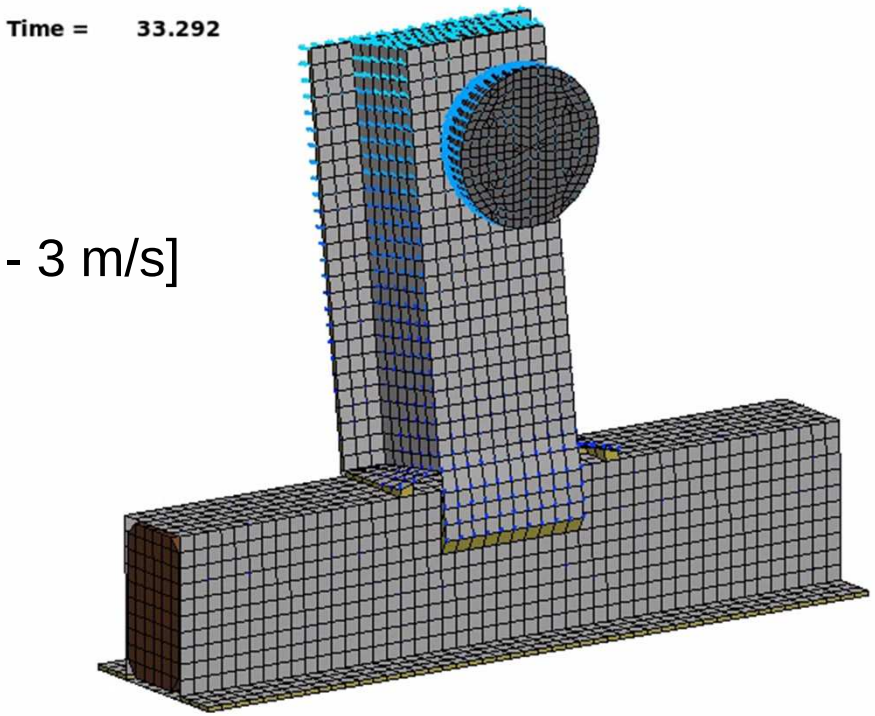
Dynamic implicit

- Process time = 50 ms (“slow“)
- Compare to “slow“ explicit run





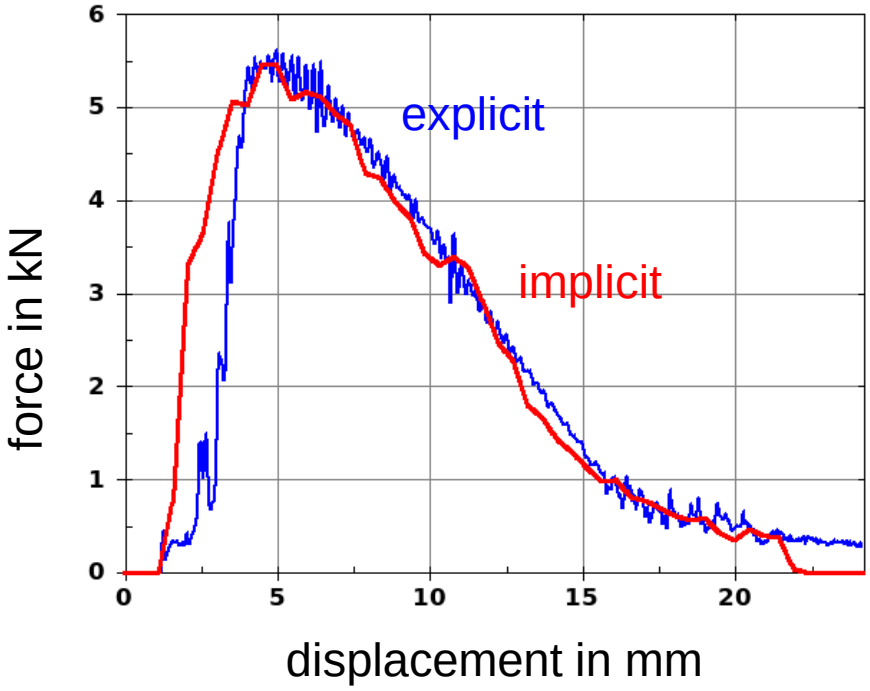
velocity [0 - 3 m/s]

