Webinar, 2022-12-15, 10:00 CET

Mass-Scaling and Subcycling in LS-DYNA

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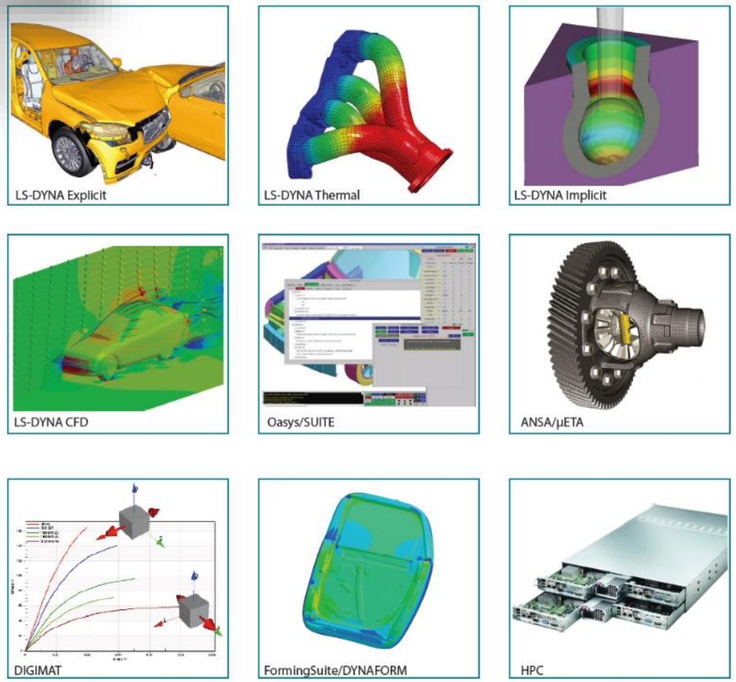
- www.dynaexamples.com – LS-DYNA example models from crash to DEM



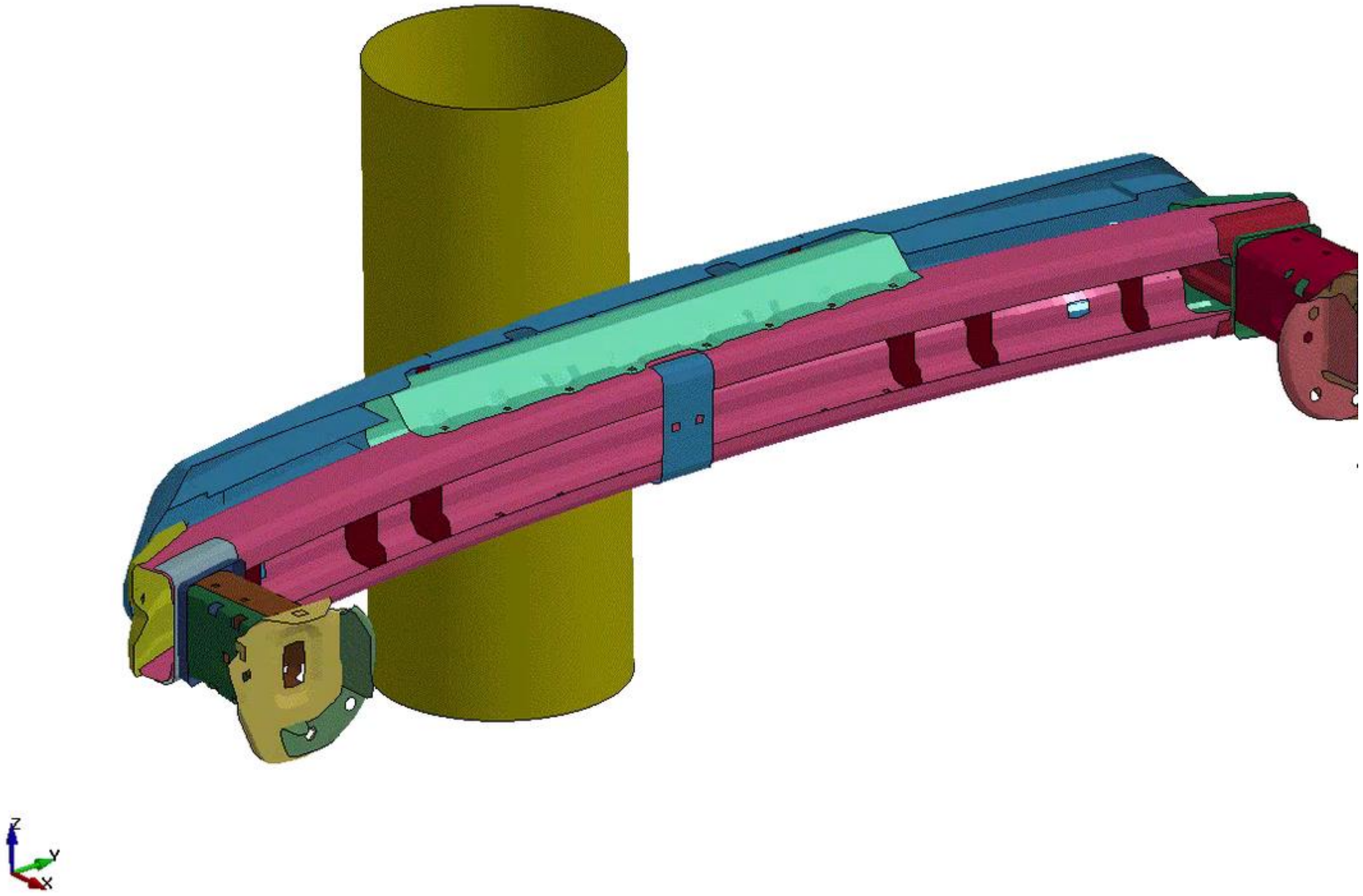
Introduction

- Mass-Scaling decreases computational cost in explicit analyses by increasing the critical time-step through added artificial mass. Excessive use induces dynamics in the solution.
- Conventional mass-scaling scales down all eigenfrequencies indiscriminately, a broadsword.
- Selective/Advanced mass-scaling only scales down the highest eigenfrequency, which the critical time-step is inversely proportional to, a scalpel.
- Time-Scaling decreases computational cost by speeding up the velocities in the analysis. Excessive use induces dynamics in the solution.
- Subcycling is a method of dividing up a model into domains that run with different time-steps to reduce computational cost.
- Multiscale is basically the same thing but the user specifies the domains and their respective time-steps manually.

Agenda

- Problem types depending on level of dynamics
- The explicit time integration scheme – critical time-step
- Conventional mass-scaling
- Selective mass-scaling
- Time-Scaling
- Subcycling
- Multiscale simulations
- Conclusion

Test Model



Discretization in Time

- Equations of motion at time t_{n+1}

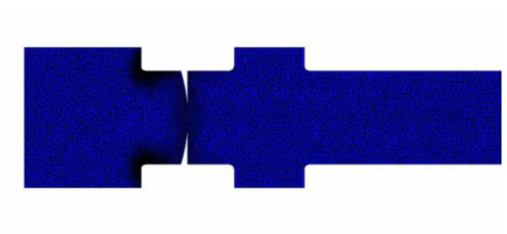
$$\mathbf{M}\ddot{\mathbf{x}}_{n+1} + \mathbf{C}\dot{\mathbf{x}}_{n+1} + \mathbf{f}^{\text{int}}(\mathbf{x}_{n+1}) = \mathbf{f}^{\text{ext}}(t_{n+1})$$

$$\underbrace{\mathbf{M}\ddot{\mathbf{U}}}_{\text{Inertia forces}} + \underbrace{\mathbf{C}\dot{\mathbf{U}}}_{\text{Damping forces}} + \underbrace{\mathbf{K}\mathbf{U}}_{\text{Internal forces}} = \underbrace{\mathbf{F}}_{\text{External forces}}$$

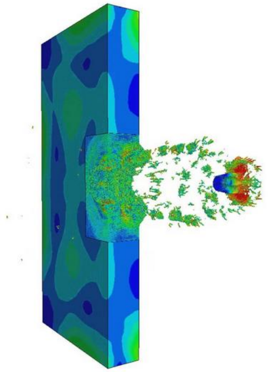
Discretization in Time – Problem Types

- Dynamic problems.
  - The mass inertia affects the results.
  - Time is real.

