Powering Innovation That Drives Human Advancement

Simulation of Pedestrian Protection in LS-DYNA
LS-DYNA 行人保护仿真介绍

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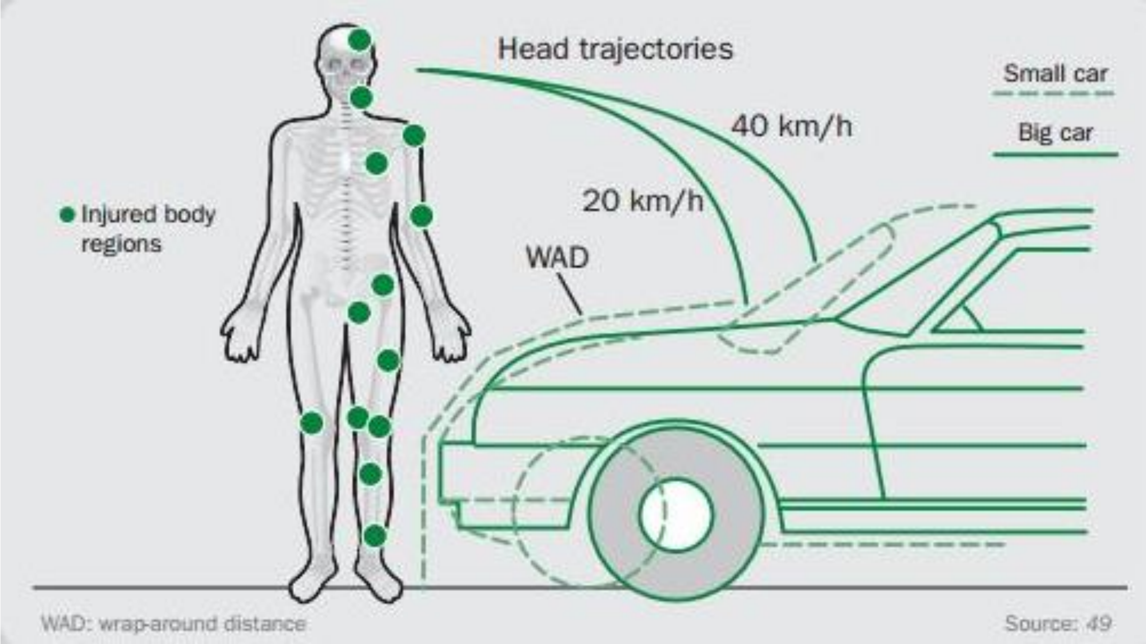
Pedestrian Protection Overview

Scenario: vehicle frontend hits crossing pedestrian

Factors determine injuries

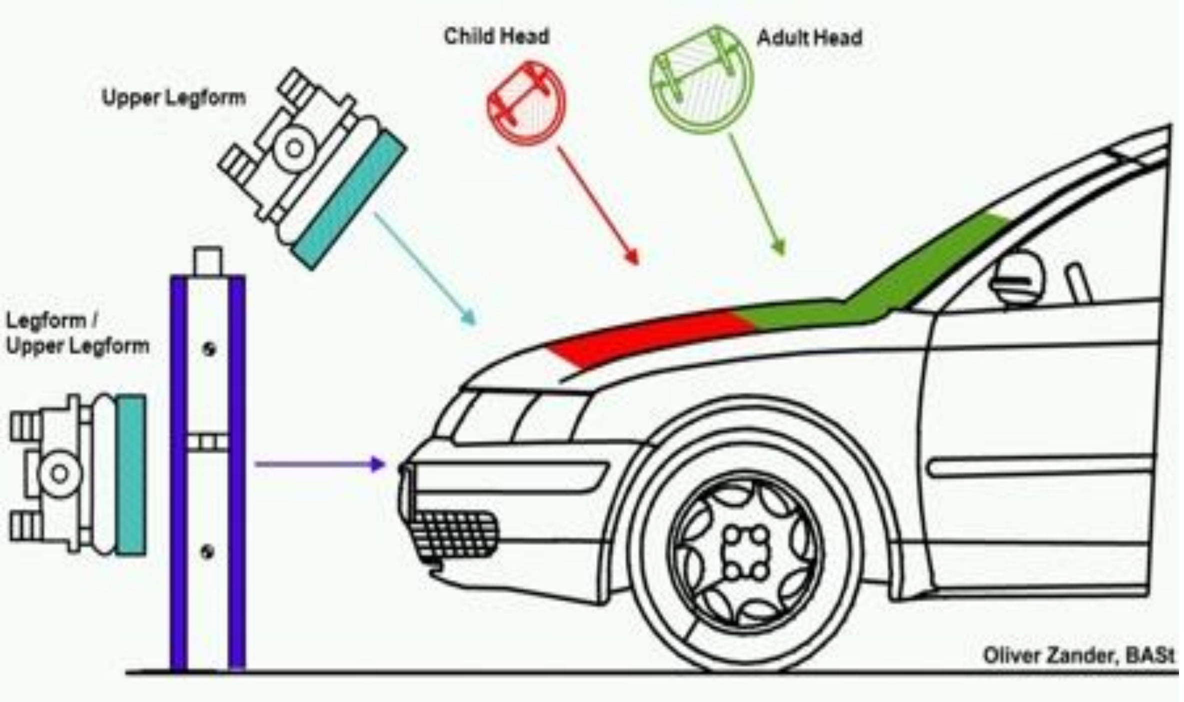
- Vehicle speed
- Pedestrian height
- Frontend shape
- Hood length



For regulatory and NCAP testing:
impactors representing different human body parts hit vehicle frontend

Model capacities required

- Windshield
- Hood
- Frontend
- Pedestrian



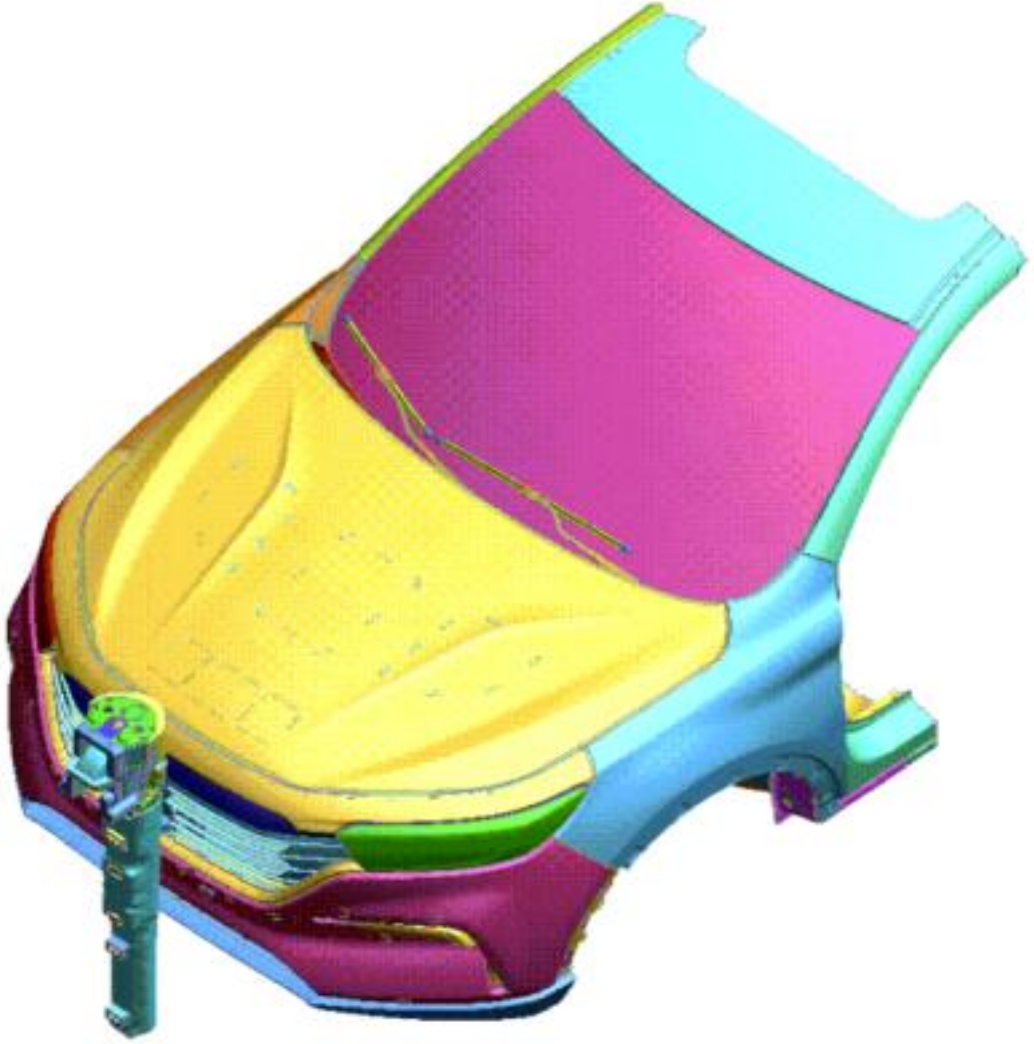
Courtesy: BASt

How to...

accurately model the key components like windshield?

design a better hood for less severe injury?

better represent a pedestrian?



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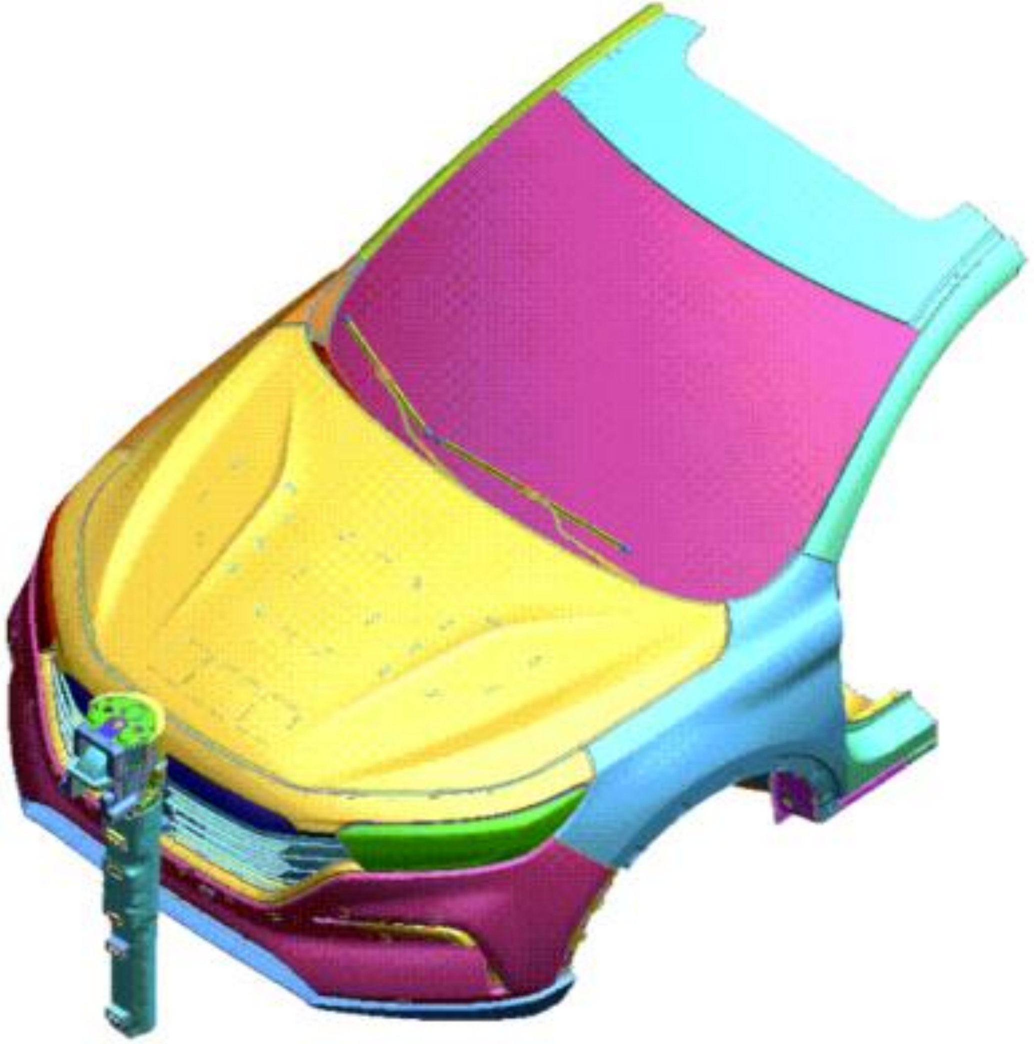
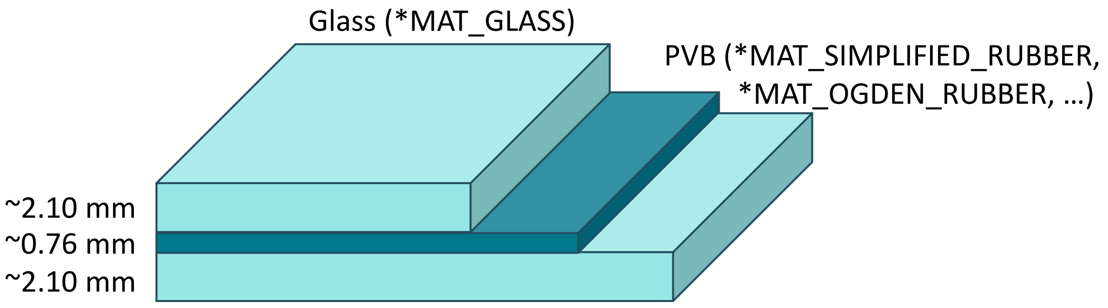
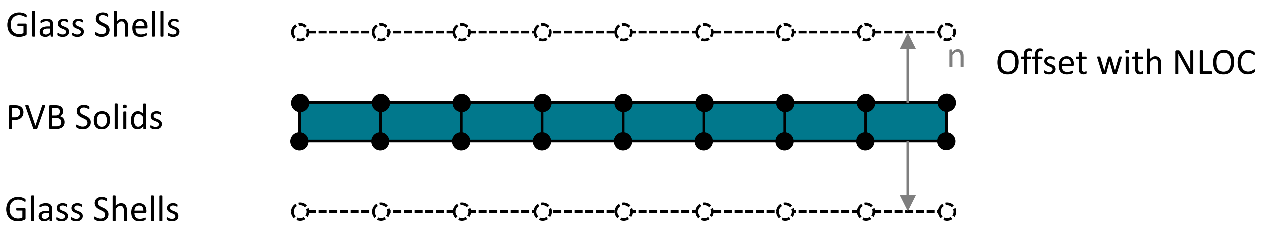


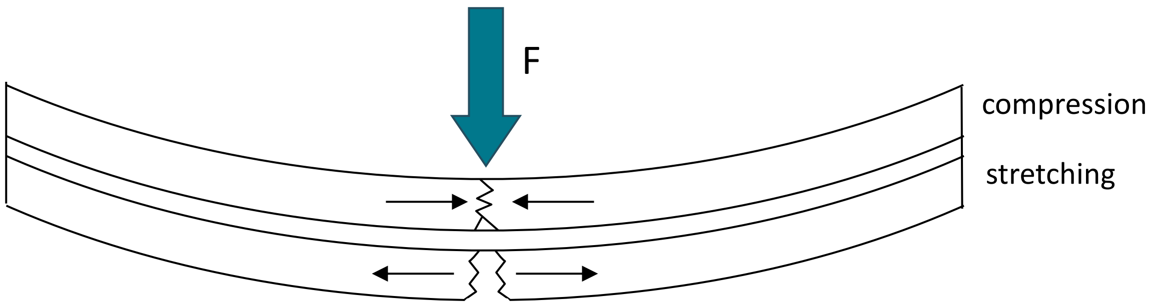
A Model for Laminated Glass

Discretization

- Laminated glass consists of at least 3 layers
  - 2 glass panes: shell elements with MAT_GLASS (MAT_280)
  - PVB interlayer: transverse shear deformation important
    → **solid elements**
- Contact between layers: shared nodes
- Offset the glass layers with NLOC parameter (SECTION_SHELL)





