DYNAmore Express

Implicit Analysis using LS-DYNA

Tips & Tricks for successful implicit analyses

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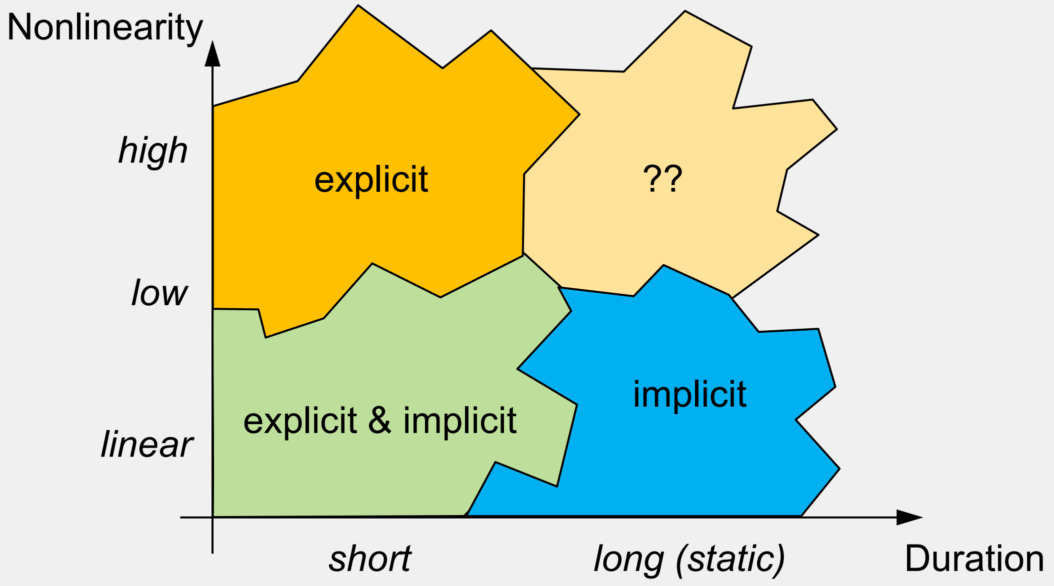
Why implicit ?

- Prestressed, quasi statically loaded structures
- Long duration analysis > 500 ms

- Different time scales in process
  - e.g. static loading followed by transient loading
  - or transient loading followed by static loading

- Applications
  - metalforming, roof crush, door sag, dummy seating, strength analysis, ...

- LS-DYNA provides explicit and implicit solution schemes
  - one code – one license – one data structure
  - one input / output



How short is short duration?

Before supercomputers (prior to 1980) short < 5 milliseconds.
Hence problems mainly in ballistics!

After supercomputers: short < 100 milliseconds.
Hence, problems in crashworthiness became feasible!

Explicit vs. Implicit (dynamics)

$$\boxed{\rho\,\mathbf{u}_{,tt} = \nabla\cdot\boldsymbol{\sigma} + \mathbf{f}}$$

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

Explicit scheme $\mathbf{x}_{n+1} = \mathbf{f}(\mathbf{x}_n, \dots)$	**Implicit scheme** $\mathbf{f}(\mathbf{x}_{n+1}, \mathbf{x}_n, \dots) = \mathbf{0}$
+ Solution: directly + Decoupled: fast, efficient	- Solition: iteratively - Linearization necessary
- Many small time steps - Conditionally stable (Courant)	+ Few large time/load steps + Unconditionally stable
Equilibrium ? Energy balance !	Equilibrium ! **Convergence ?**
Short time dynamics High frequency response, Wave propagation ➡ Impact, crash, …	**Structural dynamics** Low frequency response, Vibration, Oscillation ➡ Earthquake, machines, …

Explicit vs. Implicit

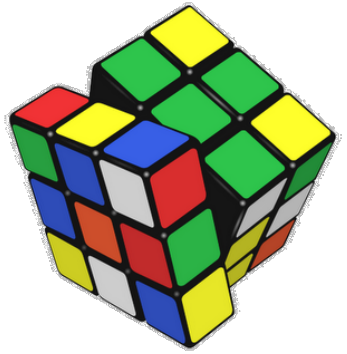
- Explicit
  - inevitably includes inertial effects and
  - resolves high frequencies

wether you want it or not

"Explicit is handcraft"

- Implicit
  - can neglect inertial effects and
  - the selected time step size determines resolved frequency spectrum

- Consequences for FE models
  - "cleaner" models in implicit for the sake of convergence, e.g. no initial penetrations, smooth material curves, …
  - 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



“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

General philosophy

”Increased accuracy implies better convergence”

Common 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 the most recent LS-DYNA version possible (e.g. R11.1, R12.0)
  - Implicit functionality is rapidly improving

- Use double precision (_d_ in the name of the executable)
  - Required for accurate linear analysis
  - Improved convergence behavior in nonlinear analysis
  - Mandatory for current releases

- Read Appendix P in the User's manual and Chapter 37 in Theory Manual
  - Nice summary about LS-DYNA's Implicit Solver

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

Memory management changed after R10
→ **next 2 slides**

Memory management up to R10

see: A Tutorial on How to Use Implicit LS-DYNA ®, R. Grimes, www.dynalook.com/...

- Estimation for memory option
  - memory = 0.75 * (available RAM) / (number of MPI processes)

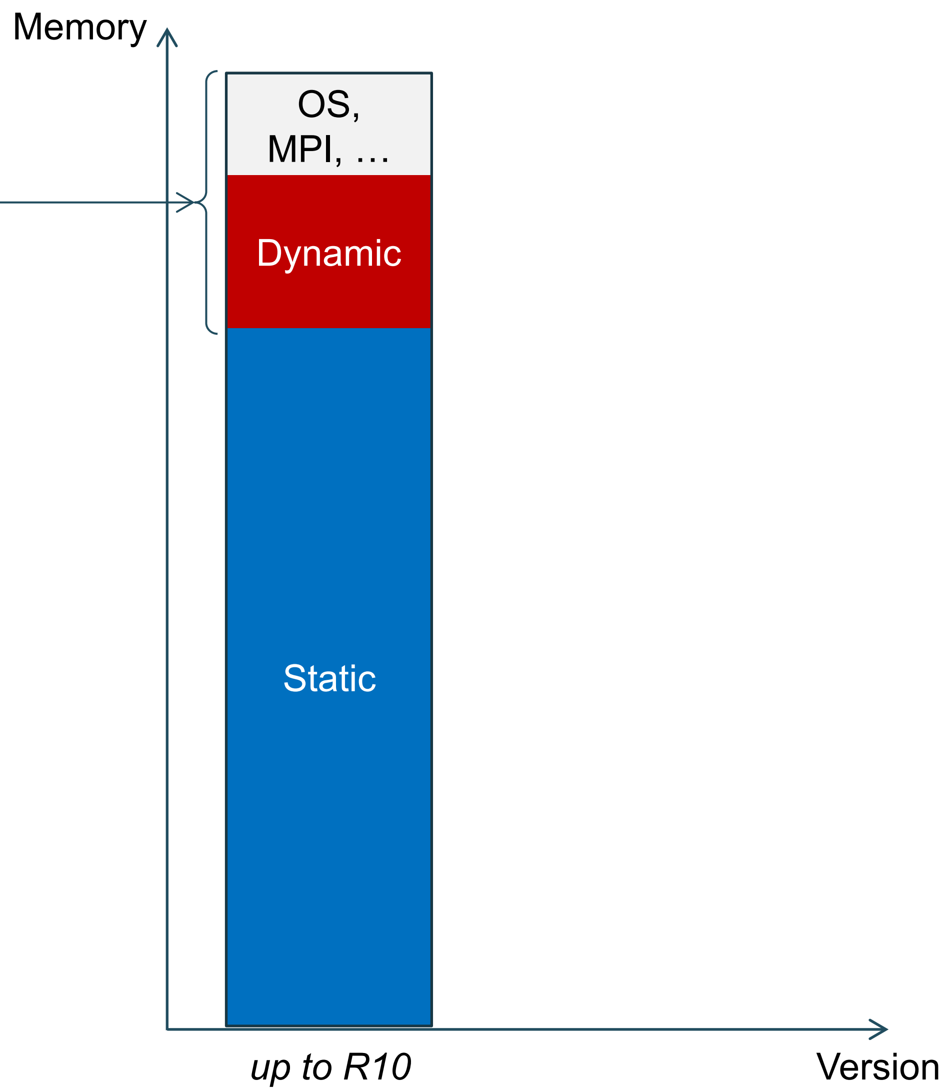
    Leave free RAM for dynamic memory
    and system tasks, MPI, …

  - For a cluster node with 256 GB = 32000m of available RAM

    memory = 1500m (16 MPI processes)

    memory = 1000m (24 MPI processes)

- memory2 **specified?**
  - If not specified – memory2=memory is set internally
  - If specified – apply above recommendation to memory2 together with a possibly larger value of memory



Memory management **after** R10

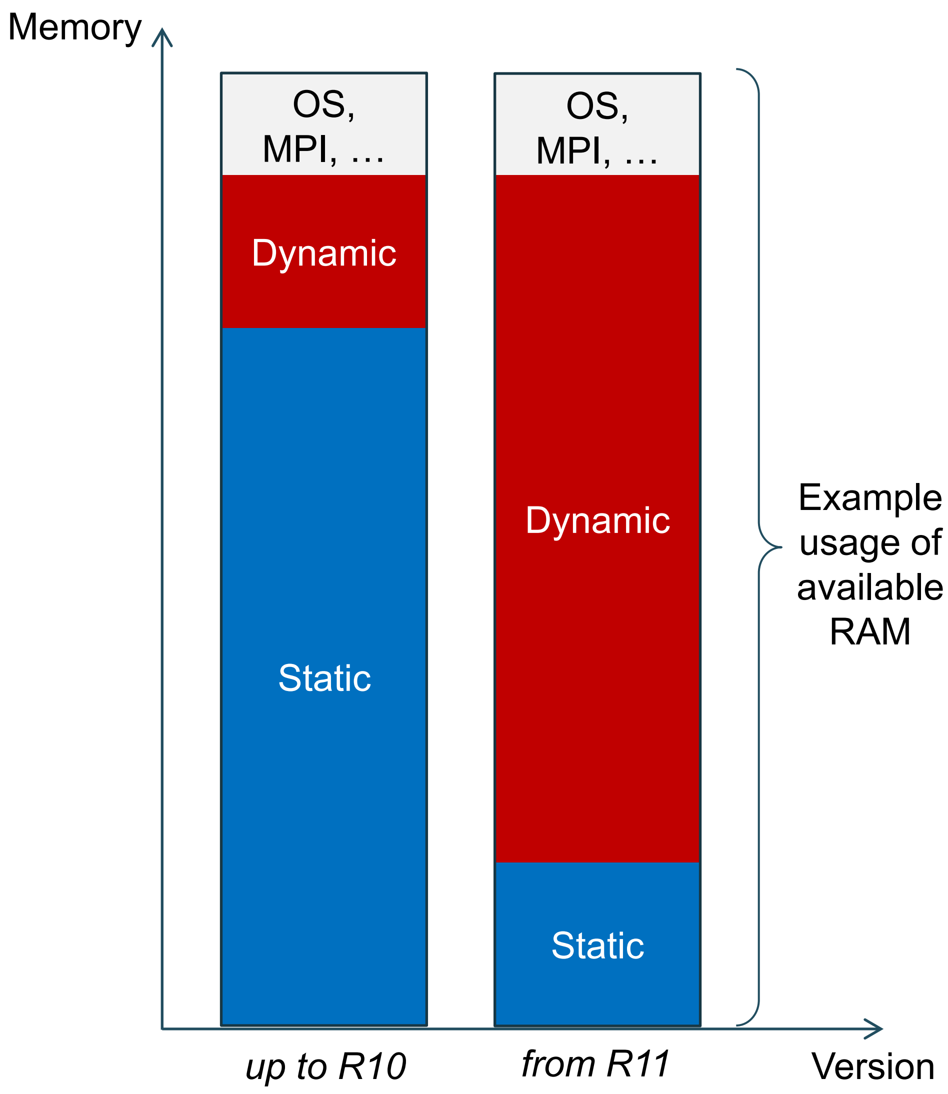
- Implicit linear algebra converted from static to dynamic memory
  - Huge dynamic and **much less static** memory needed
  - Usage alert printed at start of simulation
  - Example for MPP version

    Model with 2.1m nodes, 1.4m shells, 1.4m solids

    Compute node with 256 GB using 24 MPI processes

```
==================================================
==              IMPLICIT USAGE ALERT            ==
==================================================
== Memory Management for Implicit has changed ==
== after R10.  Please use:                      ==
==        memory=   155M memory2=    57M        ==
==================================================
```

- This does **not** mean LS-DYNA requires less memory, only the amount of static and dynamic memory changed
  - memory and memory2 are shrinking in importance



