



## **MORPACK – Model Order Reduction PACKage**

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**Project:** MORPACK – Model Order Reduction PACKage

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**Objective target:** Using MORPACK reduced elastic bodies based on FE-models are generated automatically, which are applicable for elastic multi-body-simulation (EMBS) and various FE-programs. The automated process contains the steps data import, model preparation (definition of connections and additional master-nodes), model order reduction (including back-transformation and mode-truncation), quality assurance by correlation techniques, and data export. An associated objective is the consideration of boundary conditions under inset-conditions by pre-simulation within the EMBS-assembly.

**Current status:** The software MORPACK covers the whole generation process of elastic bodies and was tested and proved for numerous models of different size. For several settings an optimal pre-selection exists. Right now, the final settings for the greatest possible automatization are determined using different verification models. The software is continuously extended and improved concerning user friendliness and efficiency.

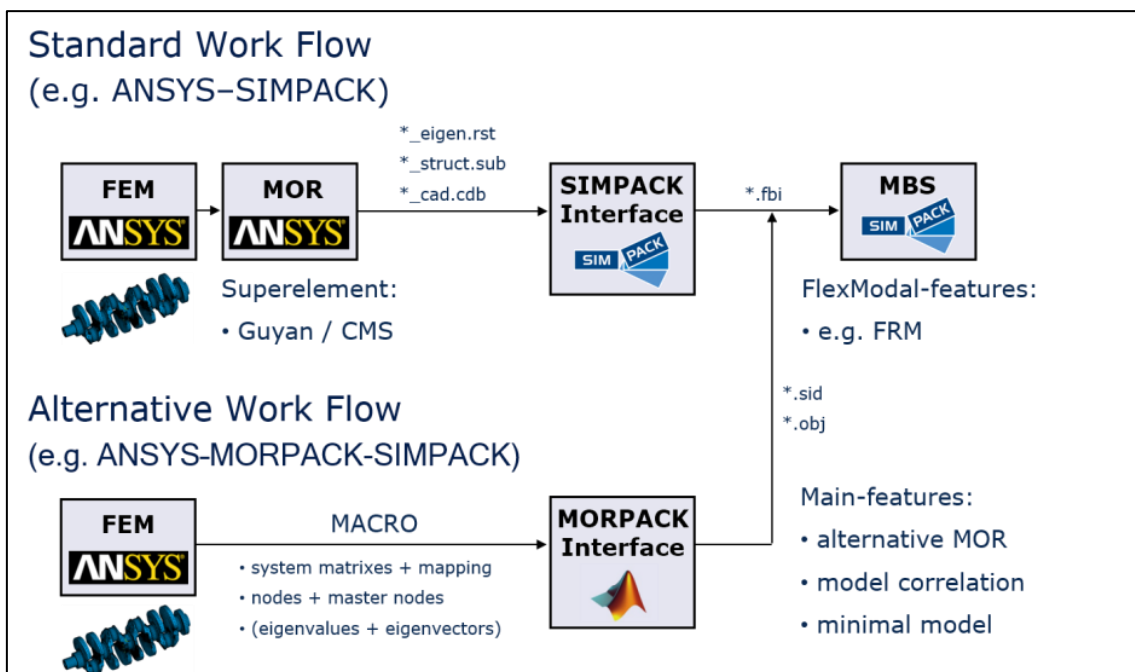
**Duration:** since 2008

**Funding/Partner:** self-funding

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The utilization of elastic bodies in elastic multi-body-simulation (EMBS) is state of the art, when simulating dynamic processes close to reality in machinery and its drive trains. The generation of elastic bodies based on FE-models makes up a crucial step, which nevertheless is little standardized yet. The whole process chain including model preparation, model reduction and export of the elastic body requires a lot of sub steps in different software. Thus, the process is barely automated, little user-friendly and very error-prone due to the variety of possible settings. The software MORPACK overcomes these drawbacks. In the first place all sub steps and settings are systematized. In the following, the settings are determined automatically depending on the model, leading to the greatest possible automatization and standardization of the whole process.

The tool MORPACK is developed at the chair of dynamics and mechanism design and designed to reduce and validate FE-models by using alternative reduction techniques and suitable correlation techniques. By using MORPACK, the whole process for generating elastic bodies is combined in one tool. The generation is done automatically using a comfortable GUI and tailored to the special user requirements within the EMBS-process. MORPACK acts as an interface between FE-program and MBS-software (Figure 1).



**Figure 1:** Workflow at the example of ANSYS and SIMPACK using conventional software (top) and using MORPACK (bottom)

MORPACK is completely implemented in MATLAB and under research at the moment. The software is extended and improved continuously. Currently, MORPACK is not commercially available. For research-related cooperation or student research projects a temporary test version can be provided. Our services also cover the reduction and validation of your FE-models up to the generation of elastic bodies for SIMPACK. The associates of the chair are at your disposal for questions, demonstrations and inquiries at any time.

## Publications

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**Lein, C.; Beitel Schmidt, M.:** *Challenges in Modeling Flexible Bodies based on Experimental Data with Utilization in Elastic Multibody Simulation*. PAMM-Proceedings of Applied Mathematics and Mechanics, submitted 2017.

**Zhang, J.; Lein, C.; Beitel Schmidt, M.:** *Model reduction methods with application to frequency-dependent viscoelastic finite element model*. Proceedings 27th ISMA (International Conference on Noise and Vibration Engineering), Leuven, Belgium, pp. 1813-1827, 2016.

**Woller, J.; Lein, C.; Zeidler, R.; Beitel Schmidt, M.:** *A Numerical Study of the Structure-Borne Sound Transmission of a Bogie*, Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Cagliari/Sardinia, Italy, April 2016.

**Beitel Schmidt, M.; Vonstein, T.; Lein, C.:** *Verification and Optimization of Reduced FE-Models with Regard to Specific Boundary Conditions within the MBS-Assembly*, NAFEMS European Conference on Coupled MBS-FE Applications, Turin, Italy, October 2015.

**Lein, C.; Beitel Schmidt, M.:** *Back-Transformation into Physical Configuration Space after Model Order Reduction onto a General Subspace*. PAMM-Proceedings of Applied Mathematics and Mechanics, Vol. 15, No. 1, October 2015.

**Lein, C.; Beitel Schmidt, M.; Bernstein, D.:** *Improvement of Krylov-Subspace-Reduced Models by Iterative Mode-Truncation*, 8th Vienna International Conference on Mathematical Modelling, Wien, February 2015.

**Lein, C.; Beitel Schmidt, M.:** *Comparative study of model correlation methods with application to model order reduction*. Proceedings 26th ISMA (International Conference on Noise and Vibration Engineering), Leuven, Belgium, pp. 2683-2700, 2014.

