DRAFT
29-06-2009

« Advanced in Numerical Simulation – End-to-End Virtual Prototyping and High Performance Computing »

Alain de Rouvray
ESI Group Chairman & CEO
June 30th, 2009

Content

- A Brief History of Simulation in MCAE
- From Numerical Analysis to Virtual Prototyping
- End-to-End Virtual Prototyping with High Performance Computing
- Leveraging HPC for End-to-End Virtual Prototyping's gain
- Industry Adoption and Trends
- Virtual Prototyping Illustrations

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A Brief History of Simulation in MCAE

History of Simulation in MCAE 1970 – 2009…

Digital Design (CAD)

Digital Analysis (FEA)

Digital Simulation / *Hybrid* (NL-FEA)

« **Ideal** »
Forms, Functionalities,
Formulas
and
IT Data Mgmt

Virtual Testing (φ)/ *Intrinsic*

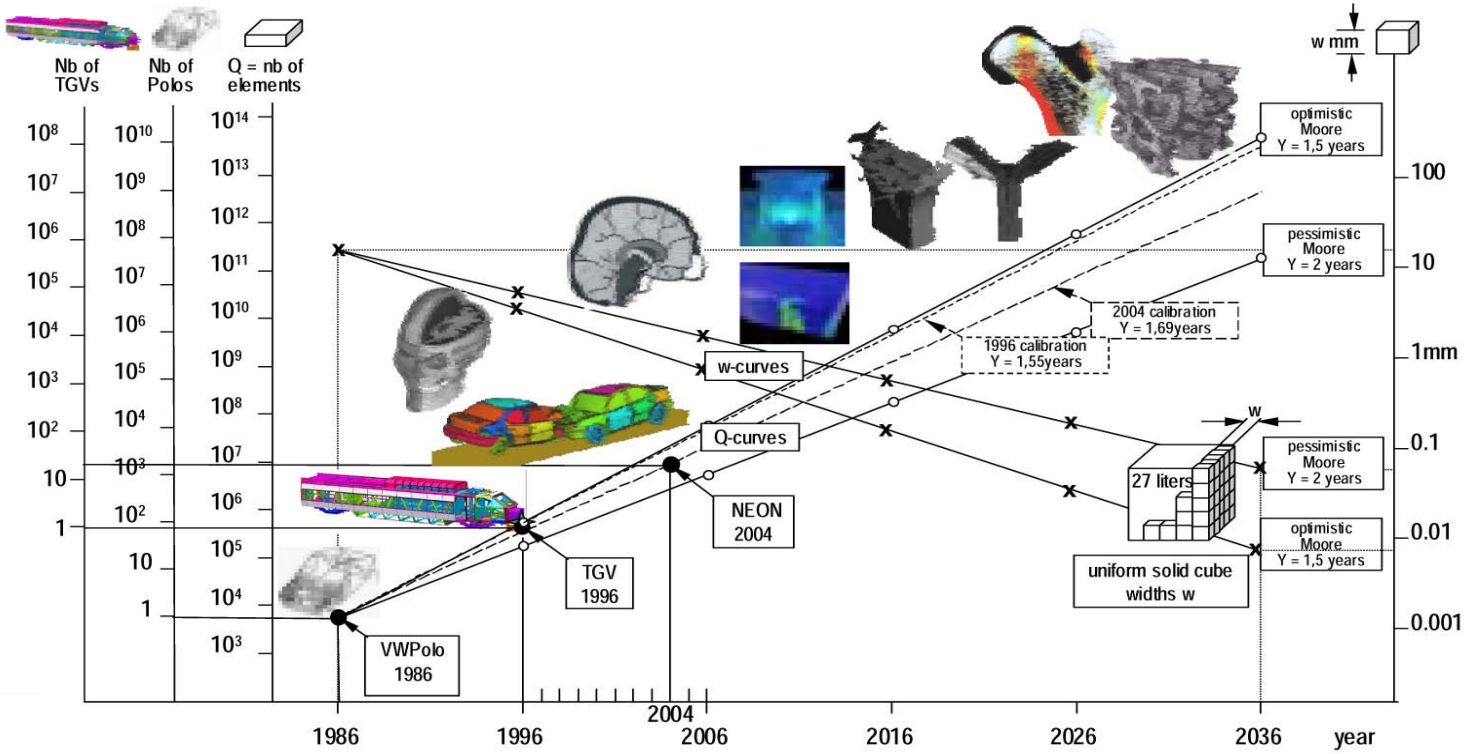
Virtual Prototyping +
Compute Model Mgmt
(Visual*DSS* Platform)

PLM integration
Process & Workflow (Vdot)

« **Realistic** »
Material Physics
and
Model Content Mgmt

Moore's law applicable to Crash?

Model size:
x 1000
In 18 years



"Future nano-scale crash models? All bets are open! But one thing is sure: Provide an analyst with all the available compute power, then he or she will use it up in an astonishingly short lapse of time."

Eberhard Haug

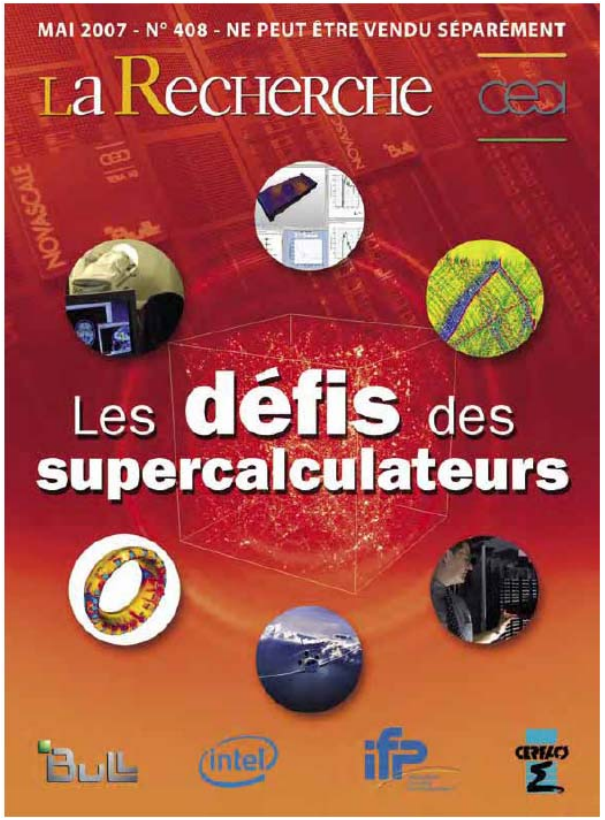
Very High Performance & Cloud Computing

- Petaflop computing is coming to industry
- Very Large Computing Centers to sprout in Europe by 2010

  (ex.: Saclay – France TGCC)
  VHPC availability on site of Bruyères-le-Châtel

  - 2007 : 50 teraflops
  - 2010 : 1 **petaflop**

Ter@tec



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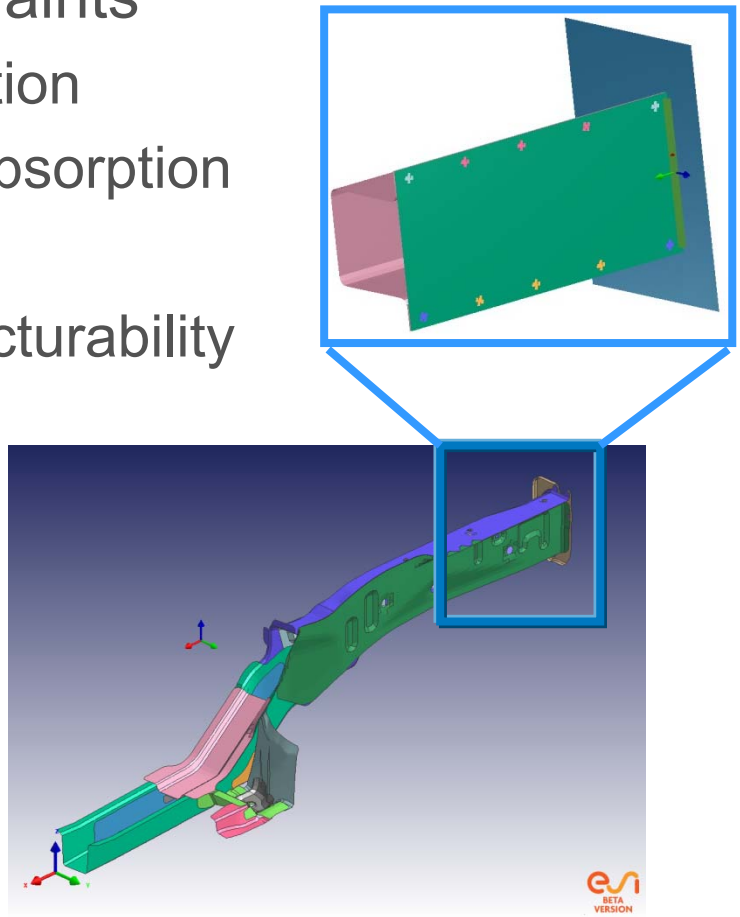
From Numerical Analysis to Virtual Prototyping

Some illustrations

End-To-End Virtual Prototyping in Visual*DSS*

Case Study: ***Rail Illustration***

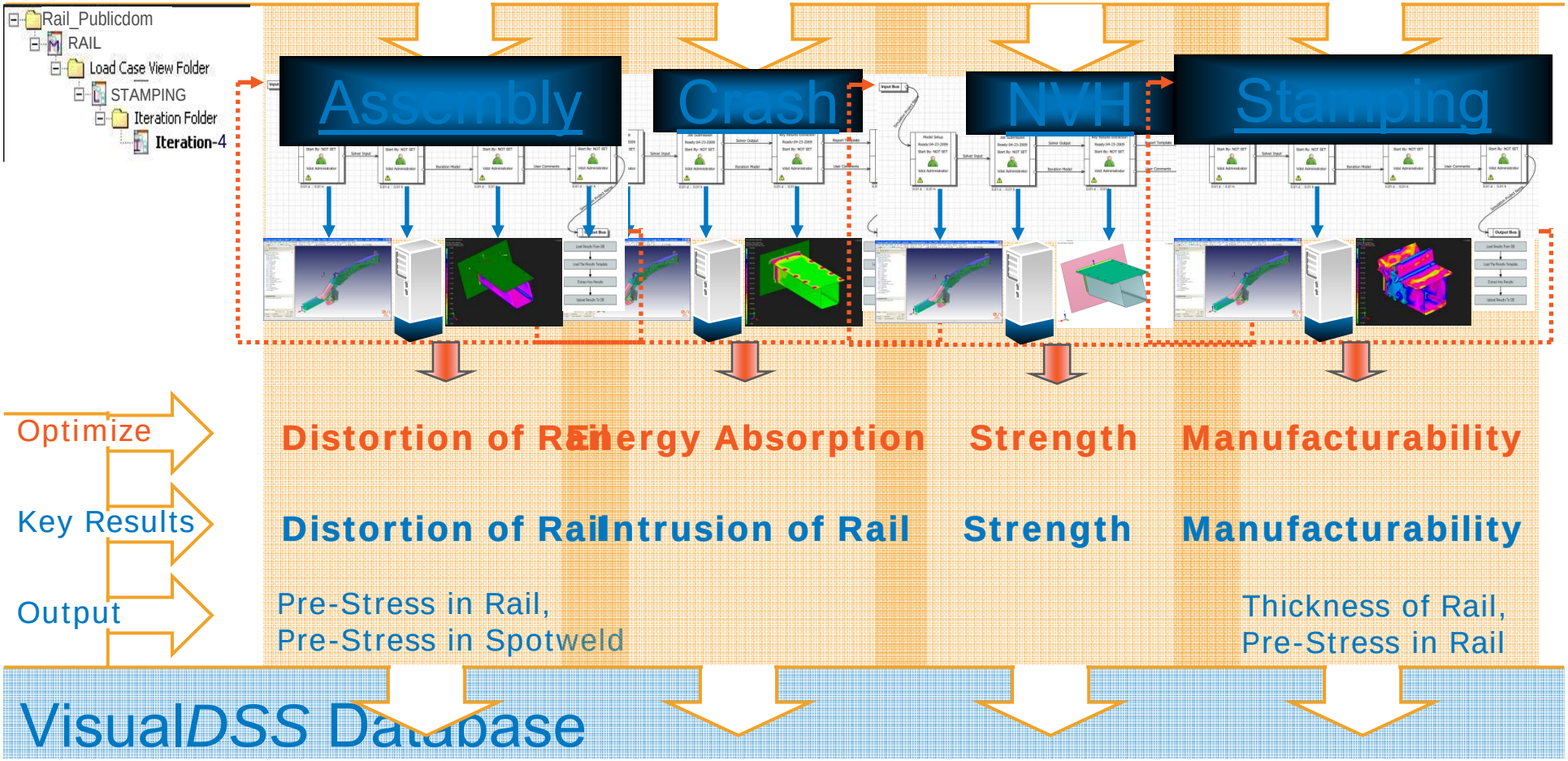
- Weight optimization of a RAIL while meeting the following optimization constraints
  - Assembly – Minimize distortion
  - Crash – Maximize energy absorption
  - NVH – Maximize strength
  - Stamping – Ensure manufacturability
- Design variables
  - Shape of the RAIL
  - Thickness of the RAIL



End-To-End Virtual Prototyping in Visual*DSS*

Rail Illustration: Assembly, Crash, NVH, Stamping Simulation

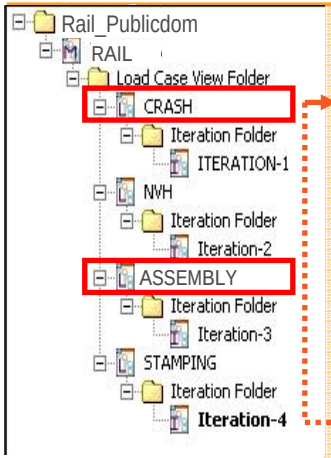
Business Processes

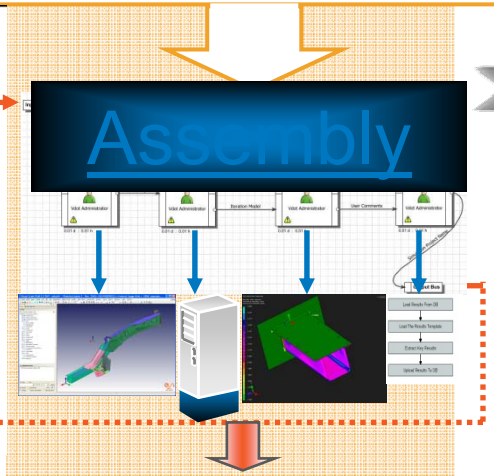


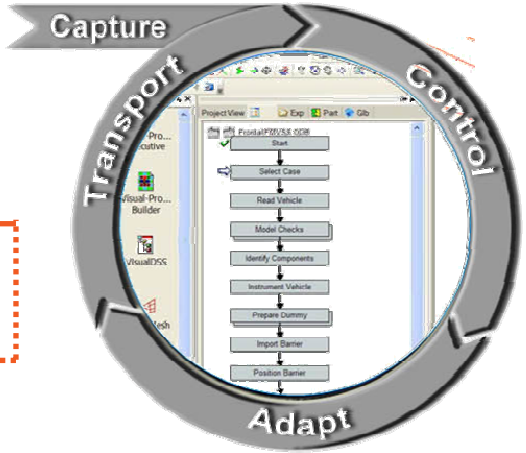
End-To-End Virtual Prototyping in Visual*DSS*

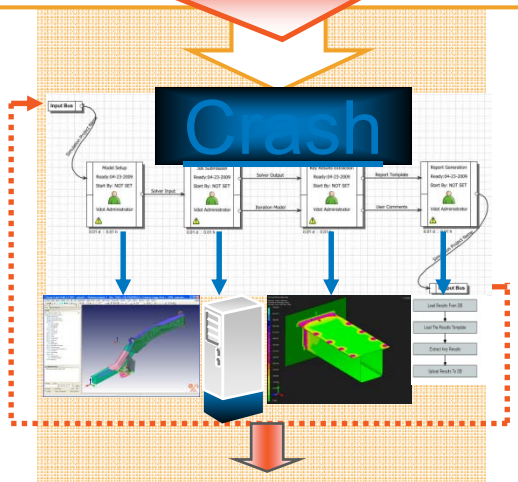
Rail Illustration: Managing Assembly & Crash Interaction

Business Processes









Optimize

Key Results

Output

Distortion of Rail

Distortion of Rail

Pre-Stress in Rail,
Pre-Stress in Spotweld

To predict its effect on Crashworthiness in a *REALISTIC* way

Energy Absorption

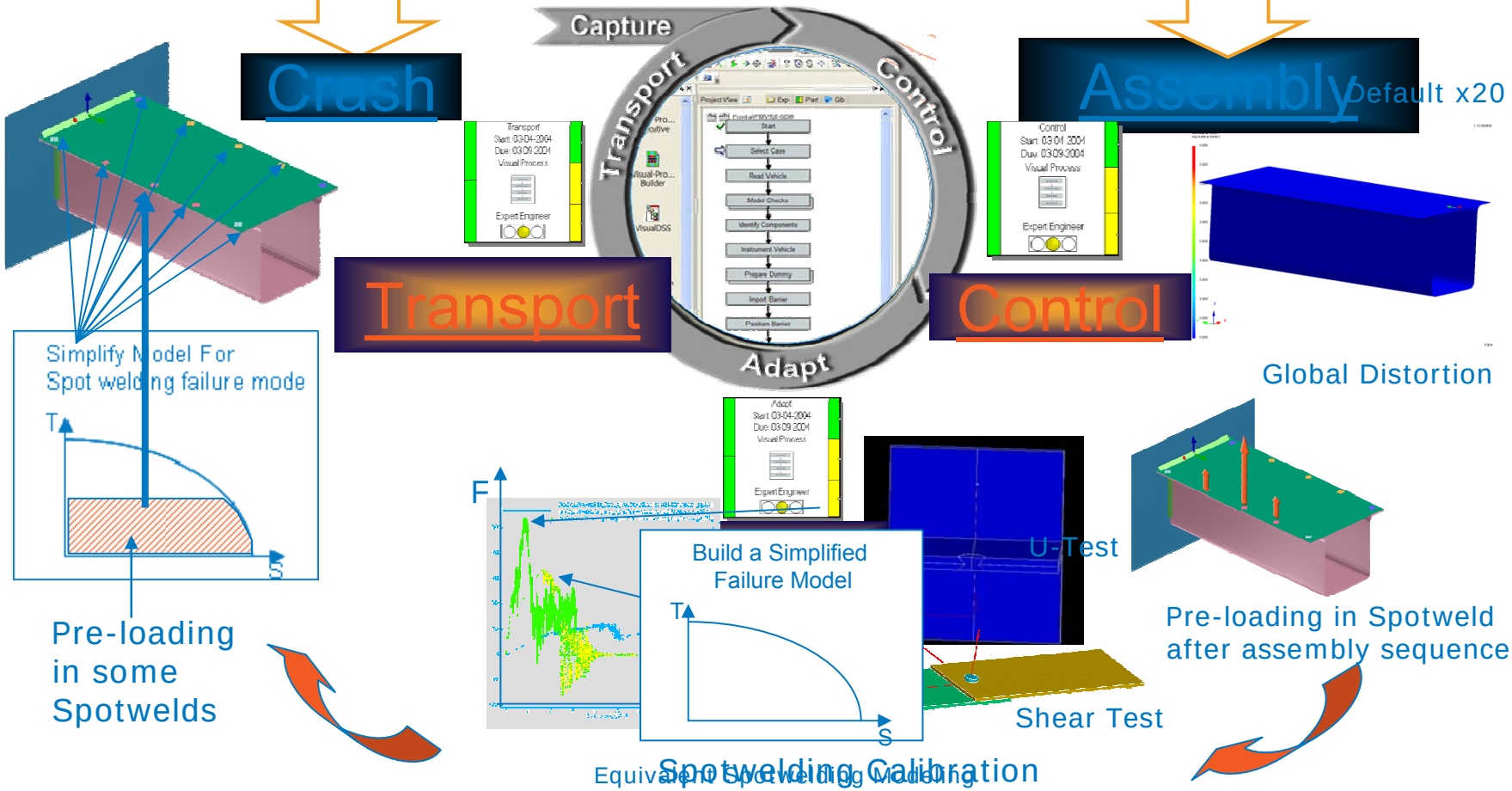
Intrusion of Rail

Visual*DSS* Database

End-To-End Virtual Prototyping in Visual*DSS*

Rail Illustration: Managing Assembly & Crash Interaction

Business Processes



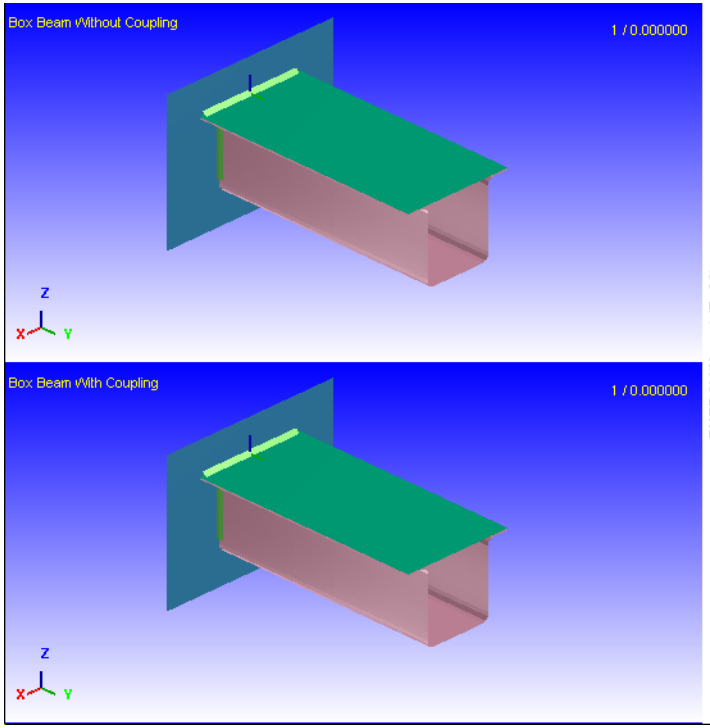
End-To-End Virtual Prototyping in Visual*DSS*

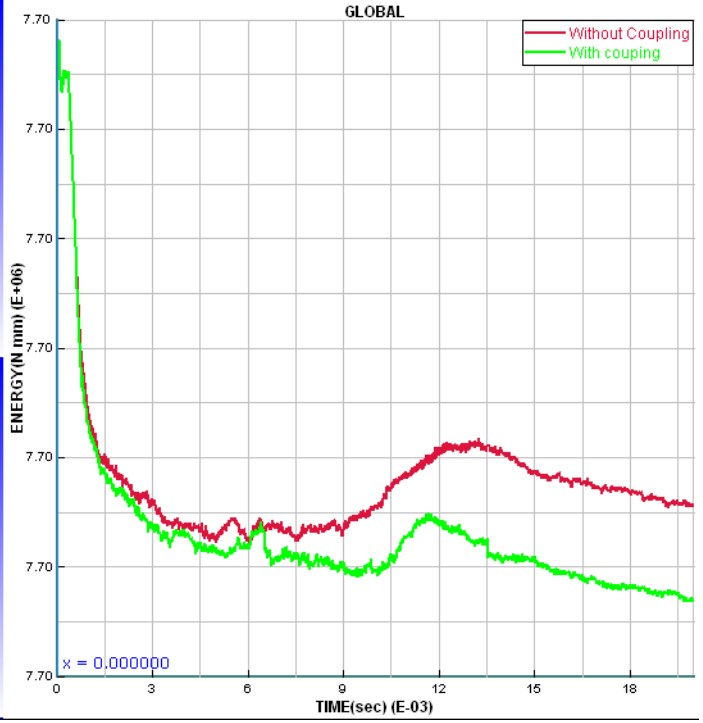
Rail Illustration: Managing Assembly & Crash Interaction