Recommendations cont'd

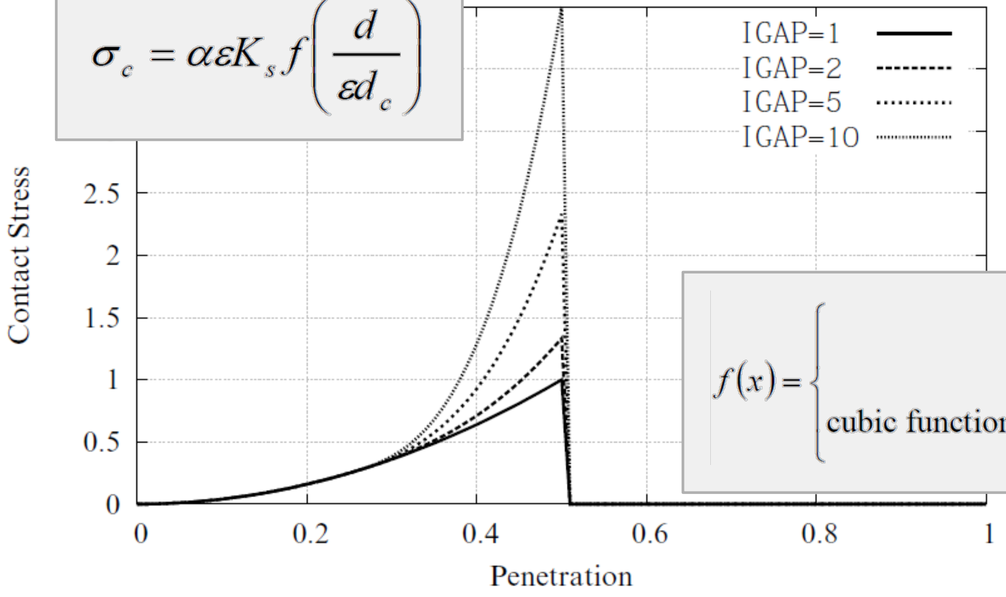
- Element types
  - For solids use type 1, -1, -2, 13 or 16 elements for non-linear analysis
  - For shells use type 6 or 16 elements for non-linear analysis
  - Try to avoid pentahedral solid elements
  - Beware of free rotations when merging shells and beams to bricks

- Contact
  - Try to avoid initial penetrations or try IGNORE=1
  - Use Mortar contact press-fit option (IGNORE=3 or 4) for intended initial penetrations
  - Switch (temporarily) to tied contact to identify problems
  - Use Mortar contacts or try IGAP=2 (on additional card C)
  - Try to decrease contact stiffness, 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
  - Better use separate contacts instead of only one "big" contact

IGAP has different meaning for Mortar → next slide

Mortar's IGAP – contact stiffness scaling

$$\sigma_c = \alpha \varepsilon K_s f\left(\frac{d}{\varepsilon d_c}\right)$$



α = stiffness scaling factor (SFS * SLSFAC)

K_s = stiffness modulus of slave segment

d = penetration distance

ε = 0.03

d_c = characteristic length

$$f(x) = \begin{cases} \frac{1}{4}x^2 & x < \frac{1}{4\varepsilon} \\ \text{cubic function that depends on IGAP} & \frac{1}{4\varepsilon} \leq x \end{cases}$$

- IGAP=1 (default)
  - contact stiffness is parabolic with respect to penetration up to a penetration depth corresponding to half of the maximum penetration
- IGAP > 1
  - functions as scaling factor on that contact stiffness
  - contact will stiffen for larger penetrations, in fact it will become cubic

Recommendations, cont‘d

- General
  - Apply second order stress update by setting **OSU=1**, *CONTROL_ACCURACY
  - Try accuracy option **IACC=1** on *CONTROL_ACCURACY (starts with version R9)
  - Try to model displacement driven simulation instead of force driven simulation
  - IGS=1 (not default) on *CONTROL_IMPLICIT_GENERAL may help in some cases (structures under tension)
  - Set **DNORM=1** on *CONTROL_IMPLICIT_SOLUTION, DCTOL can often be increased then, 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 first
  - Keep an eye on time step evolution, choose reasonable step size to avoid “yo-yo” effect
  - Try to avoid discontinuities, e.g. in material curves, geometry, ...
  - In problems where there is much rigid body motion the displacement tolerance DCTOL may be insufficient, in some problems a tighter energy tolerance, e.g. ECTOL=0.001, may be advisable.
  - Be aware of causes and consequences of ill-conditioning

→ see next slides for more details

Try accuracy option IACC=1 on *CONTROL_ACCURACY

Variable	OSU	INN	PIDOSU	IACC				
Implicit default	1	2	0	0				

Use implicit accuracy option **IACC=1**

In line with the general philosophy **"Increased accuracy implies better convergence"**

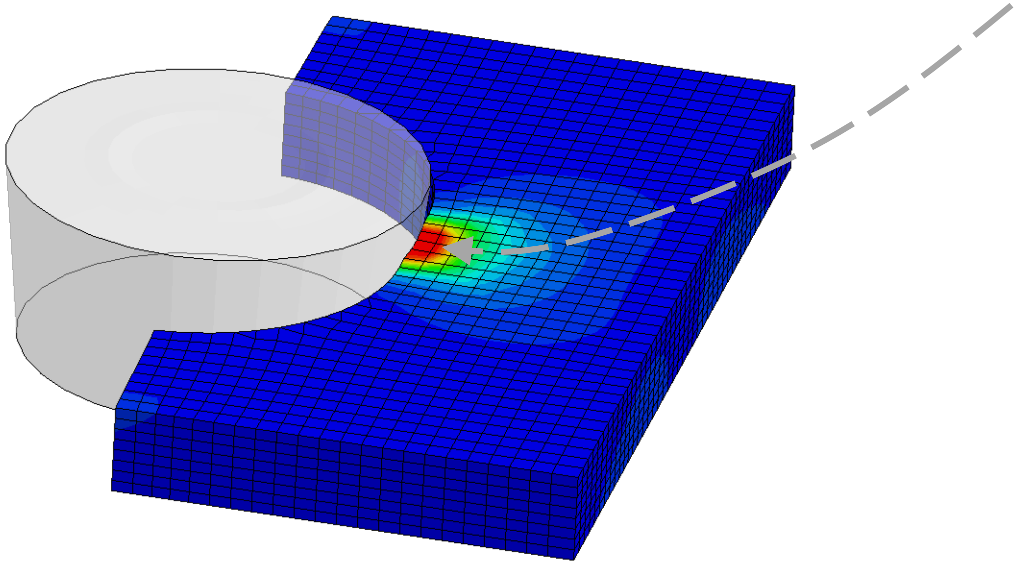
- Higher accuracy in selected material models (24, 123, …)
  - Fully iterative plasticity, tightened tolerances, smooth failure
- Strong objectivity and consistency in selected tied contacts
  - Physical (only ties to degrees of freedoms that are "real")
  - Finite rotation
- Strong objectivity in selected element types
  - Finite rotation support for hypoelasticity
- … see more in User's Manual

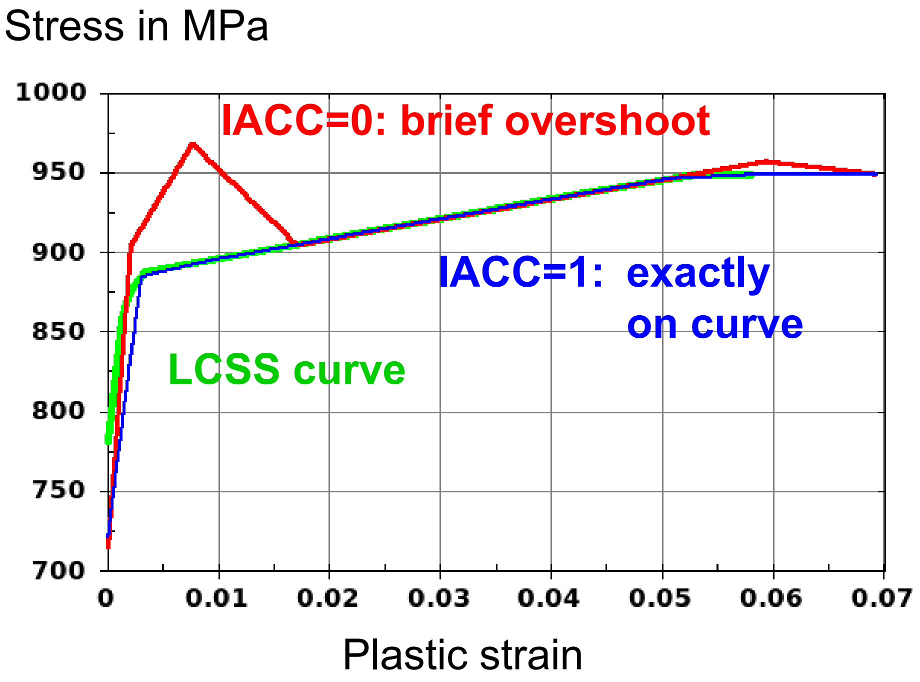
Contact features activated for IACC = 1	*Implicit*	*Explicit*
Strong objectivity in tied contacts listed on *CONTACT, meaning that large rotations will not induce contact stresses. These contacts also include bending and torsional constraints whenever those are physically justified.	Yes	No

Material features activated for IACC = 1	*Implicit*	*Explicit*
Large strain/temperature accuracy in some materials (types 4 shells/solids, 60 solids, 106 solids).	Yes	No
Stiffness smoothing of tension/compression transition in material 83, for enhanced implicit convergence characteristics.	Yes	No
Accurate Jacobi iterations in some hyperelastic material models (type 30 solids, 77 solids, 83 solids), for better strain assessment and implicit convergence characteristics.	Yes	No
Fully iterative plasticity in some metallic material models (type 3 solids, 24 shells/solids, 123 shells/solids), for enhanced accuracy and implicit convergence.	Yes	No
Consistent tangent modulus in material 24, accounting for relatively large plastic strains.	Yes	No

Try accuracy option IACC=1 on *CONTROL_ACCURACY

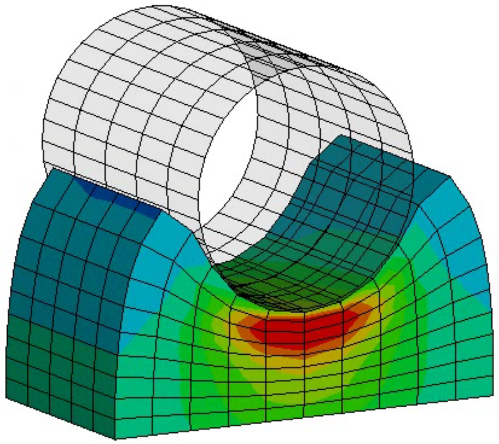
- Example: Plastic deformation of metal part
  - *MAT_024 with LCSS
  - DNORM=1
  - ENDTIM=0.014
  - DTMAX=0.001
  - Only a few large steps in implicit analysis for plastic straining of 7 %
  - Smaller steps would also help, or other material models