**Lein, C.; Beitel Schmidt, M.:** *Impact of Geometry Simplification and Element Size on the FEM-MBS-Coupling-Process*, NAFEMS European Conference on Coupled MBS-FE Applications, Frankfurt, November 2013.

**Lein, C.; Beitel Schmidt, M.:** *MORPACK-Schnittstelle zum Import von FE-Strukturen nach SIMPACK*, at-Automatisierungstechnik, Jahrgang 60 (2012) Heft 9, Oldenbourg Wissenschaftsverlag, München, Germany, pp. 547-559.

**Lein, C.; Beitel Schmidt, M.:** *MORPACK-Schnittstelle zum Import von FE-Strukturen nach SIMPACK*. GMA-Fachausschuss 1.30, Salzburg, Austria, September 2011.

**Lein, C.; Beitel Schmidt, M.:** *MORPACK interface for importing FE-structures into SIMPACK by using alternative MOR-methods*, SIMPACK User Meeting, Salzburg, Austria, May 2011.

**Koutsovasilis, P.; Beitel Schmidt, M.:** *Model order reduction of finite element models: improved component mode synthesis*. Mathematical and Computer Modelling of Dynamical Systems, Volume 16, Issue I, February 2010, pp. 57-73.

**Koutsovasilis, P.:** *Model Order Reduction in Structural Mechanics - Coupling the Rigid and Elastic Multi Body Dynamics*. Dissertation, Technische Universität Dresden, 2009.

**Koutsovasilis, P.; Beitel Schmidt, M.:** *MORPACK Toolbox for Coupling Rigid and Elastic Multi-body Dynamics*. NAFEMS World Congress, 2009.

## Overview

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### **Model order reduction with conventional FE-software**

- 2 available reduction methods: Guyan-reduction and Component-Mode-Synthesis (CMS), e.g. in ANSYS
- no elaborate validation
- no user feedback
- no automatization

### **Advantages of MORPACK compared to conventional FE-software**

- qualitatively better reduced and smaller models compared to standard techniques by using sophisticated reduction methods
- reduction quality independent from choice of master-nodes
- efficient data handling
- large variety of methods and selections for advanced users
- standard selections for beginners, which were determined by numerous tests
- utilization of measured data for elastic bodies with application to EMBS

### **Module overview of MORPACK**

#### ***Import-Module:***

interfaces for different software packages available (ABAQUS, ANSYS, NASTRAN, LsDyna, SALOME and SIMPACK) as well as import of measurement data from experimental modal analyses (e.g. ME-Scope and UFF)

#### ***Connection-Module:***

automated definition of interface connections (rigid/elastic)

#### ***Additional-Nodes-Module:***

automated and optimal selection of additional master-nodes (for correlation and reduction purposes)

#### ***Reduction-Module:***

numerous combined reduction methods for generation of minimal models (including back-transformation as well as generation of additional modes)

#### ***Correlation-Module:***

numerous correlation methods for validation of interface connections and reduction quality (based upon modal data, frequency response function and system matrices)

#### ***Export-Module:***

model export to SIMPACK, ANSYS, NASTRAN and LsDyna

#### ***EMBS-Module:***

simplified and 3-dimensional EMBS-algorithm in MATLAB for validation of elastic bodies and consideration of boundary conditions under inset-conditions (EMBS-assembly)

## Further features of MORPACK

- modular concept for individual solutions
- implemented in MATLAB with comfortable GUI and batch-modus
- interactive help and user feedback including plausibility check
- models with a degree of freedom larger 1 Mio. can be handled on conventional desktop PCs
- for larger models an out-of-core library can be used

