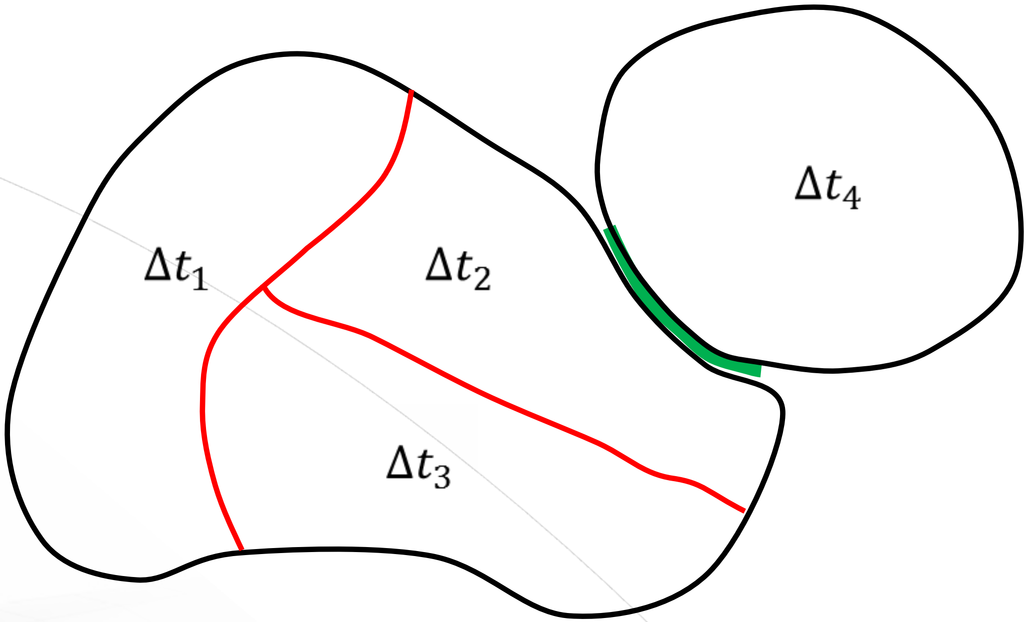
Current Status of Subcycling and Multiscale Simulations in LS-DYNA

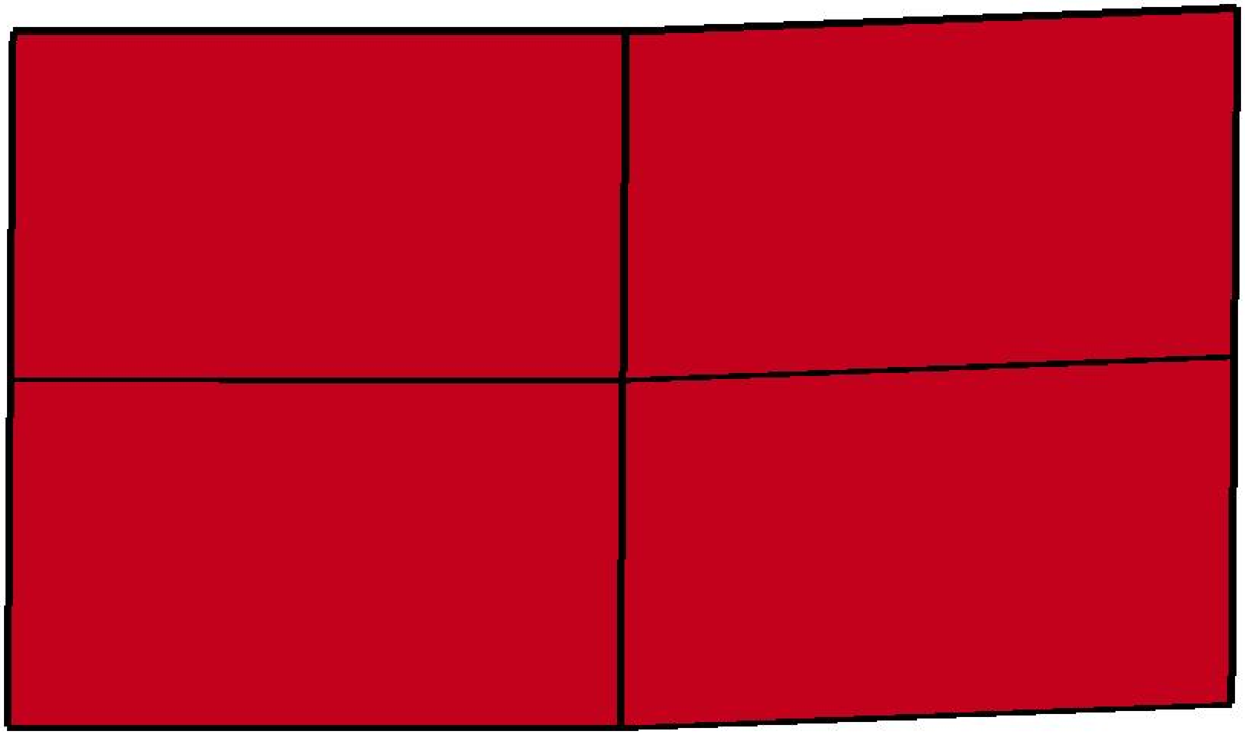
Thomas Borrvall, DYNAmore Nordic AB, Linköping, Sweden
Dilip Bhalsod, LSTC, Troy, MI
John O Hallquist, LSTC, Livermore, CA
Brian Wainscott, LSTC, Livermore, CA

Need for Speed - Subcycling



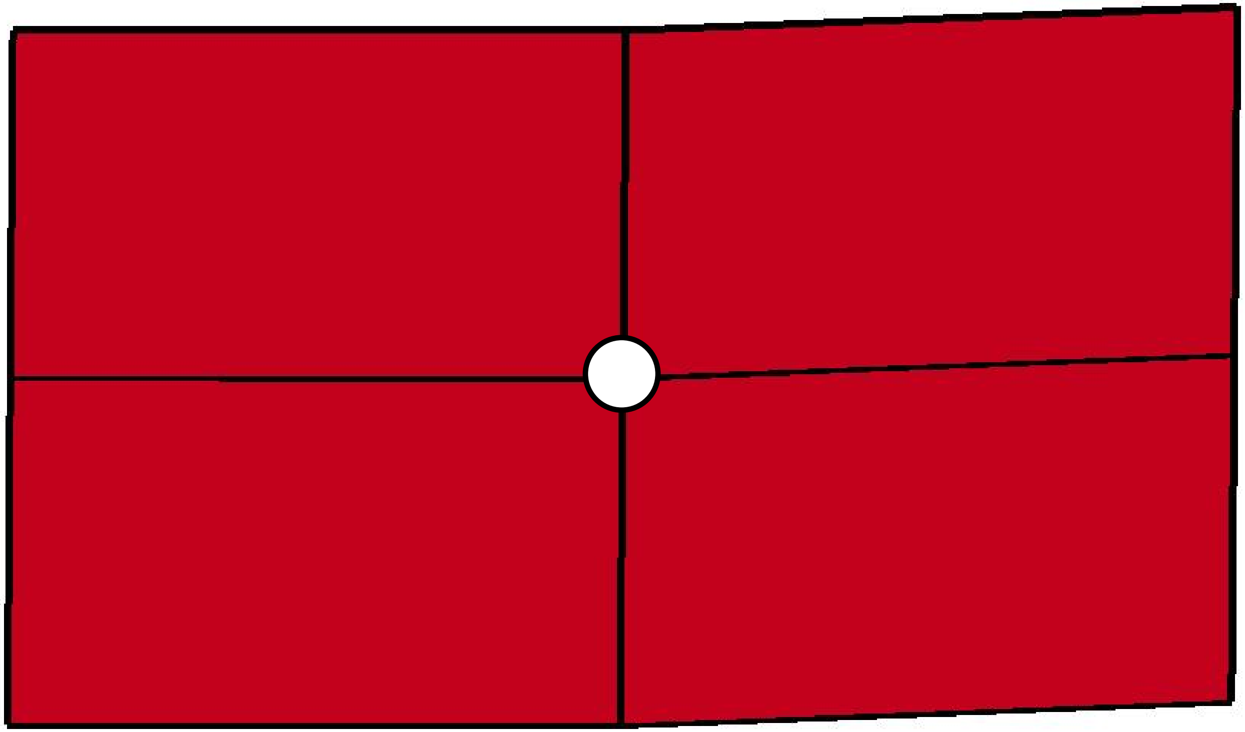
- Explicit time integration using different time steps in different subdomains
- How is one to treat boundary between domains?
  - Spurious wave propagation across domains
  - Different proposals
- Does it really work?
  - Some say yes, some say no
  - The implementation is undertaken with a positive mindset - it will work !!!