Wave propagation → Structural dynamics



Elastic wave



Blasts

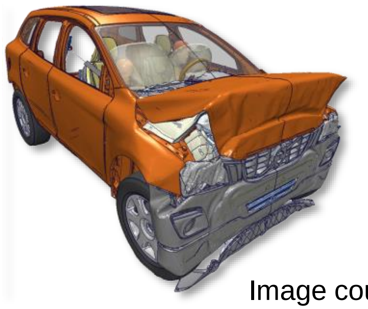
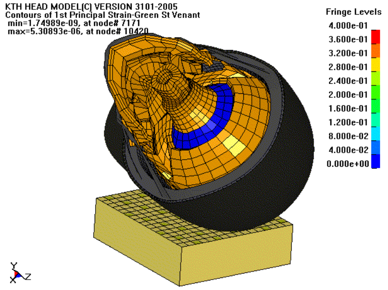


Image courtesy of Volvo Car Corporation.

Collisions



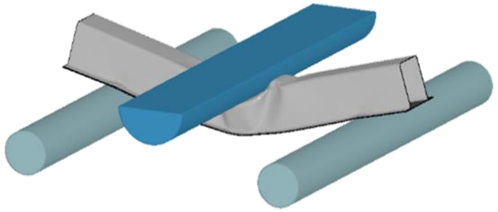
Courtesy www.mips-helmet.se & KTH

Drop tests

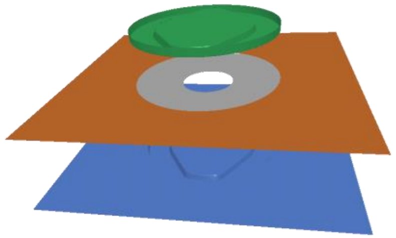
Discretization in Time – Problem Types

- Static and quasi-static problems.
  - The mass inertia should not affect the results.
  - The time should not affect the results.

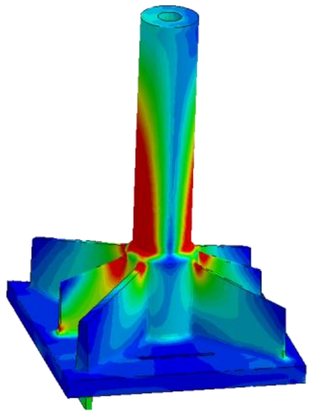
Quasi-Static → Static



Buckling test



Sheet metal forming



Stress analysis

Explicit Time Integration

- Explicit schemes give the configuration at time t_{n+1} as an explicit function of earlier configurations, i.e.,

$$\mathbf{x}_{n+1} = \mathbf{f}(\mathbf{x}_n, \mathbf{x}_{n-1}, \ldots, t_{n+1}, t_n, \ldots)$$

Explicit Time Integration - Critical Time-Step Size

- Standard Central Difference Method approximates time-step limit for LS-DYNA time integration.
- The natural frequencies are approximated at element level.

$$\Delta t_{\text{critical}} = \frac{l_e}{c_e} \qquad c_e \sim \sqrt{\frac{E_e}{\rho_e}} \qquad \Delta t_{critical} = \frac{2}{\omega_{max}}$$

- No information can propagate across more than one element per time-step.

Explicit Time Integration - Critical Time-Step Size

- LS-Dyna will automatically identify the minimum time-step and use this for the simulation.
- The 100 smallest time-steps with corresponding element can be found in the ASCII file d3hsp.
- A safety factor is used for the critical time-step. The safety factor can be changed in *CONTROL_TIMESTEP.

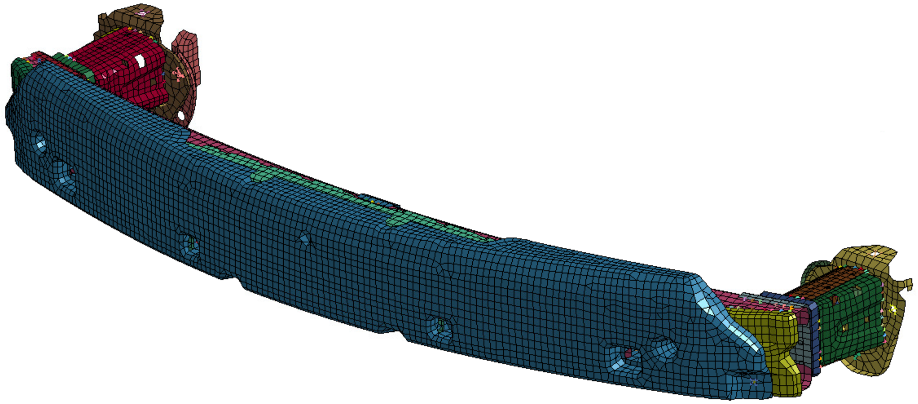
$$\Delta t = 0.9 \Delta t_{\text{critical}}$$ Default safety factor

$$\Delta t = 0.67 \Delta t_{\text{critical}}$$ Recommended for high velocities (explosives)

The simulation time-step changes due to deformed elements

```
    1 t 0.0000E+00 dt 5.52E-07
    1 t 0.0000E+00 dt 5.52E-07
 1876 t 9.9962E-04 dt 5.04E-07
 3920 t 1.9999E-03 dt 4.84E-07
 5000 t 2.5189E-03 dt 4.80E-07
 6046 t 2.9996E-03 dt 4.35E-07
 8630 t 3.9997E-03 dt 3.52E-07
10000 t 4.4709E-03 dt 3.39E-07
11540 t 4.9999E-03 dt 3.52E-07
14428 t 5.9998E-03 dt 3.38E-07
15000 t 6.1934E-03 dt 3.39E-07
17317 t 6.9998E-03 dt 3.55E-07
20000 t 7.9439E-03 dt 3.45E-07
```

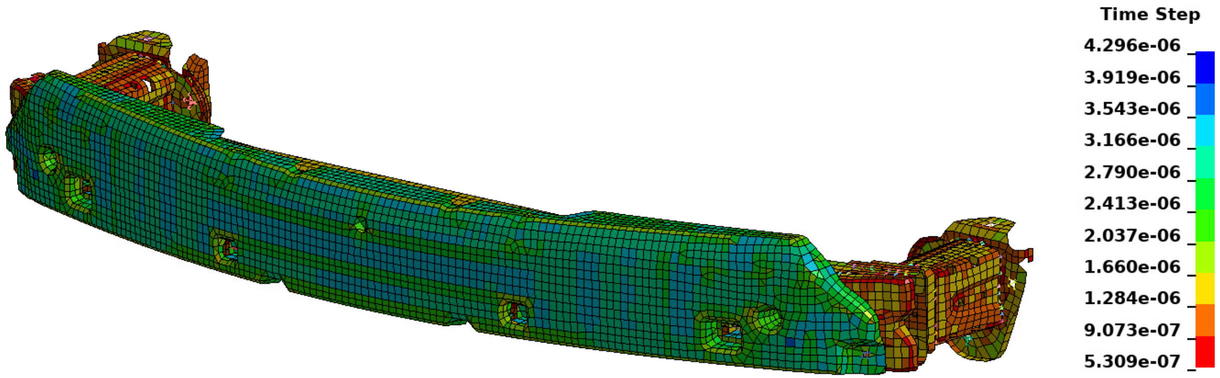
Example – Front Bumper NHTSA Honda Accord