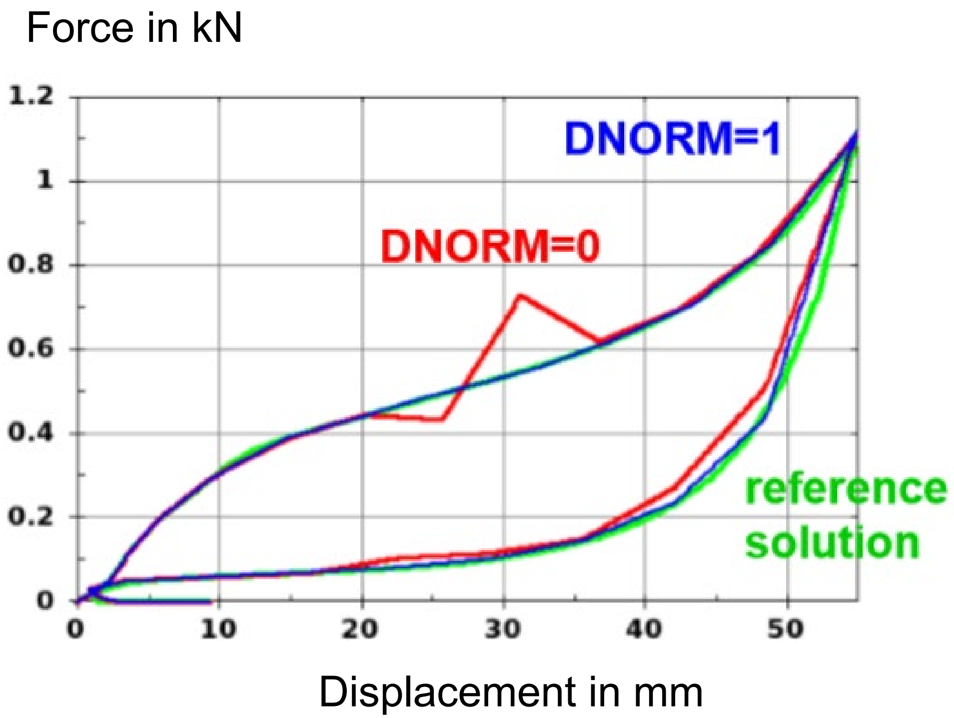




Set DNORM=1 on *CONTROL_IMPLICIT_SOLUTION

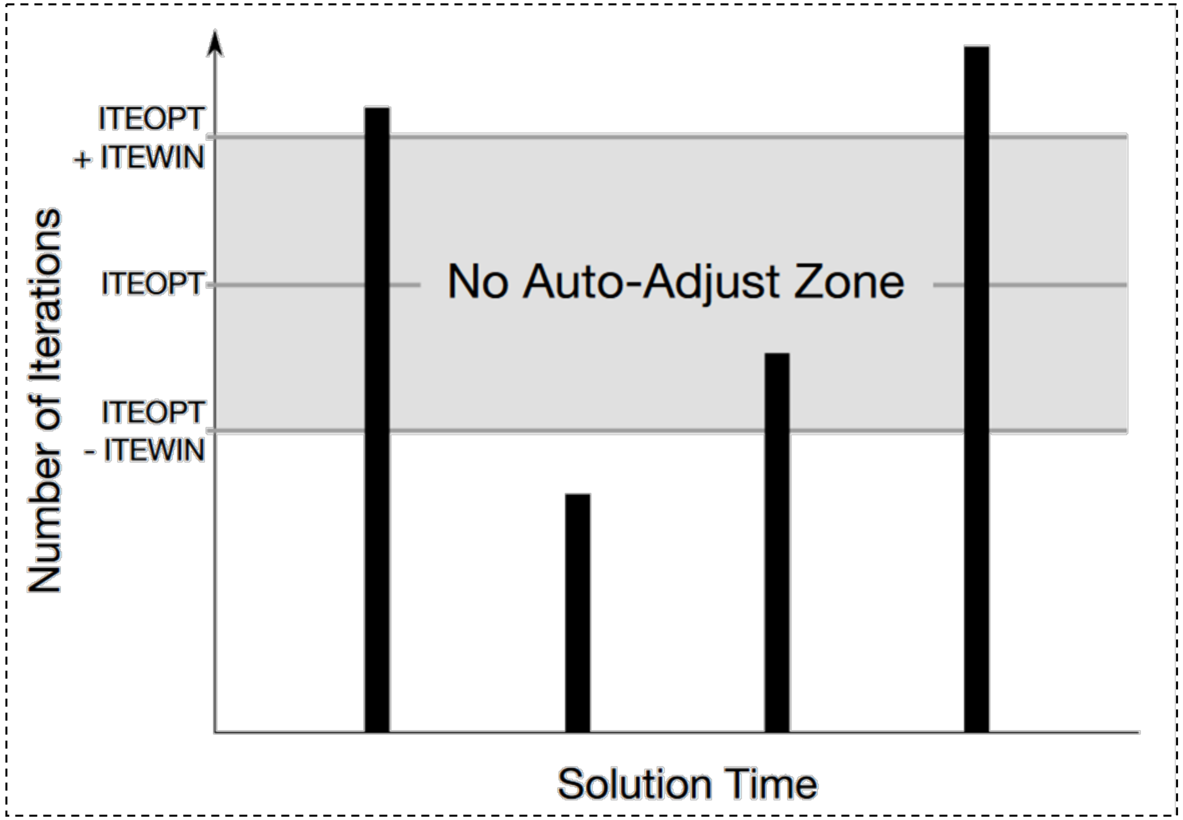
- Example: Compression of a foam block
  - *MAT_FU_CHANG_FOAM
  - ENDTIM=20.0,
  - DTMAX=1.0,
  - DCTOL=0.005,
  - ELFORM=1, IHQ=6, QM=1.0





Keep an eye on time step evolution

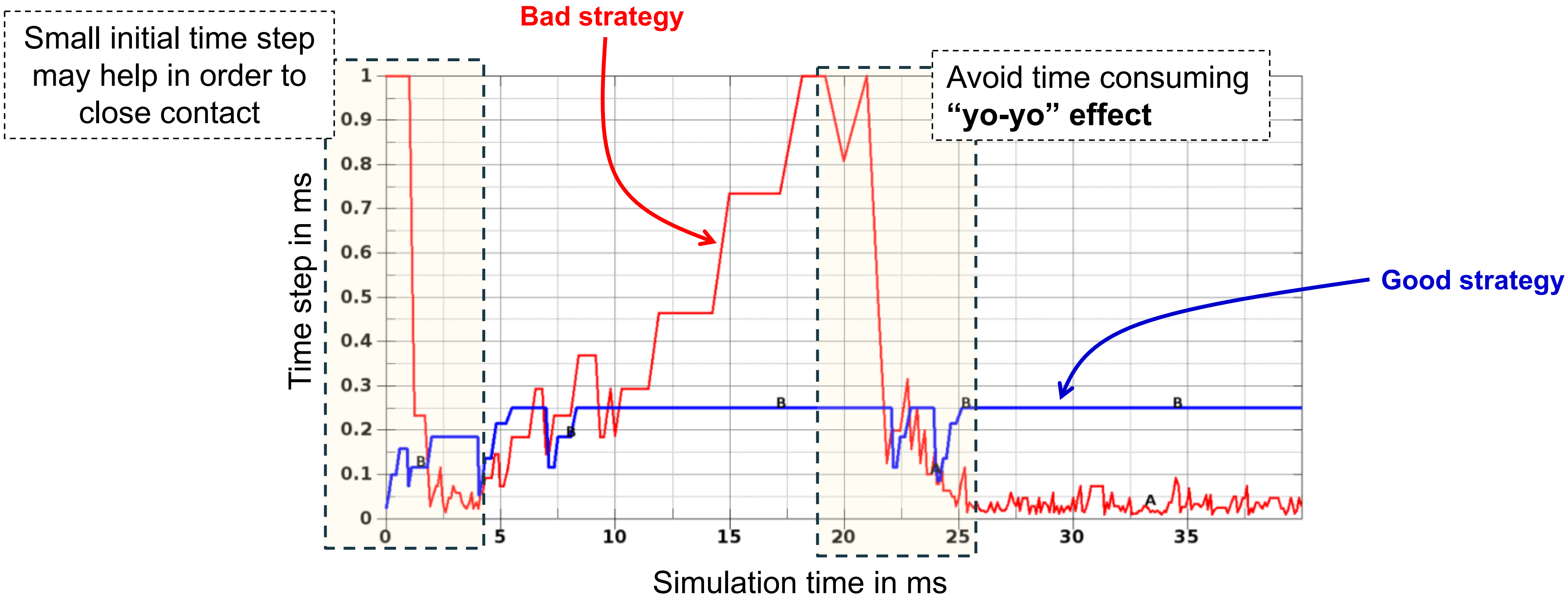
- Automatic step size control adjusts stepsize during simulation
  - Very persistent, reliable



- After successful steps
  - compare iteration count to target value ITEOPT
  - increase/decrease size of next step if difference exceeds window ITEWIN
- After failed steps
  - decrease step size
  - back up, repeat failed step with new DT
- Exponential algorithm for adjusting step size
  - Increase stepsize by 1/5 decade until DTMAX is reached
  - Decrease stepsize by 1/3 decade until DTMIN is reached
  - Error termination if convergence fails when DT=DTMIN

Keep an eye on time step evolution

… > glstat > time step



Be aware of causes and consequences of ill-conditioning

- Causes of ill-conditioning
  - Large stiffness differences (thin shells, varying stiffness moduli, etc.)
  - Elements of severe shape distortion or large aspect ratio
  - Fine meshes and mixing elements of different size
  - High Poisson's ratio (nearly incompressible materials)

A numerical measure of the ill-conditioning is the condition number of the system

$$\text{accuracy digits lost} \approx \log_{10} C(\mathbf{K})$$

- Consequences of ill-conditioning
  - Difficult (iterative) solution of linear equation system
  - Possible loss of accuracy
  - Possible bad convergence

- If a set of equations is seriously ill-conditioned
  - usually better to rework the FE model than to make heroic attempts to improve a poor solution by iteration

If a thing is not worth doing, it is not worth doing well.

Nonlinear convergence problems

- Output / Debugging
  - Activate print flags (LPRINT, NLPRINT) to get more information
  - Determine reason for termination (check d3hsp / messag files)
  - Set MINFO=1 on `*CONTROL_OUTPUT` for Mortar contact information like penetrations, release, …
  - In case of convergence problems, dump iteration states
    residual forces in d3plot and d3iter via RESPLT=1 on `*DATABASE_EXTENT_BINARY`

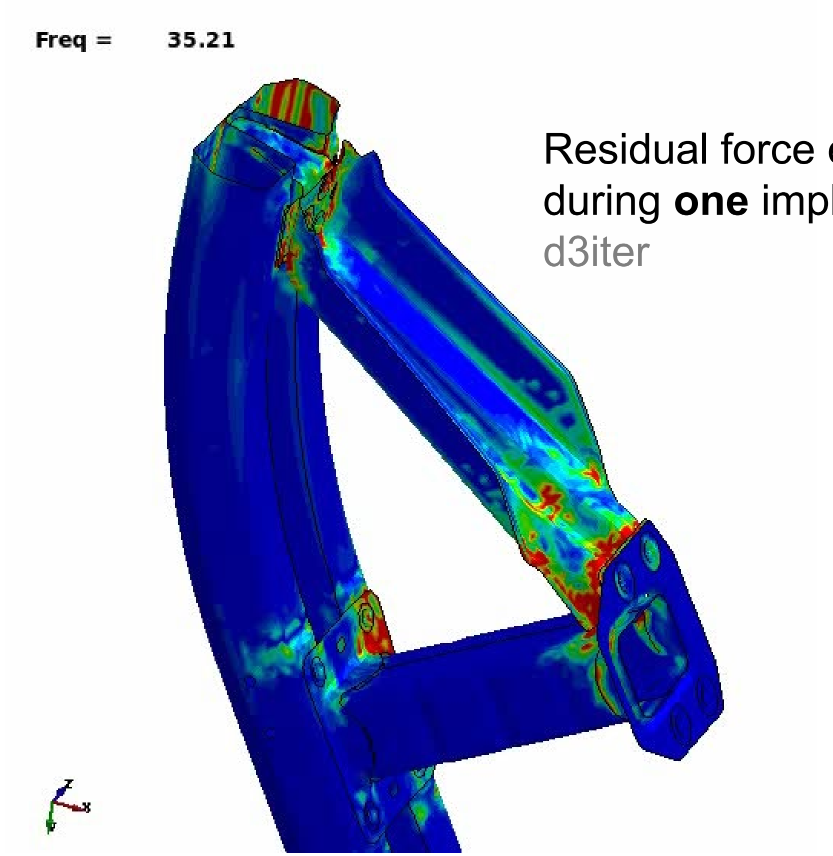
from R12.0
new option PENOUT

- Carefully inspect input deck and check …
  - if you use second order stress update (make sure you do)
  - smoothness on curves
  - material properties
  - contact penetrations, remove
  - magnitude of loads
  - contacts, make sure soft part is slave
  - elements, avoid small jacobians and distorted elements

Output of non-converged steps

- With D3ITCTL ≥ 1 on *CONTROL_IMPLICIT_SOLUTION
  - search directions for the nonlinear implicit solution are written to the d3iter database
  - together with RESPLT=1 on *DATABASE_EXTENT_BINARY, residual values can be fringed