The Courant stability criterion made intutitive



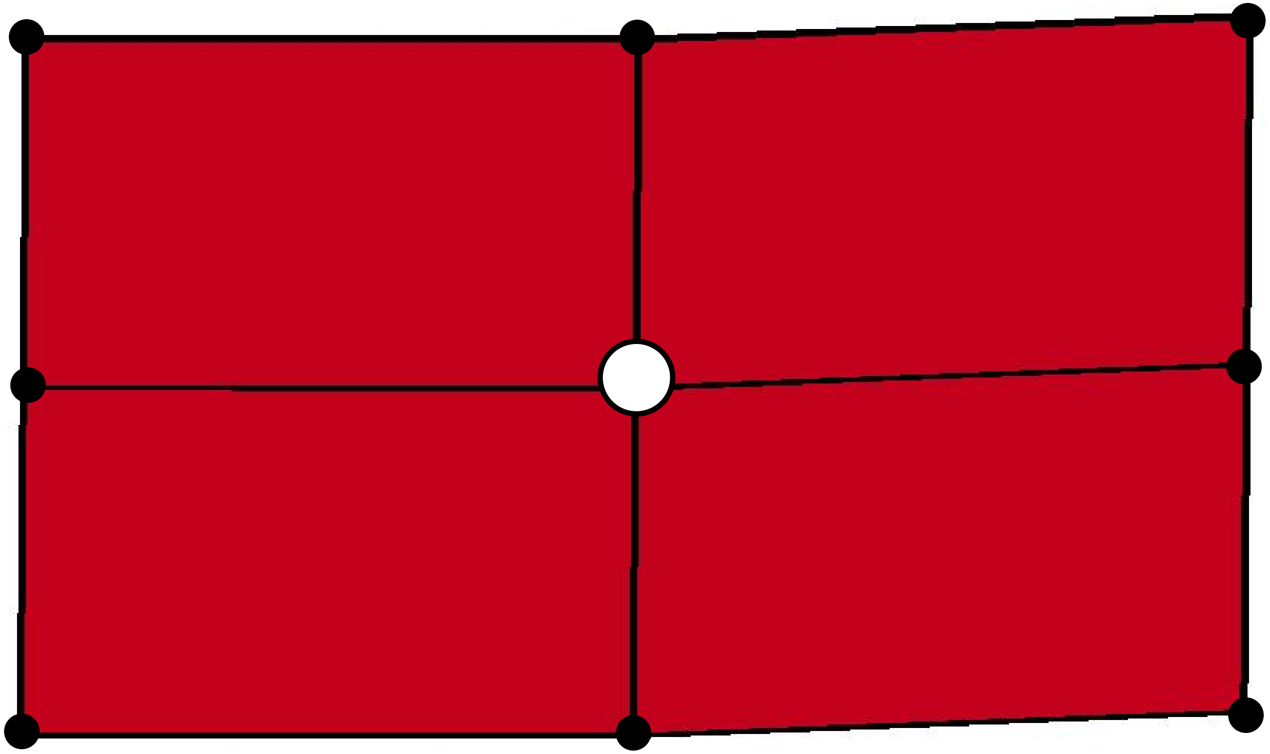
- Finite element mesh in 2D
  - Material stiffness E
  - Material density ρ
  - Characteristic length l and thickness t

The Courant stability criterion made intuitive



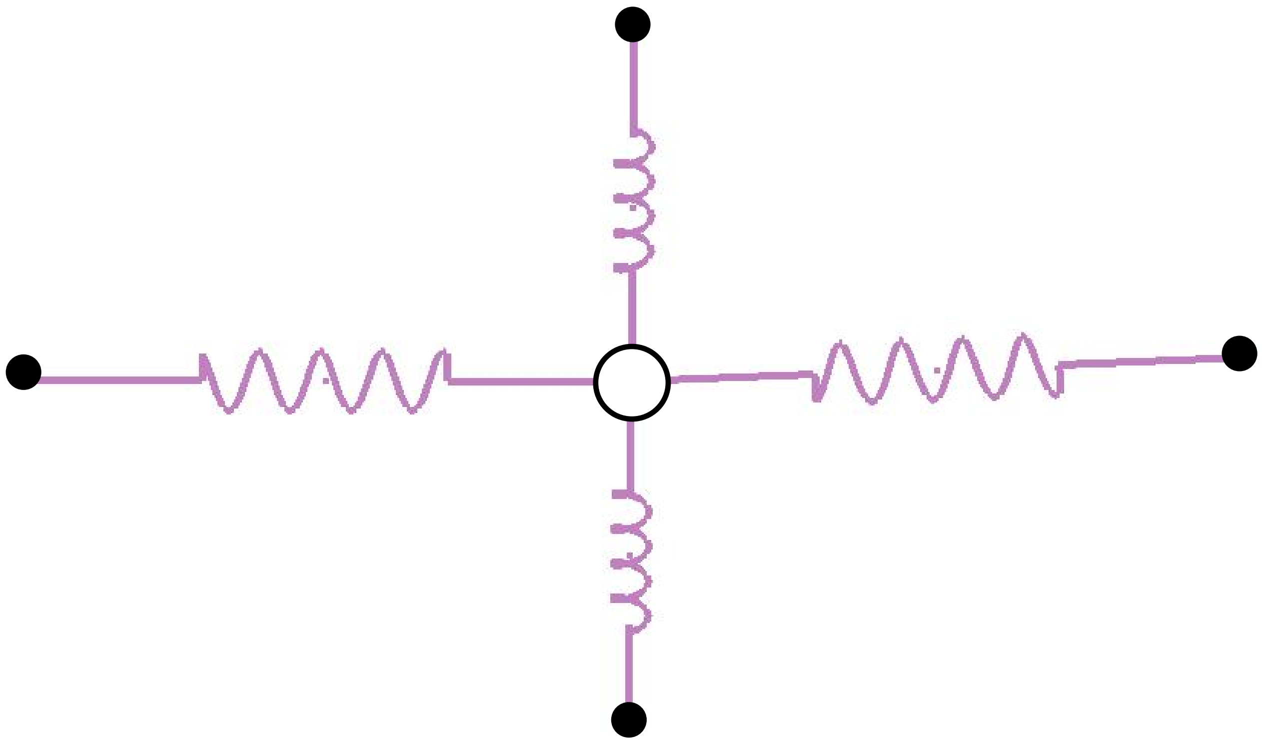
- Analyze the behavior of a particular node
  - Surroundings act as boundary conditions