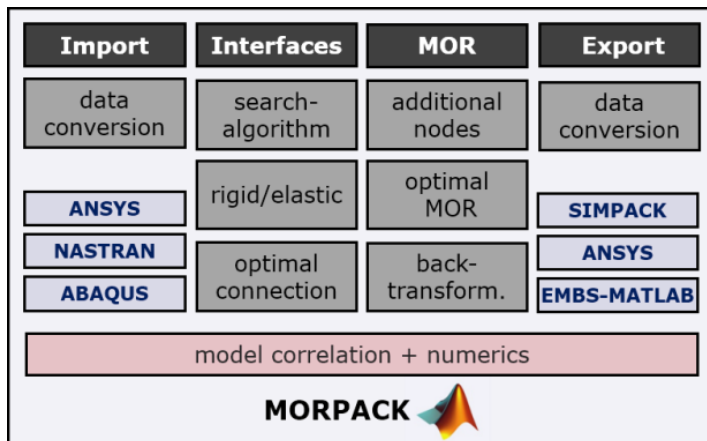


Figure 2: Workflow within MORPACK

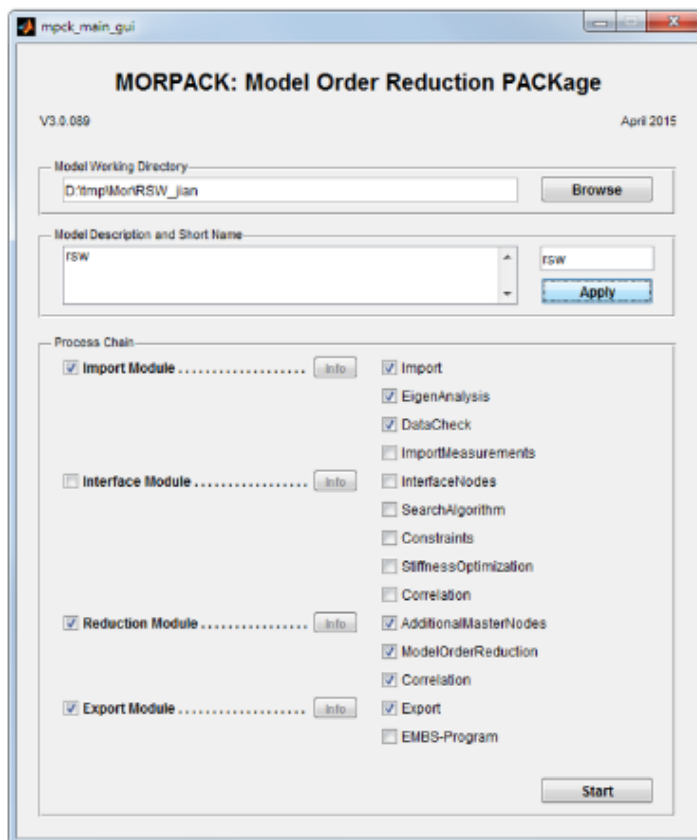


Figure 3: MORPACK start-GUI including modules

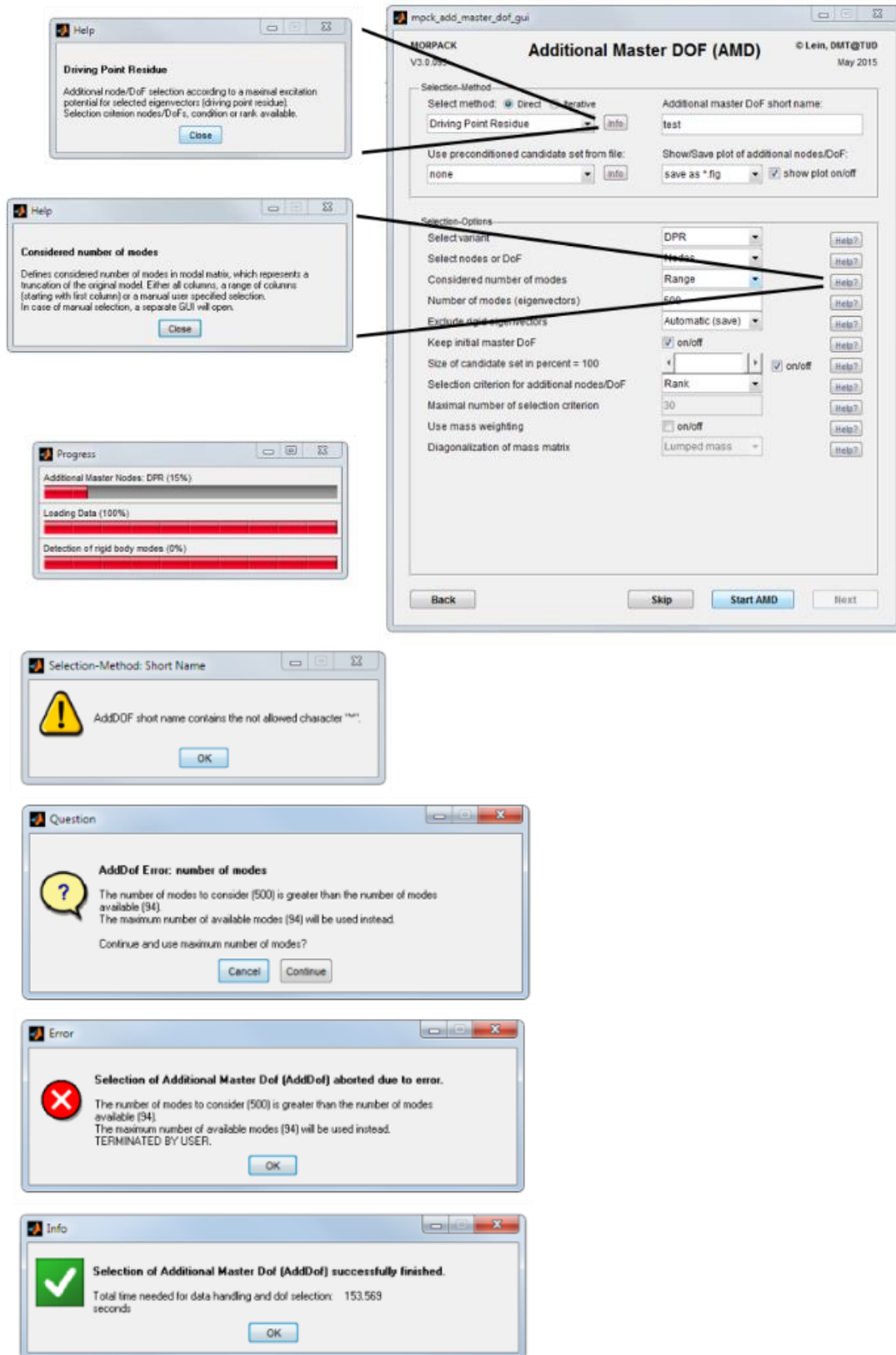


Figure 4: Comfortable GUI with interactive help and user feedback

## Import-Module

The import-module imports FE-data from the software packages ABAQUS, ANSYS, NASTRAN, LsDyna and SALOME (system matrices, node lists and node coordinates) as well as reduced order FE-models. Optionally, results from numerical modal analyses can be read in. Macros are used for the data export form the FE-programs. Furthermore, data from experimental modal analyses can be imported (e.g. ME-Scope and UFF-files).

### Features:

- interfaces for ABAQUS, ANSYS, NASTRAN, LsDyna, SALOME, ME-Scope
- automated data import via macros
- definition of different damping models or import of damping matrices
- calculation of modal analysis or import of modal data
- automated check of imported data concerning plausibility
- animation of a node-based mesh (independent from FE-mesh)