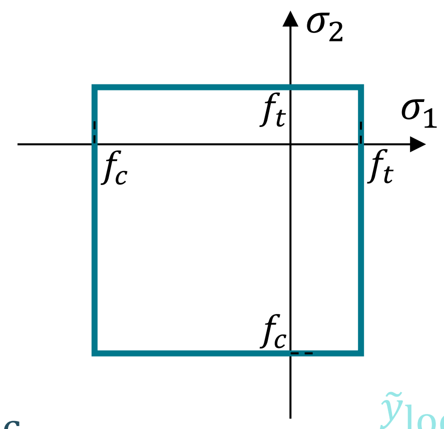


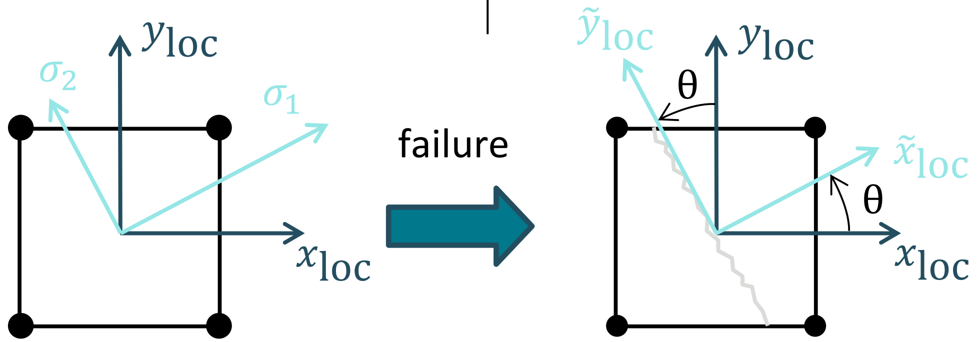
- Glass fragments are bonded
  - Difficult mechanical behavior

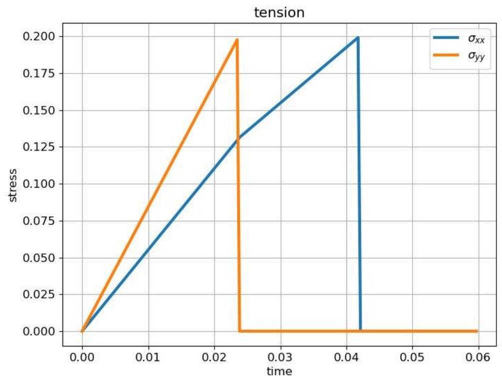
Introduction to MAT_GLASS (280)

Theoretical Background

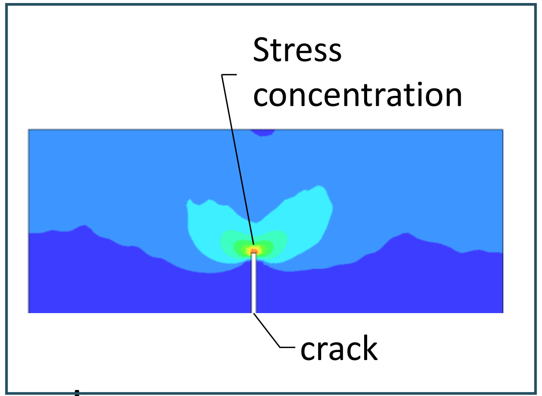
- Linear elastic until failure
- Stress based failure criteria: **Rankine**, Mohr-Coulomb, Drucker-Prager
- Compressive failure
  - Material is ‘crumbled‘
- Tensile failure
  - Single Cracks
  - Crack direction perpendicular to the 1st principal stress
  - 2nd crack can occur orthogonal to the 1st crack
  - Cracks can open and close independently
- Elements will not be automatically deleted when failed
- EPSCR (MAT_GLASS) or MAT_ADD_EROSION can help deleting distorted elements





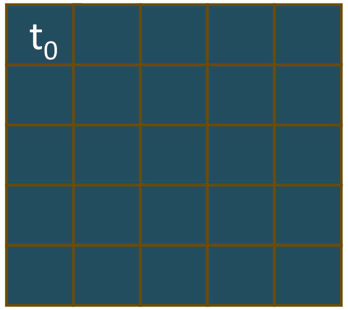


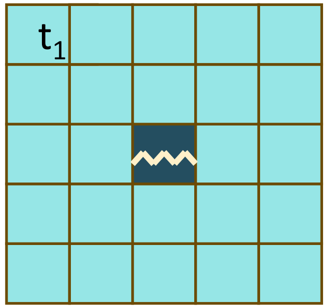
Strength Reduction

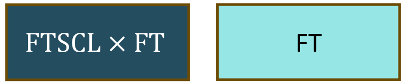


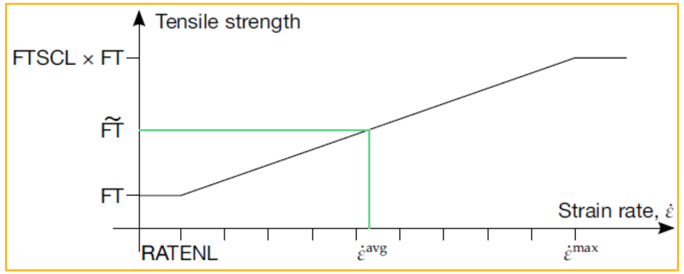
- Stress concentration in tip of crack
  - Cannot be resolved by coarse FE-mesh
  - To consider this effect in MAT_280 the tensile strength can be reduced after the first crack
- Combination of variables determines the way the strength reduction works

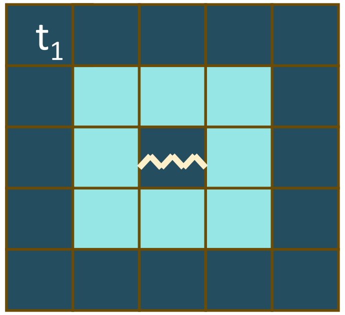
```
*MAT_GLASS_{STOCHASTIC}
$      MID        RO         E        PR                          IMOD      ILAW
         1    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                 0.2                                                        1.5
$    SFSTI     SFSTR      CRIN     ECRCL     NCYCR      NIPF
$    EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN
```







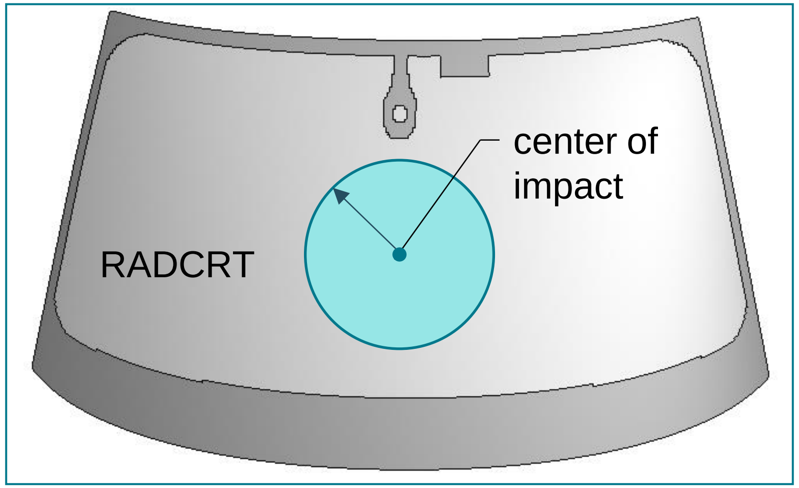




New option for *MAT_280

***MAT_GLASS_{STOCHASTIC}**

$	MID	RO	E	PR			IMOD	ILAW
	1	2.5E-6	70	0.23				
$	FMOD	FT	FC	AT	BT	AC	BC	FTSCL
		0.2						1.5
$	SFSTI	SFSTR	CRIN	ECRCL	NCYCR	NIPF		
$	EPSCR	ENGCRT	RADCRT	RATENL	RFILTF	FRACEN		



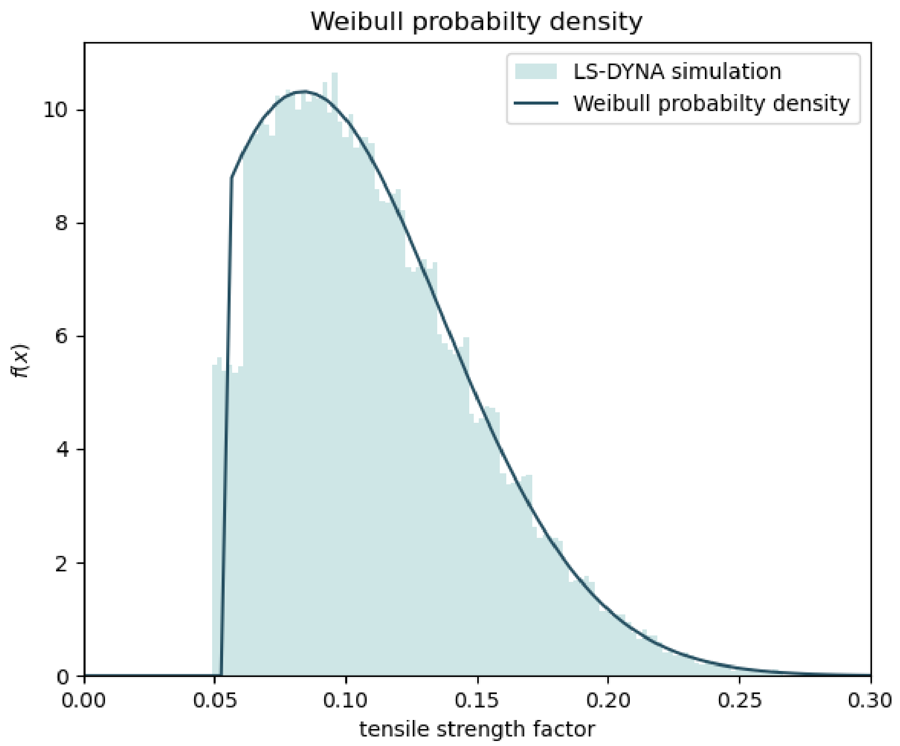
- ENGCRT/RADCRT: failure model described by Pytell/Liebertz (2011)
  - Initially deactivates failure/cracks
  - 1st element with $\sigma_{\max}$>"FT"×"FTSCL" defines center of impact
  - Internal energy of part within radius RADCRT is monitored
  - When internal energy reaches ENGCRT, failure is activated

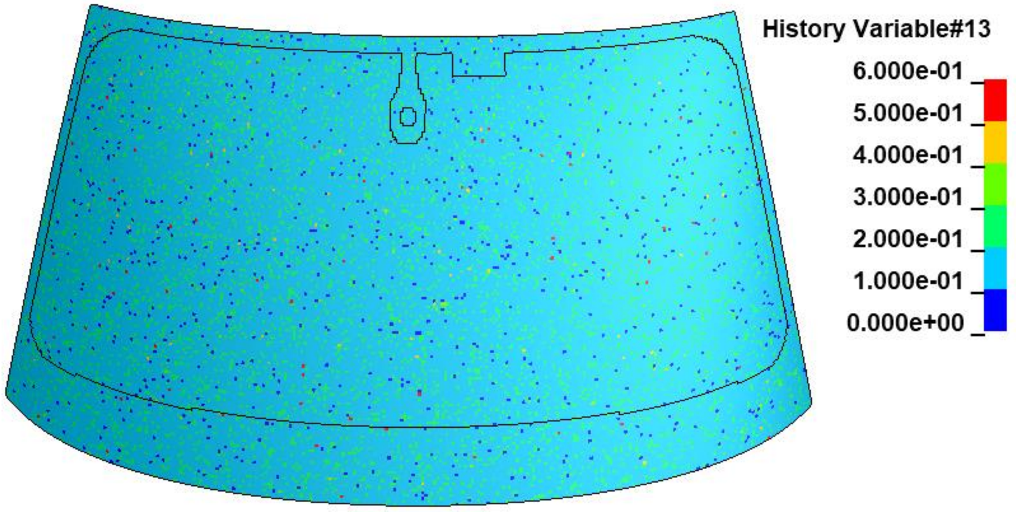
- NEW: critical energy depends on edge distance
  - ENGCRT<0 refers to *DEFINE_FUNCTION, e.g.,

```
*DEFINE_FUNCTION
       100
float func(float distx) {
  float engx;
  engx=min(0.03*distx,7.3);
$ printf("DISTANCE=%.7e, ENERGY=%.7e\n",distx,engx);
  return engx;
}
```

Stochastic Variation

- Stochastically distributed tensile strength due to microcracks
- *MAT_280_STOCHASTIC + *DEFINE_STOCHASTIC_VARIATION
  → stochastically distributed factor for tensile strength
- Kind of distribution is given by VAR_S
  - 1: Uniform random distribution
  - 2: Normal distribution
  - 3: User defined probability distribution
  - 4: User defined cumulative distribution
- History variable #13 shows factor