The Courant stability criterion made intuitive



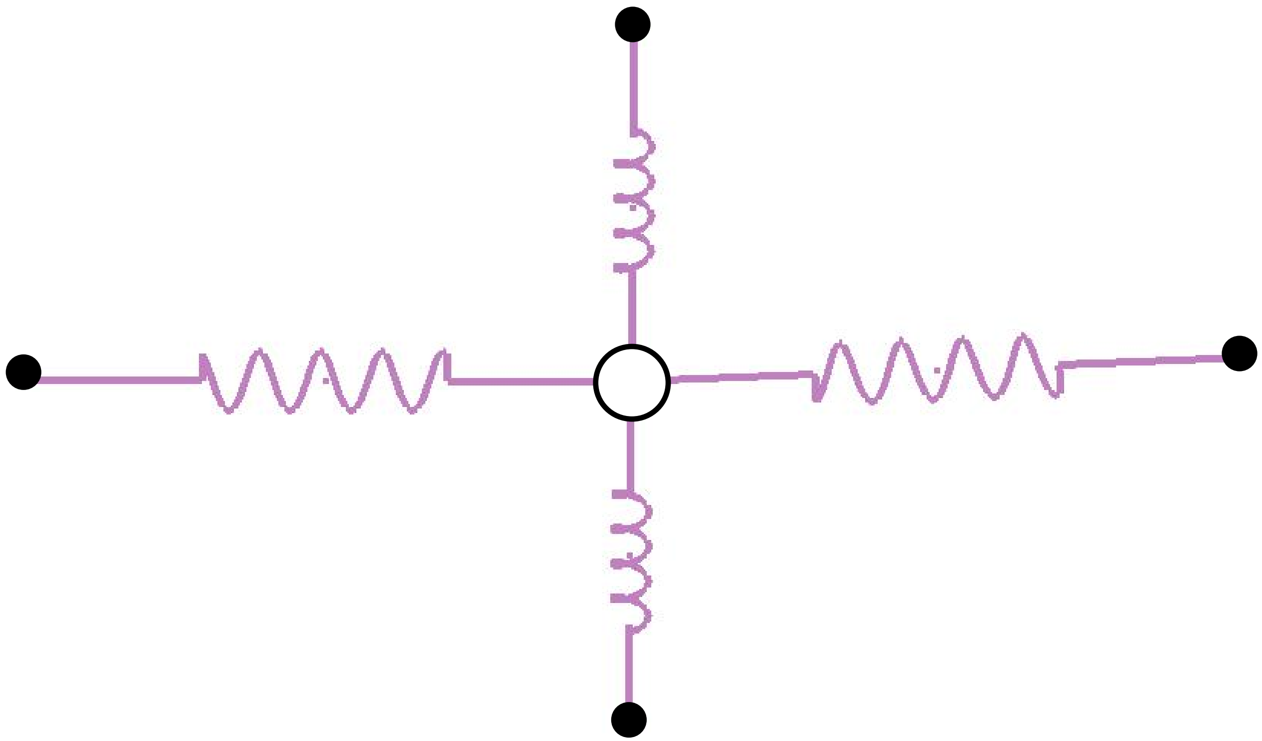
- Inertial mass internally represented by nodal masses
  - $m = \rho l^2 t$

The Courant stability criterion made intuitive



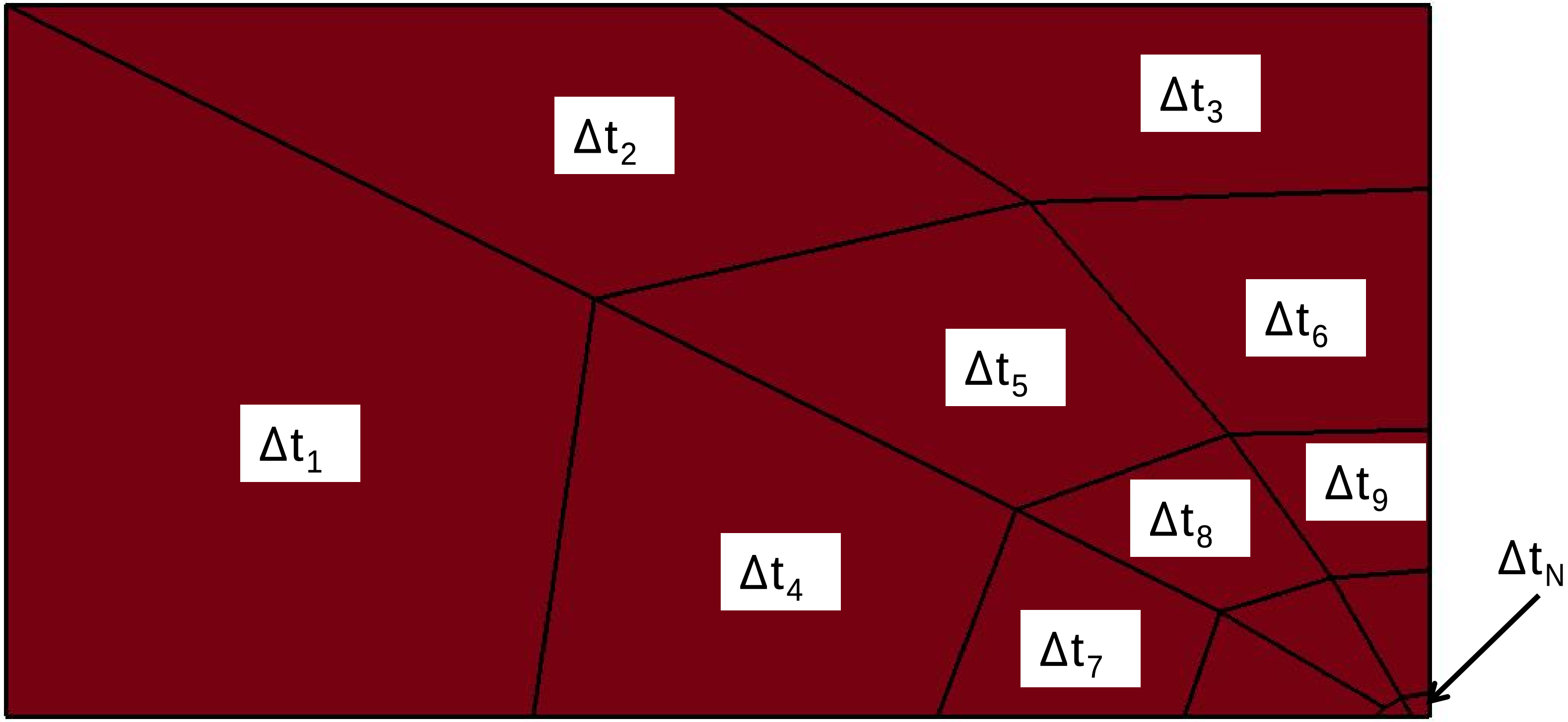
- Material stiffness represented by springs
  - $m = \rho l^2 t$
  - $k = Et$

The Courant stability criterion made intuitive



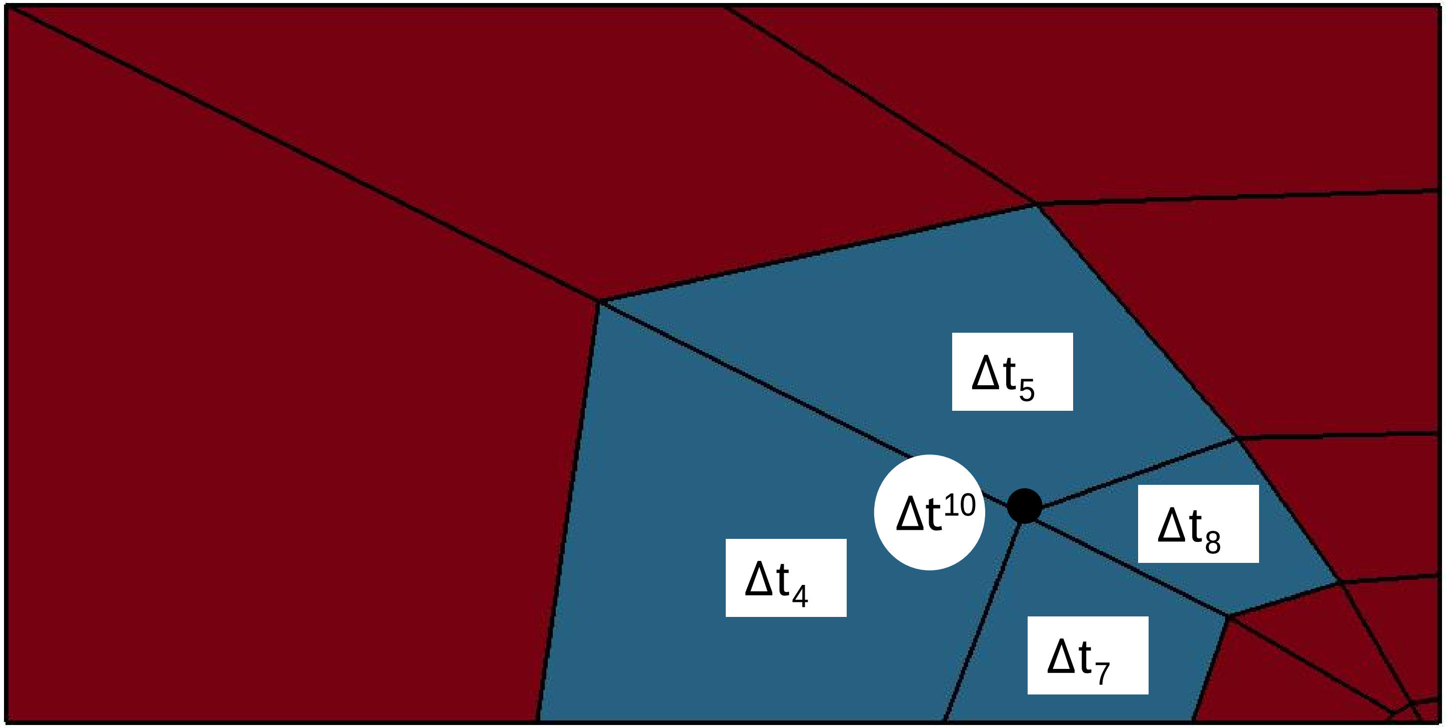
- Frequency and stable time step of node
  - $\omega = \sqrt{k/m} = \frac{1}{l}\sqrt{E/\rho}$
  - $\Delta t = l\sqrt{\rho/E}$

