Recent Enhancements for Crash Safety in LS-DYNA

11.16.2023

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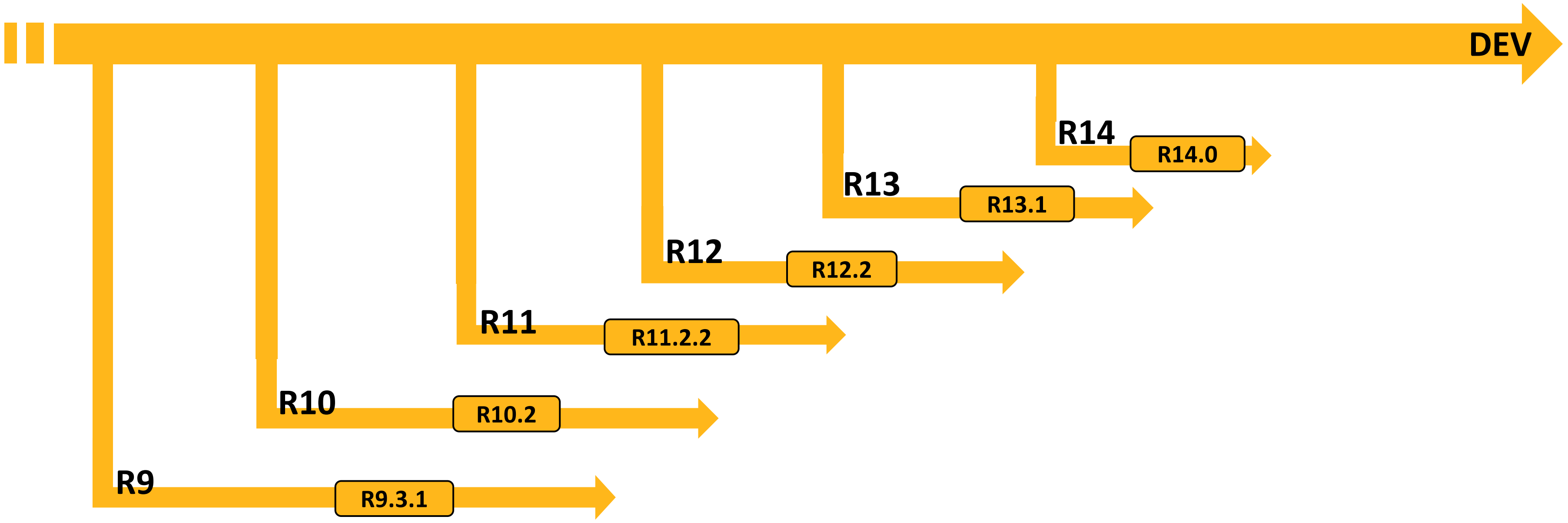
LS-DYNA Version – Current Landscape

- LS-DYNA versions available:



- Production used in automotive: R9.3.1, R10.2.1, R11.2.2, R12.2
- Latest version: R12.2 (January 2023)
- Upcoming version: R14.1 (Q4 2023), R15.0 (Q1 2024)

Agenda

- Usability:
  - Running very large models in single precision
- Contacts:
  - Ignore Tolerance (igtol) to deal with cases where thickness > mesh size
  - Performance enhancement on automatic general
- Safety:
  - *AIRBAG_PARTICLE enhancements (blockage, venting based on part pressure…)
  - *MAT_SEATBELT enhancements (bending stiffness, strain rate effect, fabric formulation)…
- Rigid body:
  - Rigidize part or all the vehicle with _OVERRIDE

Usability

Usability – Running large model is single precision

- Model size is increasing rapidly. Depending on the version used, the model content, LS-DYNA may fail during the initialization because the memory required exceeds the maximum amount of memory that can be allocated in single precision (2.147e+9 words)
- The error may occur:
  - During the keyword reading stage
  - The domain decomposition
- The following message will be written

```
 *** Warning 70025 (OTH+25) (processor # 0)
     Memory is set 16133382 words short
     increase the memory size to 2122637838

 *** Error 70241 (OTH+241) (processor # 0)
     Internal error: request to expand memory to a
     negative value. This is most likely because the problem you
     are running requires more memory than the single precision
     version can allocate. Try the double precision version of
     the program.
```

Usability – Running large model is single precision

- With the current version available for production use, there are several solutions to work around this problem:
  - Run in double precision which comes with a penalty of 15-30% in runtime.
  - 2 step process:
    - Perform the domain decomposition in double precision
    - Run in single precision
  - Identify which keyword / feature is using a significant amount of memory and modify the definition such that the model can be run in single precision. For example, from the message file

```
expanding   memory to   880300679 d    914970021 *LOAD_AXIAL_FORCE_BEAM
expanding   memory to   881127531 d    914970021 *DEFINE_ELEMENT_DEATH
expanding   memory to   955068207 d    914970021 rigidwall definitions
expanding   memory to  1650848309 d    927293467 nodal constraint sets
expanding   memory to  1652039963 d    927293467 interior solid contact
expanding   memory to  1692616806 d    939557913 contact interfaces
expanding   memory to  1717264698 d    939557913 implicit contact 1
expanding   memory to  1755386382 d    939557913 implicit contact 2
expanding   memory to  1697728501 d   1254609942 contact segment data 1
expanding   memory to  1788639119 d   1401072528 contact segment data 3
```

A significant amount of memory is used while trying to process the rigid walls. Memory expands from 9.55e+8 words to 1.650e+9 words which represent ~30% of the maximum amount of the memory that can be allocated.

Some simplification of the definition may help.

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Usability – Running large model is single precision

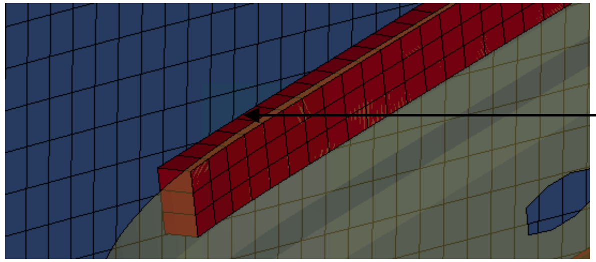
- Solution: several options have been moved to dynamic memory allocation which allows to run significantly larger models in single precision

R931. Max memory 1.491e+9 words	R1122. Max memory 8.71e+8 words	R1220 & later. Max memory 1.84e+8
Memory required for decomposition: 1491147769	Memory required for decomposition: 871680823	Memory required for decomposition: 184530832

- Very large model (over 30 million elements) can run in R1220 in single precision.

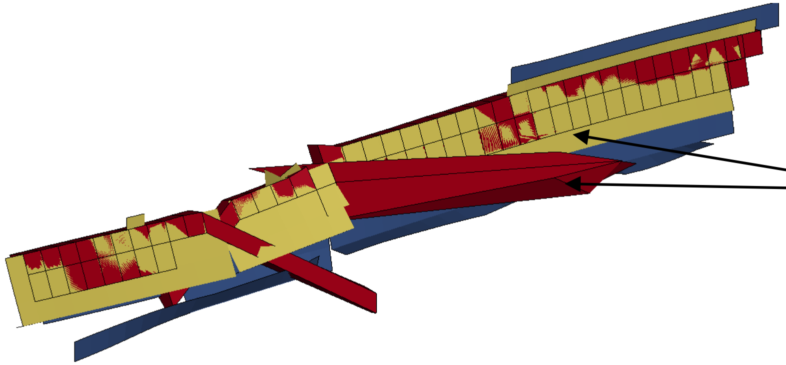
Adhesive – Automatic deletion

- *MAT_ARUP (*MAT_169) is used frequently to model structural adhesive. Different parameters can be set to define the failure in tension and shear of the adhesive.



The adhesive typically does not share common nodes with the sheet metal and is connected through a tied contact.

- If the adhesive fails before the sheet metal on which it is tied, the behavior of the adhesive is correct. However, when the sheet metal fails before the adhesive, the material can become unstable, and the simulation may terminate with a mass error or a NaN (Not A Number)



Some of the elements on which the adhesive is tied fail before the adhesive => the adhesive material becomes unstable.

Adhesive – Automatic deletion

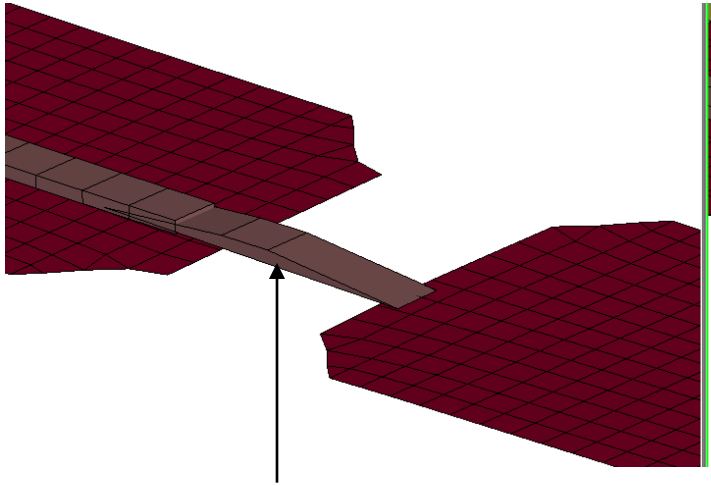
- With the current production version one way to work around this issue is to add failure on the adhesive *MAT_ADD_EROSION

```
*MAT_ARUP_ADHESIVE_TITLE
WSS-M2G576-A1|Min_Uniseal_2352|AA|00E00|70010900
$#      MID        RO         E        PR    TENMAX     GCTEN    SHRMAX     GCSHR
     130015    1.2E-6         2      0.33   0.02994   0.00414   0.02576   0.01305
$#     PWRT      PWRS      SHRP    SHT_SL     EDOT0     EDOT2    THKDIR     EXTRA
          5         5      0.57         0         0         0         1         0
*MAT_ADD_EROSION_TITLE
Tensile_Shear_Failure
$#      mid      excl    mxpres     mneps    effeps    voleps    numfip       ncs
     130015       0.0       0.0       0.0       0.0       0.0       1.0       1.0
$#   mnpres     sigp1     sigvm     mxeps     epssh     sigth   impulse    failtm
        0.0       0.0       0.0       1.0       2.0       0.0       0.0       0.0
```

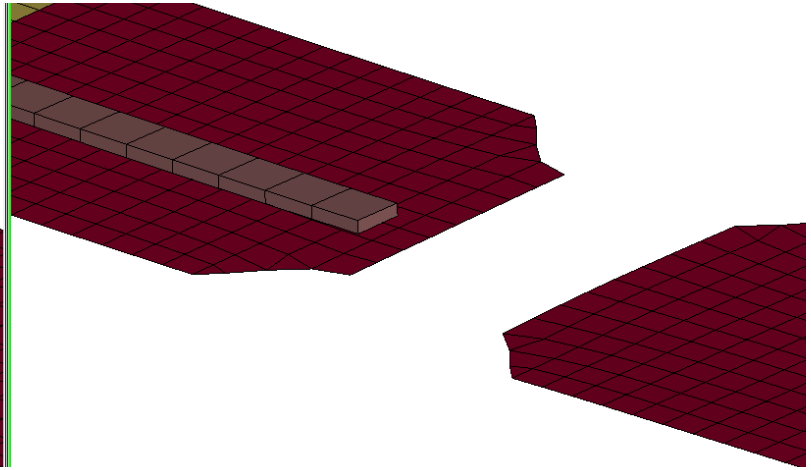
Adhesive – Automatic deletion

- Solution:

In R1220, *MAT_ARUP is compatible with Icoh=1 in *CONTROL_SOLID. When the master segment on which a node of MAT_ARUP is tied, is deleted, the element will be automatically deleted. Adding *MAT_ADD_EROSION is no longer required in most instances.