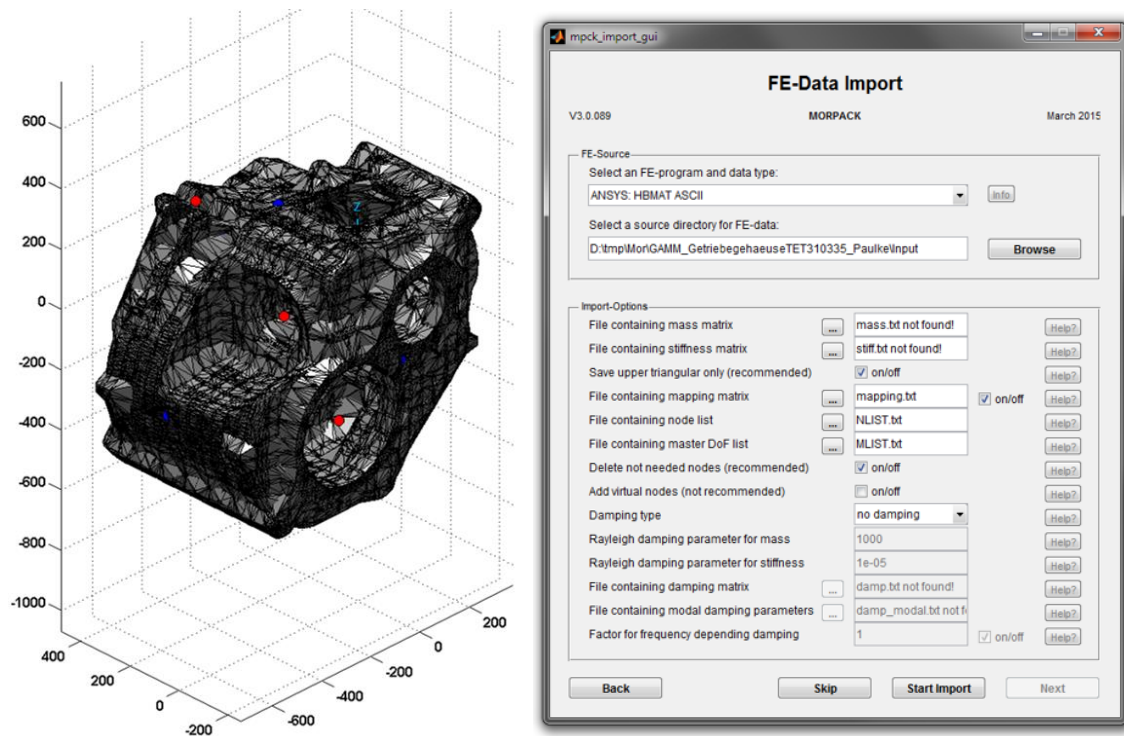


Figure 5: Import with GUI at the example of a gear box housing

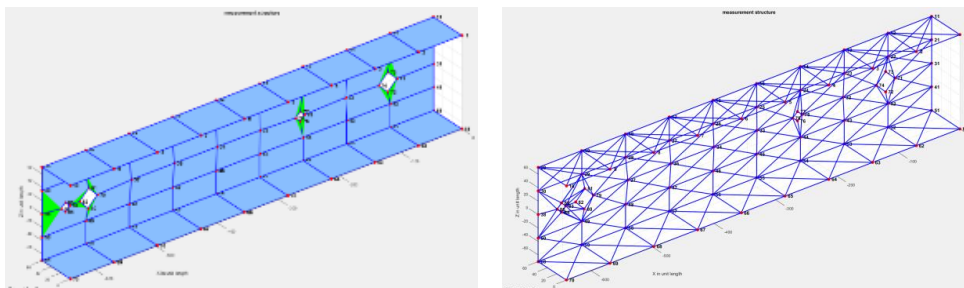


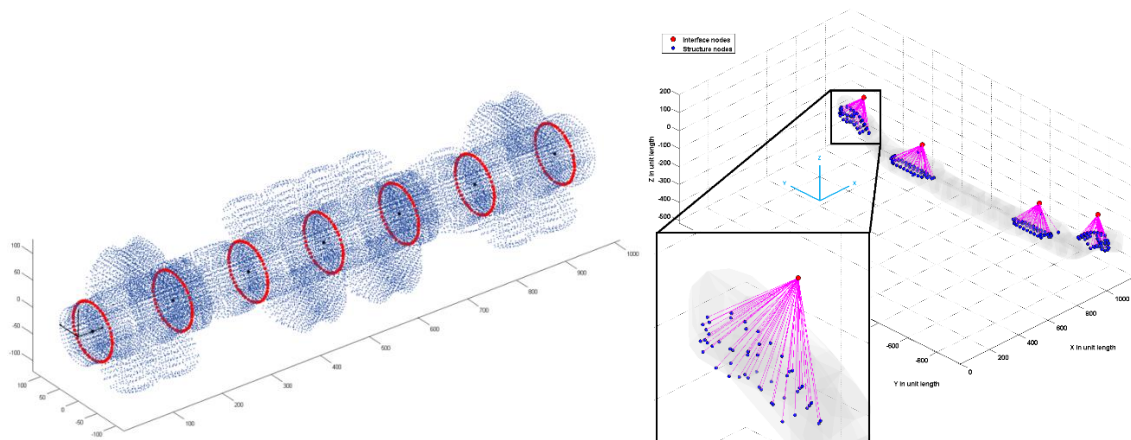
Figure 6: Import of ME-Scope data of a truss

## Connection-Module

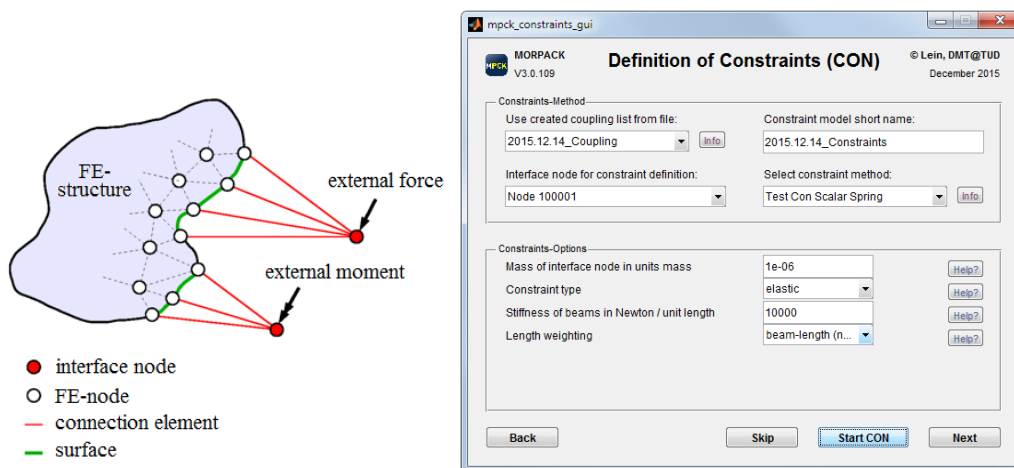
Within the connection-module connections between FE-structure and master-nodes are defined. This step is mandatory, since the EMBS requires interface nodes with 6 DoF per node. The connection definition is a crucial aspect and essentially influences the dynamic behaviour of the model. The generation of connections in conventional software is often confusing and therefore error-prone.

### Features:

- automated generation of rigid or elastic connections
- node-search-algorithm for automated selection of nodes on the FE-structure according to connection type (bearing, surface, circumference, etc.)
- optimization of connection definition
- automated correlation of the modified model compared against the original model



**Figure 7:** Connection definition at the example of a crank shaft and an axle



**Figure 8:** Connection principle and GUI



## Additional-Nodes-Module

By using the additional-nodes-module, additional master-nodes are chosen for correlation and some reduction methods. Therefore, 7 direct and 8 iterative techniques are available, which are based upon energetic relations. An automated selection concerning the linear independence of modes is considered.

### Features:

- direct algorithms (e.g. MKE)
- iterative algorithms (e.g. Efl)
- the iterative algorithms are distinguished into expanding and reducing techniques
- automated and optimal selection according to different quality measures
- animation of selected nodes

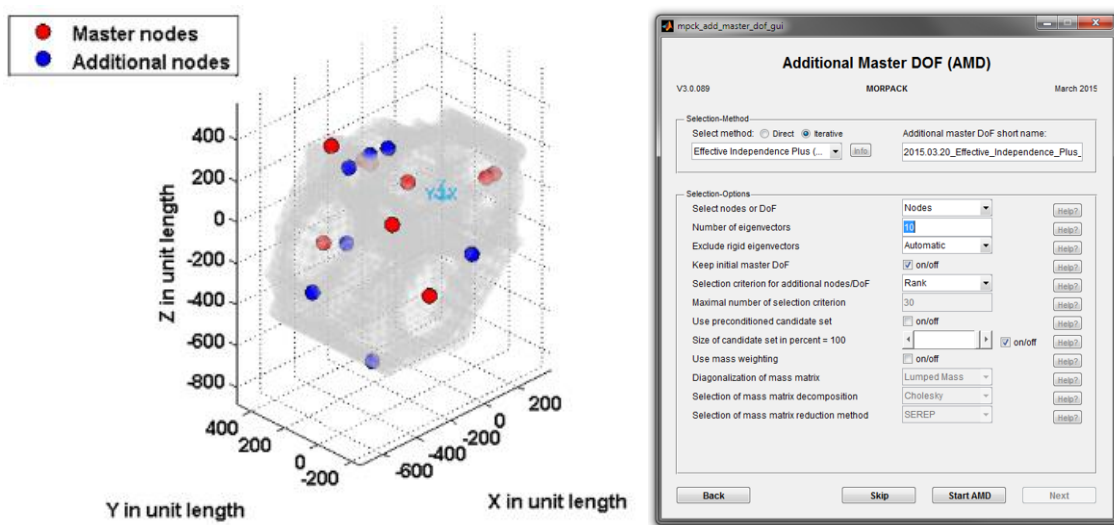


Figure 9: Selection of additional nodes with GUI at the example of a gear box housing