Deformation history
d3plot



Residual force evolution during **one** implicit step
d3iter

Recommendations, cont‘d

- For “typical” implicit analysis, the following keyword setting is a good start

```
*CONTROL_ACCURACY
$       osu       inn    pidosu      iacc
          1         4                   1
*CONTROL_IMPLICIT_GENERAL
$    imflag       dt0    imform      nsbs       igs
          1       ...                           (1)
*CONTROL_IMPLICIT_SOLUTION
$    nsolvr    ilimit    maxref     dctol     ectol     rctol  lstol  abstol
                    6                                                (1.e-20)
$     dnorm    diverg     istif   nlprint    nlnorm    d3itctl
          1                             3       (4)      (10)
$

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

Information, Help, Inspiration, …

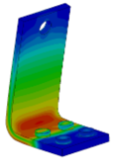
www.dynasupport.com
→ HowTos → Implicit

- Elements and material models available for implicit
- General remarks on implicit time integration
- Implicit: Contact treatment
- Implicit: Convergence
- Implicit: Dynamic relaxation
- Implicit: Loads on rigidbodies
- Implicit: Memory notes
- Implicit: Recommendation on solid element formulation
- Some guidelines for implicit analyses using LS-DYNA
- Switching from implicit to explicit
- Implicit: Mortar Contact
- Implicit: Checklist

Starter kit including guidelines

- Basic control card settings suitable for different implicit analysis
- types Accompanied by some basic examples.
- Purpose is to reduce the effort of getting started with implicit analysis
- also includes information about Implicit Mortar Contact Problems

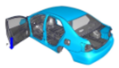
www.dynaexamples.com/implicit



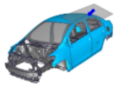