Icoh=0, the adhesive behaves incorrected once the element on which it is bonded is deleted



Icoh=1, the adhesive is automatically deleted once the element on which it is bonded is deleted

Connection and Contact

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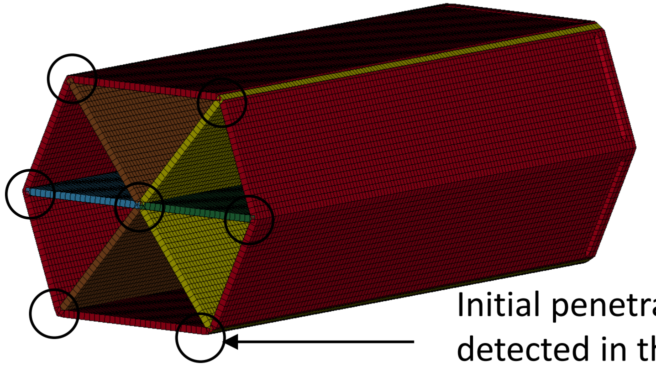
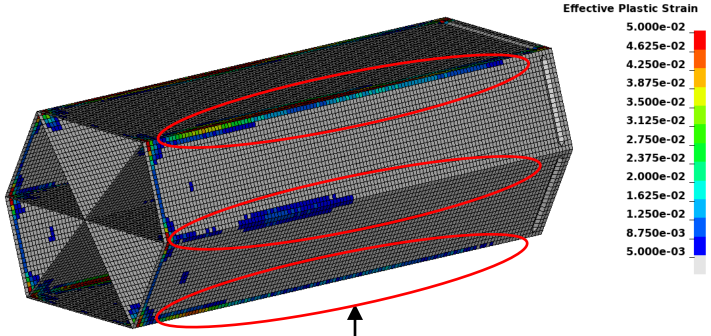
Contacts – Ignore Tolerance

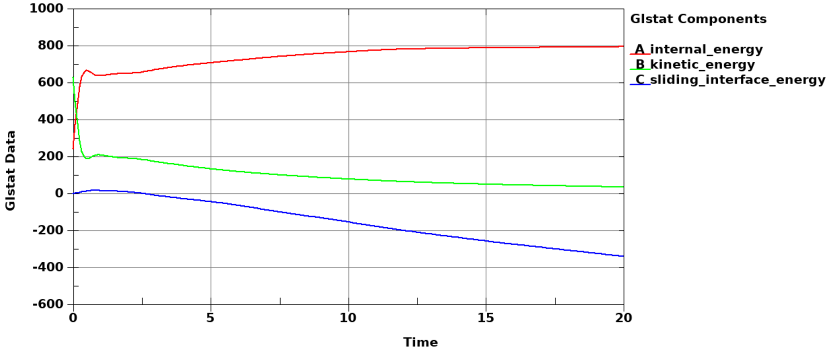
- Ignore Tolerance (Igtol) for Soft=0/1
  - Mesh size is decreasing, many parts are modeled with an average mesh size between 2 to 5mm .
  - Castings and extruded aluminum profiles have thicknesses between 1.5-15mm. In many instances they are modeled with shell elements. This generates some challenges when it comes to contact definition as we will detect initial penetrations due to the thickness being > mesh size.
  - These initials penetrations can be “ignored” but over time, can generate spurious deformation and energy generation in areas where no loads are applied. Current workaround is to either:
    - Model the parts in solids
    - Set OPTT in *PART_CONTACT (with OPTT < mesh size)
    - Set SSTHK to 0 instead of 1 in *CONTROL_CONTACT (the contact thickness is then limited by the minimum edge length)



Initial penetrations will be detected in the corners

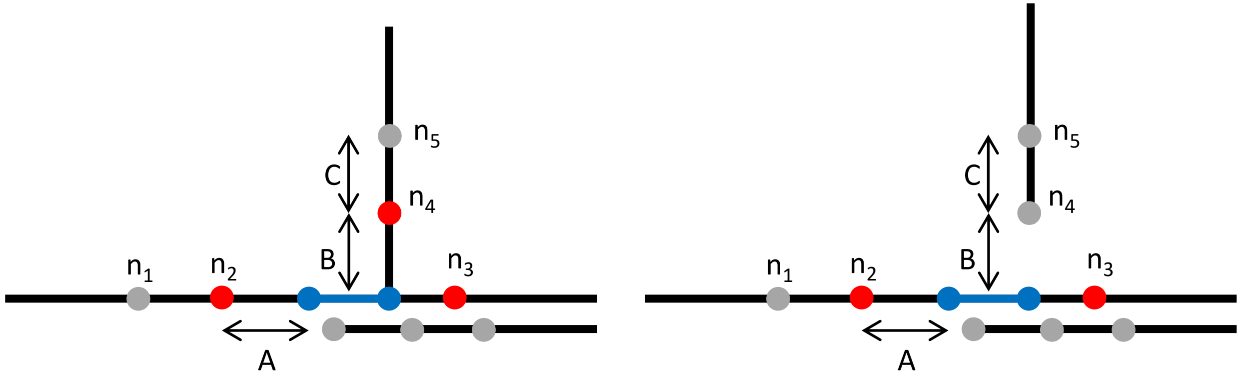


Spurious deformation



Contacts – Ignore Tolerance

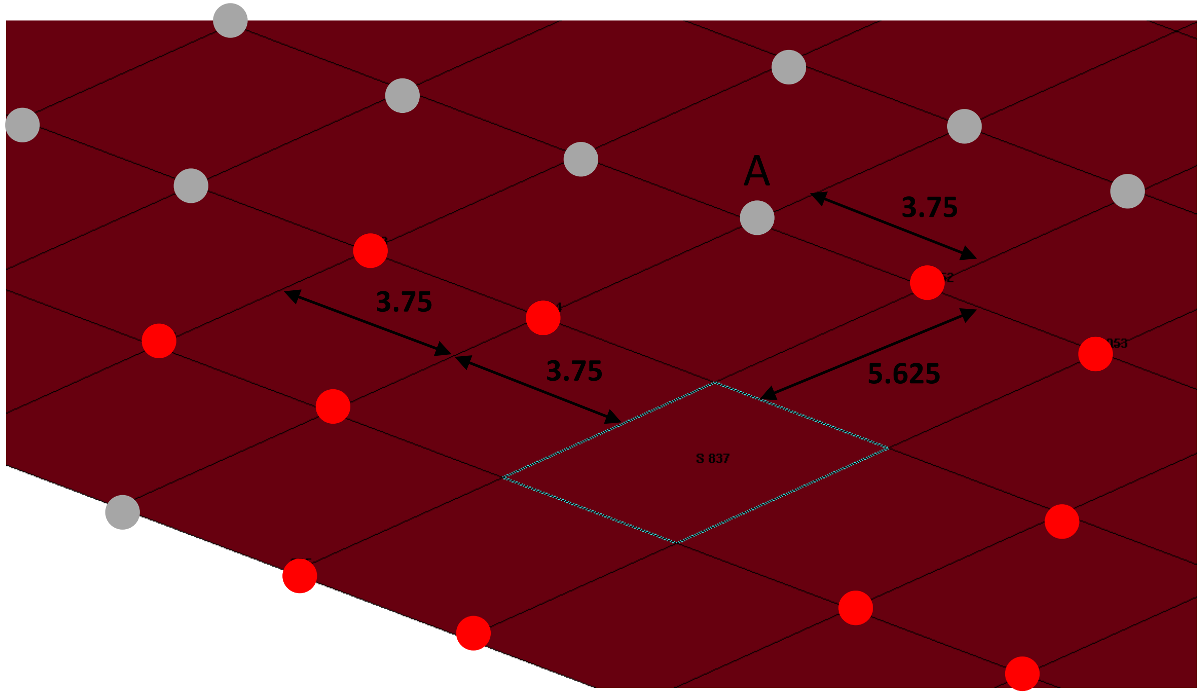
- Ignore Tolerance (Igtol) for Soft=0/1
  - The idea is to exclude nodes based on connectivity and contact thickness. When the distance of a slave node to a segment (measured using connectivity) is smaller than Igtol*(segment thickness + node thickness), the nodes are added to an exclusion list for that segment.
  - The below figure illustrates two different scenarios for excluding nodes from contact with the segment in blue. In both scenarios red indicates nodes excluded from contact and grey nodes not excluded. We measure the distance by moving along the edges of the contact segments.



  - In the left figure n_2 is at a distance A from the segment and n_5 is at a distance B+C from the segment.
  - In the right figure, n_4 is not excluded because it is not connected to the segment through the mesh.

Contacts – Ignore Tolerance

- Ignore Tolerance (Igtol) for Soft=0/1



Thickness is 4mm. With igtol=1.0, the exclusion distance is 8mm.

The red nodes are excluded for shell 837. The gray nodes can contact this segment.

Distance of node A to shell 837 is 5.625+3.75

Contacts – Ignore Tolerance

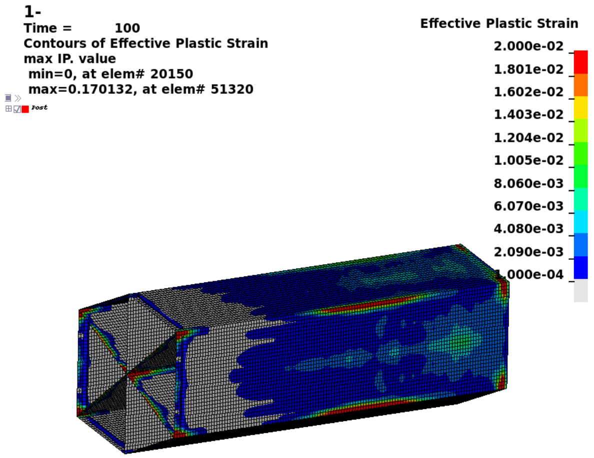
- Ignore Tolerance (Igtol) for Soft=0/1
  - To activate this option a non-zero value can be set on the 6th field of the second optional card of _MPP

```
*CONTACT_AUTOMATIC_SINGLE_SURFACE_MPP_ID
$#     cid                                                                 title
        11Vehicle_Global_Self_Contact
$#  ignore       bckt    lcbckt    ns2trk   inititr    parmax    unused    cparm8
         2                              0
$#  unused    chksegs     pensf   grpable               igtol
&                                       1                 1.0
$#   surfa      surfb  surfatyp  surfbtyp   saboxid   sbboxid      sapr      sbpr
         1          0         2         0         0         0         0         0
$#      fs         fd        dc        vc       vdc    penchk        bt        dt
       0.1        0.0       0.0       0.0       0.0         0       0.01.00000E20
$#    sfsa       sfsb      sast      sbst     sfsat     sfsbt       fsf       vsf
       1.0        1.0       0.0       0.0       1.0       1.0       1.0       1.0
$#    soft     sofscl    lcidab    maxpar     sbopt     depth     bsort    frcfrq
         1        0.1         0     1.025       0.0         0         0         1
```

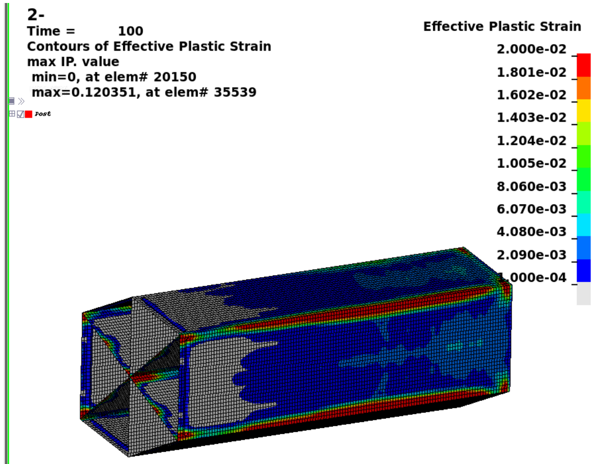
  - Note that if Igtol>0, then SSTHK is automatically set to **1 for that contact**.

