TECHNISCHE UNIVERSITÄT DRESDEN

PORSCHE

SCALE IT-Solutions for CAE

Fakultätsrechenzentrum
Fakultät Bauingenieurwesen

Master‘s Thesis

Evaluation of a Model Order Reduction Technique in Vehicle Simulation

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on 25-09-2020

Outline

I. Motivation

II. Model Order Reduction

III. Evaluation of Linear Model Order Reduction
   A. Simulation Data Management
   B. MOR Approaches in LS-DYNA
   C. Small Displacement Structural Dynamic Problem
   D. Large Displacement Structural Dynamic Problem

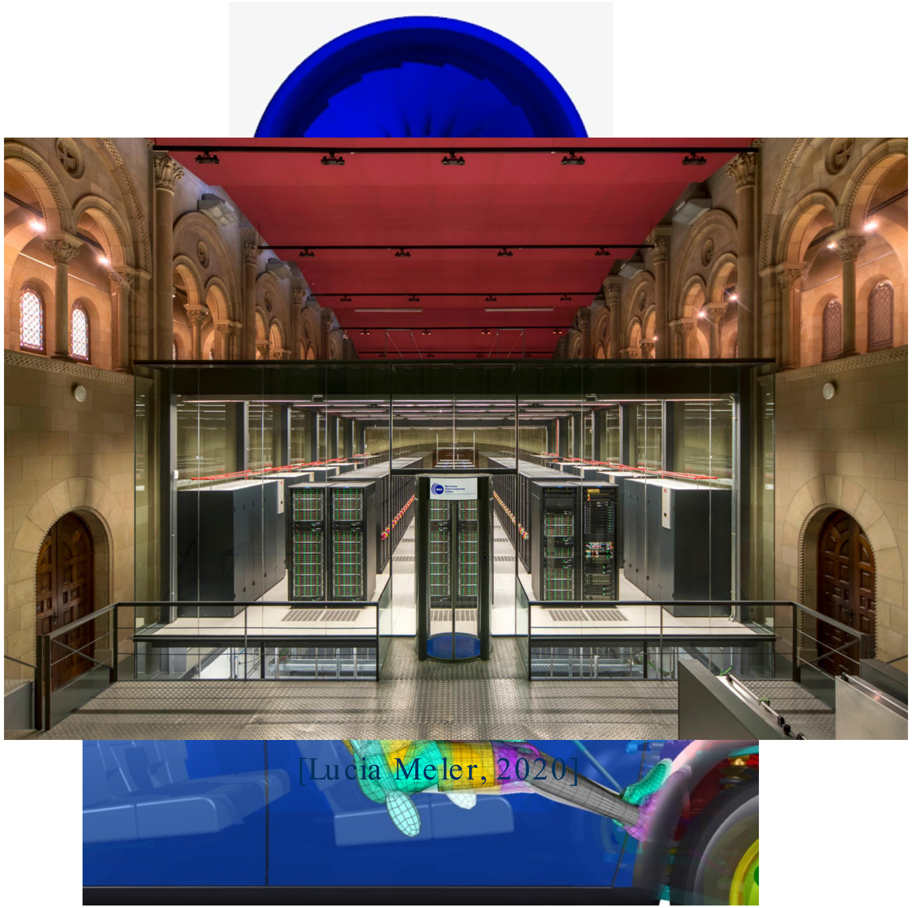
IV. Application in Crash Analysis
   A. Problem Definition
   B. Time Reduction
   C. Accuracy
   D. Decomposition Aspects

V. Conclusion and Further Investigation

I- Motivation

- ❑ Reduce time
  1. Simulation
  2. Assessment
  3. Concept-to-Market
- ❑ Reduce energy consumption

➡ Reduce cost



[Lucia Meler, 2020]

[MSc Software, 2020]

II- Model Order Reduction (MOR)

II- Model Order Reduction

- A linear system:
  1. has linear relationships
  2. can utilize superposition
- A non-linear system:
  1. has non-linear relations
  2. can't be superposed
- Forms of structural non-linearity
  1. Geometric (e.g snap-through buckling)
  2. Material (e.g plasticity)
  3. Boundary (e.g contact)

II- Model Order Reduction

- Linear MOR handles structures behaving linearly (geometric, material, boundary)
- Available since the 1960s
- Finds a transformation **T** such that :

$$\underline{x}(t) = \mathbf{T}\underline{\boldsymbol{x}}_k(t) \qquad k \ll n\ (size\ of\ \underline{x})$$

- In structural dynamics this yields:

$$\mathbf{M}_k\underline{\ddot{x}}_k(t) + \mathbf{C}_k\underline{\dot{x}}_k(t) + \mathbf{K}_k\underline{x}_k(t) = \underline{f}_k(t)$$

where each of the characteristic matrices is obtained as

$$\square_k = \mathbf{T}^T\square\mathbf{T}$$

- Are often based on modal analysis

II- Model Order Reduction

- *For a time-invariant system, the responses can be obtained as a linear combination of all the responses in the normal space (*theory of vibration)
- Displacement of a DoF calculated as

$$\underline{x}_i(t) = \varphi_{i1} q_1(t) + \cdots + \varphi_{n1} q_n(t) = \sum_{m=1}^{n} \varphi_{im} q_m(t) \quad \textbf{where} \begin{cases} \varphi_{im} \text{ modal displacement} \\ q_m \text{ modal coordinate} \end{cases}$$

- Full displacement vector

$$\underline{x}(t) = \sum_{m=1}^{n} \underline{\varphi}_m \underline{q}_m(t) = \boldsymbol{\Phi} \underline{q}(t)$$

- Reduced displacement vector

$$\underline{x}_k(t) = \sum_{m=1}^{k} \underline{\varphi}_m \underline{q}_m(t) = \boldsymbol{\Phi}_k \underline{q}_k(t) \qquad k \ll n$$

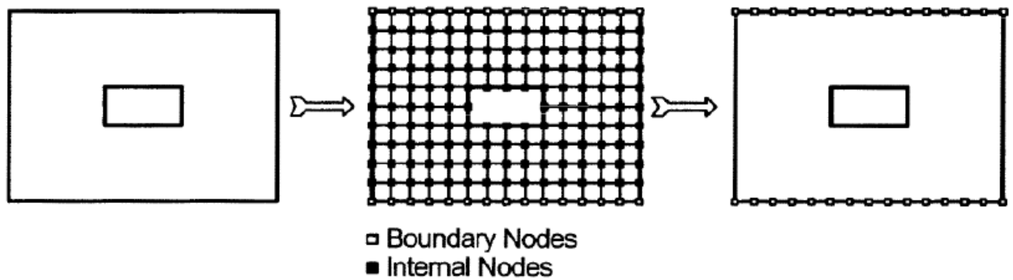
Modal Truncation

- Reduced equation of motion

$$\underline{\ddot{q}}_k(t) + \mathbf{C}_k \underline{\dot{q}}_k(t) + \boldsymbol{\Lambda}_k \underline{q}_k(t) = \boldsymbol{\Phi}^{\boldsymbol{T}} \underline{f}\,(t) = \underline{f}_{\boldsymbol{k}}(t)$$

II- Model Order Reduction

- Component Mode Synthesis
  - Divide the structure into parts
  - Form a *superelement* from certain parts



[Qu, Zu, 2004]

- Craig-Bampton reduction approximates DoFs using
  - Boundary displacements + Constraint Modes
  - Modal coordinates + reduced Eigenmodes

$$\underline{x}(t) = \begin{Bmatrix} \underline{x}_b(t) \\ \underline{x}_i(t) \end{Bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{\Phi}_c & \mathbf{\Phi}_k \end{bmatrix} \begin{bmatrix} \underline{x}_b(t) \\ \underline{q}_k(t) \end{bmatrix}$$

III - Evaluation of Linear MOR

A. Simulation Data Management

- Several benefits of using SDM
  - Manages and organizes simulation data
  - Reduces risk of confusion
  - Keeps track of project development
  - Saves time
  - Improves efficiency and productivity

- LoCo, product of SCALE GmbH, was used
  - Facilitates modifications and model assembly
  - Handles the relationship with the HPC
  - Provides easy access to the Yaris model

B. MOR Approaches in LS -DYNA

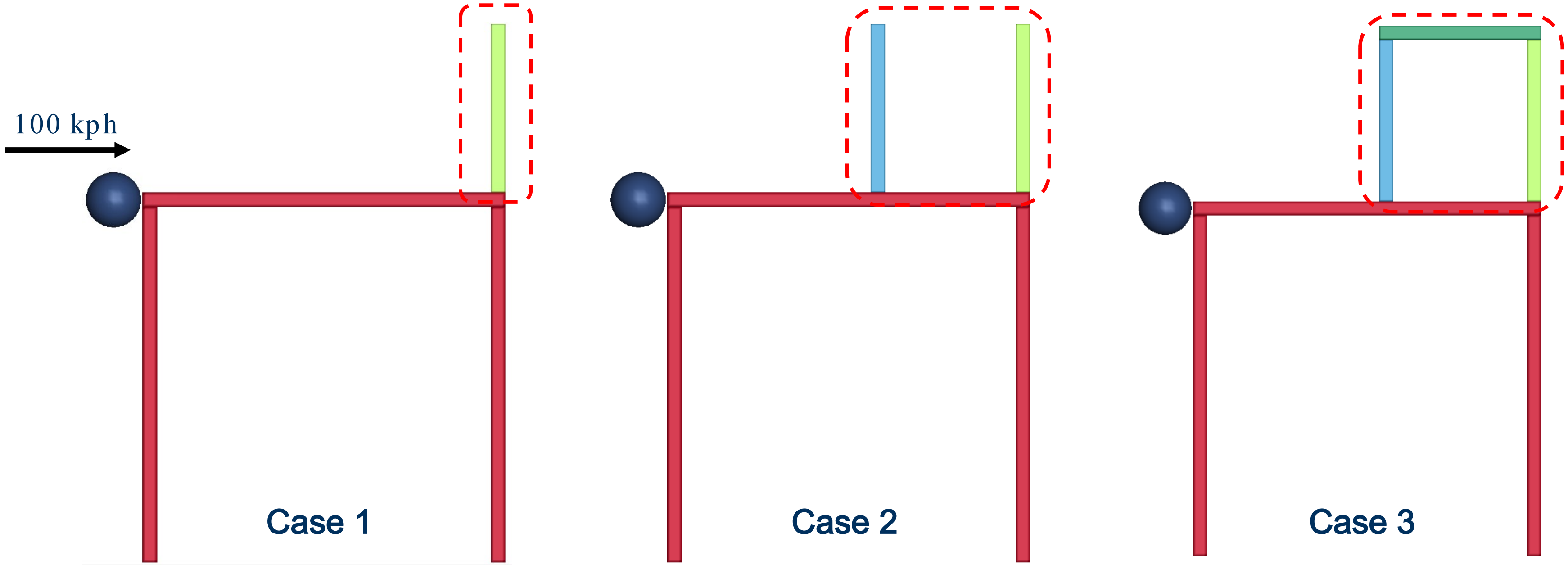
- Two approaches exist:
  - Superelement (SE)
  - Linearized Flexible Body (LFB)