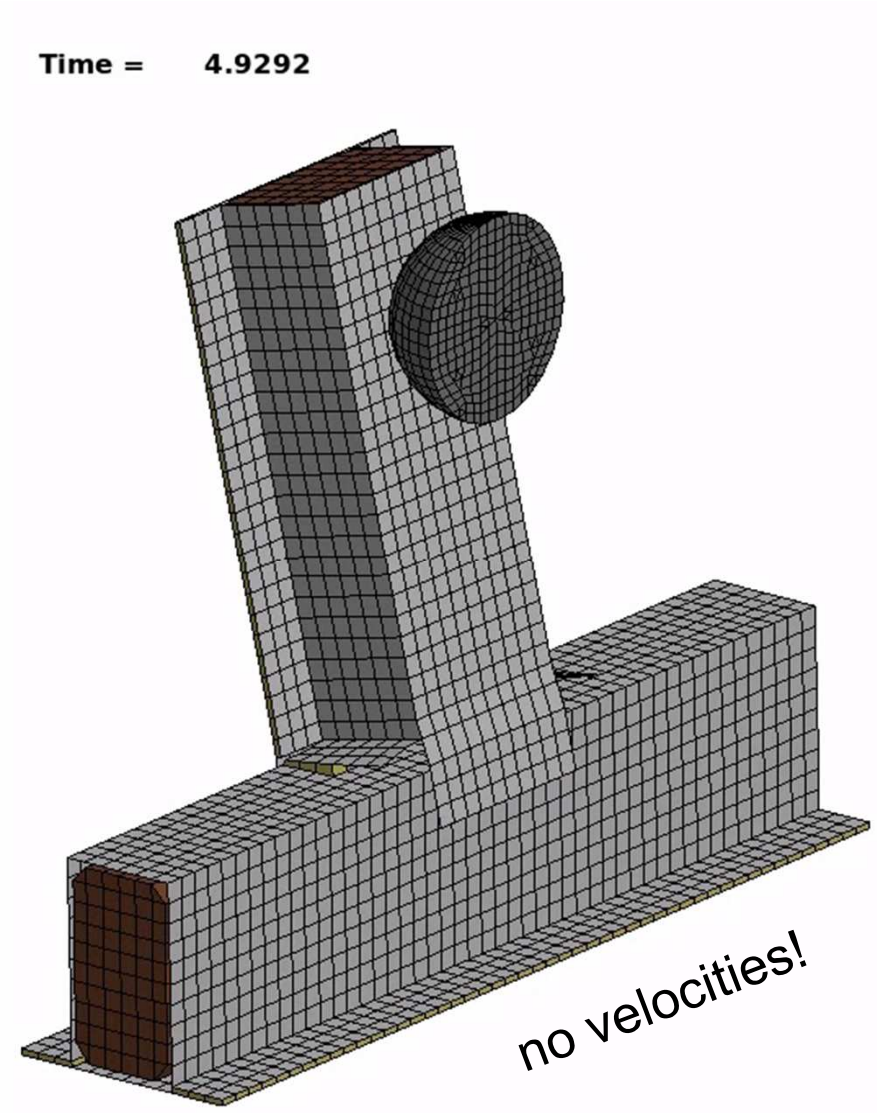


Examples

Static implicit

- Remove *CONTROL_IMPLICIT_DYNAMICS
- No initial velocity, but prescr. motion
- “time“ not physical anymore
- Real static response
- statically defined !?!