## Reduction-Module

The core of MORPACK is the reduction-module. A total of 12 basic methods including conventional and modern methods are available. By an appropriate combination (multi-step methods) 6 further methods are possible, leading to minimal models. For the calculation, 8 solvers are available, whereby a suitable solver is proposed depending on the reduction method used.

### Features:

- conventional reduction methods (e.g. Guyan, CMS, IRS, SEREP)
- modern methods (e.g. Krylov-subspace method, second order balanced truncation)
- generation of minimal models by using multi-step methods and mode-truncation
- generation of reliable models by application of convergence criteria
- methods with semi-automated parameter choice (e.g. Krylov-subspace-method with convergence criterion)
- large variety of methods and selections for advanced users as well as optimised standard selections for beginners
- back-transformation into physical configuration space for a physical interpretation of the reduced order model
- definition of additional modes (e.g. FRM)

Basic methods	physical	semi-physical	non-physical.	ANSYS	MORPACK
Static Reduction Guyan	X			X	X
Dynamic Reduction Dynamic	X				X
Standard Improved Reduction System Method IRS	X				X
System Equivalent Reduction Expansion Process SEREP		X			X
Component Mode Synthesis CMS / Craig-Bampton Method		X		X	X
Combinations based on IRS / CMS / KSM ICMS / KCMS / IKCMS		X			X
Krylov Subspace Method KSM / Rational KSM / Block-KSM			X		X
Second Order Balanced Truncation SOBT / frequency-weighting			X		X

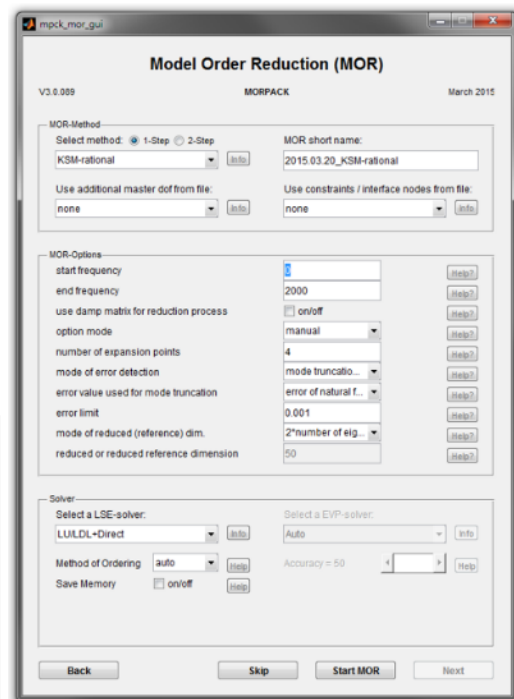


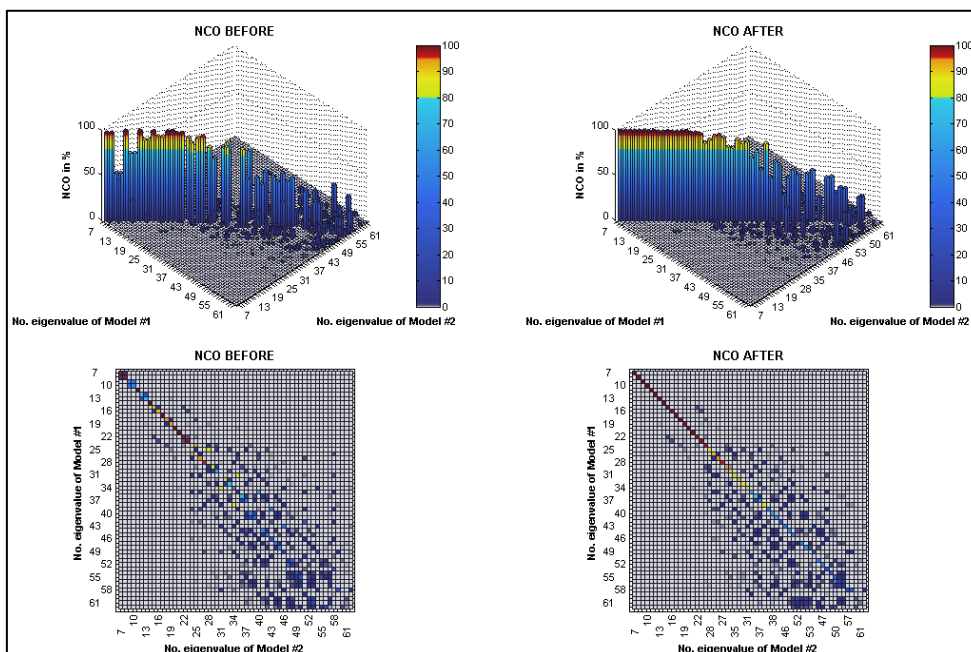
Figure 10: Model reduction methods with GUI

## Correlation-Module

An important step within the process is the quality assurance. Within the correlation-module a comparison between original and reduced model, between two different reduced order models and between two different original models is available. A verification with imported measurement data is also possible. For the correlation, over 60 criteria are available. A crucial step is the model preparation, which includes a reliable detection of rigid body modes and a dimension adaptation. By the correlation of models based on a smaller dimension, even large models can be compared efficiently and reliably. Furthermore, by using a mode-pairing and linear combination, the modes of different models are assigned correctly and reliably.