Business Processes

Crash without Coupling

Crash with Coupling





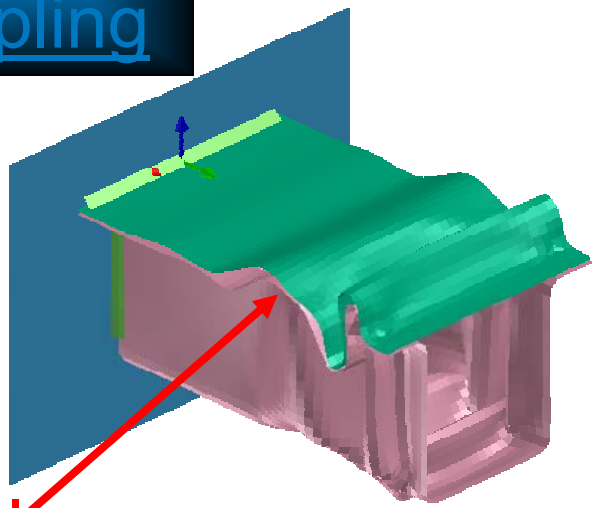
Visual*DSS* Database

End-To-End Virtual Prototyping in Visual*DSS*

Rail Illustration: Managing Assembly & Crash Interaction

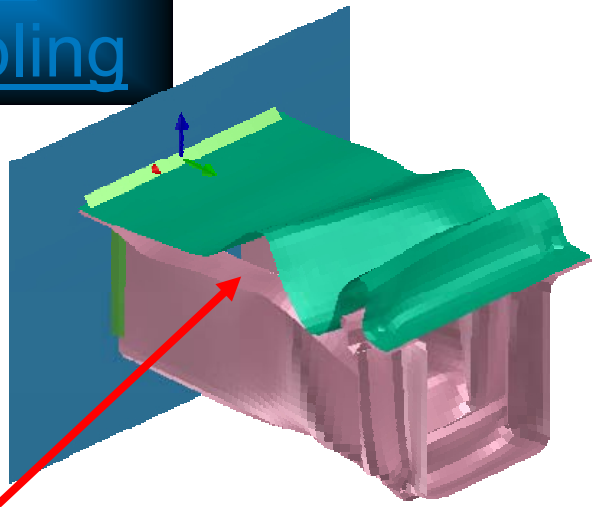
Business Processes

Crash without Coupling



No Failure

Crash with Coupling



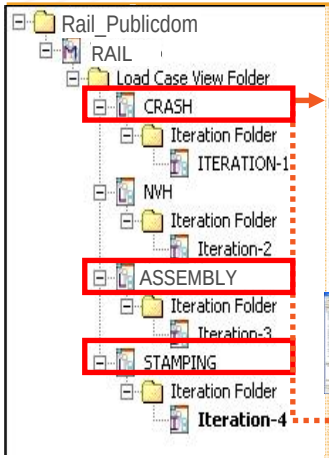
Failure

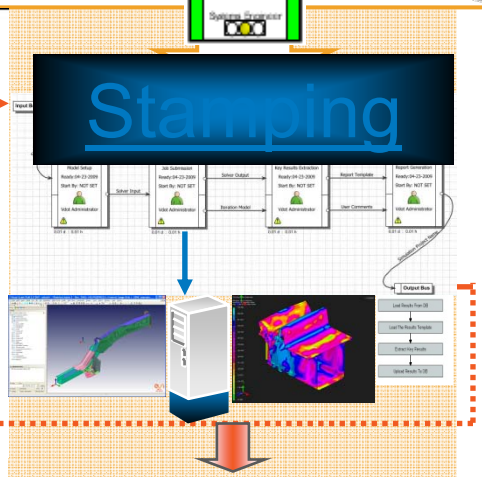
Visual*DSS* Database

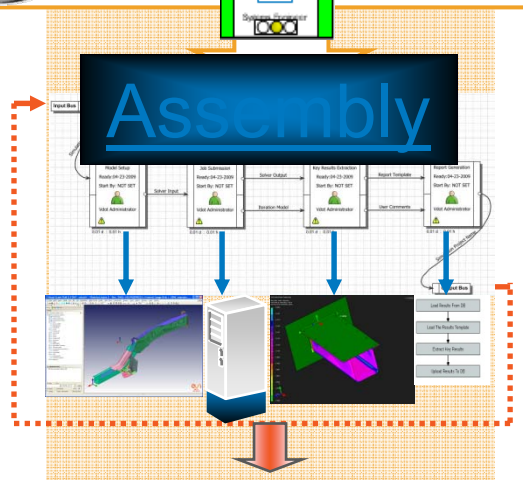
End-To-End Virtual Prototyping in Visual*DSS*

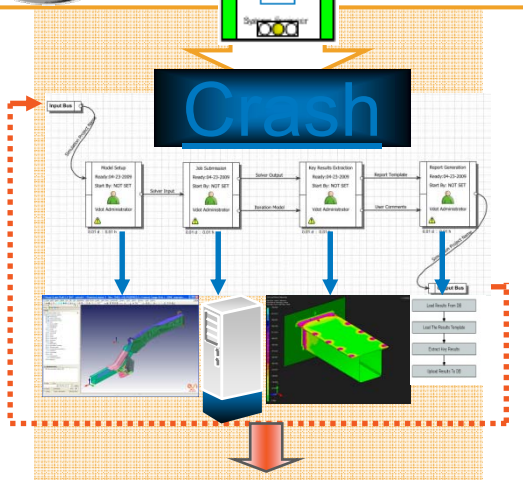
Parallel Integration: Stamping, Assembly & Crash Interaction

Business Processes









	Stamping	Assembly	Crash
Optimize	**Manufacturability**	**Distortion of Rail**	**Energy Absorption**
Key Results	**Manufacturability**	**Distortion of Rail**	**Intrusion of Rail**
Output	Thickness of Rail, Pre-Stress in Rail	Pre-Stress in Rail, Pre-Stress in Spotweld	

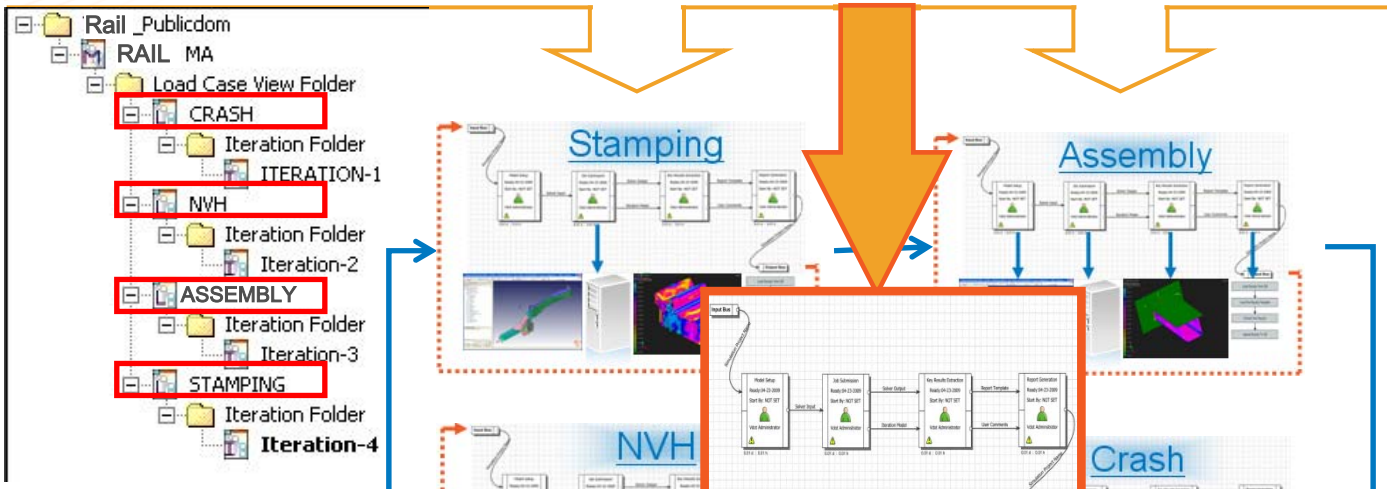
Visual*DSS* Database

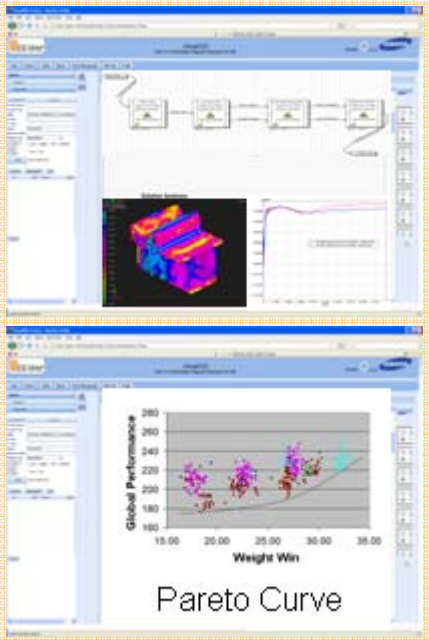
End-To-End Virtual Prototyping in Visual*DSS*

Rail Illustration: ***Multi-Disciplinary Optimization***

Business Processes

VDSS Web Client





Visual*DSS* Database

Decision Making Tool

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End-to-End Virtual Prototyping with High Performance Computing

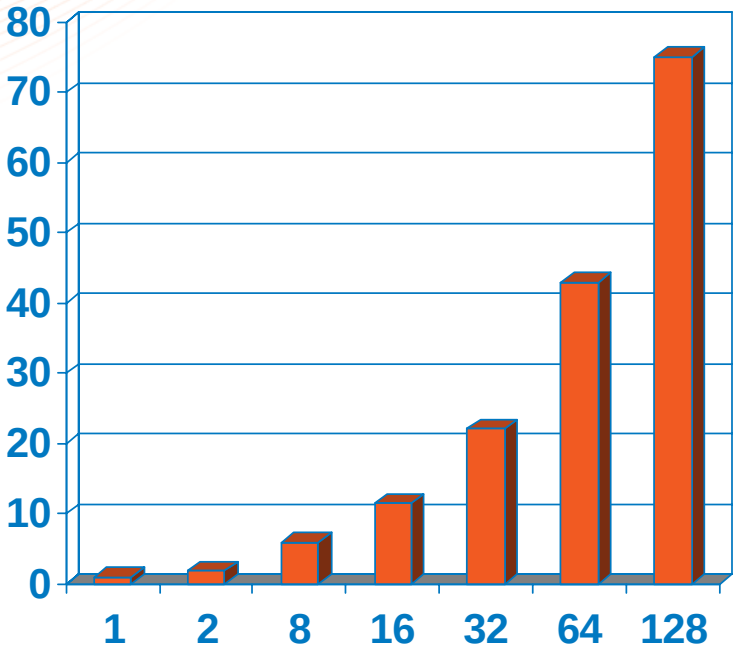
Progress in Hardware

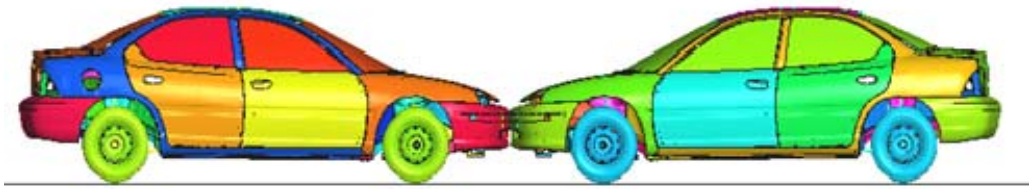
Progress in Software

Innovation in HPC

Continuous Improvement in System:

PAM-CRASH on Bull Novascale, Standard Benchmark Case





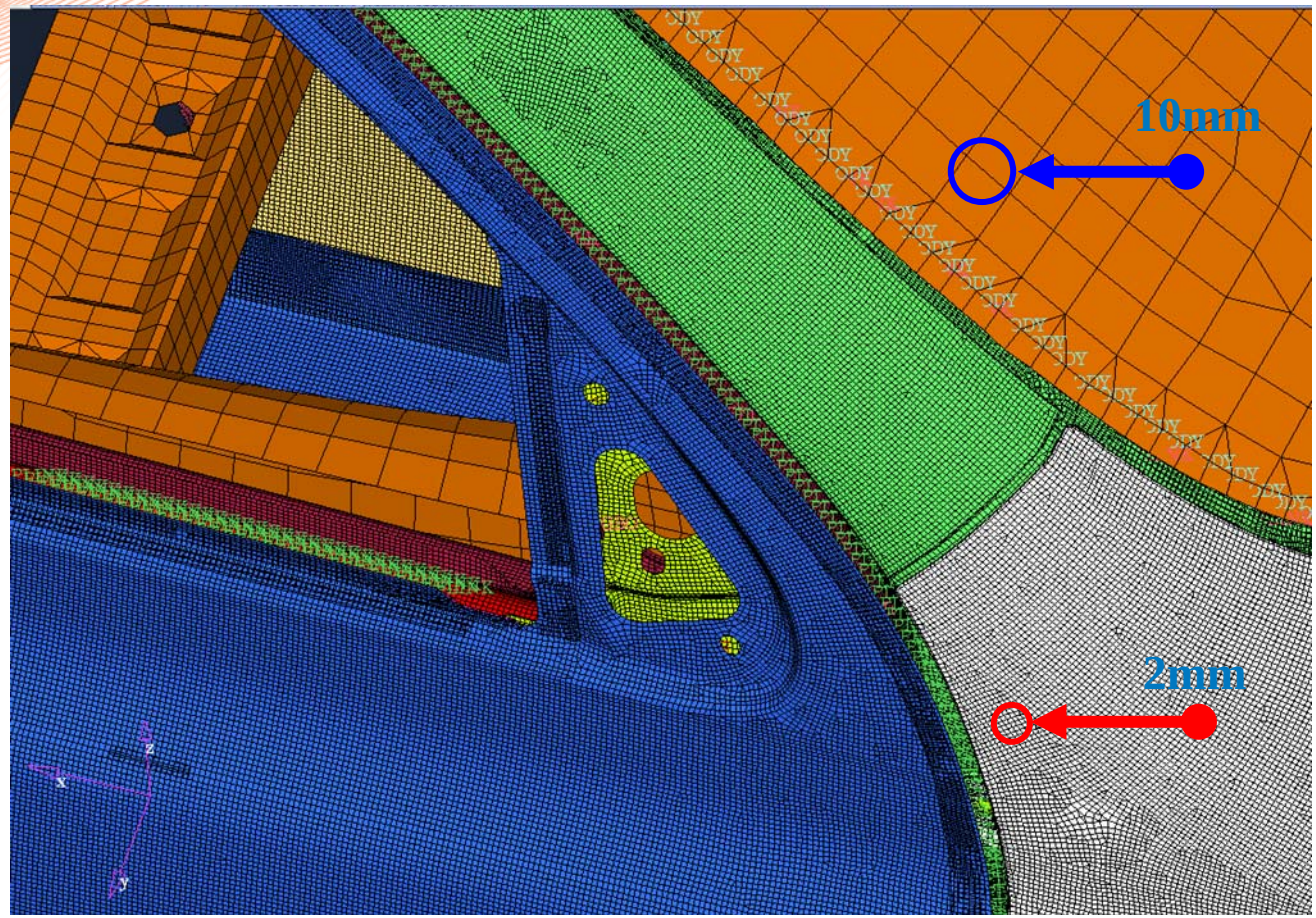
Model Size : 2,200,000 elements
Crash : Car-Car Neon Benchmark
Simulation time : 120ms
Run time : 2h @ 128 P
Overnight Threshold (12h): 24 Processors

System : Novascale 5150
16x Itanium 1.6GHz.

PAM-CRASH V2006 DMP

Benchmark Performed in 2006 by BULL

IBM Deep Computing Team K. Iijima, Nissan



IBM CAE Symposium, Detroit 2007

- **Approach ~ Condition/FE-model ~**
- **No. of Elements : 10,700K**
- **Mesh Pitch : 2mm Automatic Meshing**

This project was also performed using the Earth Simulator in Japan with the help of NEC

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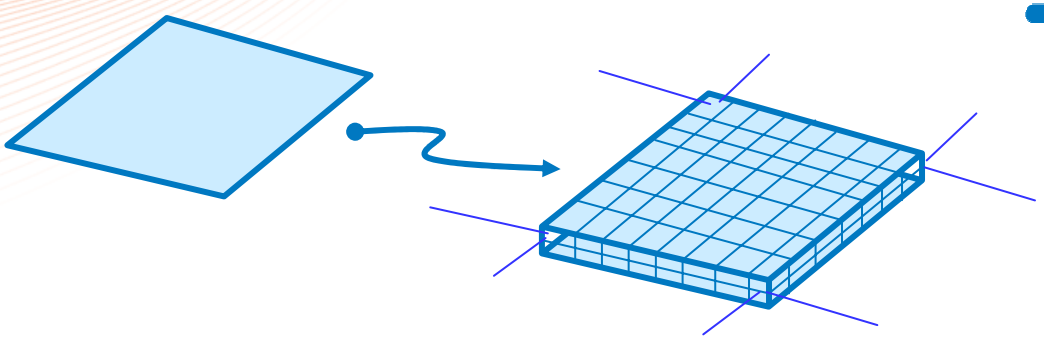
Leveraging HPC for End-to-End Virtual Prototyping's gain

Multi Model Coupling

Spotweld modeling using MMC

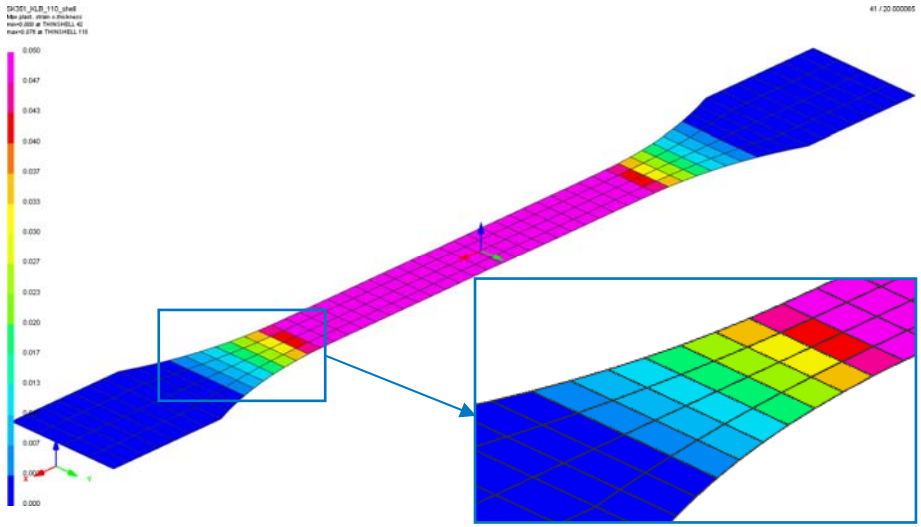
Automatic Shell/Solid Remeshing

A solution: automatic shell-solid remeshing

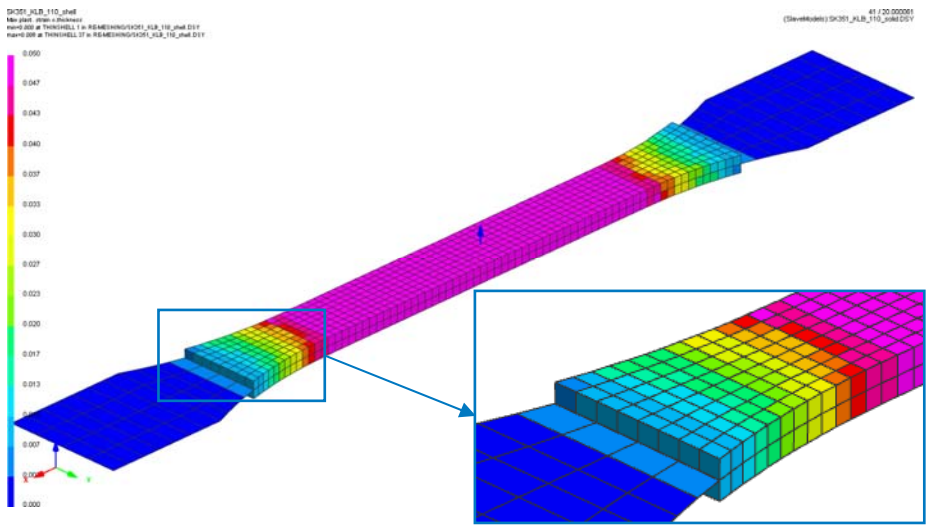


- Shell-Solid Remeshing
  - Based on multi-scale modeling technology
  - Rupture and failure modelling based on continuum mechanics approaches
  - Available in V2009 as first version

Global shell

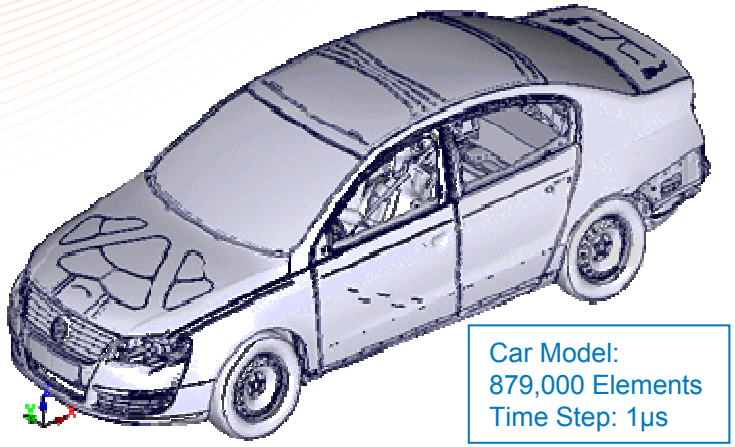


Local solid



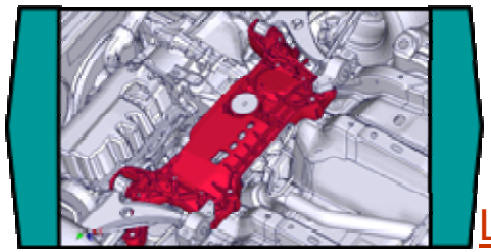
Multi-Model Coupling
Multi-Scale Modelling

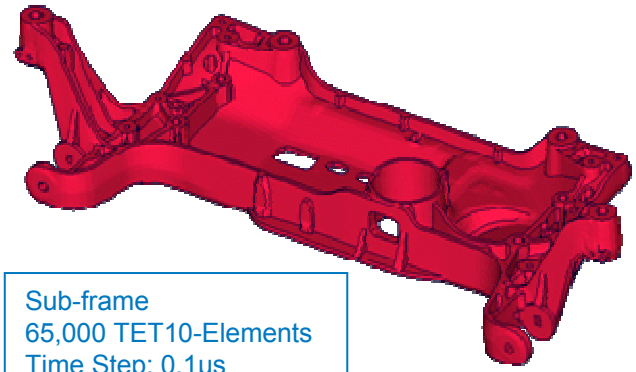
Application: ODB Front crash simulation
with sub frame failure prediction



Car Model:
879,000 Elements
Time Step: 1µs

Contact interface
Matching Grid connections

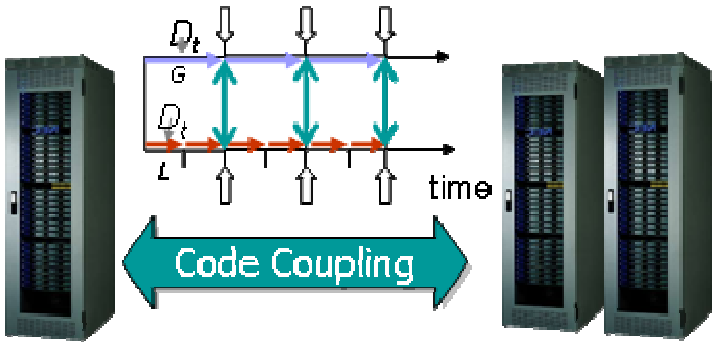


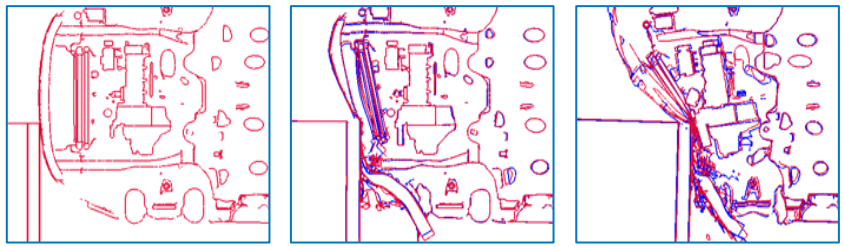


Sub-frame
65,000 TET10-Elements
Time Step: 0.1µs

Global Model:
complex, but large time step
E.g. BIW, Engine, Dummies, etc.