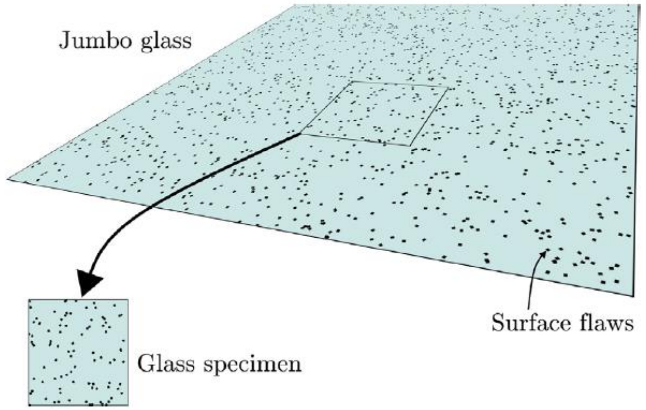


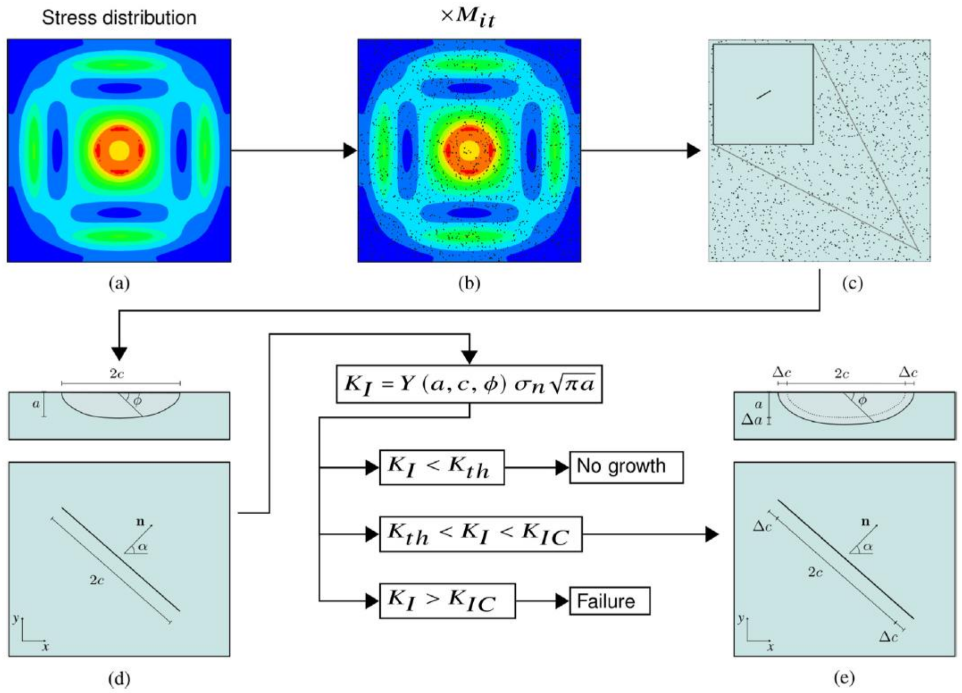


Ansys

Glass strength prediction model

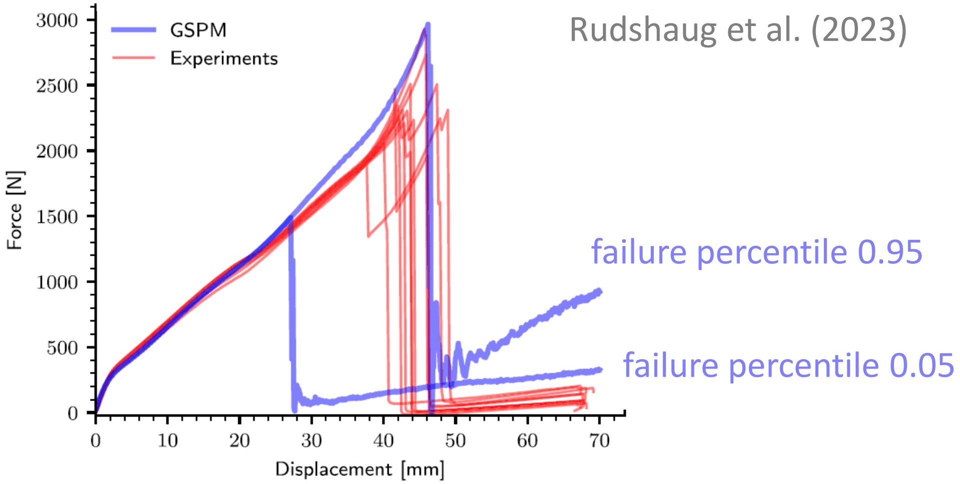
- Available as *MAT_GLASS_SPM
  - Monte-Carlo based fracture initiation predictor
  - combines the theories of linear elastic fracture mechanics (LEFM) and sub-critical crack growth (SCG)
  - generates a representative sample of virtual glass plates which are monitored during the simulation
  - GSPM predicts tensile strength, initiation location, and initiation time for the 1st crack, then *MAT_280 takes over for crack propagation
  - Model details and calibration procedure for new parameters described in Rudshaug et al. (2023)

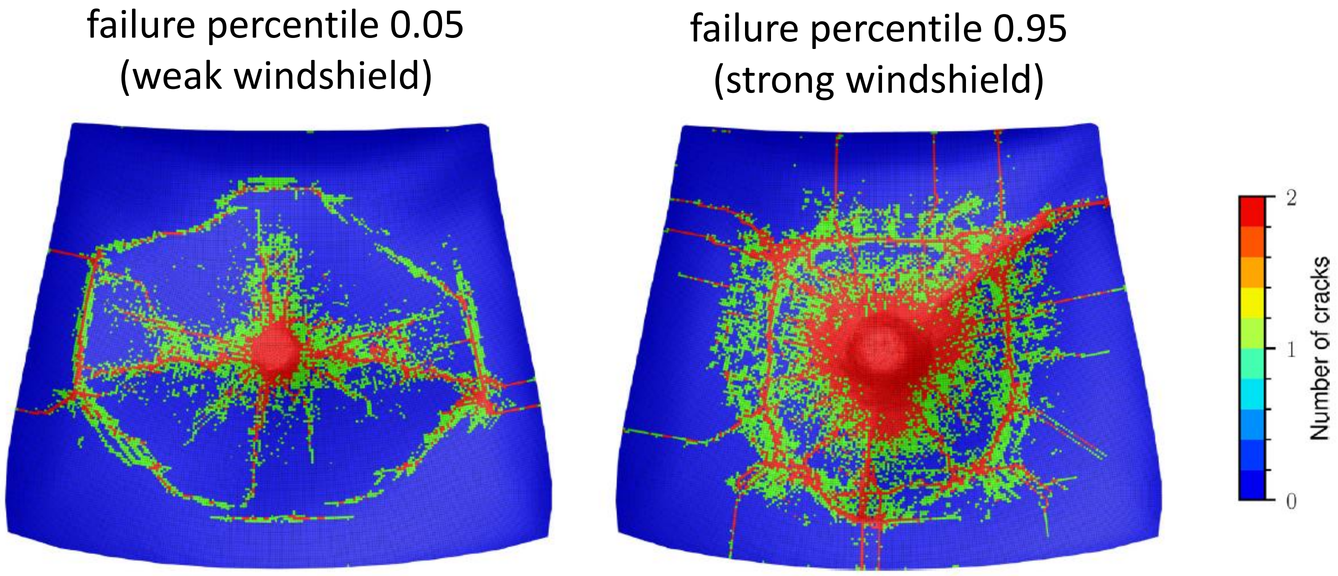




Glass strength prediction model

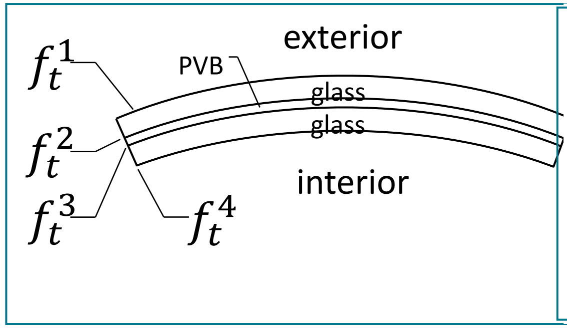
- Capabilities of the new method
  - Can describe the probabilistic fracture behavior of glass and SCG
  - Predicts the strength of glass plates of various geometries exposed to many different load cases
  - User can select a representative case of a glass plate fracture strength simply by altering the failure percentile parameter
  - Example: windshield impact

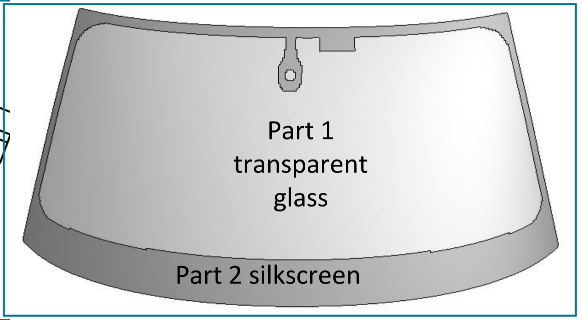




Position-Based Tensile Strength

- Laminated glass
  - tensile strength varies over thickness
- Options to consider effect in LS-DYNA
  - **INTEGRATION_SHELL**
  - PART_COMPOSITE
- INTEGRATION_SHELL is more flexible
  - Integration rule can be defined
  - For each ply, an individual stochastic variation can be defined






```
*PART
Glass outer pane
$      PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
       100       100       100         0         0         0         0
*SECTION_SHELL
$    SECID    ELFORM      SHRF       NIP     PROPT   QR/IRID     ICOMP
       100         2     0.833         3       1.0      -100         0
…
*INTEGRATION_SHELL
$ Gauss-Lobatto integration 3 IPs
$     IRID       NIP      ESOP   FAILOPT
       100         3
$        S        WF       PID
  -1.00000 0.3333333       101
   0.00000 1.3333333       101
   1.00000 0.3333333       102
*PART
DUMMY PART - Glass outer pane - air side - position 1
$      PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
       102       100       102         0         0         0         0
*MAT_GLASS
$      MID        RO         E        PR                          IMOD
       102    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC
          &ft1
```

Position-Based Tensile Strength

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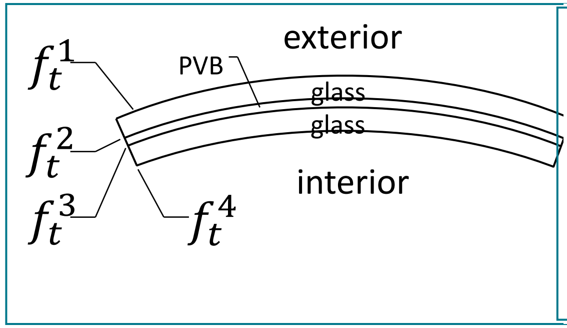
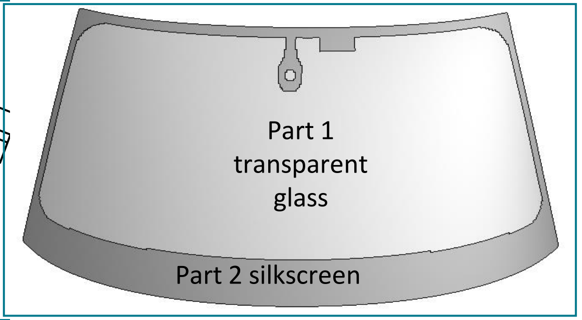


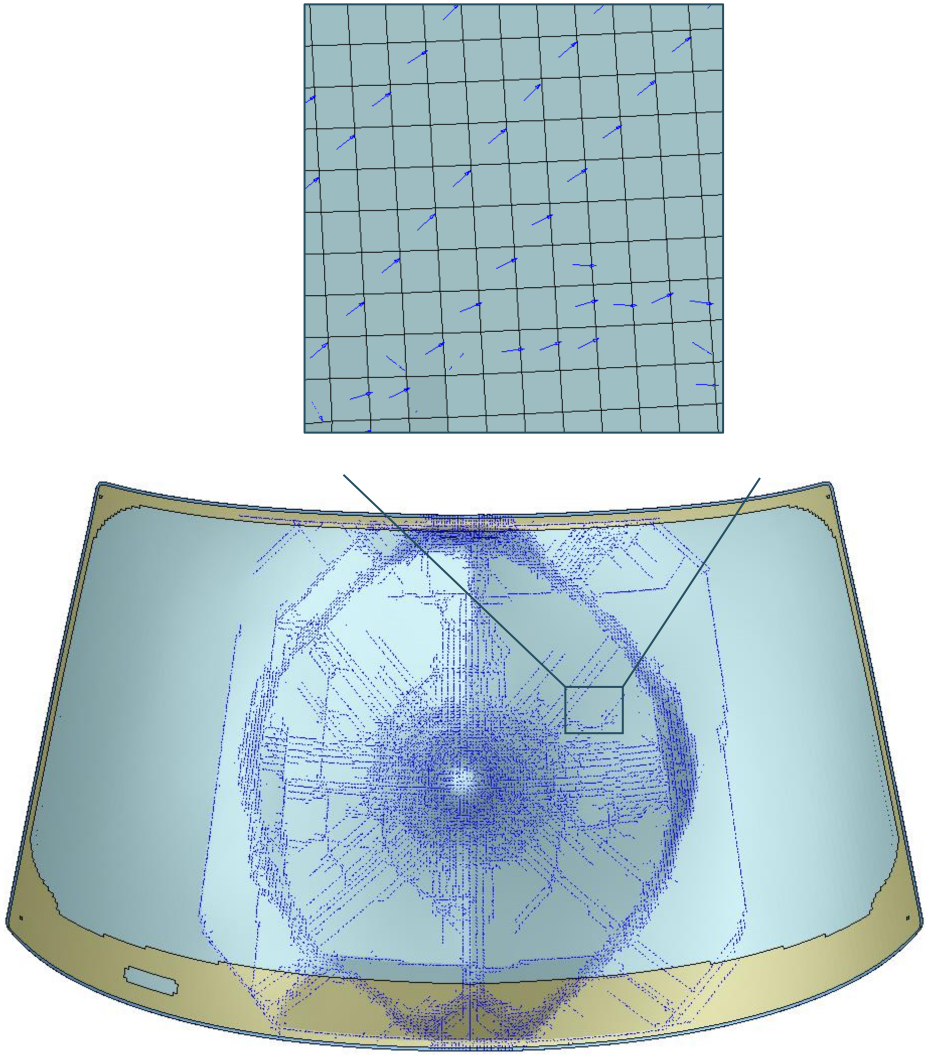


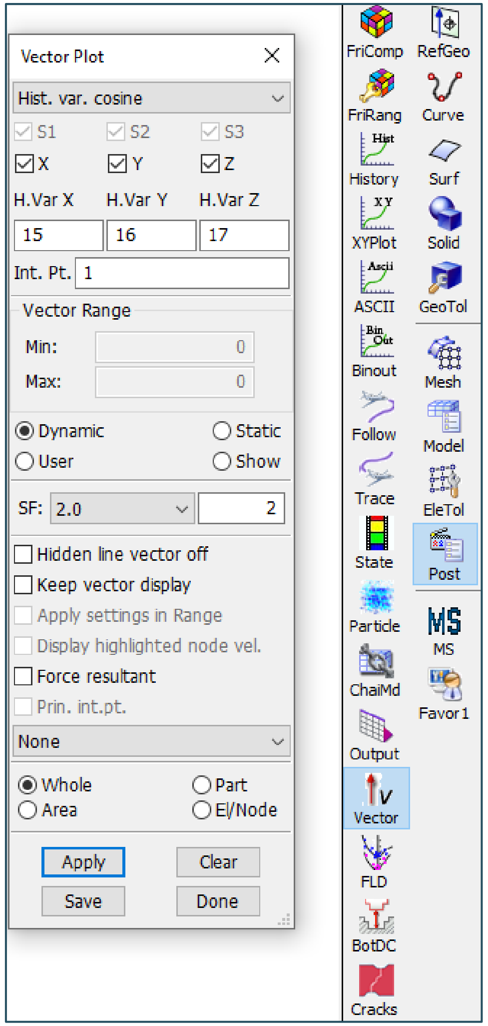

```
*PART_COMPOSITE
Glass outer pane
$      PID    ELFORM      SHRF      NLOC     MAREA      HGID    ADPOPT
       100         2     0.833                             4
$     MID1    THICK1        B1     TMID1      MID2    THICK2        B2
       100      0.05
       100       0.5
       100       0.5
       100       0.5
       100       0.5
       200      0.05
*MAT_GLASS_TITLE
PVB side
$      MID        RO         E        PR                          IMOD
       100    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC
          &ft2
…
*MAT_GLASS_TITLE
air side
$      MID        RO         E        PR                          IMOD
       200    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC
          &ft1
…
```

Crack visualization

Option I

- Head impact on windshield
- Cracks can be visualized as a vector plot using history variables #15, #16, and #17
  - Crack direction is shown
  - So far only shows 1st crack
  - Available since R15