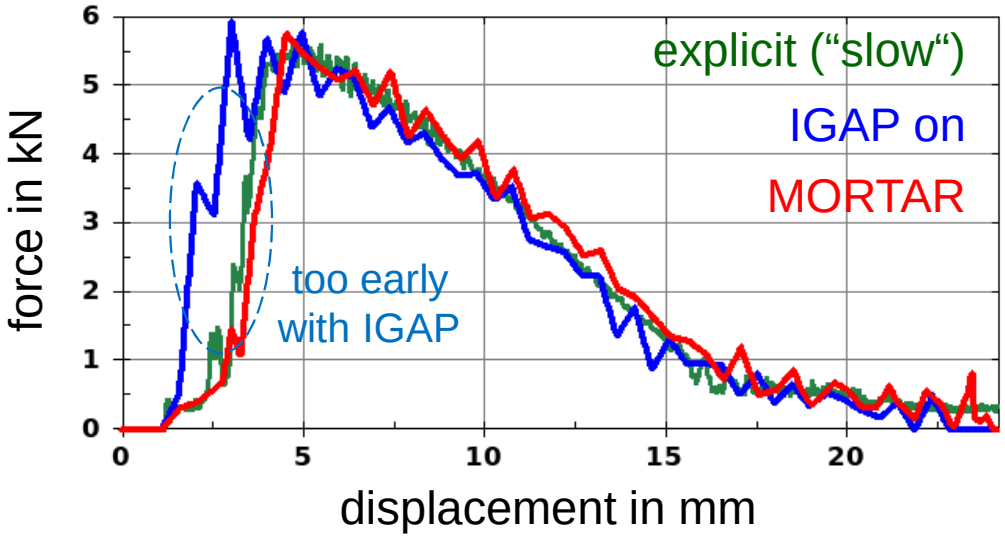




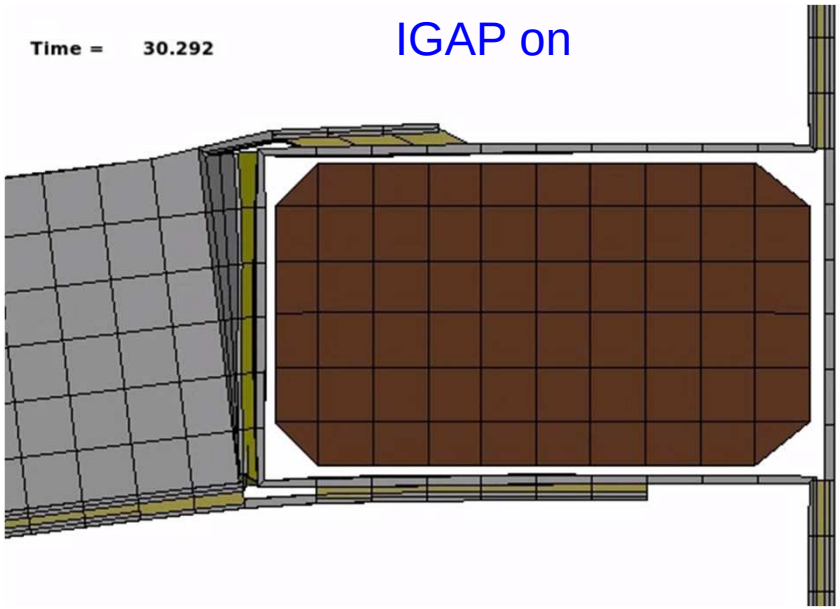
Examples

Implicit contact

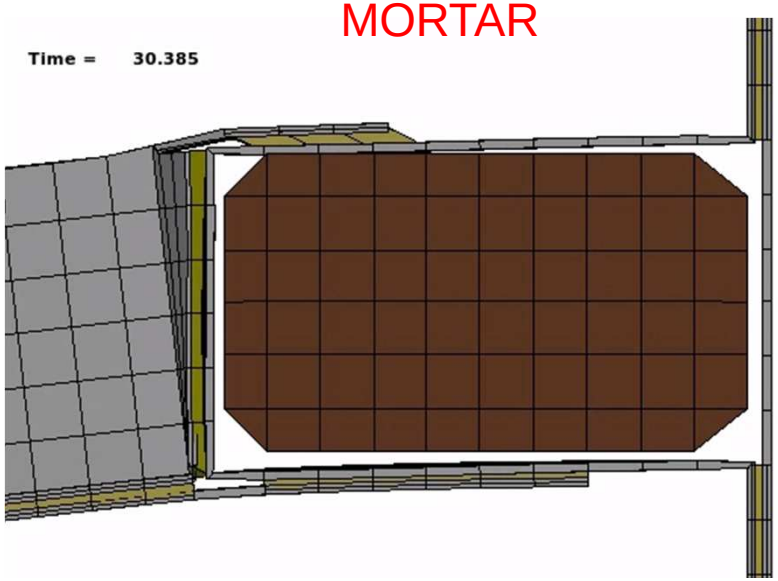
- Contact is very important issue (especially) in implicit analysis
- User should know about IGAP options (“sticky contact“) and mortar contact (continuous tangent)
- Dynamic implicit shown here