### Features:

- methods based on normal frequencies (e.g. NTFD)
- methods based on normal modes (e.g. MAC and variants)
- methods based on frequency response functions (e.g. FDAC)
- methods based on system matrices (e.g. MMA)
- automated detection of rigid body modes
- automated dimension adaptation
- correlation based on an intermediate dimension for an efficient and fast evaluation of very large models
- mode-pairing and linear combination for a correct assignment of modes and consideration of a phase shift in case of axisymmetric structures
- statistic evaluation and automated determination of valid modes (valid frequency range)
- animation of mode shapes



**Figure 11:** Impact of mode-pairing and linear combination

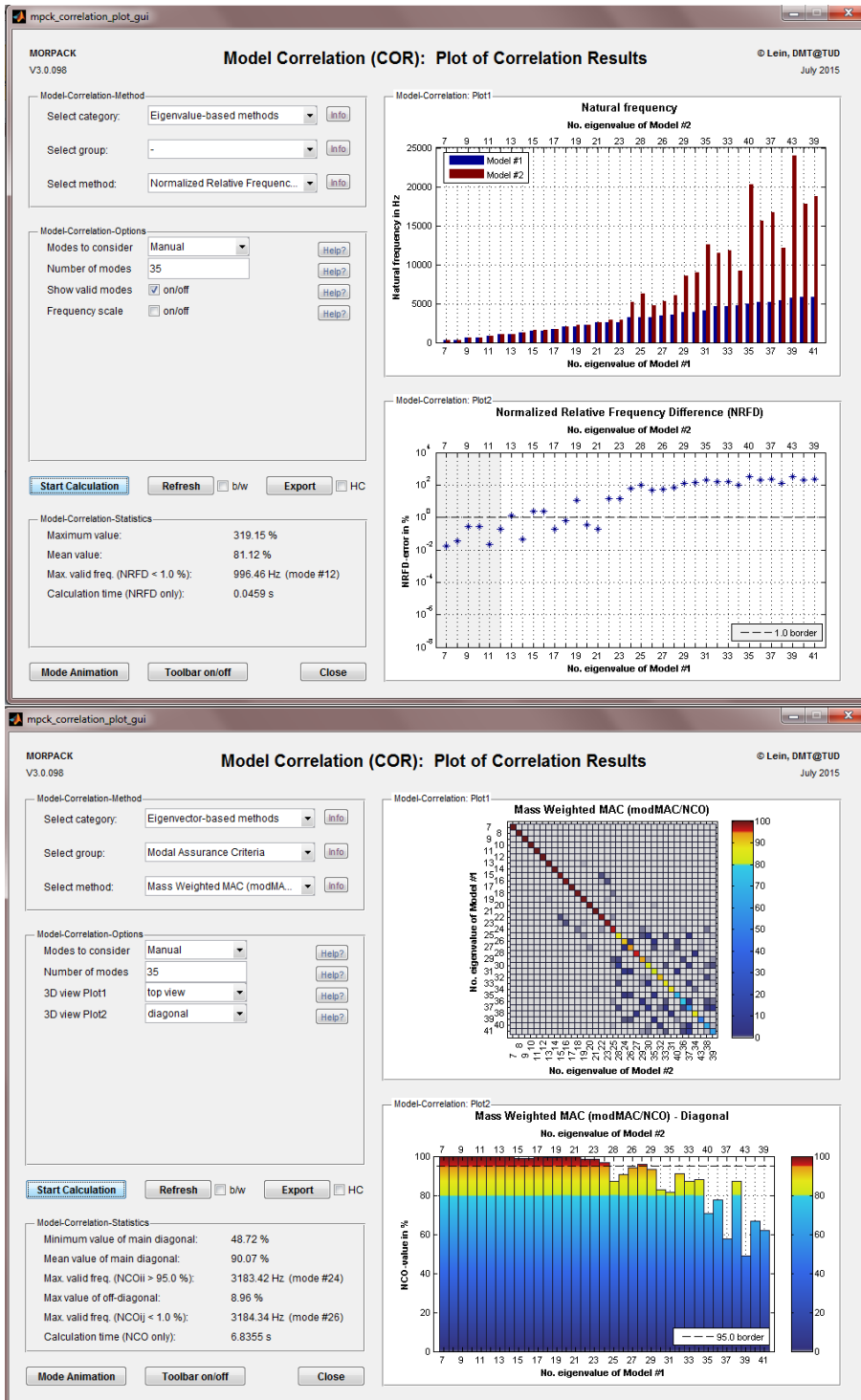


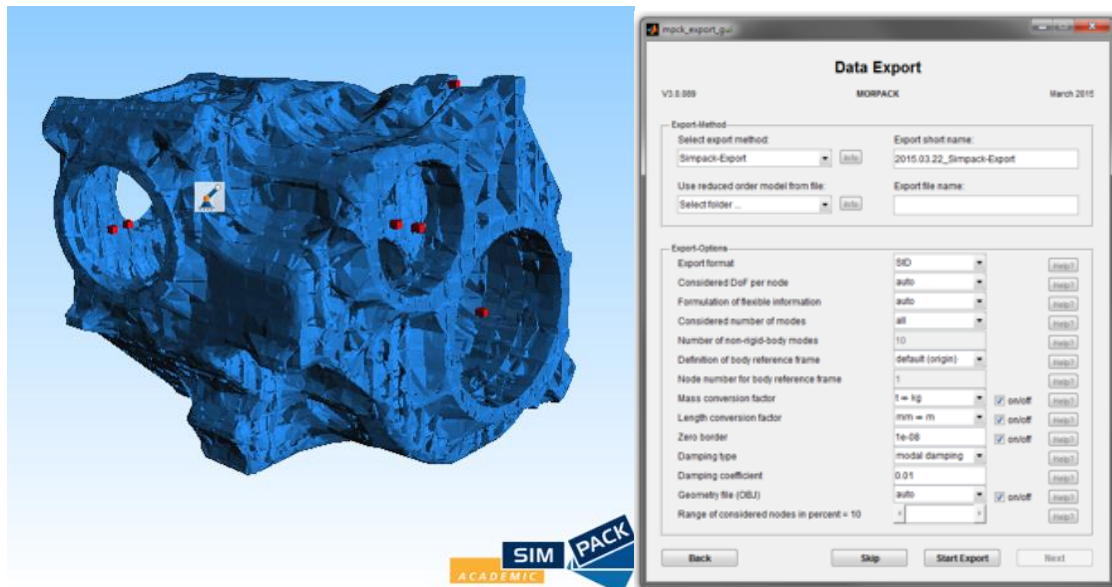
Figure 12: Model correlation GUIs (NRFD and NCO)

## Export-Module

The final step is the export of the elastic body to SIMPACK, ANSYS, NASTRAN or LsDyna. The export-module provides an automated selection of valid ansatz functions (modes), a conversion of units and a selection of the damping model. A graphical representation of the reduced order model can also be exported. Furthermore, a pre-simulation under inset-conditions can be realized within the in-built EMBS-program in MATLAB to determine relevant modes (see EMBS-module).

### Features:

- interfaces to SIMPACK, ANSYS, NASTRAN
- optimal selection of ansatz functions (modes)
- conversion of units
- different damping models
- graphical representation of the reduced order model
- consideration of the inset-conditions and the boundary conditions as well as selection of relevant modes



**Figure 13:** Export with GUI at the example of a gear box housing

## EMBS-Module

The generation of an elastic body based on a FE-model without boundary conditions is not useful in most cases and leads to distorted results. Therefore, the consideration of boundary conditions under inset-conditions by using a pre-simulation within the EMBS-assembly is an essential step for the improvement of the quality of the reduced order model. This is possible by using the EMBS-module, where the inset-conditions are pre-simulated for a simplified topology.