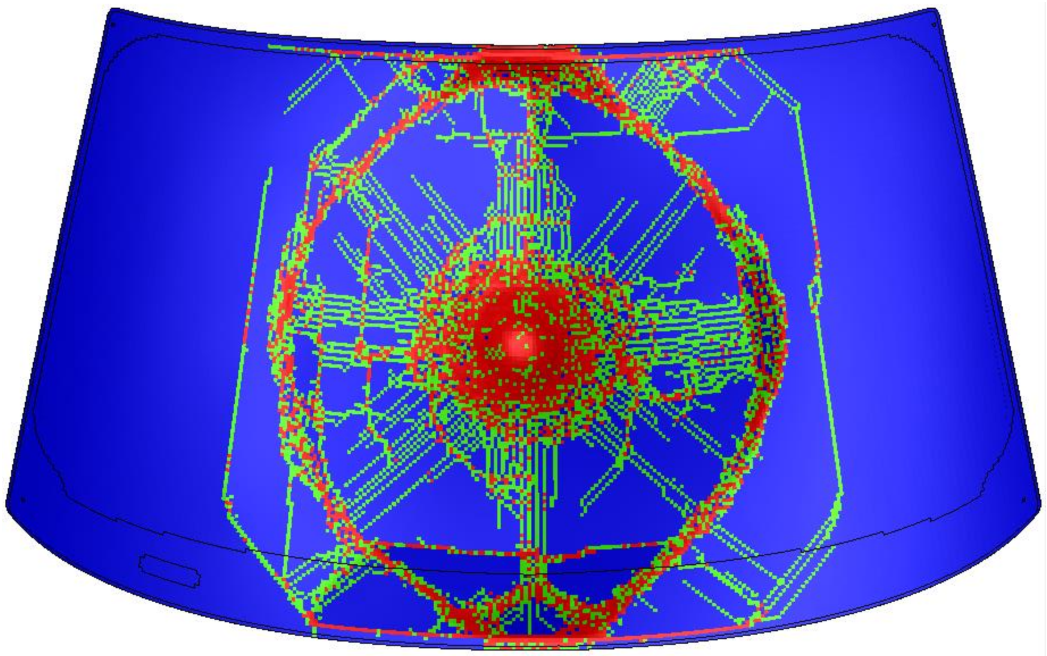


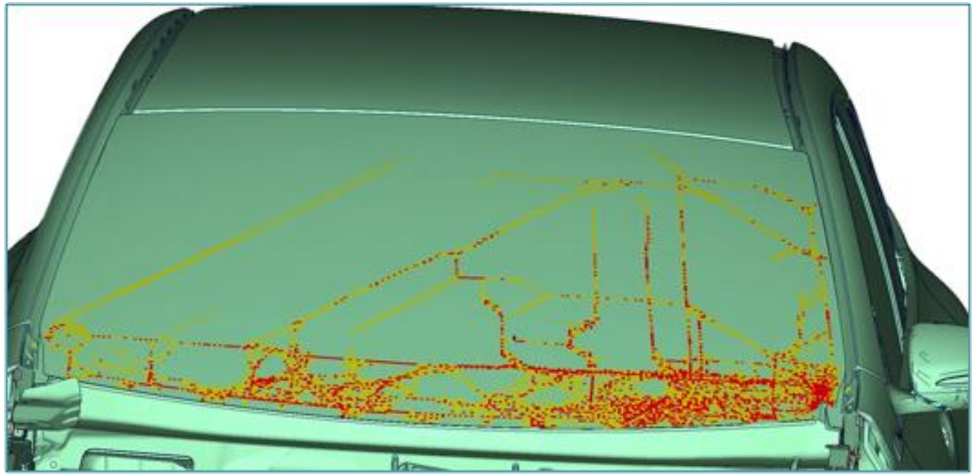


Crack visualization

Option II

- Head impact on windshield
- Cracks can be visualized by history variable #1 of MAT_GLASS
  - -1: compressive failure
  - 0: no failure
  - 1: one crack
  - 2: two cracks





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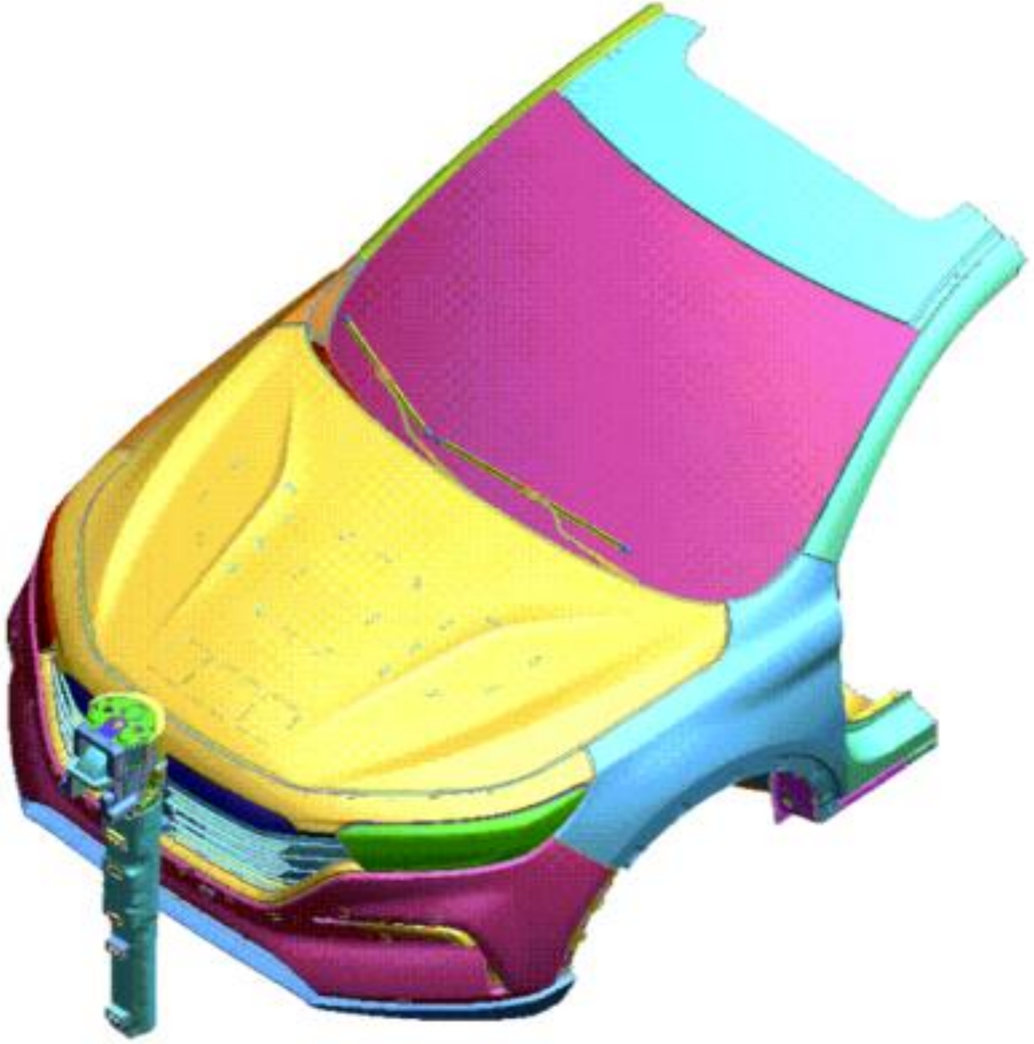
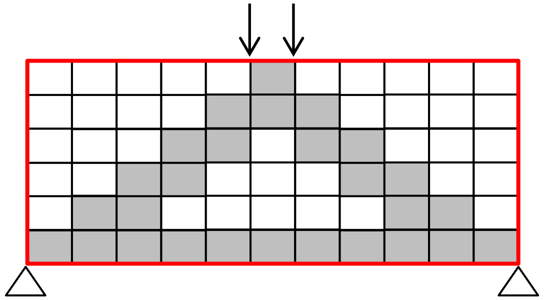
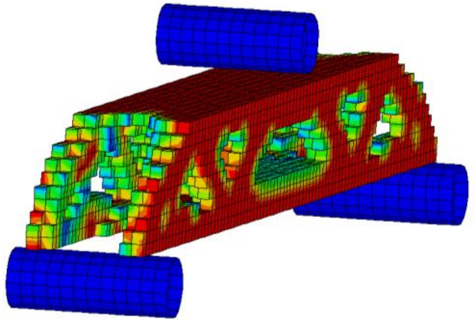


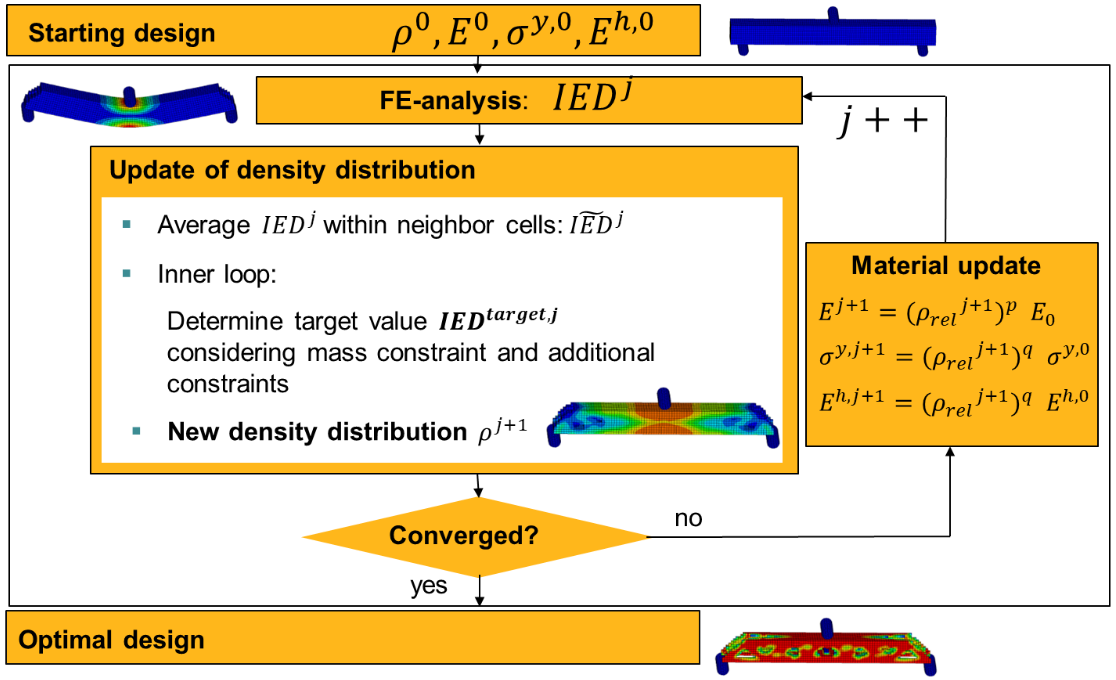
Topology Optimization using LS-TaSC





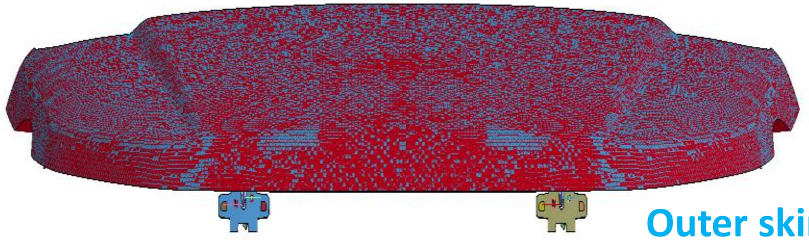
- Topology and shape optimization of non-linear problems
- Multiple load cases and disciplines
- Global constraint handling
  - Energy absorption, maximum reaction forces, …
    - → Multi-point optimization and metamodels
- Redistribution of material within a given domain
- Design variables
  - Relative density of each element
- Result
  - New material distribution
  - New shape of structure

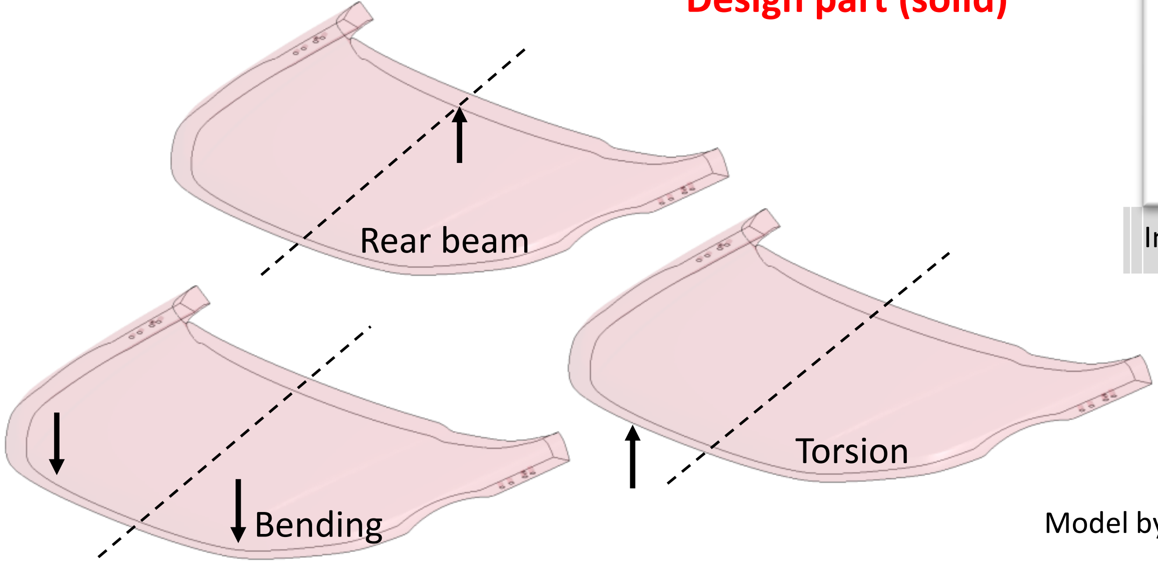
LS-TaSC Algorithm



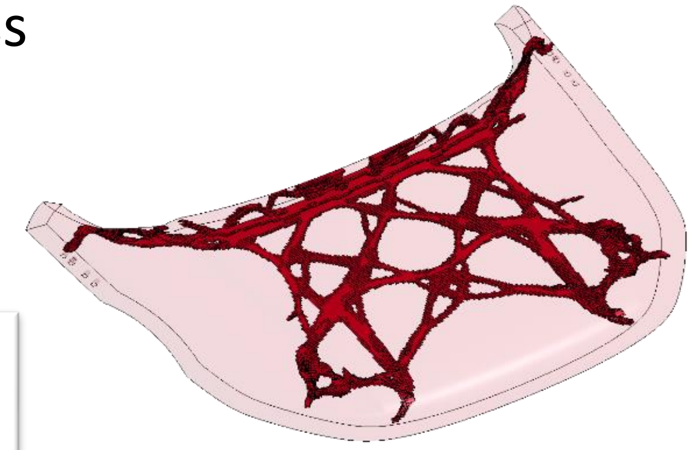
Hood Design Optimization using LS-TaSC

- Objective: Stiffest structure, satisfy constraints and minimize mass
- Constraints: rear beam, bending and torsion displacements

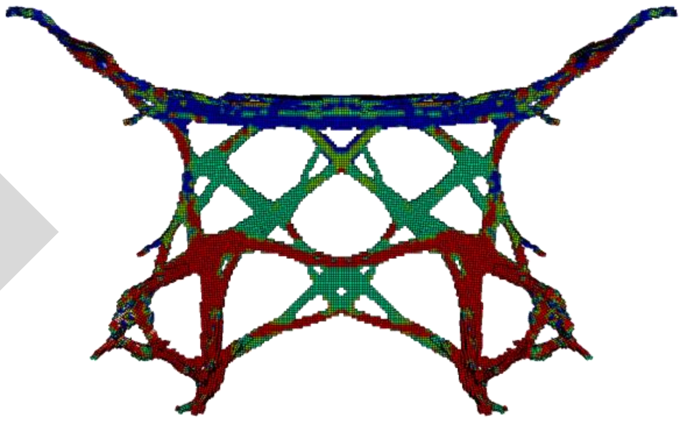




Initial Design has very low mass fraction of 0.01.