IGAP on



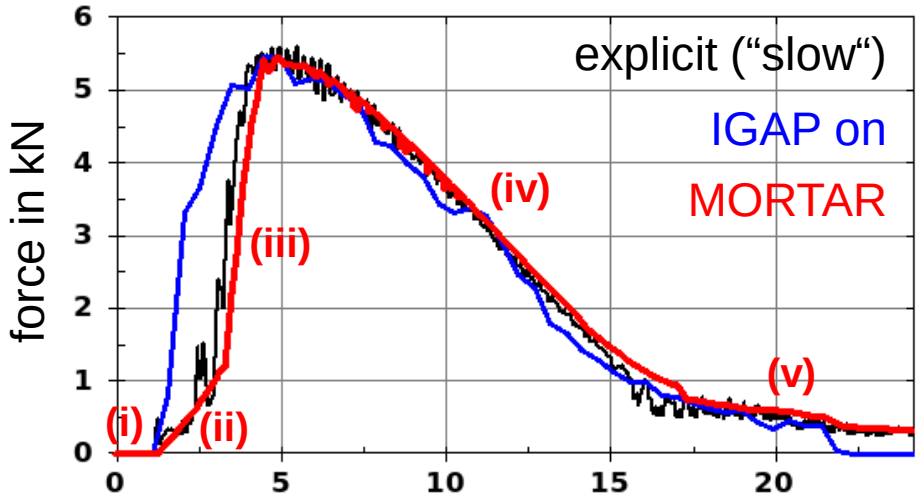
MORTAR

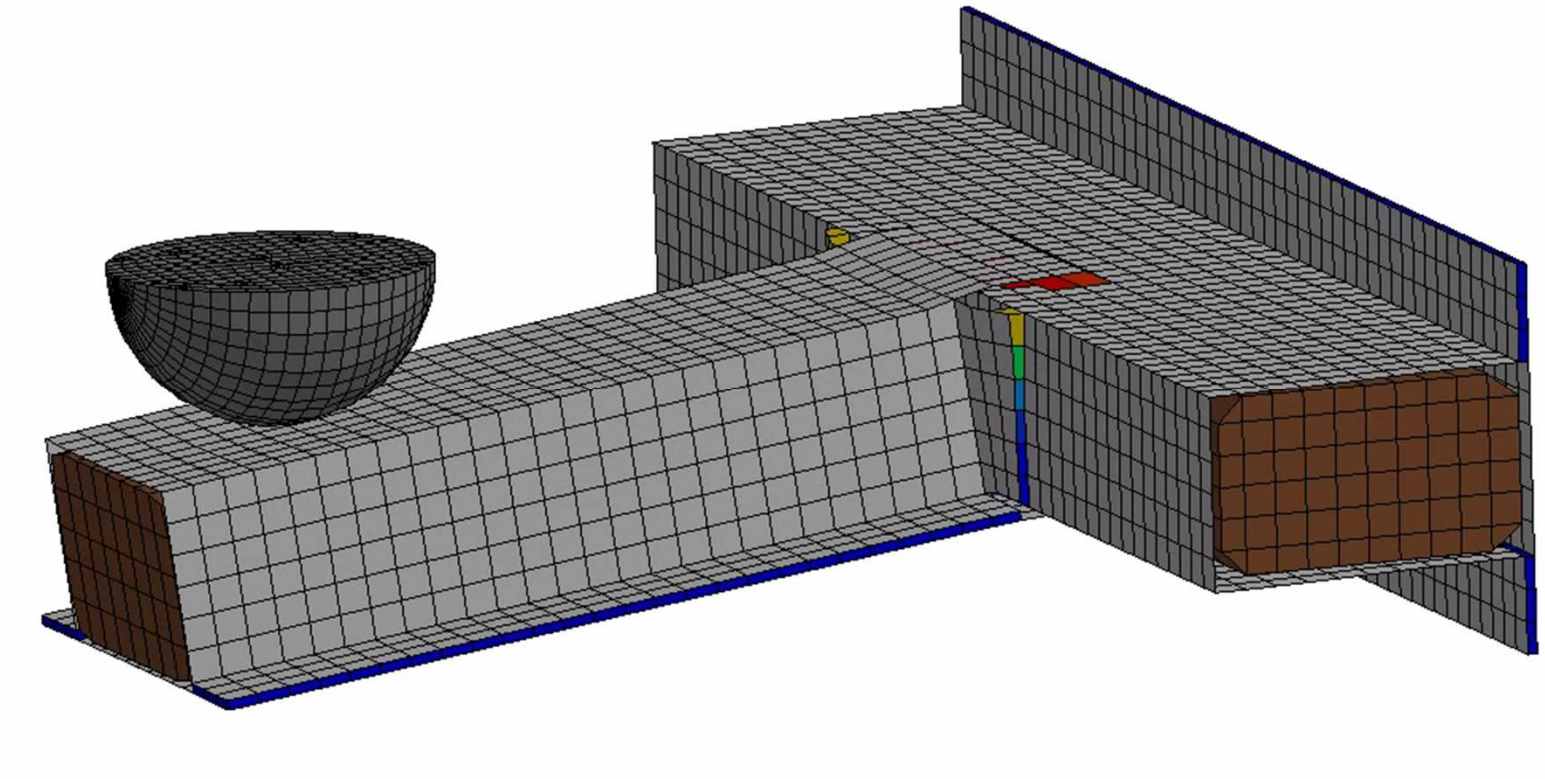


Examples

Static implicit with Mortar contact

- More realistic results with Mortar contact
- 5 different phases can be observed: no contact (i), tipping (ii), elastic bending (iii), adhesive softening (iv), and glue failure (v)