### Features:

- 3-dimensional EMBS-program in MATLAB
- simulation of one elastic body with connected rigid bodies
- arbitrary combination of joints and force elements
- standard simulation scenarios
- automated evaluation and adaption of the elastic body
- post processing and animation

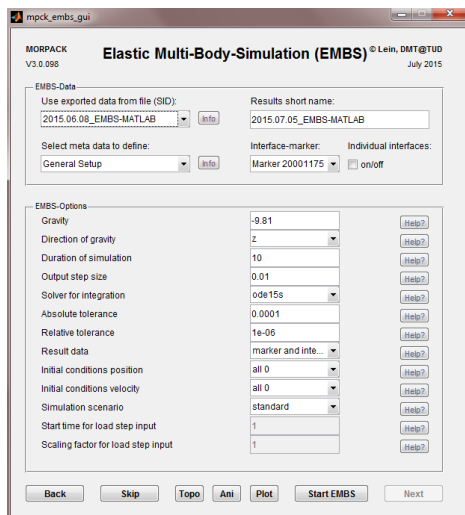
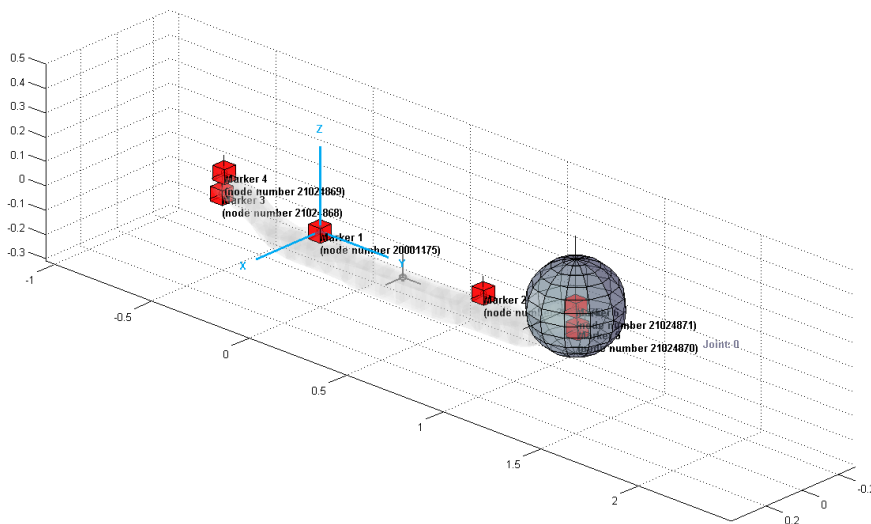
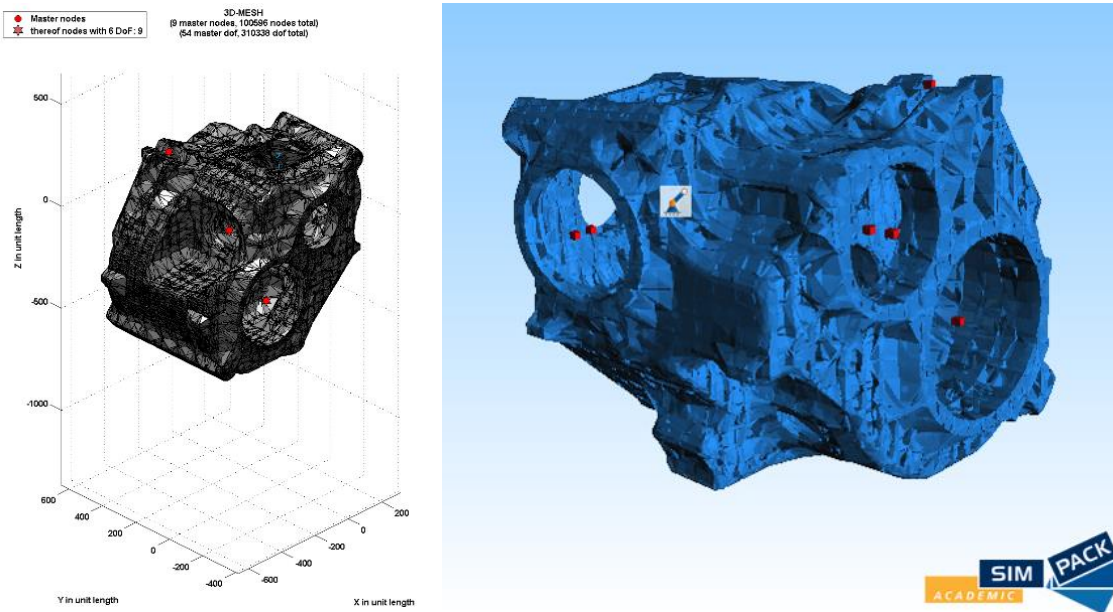
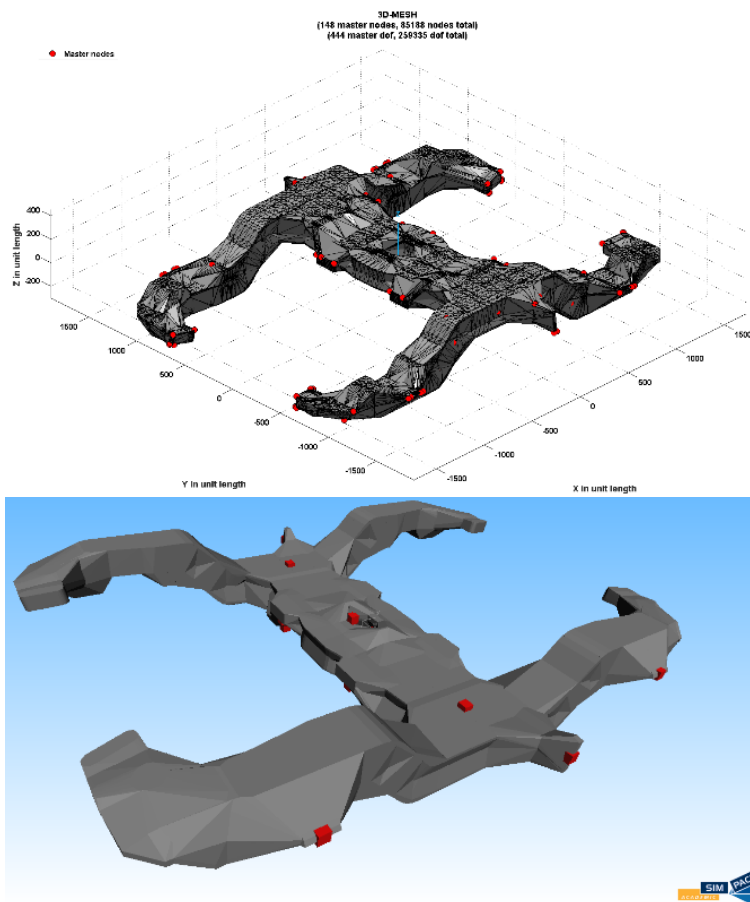