Local Model:
simple, but small time step
E.g. Cast sub-frame, B-Pillar. etc.





Crash duration

➔ **Similar deformations observed**

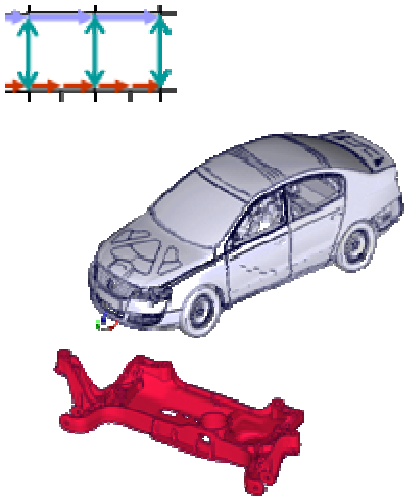
Multi-scale Modelling

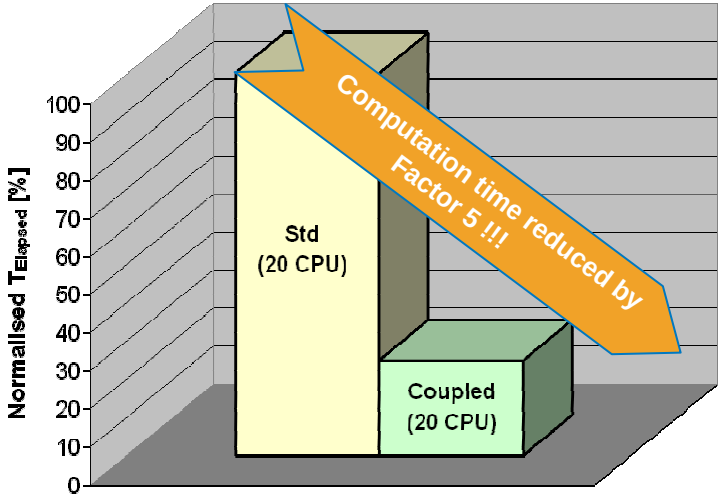
Multi-Model Coupling

- Ease-to-use since V2006
  - Single file
  - Independent numbering schemes for sub-models
  - without sub-cycling for car-to-car analysis

- Speed-up factors
  - between 3 up to 5+
    - Coupled front crash run (120ms) is completed after 22.5 hours
    - The same job without MMC would take 113.5 hours

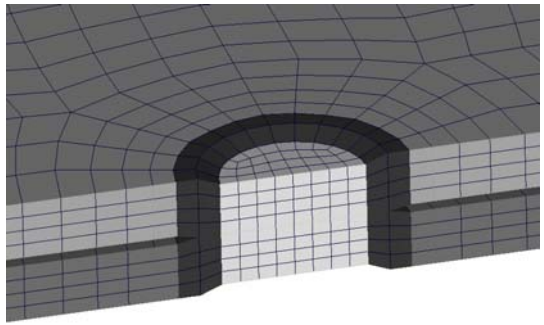
```
CPCTRL/
SUBCYCLE_ECL
END_CPCTRL
$
MODULE/     1
NAME x1
INCLU / file1.inc
END_MODULE
$
MODULE/     2
NAME x2
INCLU / file2.inc
END_MODULE
```



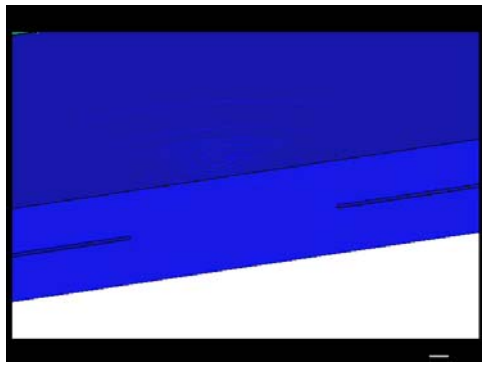


Spotweld modeling using Multi Model Coupling (MMC)

- Detailed 3D SOLID spotweld model
  - Possible to use rupture model and predict rupture mode
  - Possible to take into account different material properties



Cut spotweld model
Zones based on hardness test

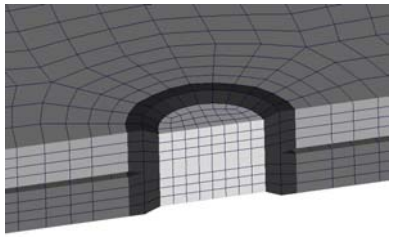


Rupture in traction test at
45 degrees (KS-II) – fine model

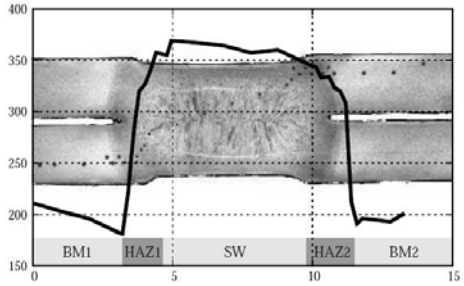
- Aim: use benefits of the detailed spotweld model in car structure using MMC (connect separated spotweld trough MMC to surrounding structure)

Spotweld modeling using MMC

- EWK rupture model with automatic parameter identifier is used
- Material properties across the spotweld - 2 options
  - Experimental:
    Daimler AG methodology for material identifying from the hardness test is used

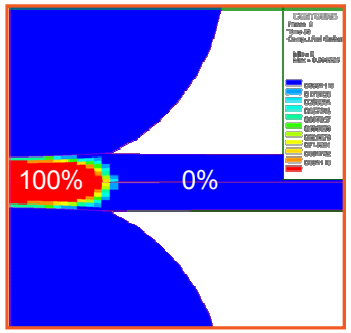


Cut of a spotweld

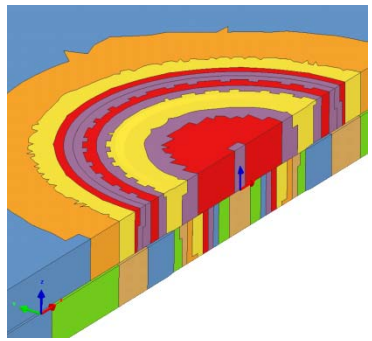


Vickers hardness test (Daimler AG)

  - Simulation-based mapping of SYSWELD results (phases, hardening)

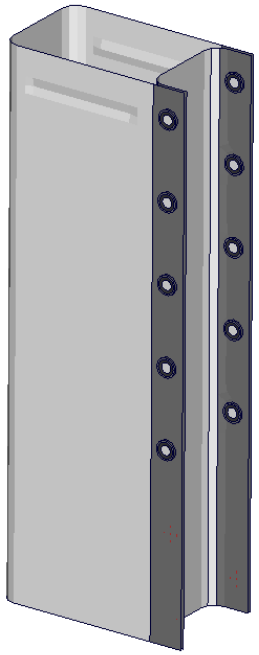


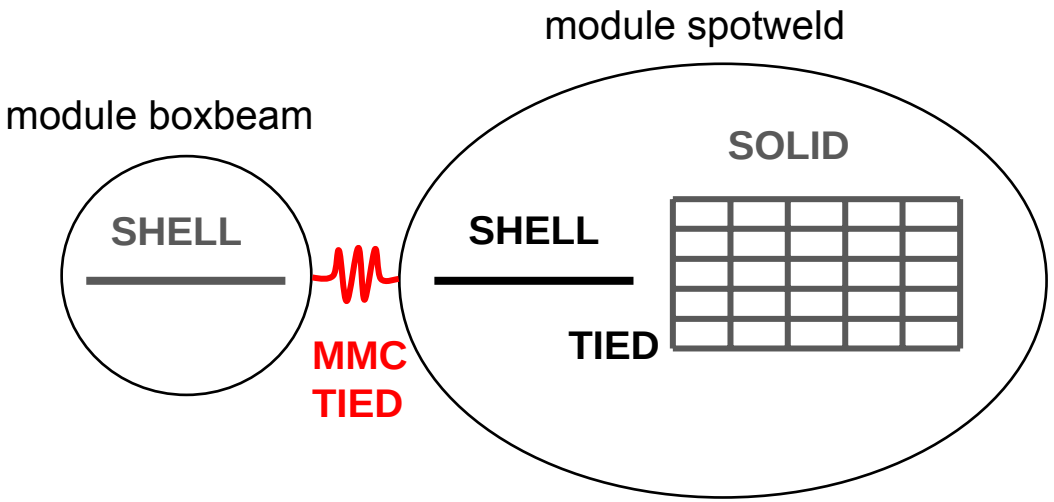
Martensite



Application on a boxbeam

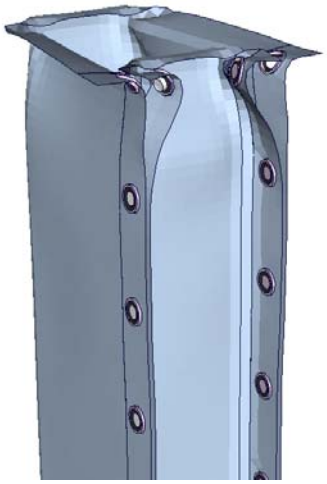
- Application on a boxbeam
  - First module contains boxbeam without flanges
  - Second module contains 10 detailed meshed SOLID spotwelds and boxbeam flange





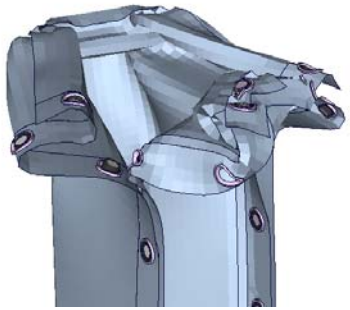
Application on a boxbeam

- Simulation results
  - Component disassembling
  - 6 ruptured spotwelds
  - Nugget pullout fracture mode

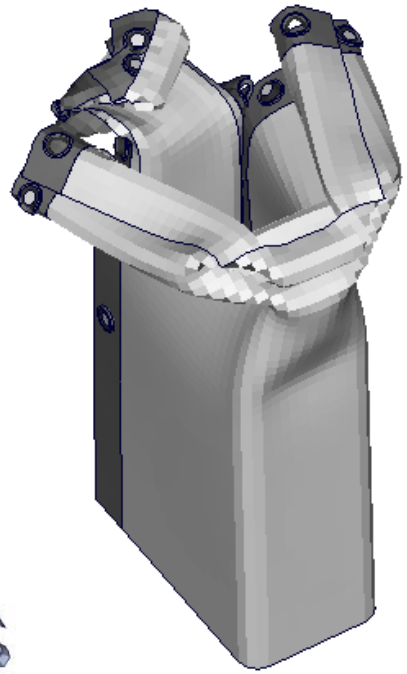


2 ms

4 ms



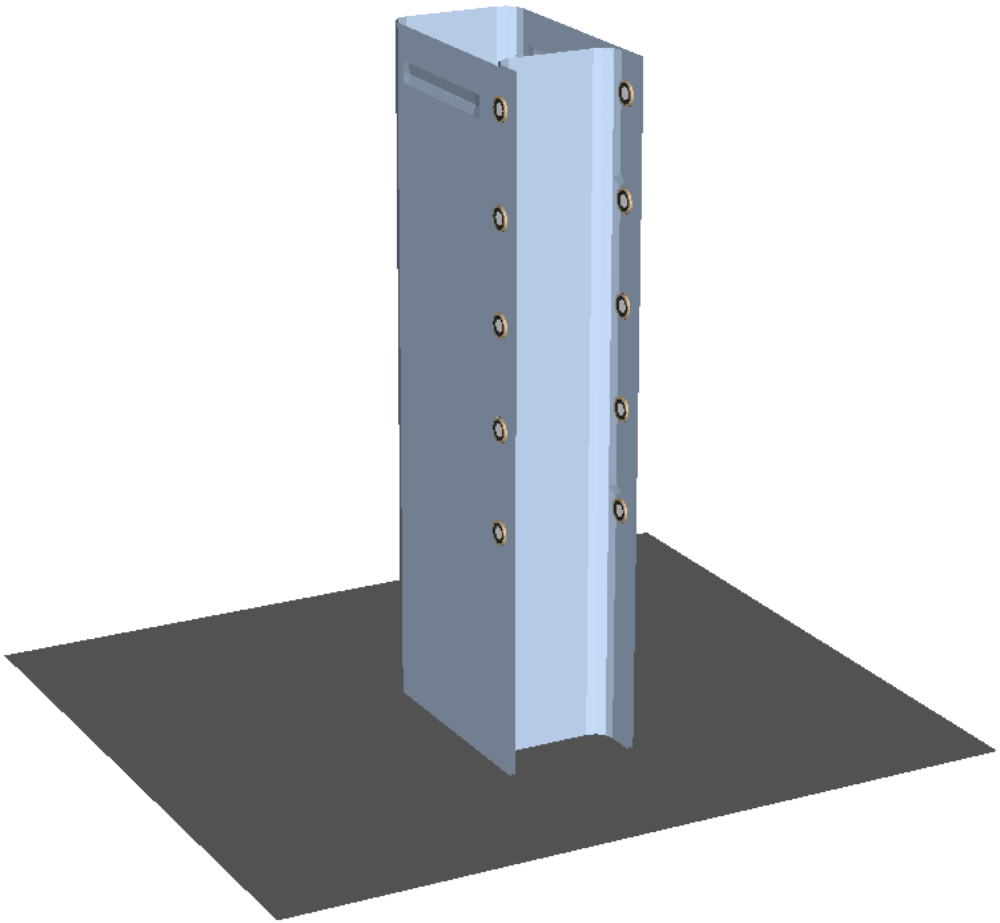
10 ms



final deformed shape

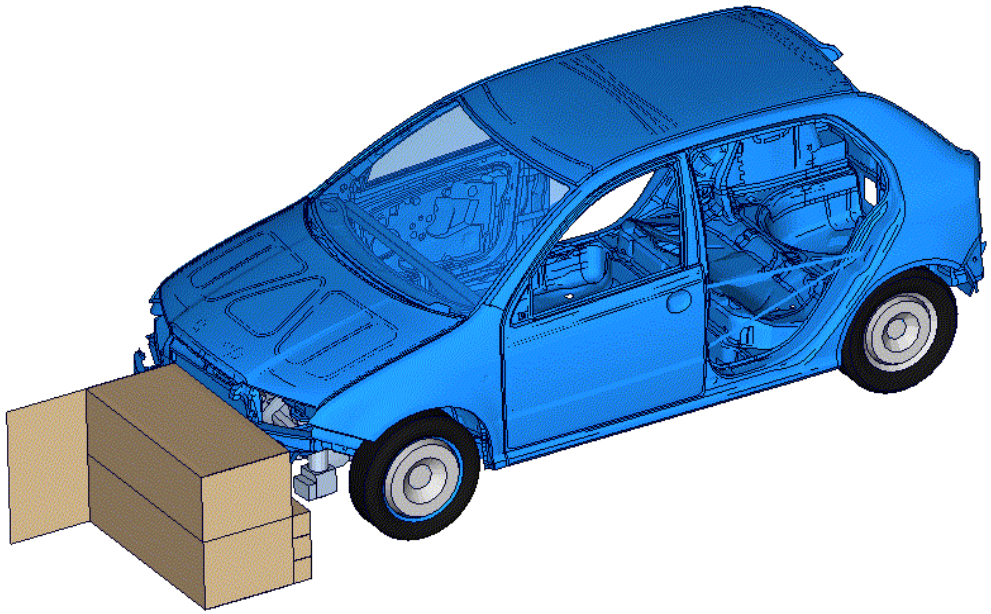
Application on a boxbeam

- Results animation



Full car model

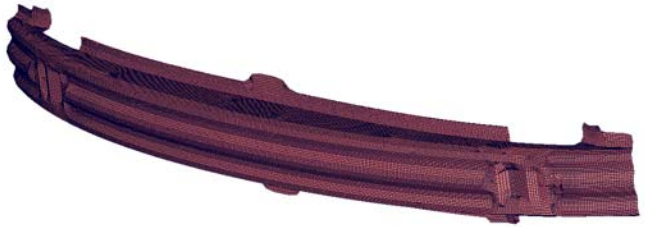
- Source model: SK240, released for educational use
- ~226 k elements
- Crash: frontal offset, 64 km/h

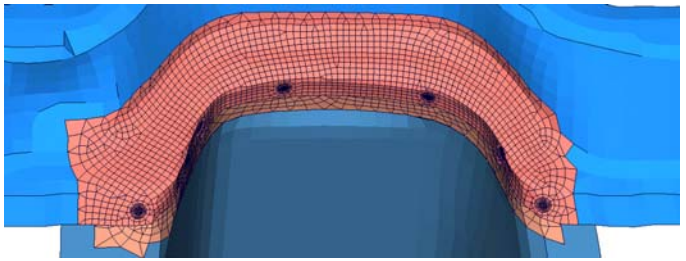


Full car model

Parts for detail simulation:

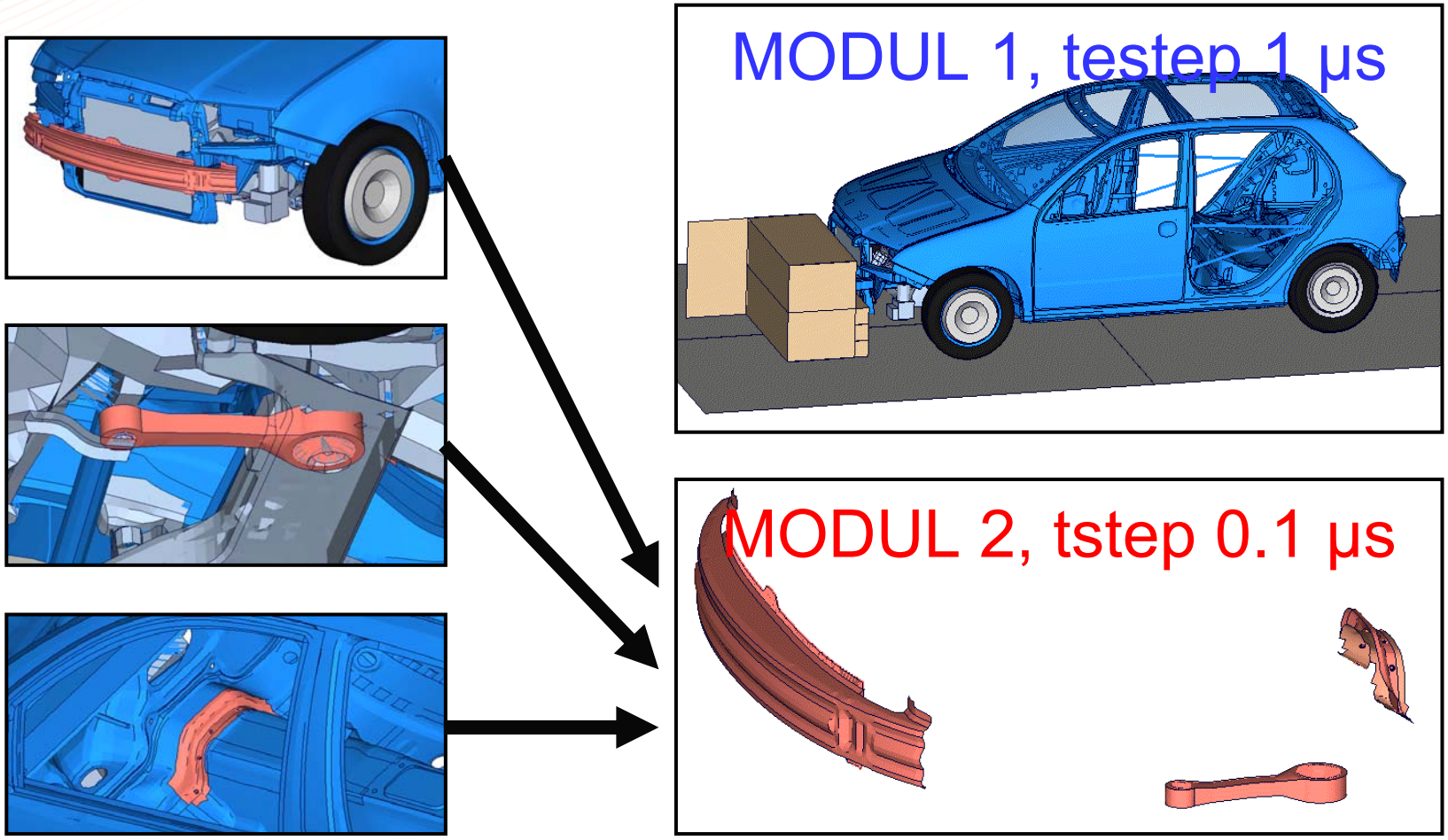
- Bumper reinforcement
  - Shells
  - 36 k elements
  - MAT 106
  - Failure: thinning
- Torque brace
  - Solids
  - 48 k elements
  - MAT 1
  - Failure: max. pl. deformation
- Tunnel flange with line of welds
  - trial weld methodolody
  - 9 k elements





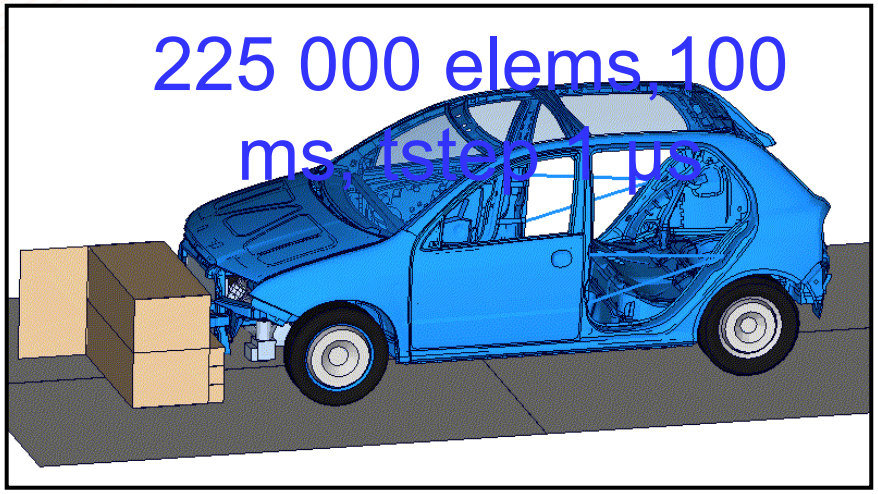
Full car model

Detail parts share one modul with common time step:



Full car model

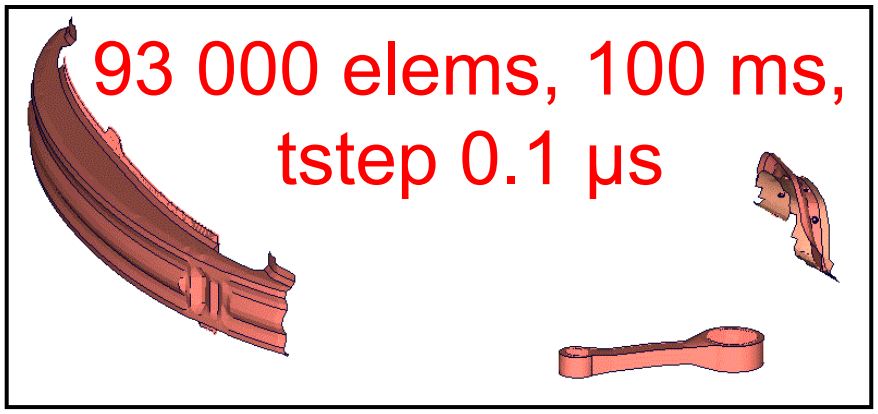
Processors distribution: given **total 8 CPU**



225.000 elements × 100.000 cycles

= 22.5 bil. element-operations

22.5/(22.5+93)*8=1.6 ≈ 2 CPU



93.000 elements × 1.000.000 cycles

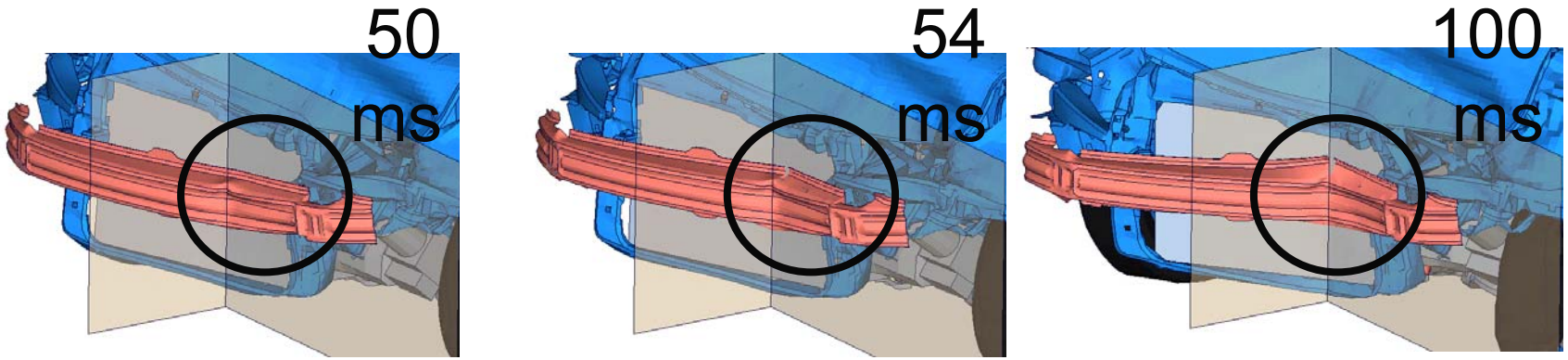
= 93 bil. element-operations

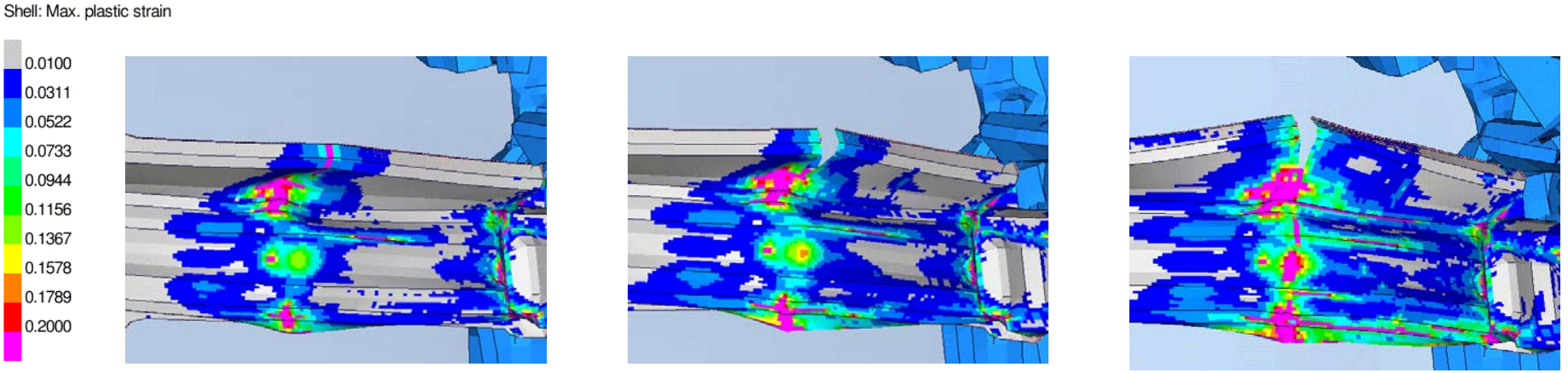
6.4 ≈ 6 CPU

Results: bumper reinforcement

Results: Bumper reinforcement

- Failure after contact with rigid part of barrier, 51 ms



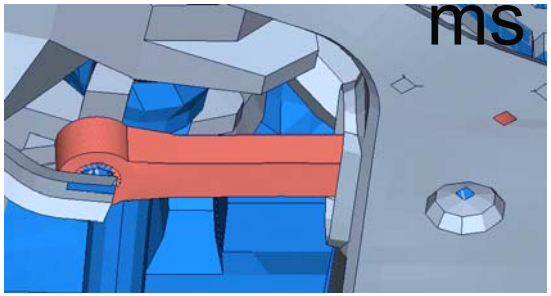


Results: torque brace

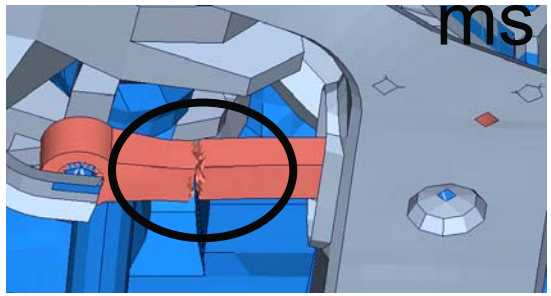
Results: Torque brace

- failure time: 54 ms

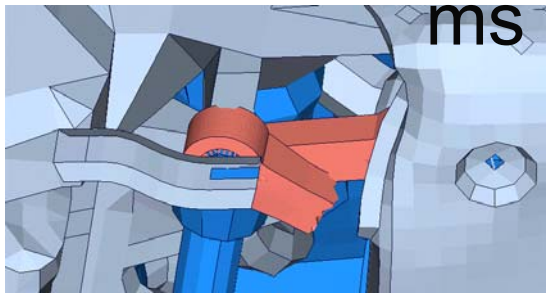
50 ms



54 ms

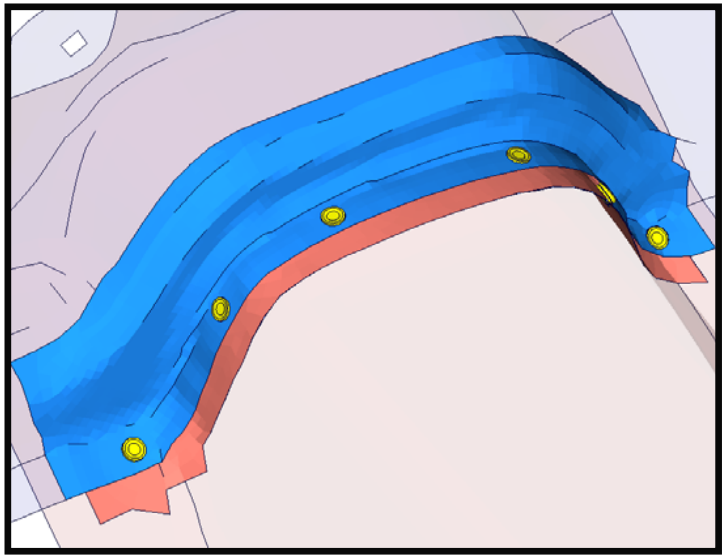


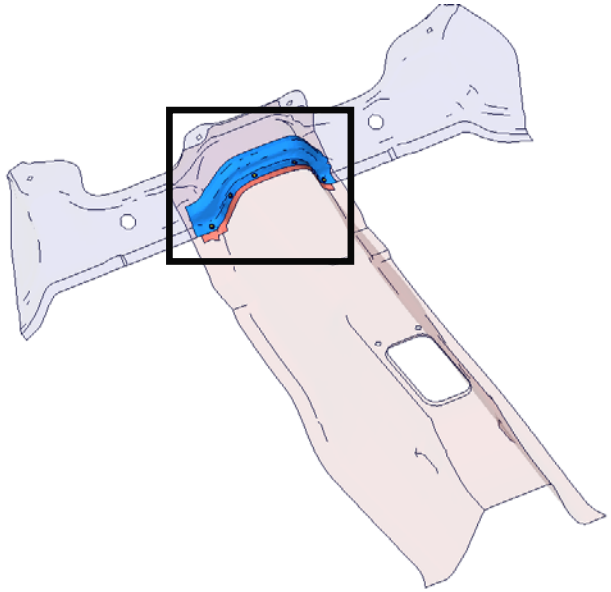
100 ms



Results: spotwelds

- Model definition
  - tunnel - firewall connection is realized trough 6 detailed solid spot welds
  - module 2 contains except spot welds also part of tunnel and firewall

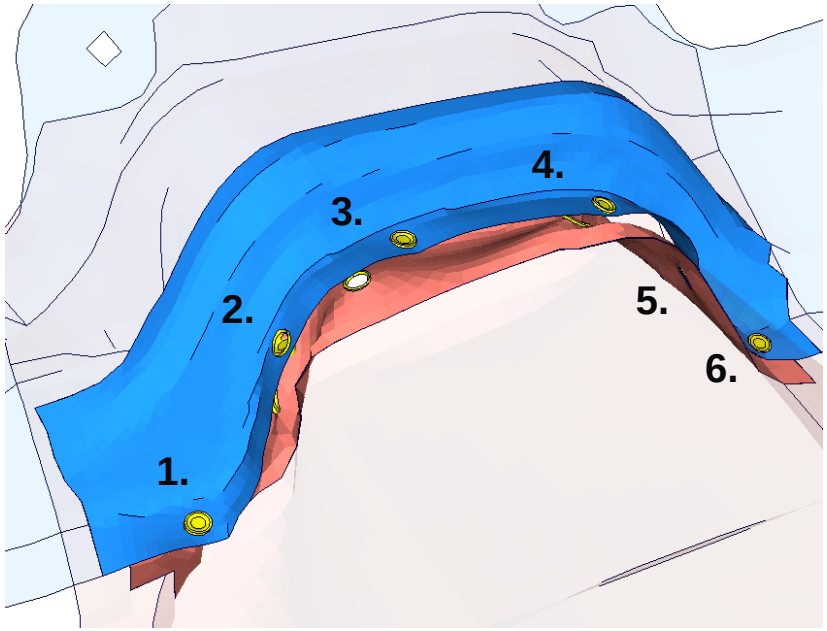




Results: spotwelds

- Results
  - One partial damaged spot weld, three ruptured, two without damage

spw	def. mode	max. force [kN]	time in max [ms]
1.	part. failure	10.9	64
2.	fails	15.0	67
3.	fails	12.3	70
4.	fails	13.8	76
5.	OK	10.3	66
6.	OK	9.7	71

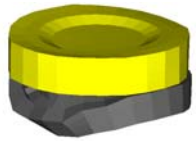


tunnel-firewall connection 100 ms

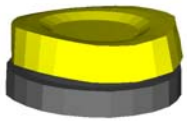
Results: spotwelds

- Forces in spotwelds

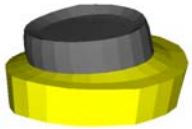
partial damage

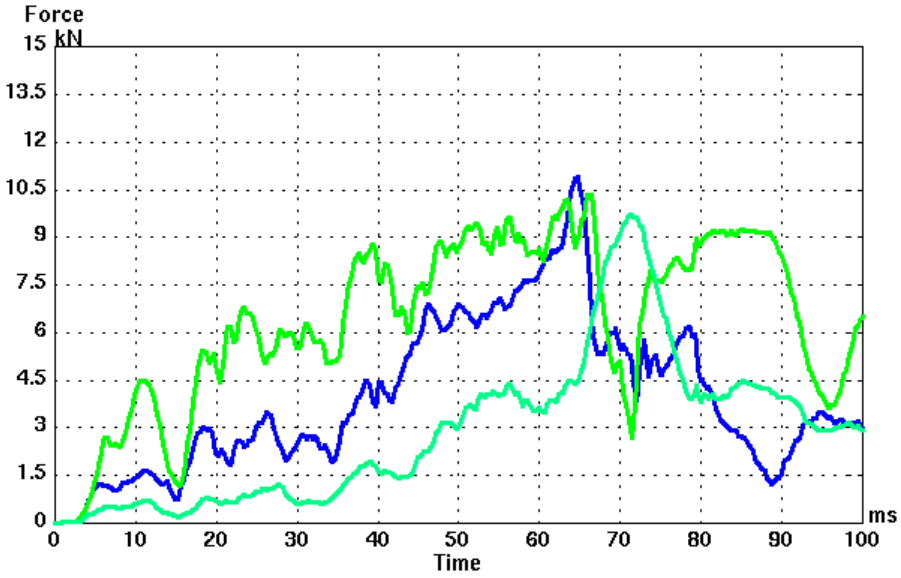


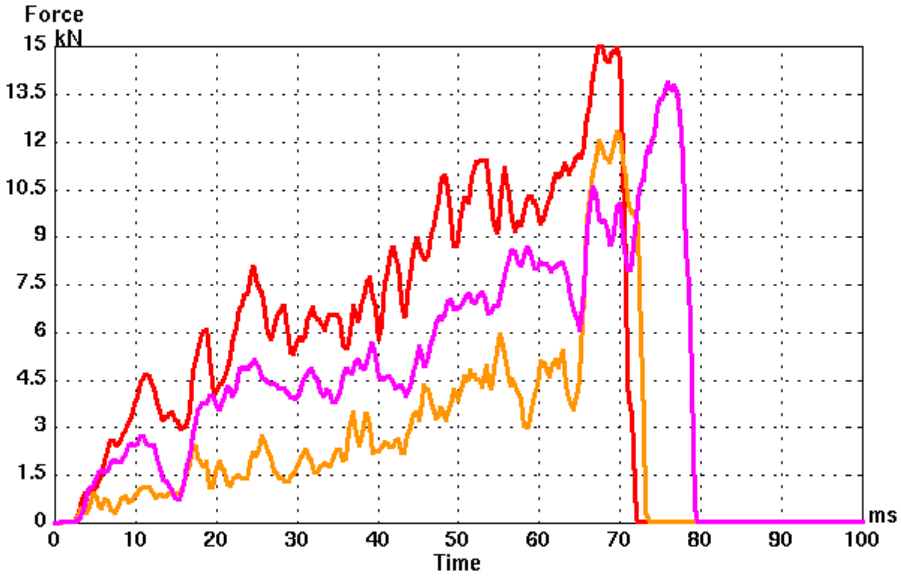
OK



total damage







Results: elapsed time

- MMC run:
  12.5 h on 8 CPU

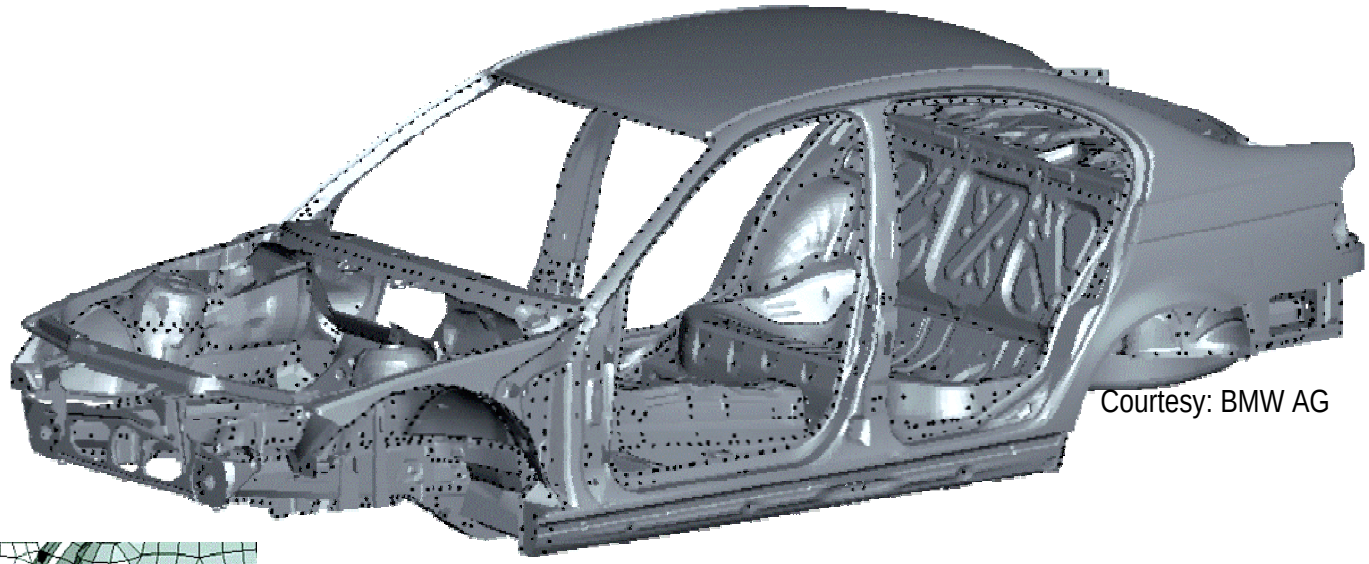
- Estimation for run without MMC
  (based on no. of elements, cycles)

  12.5 h * (22.5+93)/(225+93) = **34 h**

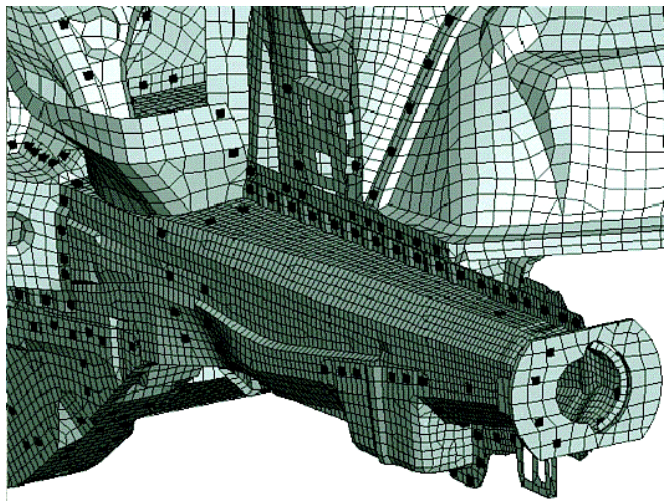
- **Estimated speed-up: 2.7**

get it right™

HPC challenge for End to End Virtual Prototyping



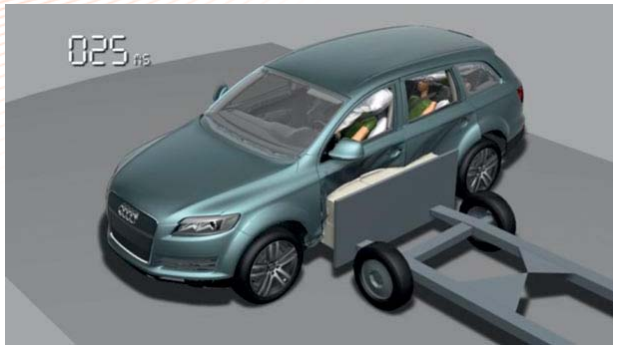
Courtesy: BMW AG

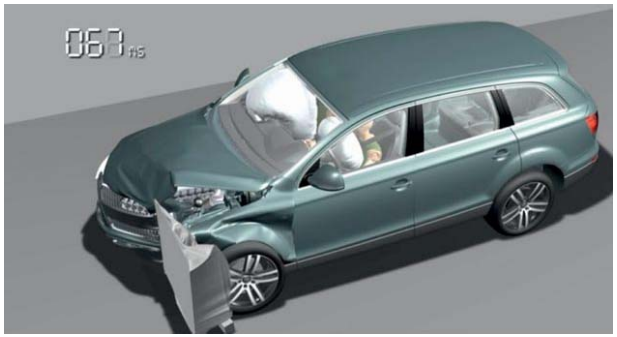


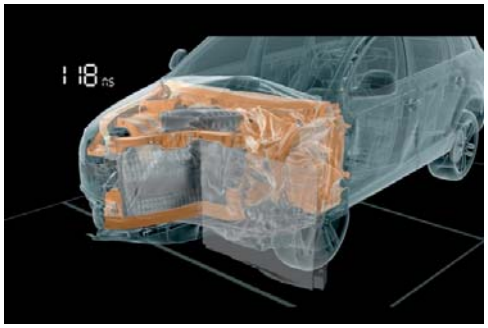
Bringing 6000 Spotwelds into a Car Body Model

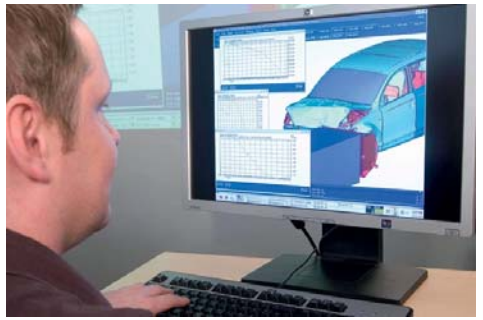
Industry Adoption & Benefits

Virtual Performance Solution deployment at Volkswagen Group









*"With this further development of the software suite, ESI Group has achieved a **quantum leap** in the field of simulations. By being able to utilise a unique mathematical model for both, crash and load testing, we're improving our development efficiency at several stages of a project. Given the ever-shortening development cycles in the automobile sector, this gives us a **decisive competitive edge**."*

***Dr. Ralph Sundermeier**, Head of Functional Calculation and Methods at Volkswagen*

Building up Virtual Prototyping
An integrated solution
at Volkswagen Group

Status: Crash/NVH test simulations:

VOLKSWAGEN

Simulationssoftware im Karosseriebau Einsatzgebiet

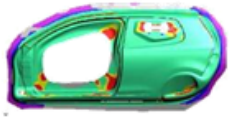
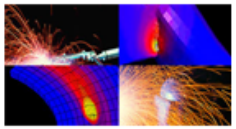
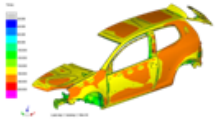
Stand: 15.09.2008

K-P KONZERN-PRODUKTION

K-PPI-T | Sebastian Pinner | Tel.