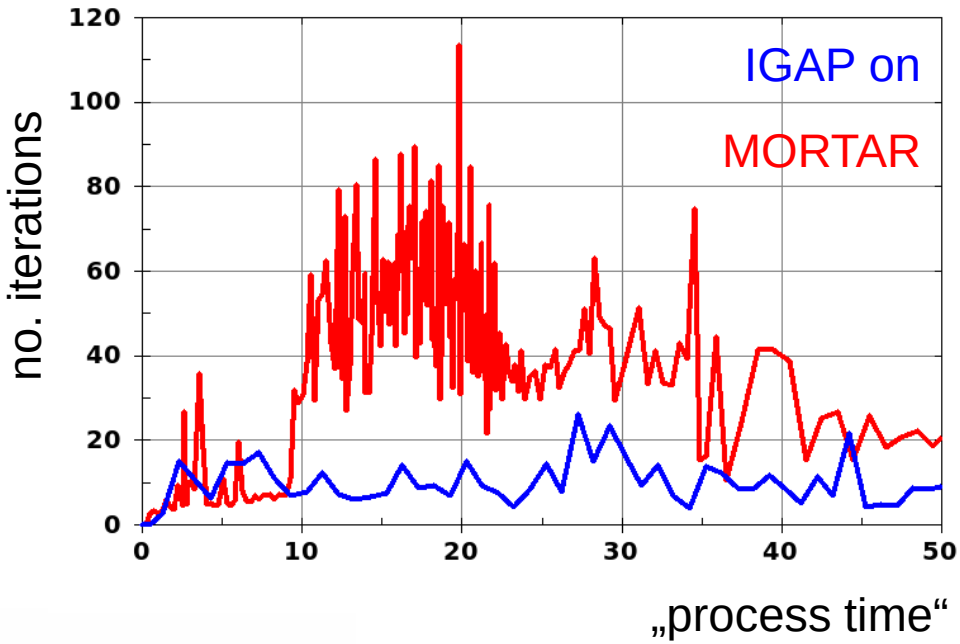


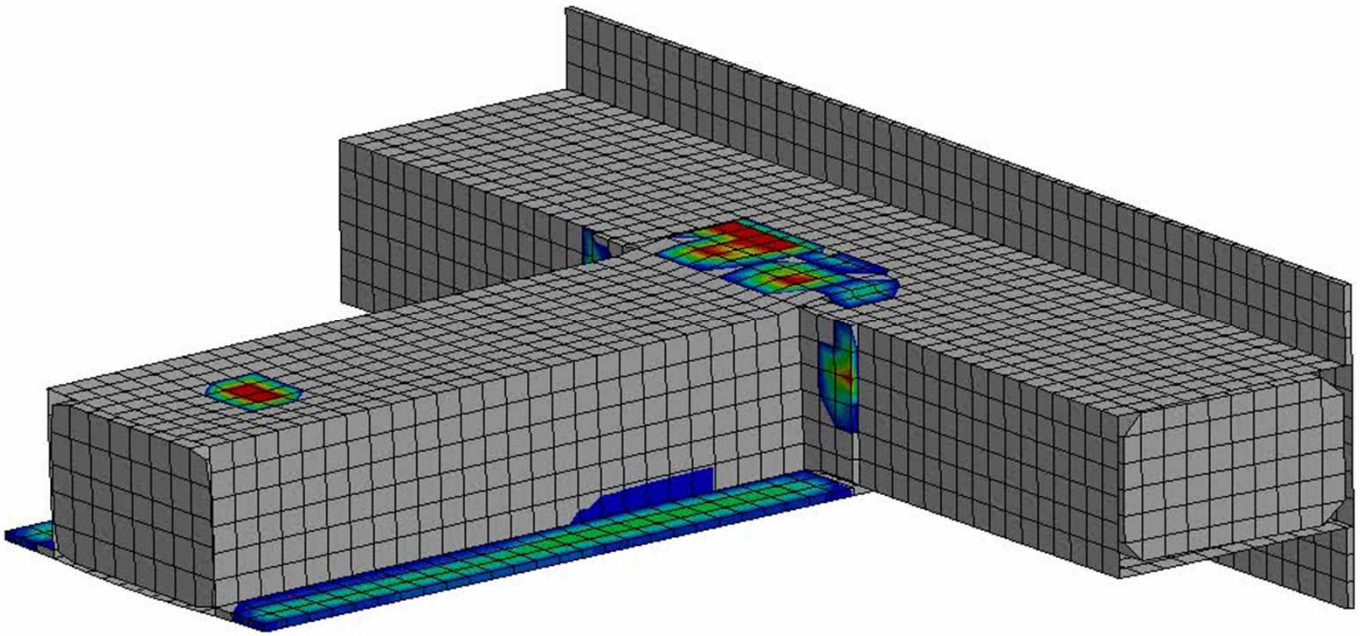


Examples

Static implicit with Mortar contact

- Convergence becomes more difficult
- Reason(s) for difficulties can be detected with special “iteration plot database“ d3iter
- Evolution of out-of-balance forces during iteration process shows critical areas