Salzburg 2017
Linear Examples 1-6 and Nonlinear Examples 1-3 from "A Roadmap to Linear an Nonlinear Implicit Analysis in LS-DY... more

Yaris Static Suspension System Loading
This example shows the static loading of the TOYOTA Yaris suspension system. The car model is based on the CCSA (former... more

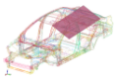
Yaris Dynamic Suspension System Loading
In this example we want to demonstrate the dynamic loading of the TOYOTA Yaris suspension system as an alternative... more



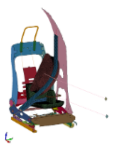
Yaris Static Door Sag
In the door sag load case a z-force is applied to the opened vehicle door in a quasi-static manner. The slow mode... more



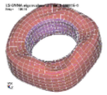
Yaris Dynamic Roof Crush
One of the tests used in occupant safety analysis is a roof crush test. It is used to evaluate how a car will deform durin... more



Implicit Roof Crush
This problem demonstrates the ability to solve a complex, highly dynamic and nonlinear problem using the implicit... more



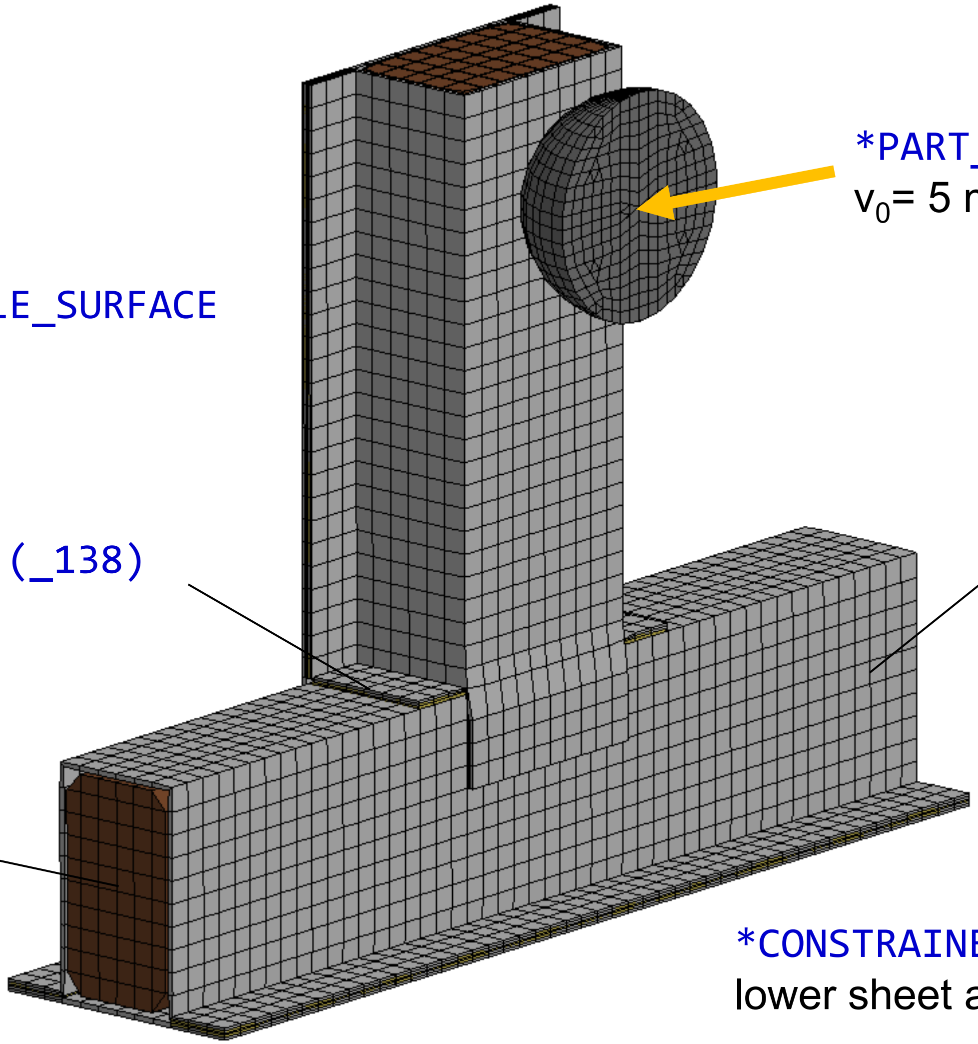
Implicit Seat Pull
This problem demonstrates the ability to solve a complex, highly dynamic and nonlinear problem using the implicit... more



Basic Examples
Set of basic examples to demonstrate the implicit capabilities of LS-DYNA.

Advanced and basic examples

T-joint component



*PART_INERTIA
v_0= 5 m/s

*CONTACT_AUTOMATIC_SINGLE_SURFACE
overall contact

*MAT_024
DP 800

*MAT_COHESIVE_MIXED_MODE (_138)
adhesive bond with failure

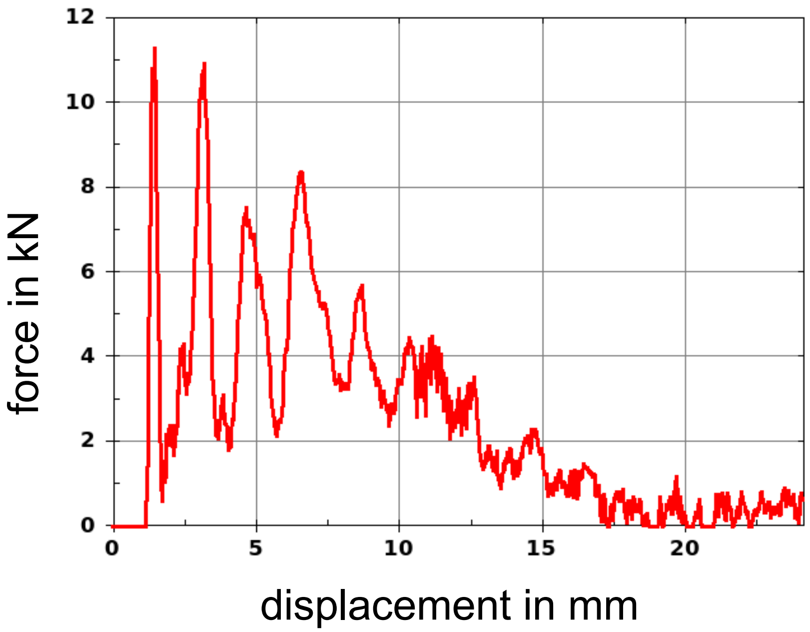
5 mm mesh
for steel parts

*MAT_024
wooden blocks

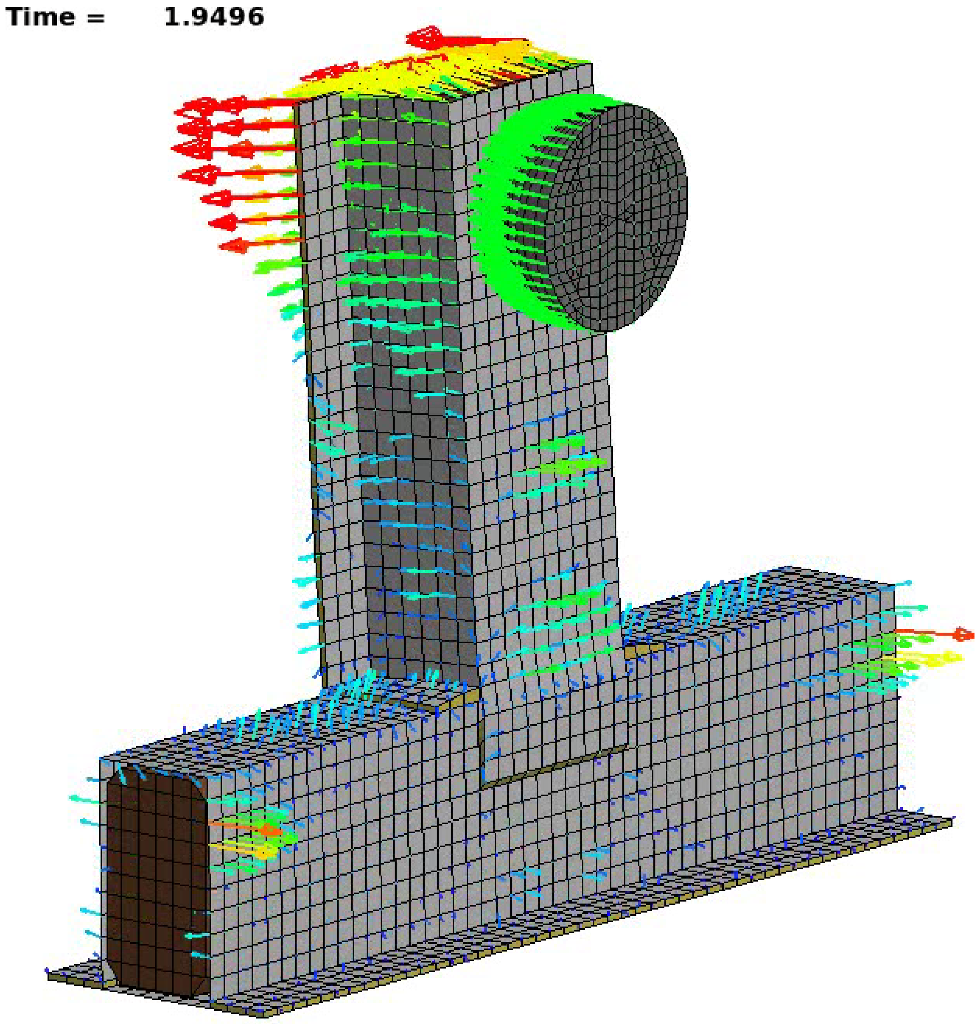
*CONSTRAINED_RIGID_BODY
lower sheet and wooden block

run with LS-DYNA version R7.1.1 MPP, single and double precision