Optimum



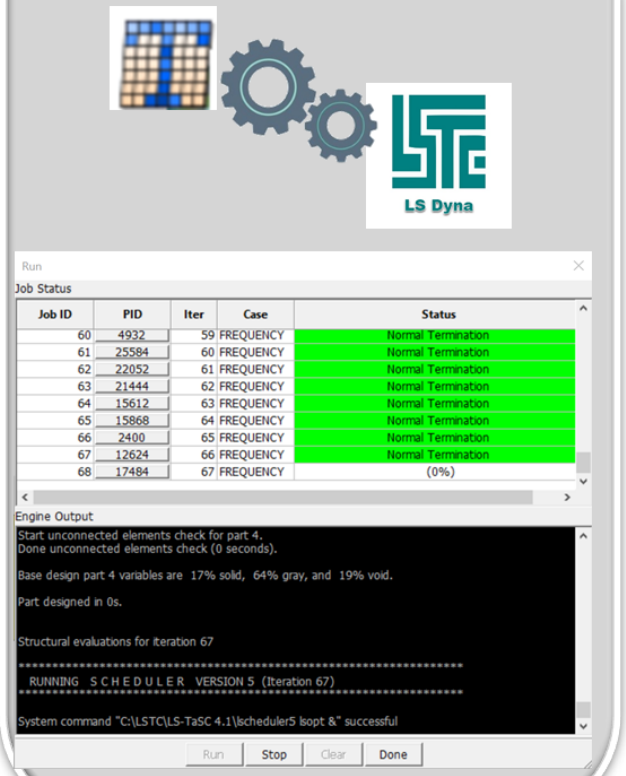
Design Contribution Plot
(Rear beam, torsion, bending)

Model by courtesy of Jaguar Land Rover

Integration

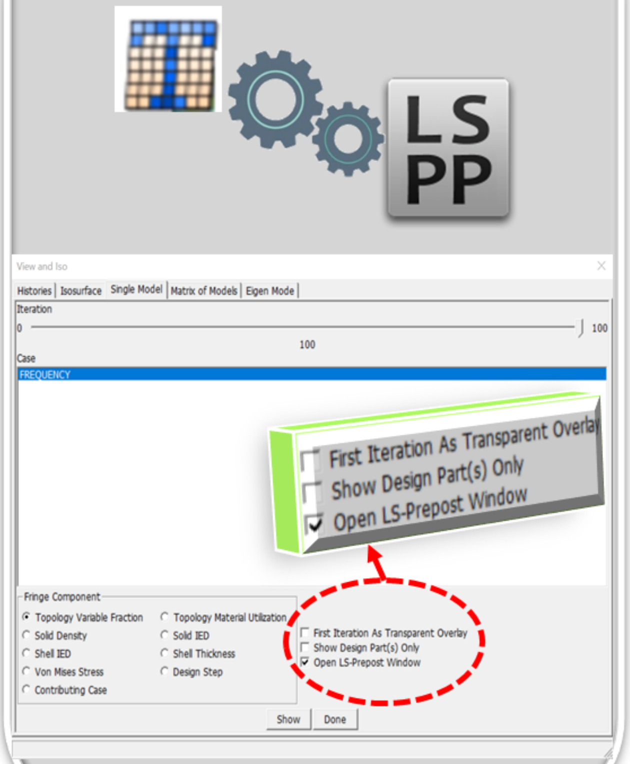
LS-TaSC with LS-DYNA

- no special treatment for nonlinearties



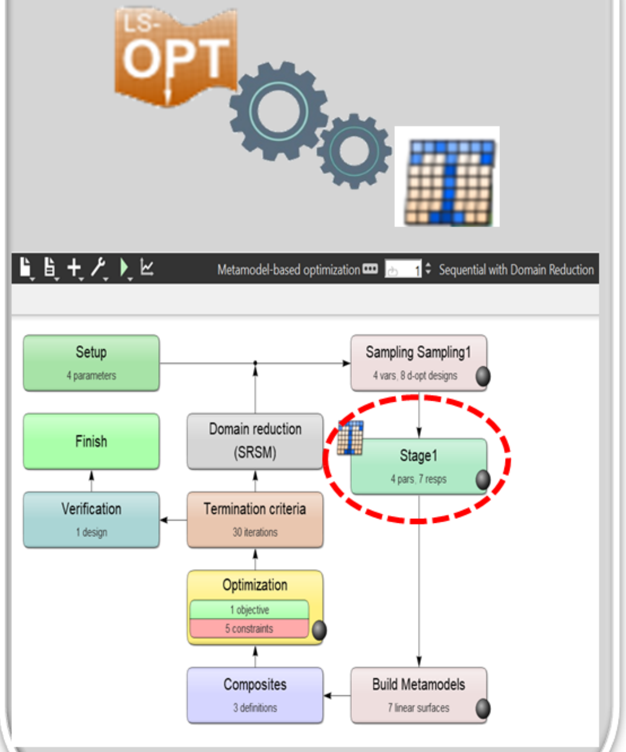
LS-TaSC with LS-PrePost

- results visualization
- model editing



LS-TaSC with LS-Opt

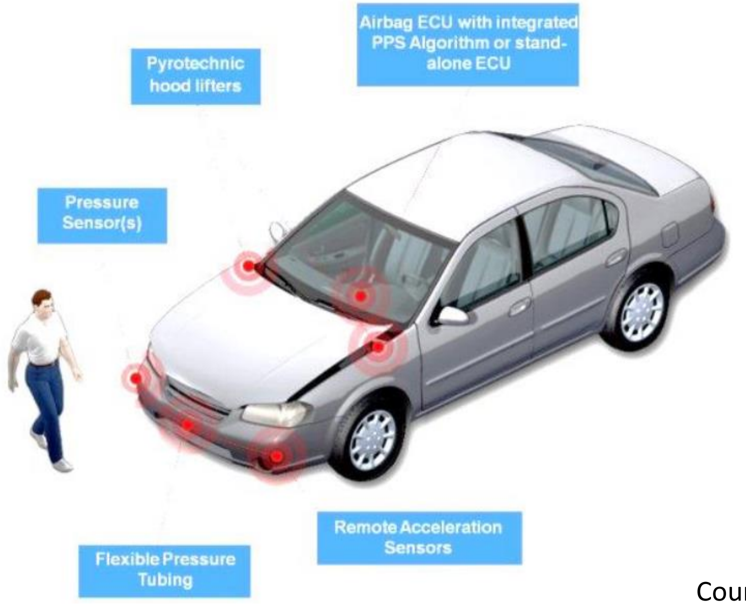
- multilevel and complex design schemes



Active hood system

- Active hoods to provide more deformation space between the hood and the engine compartment package

Courtesy: Continental

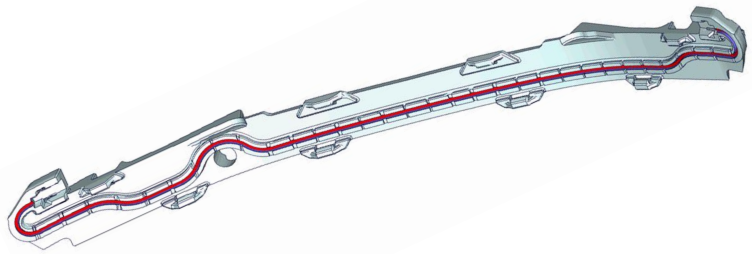


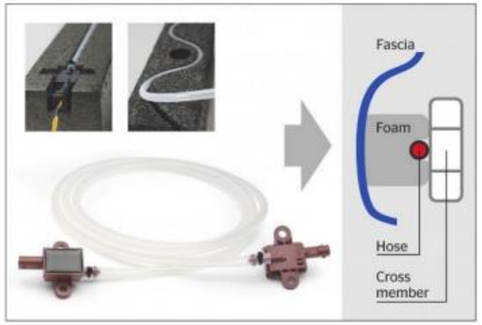
Courtesy: ZF

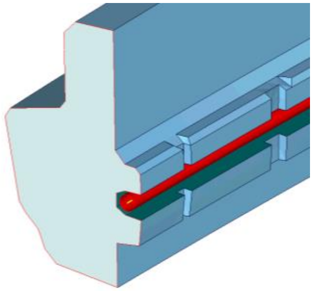
- Sensing system to identify a pedestrian impact (fiberoptics, pressure tube)
- Active system (actuator at hinge) to deploy the hood
- Special requirements to prove that hood is fully deployed prior to the head impact

Pressure tube sensor

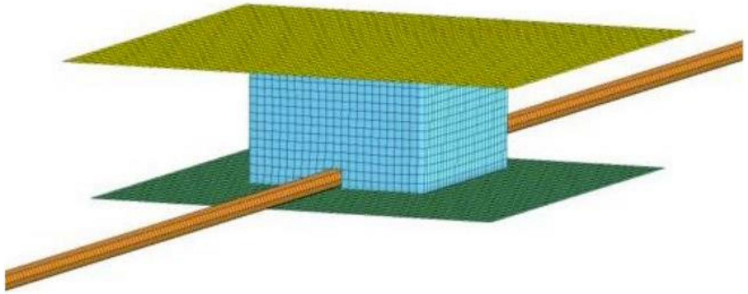
- Pressure tubes along the bumper foam
- Sensing locations at the ends of the tube

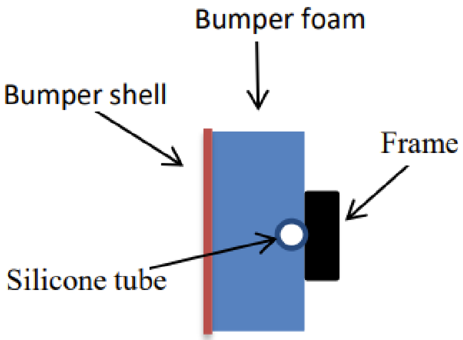


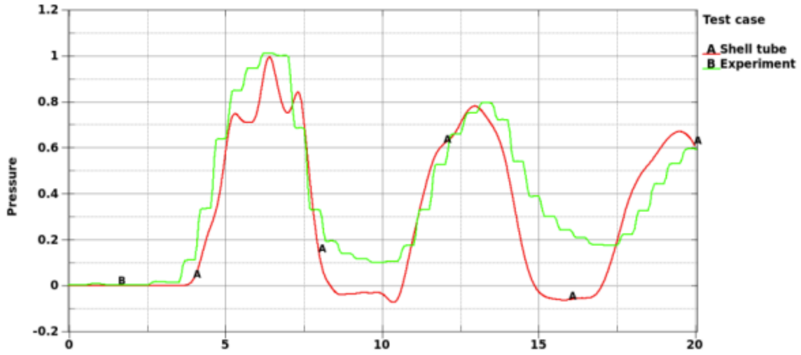




- Impact will compress tube and create pressure wave traveling along the tube
- Tube modeling including physical properties defined by *DEFINE_PRESSURE_TUBE







*Reference: "Recent Developments in *DEFINE_PRESSURE_TUBE for Simulating Pressure Tube Sensors in Pedestrian Crash" by Jesper Karlsson*

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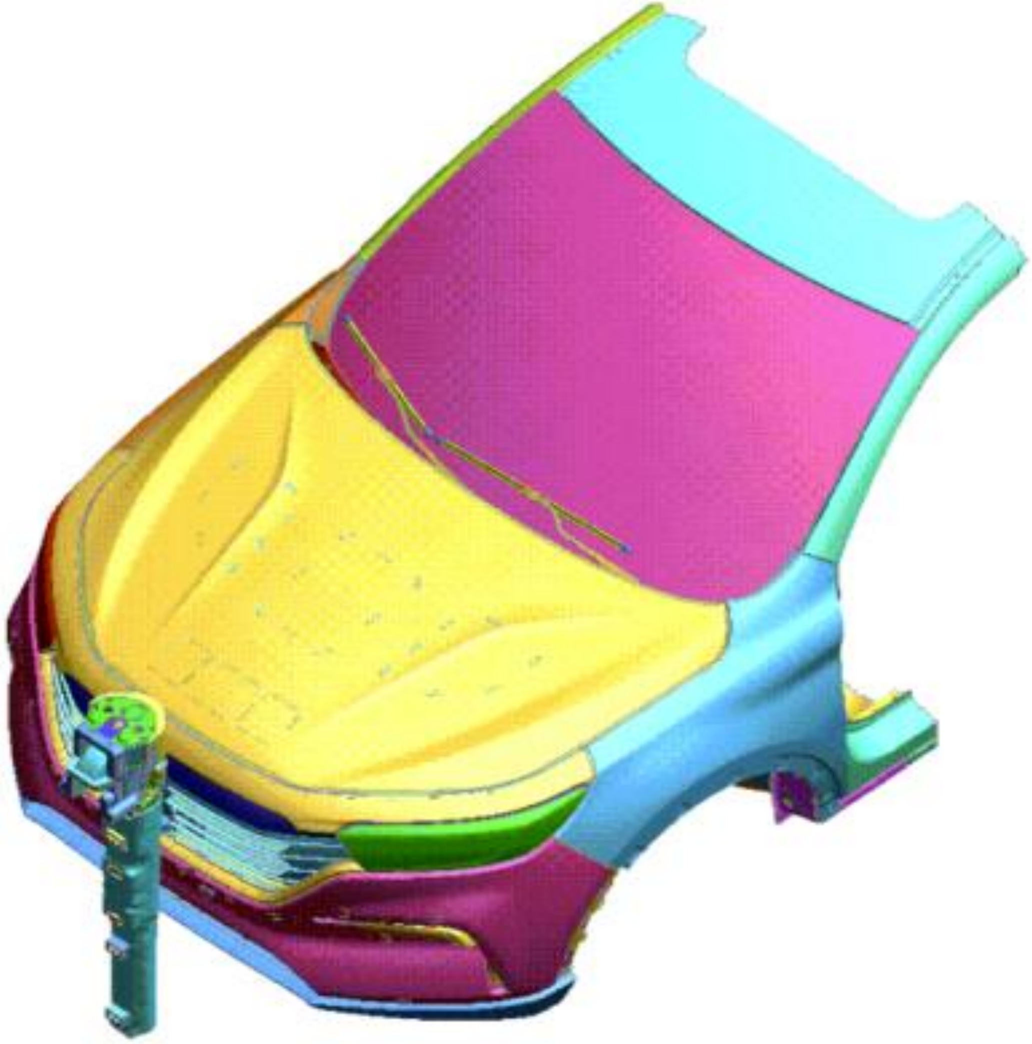
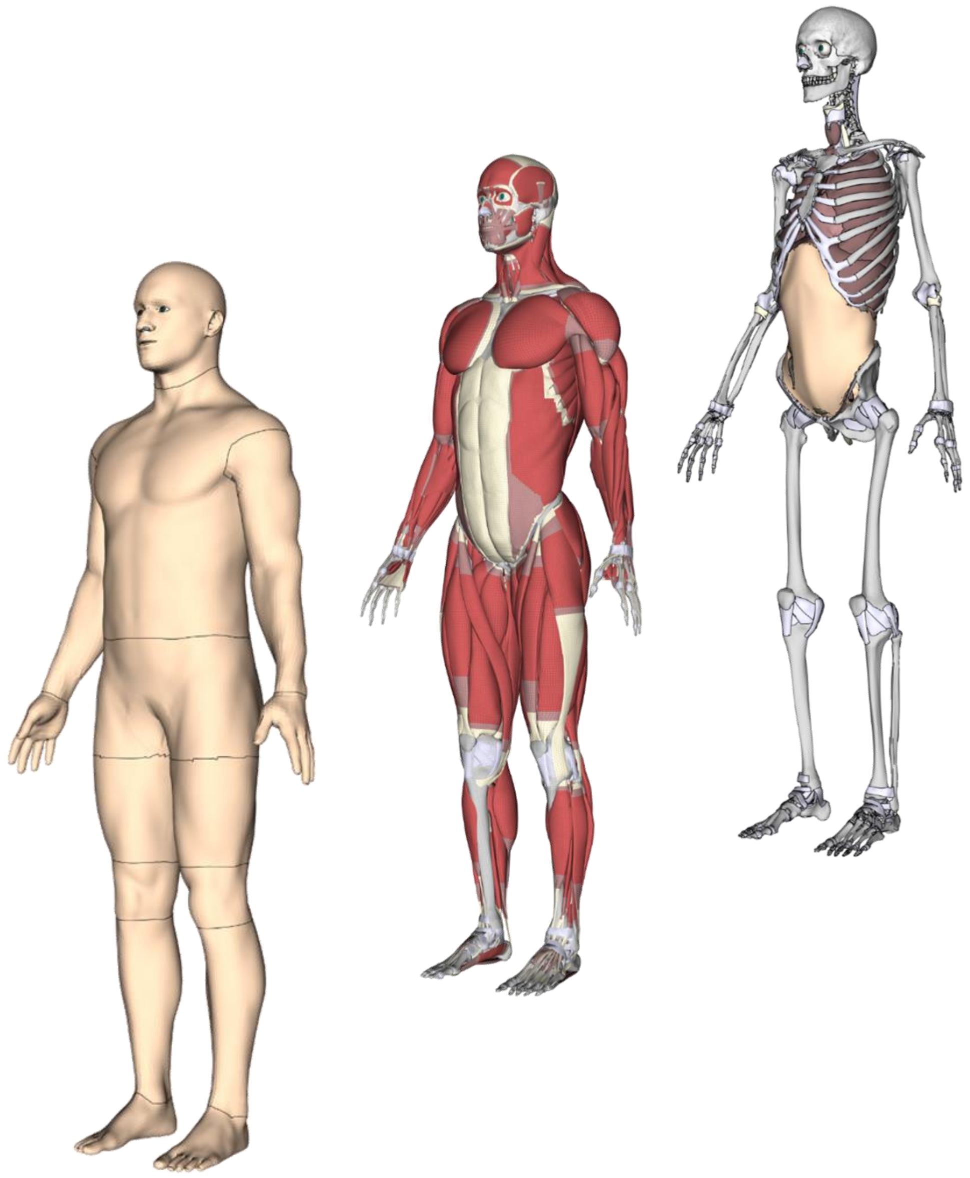