Contacts – Ignore Tolerance

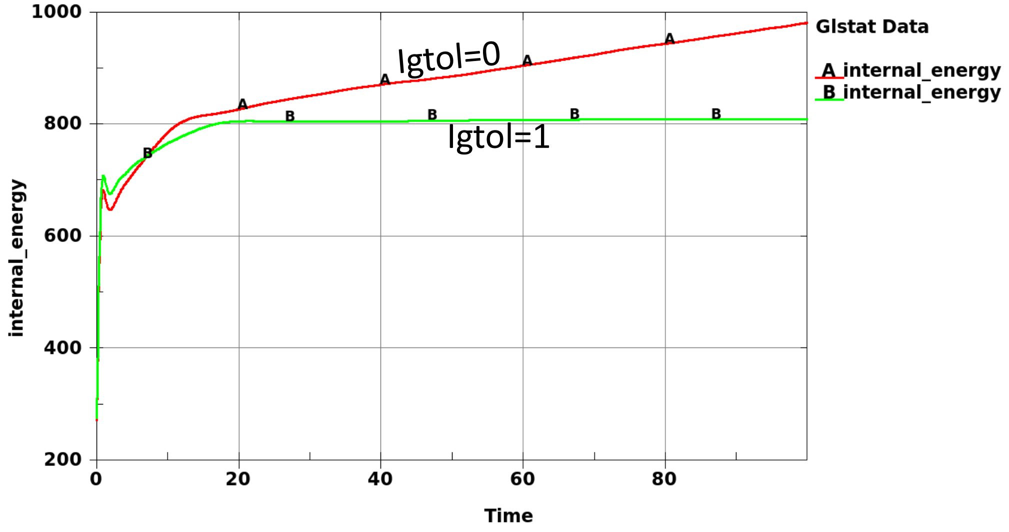
- Ignore Tolerance (Igtol) for Soft=0/1
  - Helps prevent spurious deformation that may occur mesh size < thickness.



Igtol = 1



Igtol = 0



  - No significant effect on runtime. Current limitation in R12.2: the penetration checking will not account for igtol>0 as the exclusion lists are built at cycle 1 while the penetration checking is performed at cycle 0. This has been fixed in later versions of LS-DYNA.

AUTOMATIC_GENERAL - Problem Statement

- *CONTACT_AUTOMATIC_GENERAL is used frequently for its edge-to-edge capabilities:
  - Beam to beam
  - Beam to shell edge
  - Shell edge to shell edge
- *CONTACT_AUTOMATIC_GENERAL_INTERIOR provides the ability to handle edge-to-edge between external and interior shell edges.
- On full vehicle or occupant model this contact types are used often and depending on the number segments / beams they can significantly affect runtime. Distributing these contacts do not necessarily yield significant improvement in performance.

Impact Mode	With Automatic General	Without Automatic General	Reduction
Front ODB	24h07min	19h13min	-20.4%
Rear MDB	21h32min	17h04min	-20.8%

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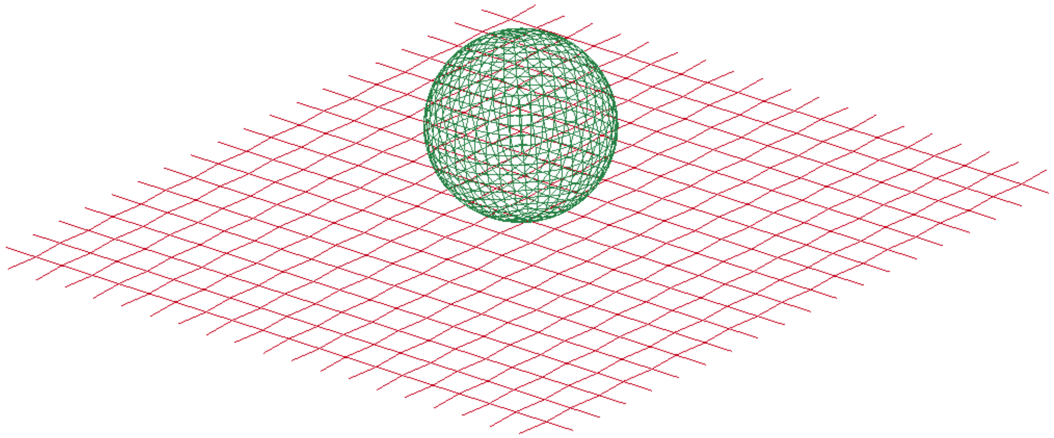
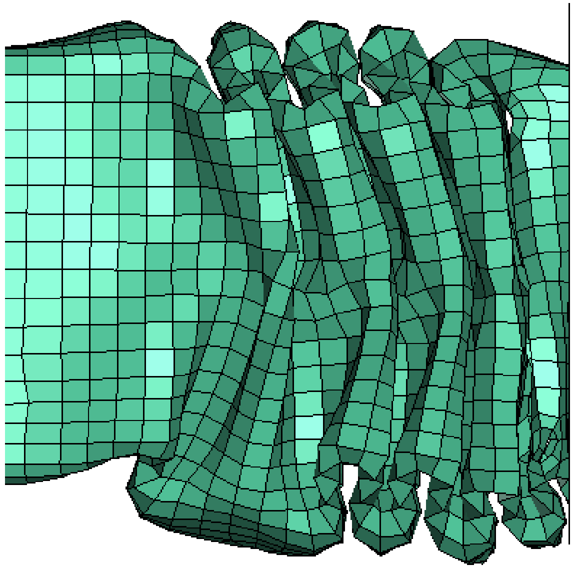
AUTOMATIC_GENERAL – Application on basic model

- Several enhancements have been made to improve the performance of the edge-to-edge treatment in *CONTACT_AUTOMATIC_GENERAL (and _INTERIOR).
- First the effect of the performance enhancements were assessed on simple models like shown below:



Drop test of a rigid sphere on a net meshed with beam elements



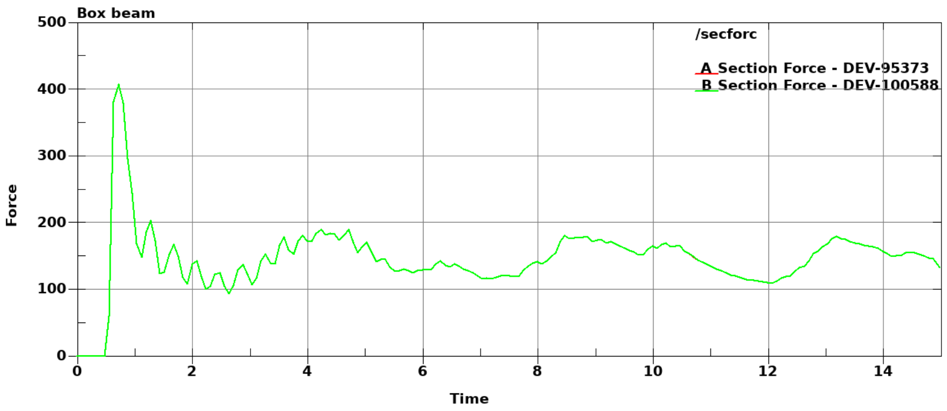
Axial crush of an extruded profile

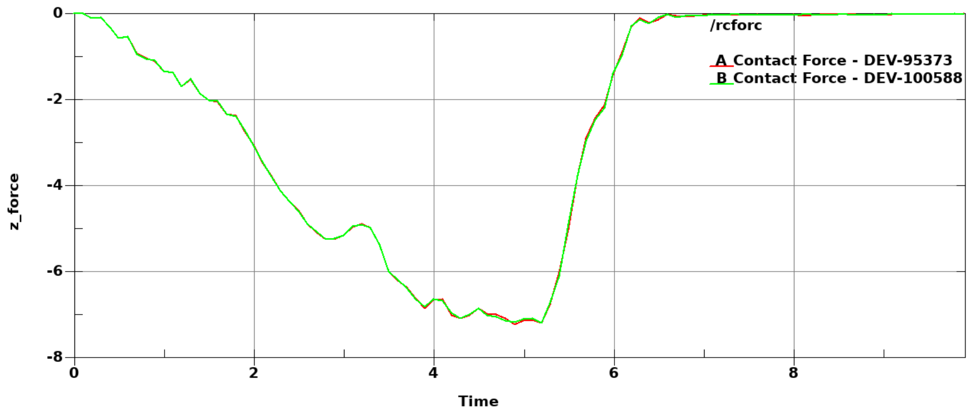
AUTOMATIC_GENERAL Enhancement – Application on basic model

- Runtime comparison:

Model #	DEV-95373-gb5f06d1	DEV-100588-gc78b2fa244	Reduction
1	189s	13s	-93%
2	1205s	161s	-86%
3	695s	84s	-88%

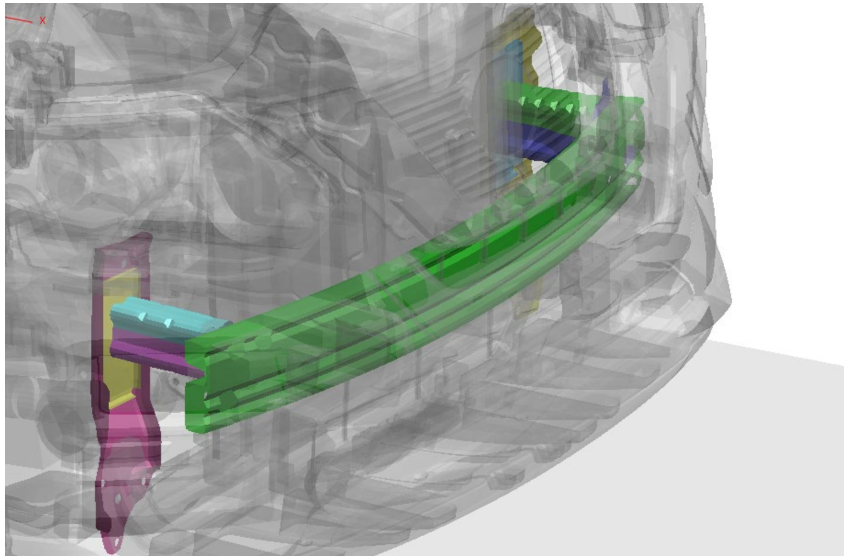
- Results comparison:





AUTOMATIC_GENERAL Enhancement – Application on full model

- There may be multiple *CONTACT_AUTOMATIC_GENERAL definition on a full vehicle model. In this example:
  - On the front crush can, a *CONTACT_AUTOMATIC_GENERAL_INTERIOR is defined.