Generalization in explicit analysis – no subcycling



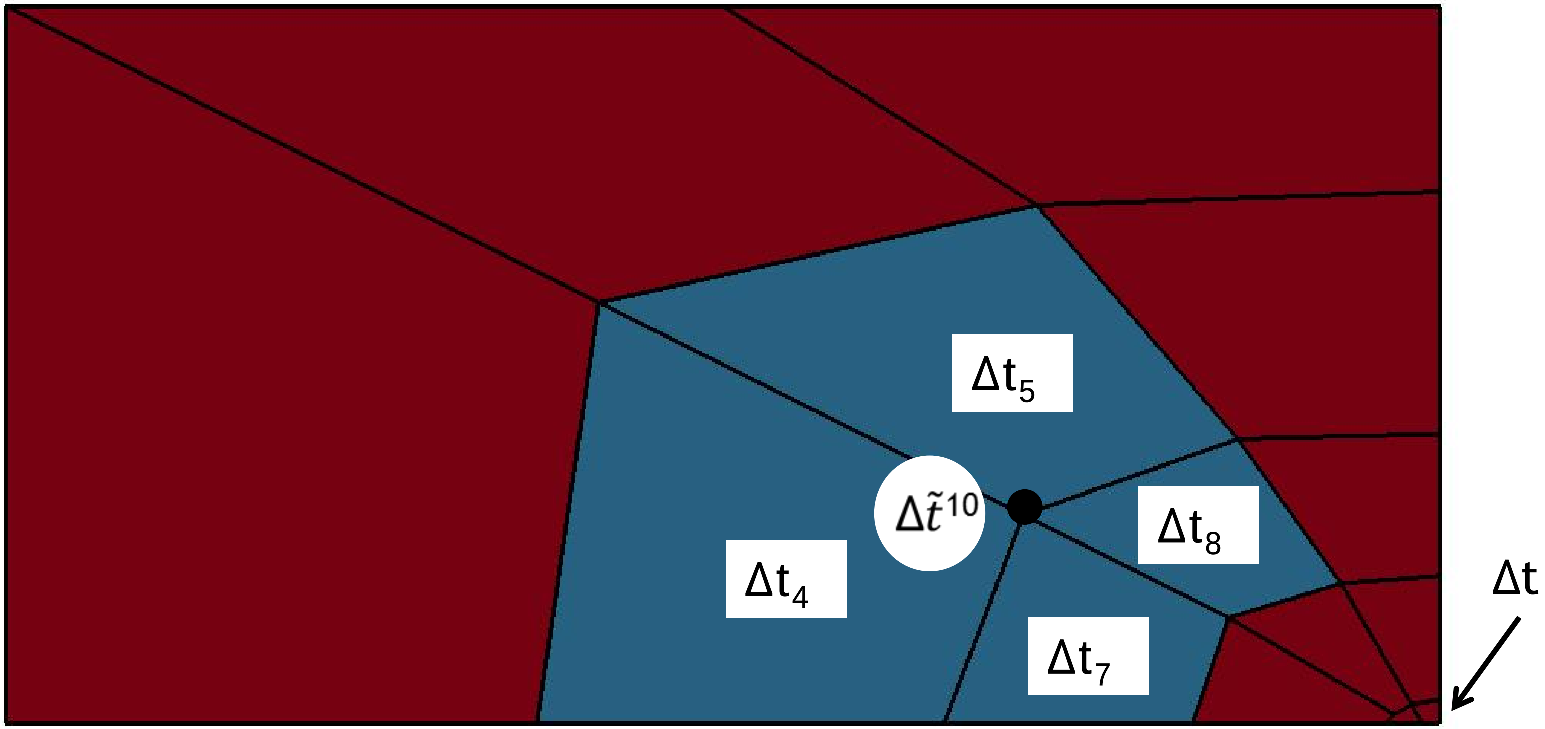
- Global time step is smallest element time step
  - $\Delta t = \min_{i=1,\ldots,N} \Delta t_i = \min_{i=1,\ldots,N} l_i \sqrt{\rho_i / E_i}$

Locality in subcycling



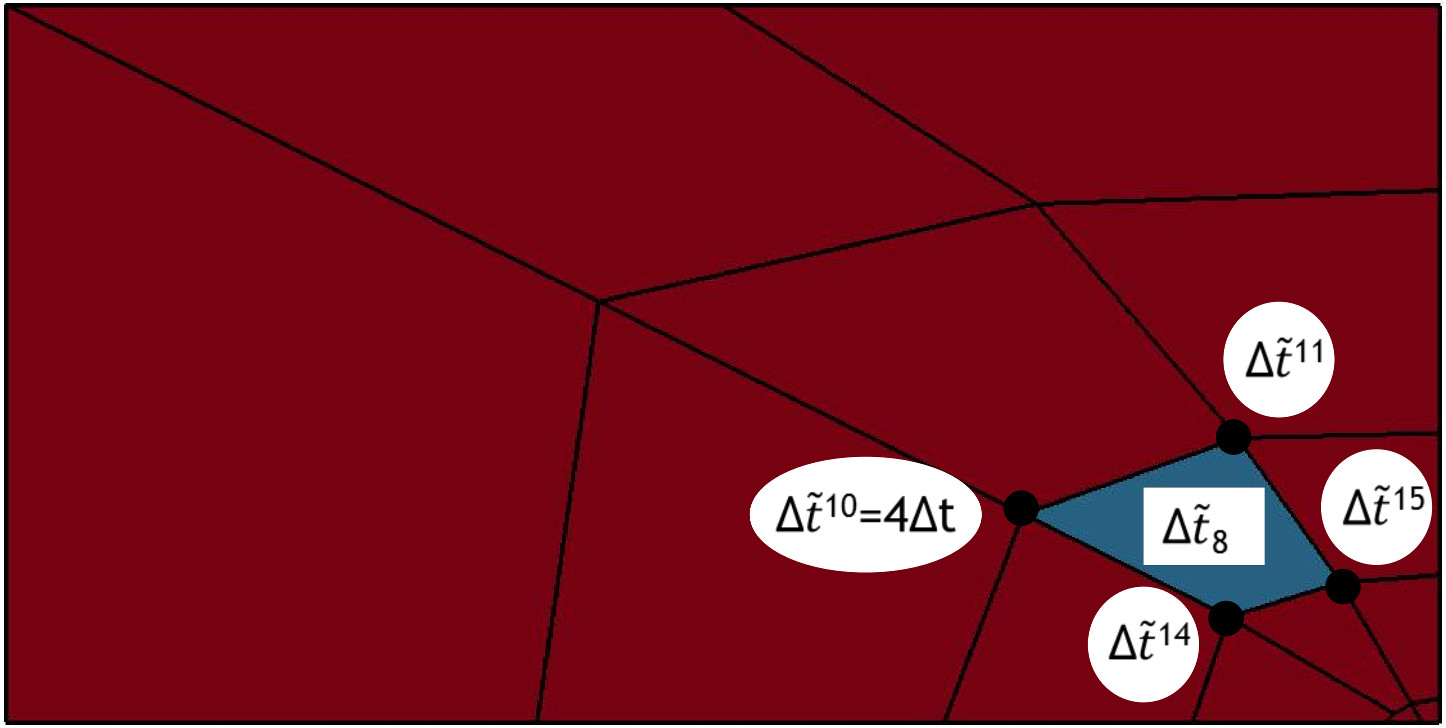
- Assume each node can have individual time steps
  - $\Delta t^j = \min_{i \in M_j} \Delta t_i$
  - $\Delta t^{10} = \min(\Delta t_4, \Delta t_5, \Delta t_7, \Delta t_8)$