VOLKSWAGEN

Simulationssoftware im Karosseriebau


Umformen	Fügen	Lack	Crash
▪ Pam-Stamp ▪ AutoForm ▪ Indeed ▪ LS-DYNA	▪ Sorpas (WPS) ▪ Pam-Stamp (Rollfalzen) ▪ Schweißplaner ▪ SIMUFACT (Test) ▪ SYSWELD	▪ Pilotprojekt mit VirtualPaintShop (VPS)	▪ Pam-Crash

K-P KONZERN-PRODUKTION

K-PPI-T | Sebastian Pinner | Tel.: 86573 | Stand: 15.09.2008 | Seite 2

connected via UGS/TeamCenter & ESI/Visual-Process

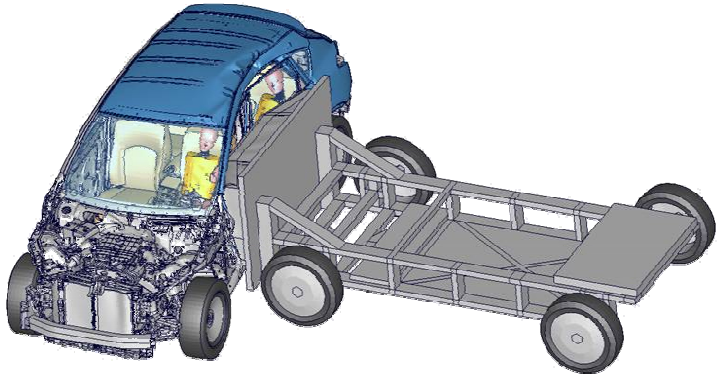
Building up Virtual Prototyping for Innovation & performance at Nissan

"Using ESI's Virtual Performance Solution, we were able to meet the targeted performance in our design.

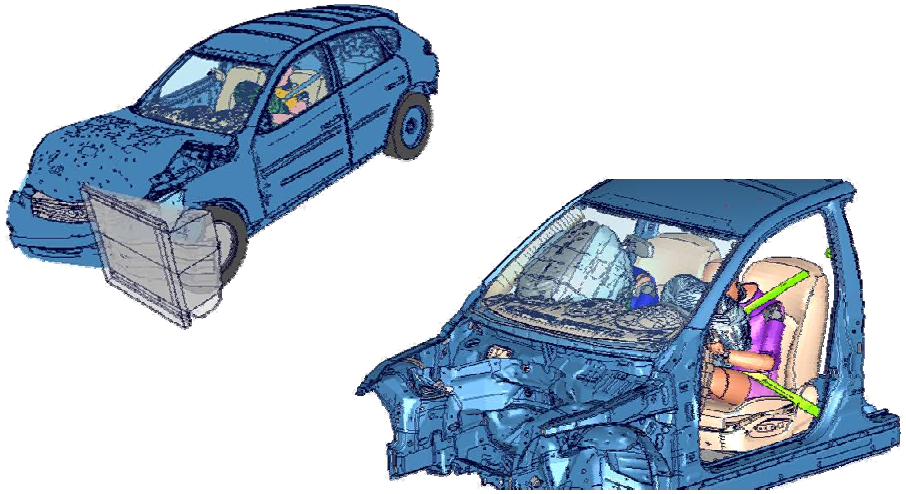
*We had **very accurate results** especially in the assessment of structural failure scenarios in crash conditions using ESI's (EWK) damage and rupture model.*

*ESI Group supports our product **innovation** by offering an all-inclusive scalable simulation solution: Virtual Performance Solution allows cost and time savings in our Product Development Cycle".*

***Kazuhiro OBAYASHI**, Integrated CAE Department Manager at NISSAN MOTOR CO. LTD.*



Side impact, Courtesy of NISSAN MOTOR CO. LTD



Frontal impact, Courtesy of NISSAN MOTOR CO. LTD

Building up Virtual Prototyping for Vibro-Acoustics in Space industry at NASA

*"**The** VA One **combined tools provide an efficient analysis environment** when performing **full spectrum** analysis to support space shuttle and International Space Station requirements."*

Ed O'Keefe, Associate Technical Fellow.
Boeing Integrated Defense

VA One

as a **preferred tool for the Moon, Mars and Beyond program**

*"VA One is **intuitive and straightforward to use**. I was able to complete a detailed coupled Boundary Element analysis the first time that I used the code"*

Jeffrey Larko, Aerospace Engineer Structural Dynamics,
NASA GLENN Research Center

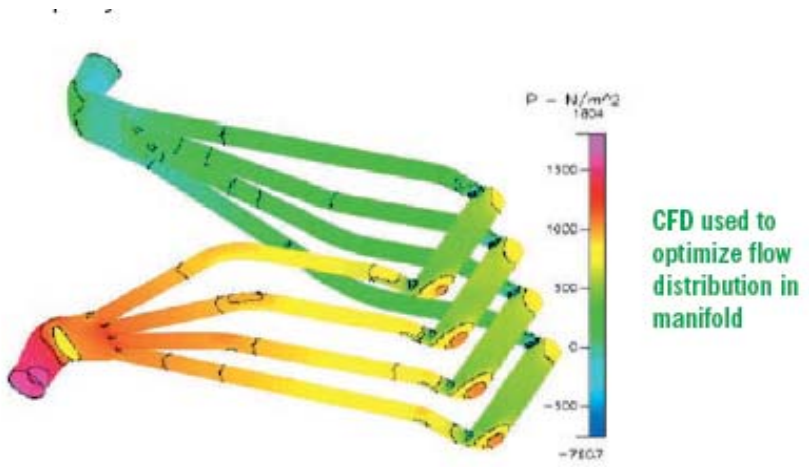
Building up Virtual Prototyping for Micro-mechanical simulation in Energy

Reactive Fluid/Flow simulation improves design and reliability of fuel cells

BALLARD®

" Simulation has helped us to significantly ***increase the efficiency*** *and life of proton exchange fuel cells (PEMFCs) by reducing variations in flow between the individual cells, and within individual cells."*

Sanjiv Kumar
Ballard Power Systems
Burnaby, British Columba



CFD used to optimize flow distribution in manifold

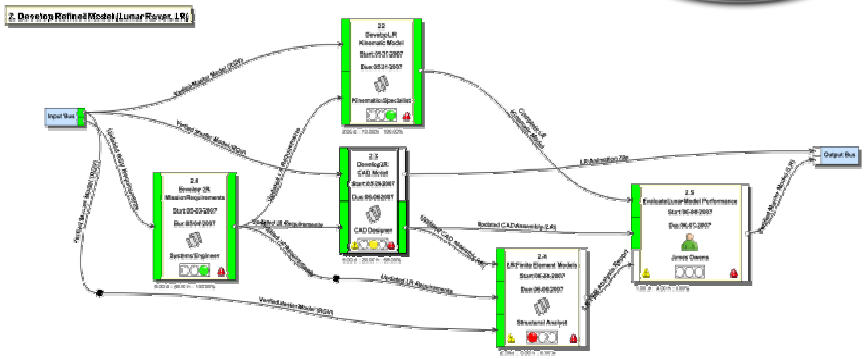
CFD-ACE+

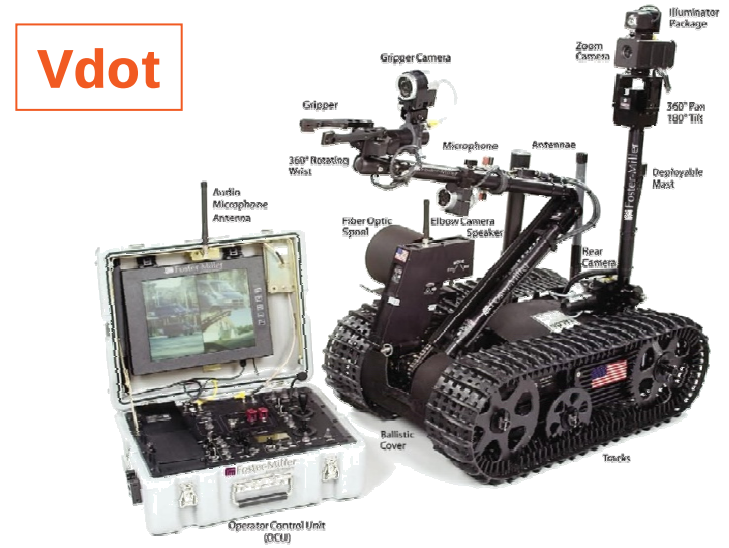
Building up Virtual Prototyping for Lean project/process management at NASA

Vdot @ NASA and Qualis Corporation improves performance on Rover robotics study

*"Vdot supports management's ability to **quickly assess problem** areas and **greatly reduces the uncertainty** of who is directly responsible for work accomplished at any point in the project life cycle. Vdot was **invaluable in managing** a development project with a very distributed engineering team, spread across several disciplines and development tools"*

Roger Herdy
Qualis Corporation, Program Manager
NASA Marshall Space Flight Center





End-to-End Virtual Prototyping in Automotive

Car Body

Hood Design

illustration

The Challenge

Materials

Mild Steel
IF Steel
High Strength Steel
BH Steel
DP Steel
TRIP Steel
Hot Forming Steel
Sandwich Material

Product Performance

Weight
Quality
Part Cost
Assembly Cost
Rigidity
Durability
NVH
Corrosion
Recycling

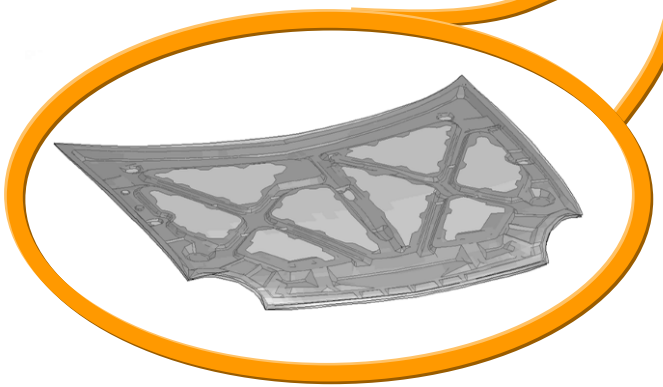
Manufacturing Process

Deep Drawing
Roll-Forming
Hydro-Forming
Resistance Spotwelding
Arc Welding
Laser Welding
Weld Bonding
Adhesive Bonding
Mechanical Joining
Tailored Blanking
Thin Wall Casting

Market problem

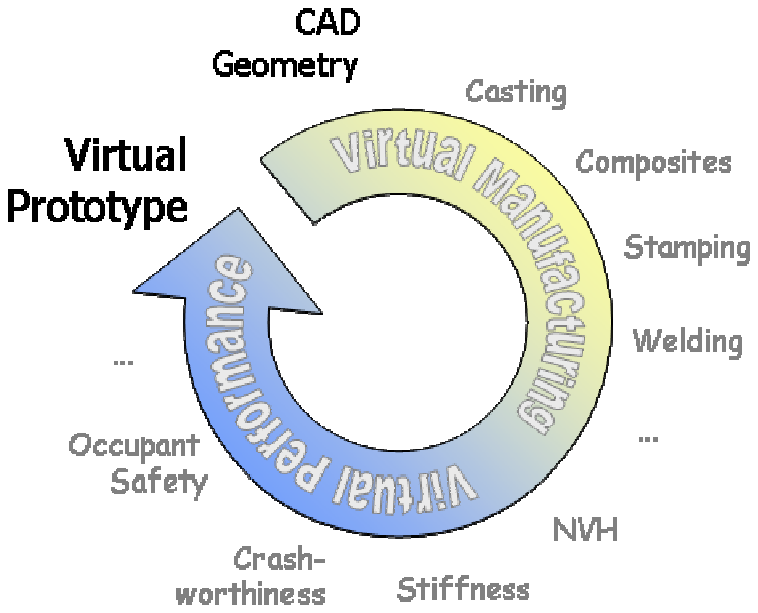
Objective: Weight reduction
(∑Component weight reduction)

Full car model



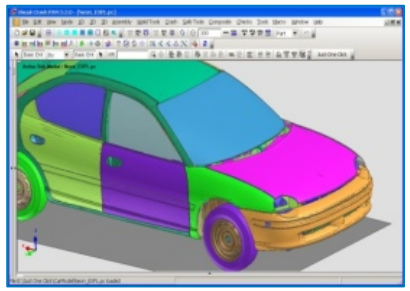
Component model

Constraints



End-to-End Auto-Body Solution
Example: Front Hood

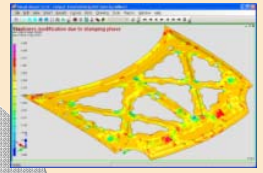
CAD* based Model



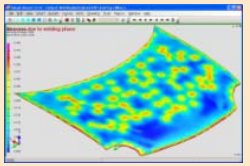
Virtual Prototype

Virtual Manufacturing

Optimization Loops



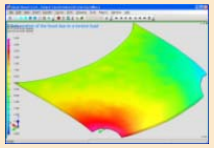
Stamping



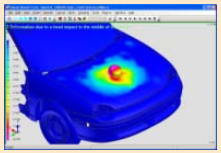
Welding

Virtual Performance

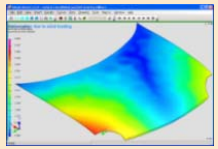
Optimization Loops



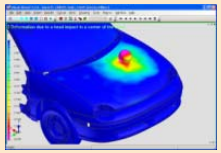
Stiffness *Torsion*



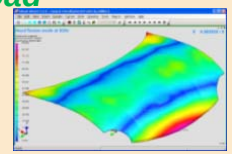
Head impact 1



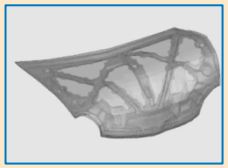
Stiffness *Wind load*



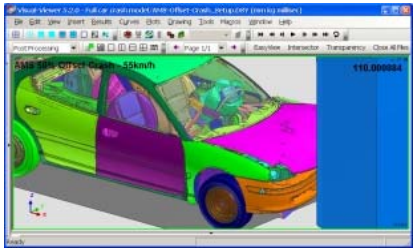
Head impact 2



NVH *Eigen modes*



Hood crash

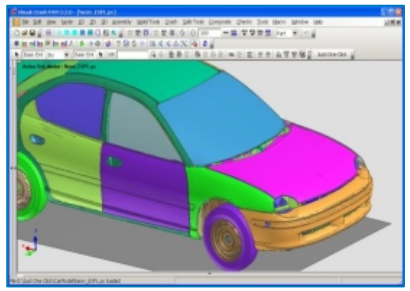


Full car crash

*CAD: Computer-Aided Design

End-to-End Auto-Body Solution
Example: Front Hood

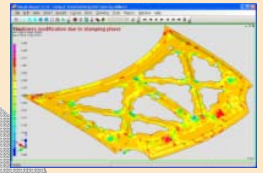
CAD* based Model



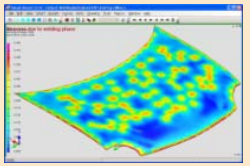
Virtual Prototype

Virtual Manufacturing

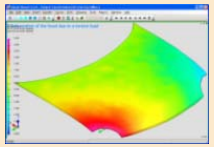
Optimization Loops



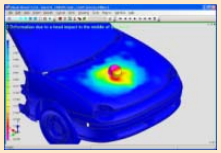
Stamping



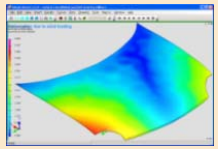
Welding



Stiffness *Torsion*



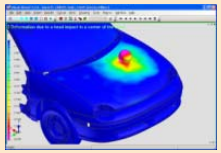
Head impact 1



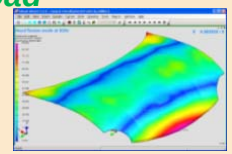
Stiffness *Wind load*

Virtual Performance

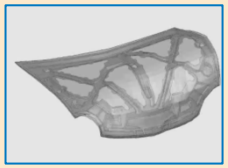
Optimization Loops



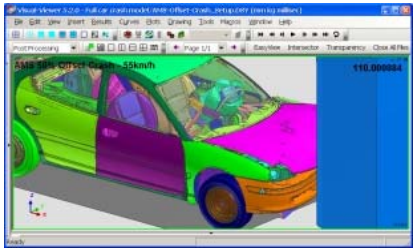
Head impact 2



NVH *Eigen modes*



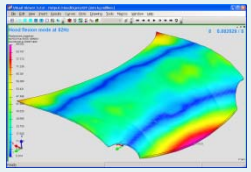
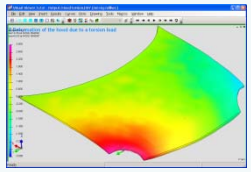
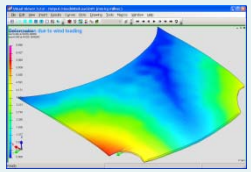
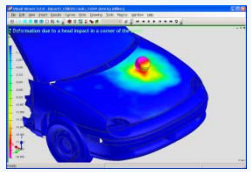
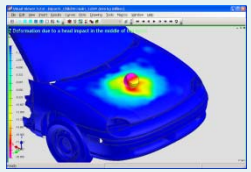
Hood crash



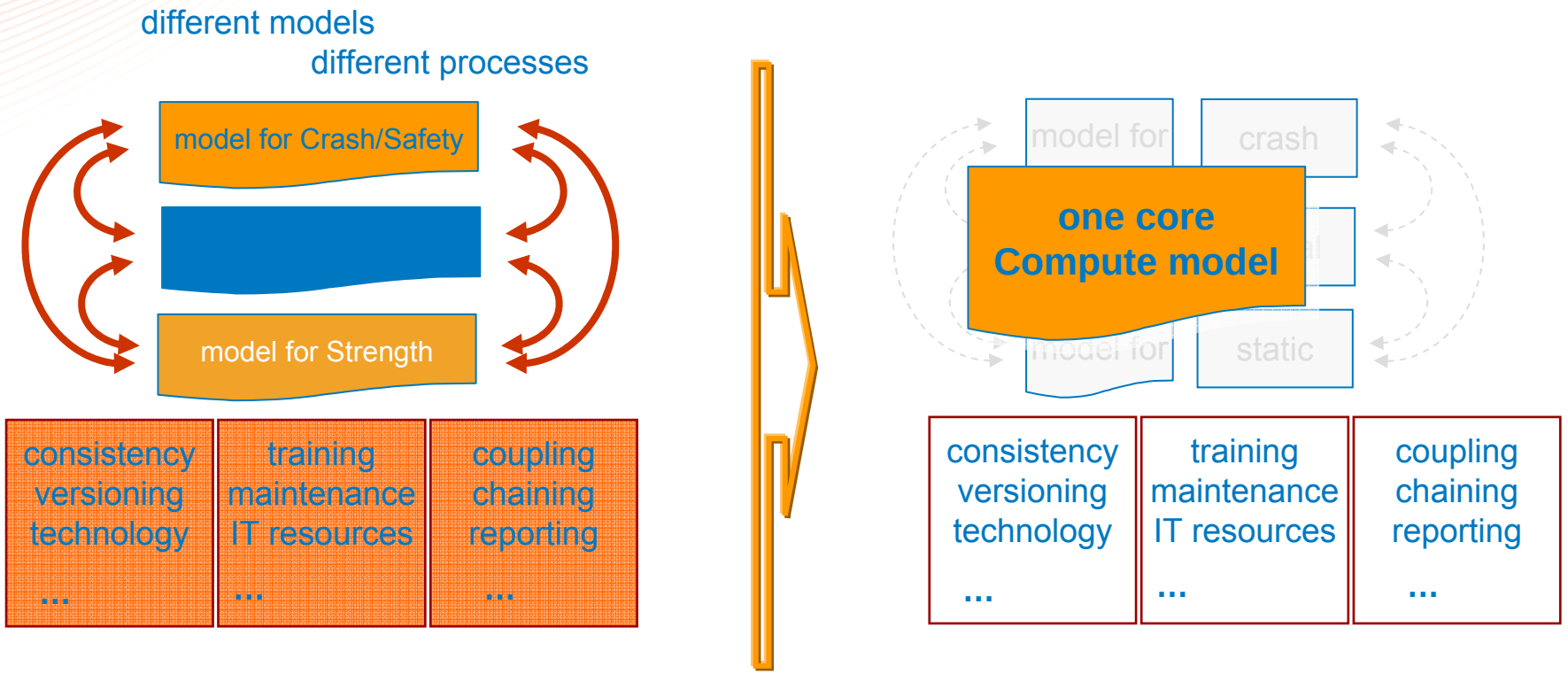
Full car crash

*CAD: Computer-Aided Design

Influence of manufacturing on performance testing

		With manufacturing effects		Without manufacturing effects		
	Eigen modes 	Torsion at Flexion at Next at	42.9 Hz 81.9 Hz 89.3 Hz	Torsion at Flexion at Next at	42.2 Hz 81.4 Hz 89.8 Hz	→
~ 35% ⇨	Torsion 	Min ΔZ Max ΔZ	-2.38mm +3.67mm	Min ΔZ Max ΔZ	-1.77mm +2.33mm	↘
	Wind load 	Min ΔZ Max ΔZ	-5.66mm +3.91mm	Min ΔZ Max ΔZ	-5.93mm +3.92mm	→
~ 5% ⇨	Head impact 1 	HIC =	1688	HIC =	1603	↘
~ 5% ⇨	Head impact 2 	HIC =	1652	HIC =	1737	↗

End-to-End Virtual Prototyping Benefits



"Control, Adapt and Transport" *the compute model across Domains*

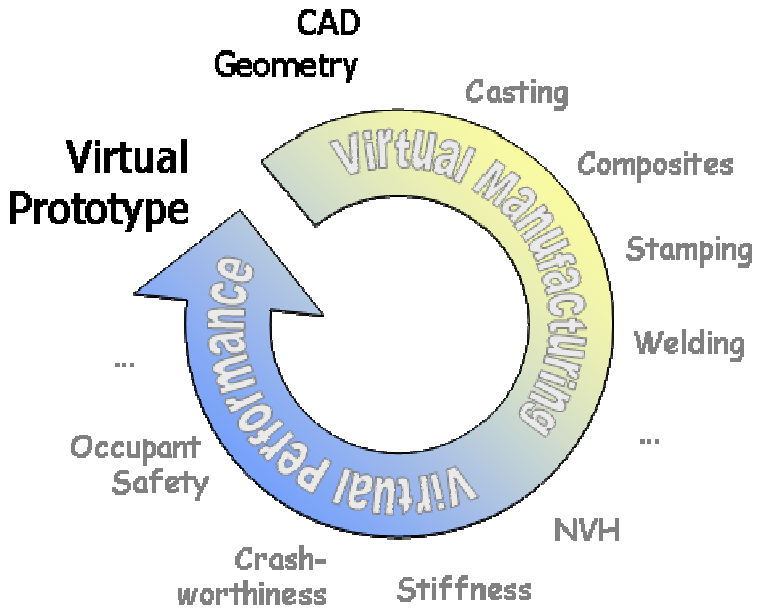
➔ *Efficient support for design variation and engineering changes*

Design variation

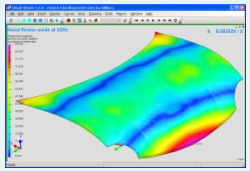
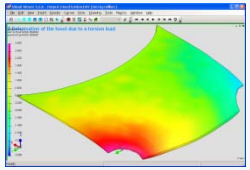
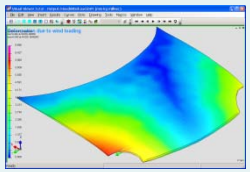
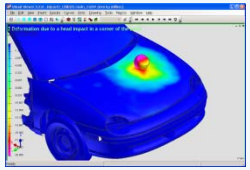
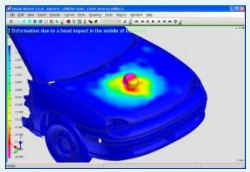
Hood weight : 21.8 Kg