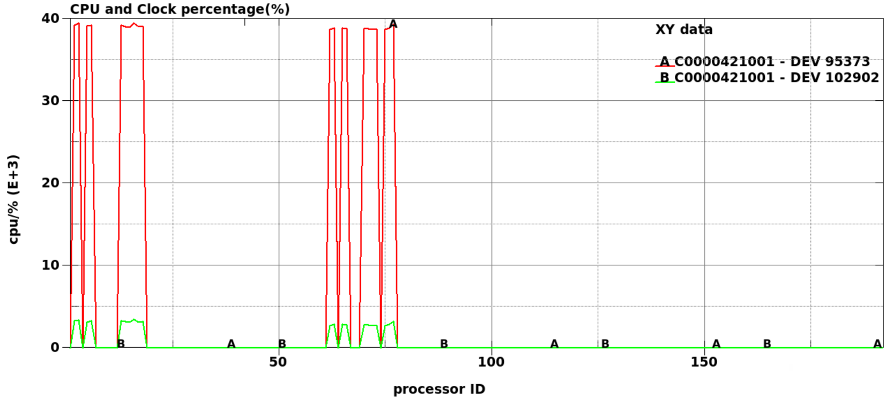
  - To capture local edge to edge, 6 *CONTACT_AUTOMTATIC_GENERAL are defined at various location on the vehicle (subframe, door latches…)

AUTOMATIC_GENERAL Enhancement – Application on full model

- Runtime comparison:

Impact Mode	DEV-95373	DEV-102902	Reduction
Frontal low speed	23h19min	16h3min	-31.1%

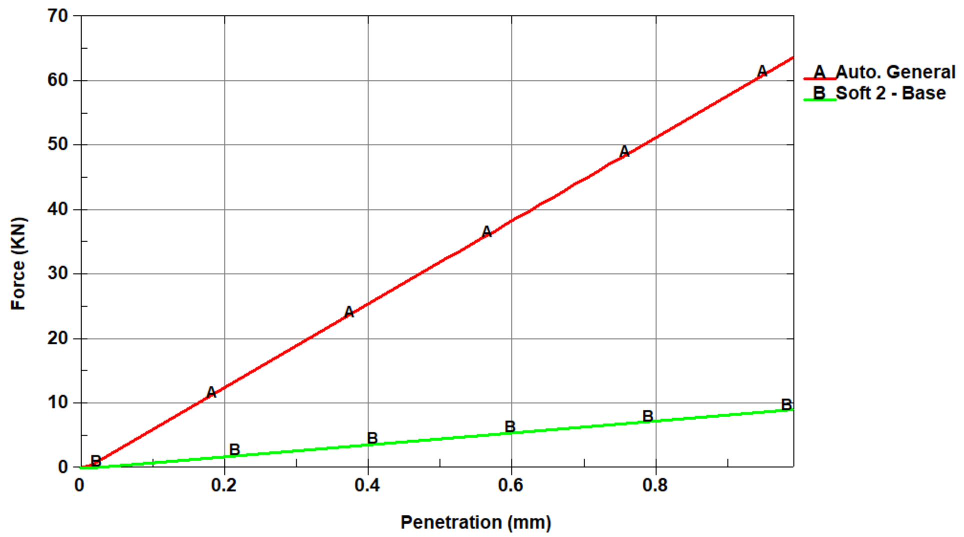
  - On this example, the *CONTACT_AUTOMATIC_GENERAL_INERTIOR defined on the crush can takes a significant amount of time to process. The enhancement made in R15 leads to significant reduction in runtime.

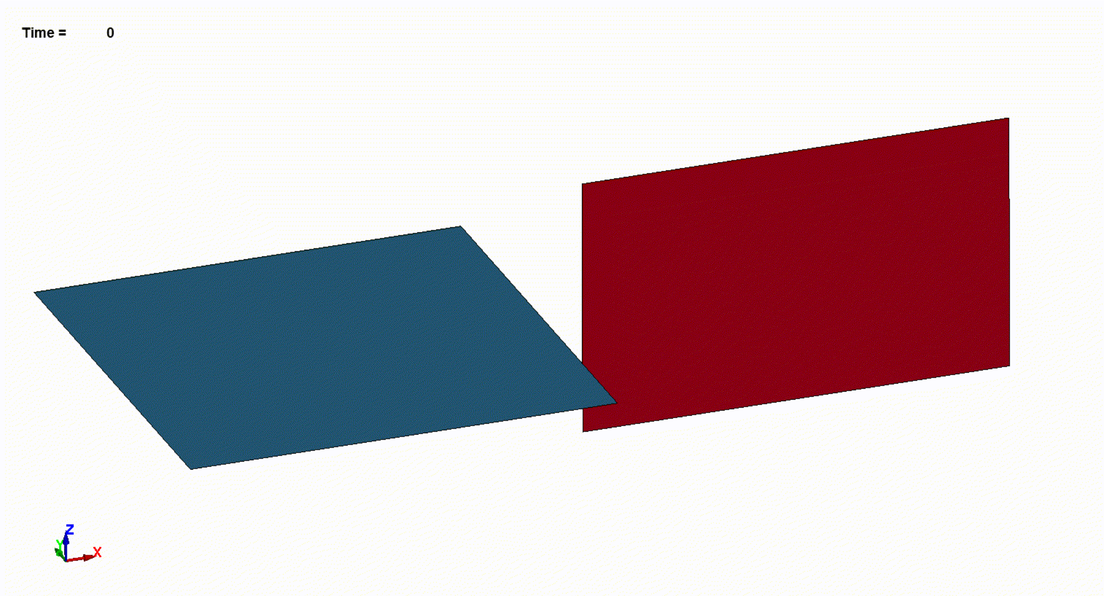


  - Note that the reduction in runtime purely depends on how much time it takes to process *CONTACT_AUTOMATIC_GENERAL on that model. Depending on the model content, how much time is takes to process this contact type, the performance improvement will vary.

Contacts – Soft=2 – edge-to-edge contact stiffness

- Soft=2 – EDGEK
  - Problem: The edge-to-edge contact stiffness with Soft=2 and depth=5 or 35 is lower than the one from *CONTACT_AUTOMATIC_GENERAL. The contact stiffness of the edge-to-edge component cannot be controlled independently from the surface-to-surface component

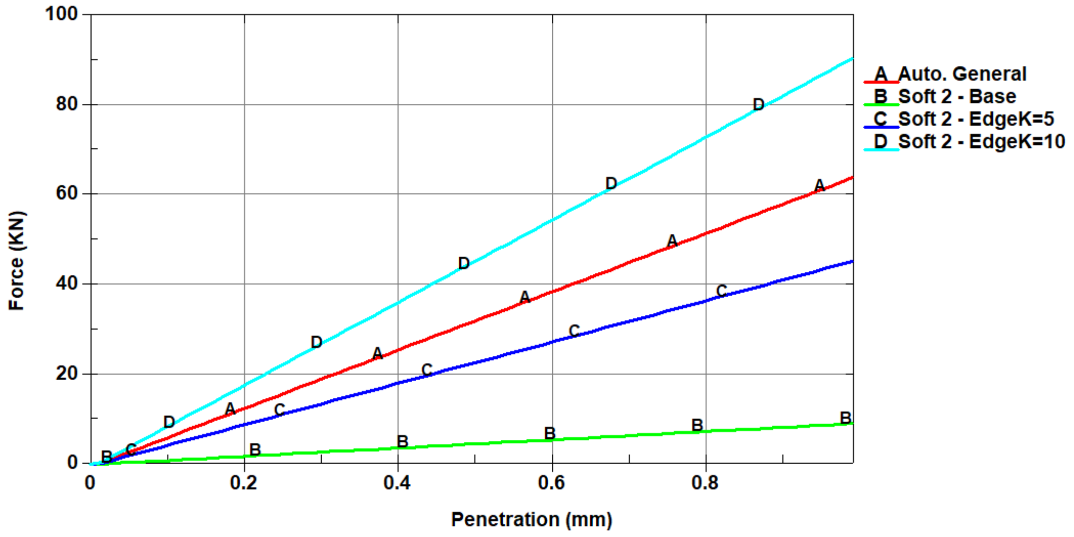




Contacts – Soft=2 – edge-to-edge contact stiffness

- Soft=2 – EDGEK
  - Solution: A new parameter is introduced named EDGEK which allows to scale the edge-to-edge contact stiffness for soft=2 when depth=5 or 35 are used. Applies to both shell and solid segment edges.
  - In R14.0, implemented depth=55 which should improve the robustness of the edge-to-edge checking over depth=25/35, reducing the risk of penetration further.

```
*CONTACT_AUTOMATIC_SINGLE_SURFACE_ID
        11Global_Self_Contact
$#    surfa     surfb  surfatyp  surfbtyp   saboxid   sbboxid      sapr      sbpr
          1         0         2         0         0         0         0         0
$#       fs        fd        dc        vc       vdc    penchk        bt        dt
        0.1       0.0       0.0       0.0       0.0         0       0.01.00000E20
$#     sfsa      sfsb      sast      sbst     sfsat     sfsbt       fsf       vsf
        1.0       1.0       0.0       0.0       1.0       1.0       1.0       1.0
$#     soft    sofscl    lcidab    maxpar     sbopt     depth     bsort    frcfrq
          2       0.1         0     1.025       3.0        35         0         1
$#   penmax    thkopt    shlthk     snlog      isym     i2d3d    sldthk    sldstf
        0.0         0         0         0         0         0       0.0       0.0
$#     igap    ignore    dprfac    dtstif     edgek    unused    flangl   cid_rcf
          2         0       0.0       0.0         5                 0.0         0
```