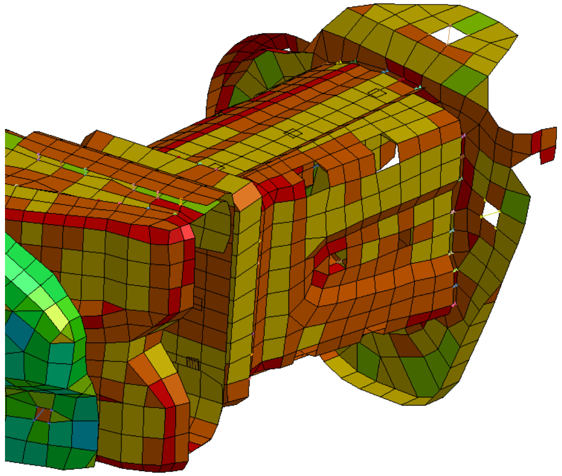


Steel: 7850 kg/m^3
210 GPa

Plastic: 1000 kg/m^3
5.6 GPa

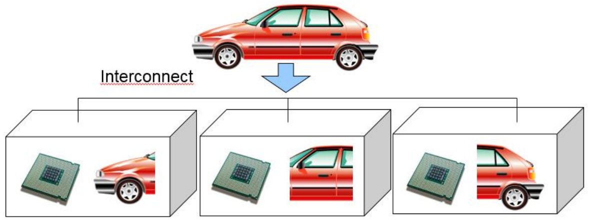
Element size ranging from 3.5 to 12 mm, typically 7 mm
Smallest time-step is 1.8e-7 s, and are spotweld solid elements.

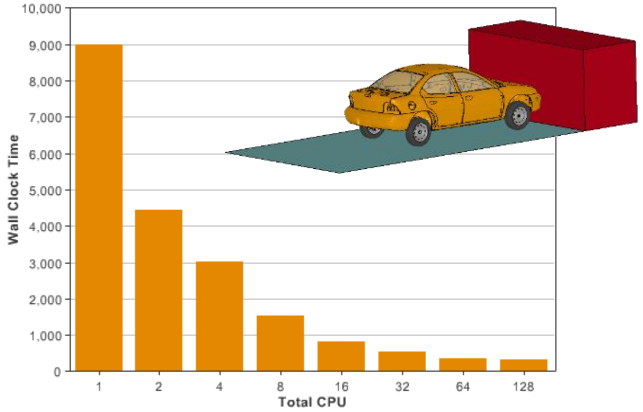




All simulations are run in mpp R11.0 single precision.

Ways to Decrease the Simulation Time..





- Simulation time depends on:
  - Time-step size/number of time-steps.
  - Model size (number of elements/integration points).
  - Termination time.
  - Modelling technique (number of contacts, ..).
  - Parallelization (number of processors, partitioning).

- The time-step can be modified by increasing the mass of the model. – MASS-SCALING.

- The simulation time can be modified by scaling up the velocities. - TIME-SCALING.

- For Quasi-Static problems where mass has no influence, both mass and time-scaling is possible as long as the problem does not become dynamic.
- For structural dynamics problems, only mass-scaling can be done since time is “real”. Also, mass-scaling has to be done without affecting the results.

Explicit Time Integration – Mass-Scaling

- Mass-scaling can be used to increase the time-step.

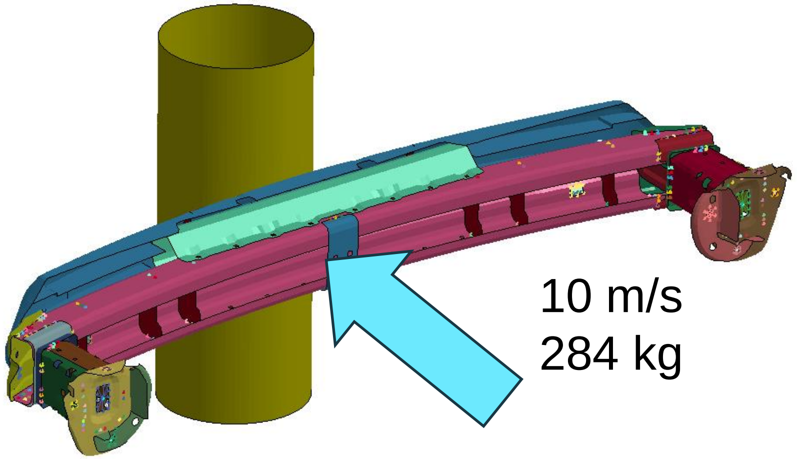
$$\Delta t_{\text{critical}} = \frac{l_e}{c_e} \qquad c_e \sim \sqrt{\frac{E_e}{\rho_e}} \qquad \rho_e \uparrow \quad \Longrightarrow \quad \Delta t_{\text{critical}} \uparrow$$

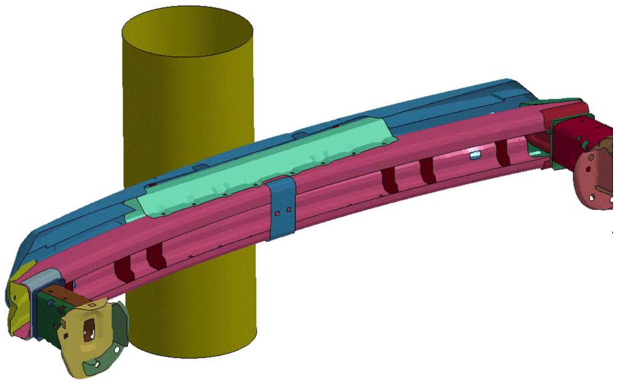
- The mass-scaling is activated in *CONTROL_TIMESTEP.
- Set the time-step in DT2MS. Use a negative value to only scale the elements that needs mass-scaling.

```
*CONTROL_TIMESTEP
$#  dtinit    tssfac      isdo    tslimt     dt2ms      lctm     erode     ms1st
       0.0       0.9         0       0.0 -1.200E-6         0         0         0
$#  dt2msf   dt2mslc     imscl    unused    unused     rmscl
       0.0         0         0                         0.0
```

```
calculation with mass scaling for minimum dt
   added mass    =   2.2481E-03
   physical mass=   4.9051E-01
   ratio         =   4.5831E-03
      1 t 0.0000E+00 dt 1.08E-06 flush i/o buffers            05/22/19 10:32:23
      1 t 0.0000E+00 dt 1.08E-06 write d3plot file            05/22/19 10:32:23
```