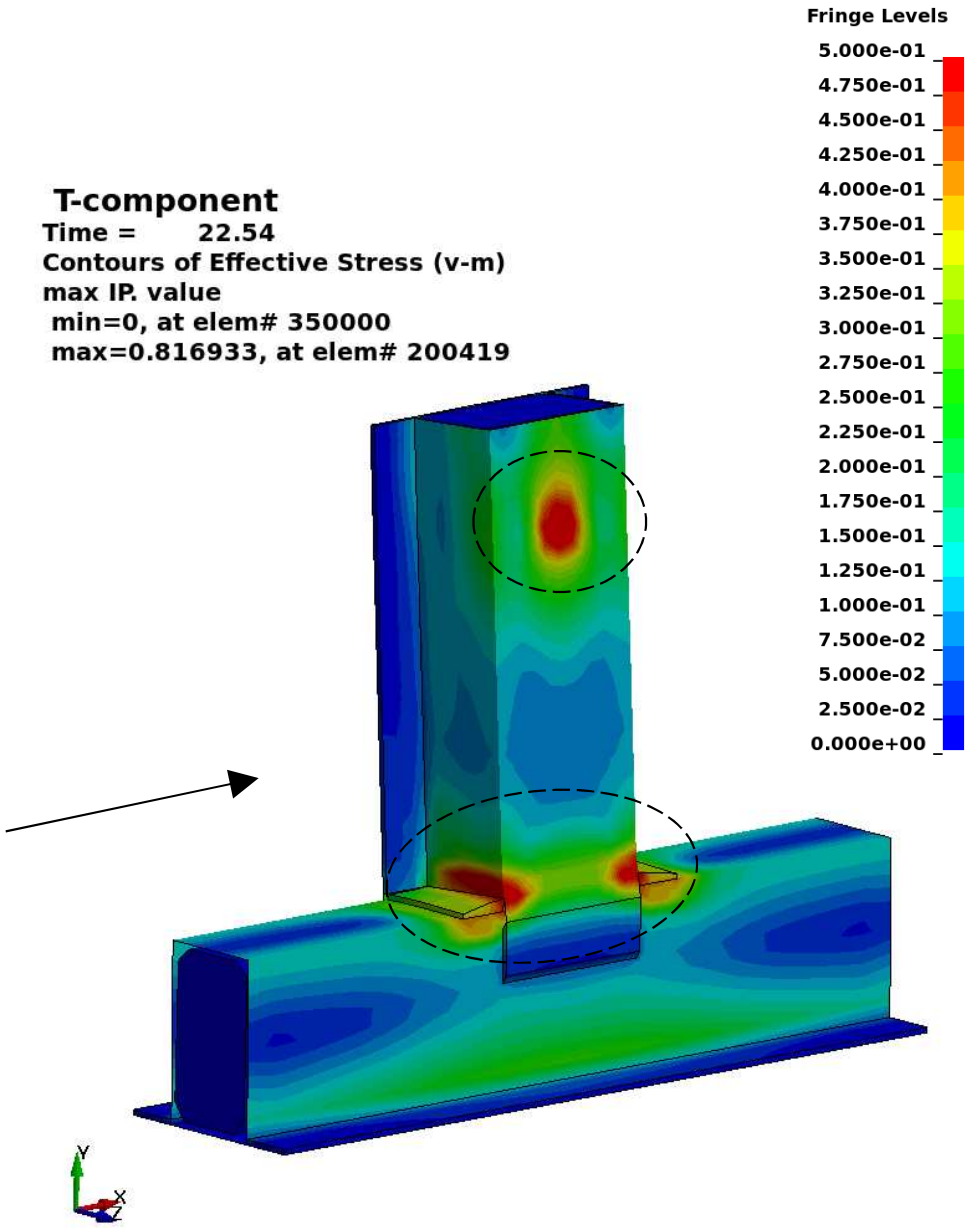


Troubles from contact and damage evolution in cohesive material

Examples

Ideas for improvement

- Perhaps Full Newton better suited for this problem (ILIMIT=1)
- Modify other implicit settings (timestep size, tolerances, …) or contact parameters (IGAP, …)
- But maybe better to improve the model itself:
- Replacement for cohesive material (MAT_186 with smooth curve?)
- Mesh refinement in critical areas?
- Dynamic implicit – very slow
- …



Summary

- Explicit analysis runs into ist limits for long duration processes or even real static load cases.
- Therefore, implicit analysis is often preferrable.
  Actually, computation time can be decreased in many cases.
- But: more demanding to get a solution, especially if large deformations, contact, and nonlinear material behavior is involved.
- Users must be aware of crucial differences between explicit (e.g. time step size) and implicit (e.g. “smooth“ model)
- Often greater effort is needed to obtain a functional model in implicit, but also the feeling of success is greater in the end