- The SE approach:
  - Formed using Craig-Bampton or Static Condensation
  - Represented via a set of matrices
  - Can't be mass scaled

- The LFB approach:
  - Formed using Craig-Bampton or Modal Truncation
  - Combines modal superposition with rigid body motion
  - Represented as rigid bodies
  - Can be mass scaled

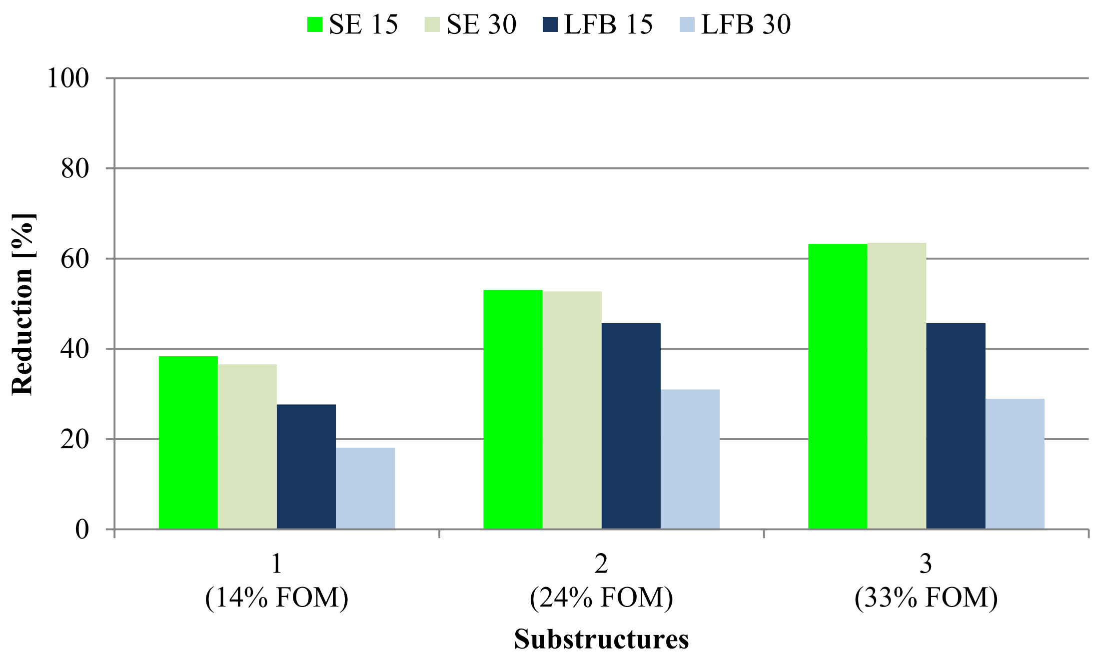
C. Small Displacement Structural Dynamic Problem

- Different variants of a structural frame were assessed
- SE vs. LFB
- Different number of modes



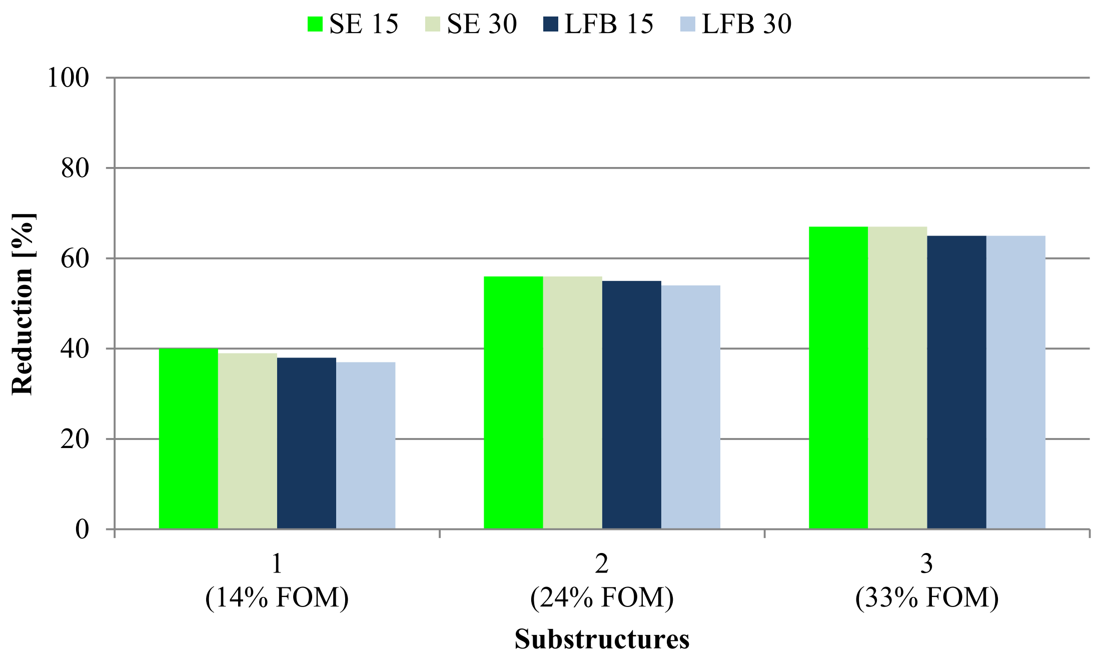
C. Small Displacement Structural Dynamic Problem

- Time reduction of **all processes**



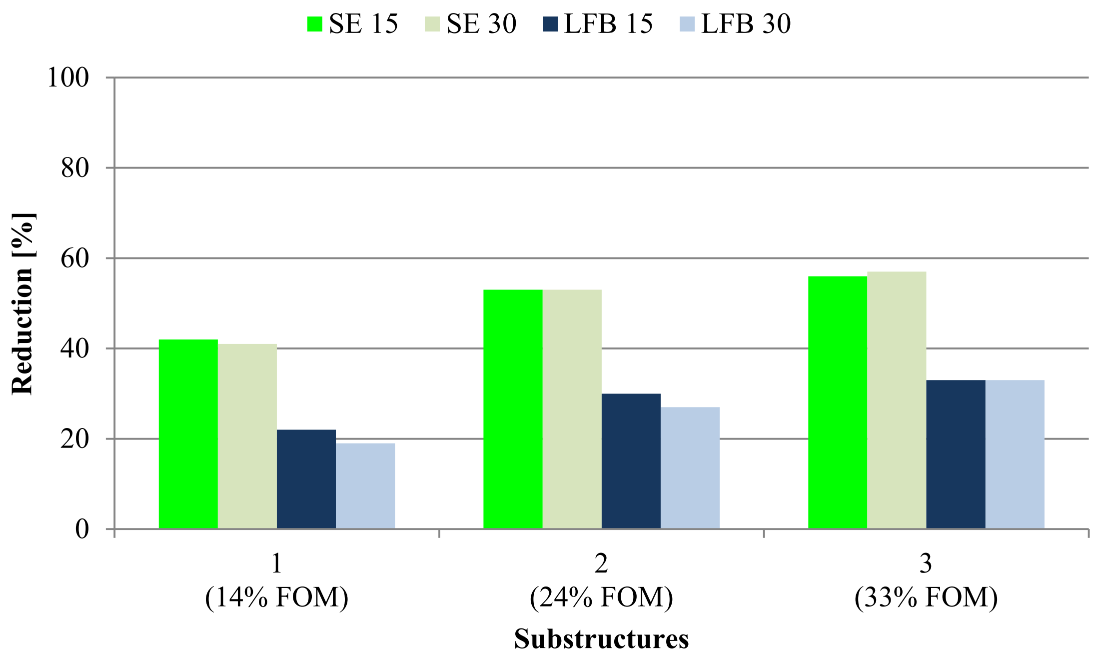
C. Small Displacement Structural Dynamic Problem

- Time reduction of **element processing**



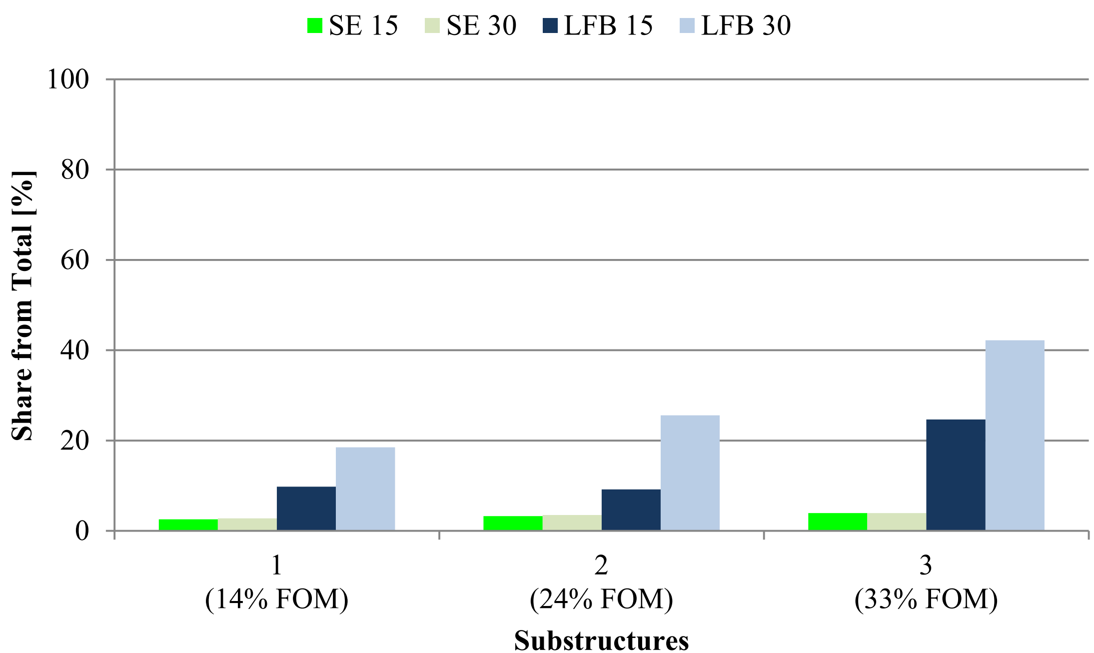
C. Small Displacement Structural Dynamic Problem

- Time reduction of **contact algorithm**



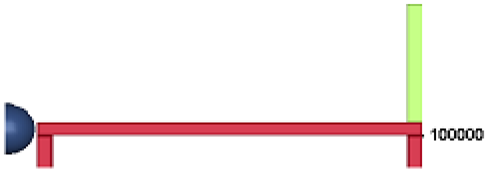
C. Small Displacement Structural Dynamic Problem