- 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]



Now, we want do a static analysis of that process

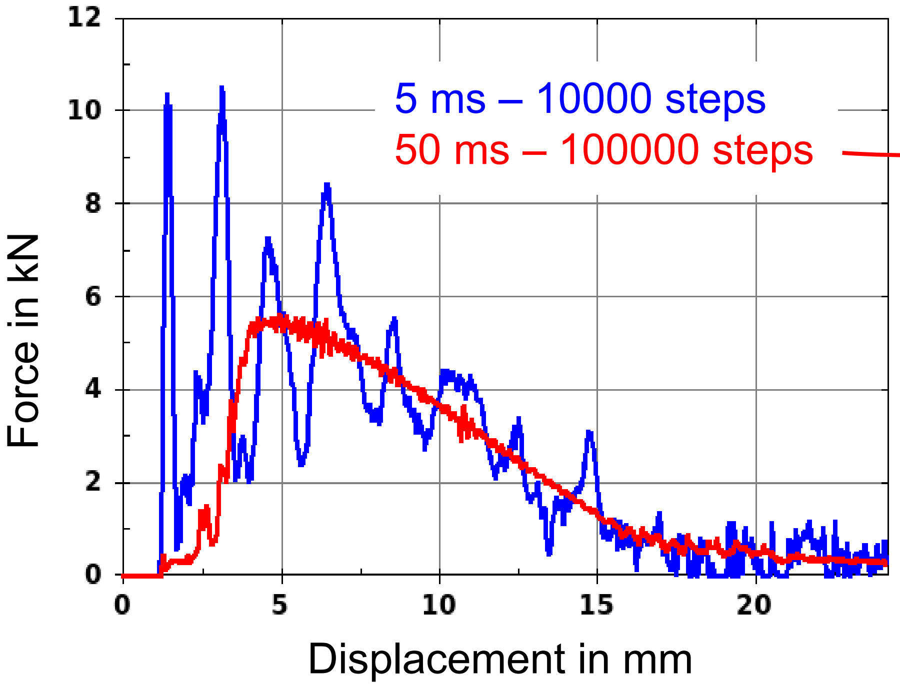
Step by step

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

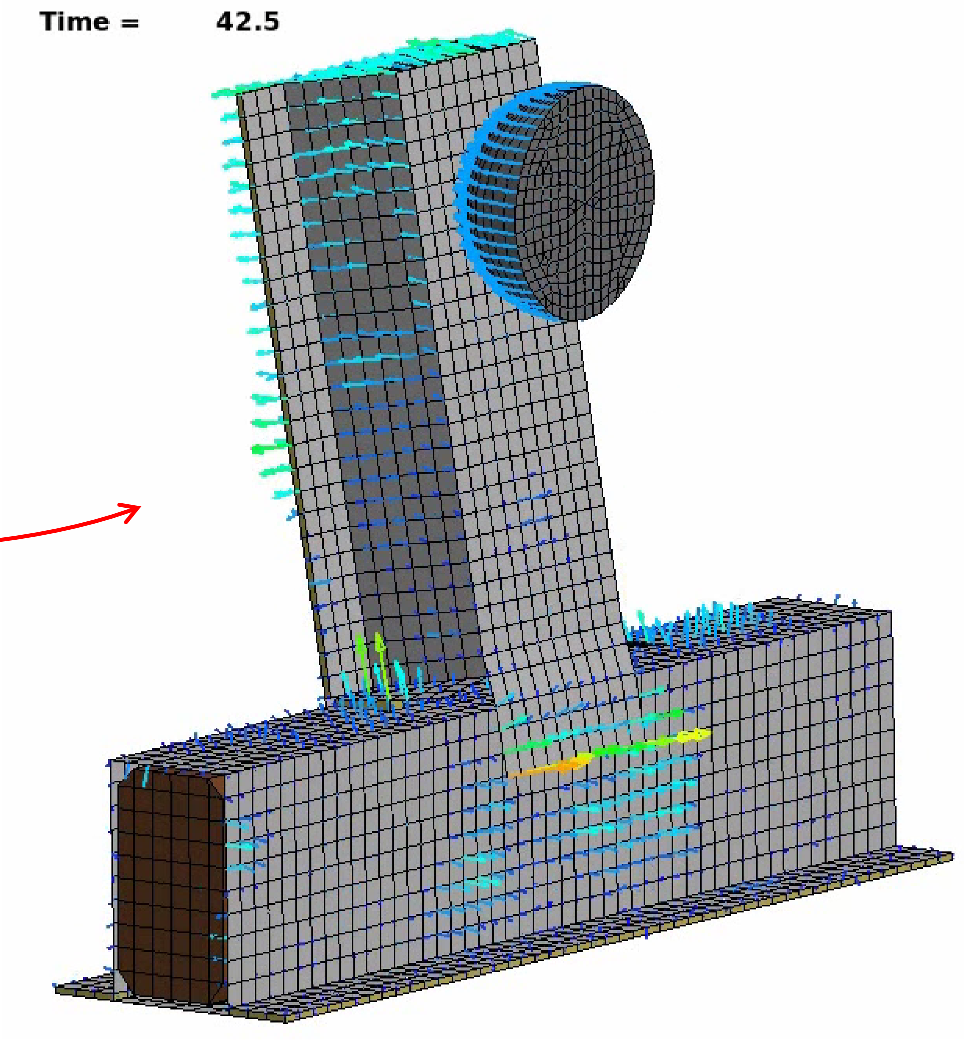
2. Add implicit cards needed for dynamic implicit analysis
   “fast“ and “slow“ loading

3. Remove dynamics and perform pure static analysis
   no physical time – only process time

- Static (??) explicit
  - Process time = 5 / 50 ms
  - Circa 10,000 / 100,000 time steps
  - No initial velocity, but prescribed motion
  - 52 cohesive elements fail
  - Response still dynamic
  - Damping … ??



velocity [0 - 3 m/s]



- Dynamic implicit (default)
  - Process time = 5 ms (“fast“)
  - *CONTROL_IMPLICIT_GENERAL

    DT0 = 0.05 (100 steps)
  - *CONTROL_IMPLICIT_DYNAMICS

    IMASS = 1

→

- 100 steps
- 2779 problem cycles
- 58 failed cohesives

- + Recommendations
  - *CONTROL_ACCURACY

    OSU=1
  - *CONTROL_IMPLICIT_SOLUTION

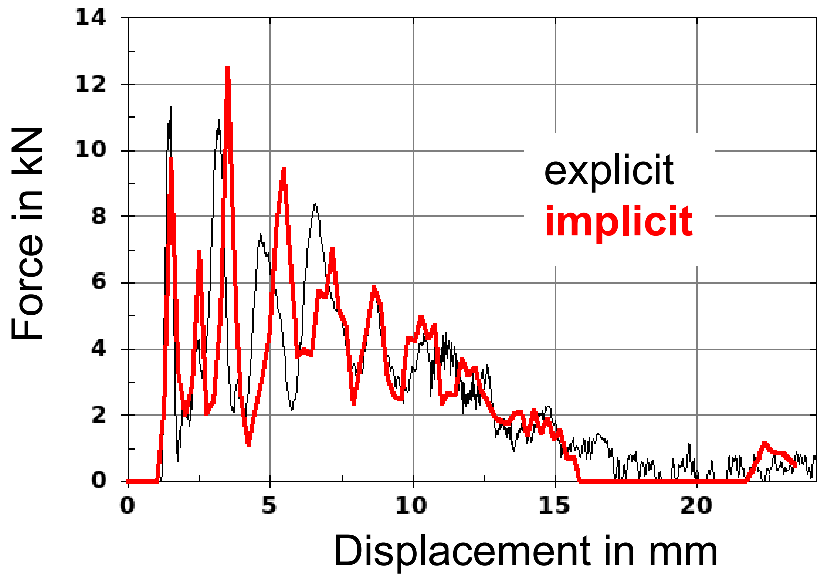
    NSOLVR=12, ILIMIT=6,
    DNORM=1 (DCTOL=0.005)
  - *CONTROL_IMPLICIT_AUTO

    ITEOPT=30, ITEWIN=10, DTMAX=0.1

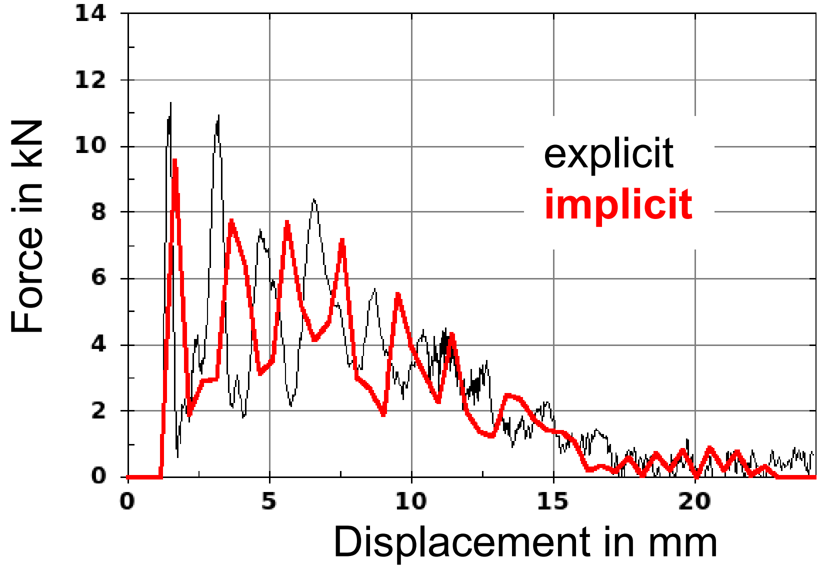
→

- 51 steps
- 1063 problem cycles
- 52 failed cohesives

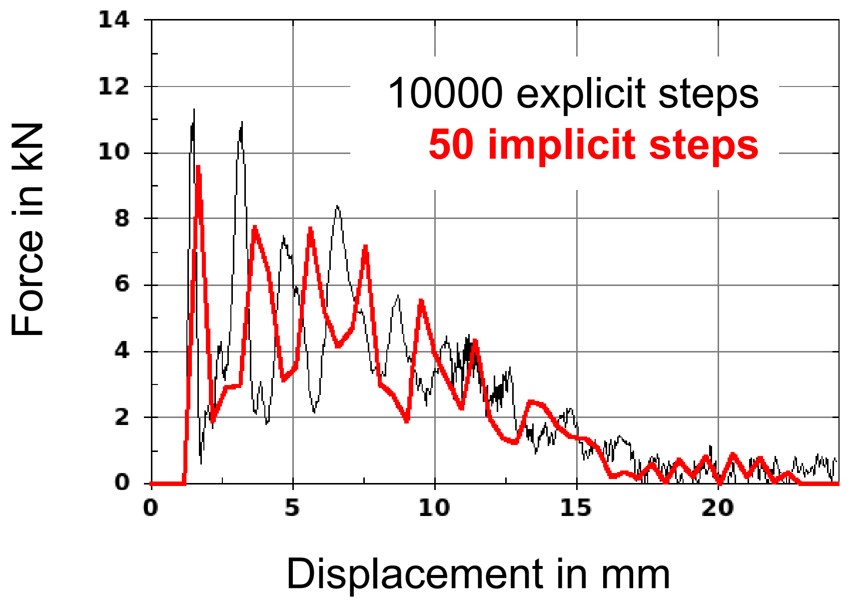
- Dynamic implicit (default)
  - Process time = 5 ms (“fast“)
  - *CONTROL_IMPLICIT_GENERAL
    DT0 = 0.05 (100 steps)
  - *CONTROL_IMPLICIT_DYNAMICS
    IMASS = 1

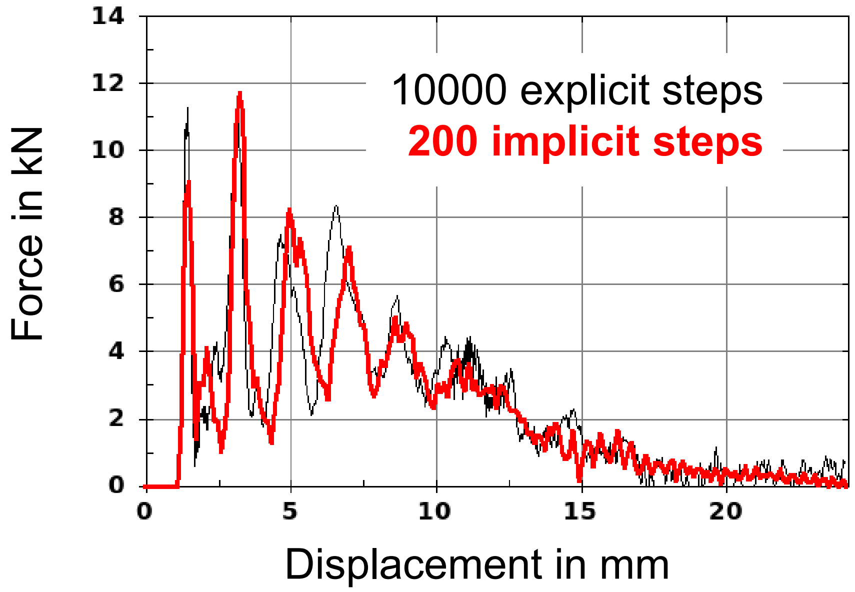


- \+ Recommendations
  - *CONTROL_ACCURACY
    OSU=1
  - *CONTROL_IMPLICIT_SOLUTION
    NSOLVR=12, ILIMIT=6,
    DNORM=1 (DCTOL=0.005)
  - *CONTROL_IMPLICIT_AUTO
    ITEOPT=30, ITEWIN=10, DTMAX=0.1

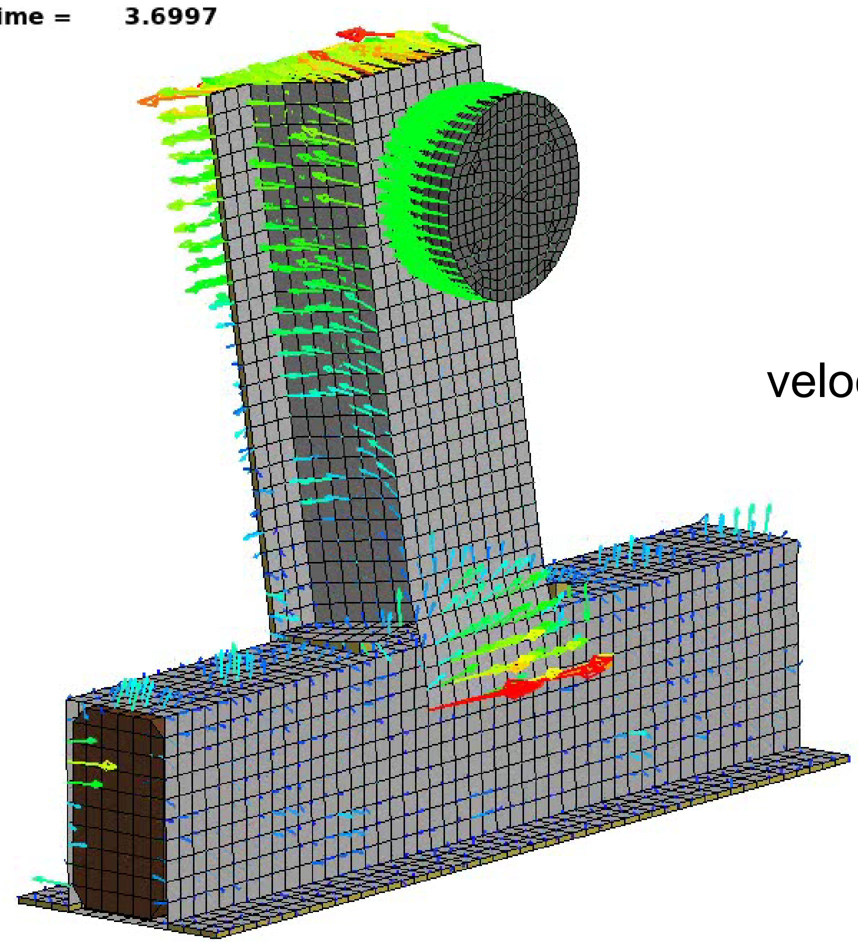


- Dynamic implicit