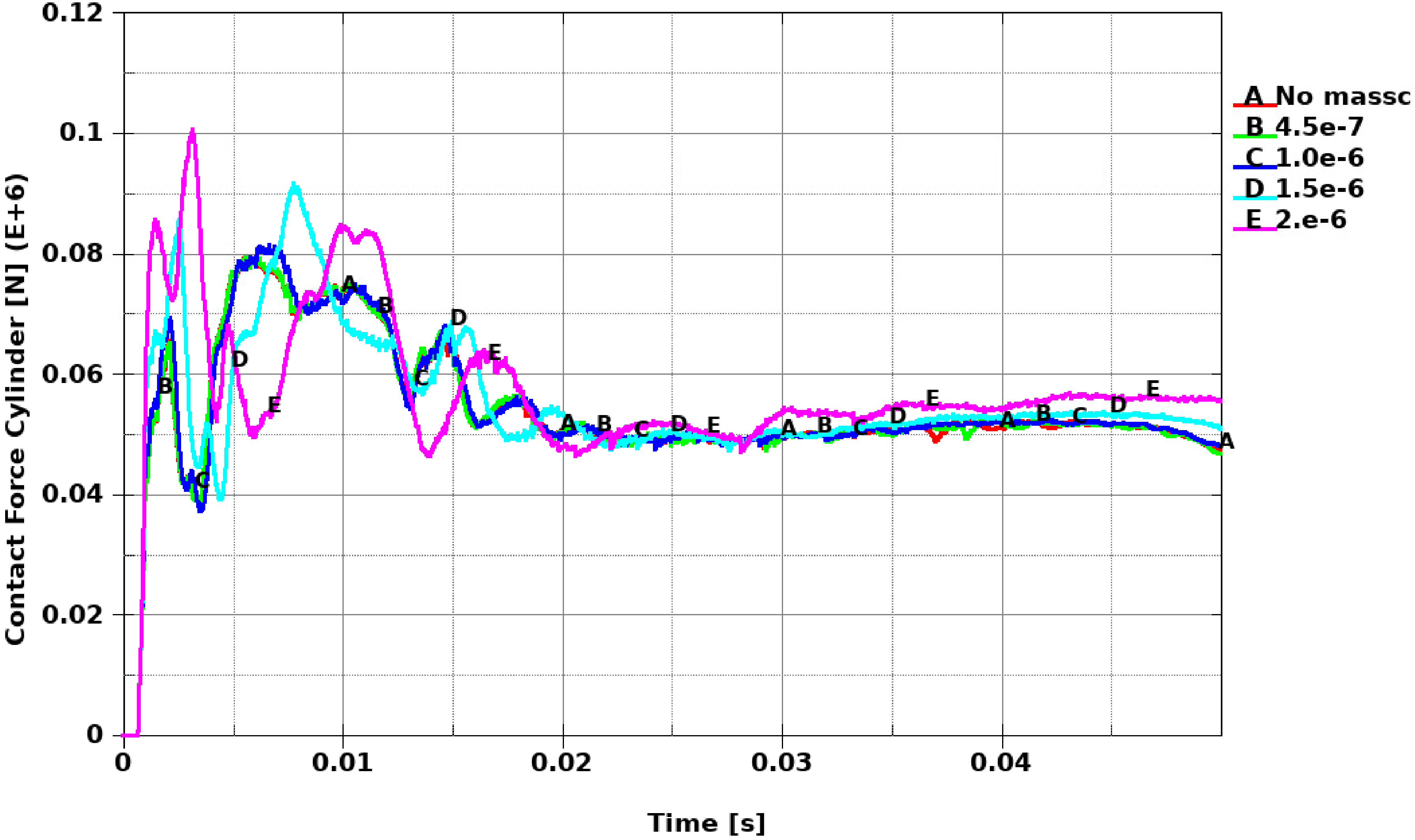
Example – Front Bumper NHTSA Honda Accord





Time-Step [s]	Mass-Scaling [kg, %]	Simulation Time (mpp,16 cores)	MAX Error % [RMS contact force]	Mean Error % [RMS contact force]
1.8 E-7	0,0	421 s	0	0
4.5 E-7	0.0372 , 0.013	181 s	2.7	0.3
1.0 E-6	2.2, 0.8	80 s	18.9	4.3
1.5 E-6	12. , 4.2	60 s	94.3	20.
2.0 E-6	33. , 11.6	46 s	154.	33.6

Mass-Scaling – Contact Force



Selective Mass-Scaling

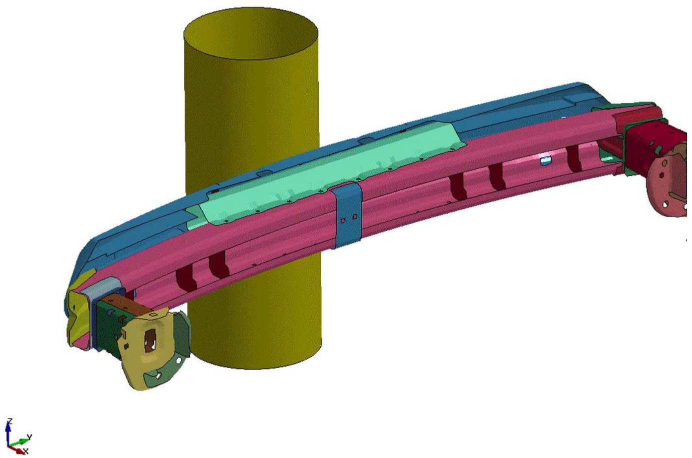
- Selective mass-scaling only scales the critical (high) eigenfrequencies. Thus, rigid body motion and lower order deformation is unaffected.
- Selective mass-scaling creates a non-diagonal massmatrix. The more mass-scaling yields more banded massmatrix.
- Solving the equation of motion involves a matrix assembly and inversion and is thus CPU intensive.


*CONTROL_TIMESTEP (1)

1	DTINIT	TSSFAC	ISDO	TSLIMT	DT2MS	LCTM	ERODE	MS1ST
	0.0	0.9000000	0	0.0	-2.200e-06	0	0	0
2	DT2MSF	DT2MSLC	IMSCL	UNUSED	UNUSED	RMSCL		
	0.0	0	1	0	0	0.0		

- IMSCL=1: Activates selective mass-scaling.
- IMSCL < 0: |IMSCL| is a *SET_PART that will undergo selective mass-scaling, e.g. solid meshed spotwelds. Recommended to limit the increase in CPU time.

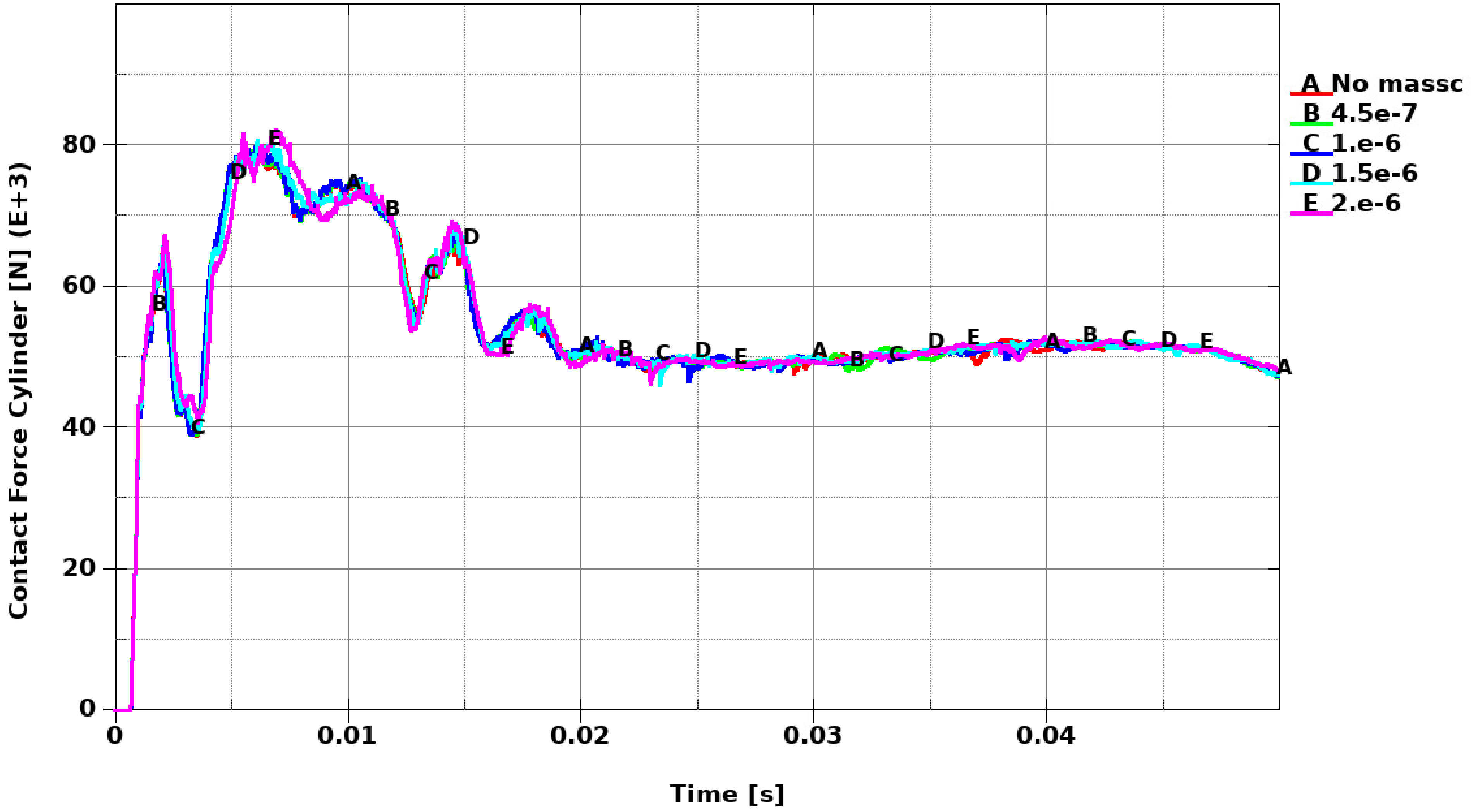
Example – Front Bumper NHTSA Honda Accord



```
calculation with selective mass scaling
   physical mass=    4.9051E-01
   added lf mass=    6.6365E-12
   ratio         =   1.3530E-11
   added hf mass=    3.7274E-05
   ratio         =   7.5989E-05
```