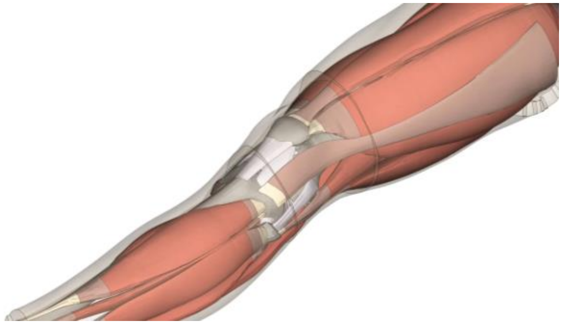
Introducing HANS

- Hans is a high-fidelity LS-DYNA human body model
- Commercial model licensed separately
- Hans represents an average male person – AM50
  - Body Specs: ~77kg, 176cm, BMI 24.9, Age 30-40
  - Model size
    - Number of nodes: ~1.6Mio
    - Number of elements: ~2Mio
    - Number of parts: 1,978
    - Macro Fiber Parts (keep adding): 138
  - Contacts
    - 1 single surface contact
    - 5 tied contacts to attach soft tissue
  - Recommended time step: 0.5µsec



Modeling Fundamentals

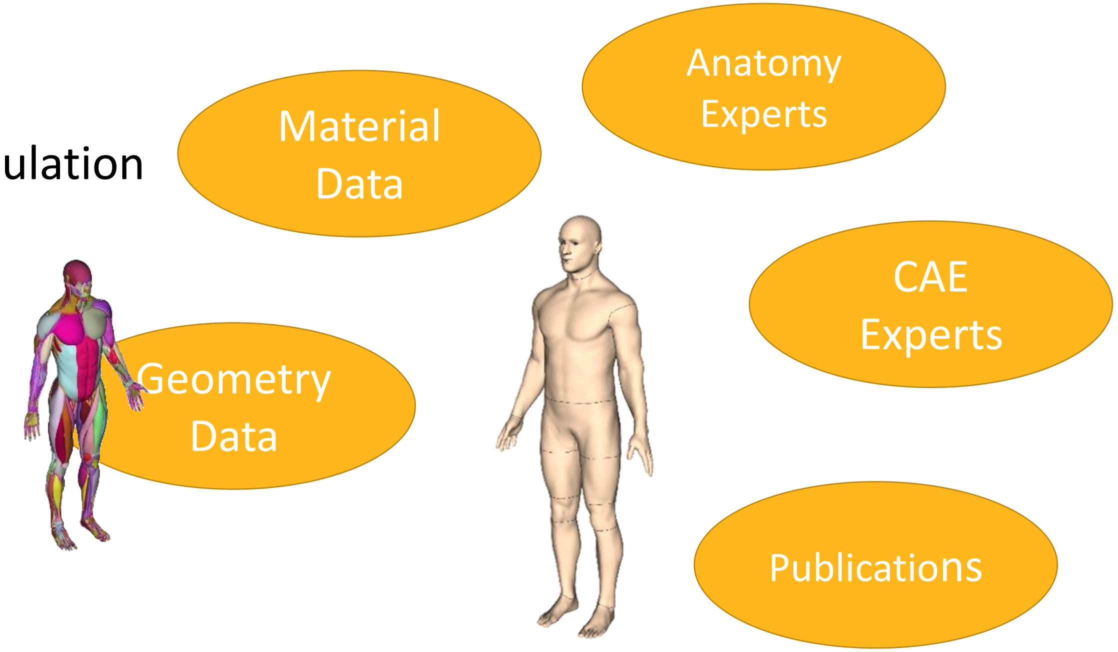
- **Passive model** targeted for any kind of **explicit** impact simulation
- Focus on the musculoskeletal system at first
- **Modeling the physics**:
  - Model the human body with a high level of detail

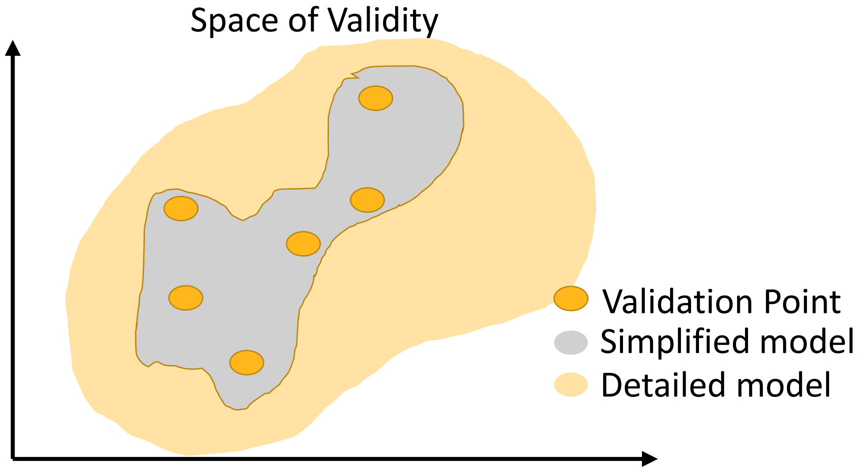


  - Avoiding abstraction and substitute approaches
    - Geometry and materials are modeled **as is**

    → **Less tweaking** needed to correlate to test data

    → **Better confidence** in load cases that are not covered by test
- **Following** the modeling approaches of the successful **DYNAmore Dummy models**





Motivation

Product development

- So far, many industries rely on **physical and virtual dummies** for product development
- Human Body models can overcome some downsides of dummies, as they are
  - a **more accurate** approximation of a human
  - are **non-directional**
  - ...
- Increasingly sophisticated safety systems and new application areas require **higher fidelity models**
  - “Made for humans - not for dummies”

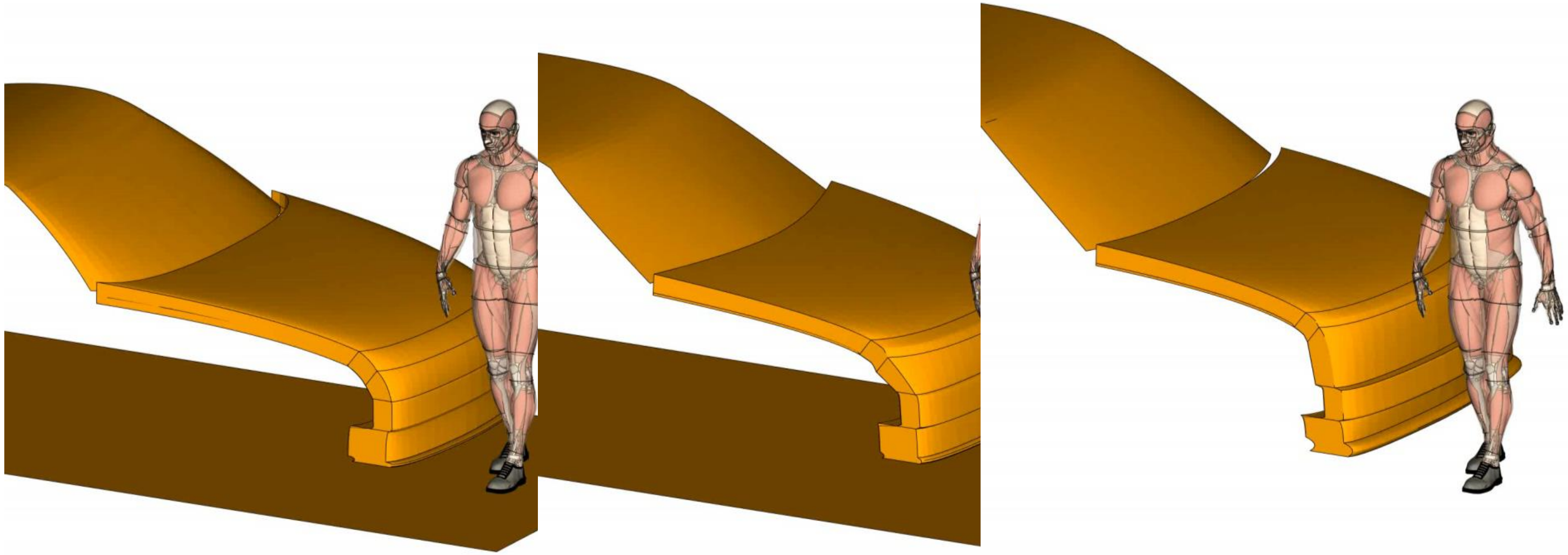
Product Certification

- There are initiatives in serveral industries to establish **virtual product certification** using HBMs
  - EuroNCAP, IIHS, C-NCAP, ... are actively working on such protocols
  - DYNAmore/ANSYS is involved in the EuroNCAP activities
  - Virtual Tests require **qualified human body models**

Vulnerable Road Users (VRUs) – EuroNCAP TB024

- Qualification model included in the delivery package
- In total 9 (3 generic vehicles x 3 impact speeds) are carried out for qualification

Roadster 50kph Family Car 50kph SUV 50kph



How to... in summary

accurately model the key components like windshield?

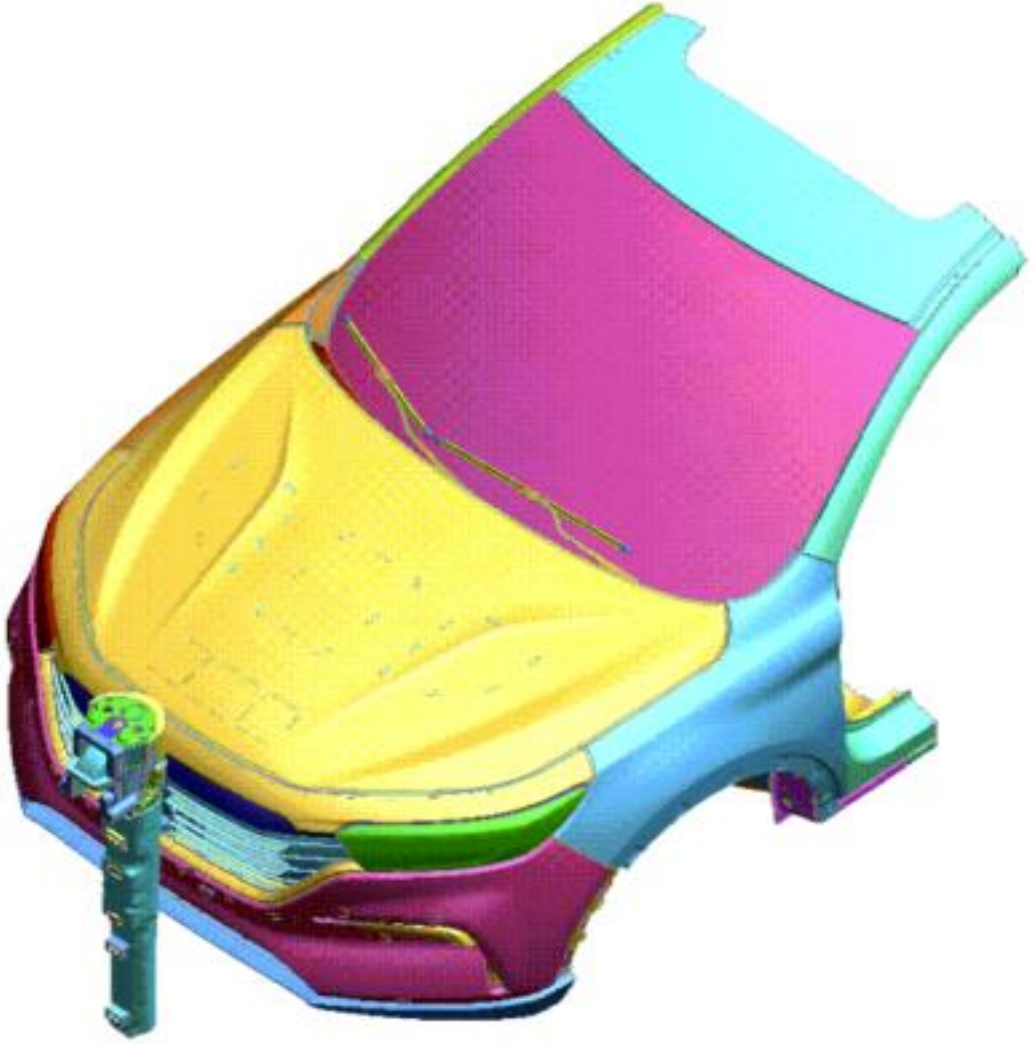
Laminated glass model with MAT_GLASS + added features

design a better hood for less severe injury?

Use optimization tools such as LS-TaSC and active hood

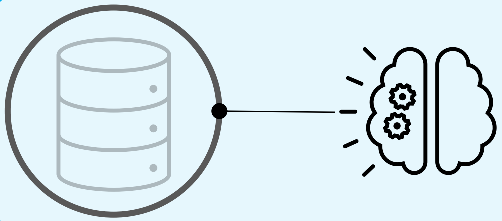
better represent a pedestrian?