- Share of **rigid body handling**

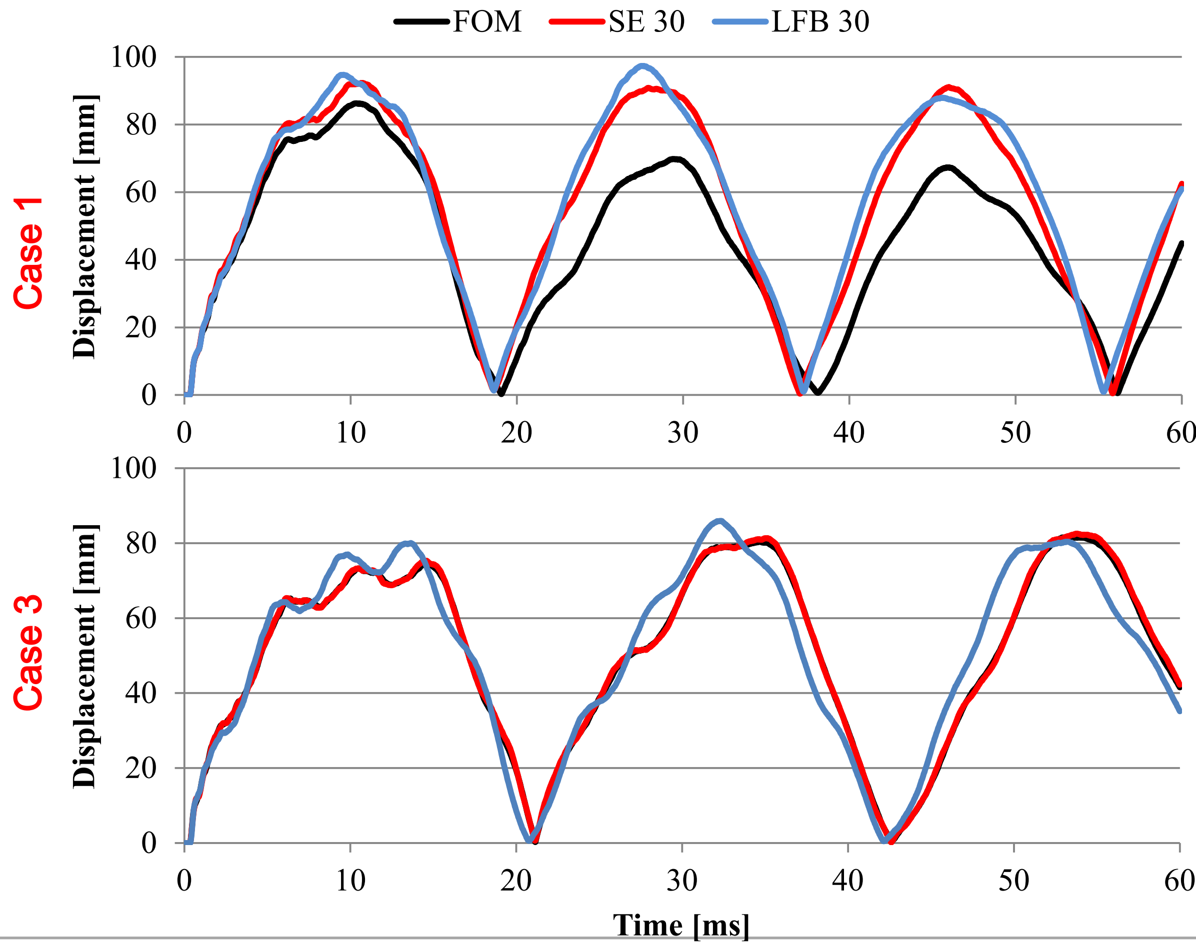


C. Small Displacement Structural Dynamic Problem

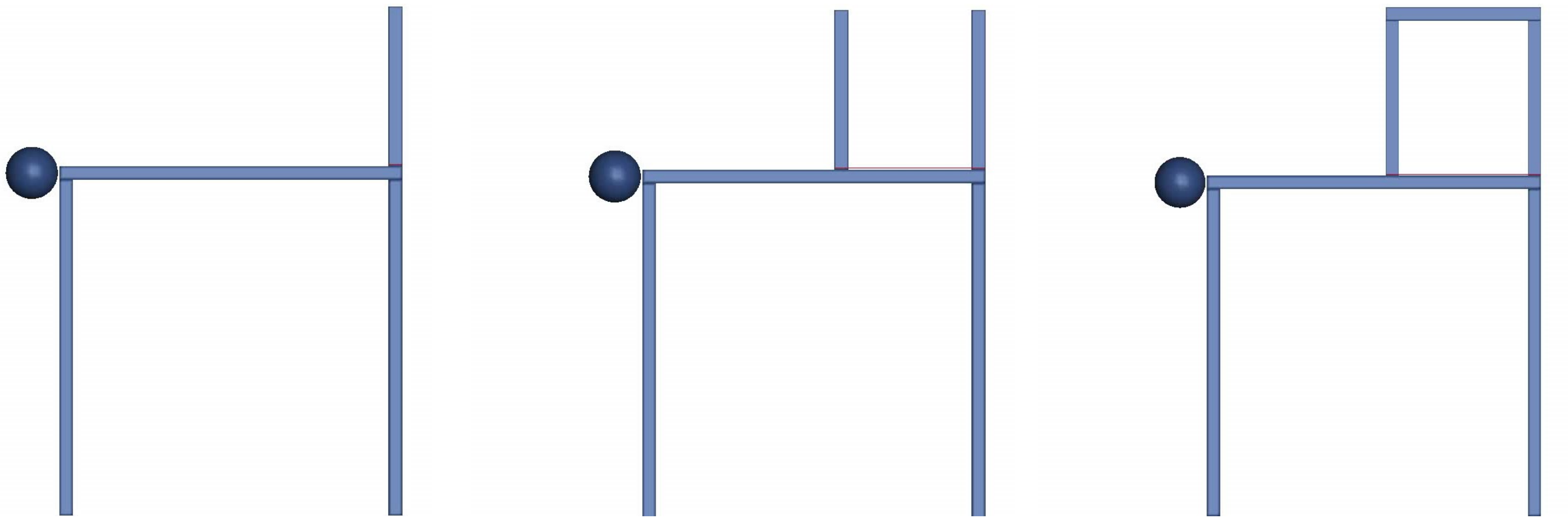
- Accuracy using resultant displacement



- Case 2 resembles case 1

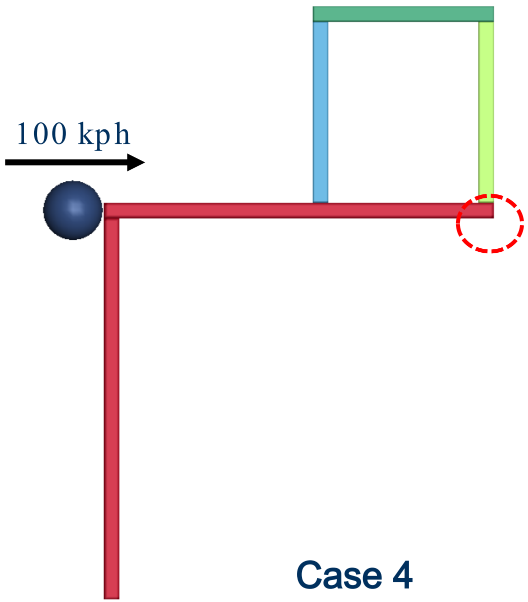


C. Small Displacement Structural Dynamic Problem

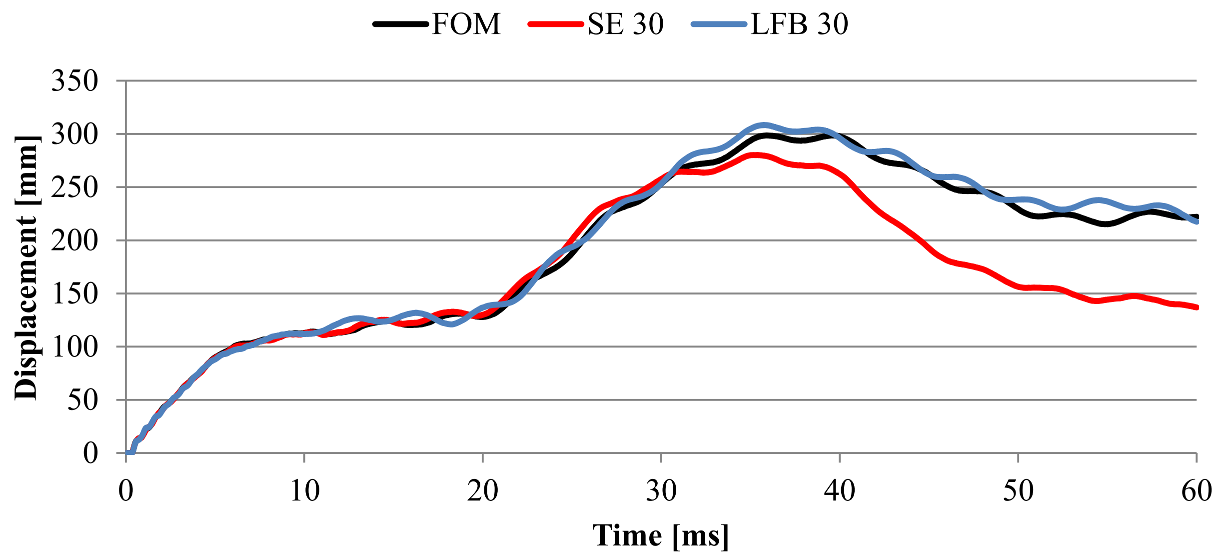


D. Large Displacement Structural Dynamic Problem

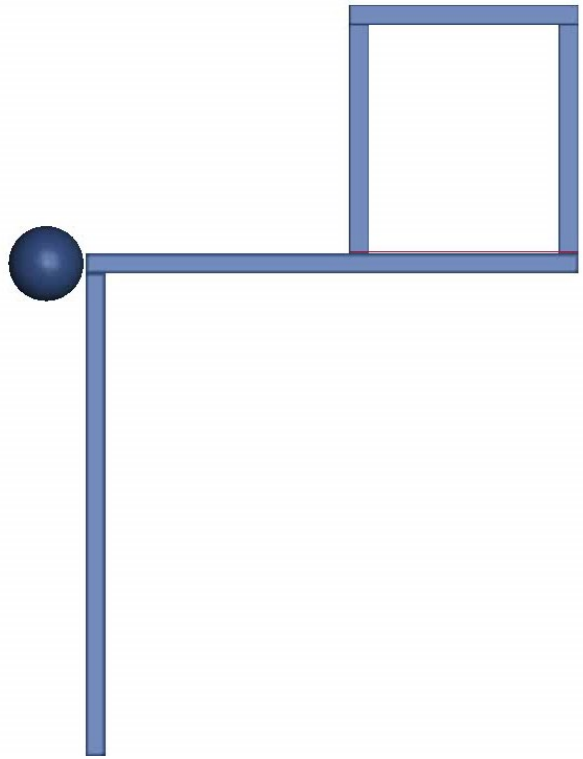
- Successful case 3 → modified for large displacements
- Reduction by SE 72%
- Reduction by LFB 54% with 15 EM and 35% with 30.