Synchronization restriction – nodal simulation time step



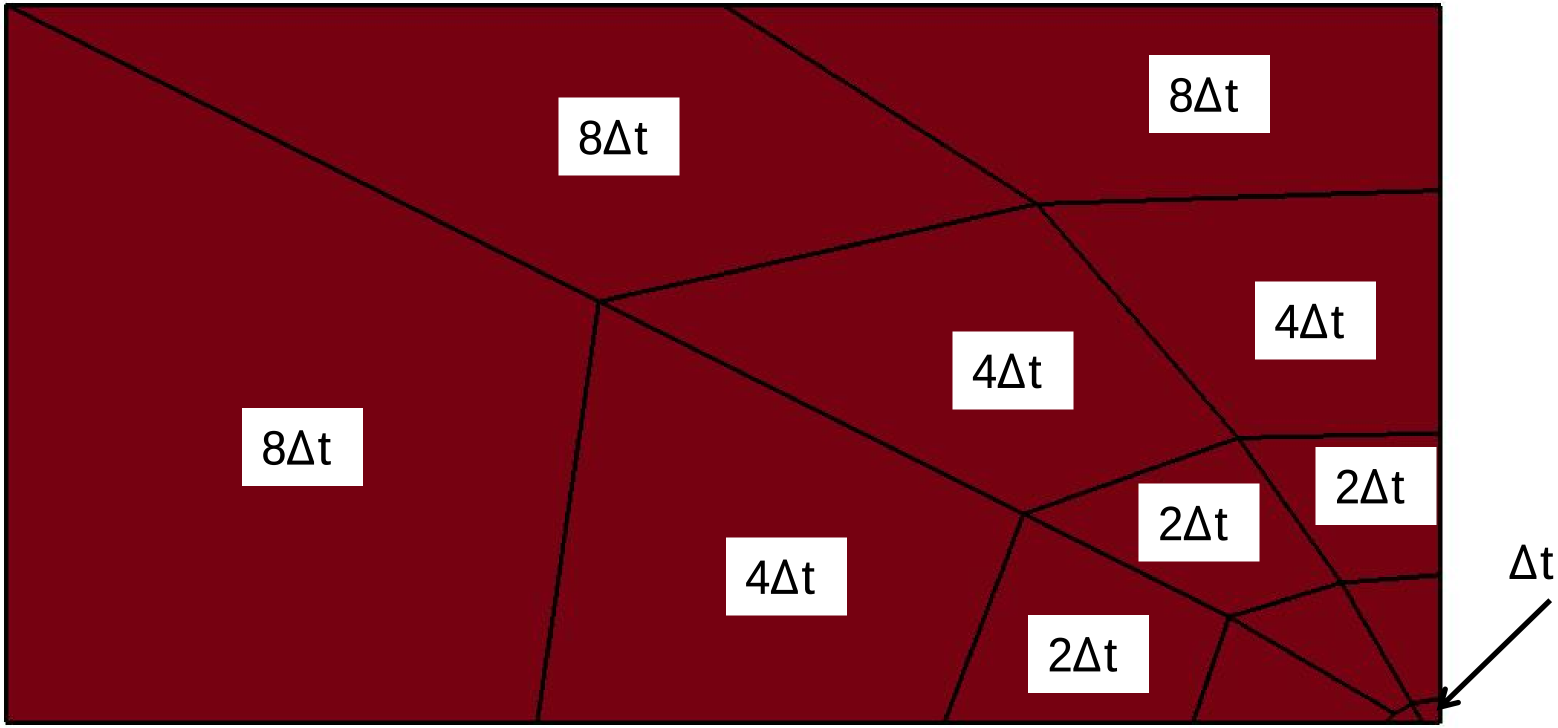
- Each time step must be a 2-power multiple of the smallest step
  - $\Delta\tilde{t}^j = \max\limits_{\Delta\tilde{t}^j < \Delta t^j} (\Delta t, 2\Delta t, 4\Delta t, 8\Delta t, 16\Delta t, 32\Delta t, 64\Delta t)$
  - $\Delta\tilde{t}^{10} = 4\Delta t$
- The subcycling nodal integration scheme complete !!!

Element simulation time step – internal forces



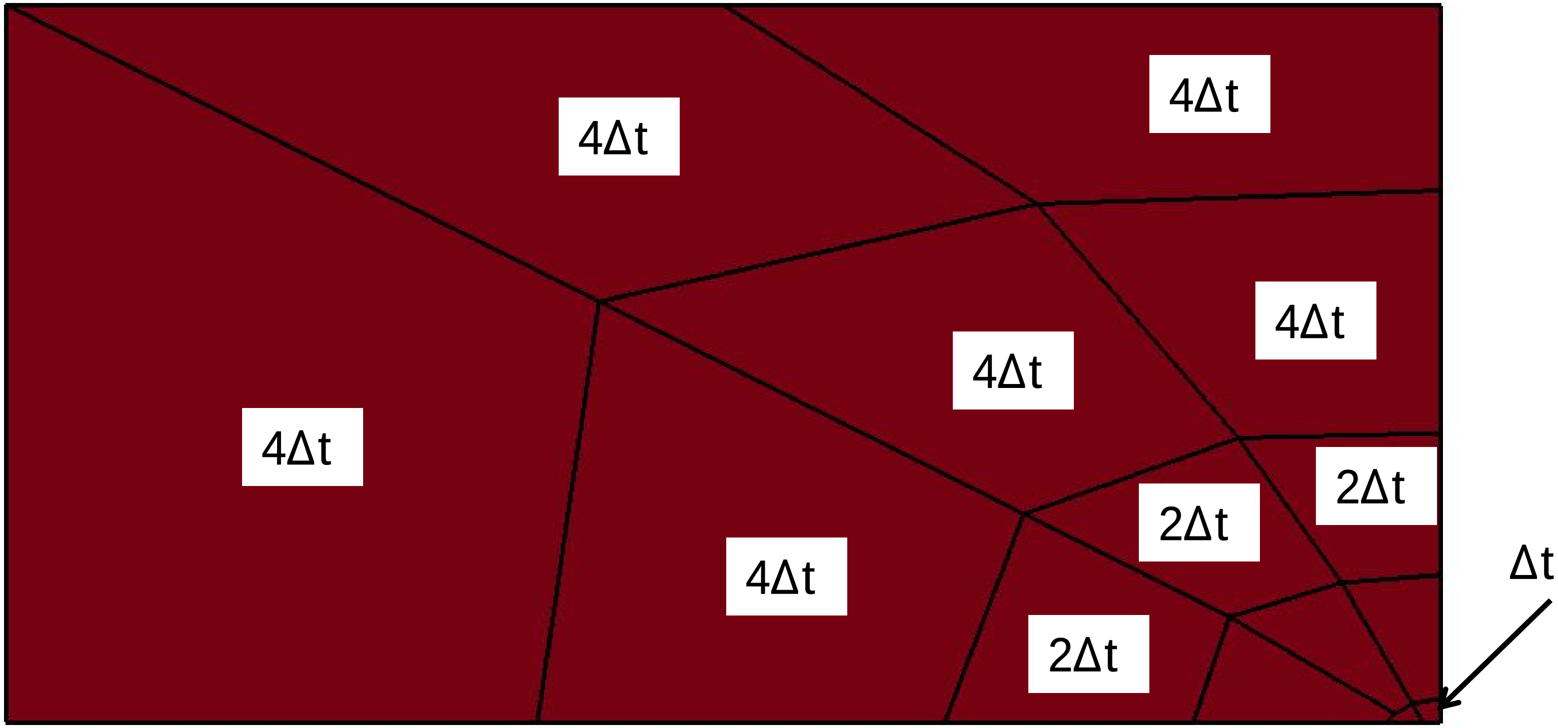
- Element time step must not exceed surrounding nodes
  - $\Delta\tilde{t}_i = \min_{j\in N^i} \Delta\tilde{t}^j \qquad \Delta\tilde{t}_8 = 2\Delta t$
- Nodal coordinates act as boundary conditions for element calculations
  - The *constant velocity* approach - nodal coordinates linearly interpolated
- Subcycling algorithm complete !!!