HANS! For virtual certification



Ansys

SimAI Objective

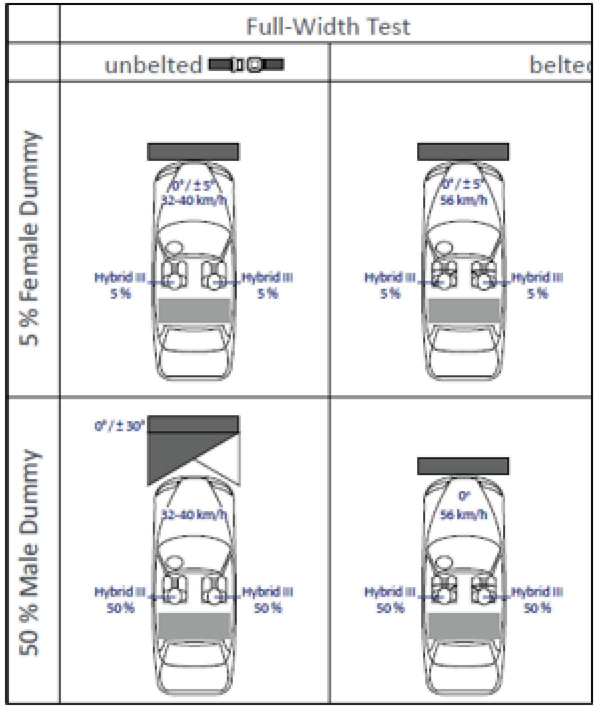


Learn from existing datasets

Build accurate predictive models

Generalize for early design prediction

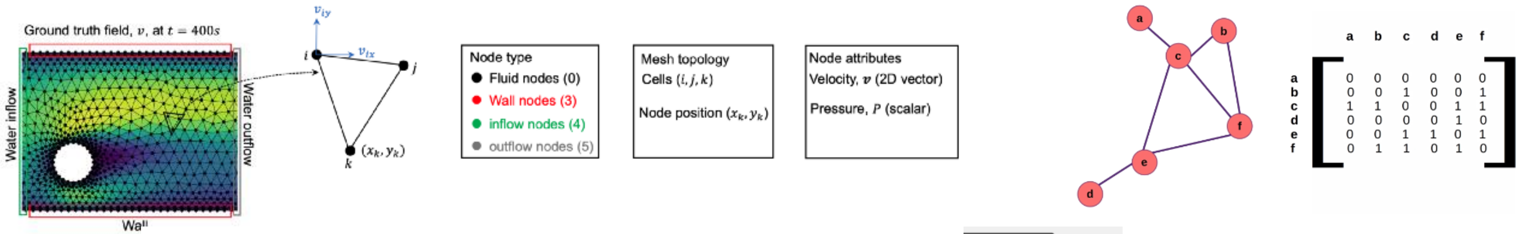
Several Designs



https://flextogo.com/en/blog-post/car-segment

SimAI – General Idea

Image Source



SimAI possesses several unique features:

(i) it is robust to varying mesh sampling, allowing for adaptability to different geometries,

(ii) it effectively captures multi-scale phenomena, resulting in state-of-the-art scores for both volume and surface evaluations,

(iii) as a continuous surrogate model, it can be used to accelerate the evaluation of different geometries during the design process, leading to significant speed-up.

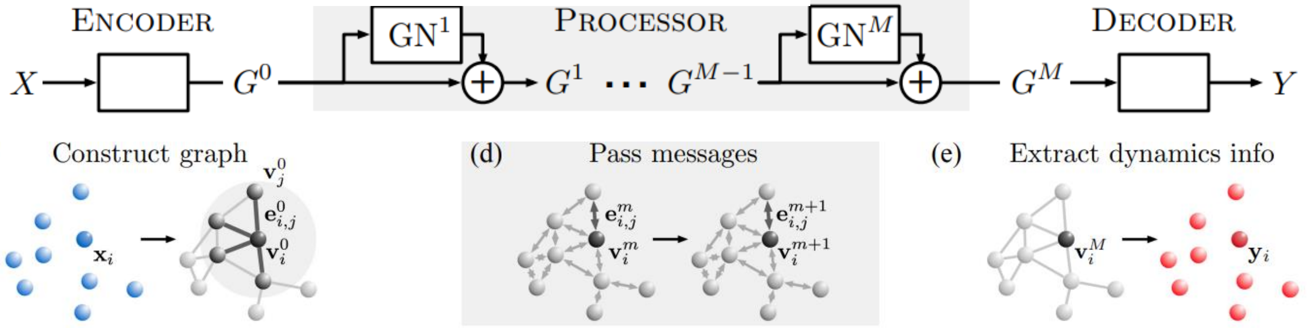


Image Source

- Encode the distance function and the normal components into latent codes
- Use the latent codes to infer predicted output codes
- Decode the output codes with modulated INRs to get the physical fields
- SimAI uses a proprietary Architecture slightly different from the one shown above

Ansys

- Total data of 106 simulations
  - Training set : 86 simulation Data points
  - Testing Data set : 20 Simulation Data points

Pedestrian Head Impact

- Challenge
  - For Pedestrian Head Impact, a grid of around 200 points on the hood are evaluated for predicted HIC value.
  - Needs to be repeated for every design change

- SimAI + LS-DYNA
  - Instead of running all 200 points, Run the simulation on 100 points. Predict HIC value for remaining points using SimAI
  - Total data of 106 simulations- 86 training set & 20 testing set

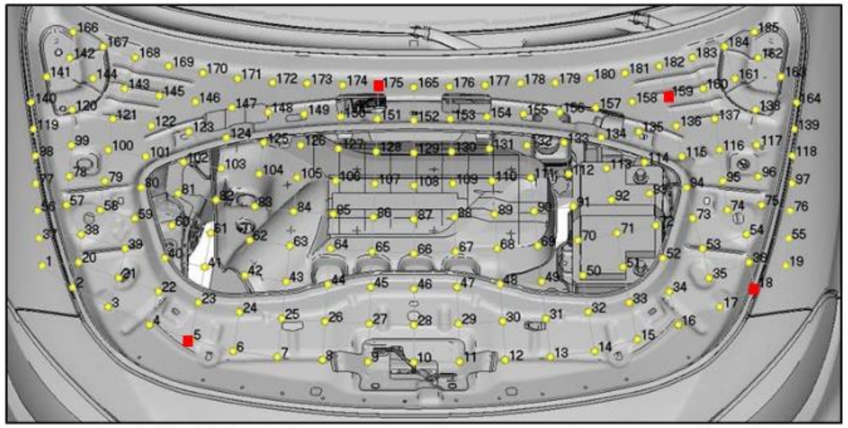
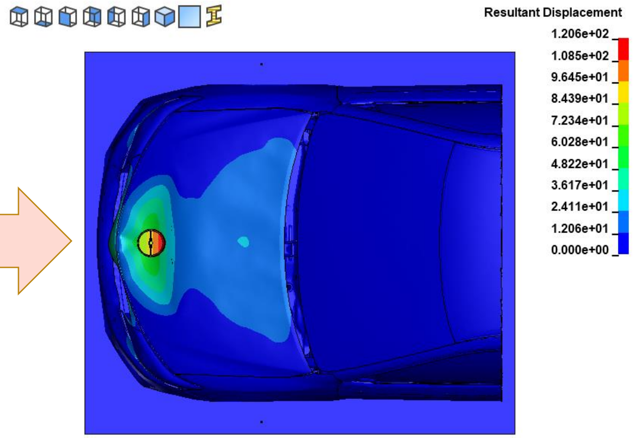
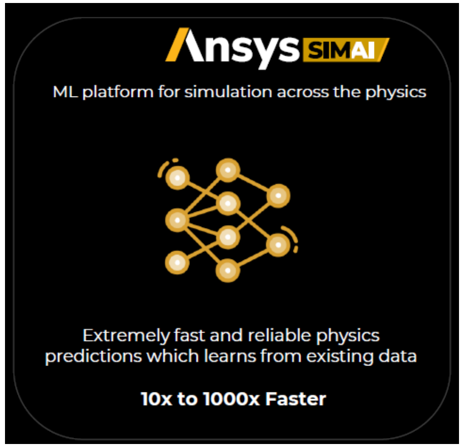


Fig 7 test impact points are shown red points
Picture courtesy: Safetywissen





Pedestrian Head Impact : SimAI Model

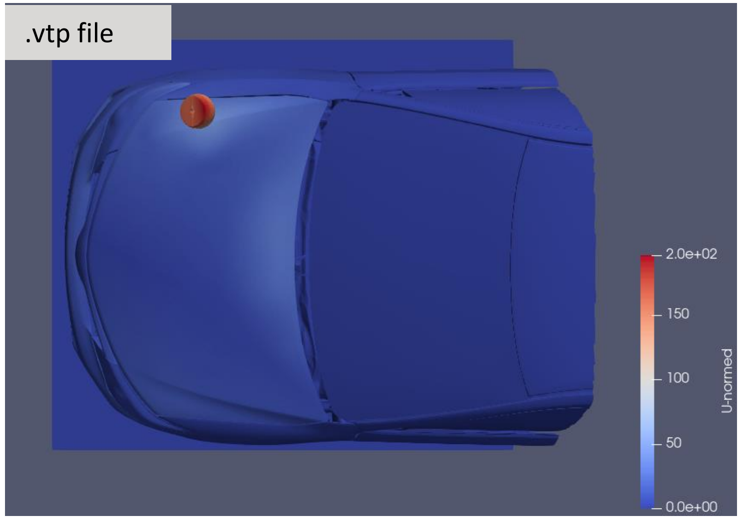
- Total data of 106 simulations
  - Training set : 86 simulation Data points
  - Testing Data set : 20 Simulation Data points

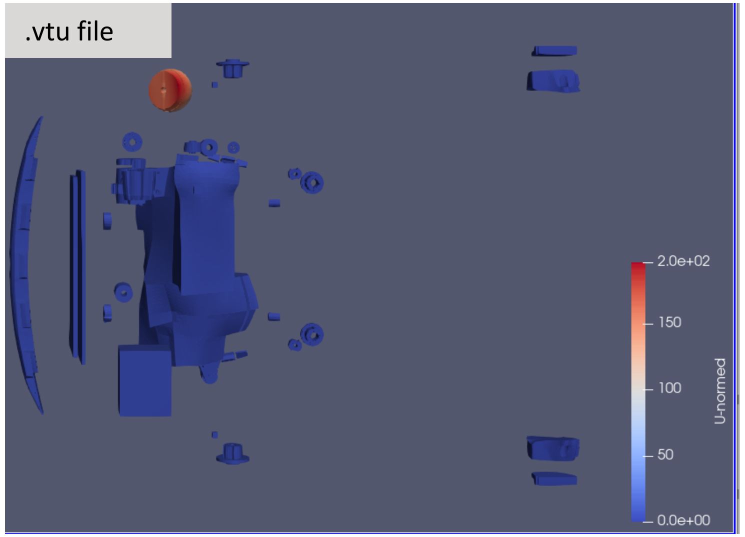
- Typical Data Point :
  - json file with input parameters
    - E.g. this case , We have considered Time
  - .vtp file : which contained displacement field and HIC value
  - .vtu file : For cast component, it has displacement field

boundary_condition.json	17-06-2024 16:47	JSON File	1 KB
surface.vtp	17-06-2024 16:47	VTP File	47,856 KB
volume.vtu	17-06-2024 16:47	VTU File	5,272 KB

json file

{"Time": 29.99936866760254}





Ansys

Model Configuration and Evaluation Report

Model configuration

Reference sample

☑ Your reference sample is valid

ML_Pdst_v4_C.5.7_28

- Boundary Condition: boundary_condition.json
- Surface file: surface.vtp
- Volume file: volume.vtu

Input/Output

Select variables

☑ Your variables are set

Model Inputs

Geometry

- Extracted from the surface

Surface

No input

Boundary Conditions

- Time

Model Outputs

Volume

- HIC
- U[X]
- U[Y]
- U[Z]

Surface

- HIC
- U[X]
- U[Y]
- U[Z]

Global Coefficients

- HIC_global, in this case 6.454e+2
- U-Normed, in this case 1.962e+2
- Ux_max, in this case 1.679e+2
- Uy_max, in this case 3.659e+1
- Uz_max, in this case 4.577e+1

Create coefficient

Domain of Analysis

☑ Your volume is set

Define domain of analysis

x position relative to design edge	Volxmin = xmin - 247.627	Length = 2971.527
y position relative to design edge	Volymin = ymin - 220.333	Width = 2643.992
z position relative to design edge	Volzmin = zmin - 142.907	Height = 1714.888

Build duration

○ Debug — 4 Data, 30min build

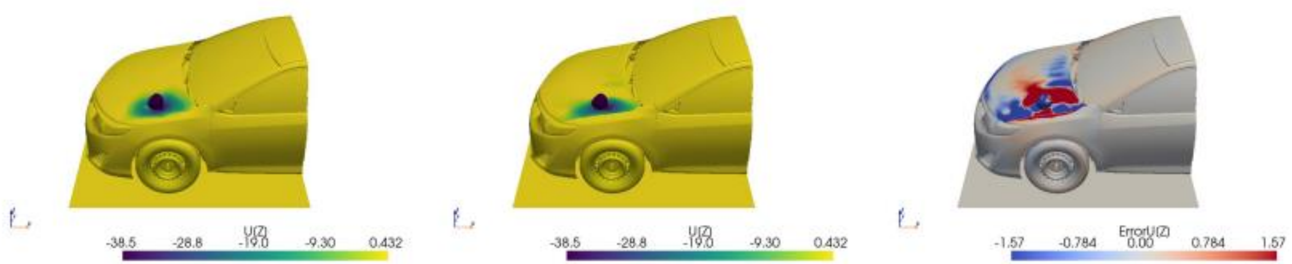
● Production — Precise

☐ Build on top of previous model (speed x5)

Go back

Build Model

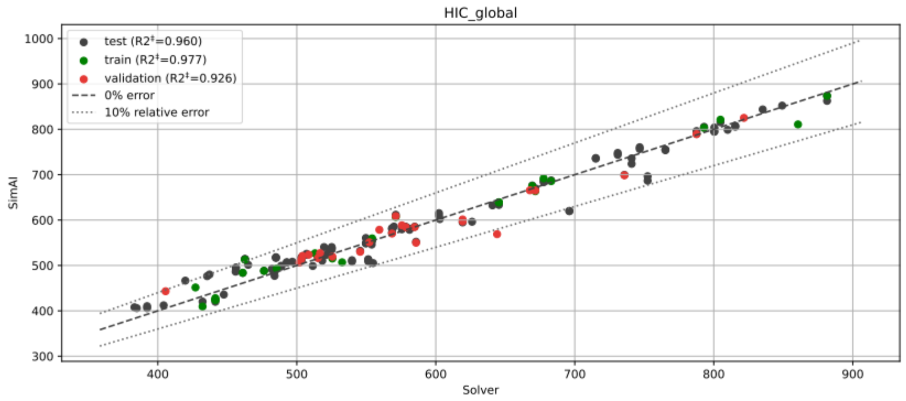
3.5.1 Test geometry 118



(a) SimAI prediction (Solver scale) (b) Solver target (Solver scale) (c) Difference (Zoomed scale)

Figure 20: Geometry mesh of U[Z]