Case 4



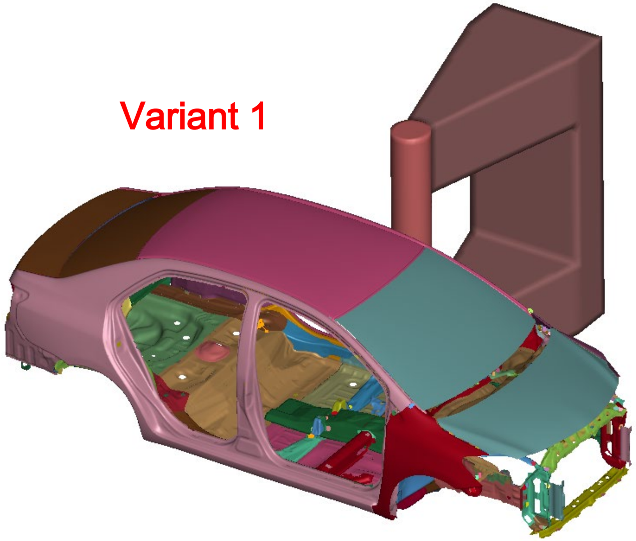
D. Large Displacement Structural Dynamic Problem

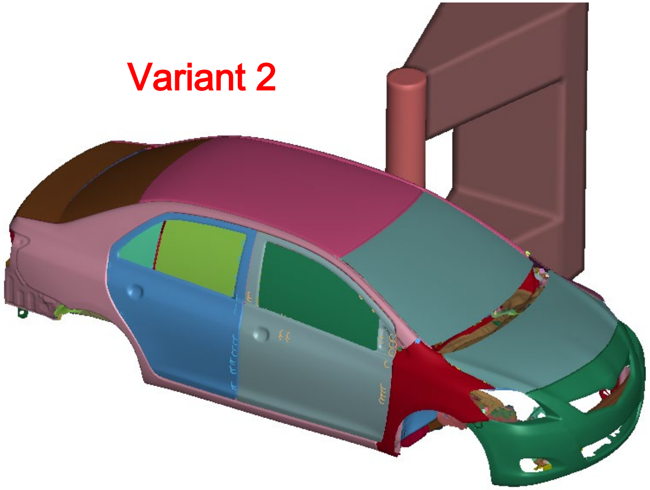


IV- Application in Crash Analysis

A. Problem Definition

- ❑ Side impact
- ❑ Rigid pole barrier
- ❑ 50 km/hr
- ❑ 120 ms simulation
- ❑ HPC used
- ❑ Two **LFB** reduction cases:
  - 2 substructures
    Hood + Hatch
  - 5 substructures
    Hood, Hatch, CMS, & Right Doors
- ❑ Additional approach assessed
  Deformable to Rigid **(D2R)**

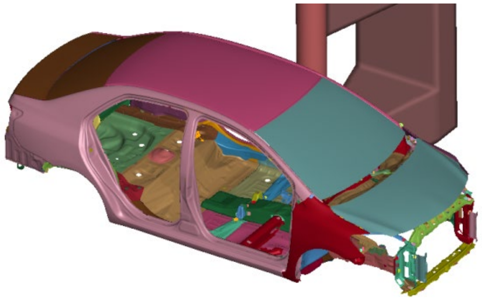




B. Time Reduction

- Distinguish between 3 computing environments:
  1. Practical (Model > 1 ; Runs > 1)
  2. Weakly isolated (Model = 1 ; Runs > 1)
  3. Strongly isolated (Model = 1 ; Runs = 1)
- Time consistency achieved by controlled **MPP decomposition** for NCPU>4

B. Time Reduction

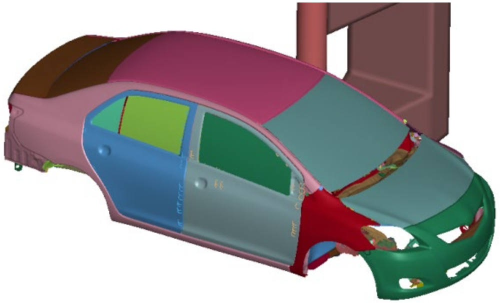


- Variant 1 (practical environment, 4 CPUs, no control)

	FOM	Separate Reduction 15 EM	Combined Reduction 30 EM
Time [s]	44,172	39,020	32,653
Reduction [%]		12	26
Element Processing [s]	18,629	15,173	13,099
Contact Algorithm [s]	17,028	14,444	11,811
Rigid Bodies [s]	423	1,427	1,522

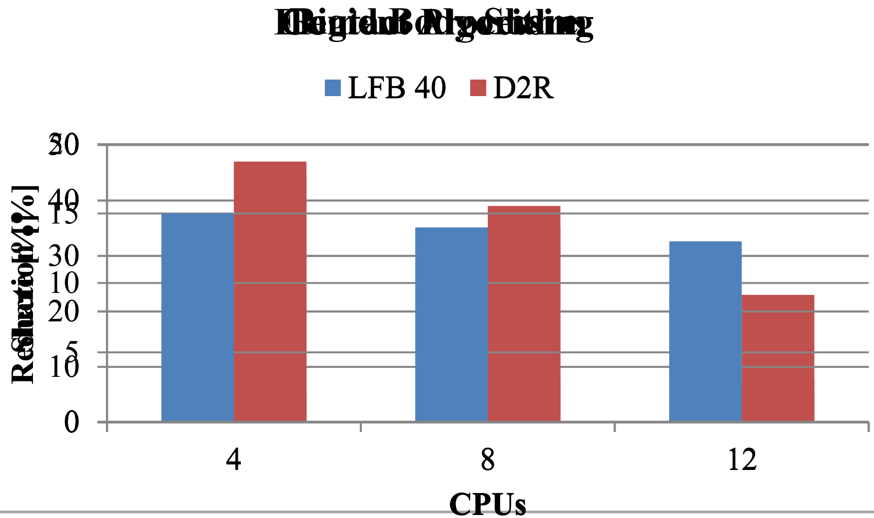
→ **Combined reduction is better**

B. Time Reduction

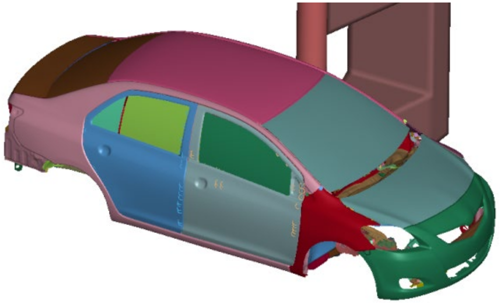


- Variant 2 (practical environment, MPP Control)

CPUs	4	8	12
LFB 40	-9	12	-7
D2R	44	35	9



B. Time Reduction



- Variant 2 (isolated environment, MPP Control, 8 CPUs)

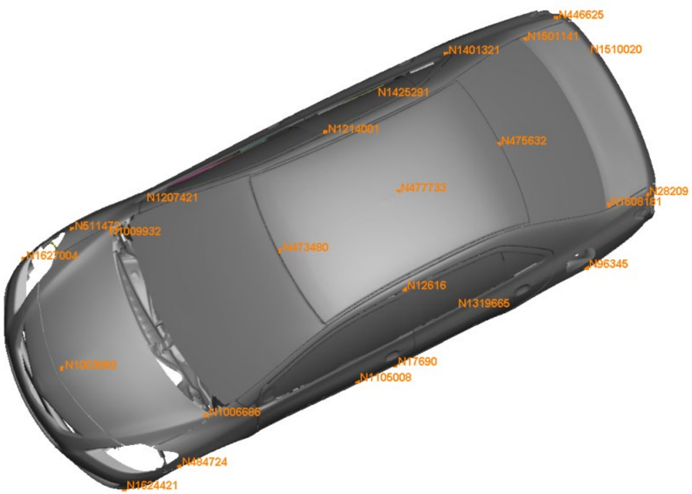
	weakly		strongly	
	LFB 40	D2R	LFB 40	D2R
Red. [%]	-5	27	-8	4

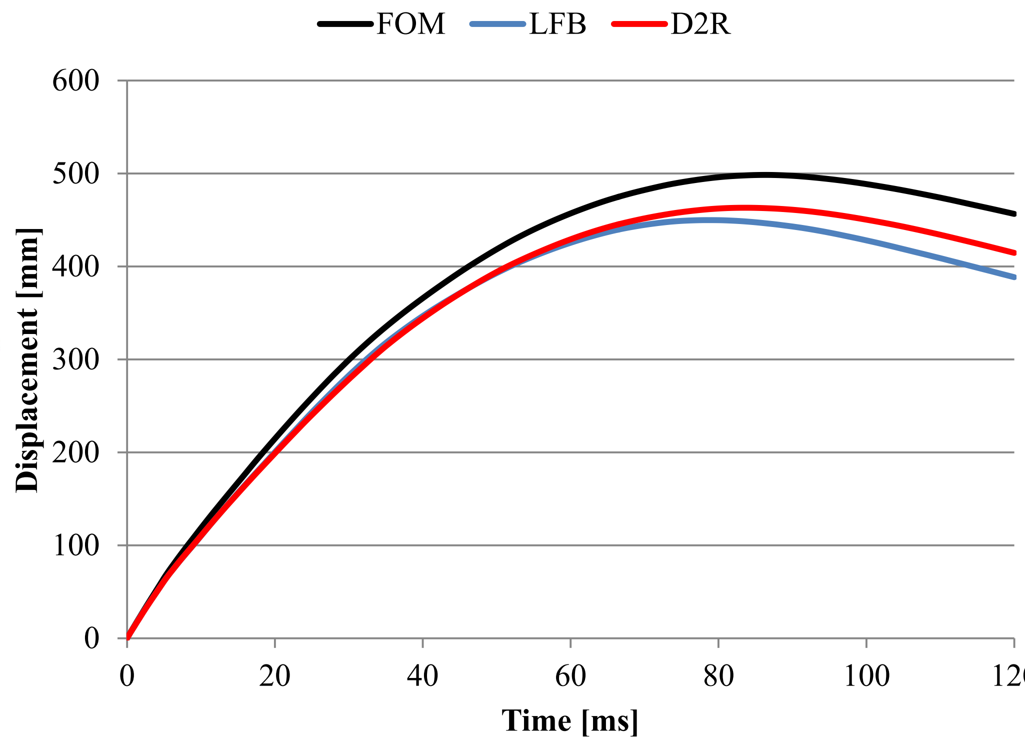
- The Strongly isolated environment reduced run time by
  - 63% for FOM
  - 62 % for LFB
  - 54% for D2R
  - and the main processes by