Safety

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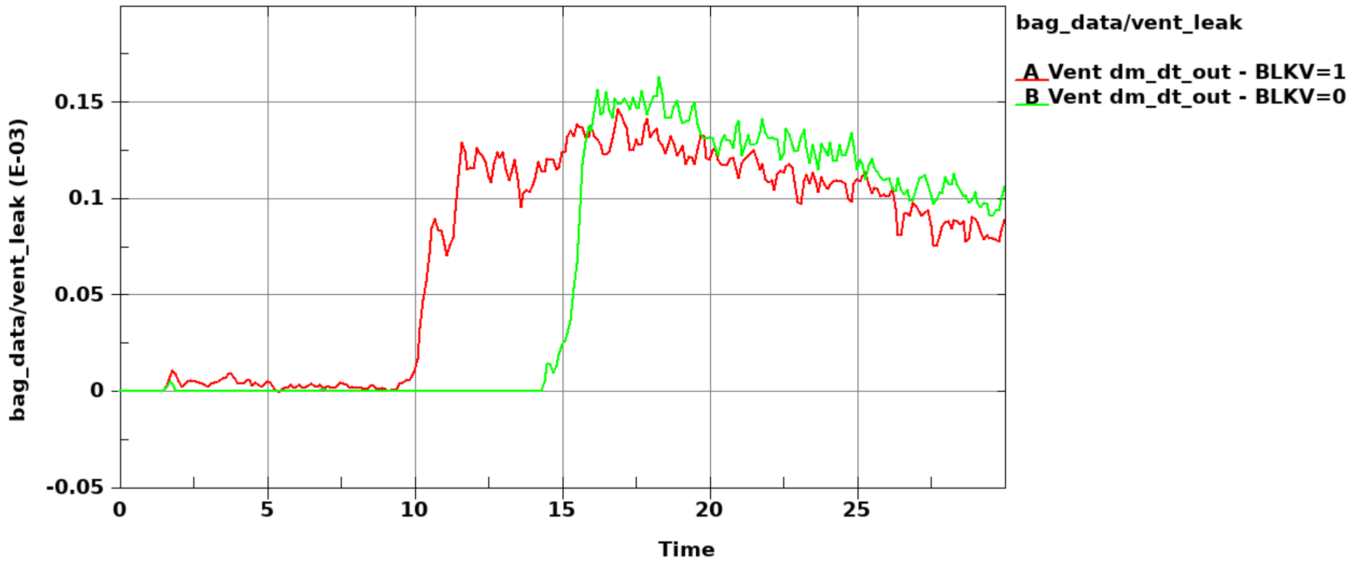
*AIRBAG_PARTICLE

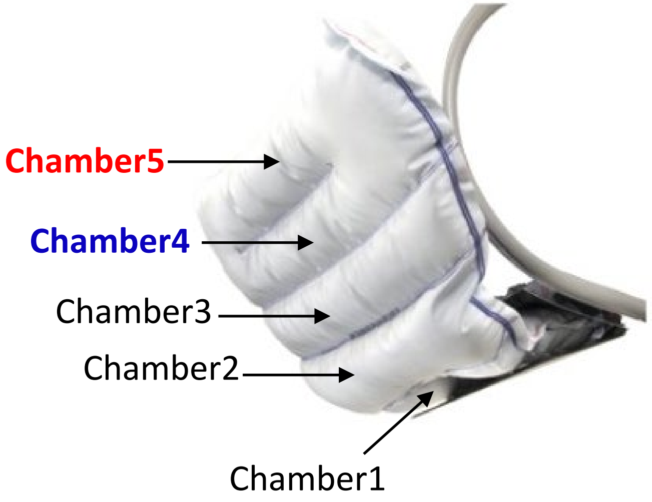
- *AIRBAG_PARTICLE
  - Problem: Blockage is too high on the external vents during the initial unfolding.
  - Solution: Provided the ability to exclude the nodal contact forces of the airbag single surface contact from being considered in the blockage of external vents.

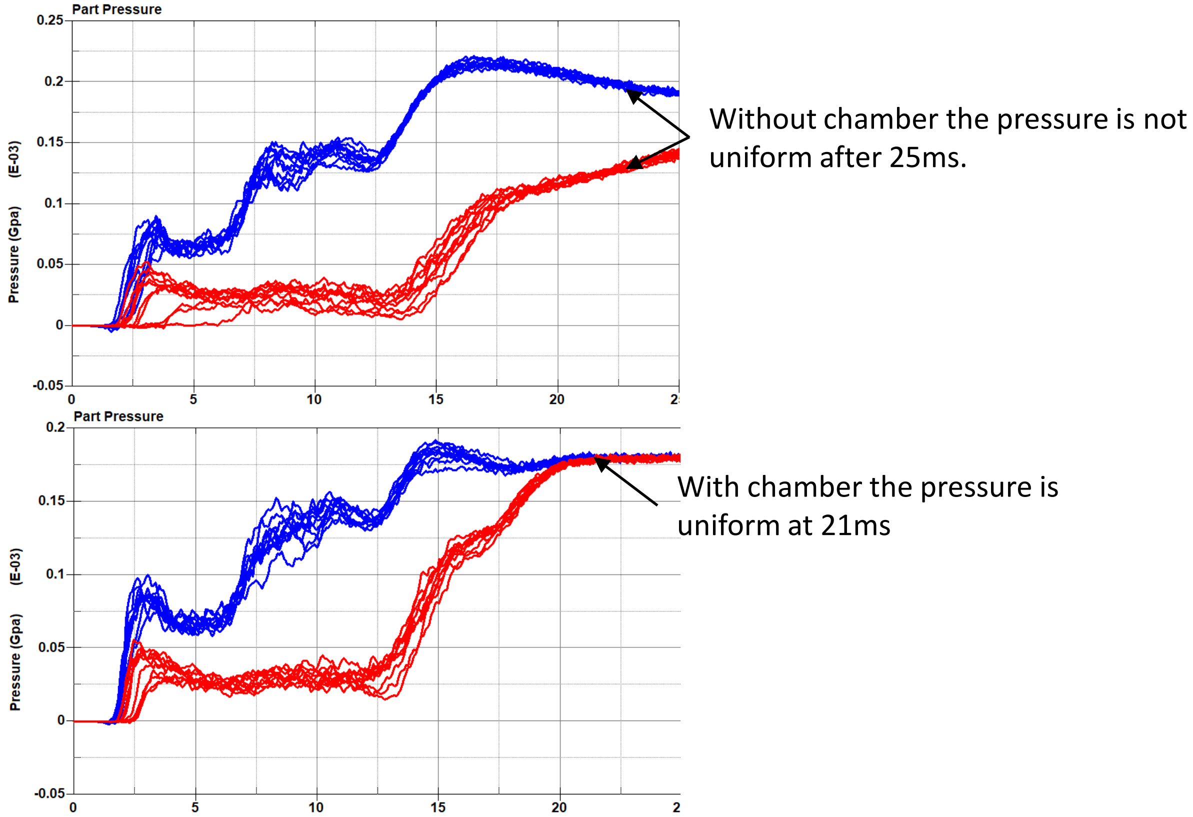
```
*CONTROL_CPM
$#   cpmout      np2p    ncpmts    cpmerr     sffdc      blkv     cpmmf    p2pmix
         11         5         0         1       1.0         1         0         0
```



*AIRBAG_PARTICLE

- *AIRBAG_PARTICLE
  - Problem: for certain multi-chambered airbag (knee airbag…) chambers need to be defined in order to correlate the inflation sequence and pressure within the chambers. Defining chambers is a time consuming and error prone process.

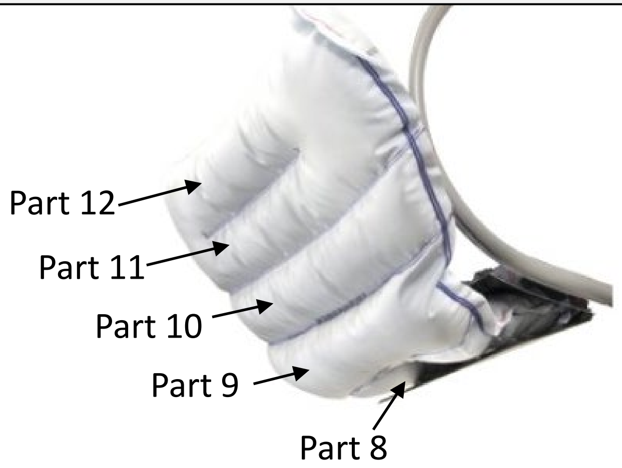


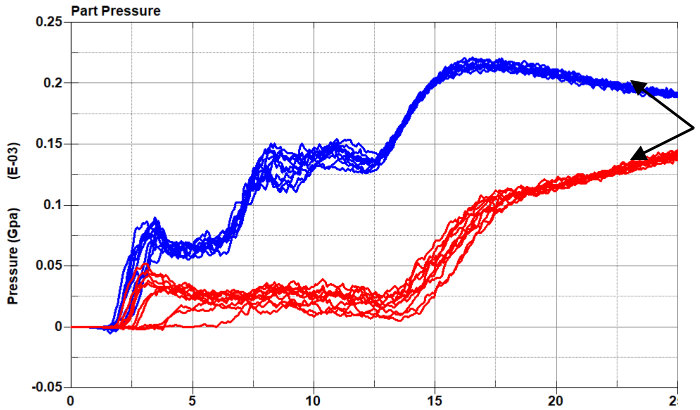


*AIRBAG_PARTICLE

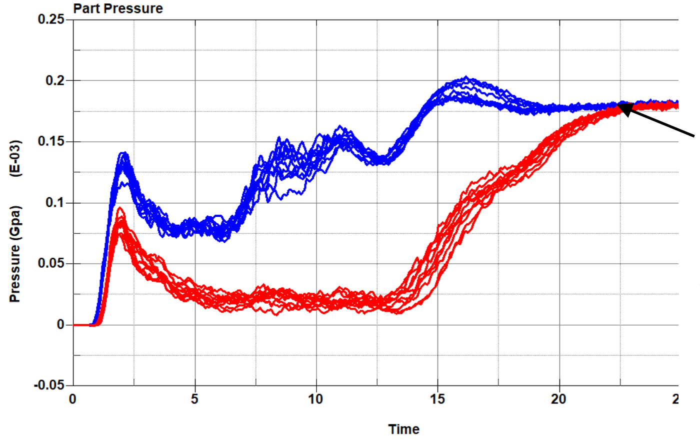
- *AIRBAG_PARTICLE
  - Solution: provide the ability to assess the vent probability function from part pressure, without defining chambers

```
*DEFINE_CPM_VENT
$:   label       c23    lctc23    lcpc23     enh_v      ppop     c23up      iopt
         1       1.0         0         0         1       0.0       1.0         0
$:      jt      ids1      ids2     iopt1      pid1      pid2      vang     lcred
         0         0         0         0         8         9         0         0
*DEFINE_CPM_VENT
$:   label       c23    lctc23    lcpc23     enh_v      ppop     c23up      iopt
         2       1.0         0         0         1       0.0       1.0         0
$:      jt      ids1      ids2     iopt1      pid1      pid2      vang     lcred
         0         0         0         0         9        10         0         0
…
```





Without chamber the pressure is not uniform after 25ms.



Without chamber but using part pressure to determine the vent probability function, the pressure is uniform at 22ms.