Weight reduction target ~ 20 %
Material change for inner part : **Steel → AL**

with a single click
re-run the whole simulation

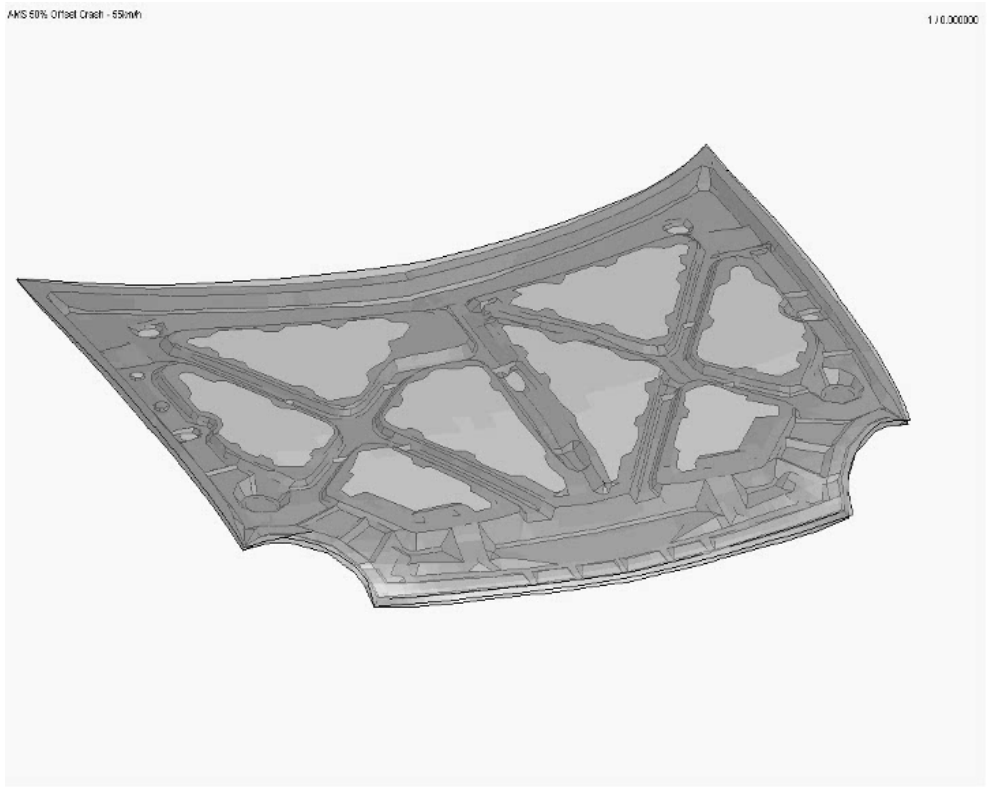


Influence of hood material on performance testing

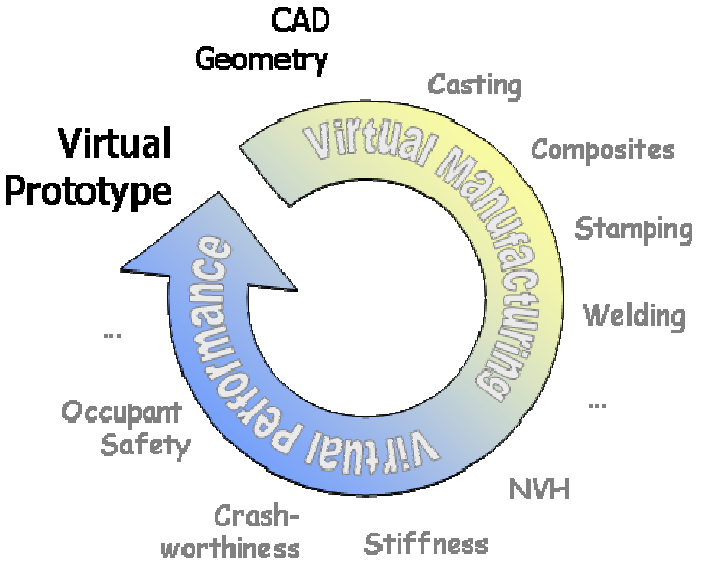
	Steel hood (21.8 kg)	Aluminium hood (15.4 kg)
Eigen modes	 Torsion at 42.9 Hz Flexion at 81.9 Hz Next at 89.3 Hz	Torsion at 35.5 Hz Flexion at 70.5 Hz Next at 75.1 Hz
Torsion	 Min ΔZ -2.38mm Max ΔZ +3.67mm	Min ΔZ -4.79mm Max ΔZ +9.19mm
Wind load	 Min ΔZ -5.66mm Max ΔZ +3.91mm	Min ΔZ -12.45mm Max ΔZ +9.44mm
Head impact 1	 HIC = 1688	HIC = 1104
Head impact 2	 HIC = 1652	HIC = 1312

Multi-Domain optimization

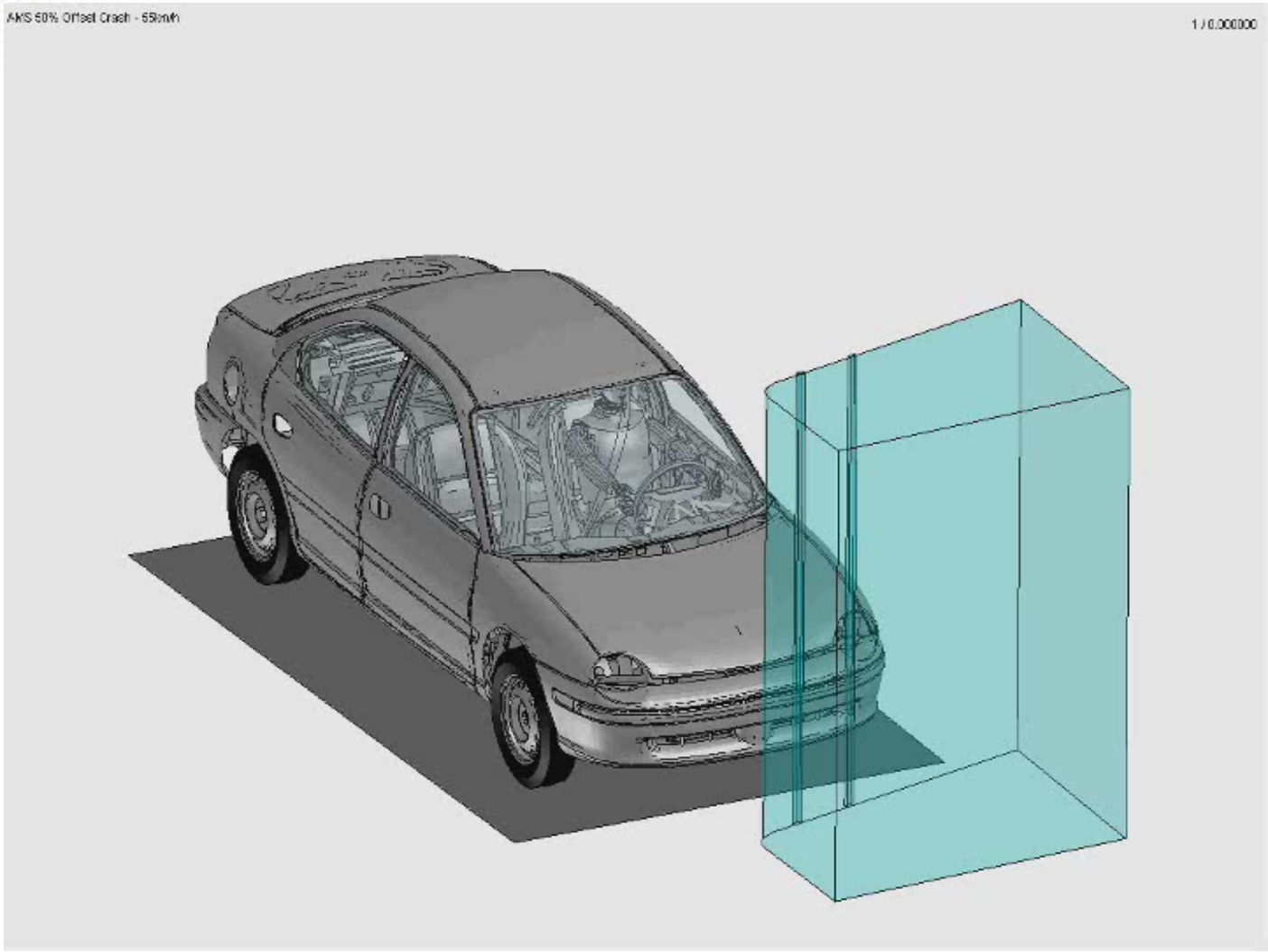
- Weight reduction ~20 %
- Design constrains