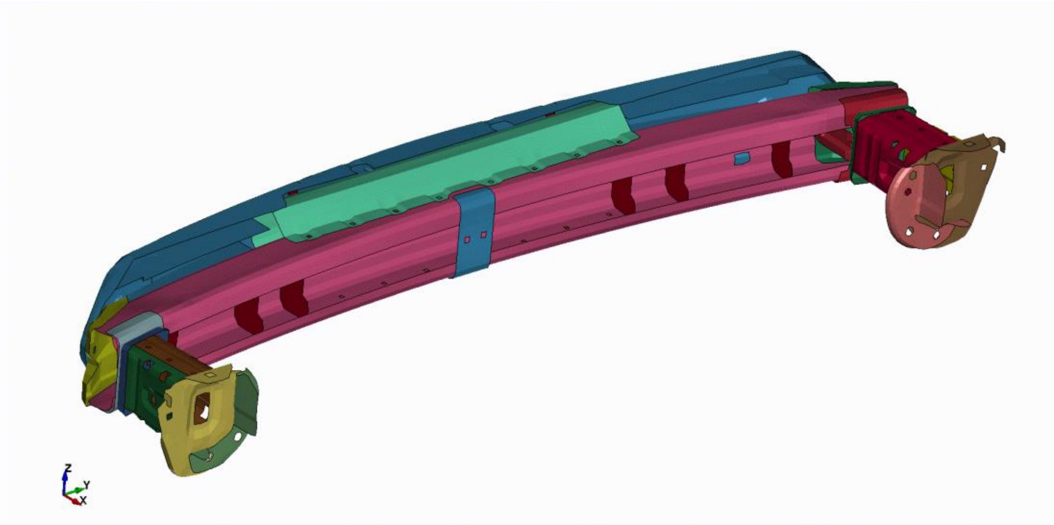
Time-Step [s]	Mass-Scaling [kg, %]	Simulation Time (mpp,16 cores)	MAX Error % [RMS contact force]	Mean Error % [RMS contact force]
1.8 E-7	0,0	421 s	0	0
4.5 E-7	0.0372, 0.013	227 s (181 s)	2.7	0.3
1.0 E-6	2.2, 0.8	116 s (80 s)	4.7	0.66
1.5 E-6	12. , 4.2	76 s (60 s)	10.5	2.7
2.0 E-6	33. , 11.6	61 s (46 s)	19.7	5.6

Selective Mass-Scaling – Contact Force



Time-Scaling

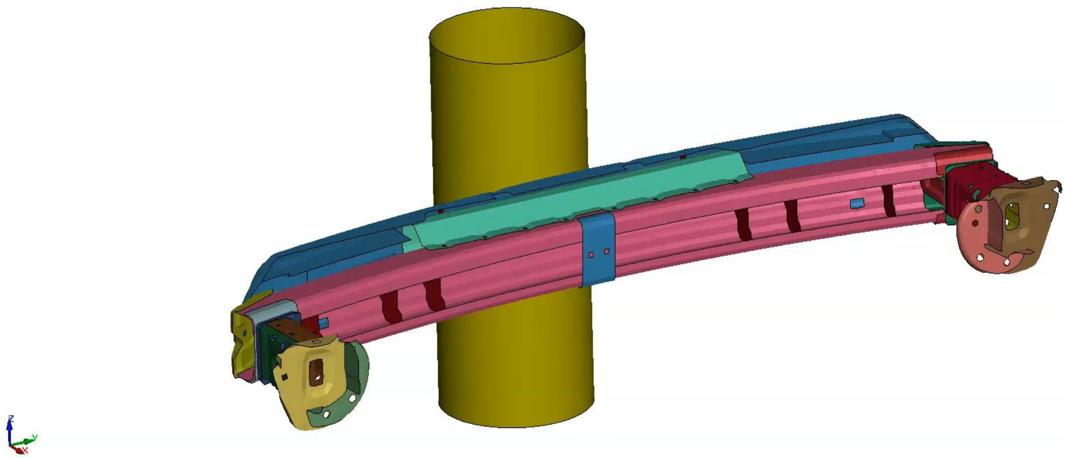
- For quasi-static problems, time does not affect the results, so time-scaling is possible.
- Examine the lowest eigenmode describing the deformation mode of interest.
- A general rule is to use: $Loading\ Rate = 10 * \frac{1}{f_{eig}}$, to decide maximum time-scaling.