The global synchronization time step



- Large element simulation time steps save CPU time
  - CPU time gain is limited by the partitioning of elements/nodes into time step groups
- Largest element time step is called synchronization step
  - $\Delta T = \max_{i=1,\ldots,M} \Delta \tilde{t}_i \qquad \Delta T = 8\Delta t$

Specifying the synchronization step – keyword input



- *CONTROL_SUBCYCLE_{N}
  - N=2,4,8,16,32,64
  - *CONTROL_SUBCYCLE_4
- N used for conservative or aggressive approach, default 16
  - Motivated by the lack of theoretical results

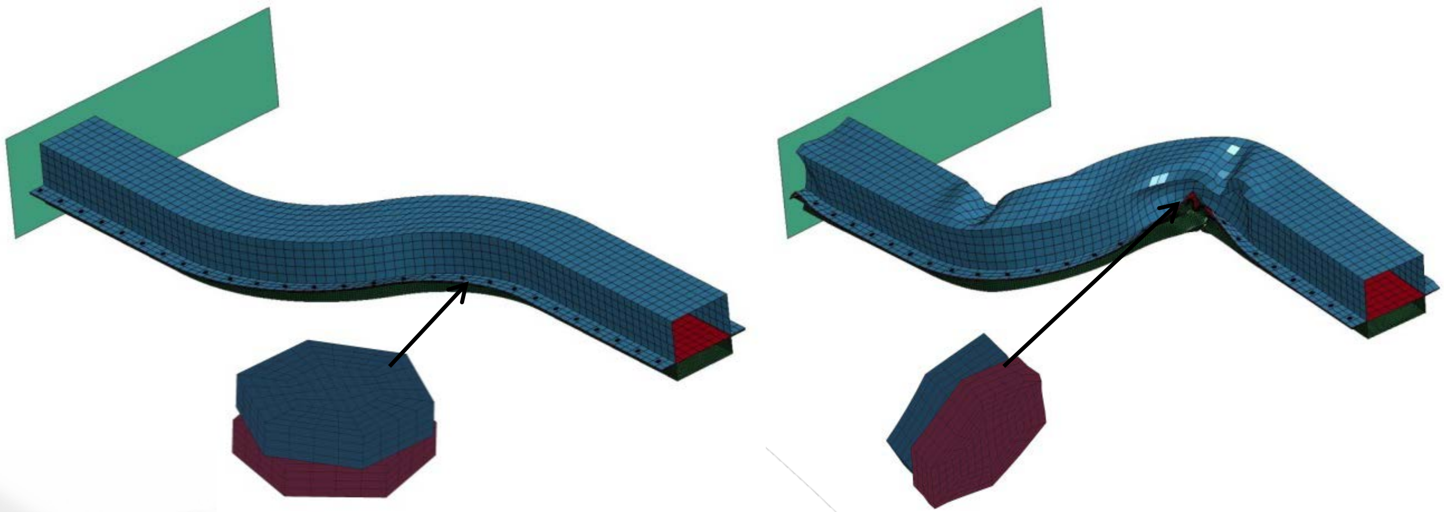
Time step restrictions – external forces

- Elements or nodes with the following properties are executed with the smallest time step
  - Rigid materials
  - Connections with rigid elements, including nodal rigid bodies
  - Connections in other ways than just by elements are treated the same way
- Time step ordering between elements is maintained by adding sufficient amount of mass, for efficiency
  - Mass scaling is ALWAYS on for subcycling
- All other features, not related to elements, are expected to run stable at some independent time step
  - Contacts in particular
- *CONTROL_SUBCYCLE_{N}_{M}
  - M specifies the maximum time step for external forces
  - M=1,2,4,8,16,32 or 64, default 1

Multiscale option when using mass scaling

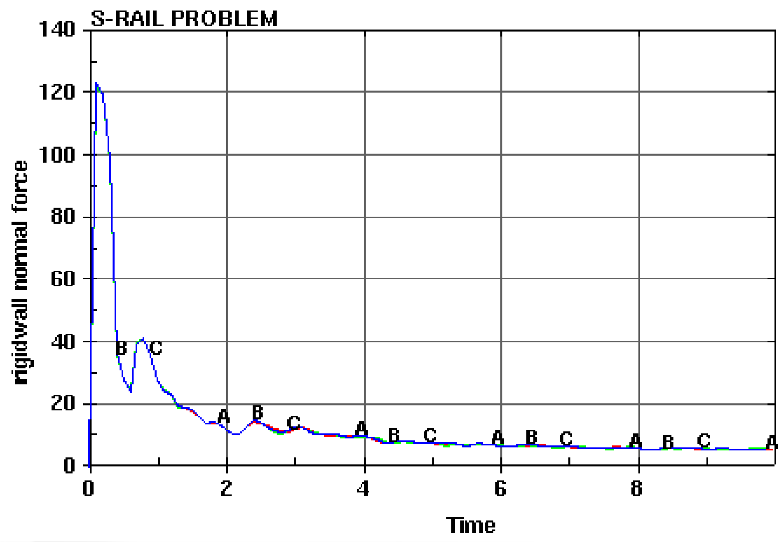
- If mass scaling is invoked, DT2MS<0, then this works similar to ”normal” mass scaling
  - $\Delta\tilde{t}^j = \max\left(\Delta t_{ms}, \Delta\tilde{t}^j\right) \qquad \Delta\tilde{t}_i = \max(\Delta t_{ms}, \Delta\tilde{t}_i)$
- Assume that a target time step is desired
  - Reached by applying mass scaling
- Highly refined parts will then be given too much inertia for its own good
  - We want to specify a smaller mass scaled time step for these
- Use *CONTROL_SUBCYCLE_MASS_SCALED_PART_{SET}
  - Allows for decreasing or increasing time step for individual parts
  - Specify part and associated time step
  - For this option, all part time steps are set by the user
  - Algorithm stays the same
  - *Multiscale* option

S-rail – refined spotwelds



- S-rail problem run with and without subcycling
  - 24640 shells, 55296 solids
  - 79 % of the nodes run on smallest time step
- Check spotweld contact and refined solid spotweld
- Used with *CONTROL_SUBCYCLE_64_4
  - No subcycling 3757 seconds
  - Subcycling 3406 seconds (9% CPU savings)
  - Multiscale 3 levels, 3454 seconds (8 % CPU savings)