This functionality is partially available in R1122

*AIRBAG_PARTICLE

- *AIRBAG_PARTICLE
  - Problem: Vent pop-pressure (PPOP) and venting coefficient vs pressure (LCPC23) are very sensitive
  - Solution: Pop-pressure and venting coefficient can now be evaluated from
    - Part pressure (PID1, PID2 to be specified in *DEFINE_CPM_VENT)
    - Chamber pressure

Vent definition	External Vent	Internal Vent
Part pressure	$P_{part} - P_{ambient}$	$P_{part1} - P_{part2}$
Chamber	$P_{chamber} - P_{ambient}$	$P_{chamber1} - P_{chamber2}$
None	(3)	(3)

1. POPP pressure is always the pressure difference between upstream/downstream
2. Priority: Part pressure > Chamber > none
3. Without part pressure / chamber, the pressure are evaluated by collecting translational kinetic energy of particles near the vent which makes the signal inconsistent.
4. UP(Switching from CPM) need more development with this feature

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*AIRBAG_PARTICLE

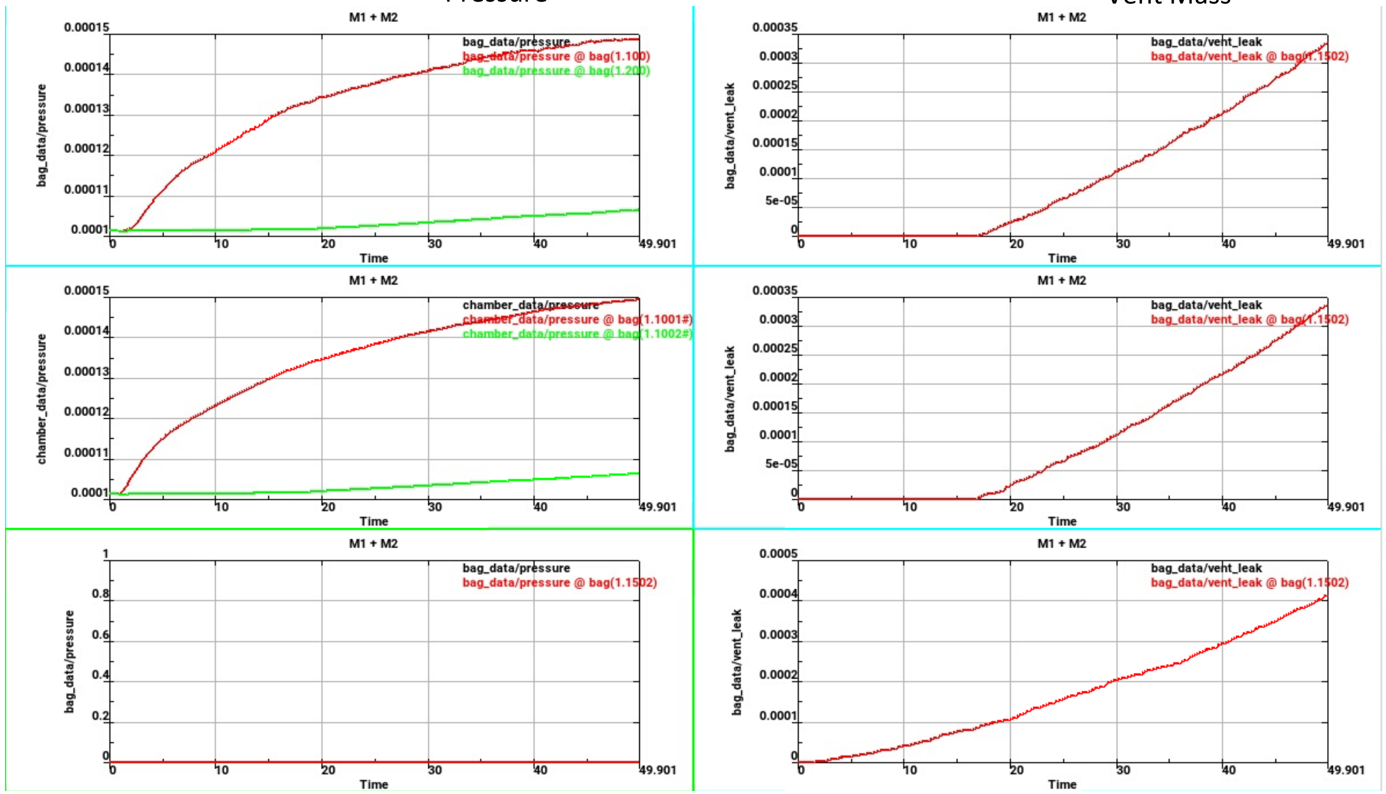
- *AIRBAG_PARTICLE
  - Problem: Vent pop-pressure (PPOP) and venting coefficient vs pressure (LCPC23) are very sensitive
  - Solution: Pop-pressure and venting coefficient can now be evaluated from

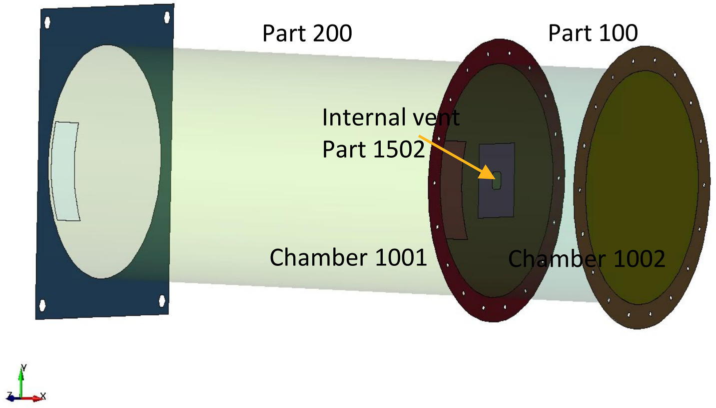
Pressure | Vent Mass

Part pressure

Chamber pressure

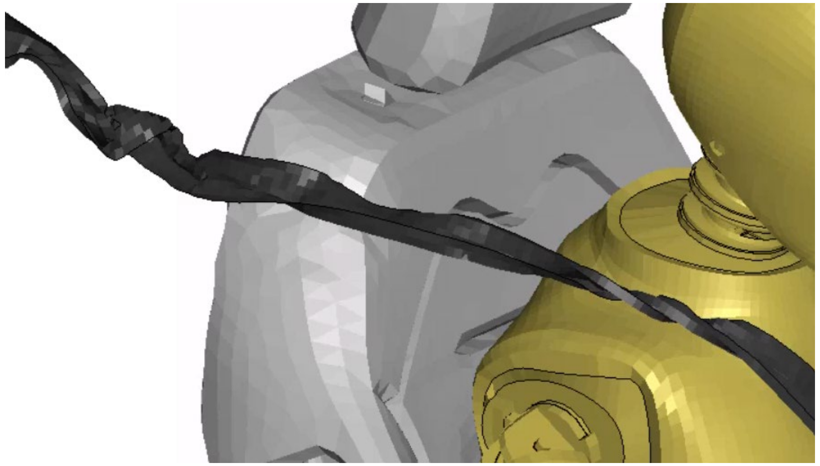
None

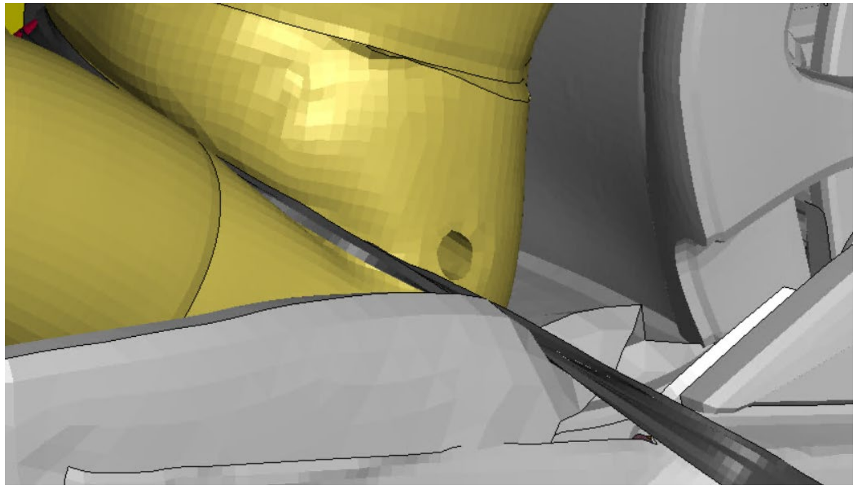




*MAT_SEATBELT_2D

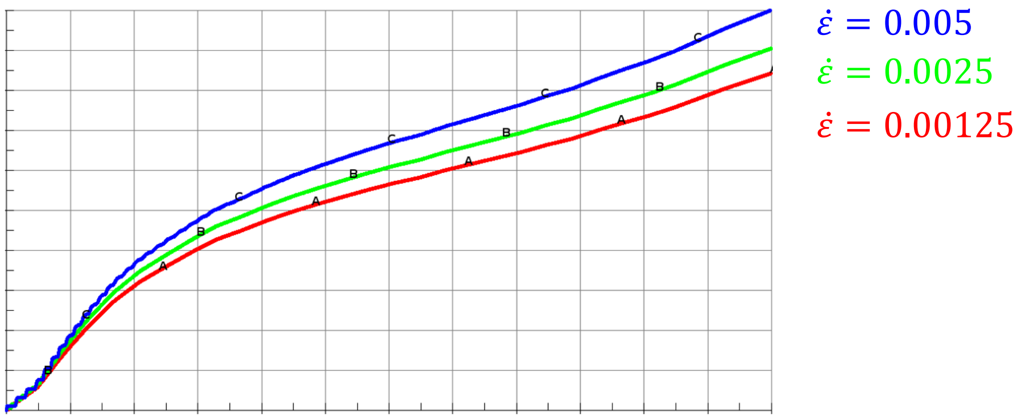
- *MAT_SEATBELT is widely used in occupant safety models to represent the restraint system. Some request were made to improve the correlation of this material compared to physical tests
  - Elements tend to collapse too easily as they do not carry bending loads. The seatbelt then tends to become a “line” when loading the pelvis.
  - During unloading the belt appears to be vibrating. Behavior appears to be unrealistic.
  - Strain rate effect cannot be considered as only a single force vs engineering strain curve can be defined.

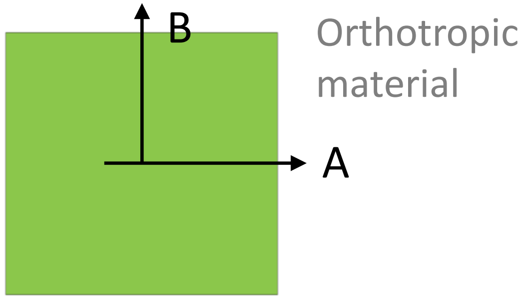


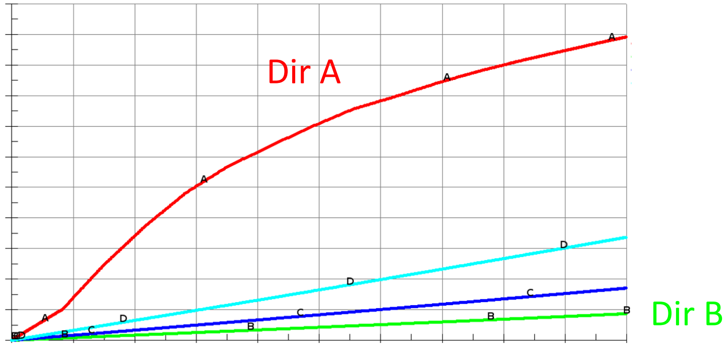


*MAT_SEATBELT_2D

- *MAT_SEATBELT : A new option is added *MAT_SEATBELT_2D which allows to define an additional card where the following input can be specified
  - Fabric material formulation (FORM)
  - Bending stiffness (available for FORM=-14) by the definition of a coating material
  - Transverse Young's modulus (Eb)
  - A table can now be referred in the LLCID field to define different force vs engineering strain curves at different strain rate.