	Full	LFB	D2R
Element	54	49	43
Contact	67	65	55
Rigid Body	78	65	61

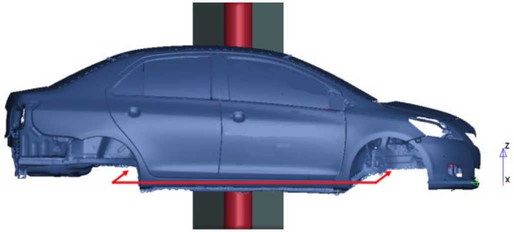
C. Accuracy

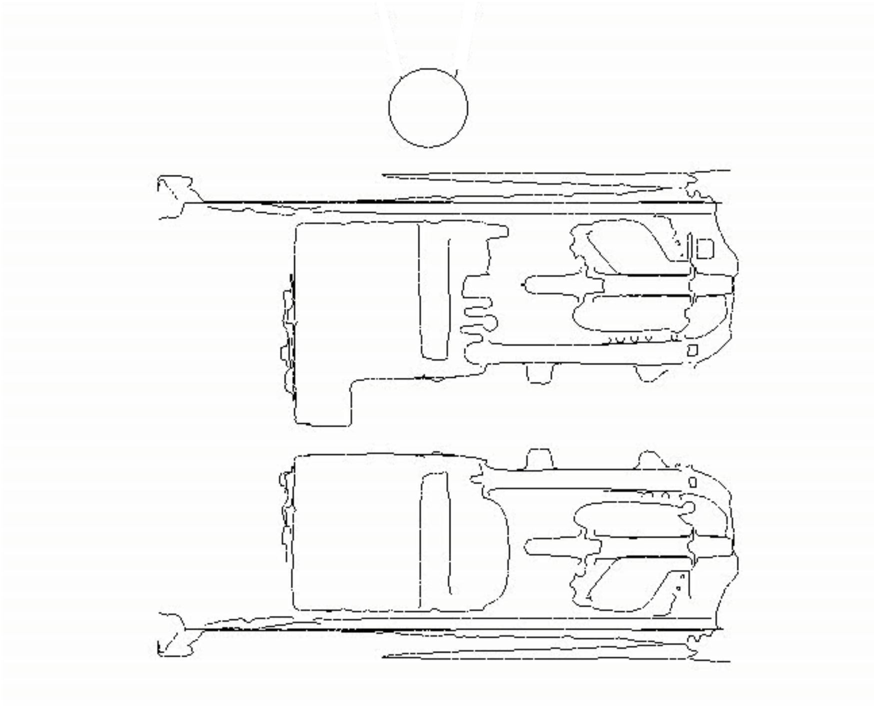
❑ Resultant Displacement of BIW



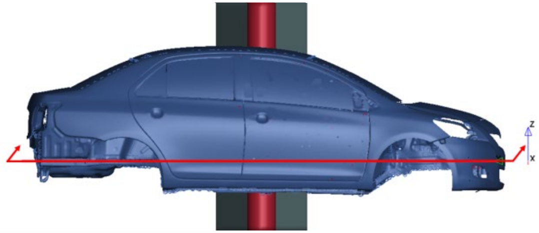


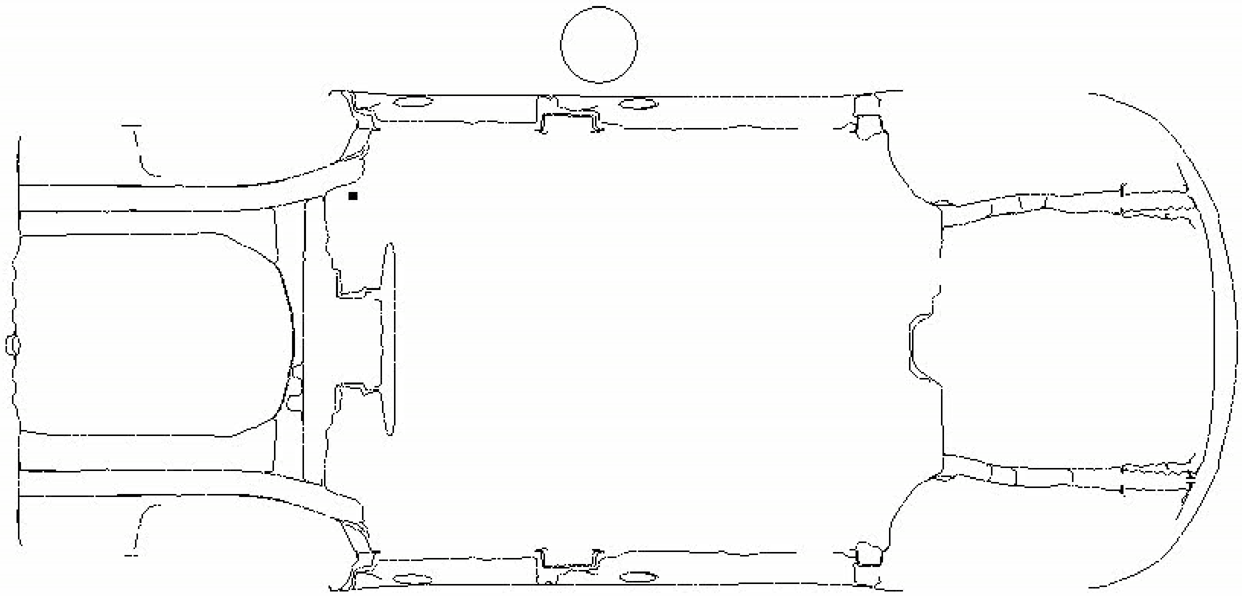
C. Accuracy





C. Accuracy





D. Decomposition Aspects

- Default Decomposition: Recursive Coordinate Bisection (RCB)
- Special Decomposition: User defined
    - Parallel to velocity

D. Decomposition Aspects

1 Color = 1 CPU

The two greens are different

RCB

Parallel to velocity

IV- Conclusion & Further Investigation

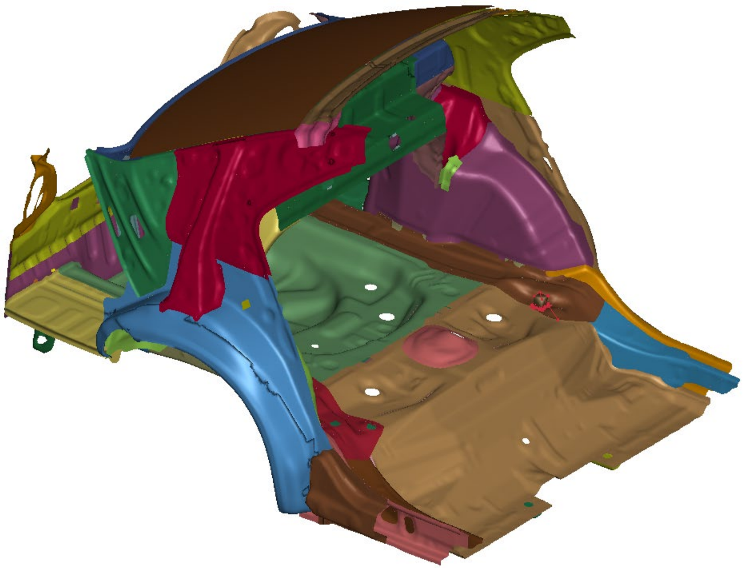
IV- Conclusion & Further Investigation

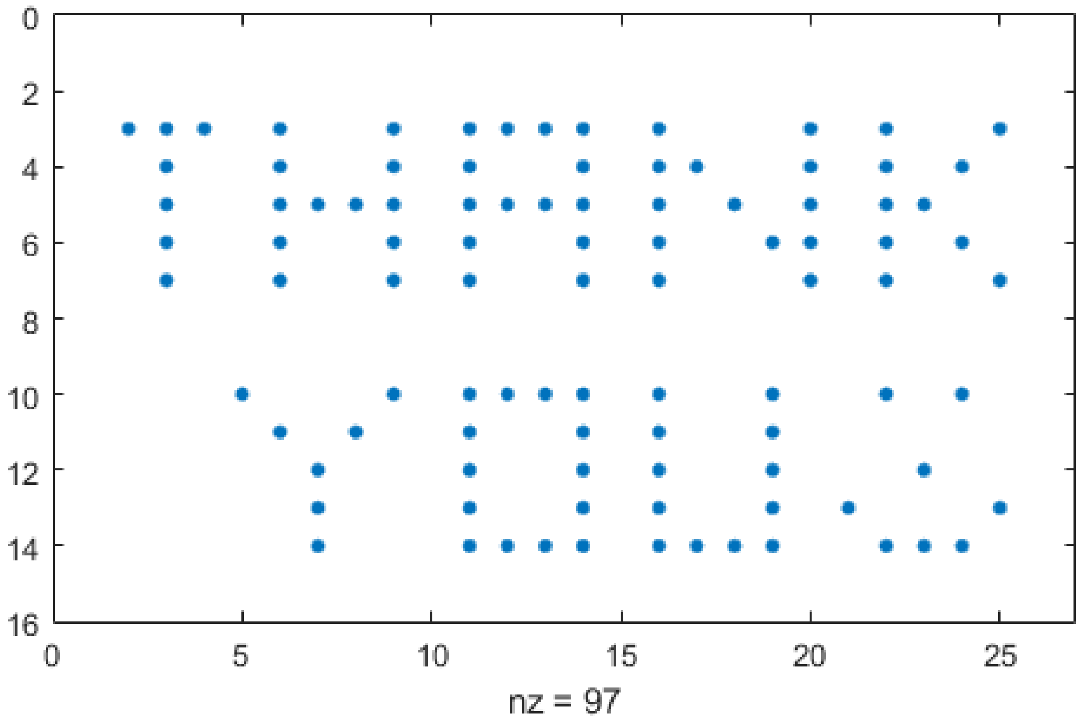
- SE provides better time performance than LFB in small displacement problems
- SE fails to achieve accuracy in large displacement problems
- SE reduces contact algorithm's time more than LFB
- SE has better rigid body handling than LFB
- Interactive nature of reduced parts influences accuracy
- Performance of LFB and D2R depends on
  - Computing environment
  - NCPU
  - MPP decomposition
- Reducing together is better than reducing alone
- Accepting the LFB and D2R approximation depends on the study's aim

IV- Conclusion & Further Investigation

- ❑ Perform a frequency analysis
- ❑ Study the scalability of LFB and D2R
- ❑ Study the influence of MPP decomposition
- ❑ Reduce a more compact part of the vehicle