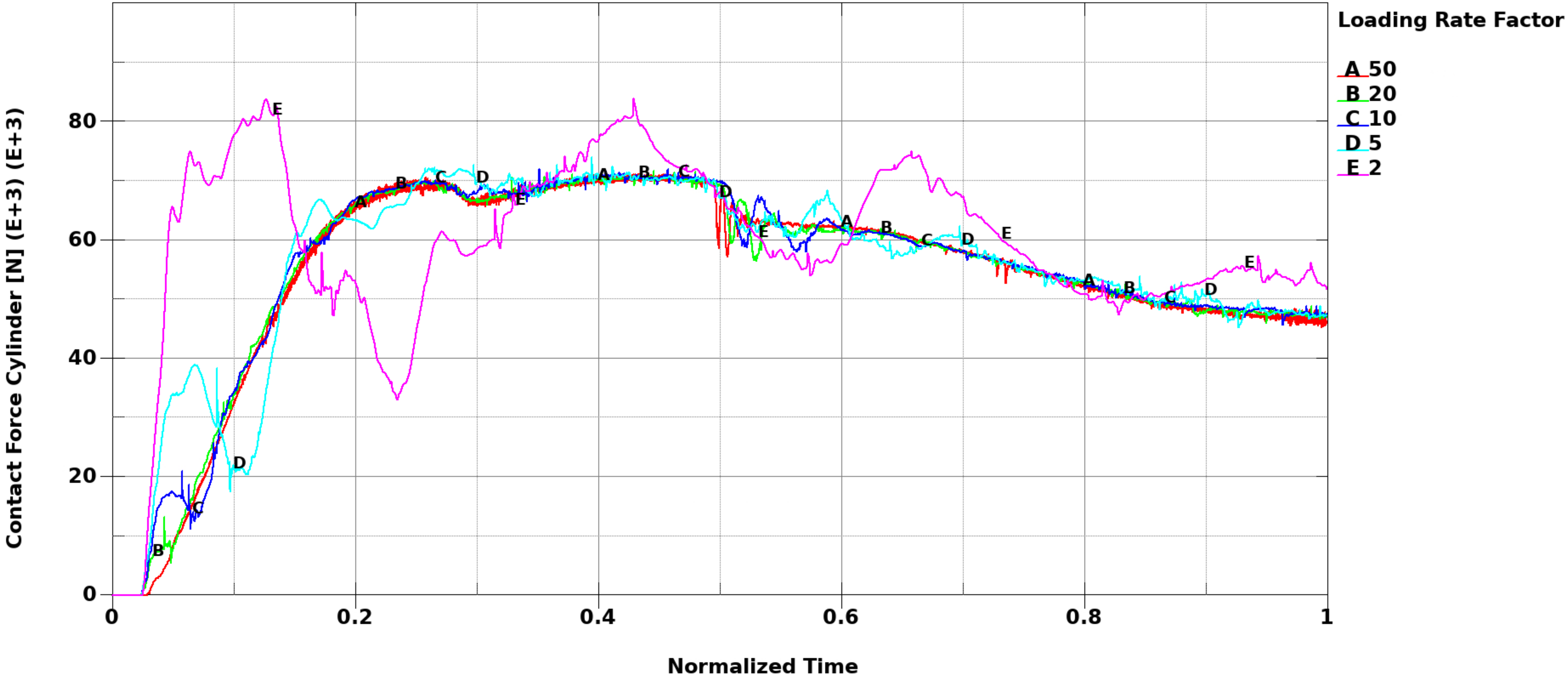
Mode 2, Frequency 140.77 Hz

Time-Scaling

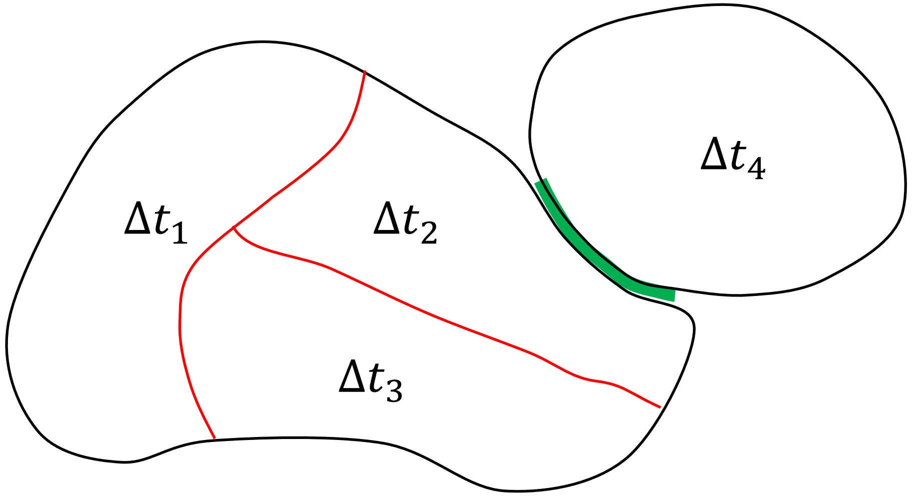
Loading Rate [s]	Loading Rate Factor	Simulation Time (mpp,8 cores)
0.35	50	618 s
0.14	20	245 s
0.07	10	123 s
0.035	5	65 s
0.014	2	27 s



Time-Scaling – Contact Forces

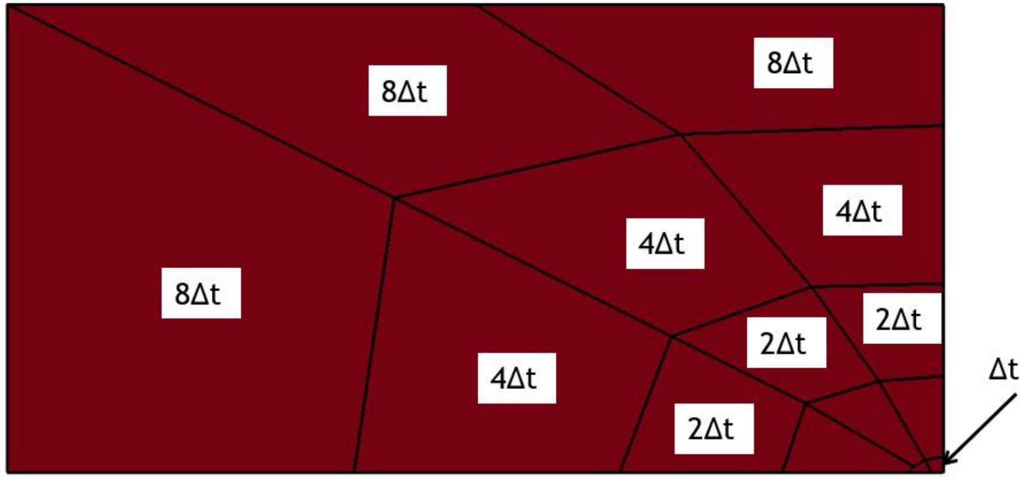


Subcycling



- Different subdomains of the model are running with different time-steps.
- Possibility to limit the mass-scaling.
- The model is divided into subdomains where each time-step must be a 2-power multiple of the smallest time-step.
- Explicit time integration time-step and external force time-step can be different.
- Difficulties in boundaries between domains (wave propagation, contact forces…).