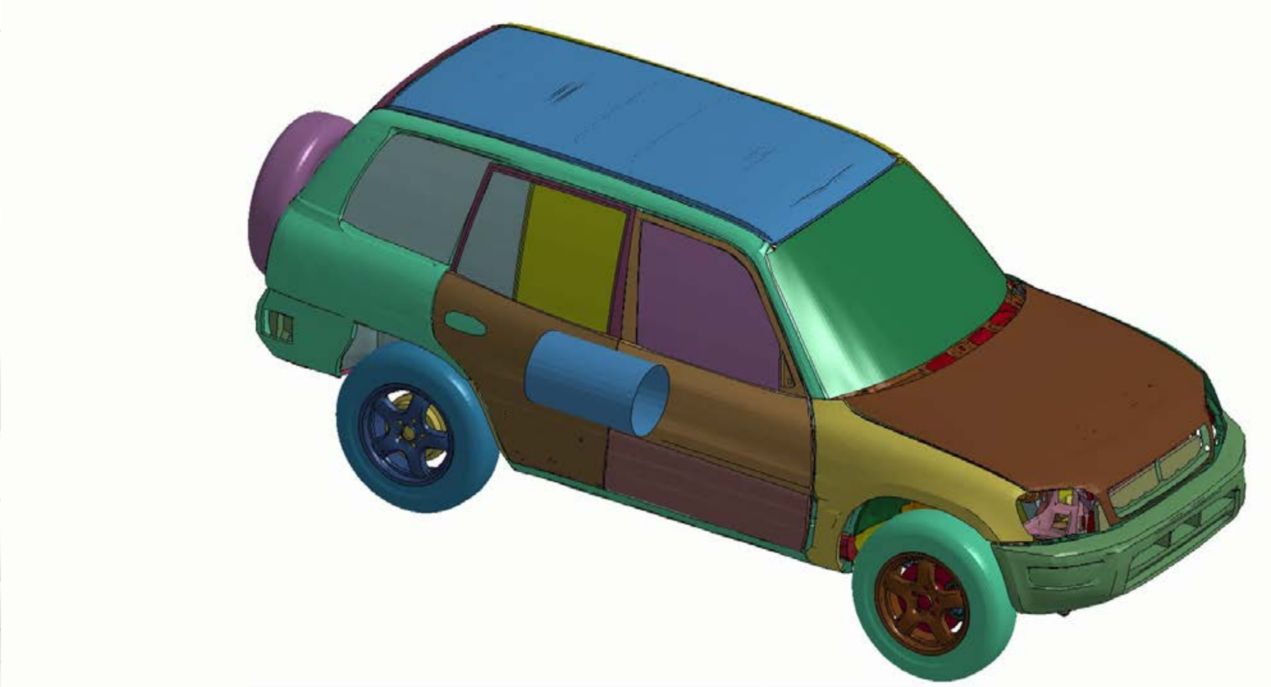
S-rail - results



- Results invariant to subcycling option
- Timings are intuitive

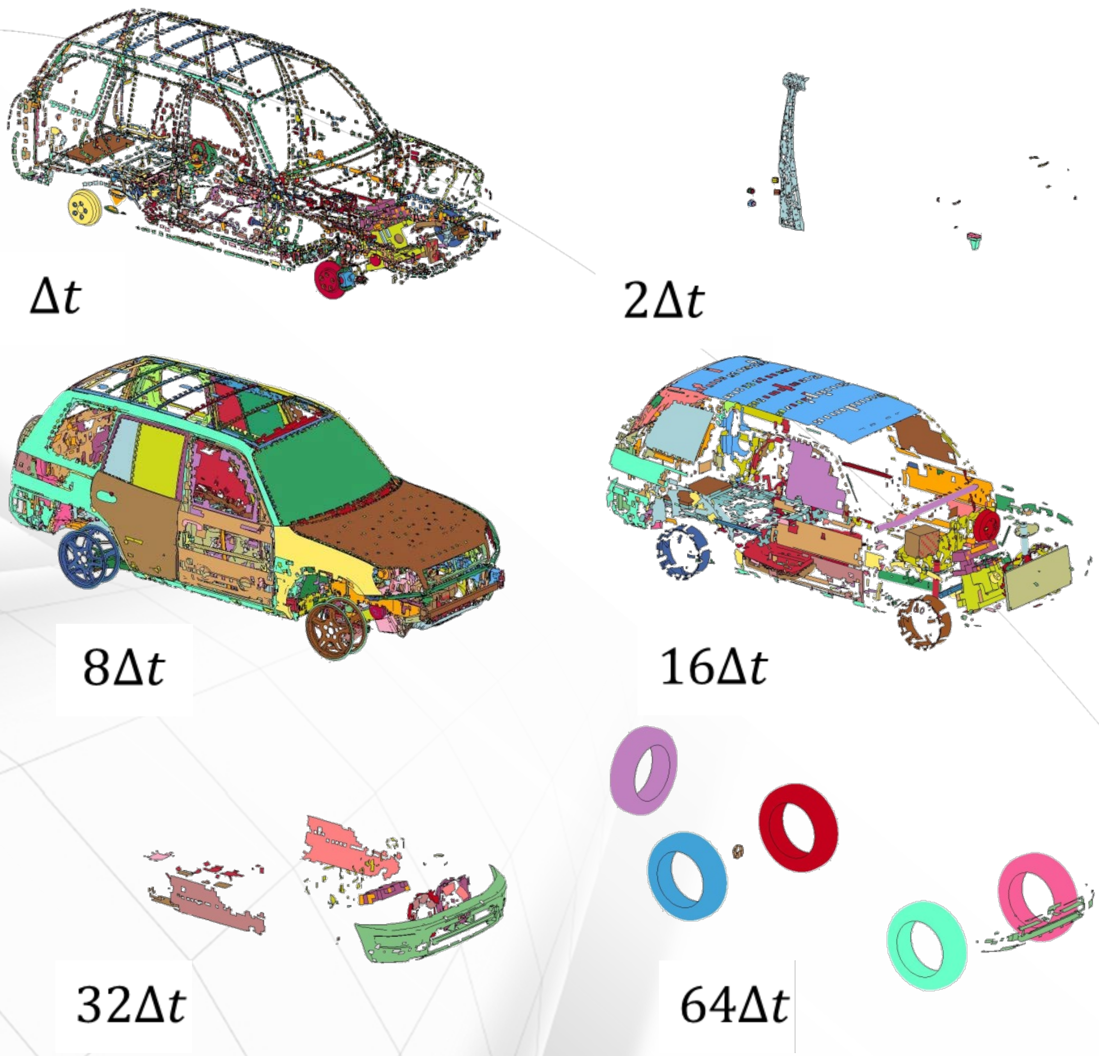
S-rail CPU timings (s)	Subcycling, N=64, M=4	Multiscale, M=4	No subcycling
Contacts	78	79	241
Elements	1783	1790	2141

RAV4 – use of multiscale



- 10 ms side hit simulation, 7 kg cylinder, 30 mph
- 501587 shells, 21539 solids, B-pillar refined
- Multiscale
  - DT2MS=-1e-3
  - DT(B-pillar)=1.3e-4
- Subcycling
  - *CONTROL_SUBCYCLE_64_4
  - 7 % of the nodes run at smallest time step

RAV4 - element partitioning

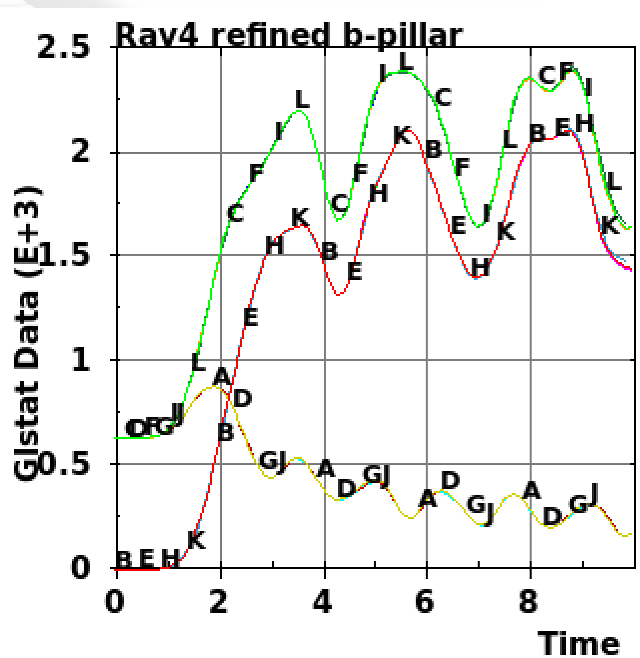


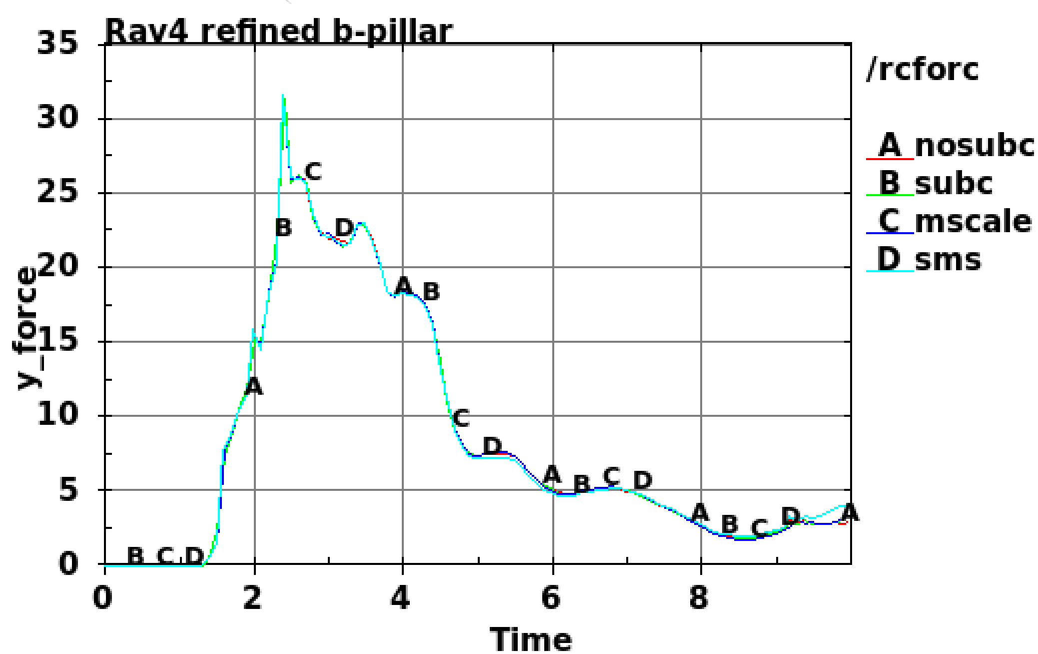
- No subcycling 1443 s
- Subcycling 795 s (45 % CPU savings)
- Multiscale 906 s (37 % CPU savings)