  - What time step size is necessary to resolve the dynamic process?
  - User needs good knowledge about the problem at hand
  - User has to decide about the solution frequency
  - Contact dominated problems need small time steps

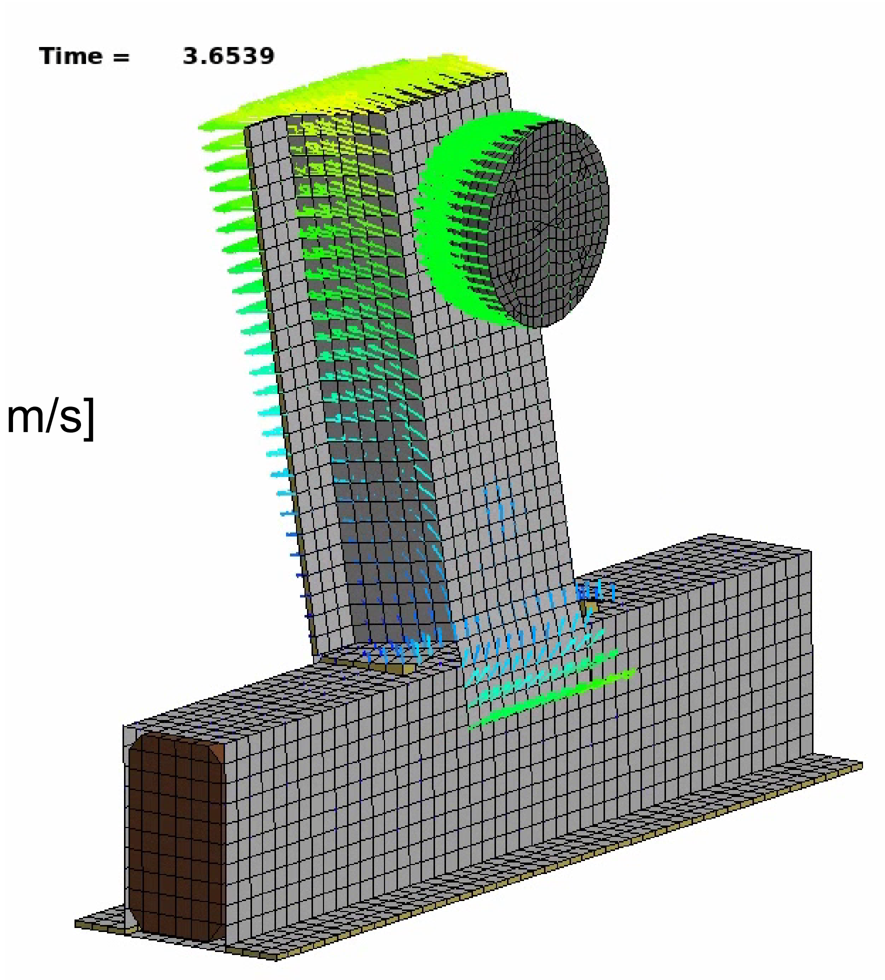




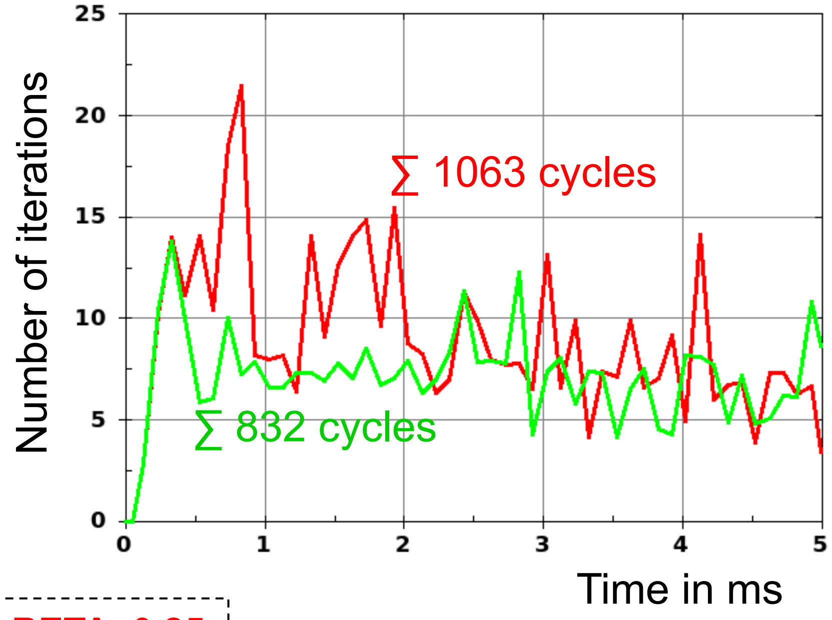
- Dynamic explicit
  - Low- and high-frequency response
- Dynamic implicit
  - Low-frequency response



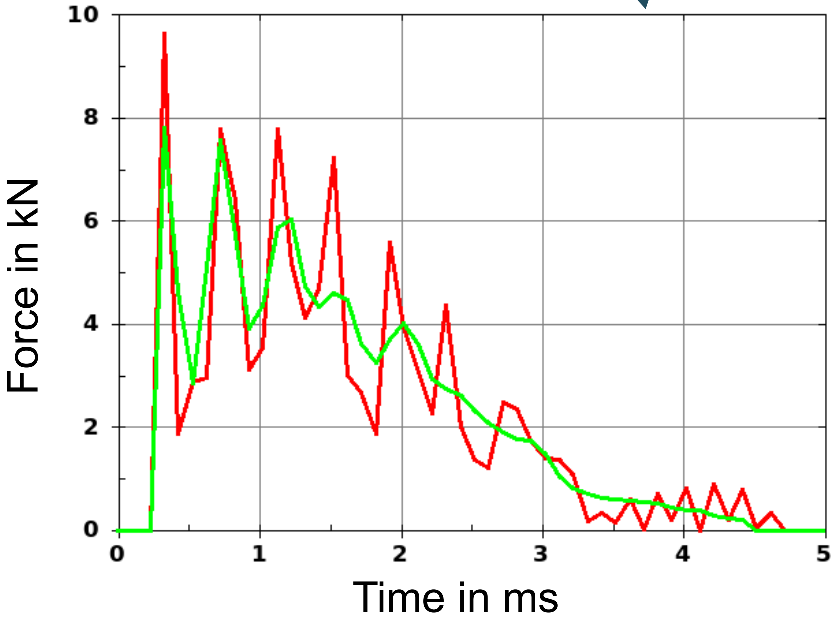
velocity [0 - 10 m/s]



- Dynamic implicit
  - Check influence of Newmark parameters GAMMA and BETA
  - Default: GAMMA=0.5, BETA=0.25
  - Larger GAMMA and BETA values introduce numerical damping
  - Often helps convergence
  - But: affects solution!



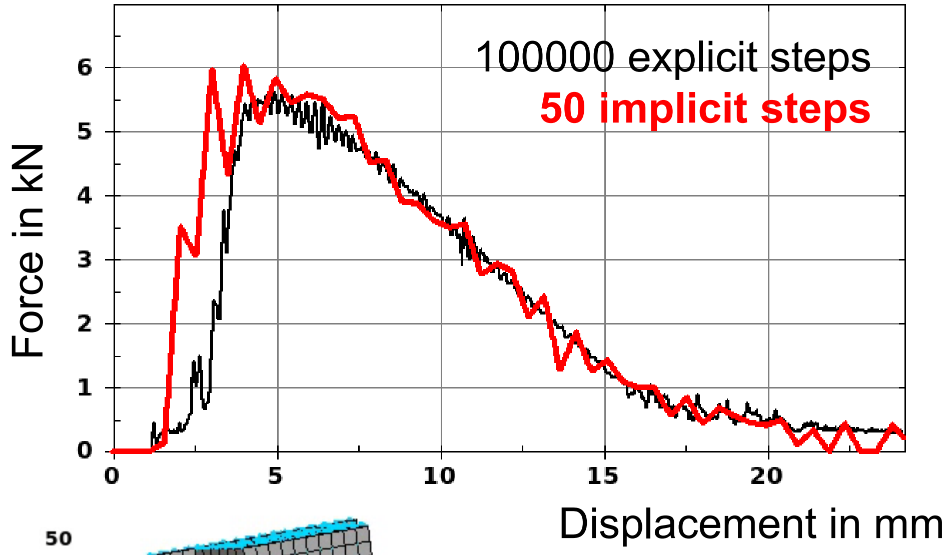
GAMMA=0.5, BETA=0.25
GAMMA=0.6, BETA=0.38

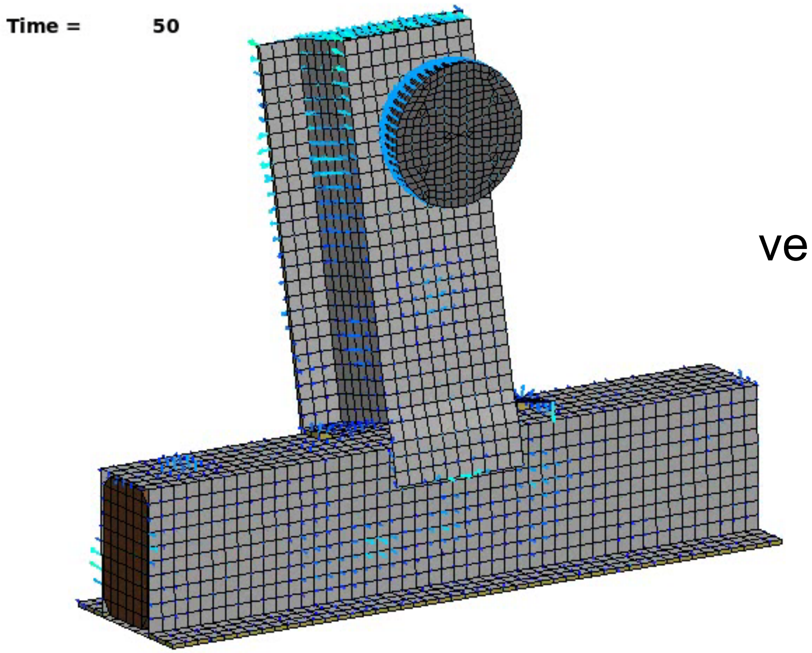


GAMMA and BETA can be used to introduce some numerical damping

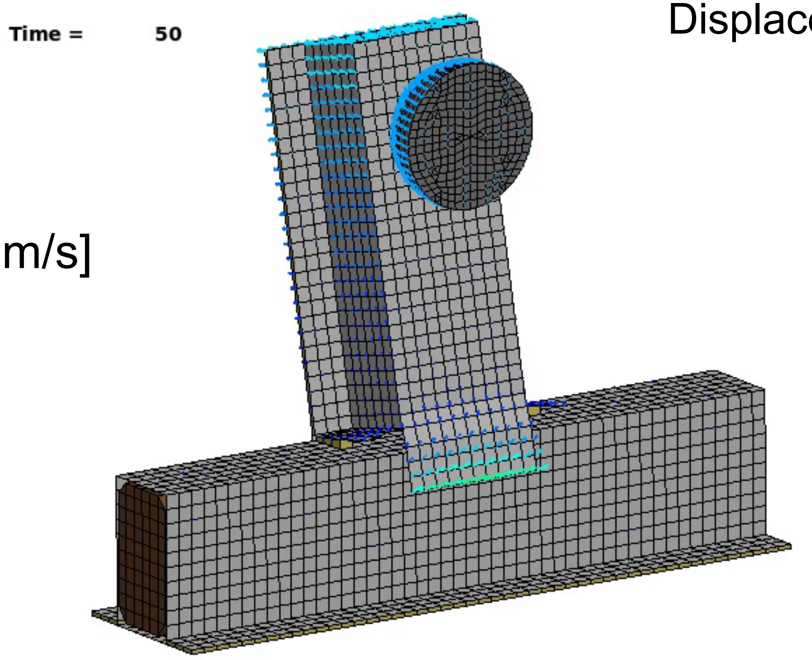
$$\gamma \geq \frac{1}{2}, \beta \geq \frac{1}{4}\left(\gamma + \frac{1}{2}\right)^2$$

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

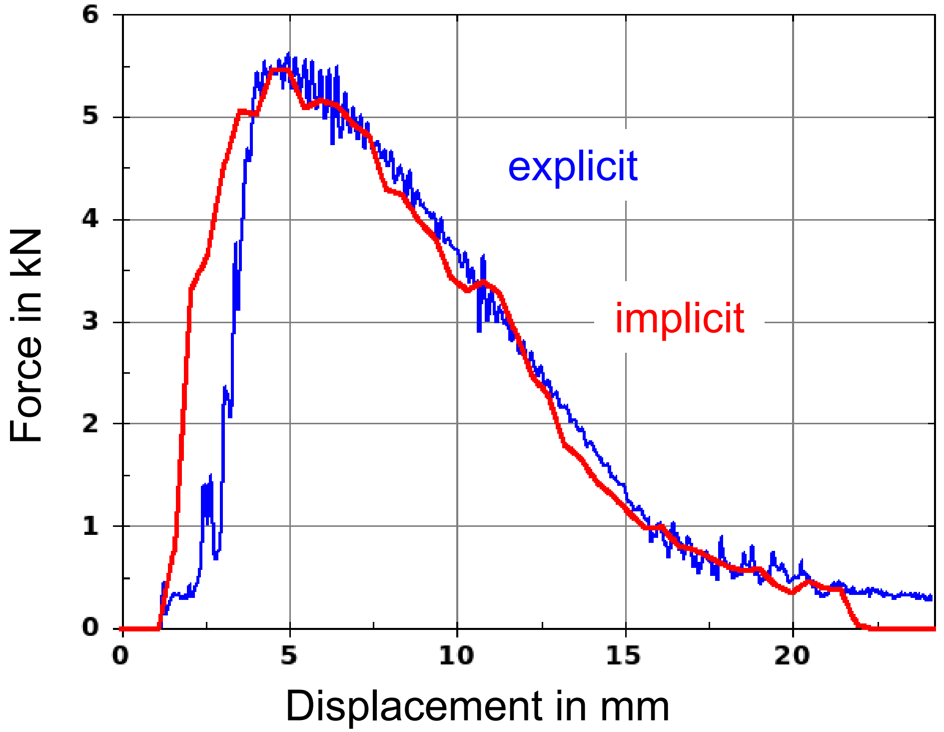


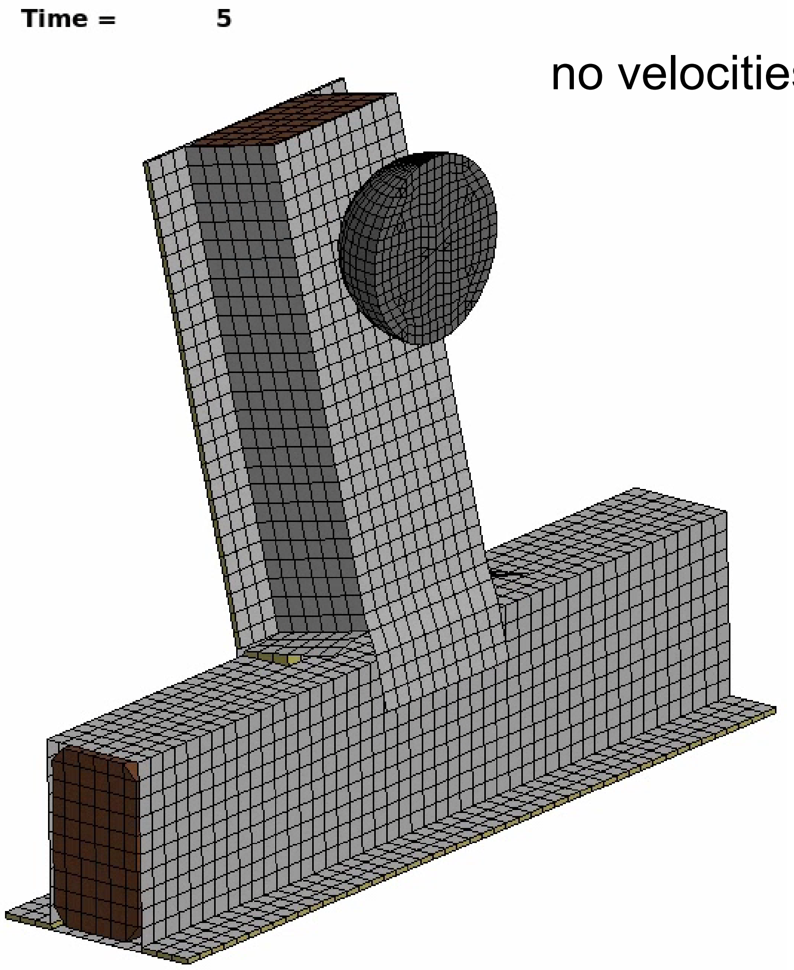


velocity [0 - 3 m/s]



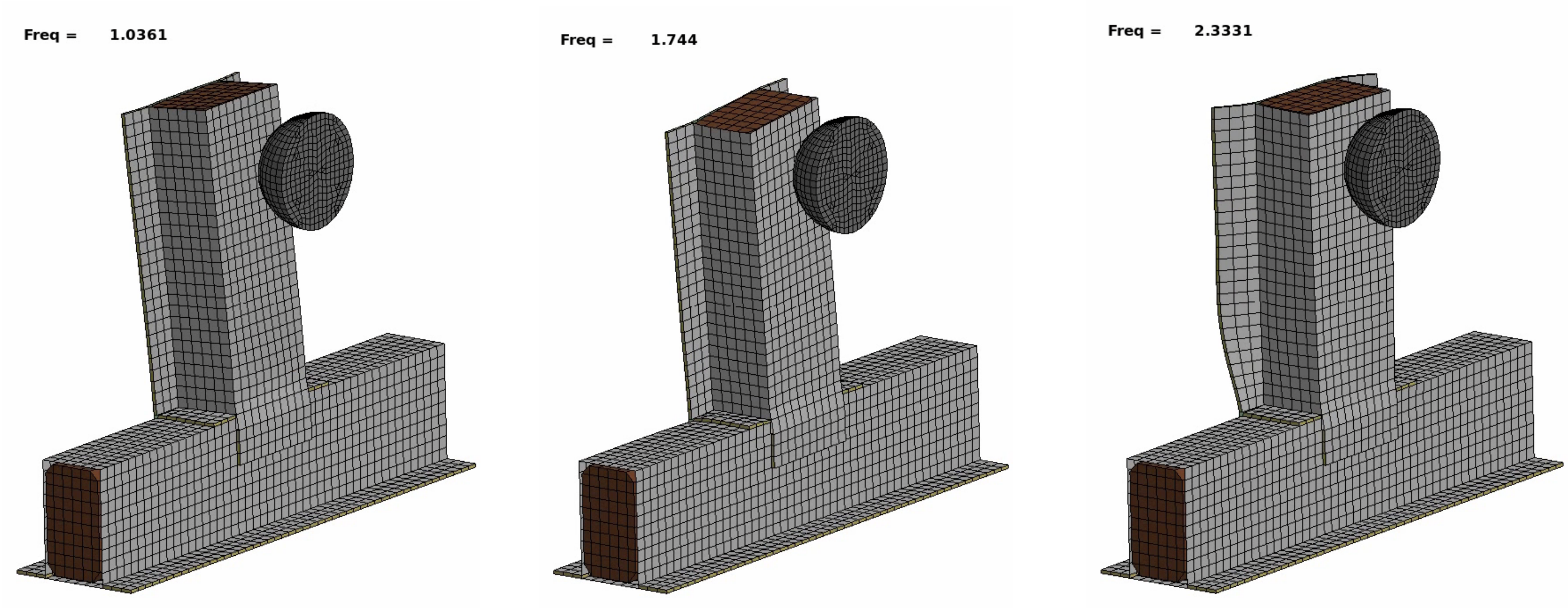
- Static implicit
  - Remove *CONTROL_IMPLICIT_DYNAMICS
  - No initial velocity, but prescr. motion
  - “Time“ not physical anymore
  - Real static response
  - Statically defined !?!



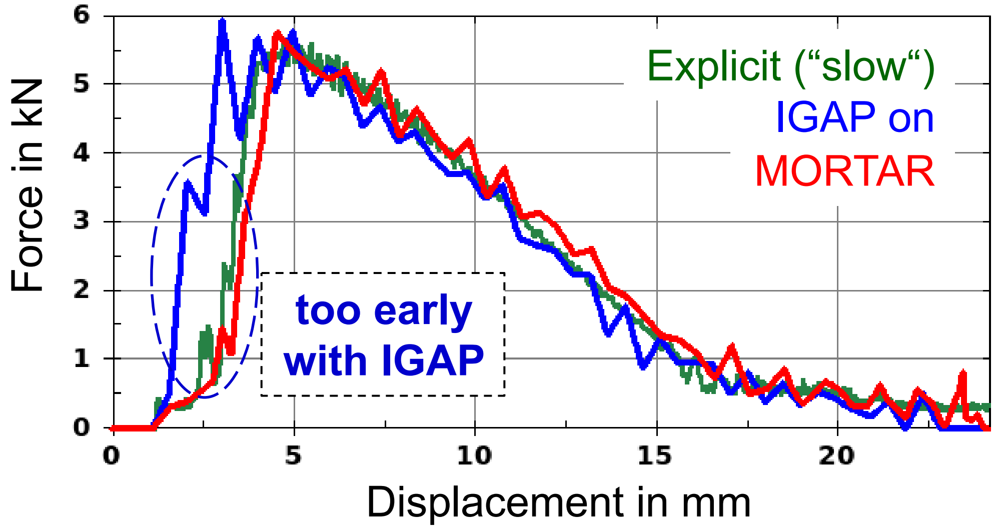


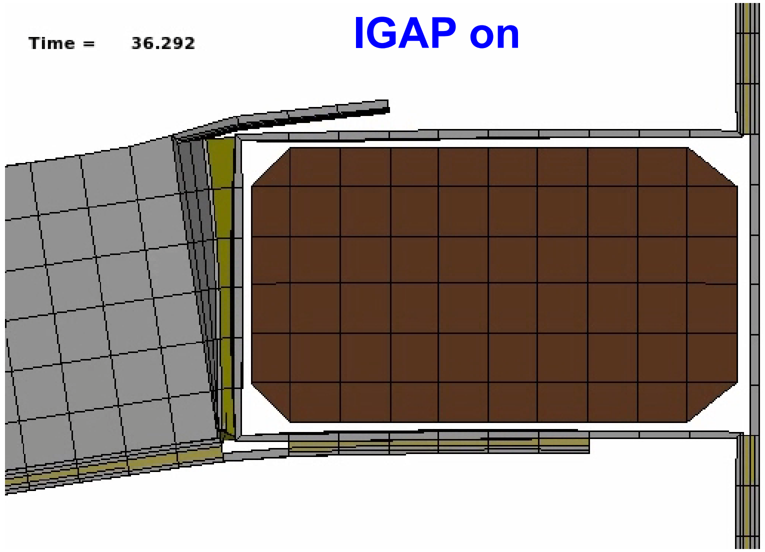
no velocities!

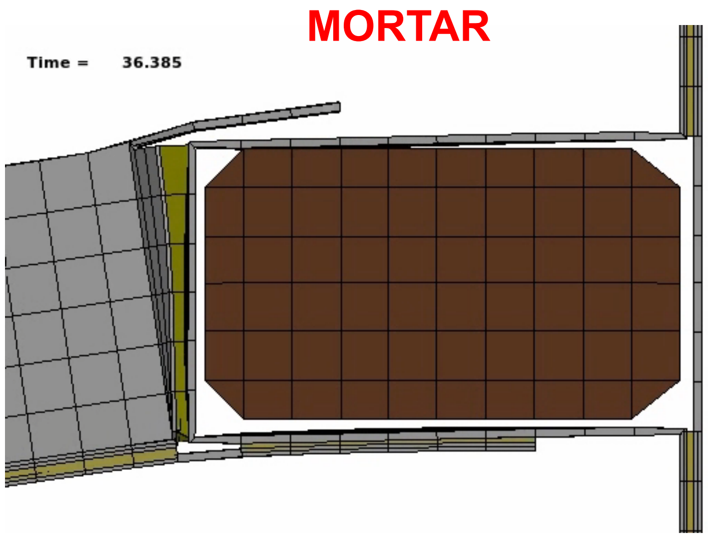
- Eigenvalue analysis
  - *CONTROL_IMPLICIT_EIGENVALUE
  - Reveals possible rigid body modes
  - Superelevated deformations in d3eigv database



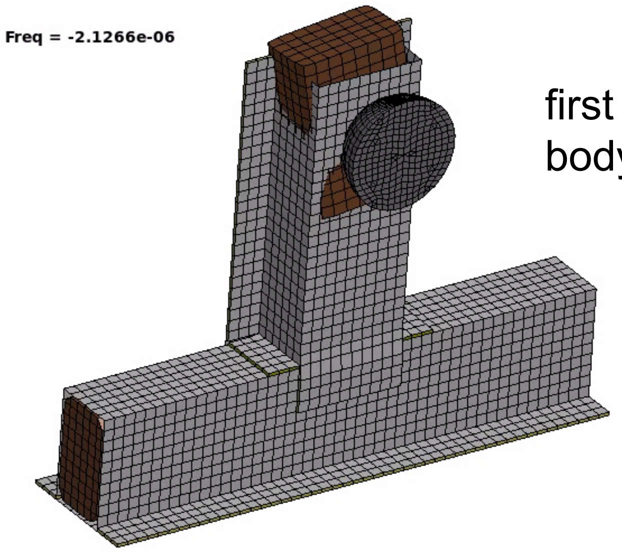