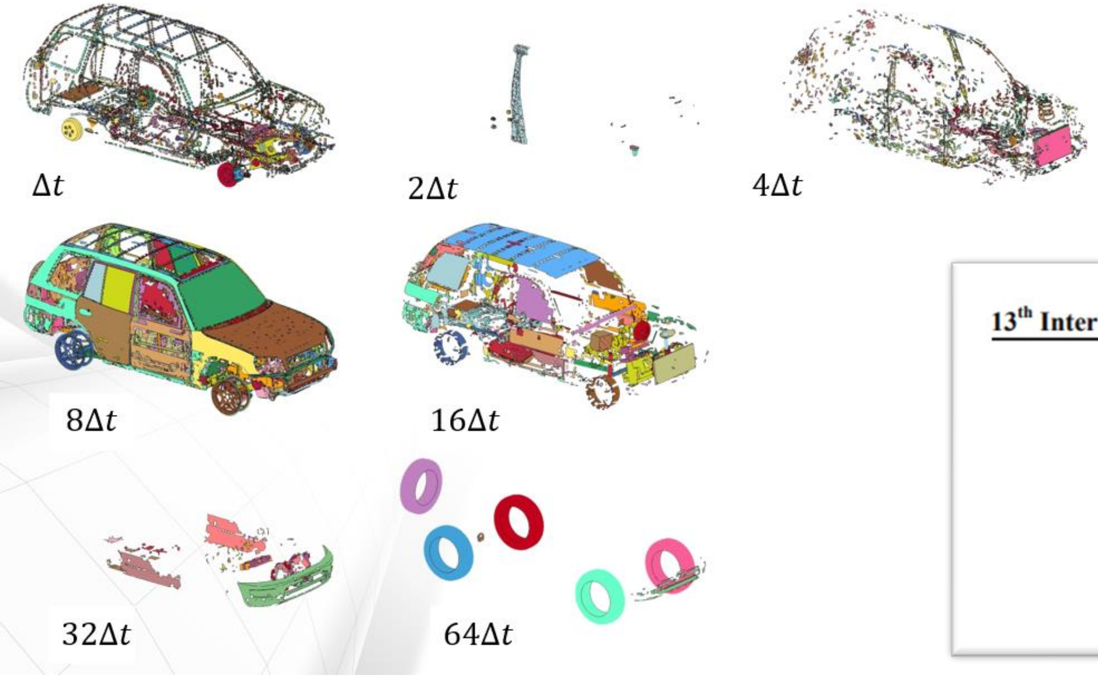
Subcycling

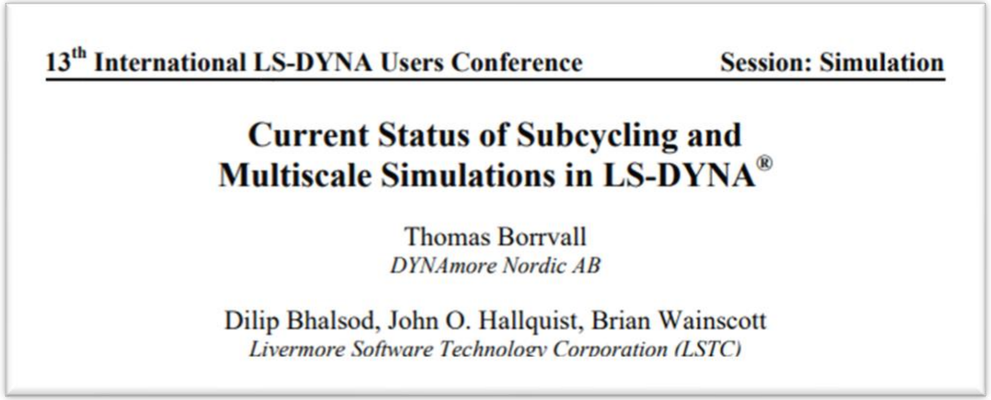


- *CONTROL_SUBCYCLE_{K}_{L}.
  - K is maximum multiple of the smallest time-step (1,2,4,8,16,32 or 64) for explicit time integration.
  - L is maximum multiple of the smallest time-step (1,2,4,8,16,32 or 64) for the external forces.
- L must be less or equal to K.
- Elements between multiples of the smallest time-step will run at a smaller time-step.
- If the critical time-step is lowered, the elements are mass-scaled to fit the critical time-step. Thus, elements are not allowed to change “time-step interval” and mass-scaling is ALWAYS on.

Subcycling – Time-Step Subdomains

- Example: A model with critical time-step 1.E-7. and K=64.
  - Subdomains will run with 7 different time-steps:
  - 1.E-7: Elements with critical timestep between 1.E-7 and 1.9999E-7.
  - 2.E-7: Elements with critical timestep between 2.E-7 and 3.9999E-7.
  - 4.E-7: Elements with critical timestep between 4.E-7 and 7.99999E-7.
  - 8.E-7: Elements with critical timestep between 8.E-7 and 15.99999E-7.
  - …



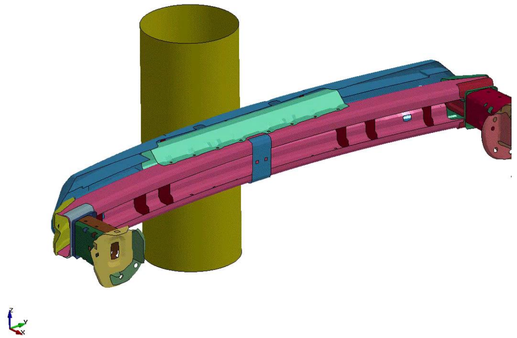

13th International LS-DYNA Users Conference Session: Simulation

Current Status of Subcycling and Multiscale Simulations in LS-DYNA®

Thomas Borrvall
DYNAmore Nordic AB

Dilip Bhalsod, John O. Hallquist, Brian Wainscott
Livermore Software Technology Corporation (LSTC)

Example – Front Bumper NHTSA Honda Accord



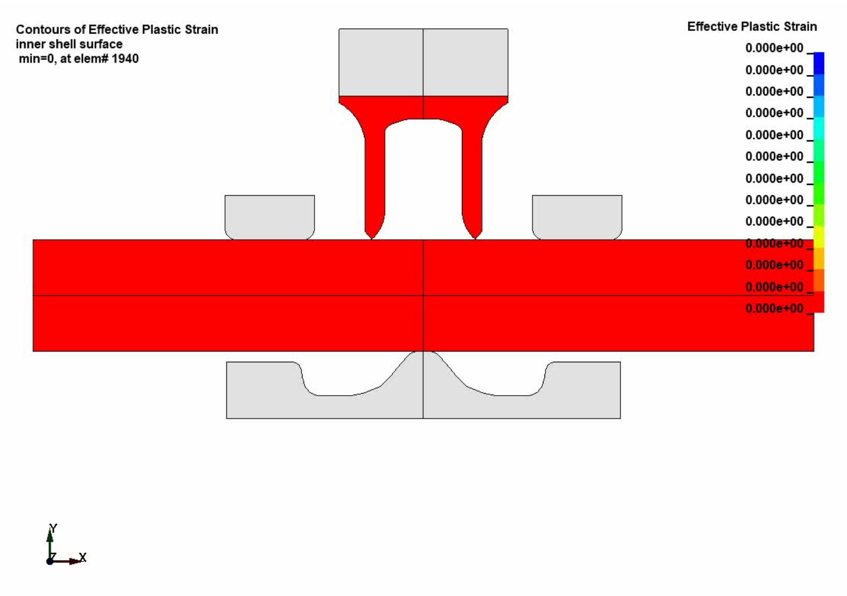
Includes 10100 rigid nodes in rigid cylinder

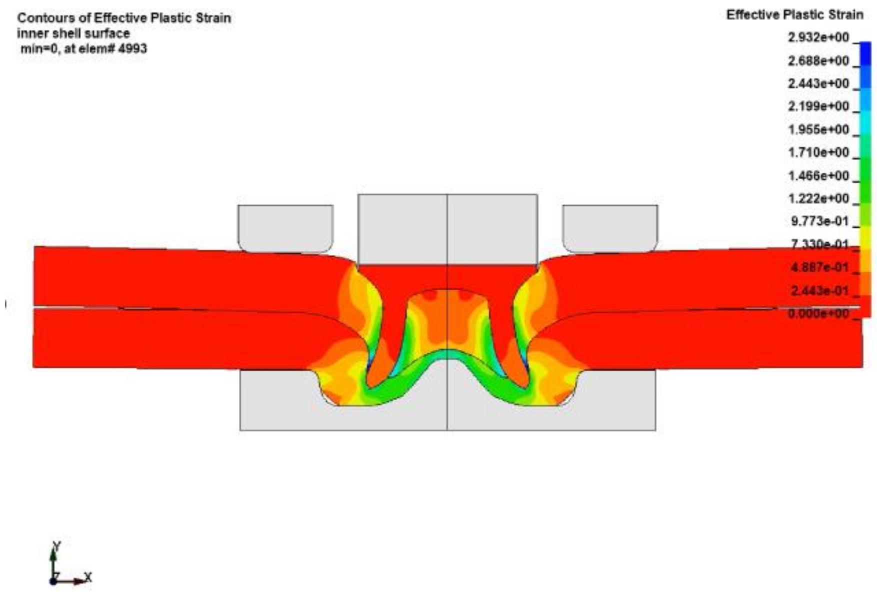
```
nodal partitioning for subcycling

minimum time step size         =    0.1821E-06
maximum time step size         =    0.2914E-05
external time step size        =    0.1821E-06
# of nodes with minimum time step size x 1 =     10422
# of nodes with minimum time step size x 2 =       862
# of nodes with minimum time step size x 4 =      7670
# of nodes with minimum time step size x 8 =      5955
# of nodes with minimum time step size x 16=       327
# of nodes with minimum time step size x 32=         0
# of nodes with minimum time step size x 64=         0
```

K,L	Simulation Time (mpp,16 cores)	MAX Error % [RMS contact force]	Mean Error % [RMS contact force]	# Nodes Δt	# Nodes $2\Delta t$	# Nodes $4\Delta t$	# Nodes $8\Delta t$	# Nodes $16\Delta t$
1,1	421 s	0	0	15134	0	0	0	0
2,1	358	2.7	0.3	322	14814	0	0	0
4,1	308	2.7	0.4	322	862	13952	0	0
8,1	309	7	0.35	322	862	7670	6282	0
16,1	315	15.2	0.6	322	862	7670	5955	327
16,1 Δt=4.5E-7	172s (181s)	15.2	0.9	2978	7313	4839	0	0

Multiscale

- Instead of automatic division into time-step subdomains the user can manually give a mass-scaling time-step for a part/part set.
- Time-step will be adjusted by LS-DYNA to a 2-power multiple of the smallest step.
- Suitable for small but highly refined parts e.g., self-piercing rivets.