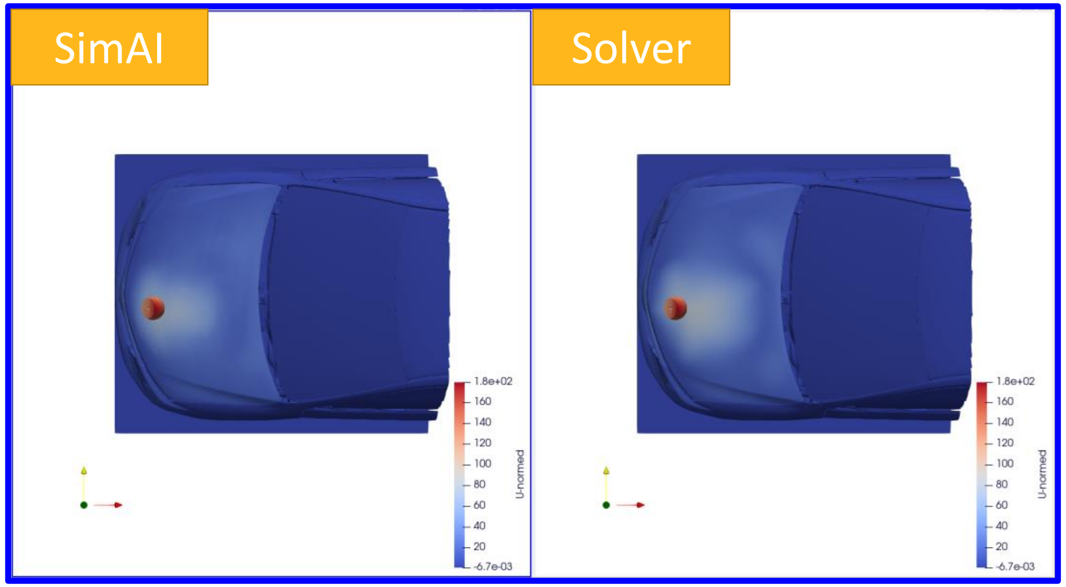
2.2.1 HIC_global



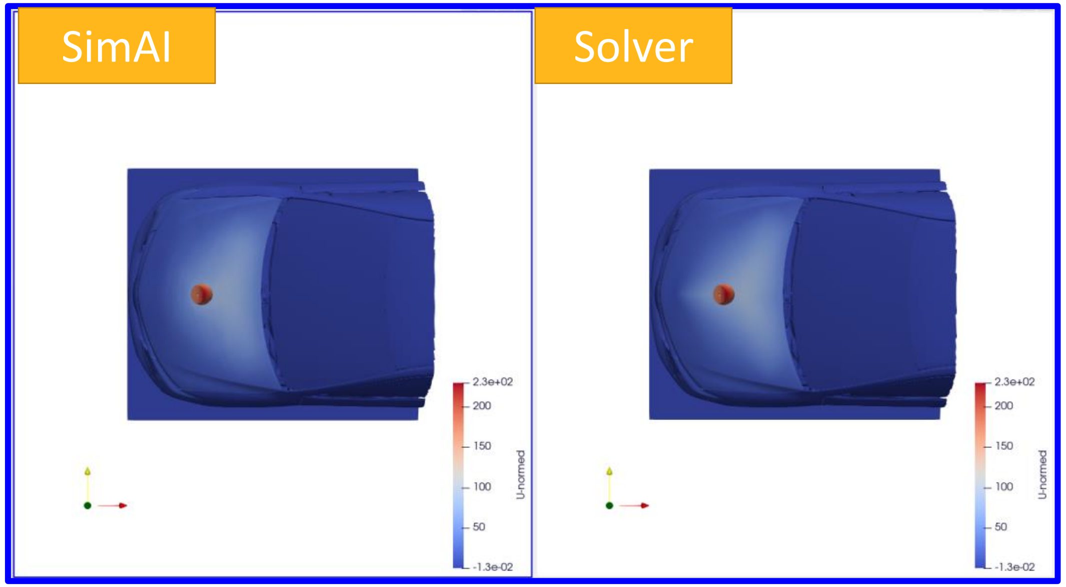
(a)

Figure 1: HIC_global trend comparison plot

Pedestrian Head Impact : SIMAI Prediction



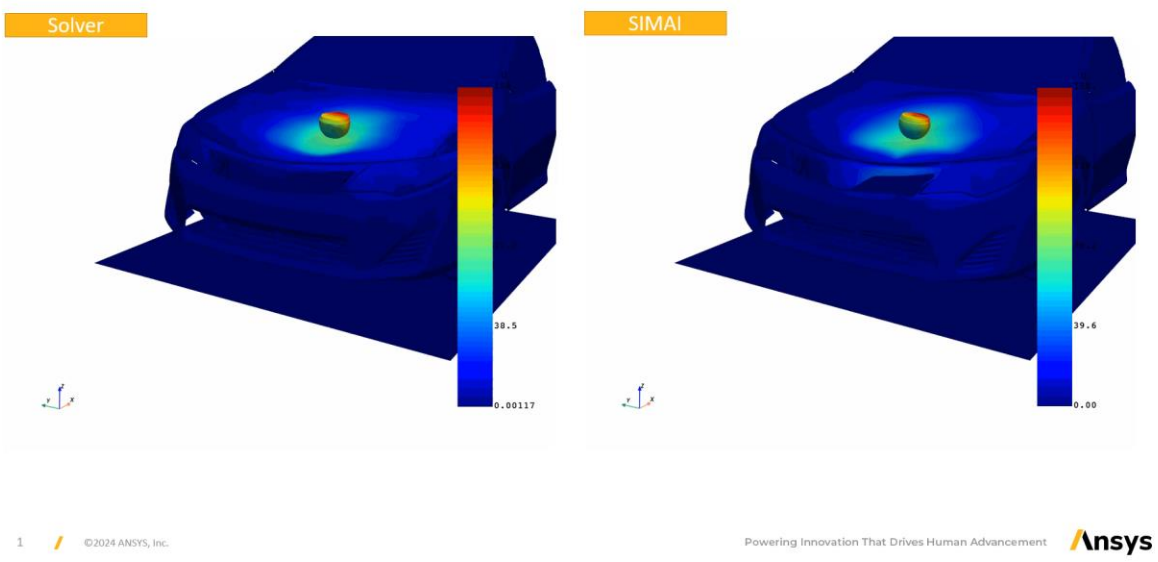
Fields	SimAI	Solver	% Error
Maximum Displacement	178.3	179.0	0.4
HIC Value	532.9	518.3	2.8



Fields	SimAI	Solver	% Error
Maximum Displacement	229.1	230.7	0.7
HIC Value	532.9	518.3	2.8

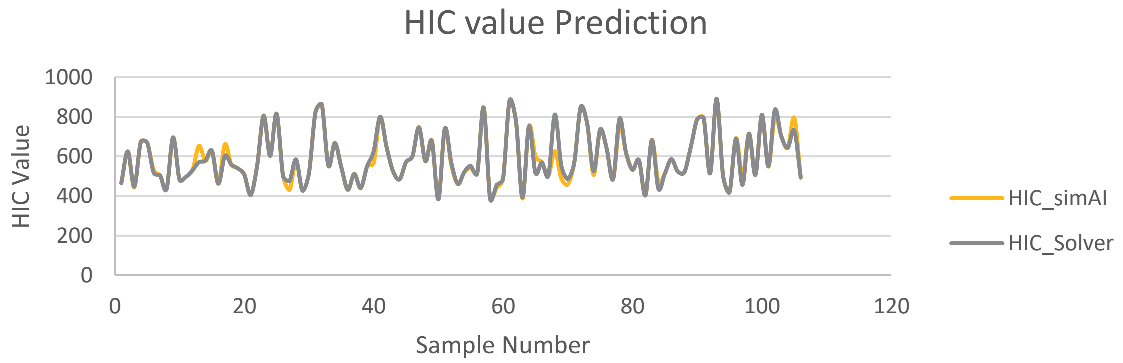
AI ML | Pedestrian Head Impact

- **Solver Time : 1hr on 96 CPUs**
- **SimAI Prediction Time : < 1min**



Fields	SimAI	Solver	% Error
Maximum Displacement	169	174	2.87
HIC Value	522	507	2.95

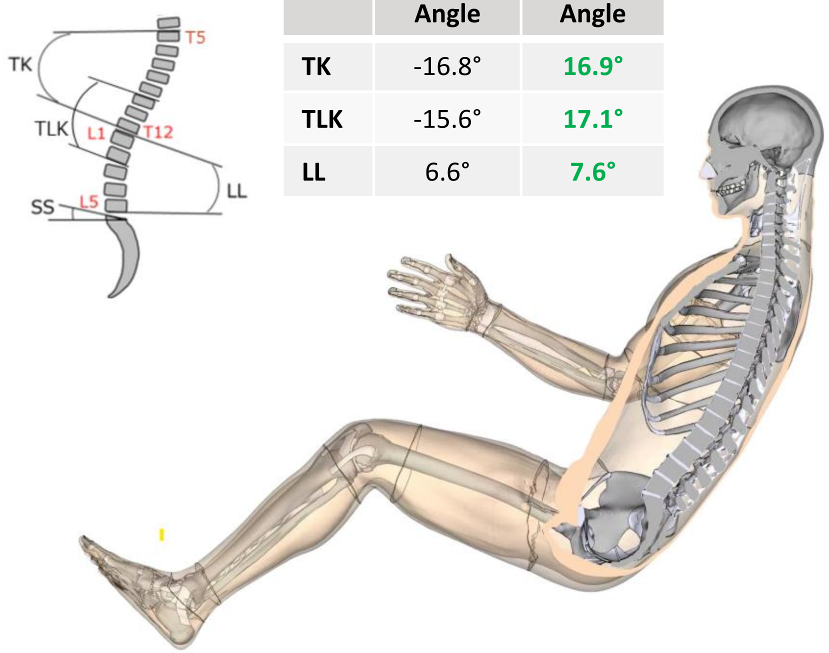
20 locations previously unseen by the model



Average Predicting Error is less than 2%

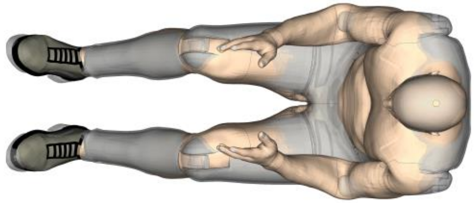
Improved Delivery Positions

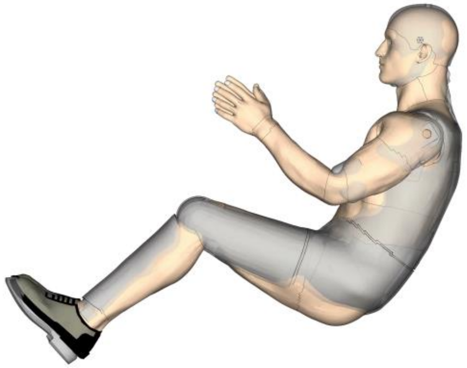
- Occupant delivery position modified based on *Rieger et al (2023)*
- Spine angle measurements from volunteer scans in car seats



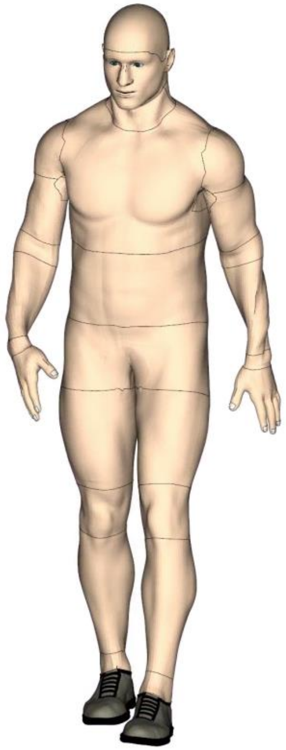
	Target Angle	Hans Angle
TK	-16.8°	**16.9°**
TLK	-15.6°	**17.1°**
LL	6.6°	**7.6°**

- Given the **same H-Point** location, the posture of Hans is close to the postures of **WorldSID50M** and **THOR-50M**
- Hans delivery position is aligned with Dummy model positions





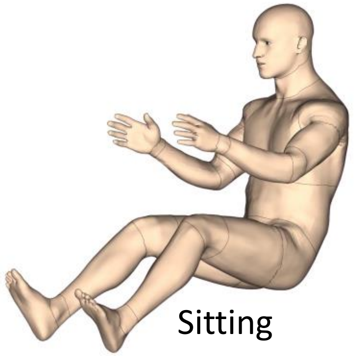
- The Pedestrian Position completely fulfils the EuroNCAP TB024 requirements



AM50		
l	Check	Deviation
34	OK	3,5%
98	OK	-3,1%
24	OK	-1,2%
82	OK	-2°
96	OK	-3°
71	OK	-1°
14	OK	-3°
.06	OK	-1°
.01	OK	1°
29	OK	3°
08	OK	3°
18	OK	-2°
35	OK	-3°
92	OK	-1mm
31	OK	-0,2%
		-100,0%
	OK	2,4%

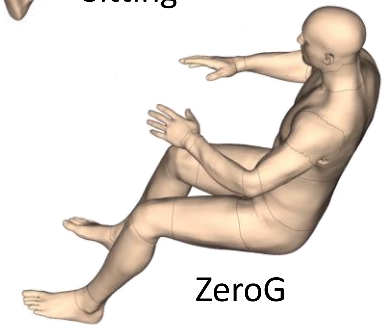
Summary

- Hans V1.2 comes with a lot of improvements for automotive customers in terms of usability and performance.
- The new release prepares the model for the upcoming/existing EuroNCAP requirements
- **R12.2** is the model development version and required to use Hans
- **Included to the delivery package:**
  - model in standing and sitting postures – **One Model**
  - Human Body Model in **three unit-systems, including parameterized renumbering**
  - Accessoires like shoes, ...
  - **Treefile for positioning** of the model in the commonly used pre-processing tools
  - Documentation/Correlation report
  - **1st class global expert support**

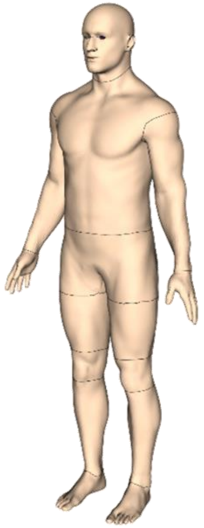


Sitting

TB024



ZeroG



Standing

Required simulation capabilities

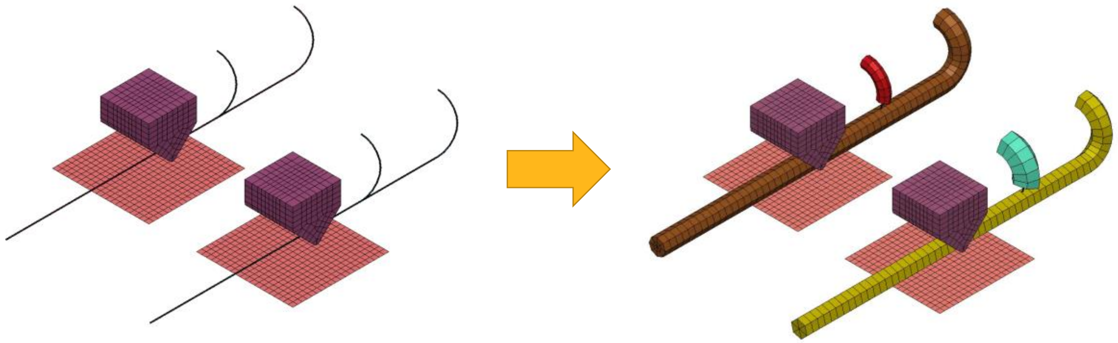
- Material properties
  - Plastic materials (headlamps, front fascia, …)
    - Including fracture
  - Windshield glass
    - Fracture and crack propagation
    - Displacement (potential secondary impact with instrument panel)
- Package parts
  - Powertrains
  - Electronic components
  - Hinges
  - Cables and cable bundles
  - Instrument panels including all parts in potential impact area

Modeling of package components

Simplified electric cable modeling with *DEFINE_CABLE

- Simple creation and analysis of electric cables for modeling wire failure in vehicle crash
  - Automatic creation of cables from beam elements
  - Final cables can be a mix of solids/shells/beams
  - Links cross-section data to each original beam element
- Data available in binout (*DATABASE_CABLE: cableout)
  - Compression (contact) force
  - Cross-section area
- Data summary available in ASCII-file
  - Time and location for maximum compression force and minimum cross-section area for each cable and for whole model

Cable generation from beam elements



Data summary

```
PART-WISE DATA:

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 maxstress=    0.4953E-01, time=    0.5000E+01, element=            46
 minarea  =    0.5891E+02, time=    0.5000E+01, element=            48
 maxforce =    0.5590E+01, time=    0.4998E+01, element=            46

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 minarea  =    0.8419E+02, time=    0.4997E+01, element=       6020579
 maxforce =    0.9542E+01, time=    0.4997E+01, element=       6020579

 Beam part=  83990005, sampling frequency=         1 cycles
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 maxforce =    0.0000E+00, time=    0.0000E+00, element=             0

DATA FOR ALL PARTS:

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 minarea  =    0.5891E+02, time=    0.5000E+01, element=            48, part=      83990001
 maxforce =    0.9542E+01, time=    0.4997E+01, element=       6020579, part=      83990002
```