Hood crash

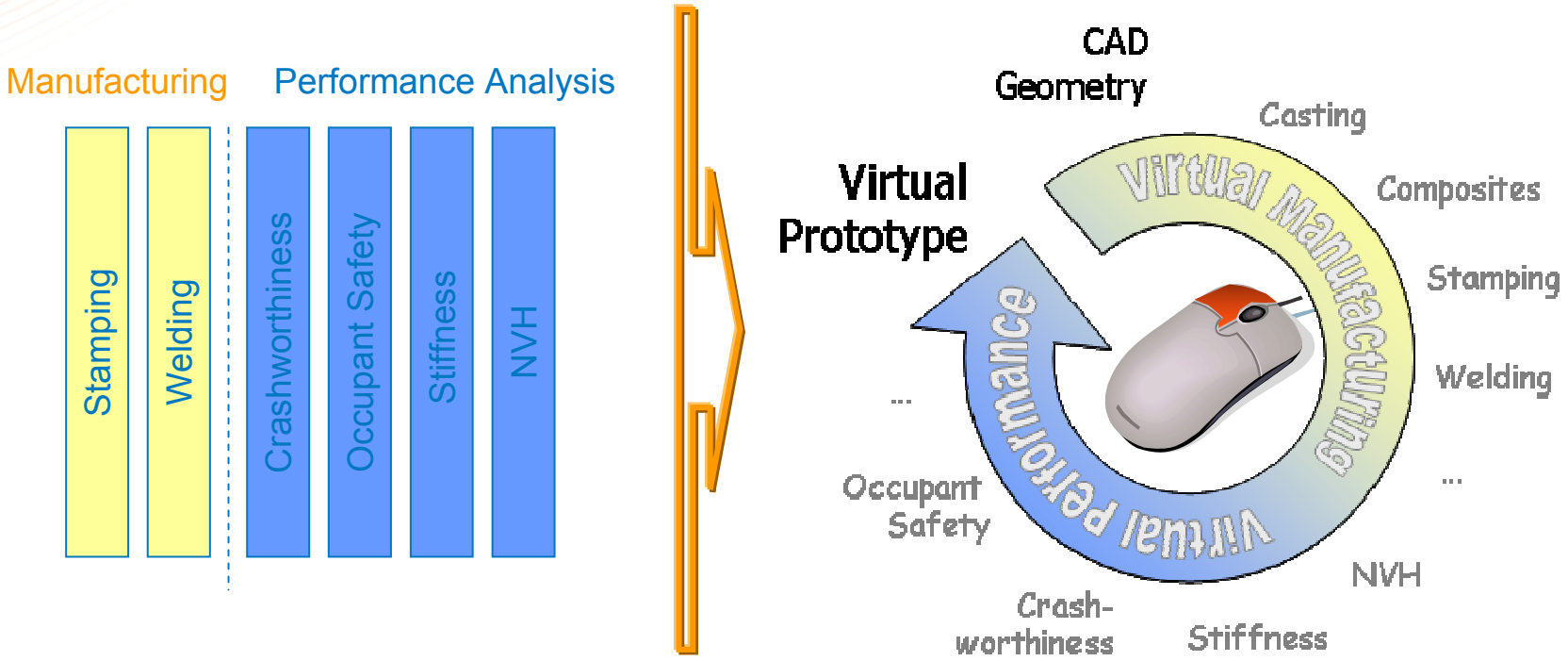


From Component to Full Car Crash Simulation



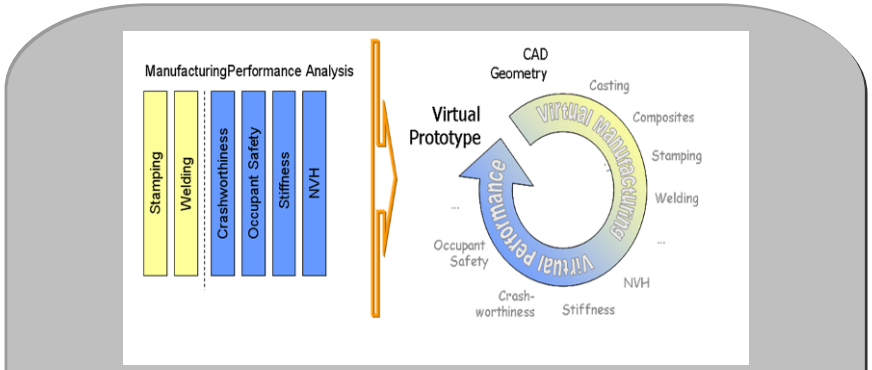
End-to-End Virtual Prototyping

A concurrent component development & multi-domain collaborative solution

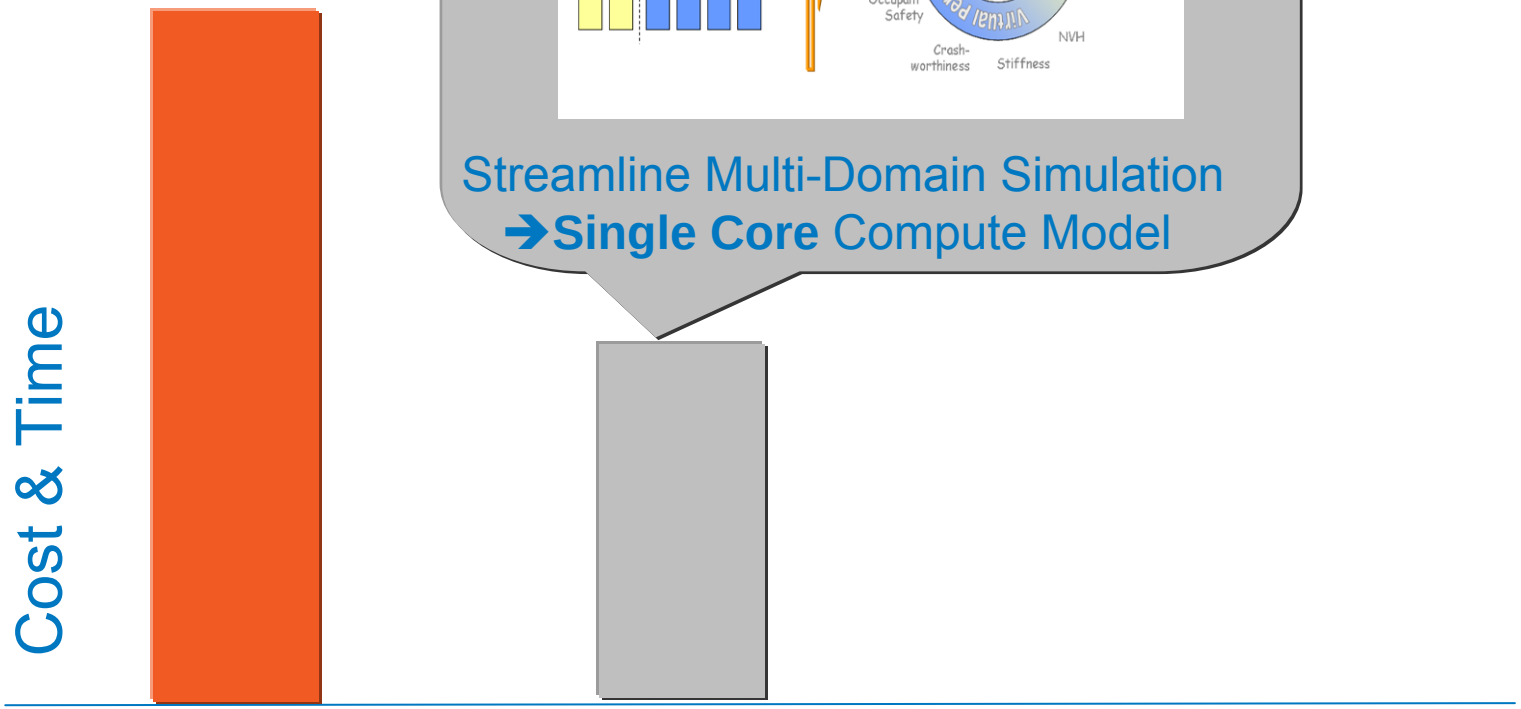


Design variations & engineering changes
➔ Update each step with just 1 click

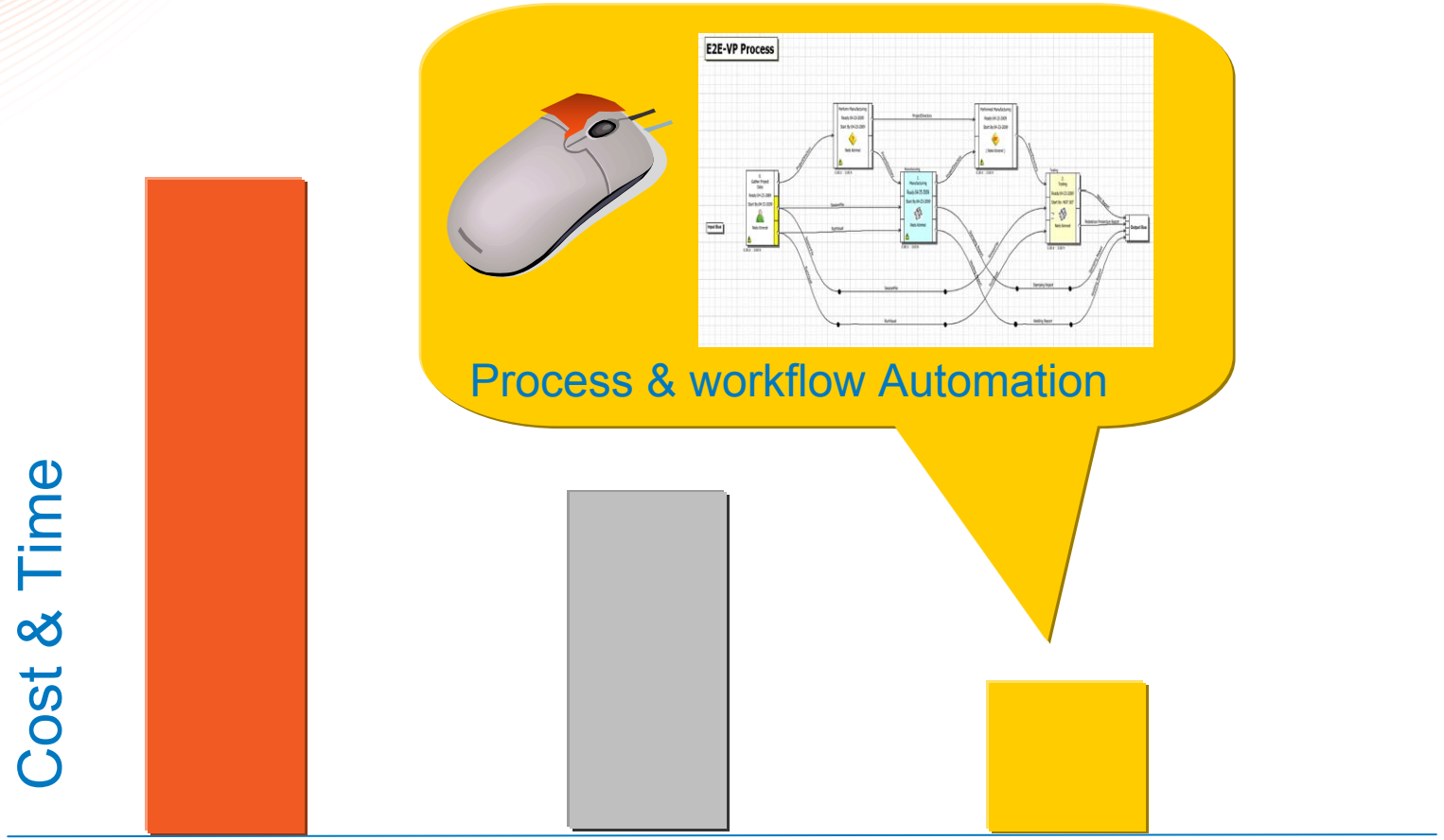
End-to-End Virtual Prototyping Benefits



Streamline Multi-Domain Simulation
➔**Single Core** Compute Model



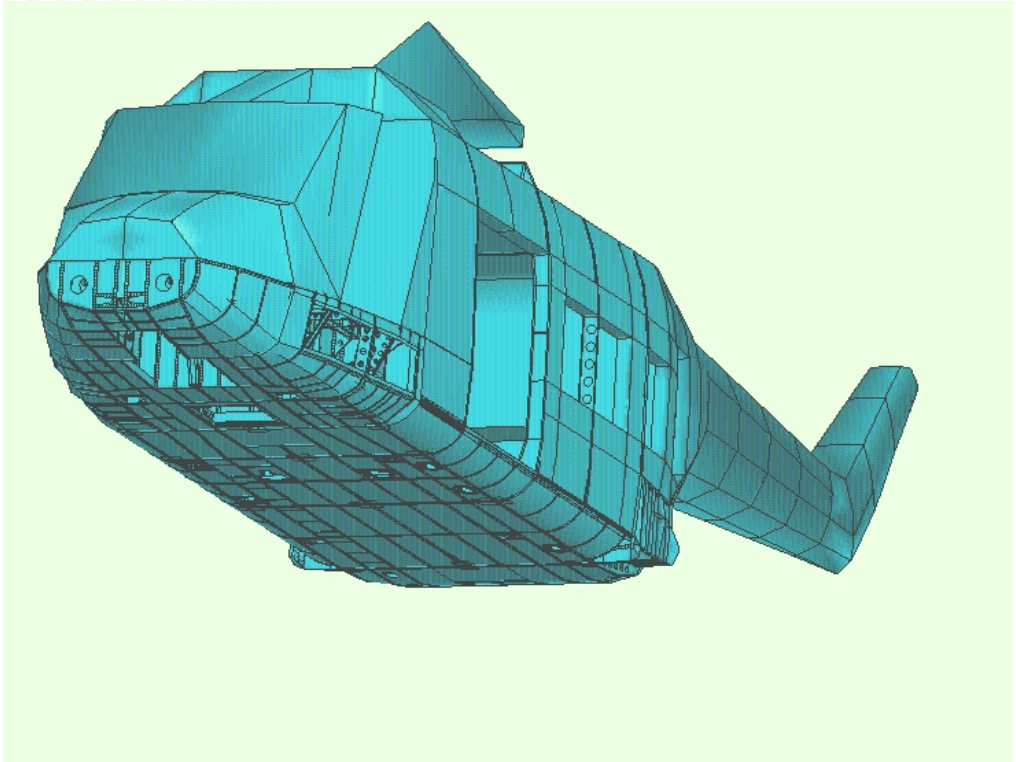
End-to-End Virtual Prototyping Benefits

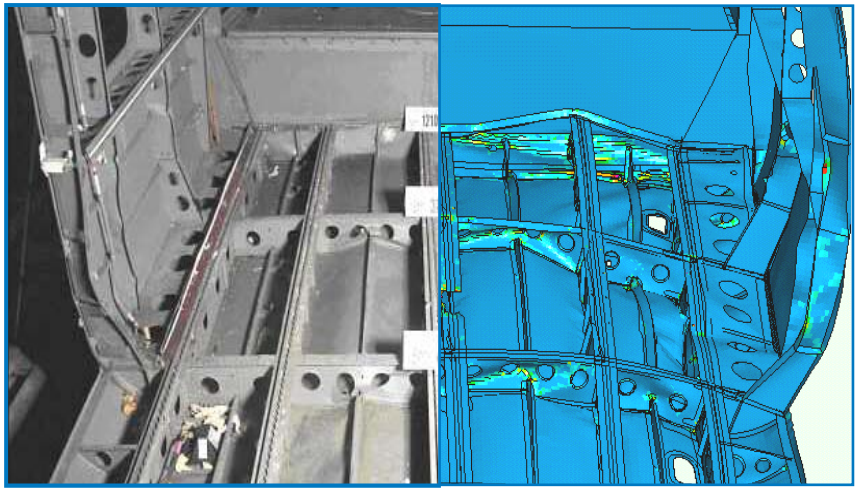


End-to-End Virtual Prototyping in Aeronautics

Aircraft impact illustration

Helicopter sea ditching

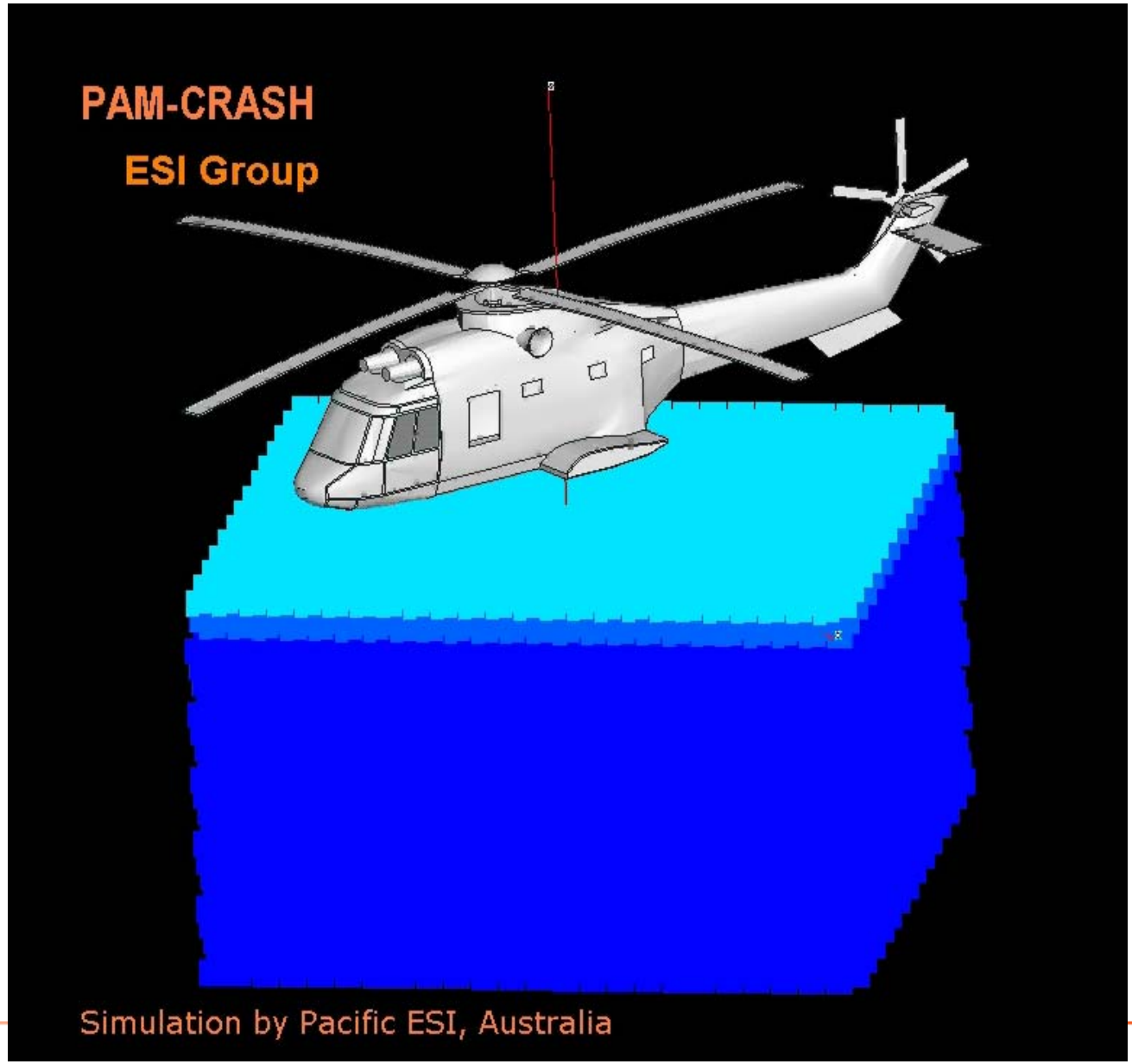




Courtesy of DLR

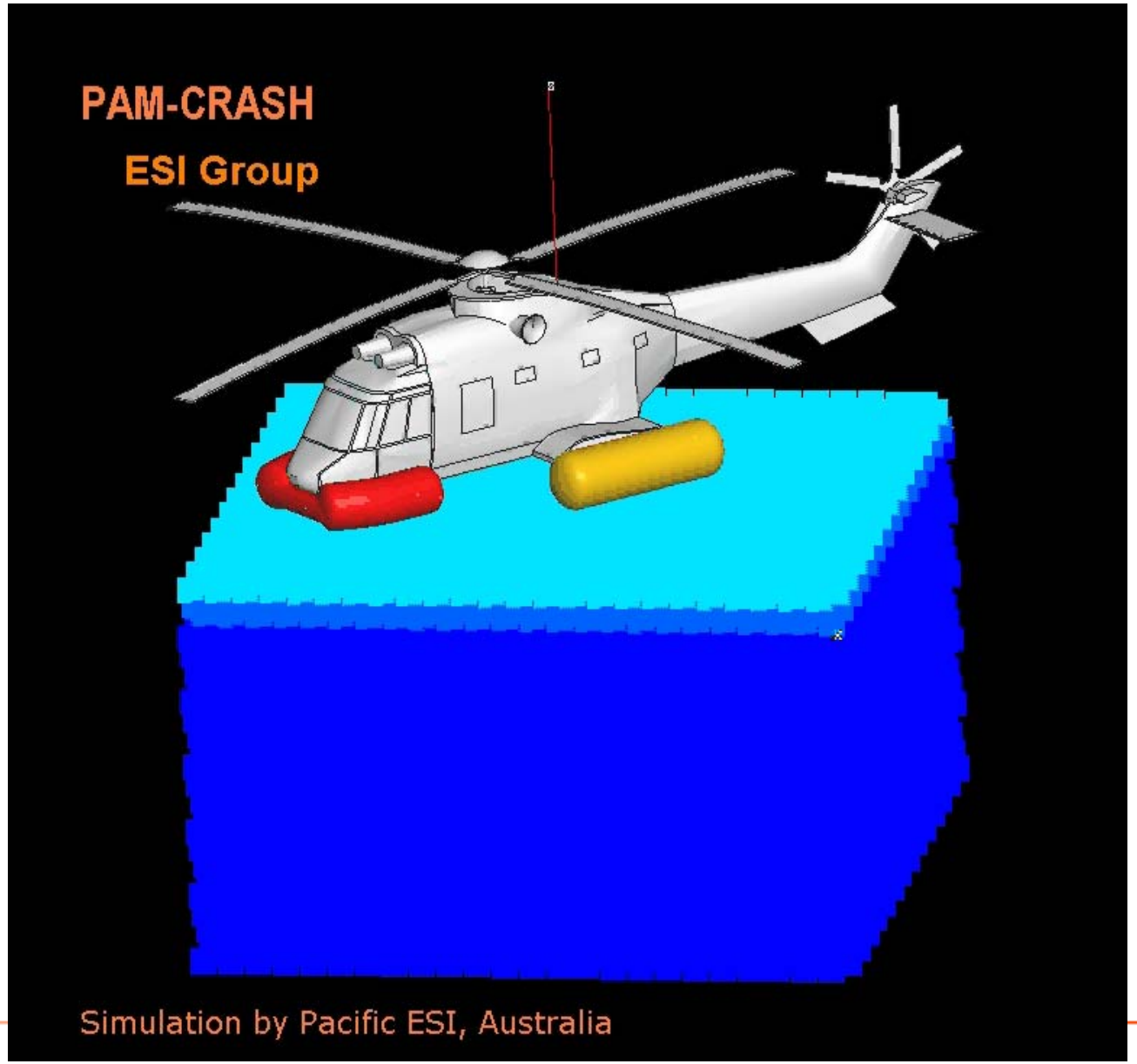
Capsizing phase of splashdown of helicopter

Capsizing of Puma without airbags



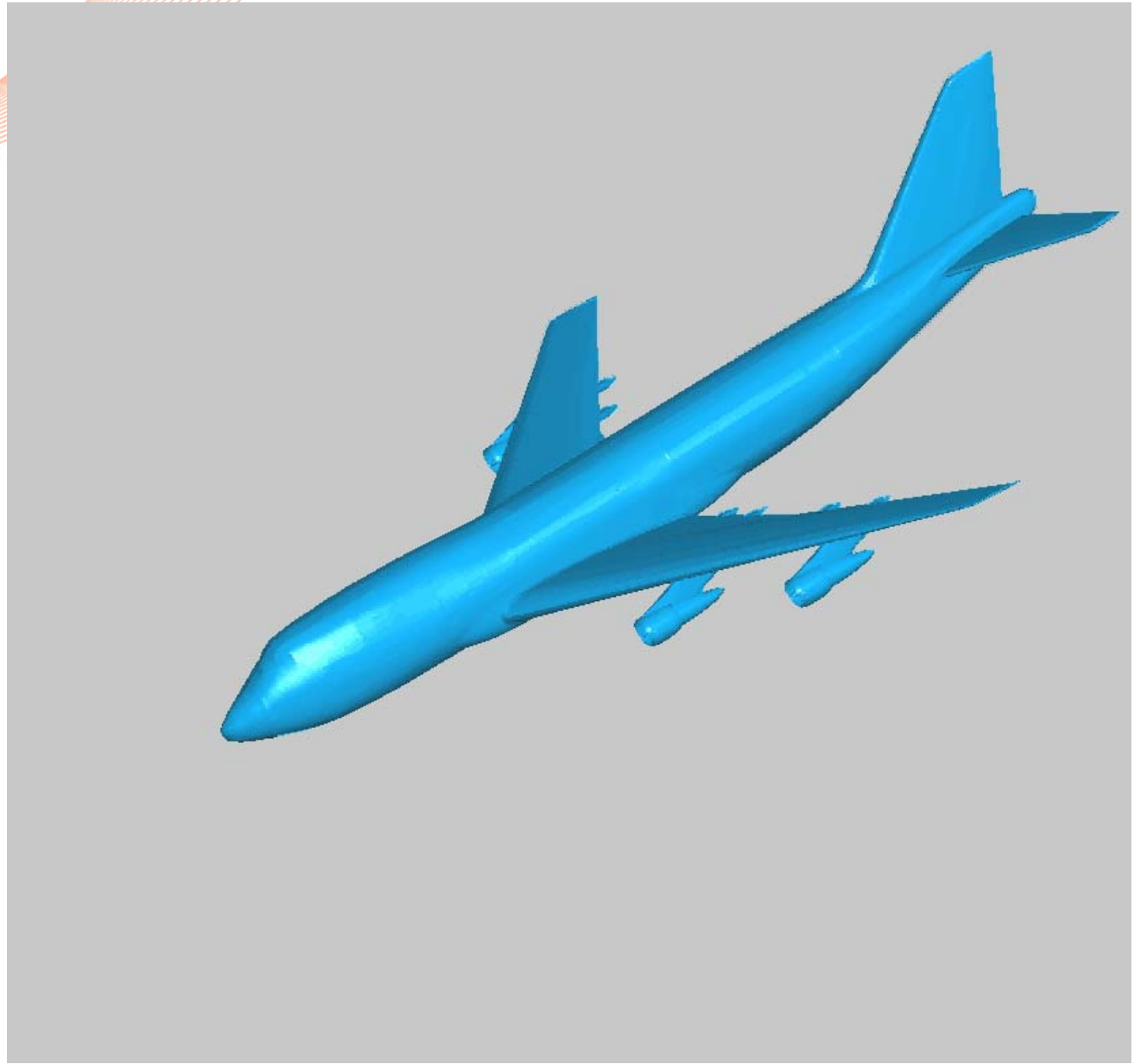
Capsizing prevention mechanisms

Effect of airbags on emergency floatation



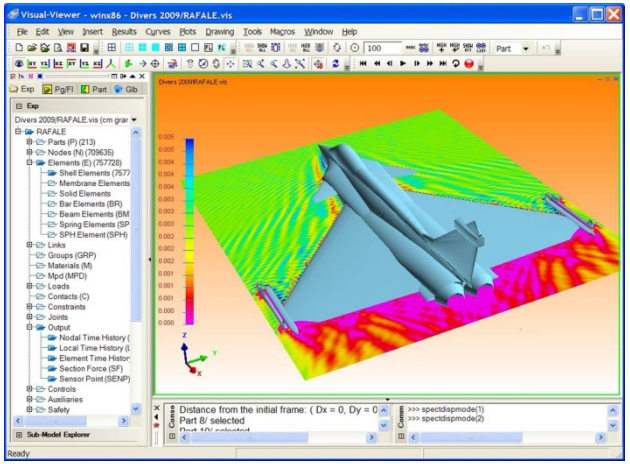
Widebody aircraft generic model impacting a perfectly rigid wall at 450km/hr

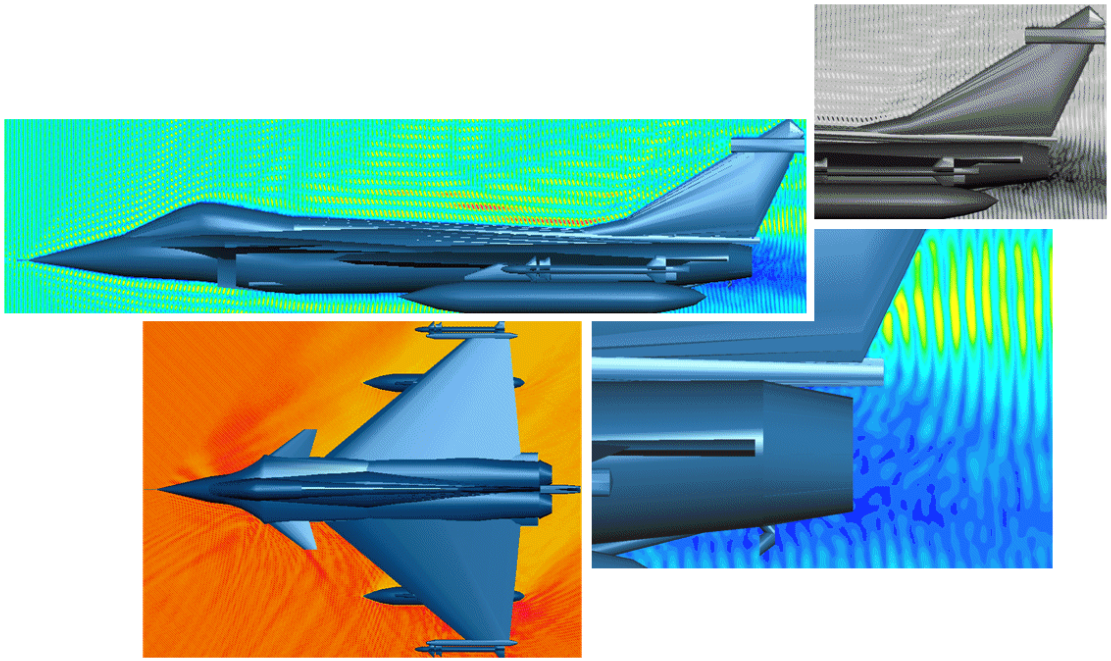
Scenario:
Impact on Building after takeoff
Crash failure
(no fuel fire effect)

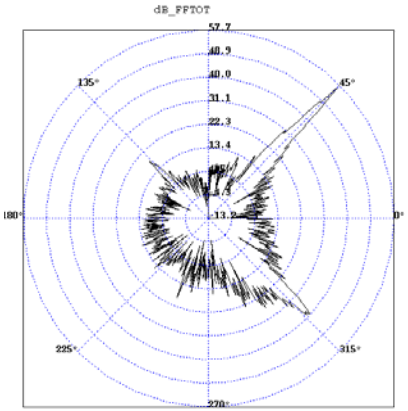


Radar Cross Sections

- RADAR Cross Section @ 10 GHz
  - Reduced scale aircraft model (1:4)
  - 11 GigaBytes RAM memory
  - 16 CPU hours on a four (4) processors SMP cluster





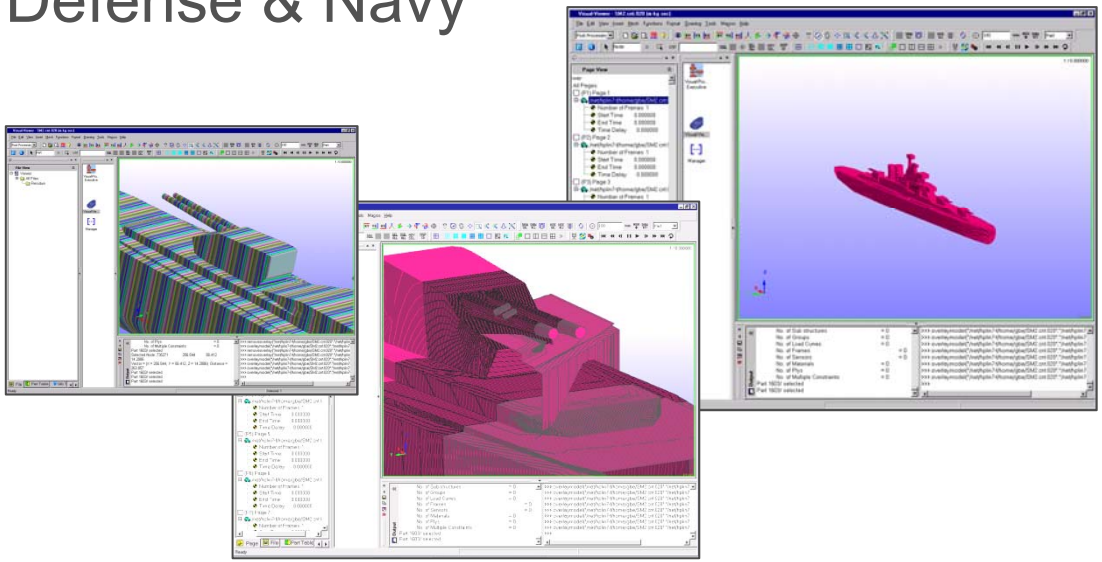


- 1321*1024*344 cells (i.e. 465 million cells)
- 2.792 billions unknowns

Others Applications in Electromagnetics

- Automotive
  - Anti-collision RADAR & advanced cruise control systems developed by most car companies
  - Very high operating frequency, from 76 up to 94 GHz.

- Defense & Navy



Models ranging from ***547 millions*** *to* ***12.508 billions*** *FD cells*

Bird-strike Simulation for Certification of the Boeing 787 Composite Moveable Trailing Edge

Steve Georgiadis[1], Andrew J. Gunnion[2], Rodney S. Thomson[2] and Bruce K. Cartwright[3]*

[1] Hawker de Havilland Pty Ltd.
226 Lorimer Street, Fishermans Bend, Victoria, Australia
[2] Cooperative Research Centre for Advanced Composite Structures Ltd.
506 Lorimer Street, Fishermans Bend, Victoria 3207, Australia
[3] Pacific Engineering Systems International Pty Ltd.
277-279 Broadway, Broadway, NSW 2007, Australia

Figure 13: FE model of the PPT-OBF and test fixture (above) and photograph showing part of the actual test setup (right)

Figure 1: Boeing 787 Dreamliner, showing breakdown of materials used and the MTE designed and manufactured by HdH

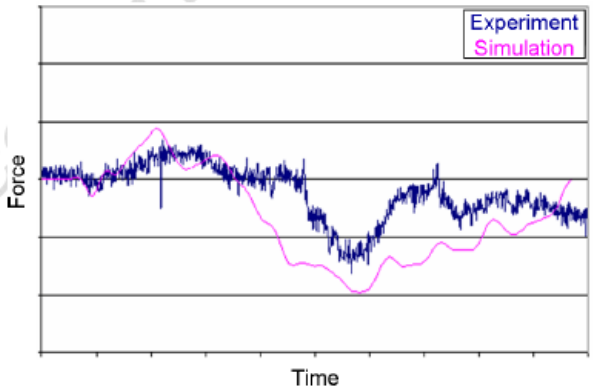


Figure 16: Comparison of experiment and simulation force-time history (non-dimensional) of the reaction loads resulting from the first test on the PPT-OBF

PAM-CRASH Composite Models:

Delamination/rupture

and SPH model for Bird

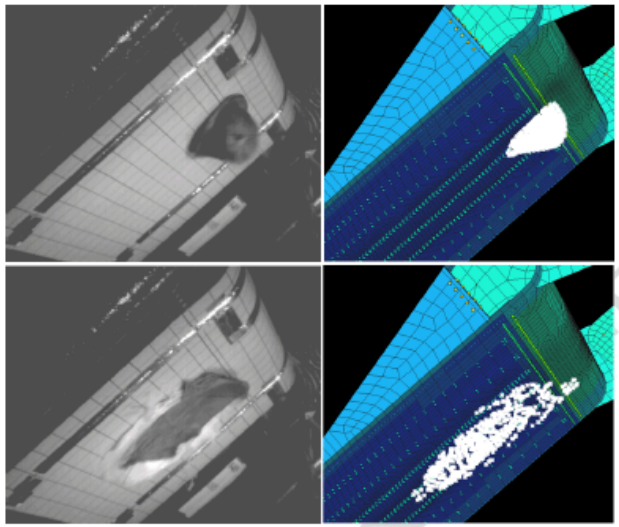


Figure 8: Images from the high-speed camera (left) and simulation (right) during the low speed impact

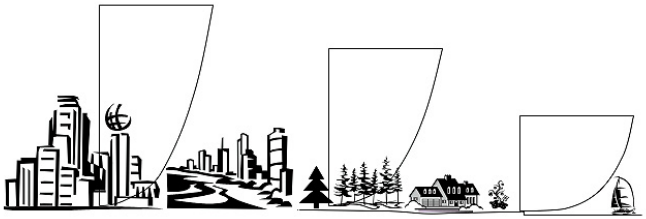
PPT-OBF = Pre-Production Test of Outboard Flap

End-to-End Virtual Prototyping in Virtual Building

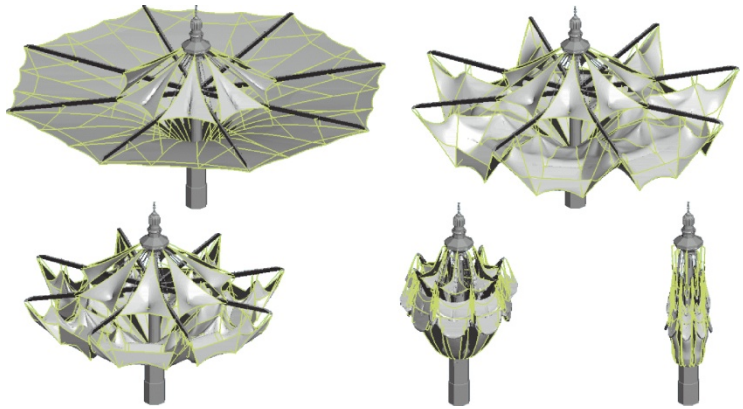
Projects related to exceptional structures under potential environment risks

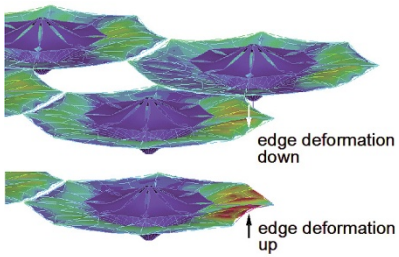
Giant Umbrella Design

- **Exceptional Structure, flexible and articulated,** submitted to wind solicitation and capable to create enormous material, human and cultural damages