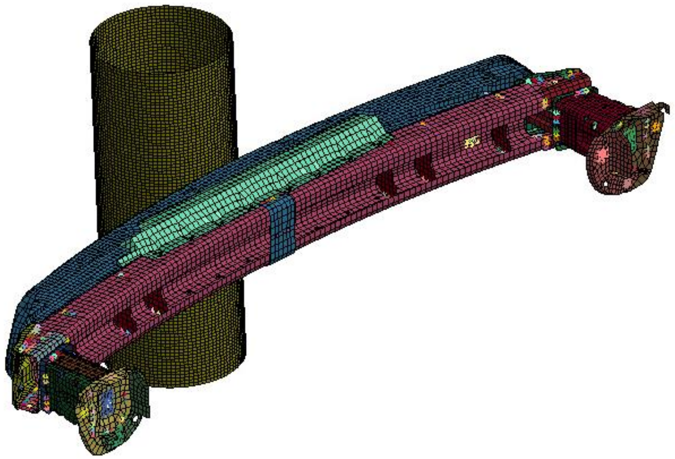


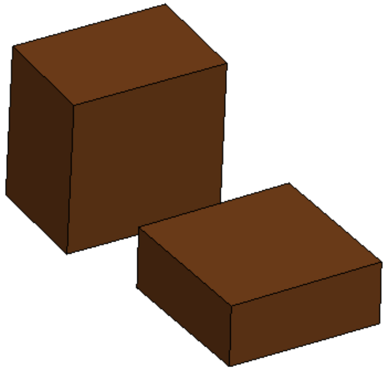
Multiscale in LS-DYNA

- *CONTROL_SUBCYCLE_MASS_SCALE_PART_{SET}.
  - Specifies mass-scaling time-step for the selected parts.
- The rest of the model will adopt the time-step set by DT2MS on *CONTROL_TIMESTEP card.
- External force calculations {L} are default 1, but can be altered by a *CONTROL_SUBCYCLE_{K}_{L} keyword. {K} is ignored in this case.

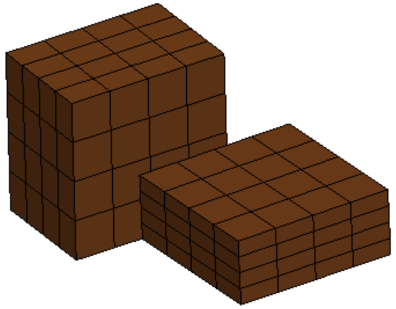
Example – Front Bumper NHTSA Honda Accord

- Highly dense spotwelds.



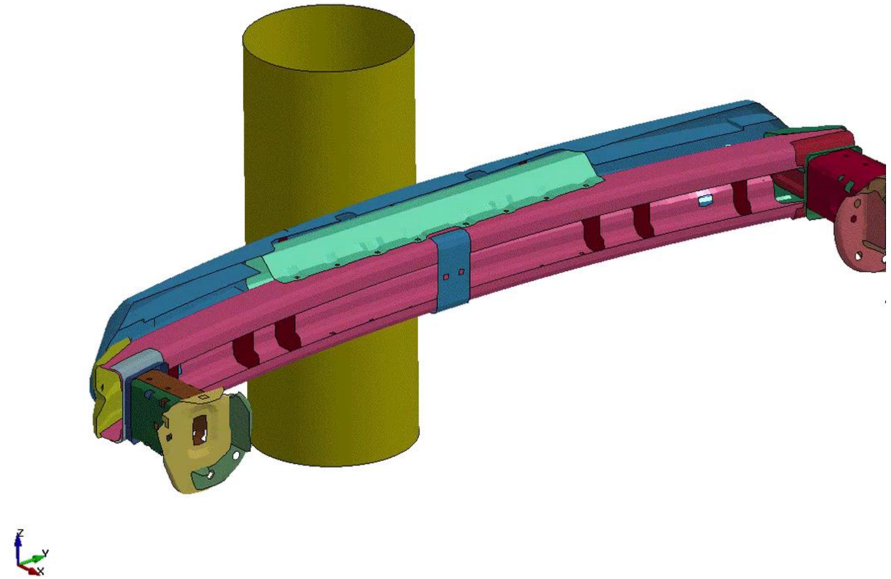


40 elements



2560 elements

Example – Front Bumper NHTSA Honda Accord



```
nodal partitioning for subcycling

minimum time step size         =    0.4480E-07
maximum time step size         =    0.3584E-06
external time step size        =    0.4480E-07
# of nodes with minimum time step size x 1 =    15102
# of nodes with minimum time step size x 2 =        0
# of nodes with minimum time step size x 4 =        0
# of nodes with minimum time step size x 8 =    14814
# of nodes with minimum time step size x 16=        0
# of nodes with minimum time step size x 32=        0
# of nodes with minimum time step size x 64=        0
```

Time-Step [s]	Mass -Scaling [kg, %]	Simulation Time (mpp,16 cores)	MAX Error % [RMS contact force]	Mean Error % [RMS contact force]
4.48E-8	0,0	1859	0	0
4.5E-8; 5.0 E-7	0., 0.	1531	1.7	0.4
4.5E-8;1.2E-6	0.06, 0.	1290	1.6	0.4

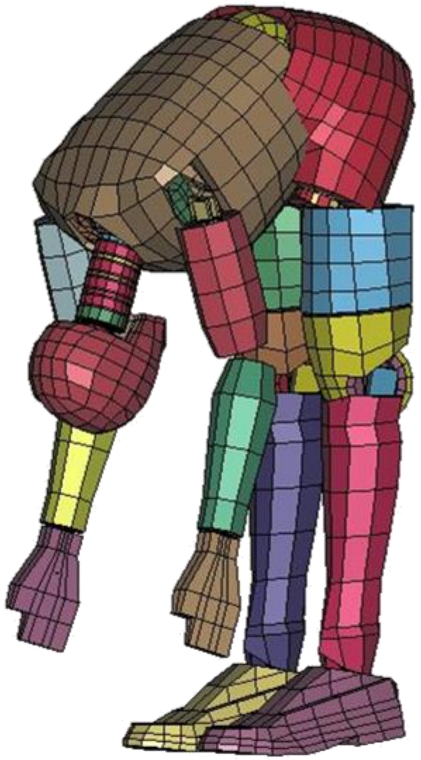
Conclusion

- Simulation times can be significantly decreased by mass-scaling.
- Mass-scaling affects the dynamics of the problem by adding mass to the elements.
- Adding too much mass will change the behaviour of your model.
- Two types of mass-scaling exist:
  - Conventional mass-scaling: Scales all eigenfrequencies.
  - Selective mass-scaling: Scales the bounding eigenfrequencies.
- Too much Selective mass-scaling is CPU intensive.
- Time-Scaling is very beneficial but should not be used too ambitiously, to avoid inducing dynamics.
- Subcycling allows for different sub-domains to run on different time-steps.
  - Subcycling: Automatic division into sub-domains with different time-steps.
  - Multiscale: Manual definition of time-step for each sub-domain by part(set).
- Time-step can be different for the explicit time integration and the external forces update.
- A too high external force update time-step may cause instabilities.

Further Reading..

- On DYNAlook
  - Du Bois J. H. and Du Bois P., A Study in Mass Scaling for Sheet Metal Forming with LS-DYNA, 15th International LS-DYNA Users Conference. (https://www.dynalook.com/conferences/15th-international-ls-dyna-conference/metal-forming/a-study-in-mass-scaling-for-sheet-metal-forming-with-ls-dyna-r).
  - Borrvall T., et al., Current Status of Subcycling and Multiscale Simulations in LS-DYNA, 13th International LS-DYNA Users Conference. (https://www.dynalook.com/conferences/13th-international-ls-dyna-conference/simulation/current-status-of-subcycling-and-multiscale-simulations-in-ls-dyna-r).

Thank You



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