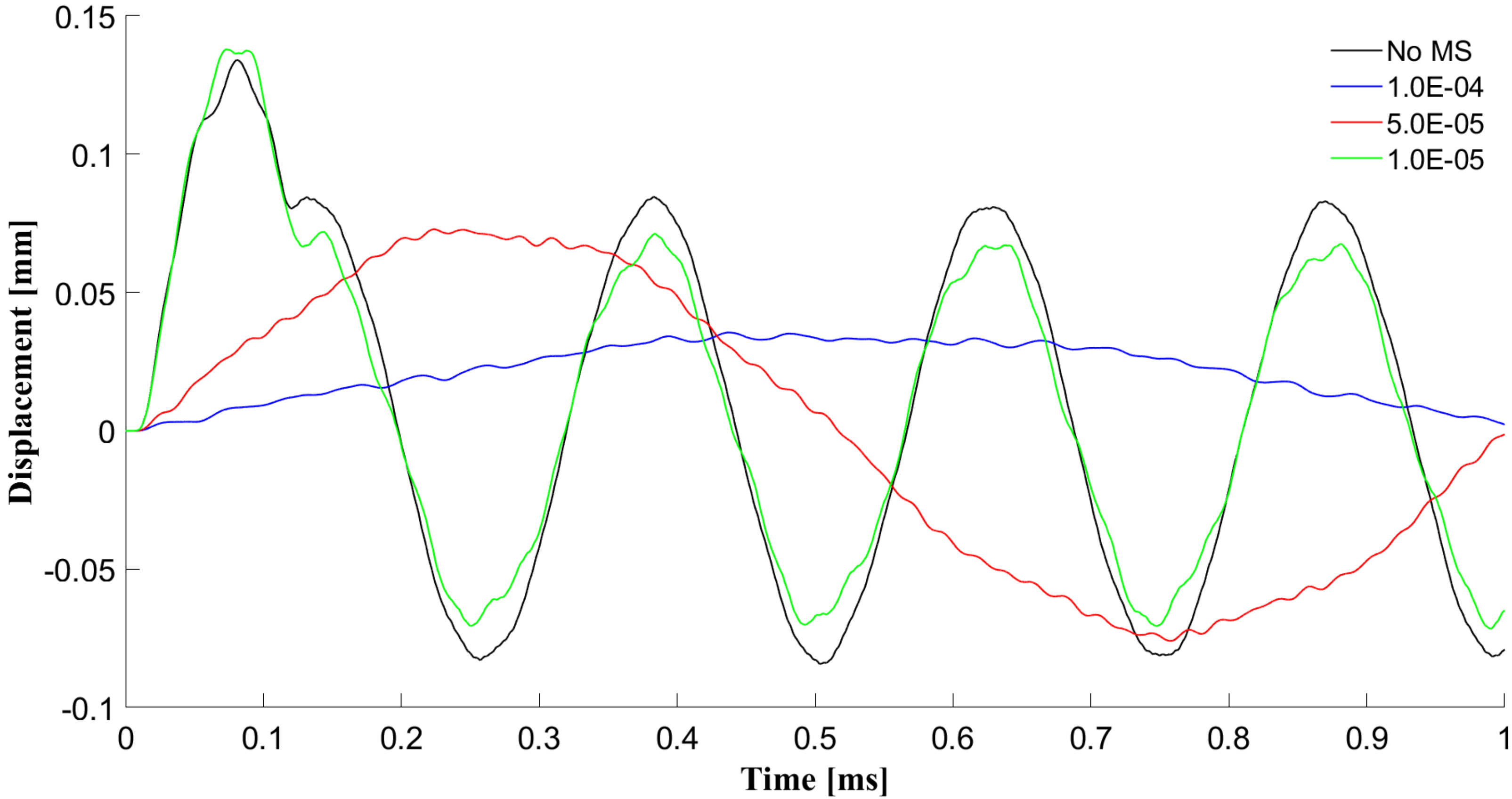
  Use the number of elements as a measure of size
- ❑ Apply reduction externally
- ❑ Test Hybrid LS-DYNA



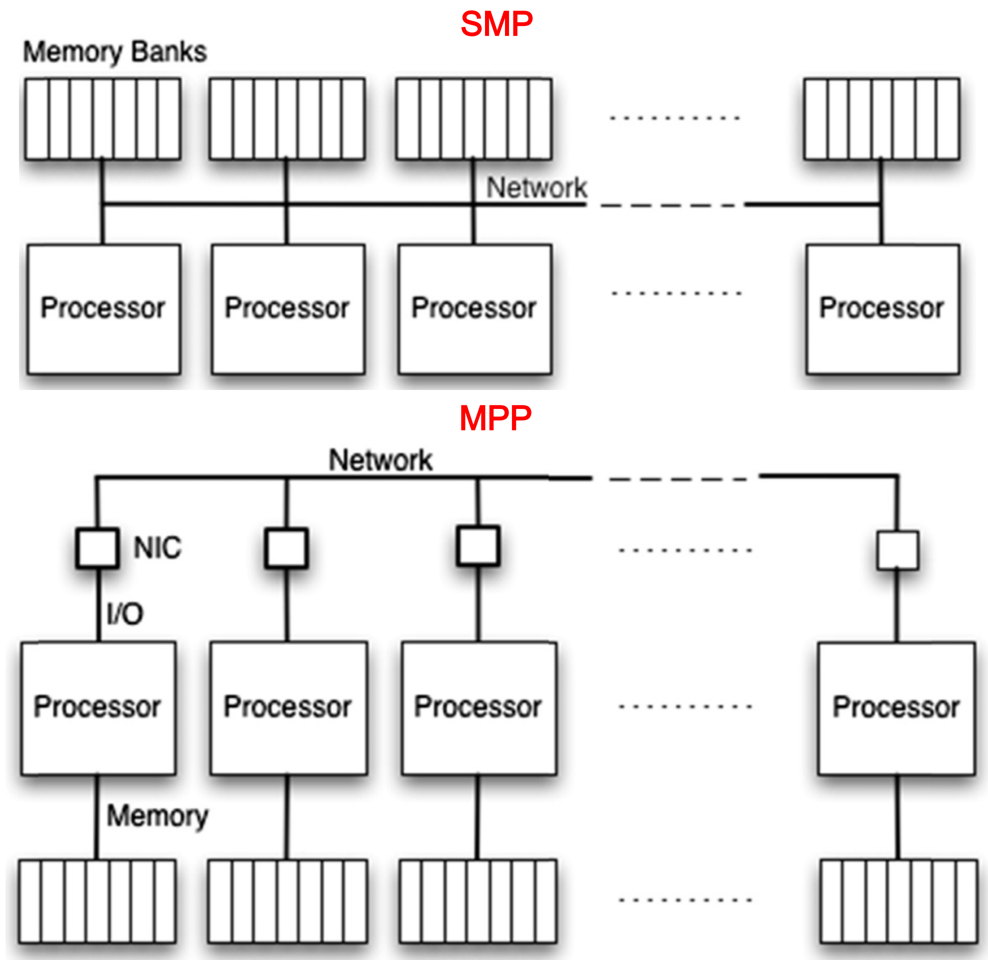

0
2
4
6
8
10
12
14
16
0
5
10
15
20
25
nz = 97

Back Slides

Effect of Mass Scaling on Accuracy



SMP vs. MPP


SMP
Memory Banks
Network
Processor
Processor
Processor
Processor
MPP
Network
NIC
I/O
Processor
Processor
Processor
Processor
Memory

Inconsistency using Recursive Coordinate Bisection

Table 15: Run time inconsistency of the FOM (*in seconds*)

CPUs	R1	R2	R3	R4	R5	Disc. [%]
4	61,440	61,404	56,606	56,409	54,755	12
8	29,450	29,921	30,943	30,892	30,910	5
16	18,109	19,779	13,891	13,861	9,169	116
40	8,745	10,895	7,873	9,639	7,988	38

Decomposition over 4 CPUs

Table 19: MPP control card influence on LFB performance using 4 CPUs (*time in seconds*)

(a) Time performance

	With Control		Without Control	
	Full	**LFB 40**	**Full**	**LFB 40**
Time	59,027	64,453	56,508	49,020
Red. [%]	-	-9	-	14
Disc. [%]	1	0.6	3	2

(b) Time breakdown

	With Control		Without Control	
	Full	**LFB 40**	**Full**	**LFB 40**
EP	24,578	19,097	22,937	15,391
CA	23,489	23,332	21,436	14,795
RB	564	9,382	476	7,586

Performance Instability in a Practical Environment

Table 21: Time performance over different time frames (work shifts)

	8 CPUs			12 CPUs		
	Time [s]	Red. [%]	Disc. [%]	Time [s]	Red. [%]	Disc. [%]
Full	33,556	-	1	16,220	-	6
LFB 40	29,720	11	67	17,562	-7	3
D2R	20,523	39	16	14,411	11	23

Time consistency using Control MPP (CPU > 4)

Table 22: Influence of CONTROL_MPP_DECOMPOSITION_AUTOMATIC on time consistency in an isolated environment (*time in seconds*)

(a) Using 16 CPUs

	R1	**R2**	**R3**	**R4**	**Mean**	**Disc. [%)]**
without	18,109	19,779	13,891	13,861	16,410	43
with	13,070	13,122	13,097	13,082	13,093	0.4

(b) 8 CPUs

	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**Disc. [%]**
without	29,450	29,921	30,943	30,892	30,910	30,423	5
with	33,192	33,113	33,073	33,030	33,008	33,083	0.56

Influence of LS -DYNA version

Table 24: Influence of LS-DYNA version on performance (*in seconds*)

(a) Time performance

	Full		**LFB 40**		**D2R**	
	10.2	**11.1**	**10.2**	**11.1**	**10.2**	**11.1**
Time	33,556	33,083	29,391	34,725	21,734	24,049
Red. [%]	-	-	12	-5	35	27

(b) Time breakdown

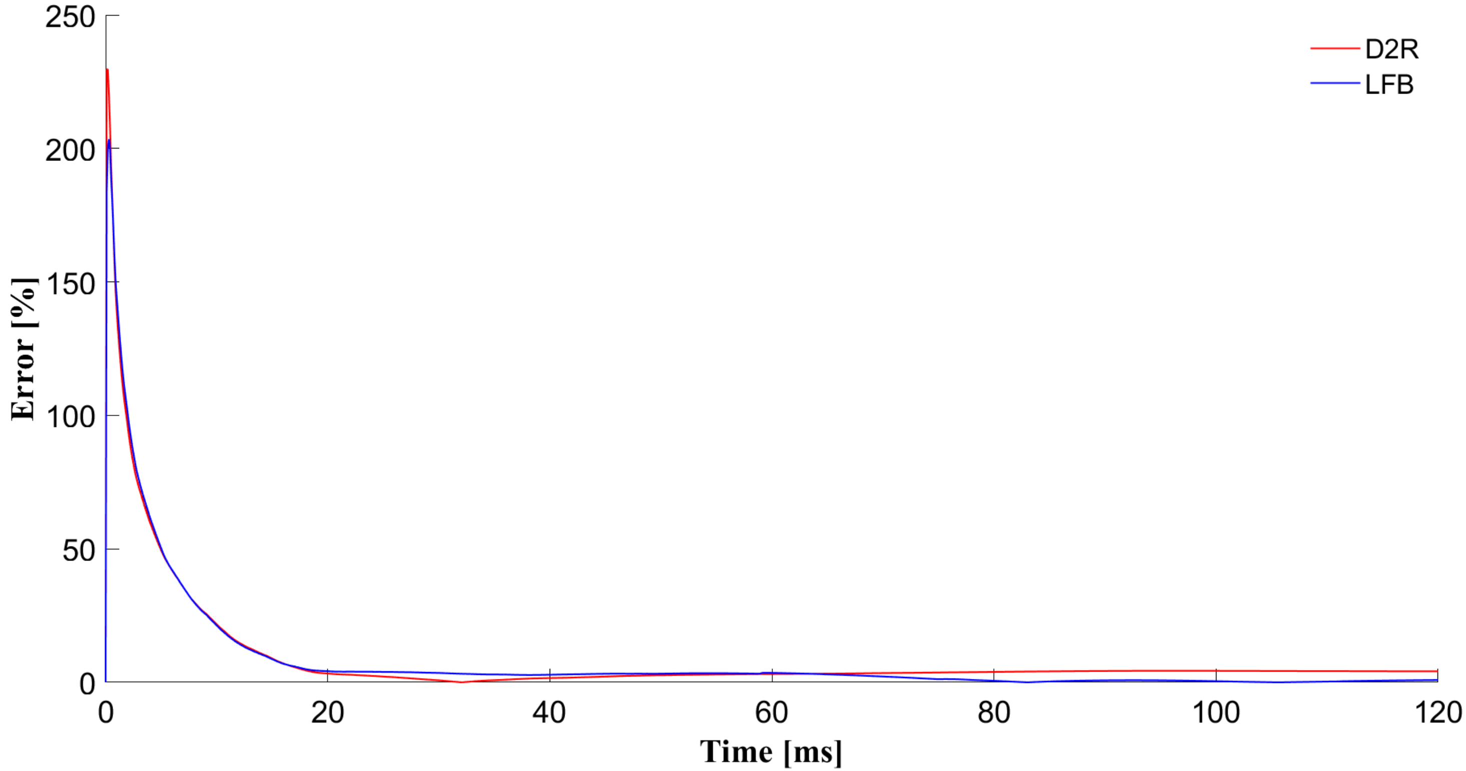
	Full		**LFB 40**		**D2R**	
	10.2	**11.1**	**10.2**	**11.1**	**10.2**	**11.1**
EP	12,056	12,133	7,844	8,968	7,705	7,990
CA	13,060	12,804	9,519	12,121	7,952	8,984
RB	602	416	4,012	6,941	562	547