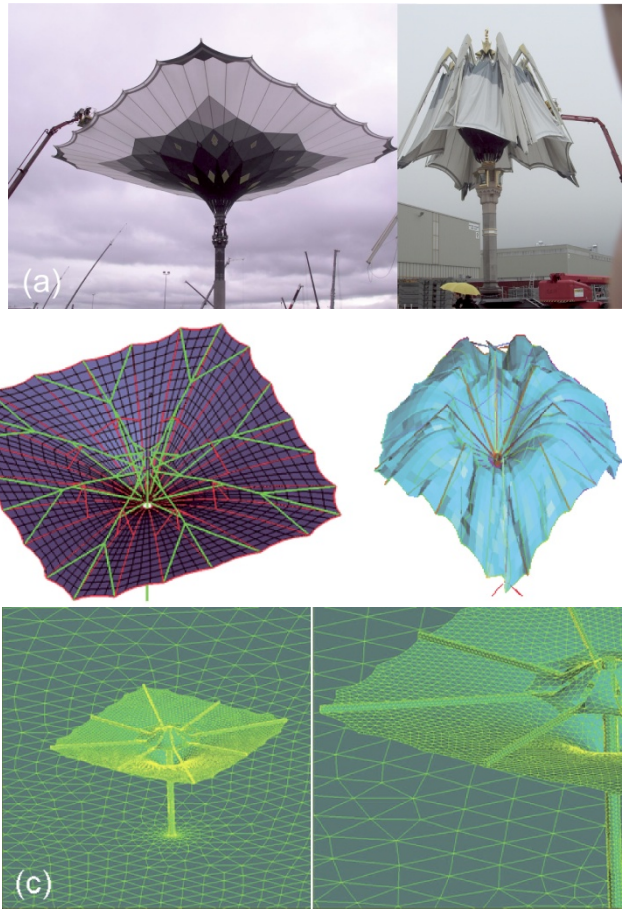


Wind profile following height





Giant Parasol
(29 x 29 meters)



Courtesy Liebherr Werke Ehingen

End-to-End Virtual Prototyping in Virtual Human

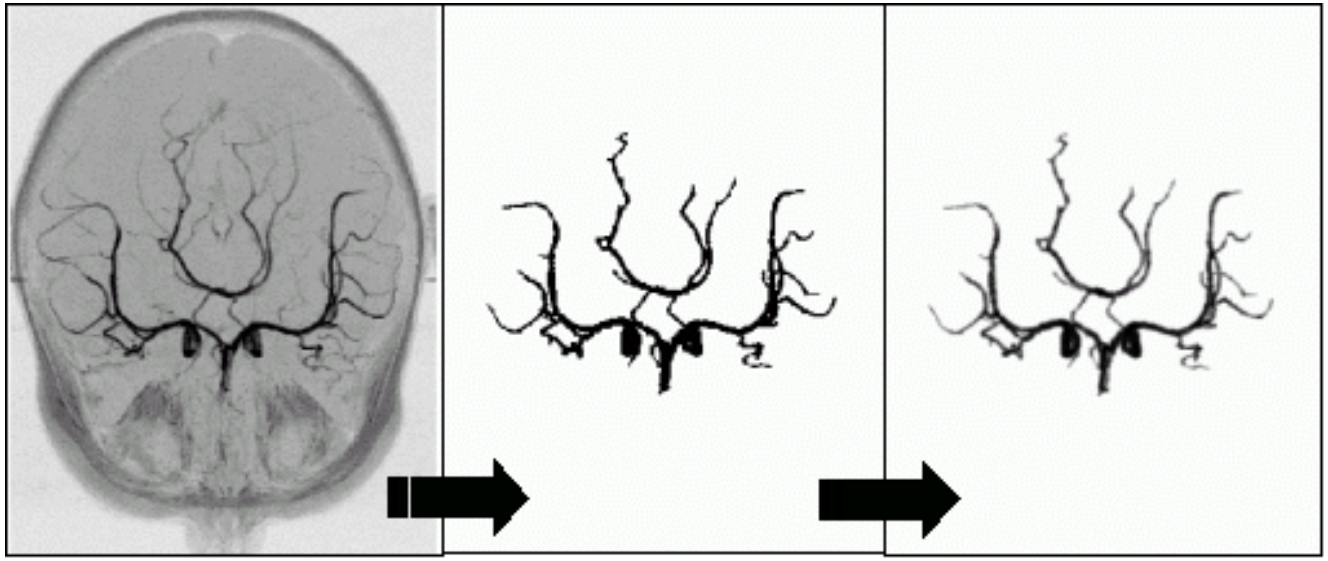
Potential Projects related to Medical Imaging

Identification of possible projects related to medical imaging

- A numerical tool for End-to-End process:
  - Patient-specific data
    - Anthropometry: medical images (3D scan / scan /MRI/….)
    - Material characterization
  - Image to mesh process
  - Simulation process
  - Decision process
- A Virtual Prototyping tool dedicated to:
  - Students: for teaching and training use
  - Surgeons: for pre-, per- and post-operator use
  - Orthopedics: for pre-, per- and post-operator use
  - Ergonomists: for comfort analysis during working or life task

Patient-specific Geometry: Image to mesh process (1/5)

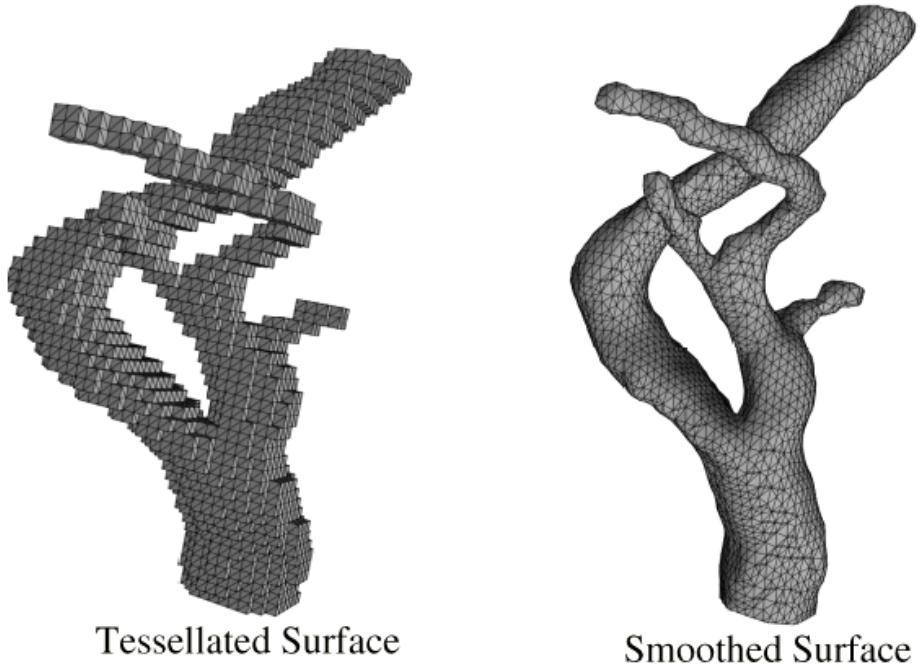
- Image Segmentation



(Courtesy of Pr. Löhner, George Mason University)

Patient-specific Geometry: Image to mesh process (2/5)

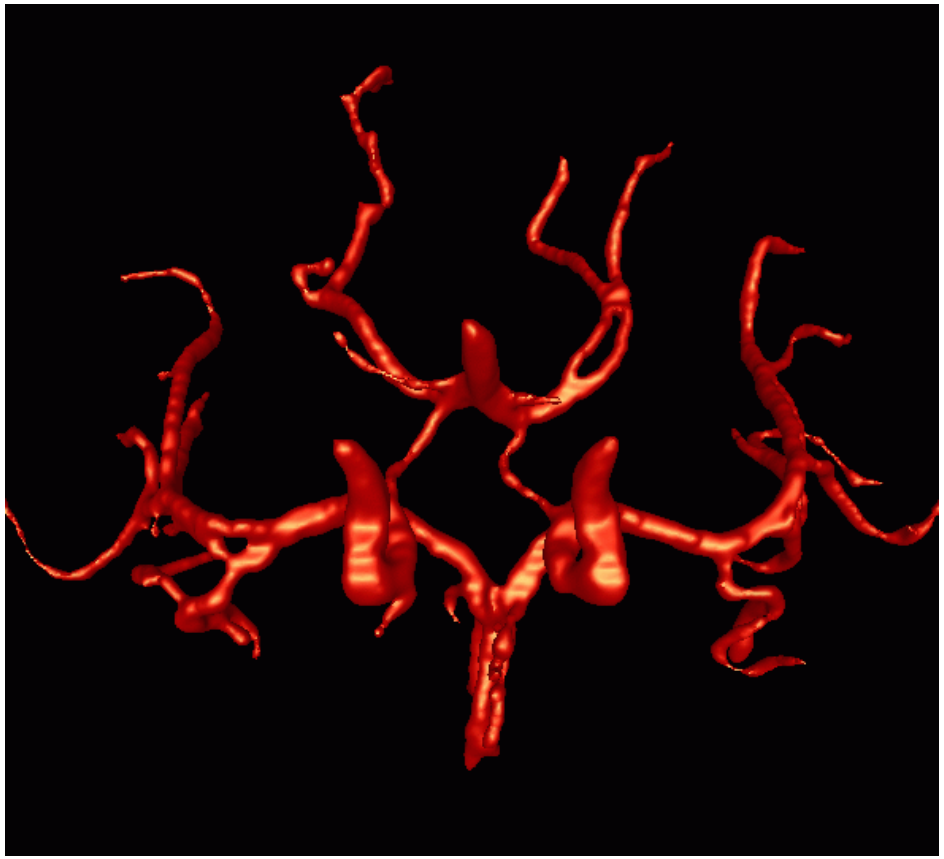
- Geometrical modeling



(Courtesy of Pr. Löhner, George Mason University)

Patient-specific Geometry: Image to mesh process (3/5)

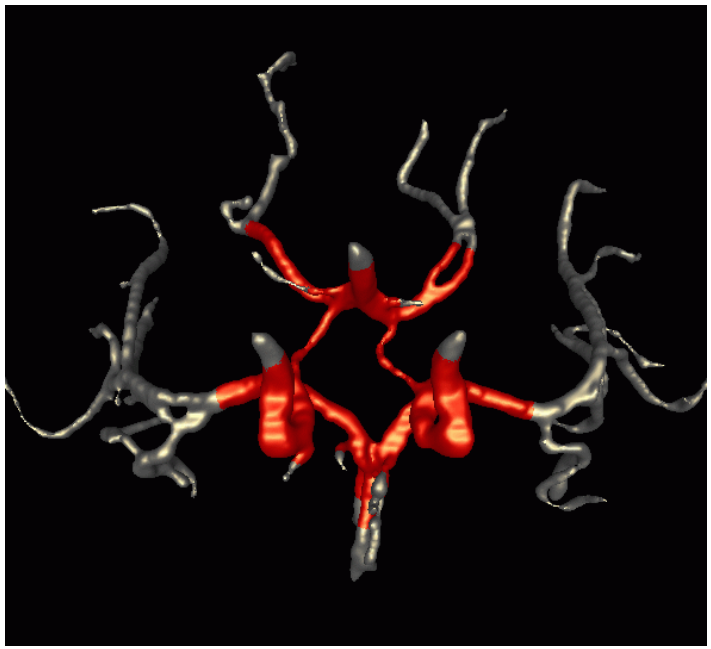
- Geometrical modeling

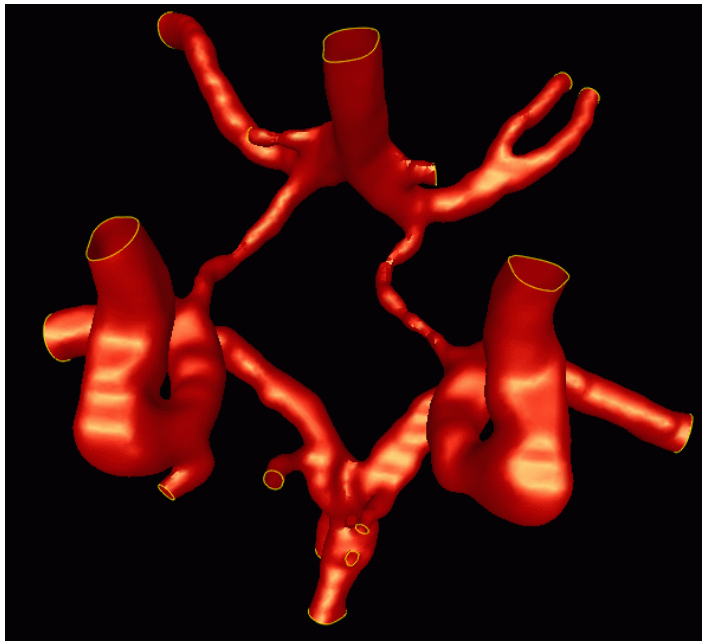


(Courtesy of Pr. Löhner, George Mason University)

Patient-specific Geometry: Image to mesh process (4/5)

- Geometrical modeling



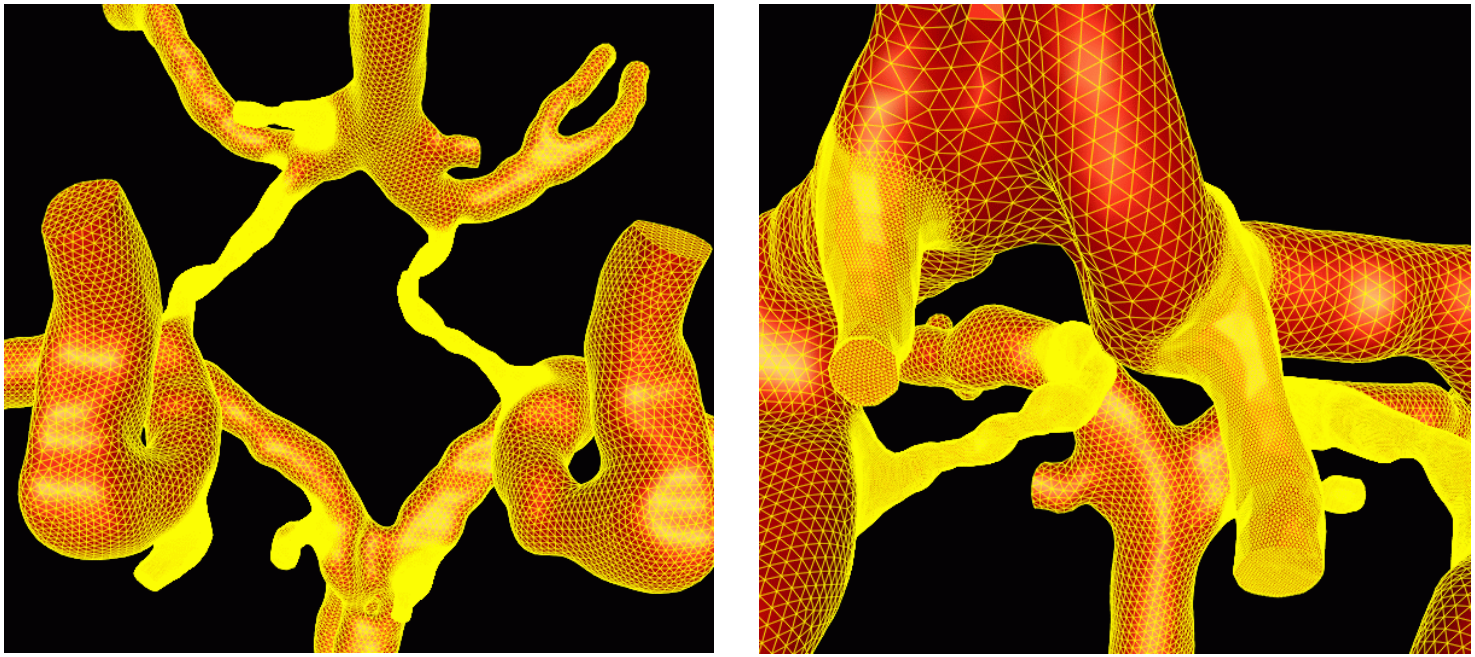


(Courtesy of Pr. Löhner, George Mason University)

Model Cutting

Patient-specific Geometry: Image to mesh process (5/5)

- Mesh generation

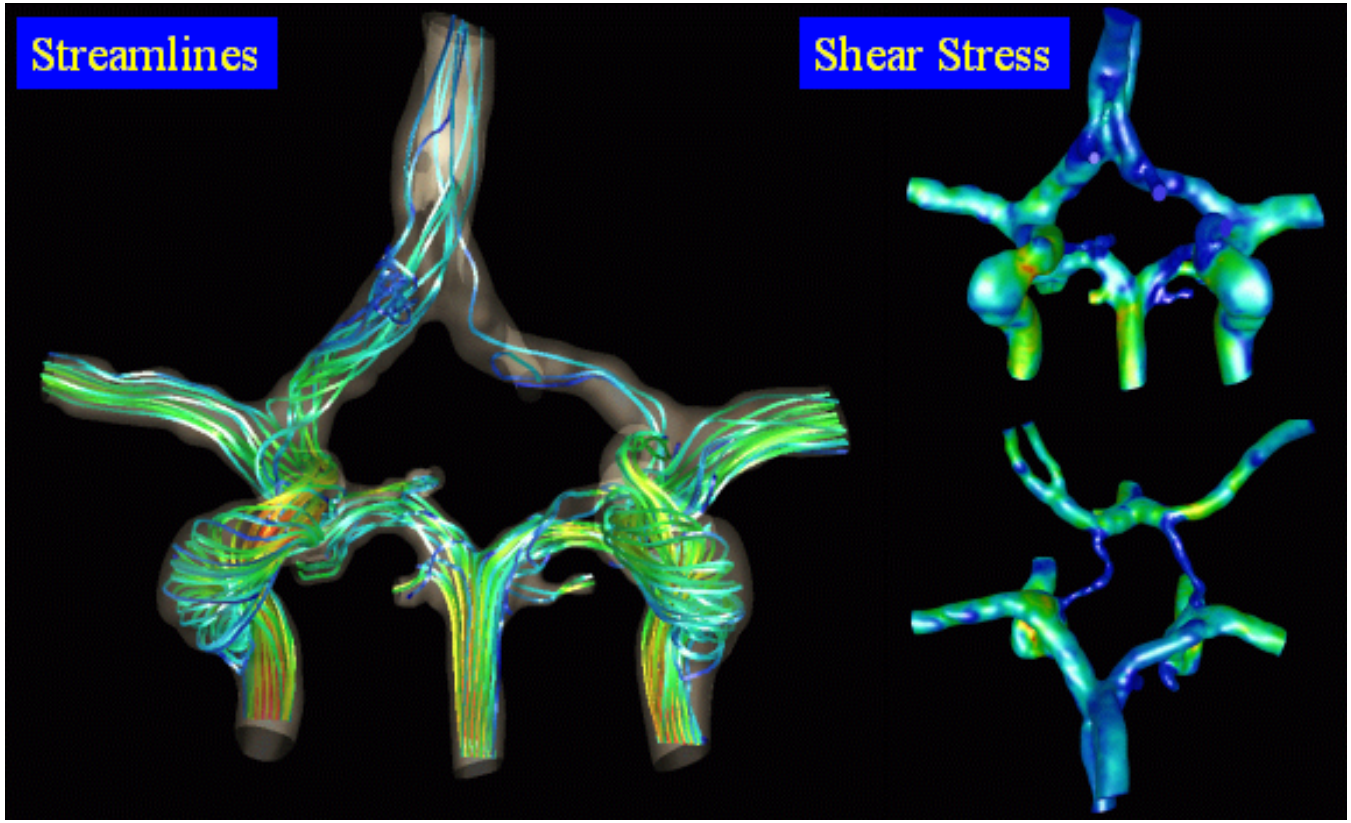


(Courtesy of Pr. Löhner, George Mason University)

Surface of CFD Mesh

Patient-specific Geometry: Simulation process (1/2)

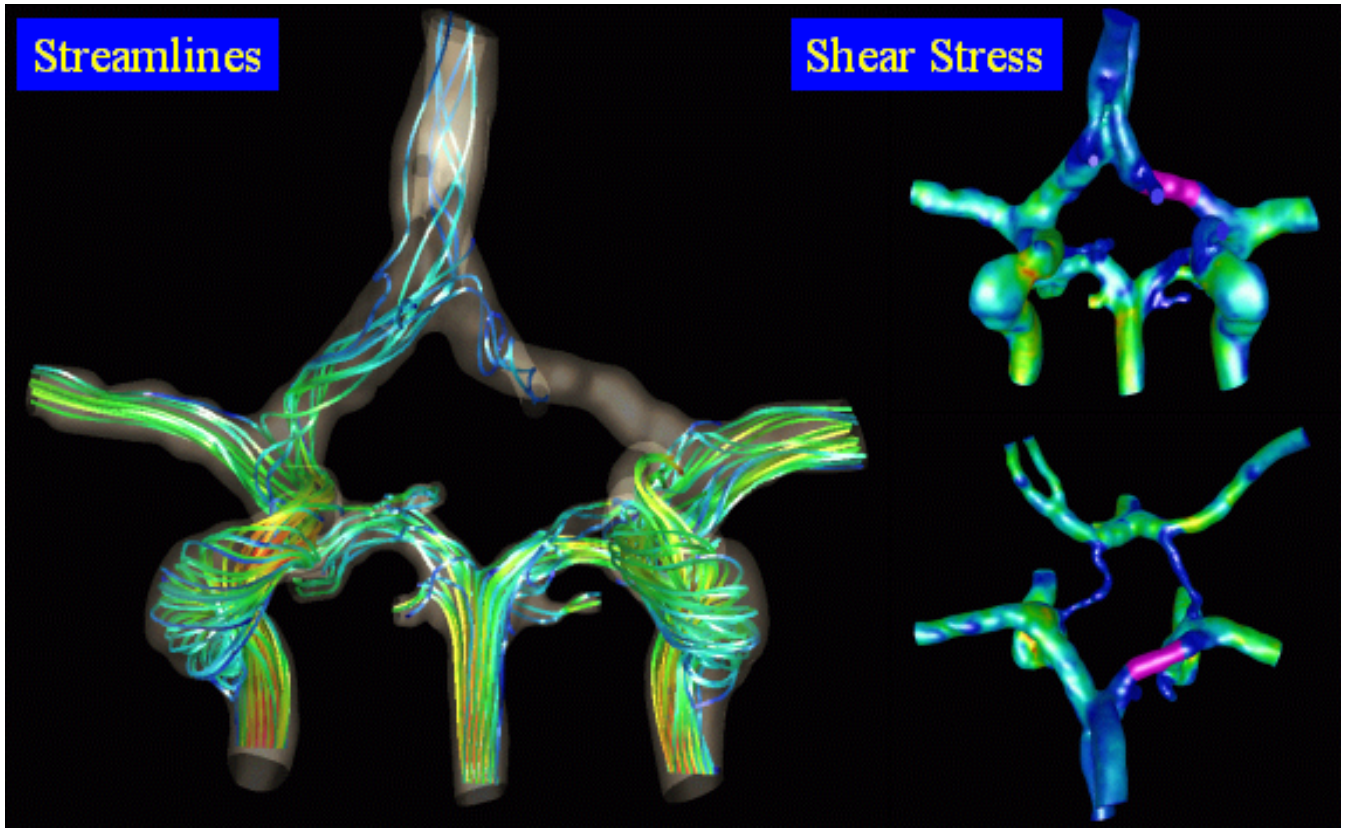
- Flow Before Clipping



(Courtesy of Pr. Löhner, George Mason University)

Patient-specific Geometry: Simulation process (2/2)

- Flow After Clipping



(Courtesy of Pr. Löhner, George Mason University)

Conclusion

- Benefits of ‘End-to-End Virtual Prototyping’:
  - Improves **Performance**
  - Accelerates **Innovation**
  - **Reduces** complexity and **risks**
  - Implements **step by step**
    (i.e.: parts; components; system assembly –
    per domain; **multi-domain optimization**) for

“Concurrent Virtual Product Development”

to get it right™

… the first time …

get it right™

THANK YOU