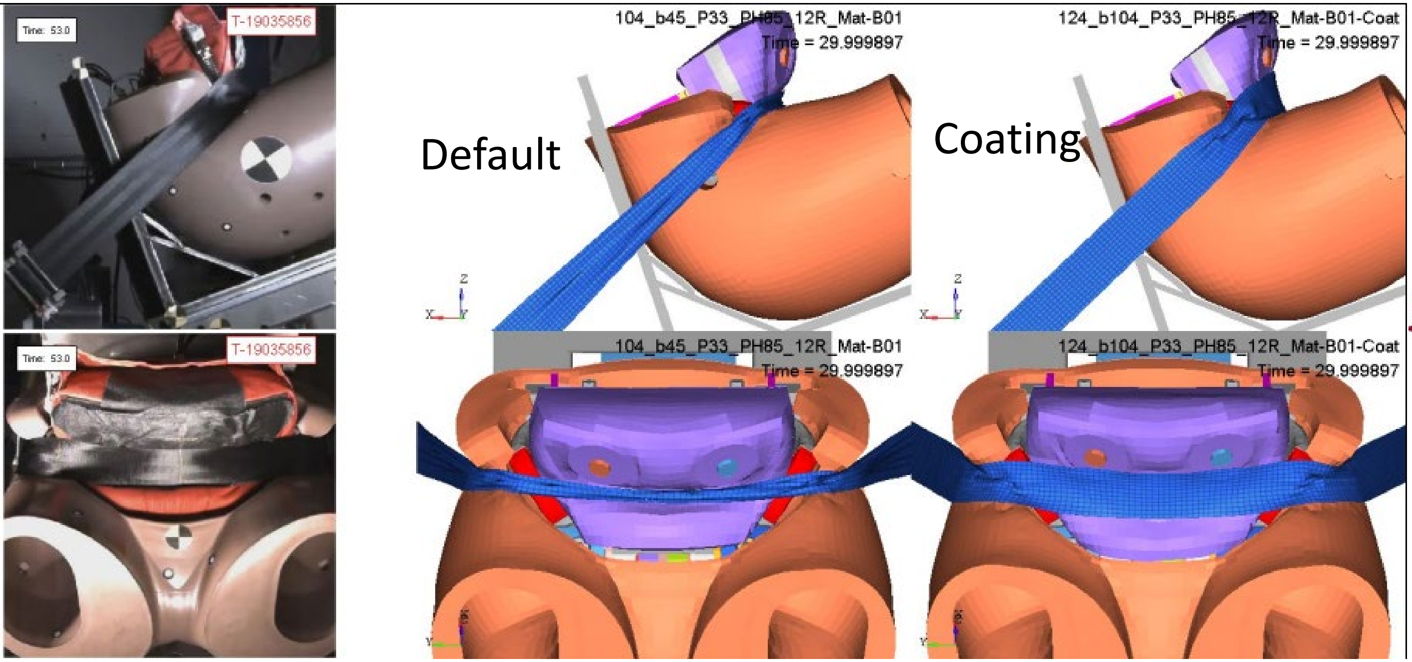


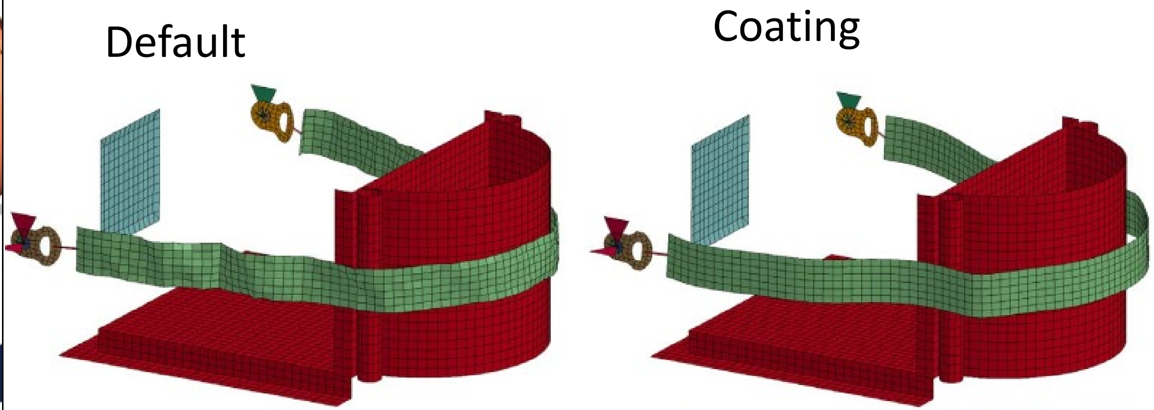


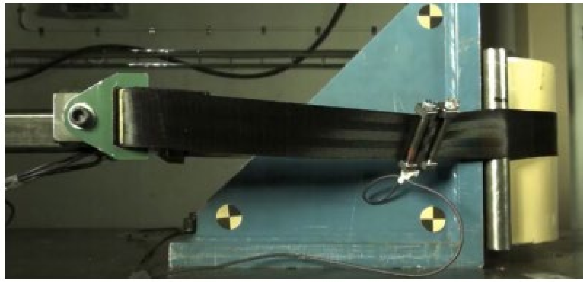


*MAT_SEATBELT_2D

- *MAT_SEATBELT
  - Defining a coating material allows to add bending stiffness and improve the behavior of the seatbelt compared to test for both loading and unloading.



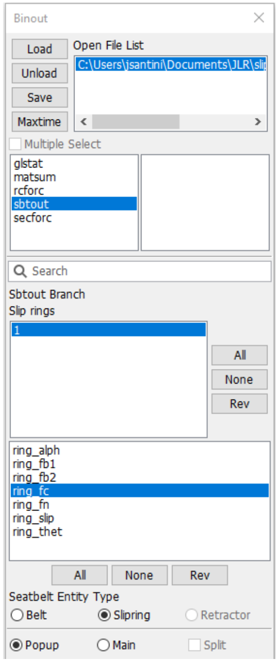


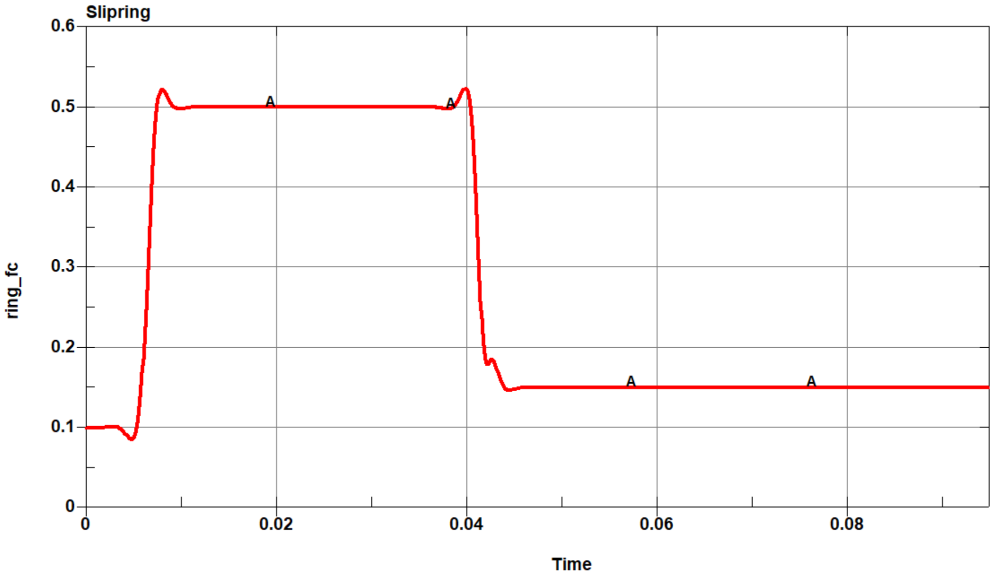


From: Belt Modelling in LS-DYNA. 16th International LS-DYNA User Conference.

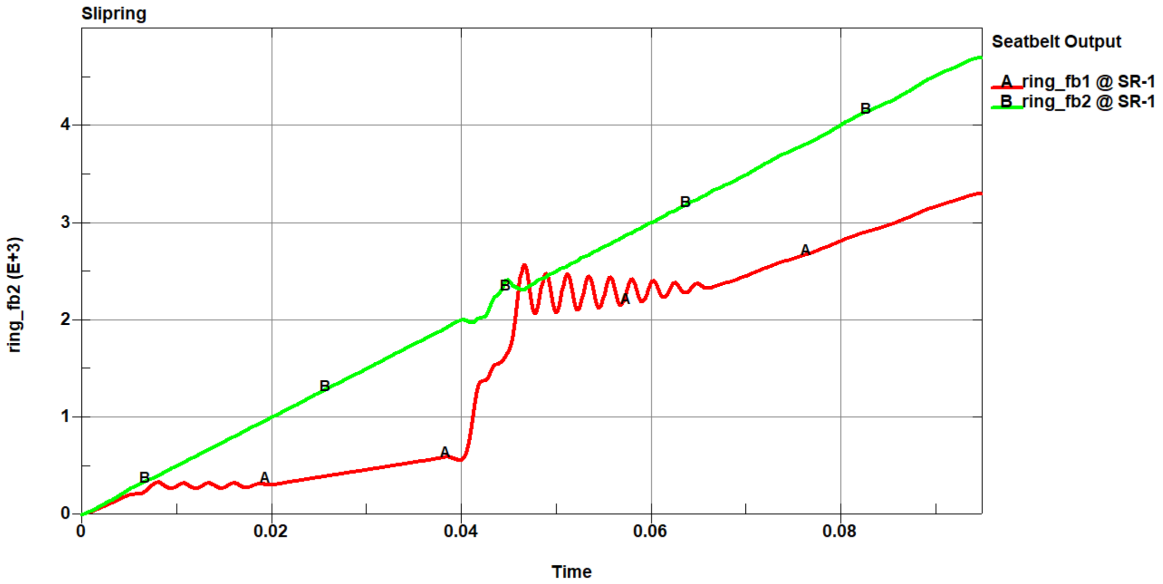
Safety - Slipring

- Provided the ability to output for slipring:
  - Friction coefficient
  - Force before and after the slipring
  - The wrap (theta) and skew (alpha) angle
  - Normal force





Actual slipring friction coefficient vs time



Force before/after the slipring

Safety – Output for *SENSOR

- The use of sensor (*SENSOR) is expanding. They are used to control for example:
  - Slipring friction (function of lap/shoulder belt force ratio…)
  - Tire deflation (based on pressure and time)
  - Deletion of elements when certain conditions are met
- To track the actual value / state of a *SENSOR the user can:
  - Use *DATABASE_CURVEOUT and *DEFINE_CURVE_FUNCTION to monitor the value of a sensor
  - Check the message file for activation a particular *SENSOR_CONTROL

```
*DATABASE_CURVOUT
$#      dt    binary      lcur      ioopt
      0.08         3
*DEFINE_CURVE_FUNCTION
      1001
SENSORD(1)
```