RAV4 – results

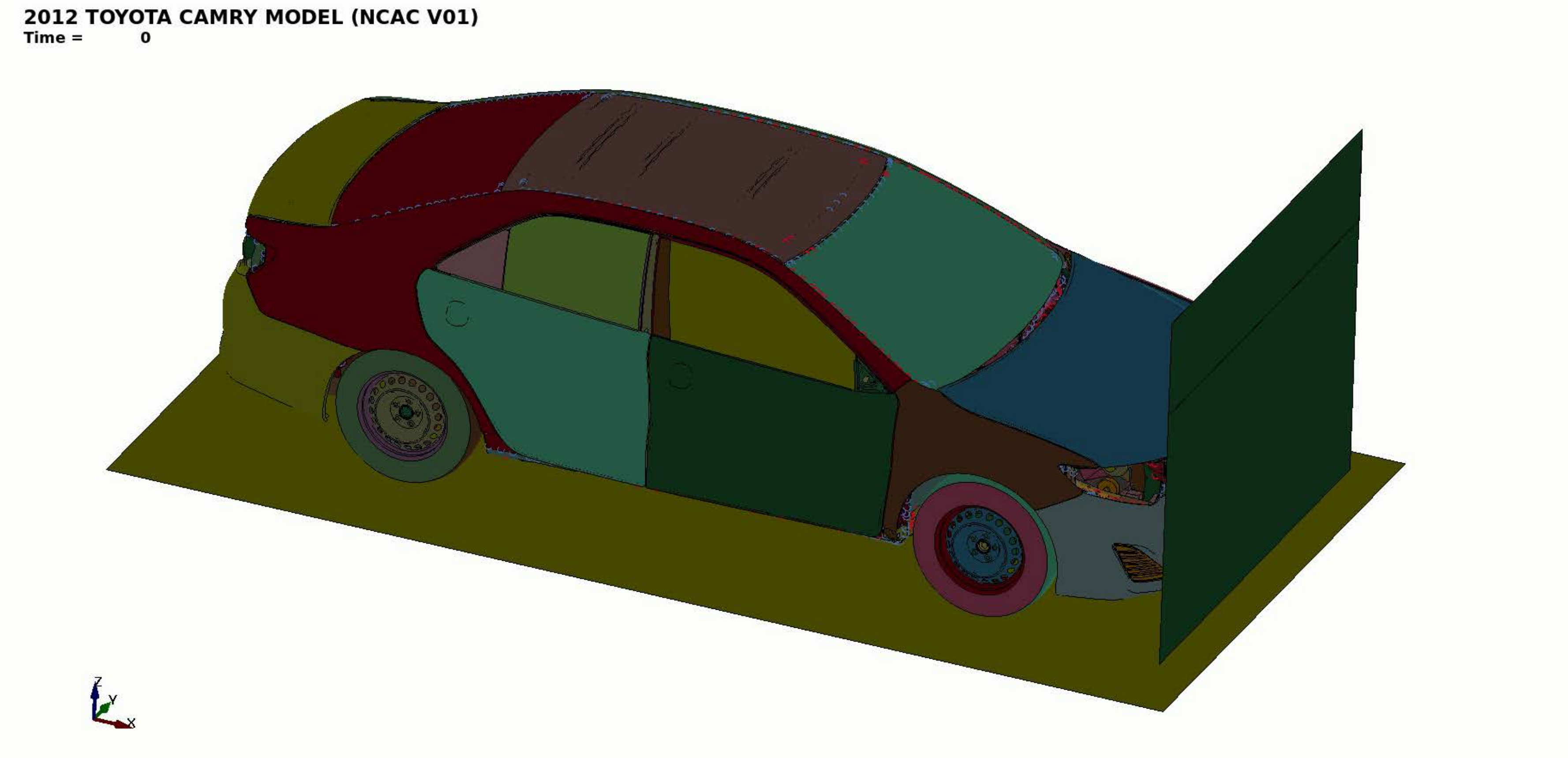
- Energies and contact force
- Results invariant to subcycling option

Rav4 CPU timings	Subcycling, N=64, M=4	Multiscale, M=4	No subcycling
Contacts	133	133	288
Elements	194	206	636





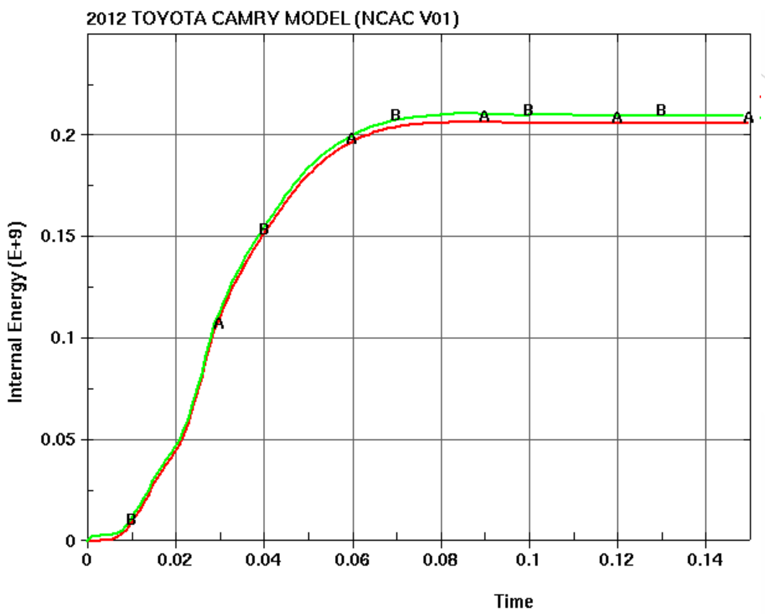
Camry – robustness of subcycling

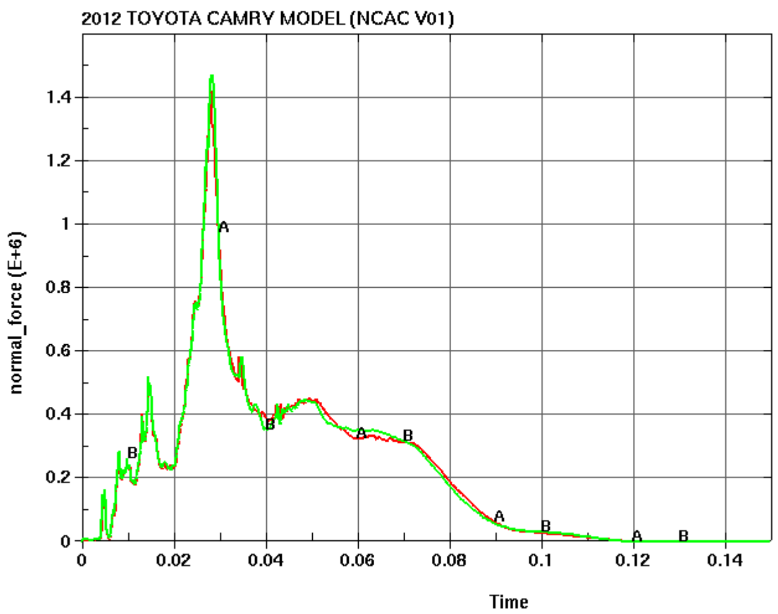


- Model taken from NCAC and slightly modified for robustness
  - 1603439 shells, 64257 solids
  - Various subcycling options and contacts
  - CONTROL_SUBCYCLE_16_1, SOFT=0 contact, SFS=0.1
  - Unfortunately, 91% of the nodes run on smallest time step

Camry – results

#CPU	No subcycling	Subcycling
12	28942	28091
24	14964	14158
48	7578	7642
96	4122	4028





- Internal energy and rigid wall force from subcycling and no subcycling

Conclusions and future work

- Subcycling implemented and tested in fairly advanced applications
  - Promising
- Some further investigations are in place
  - Contacts in particular
  - Alternate interface algorithms(?)
  - Continuous update of material time step database
- If used properly some saving can be done
  - Inferior to SMS, but stands as an alternative
- Available for usage in R8.0 of LS-DYNA
  - If used, please give feedback

Thank you!