Reduction of Main Process (Weakly vs. Strongly Isolated)

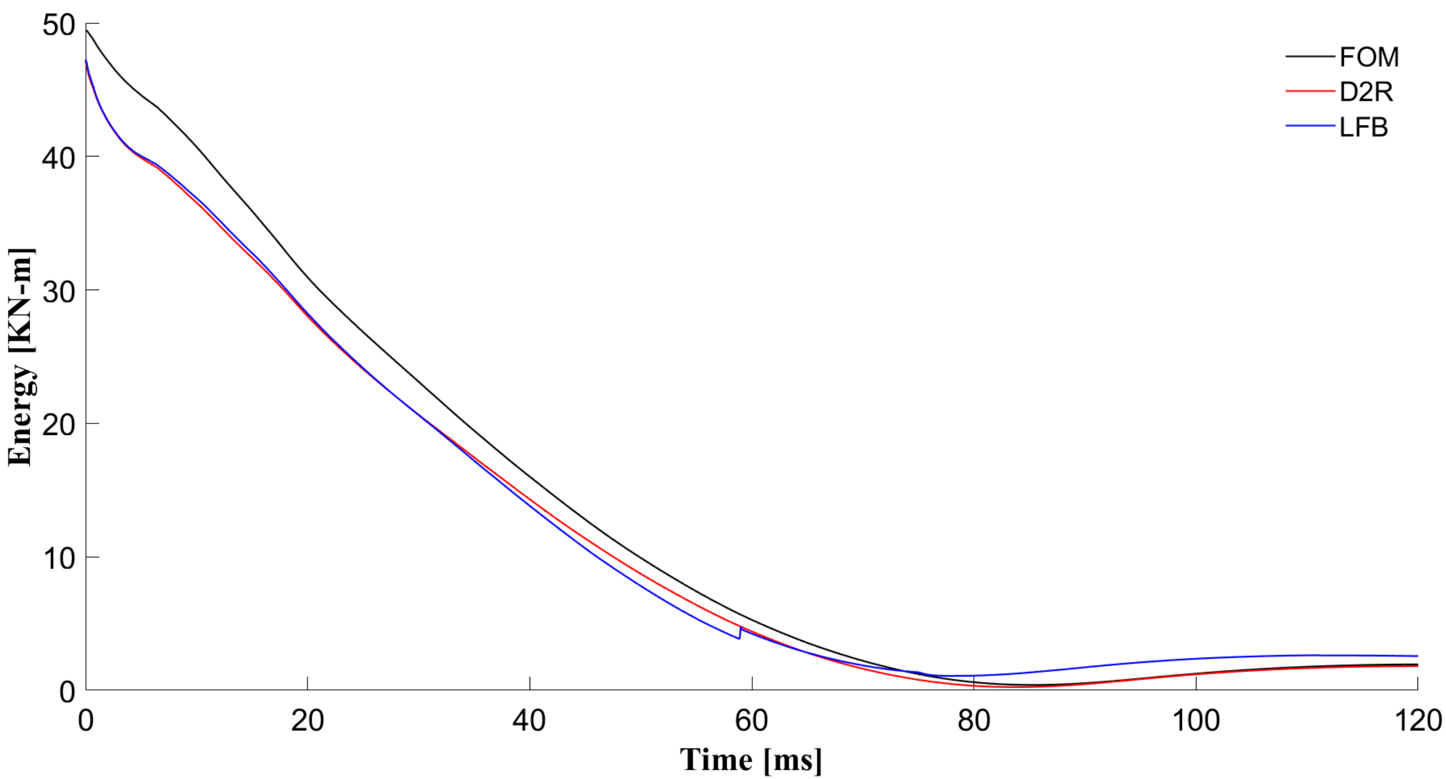
Table 26: Main processes' reduction due to strongly isolated environment (in %)