- Implicit contact
  - Contact is very important issue (especially) in implicit analysis
  - User should know about IGAP options (“sticky contact“) and Mortar contact (continuous tangent)
  - Dynamic implicit shown here



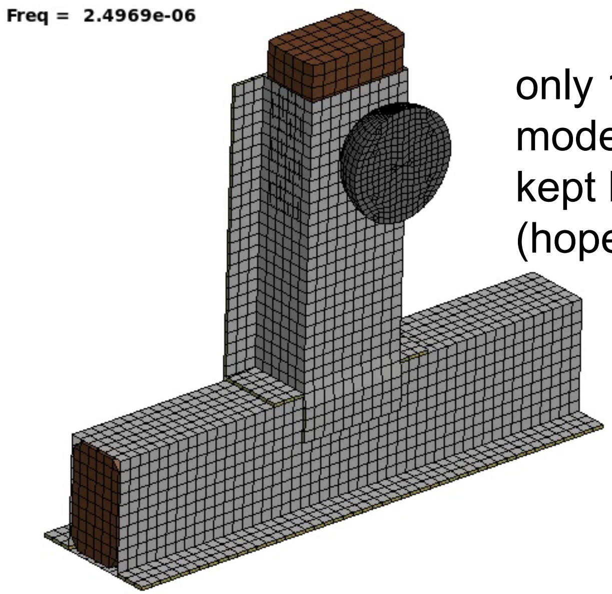




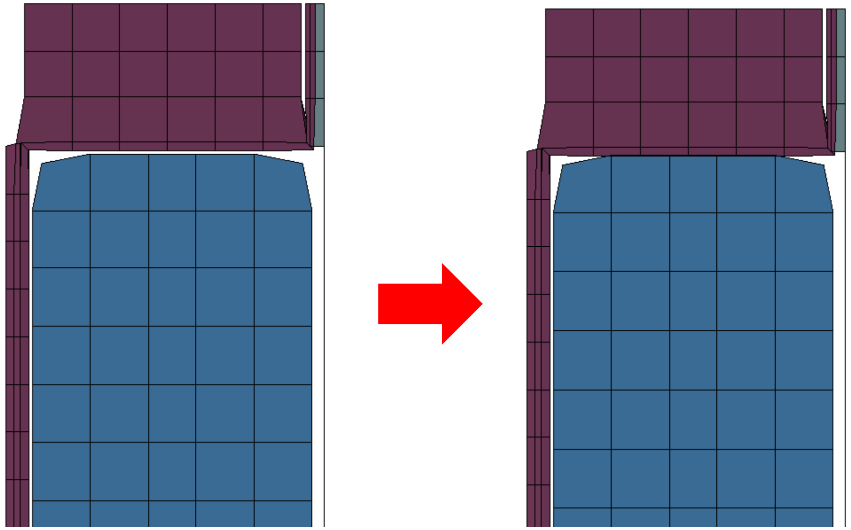
- Static implicit with Mortar contact
  - “Missing“ contact gap now reveals 6 rigid body modes (wooden block)
  - Additional action(s) needed to allow for static analysis
  - Slight **scaling** of wooden block‘s size causes initial contact penetration to get statically determined system
  - +IGNORE=1 to avoid initial contact forces



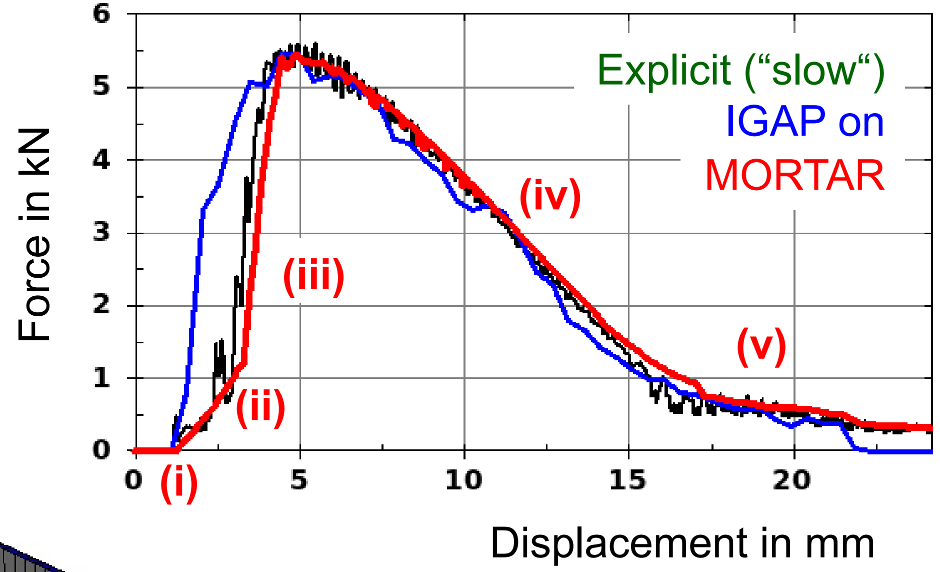
first of 6 rigid body modes

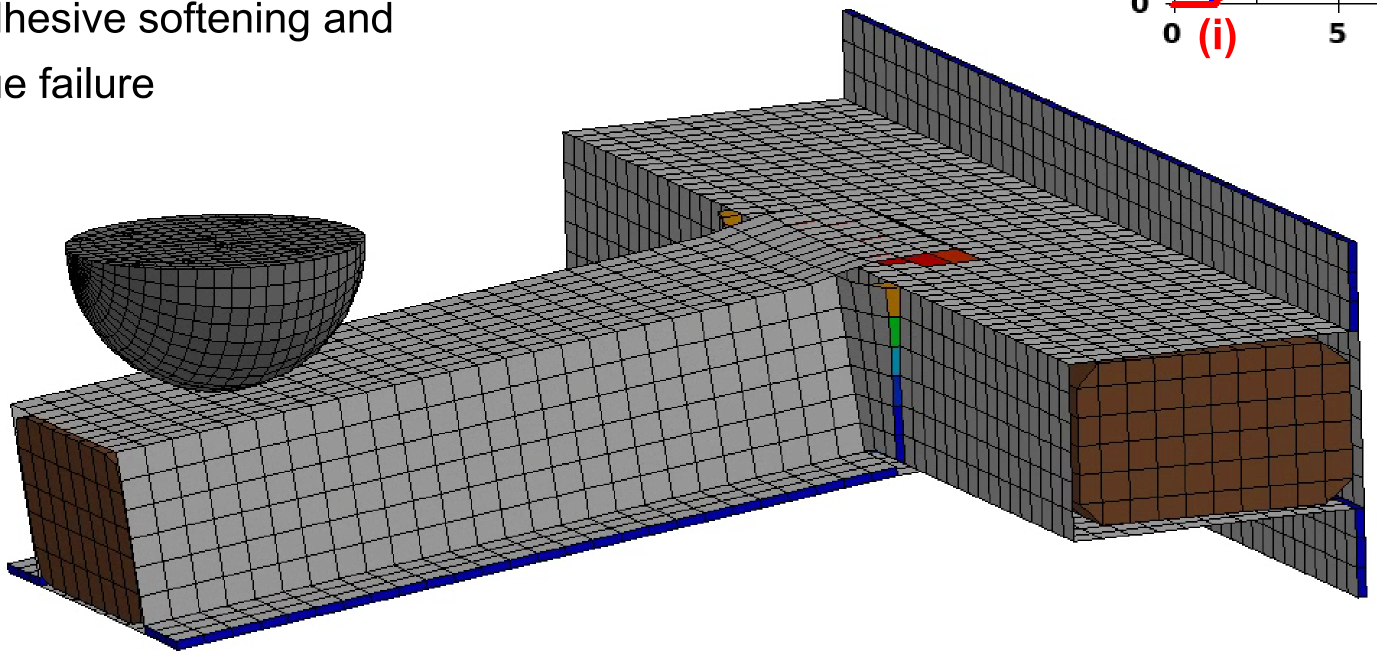


only 1 rigid body mode left, will be kept by friction (hopefully)

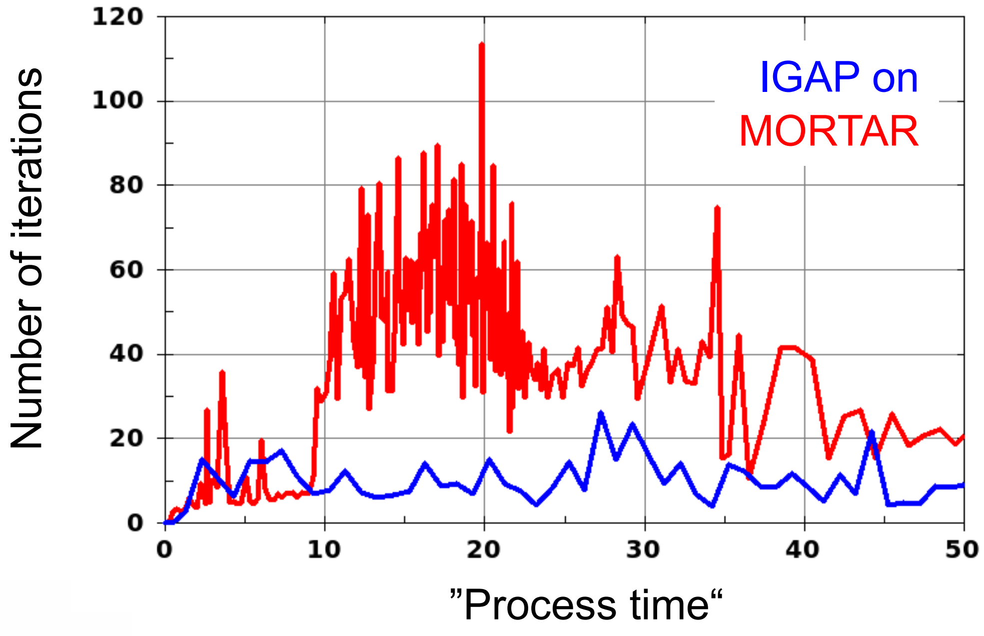


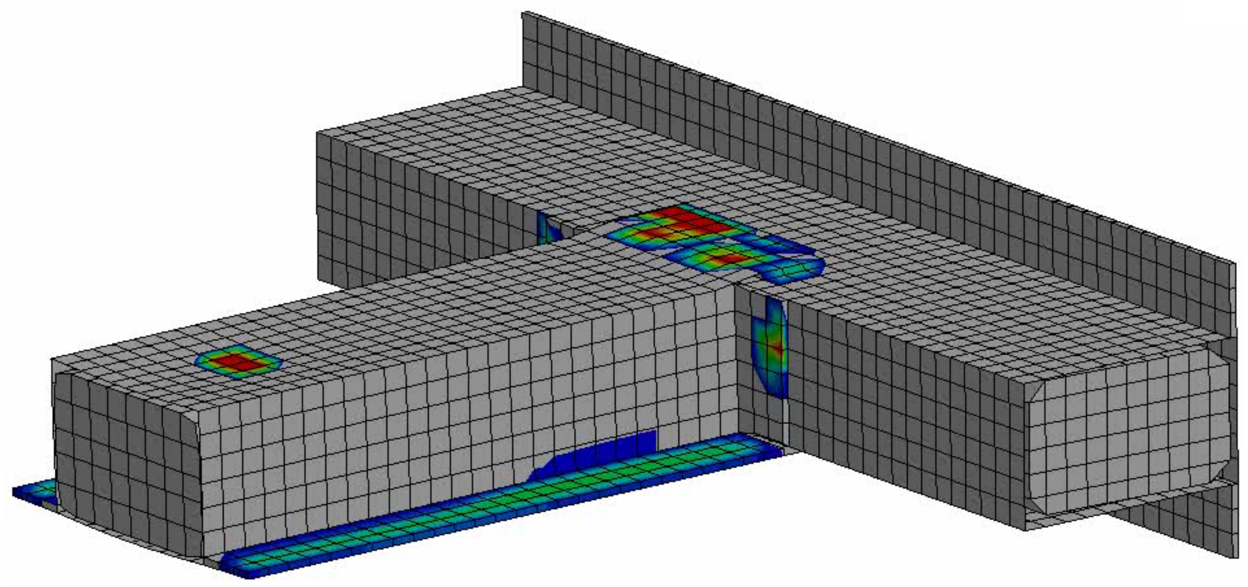
- Static implicit with Mortar contact
  - More realistic results with Mortar contact
  - 5 different phases can be observed:
    (i) no contact,
    (ii) tipping,
    (iii) elastic bending,
    (iv) adhesive softening and
    (v) glue failure





- 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

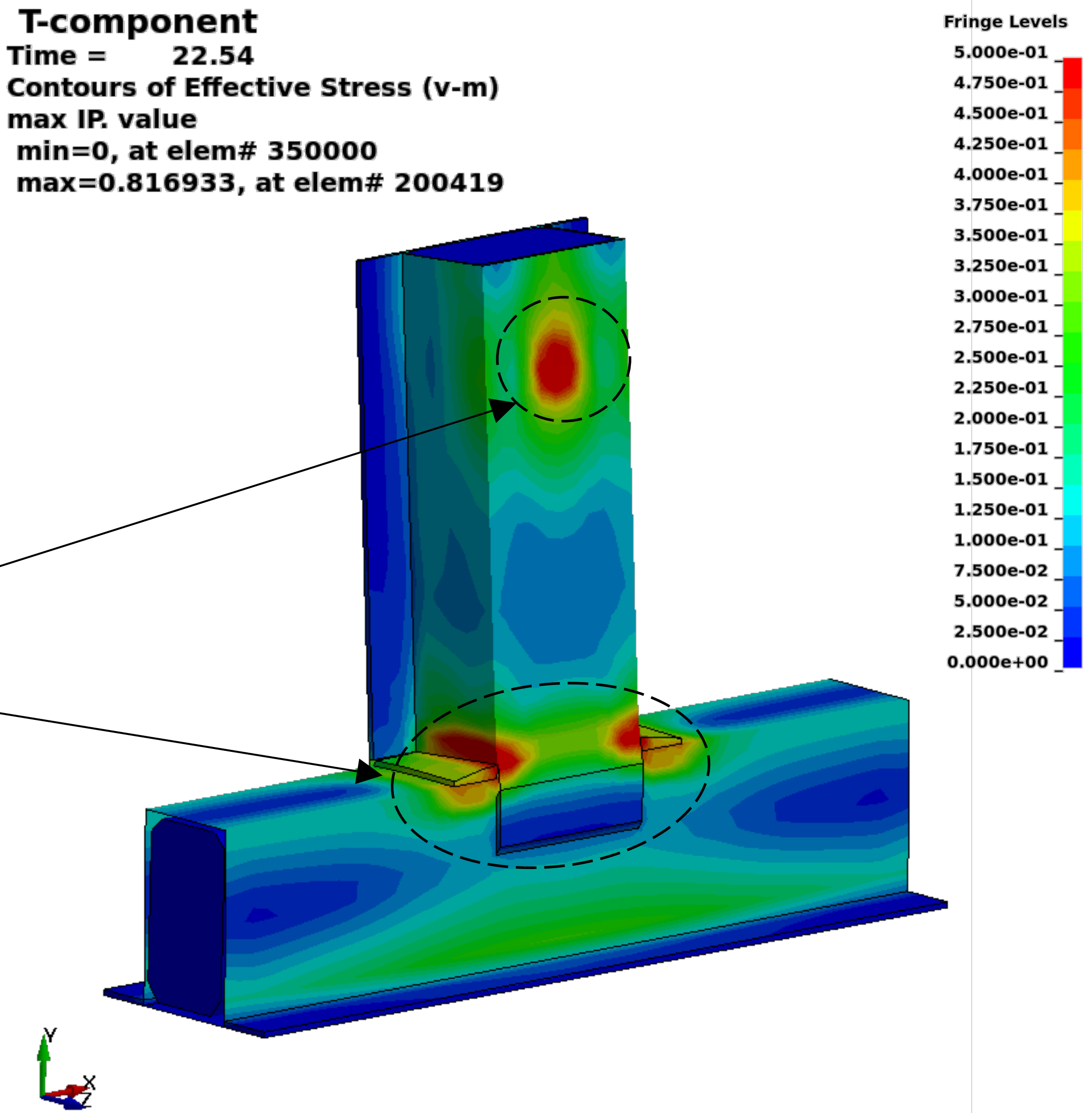




Troubles from damage evolution in cohesive material and contact to impactor

DYNA MORE

- 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 its limits for long duration processes or even real static load cases

- Therefore, implicit analysis is often preferable. Actually, computation time can be decreased in many cases

- But: more demanding to get a solution, especially for large deformations, contact and nonlinear material behavior

- 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

DYNA MORE