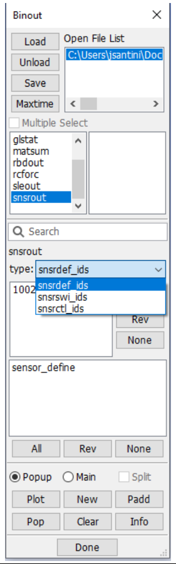
```
 12789 t 4.0000E+01 dt 2.84E-03 write d3plot file            01/28/23 10:52:44

 *** Status change by Control       1000 ***
 PRESC-MOT          1 is turned off by switch       1001 at 4.4475E+01

 *** Status change by Control       2000 ***
 PRESC-MOT          2 is turned on by switch       1001 at 4.4475E+01
```

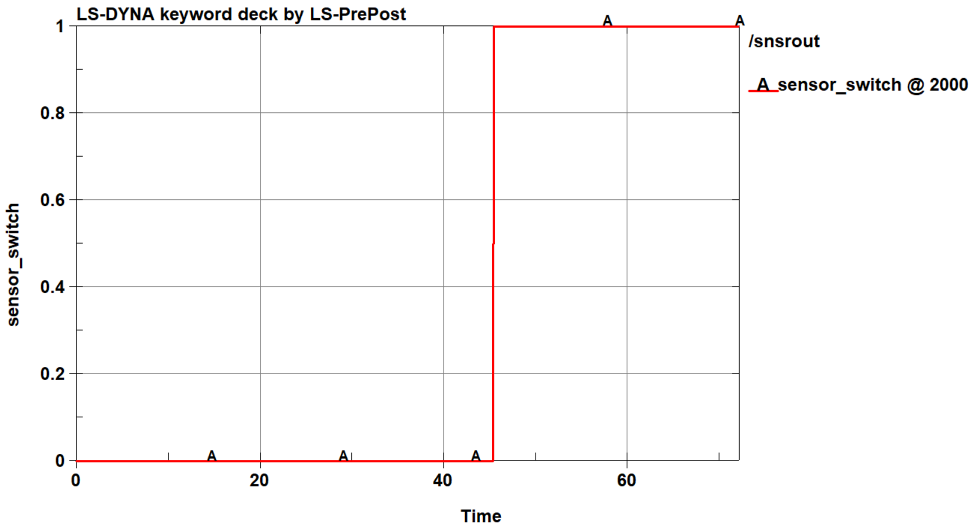
*DATABASE_SNSROUT – Output for *SENSOR

- Added new ASCII and Binary output (*DATABASE_SNSROUT) to track the value of sensor in time history

```
*DATABASE_SNSROUT
$#        dt     binary         lcur       ioopt
         0.1          3
```

- Output of *SENSOR_DEFINE, *SENSOR_SWITCH, *SENSOR_CONTROL is written to time history. Sensor value can easily be reviewed in one location.



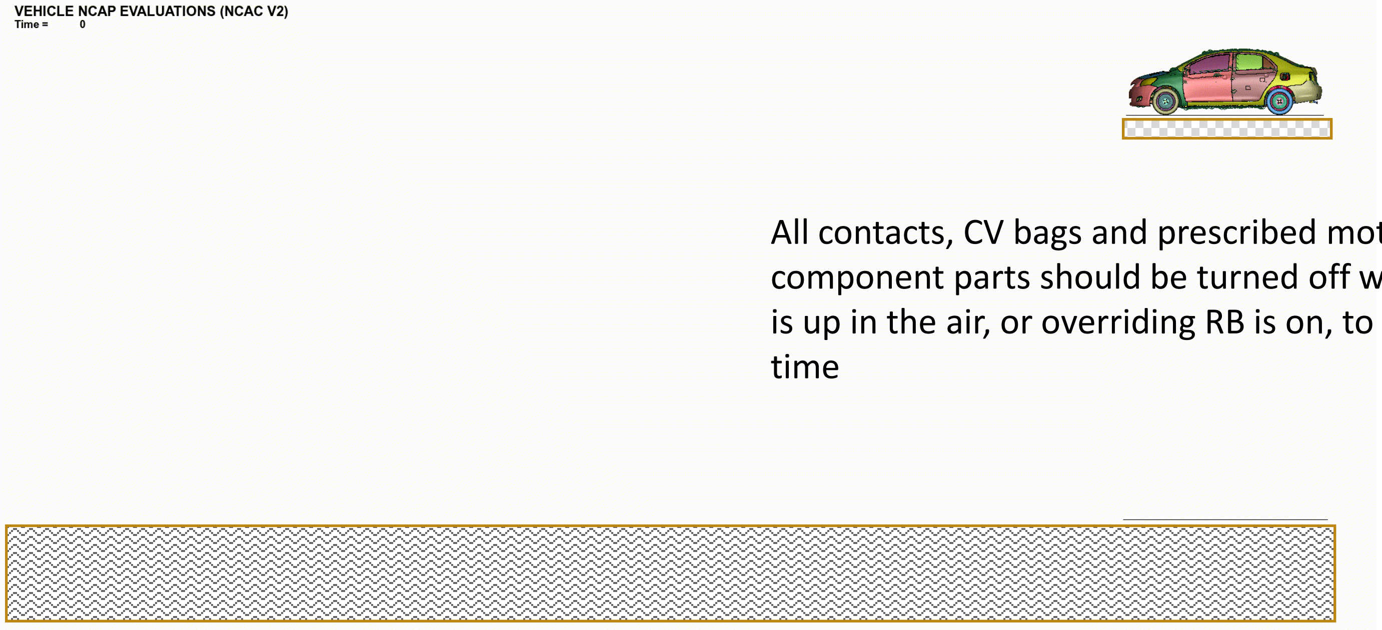


Rigid Body

*CONSTRAINED_NODAL_RIGID_BODY_OVERRIDE (or MASTER)

- Some crash scenarios involve long pre-crash simulation, during which the whole vehicle moves as a rigid body, e.g., dynamic rollover testing and autonomous driving.
- When OVERRIDE is used, all conflicting rigid body and constraints are turned off until the MASTER rigid body is turned off through *SENSOR_CONTROL. When the MASTER rigid body is turned off, the conflicting rigid bodies and constraints are turned back on automatically.
- In R13, all contacts, prescribed motion, airbags need to be turned off when the OVERRIDE rigid body is active to improve efficiency.

```
*SENSOR_CONTROL
$#   cntlid        type    typeid   timeoff       nrep      estyp
              2AIRBAG                   1         0          0BEAM/DISC/
$# initstt      swit1     swit2     swit3     swit4      swit5
       OFF          7
*SENSOR_CONTROL
$#   cntlid        type    typeid   timeoff       nrep      estyp
           11CONTACT                  1         0          0BEAM/DISC/
$# initstt      swit1     swit2     swit3     swit4      swit5
       OFF          7
*SENSOR_CONTROL
$#   cntlid        type    typeid   timeoff       nrep      estyp
       103PRESC-MOT             2         0          0BEAM/DISC/
$# initstt      swit1     swit2     swit3     swit4      swit5
        ON          7
```



All contacts, CV bags and prescribed motion for component parts should be turned off when the car is up in the air, or overriding RB is on, to save CPU time

*CONSTRAINED_NODAL_RIGID_BODY_OVERRIDE (or MASTER)

- A safety model can have up to hundred of airbag, contact and prescribed motion (ACP) cards. Manually setting up senor cards to control them could be challenging.
- An optional card to automatically turn off/on overriding-rigid-body related ACP is added.

Card 7. This card is read when the OVERRIDE keyword option is used. It is optional.

ICNT	IBAG	IPSM					

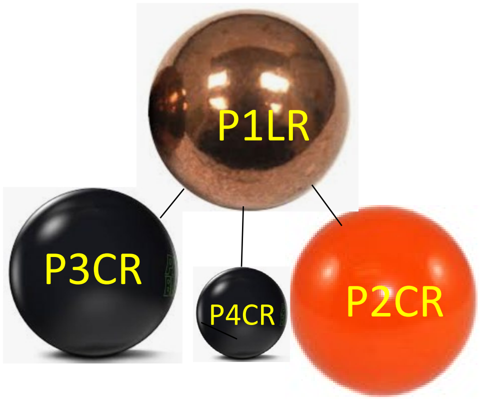
- ICTC: LS-DYNA will check all contact cards, if the involved parts are part of an overriding rigid body and no *SENSOR_CONTROL is defined for a contact, the contact will be automatically turned off when the overriding rigid body is active; and turned back on when the overriding rigid body is inactive
- IBAG: LS-DYNA will check all CV bag cards, if the involved parts are part of an overriding rigid body and no *SENSOR_CONTROL is defined for a CV bag, the CV bag will be automatically turned off when the overriding rigid body is active; they will be turned back on when the overriding rigid body is inactive with all time-related curves offset automatically.
- IPSM: LS-DYNA will check all prescribed motion cards. If the involved parts are part of overriding rigid body, the prescribed motion will be automatically turned off when the overriding rigid body is active; and turned back on when the overriding rigid body is inactive. Setting IPSM=2 will not offset the time history curves of prescribed motion.

*CONTROL_RIGID

- add option of RCVLR2D to *CONTROL_RIGID to recover the lead rigid body of constrained rigid bodies, which was changed due to *DEFORMABLE_TO_RIGID_AUTOMATIC.

Initial status:
Deformable: P2
Independent Rigid: P1, P3,
Dependent Rigid: P4
P2 and P4 share common nodes

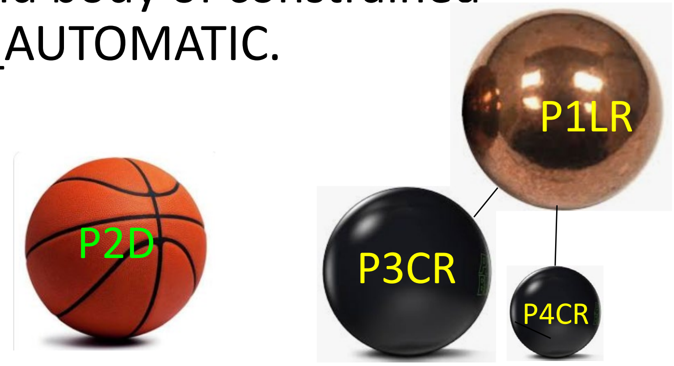
*DEF2RIG
PID=P2
LRB=P1



After DEF2RIG w. lead RB=P1:
Independent Rigid: P1
Dependent Rigid: P2, P3 & P4
P2 and P4 share common nodes

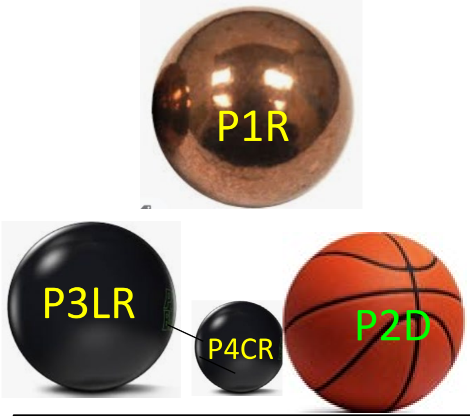
** CR: constrained RB
LR: Lead RB

*RIG2DEF



RCVLR2D=0

After DEF2RIG w. RCVLR2D=0 :
P3 & P4 remains constrained to P1



RCVLR2D=1

After DEF2RIG w. RCVLR2D=1:
P3 becomes independent from P1, P4 is constrained to P3