	Full	**LFB 40**	**D2R**
EP	54	49	43
CA	67	65	55
RB	78	65	61

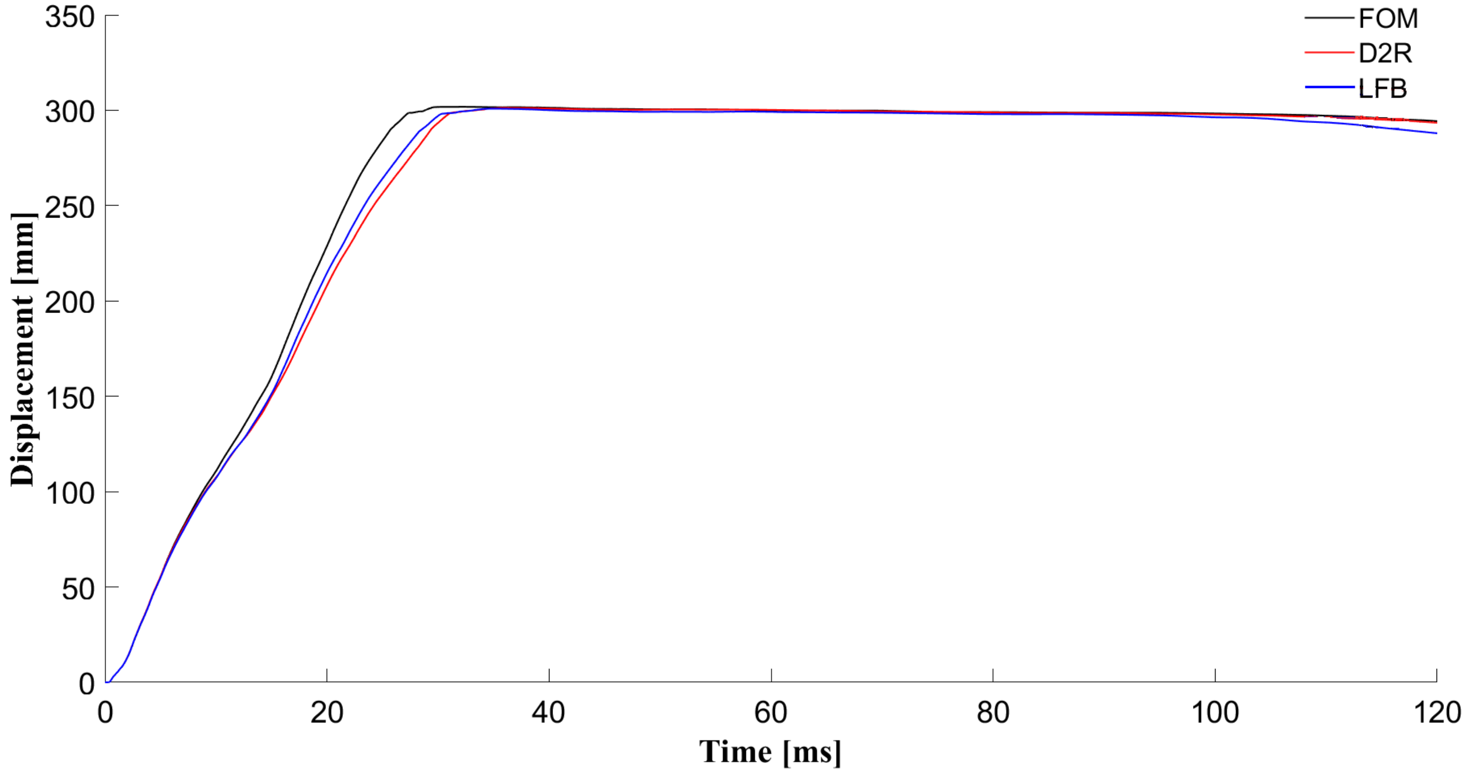
Internal Energy



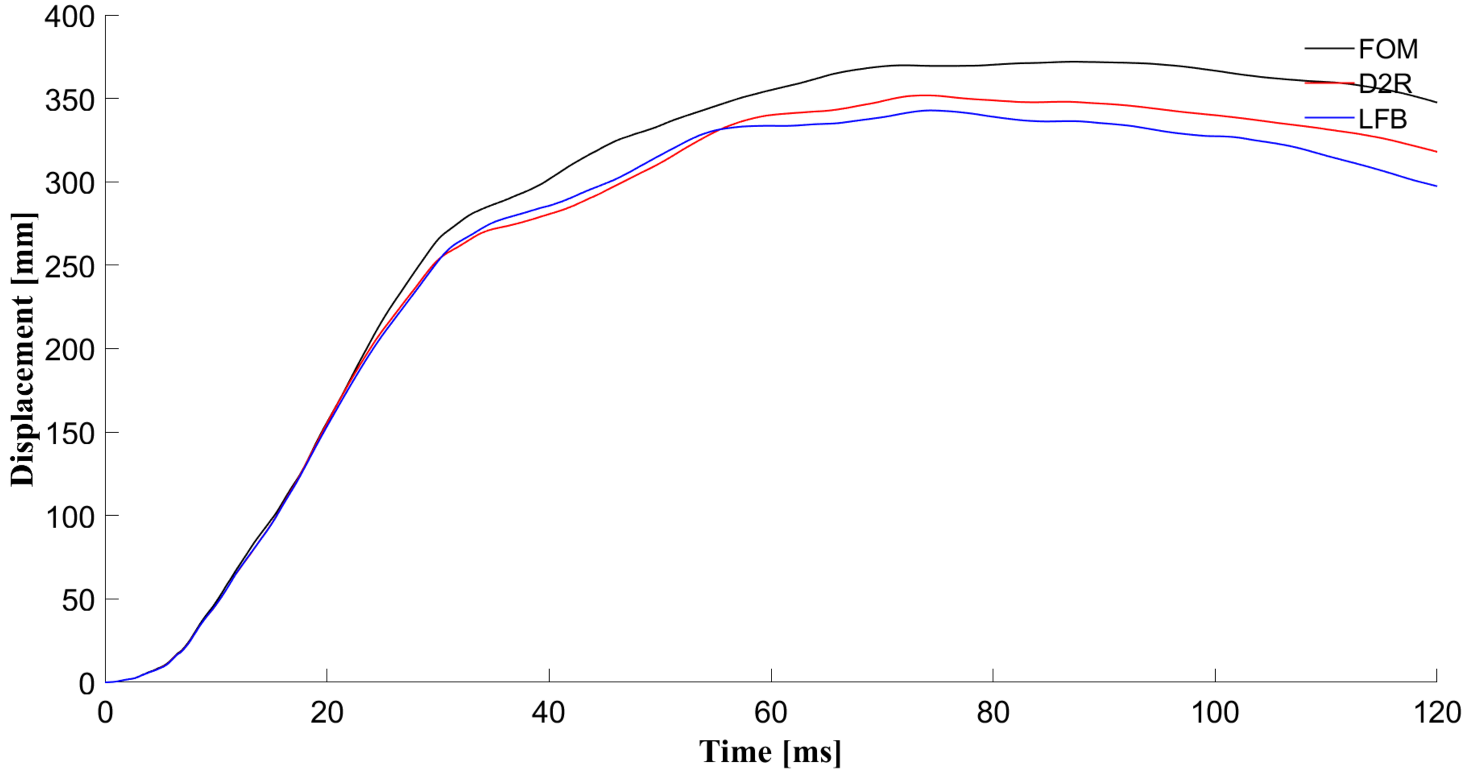
Kinetic Energy



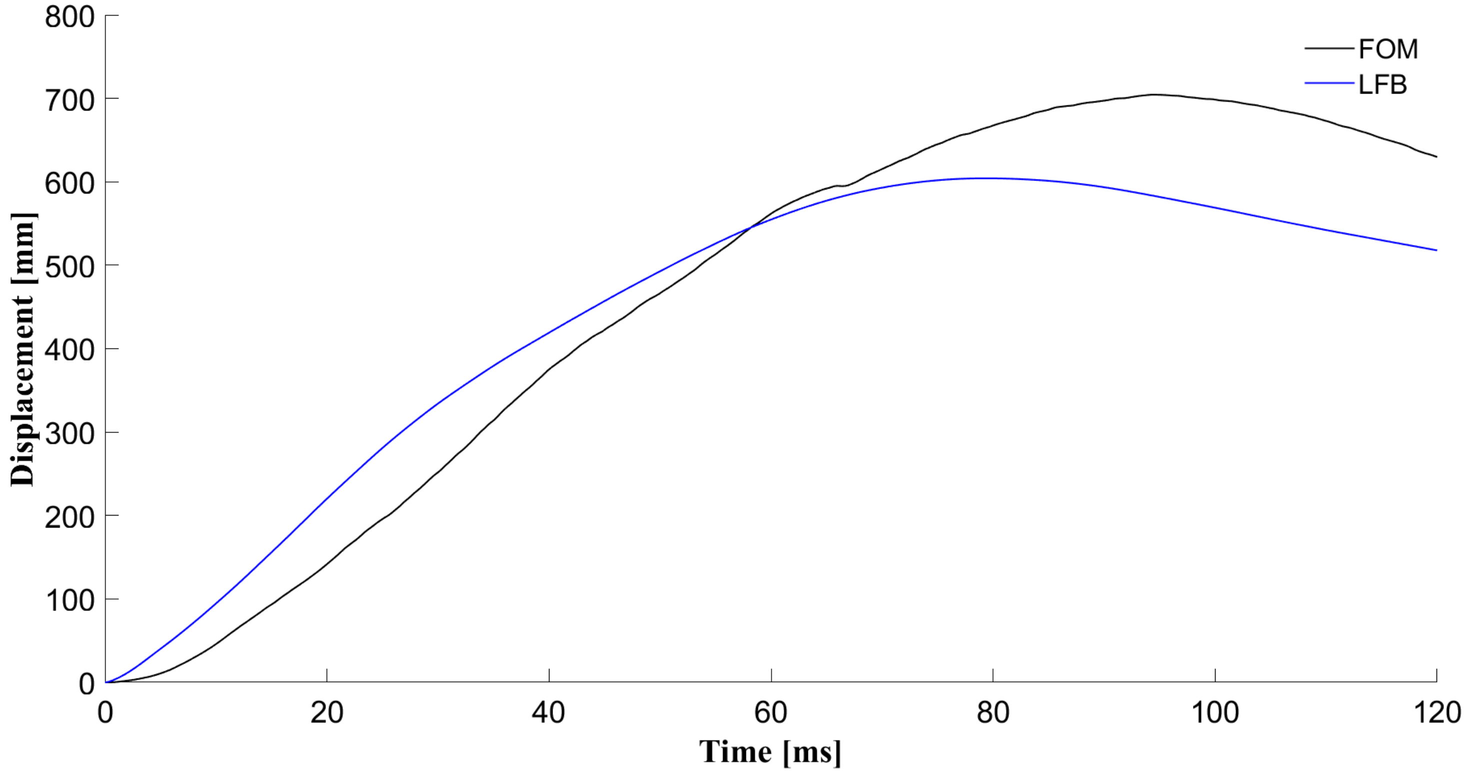
Left Front Door



Left Rear Door

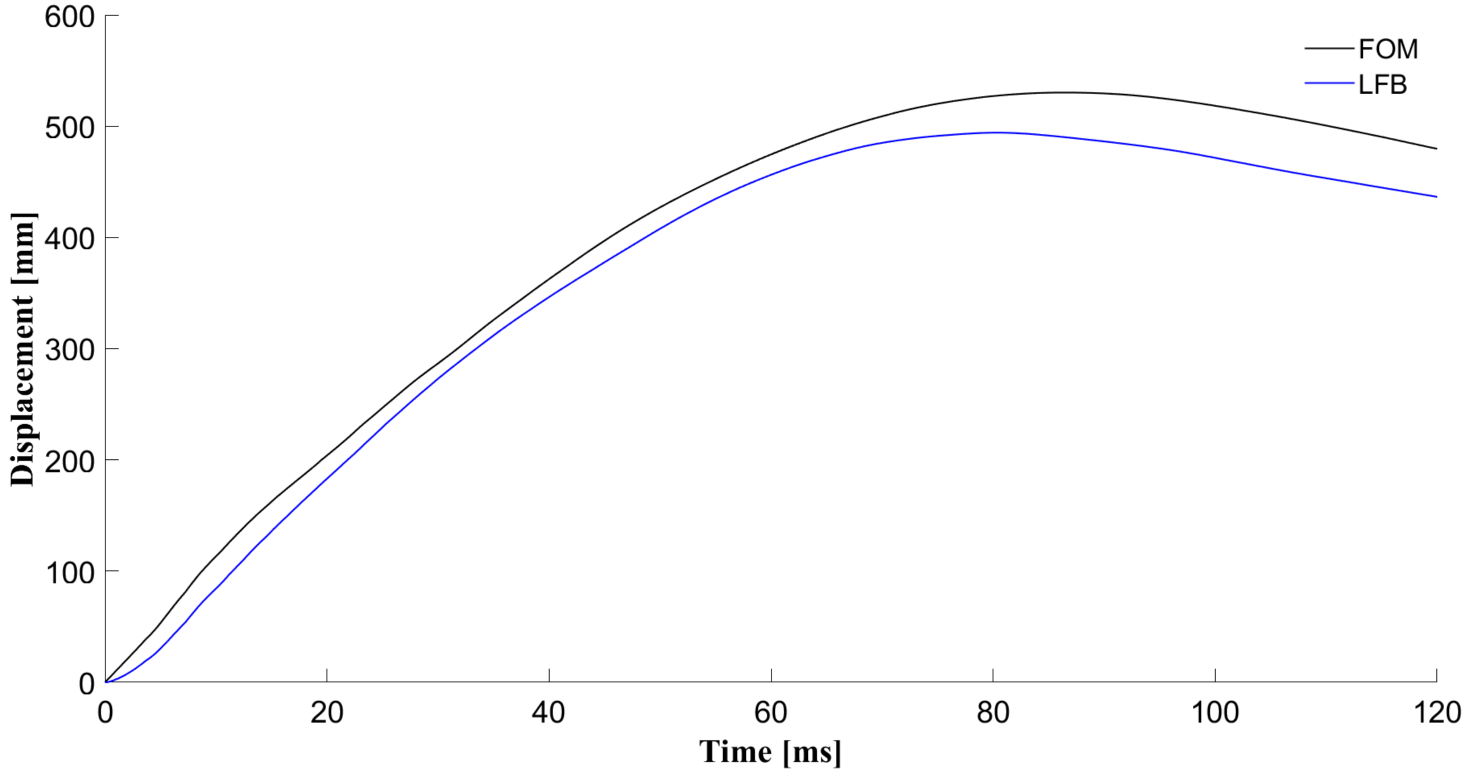


CMS



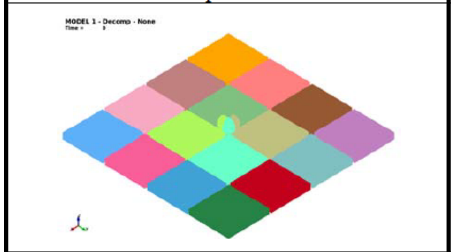
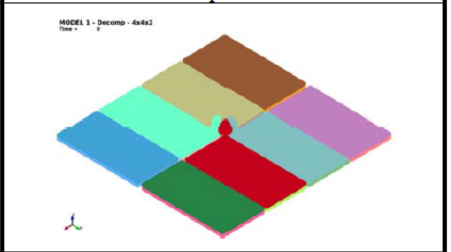
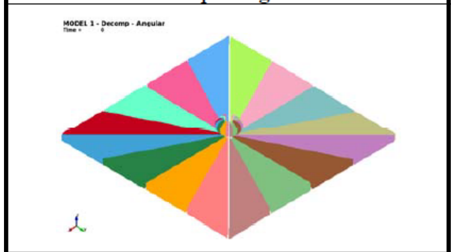
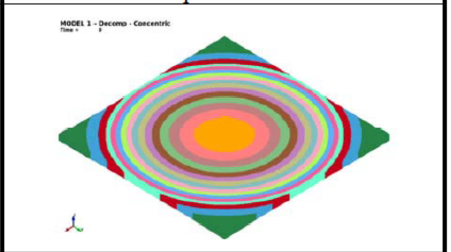
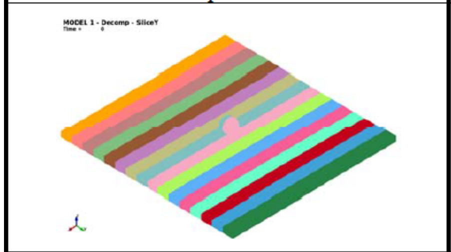
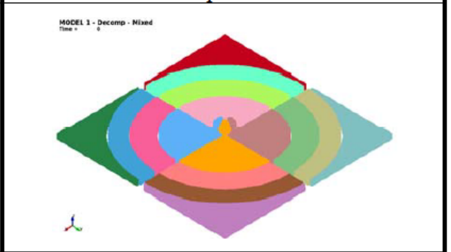
FOM
LFB
Displacement [mm]
Time [ms]
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
120

Hatch



600
500
400
300
200
100
0
0
20
40
60
80
100
120
Displacement [mm]
Time [ms]
FOM
LFB

Decomposition Example

Decomp "**Default**"	Decomp "**4x2x2**"
	
none	*"decomp {sz 8.5 sx 2 }"*
Decomp "**Angular**"	Decomp "**Concentric**"
	
"decomp {c2r 0 0 0 0 0 1 1 0 0 sy 5000} "	*"decomp {c2r 0 0 0 0 0 1 0 1 0 sx 5000}"*
Decomp "**Slice Y**"	Decomp "**Mixed**"
	
"decomp {sy 5000}"	*"decomp {c2r 0 0 0 0 0 1 1 0 0}"*