Figure 14: EMBS-program with animation and GUI at the example of an axle mounting

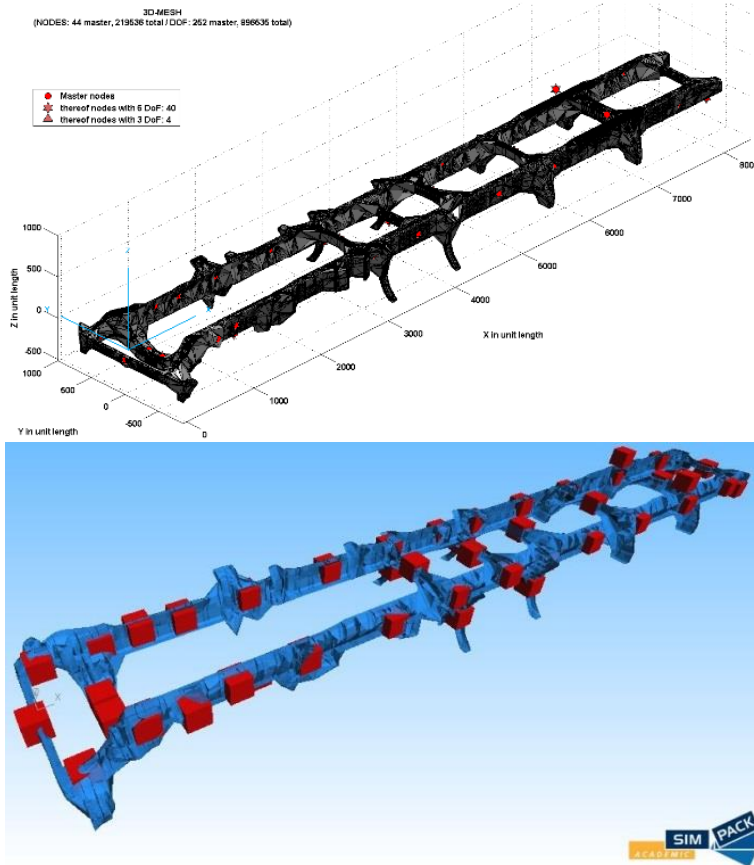
## Reference models and benchmarks



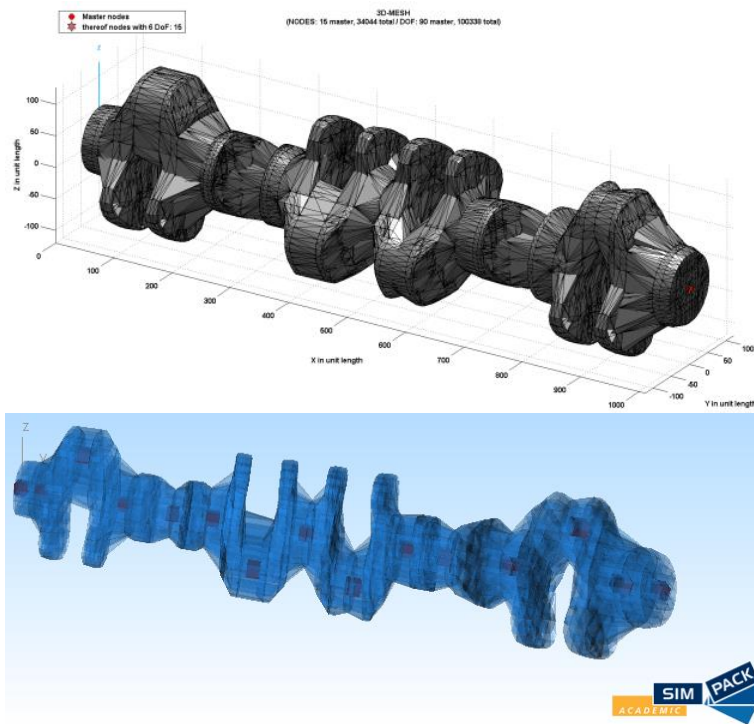
**Figure 15:** Gear box housing, DoF approx. 300,000



**Figure 16:** Bogie frame, DoF approx. 100,000 and 1,000,000

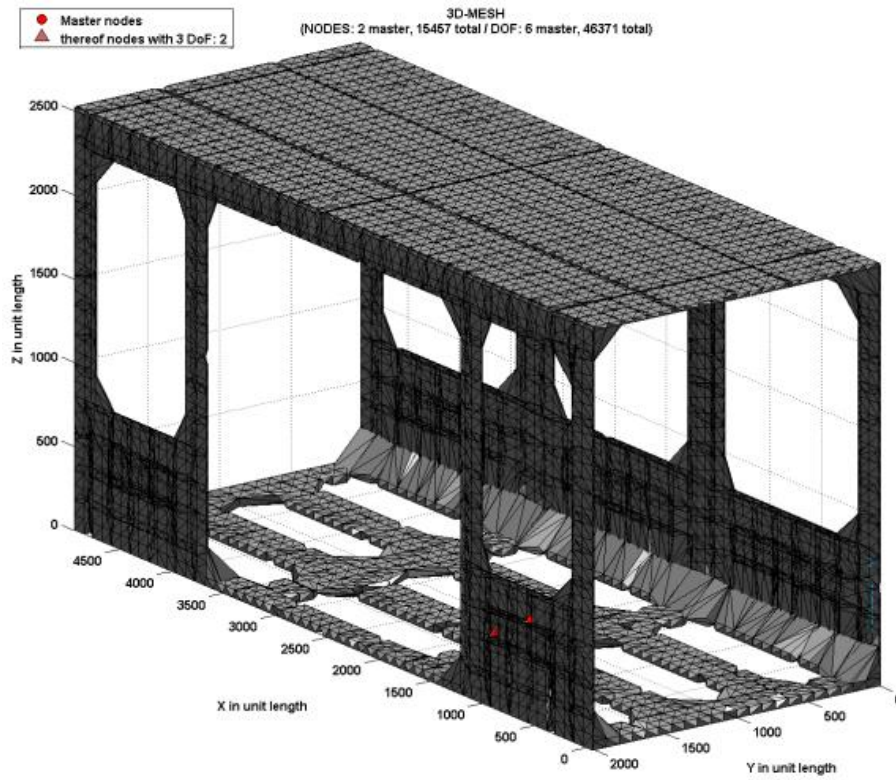


**Figure 17:** Vehicle frame, DoF approx. 1,200,000

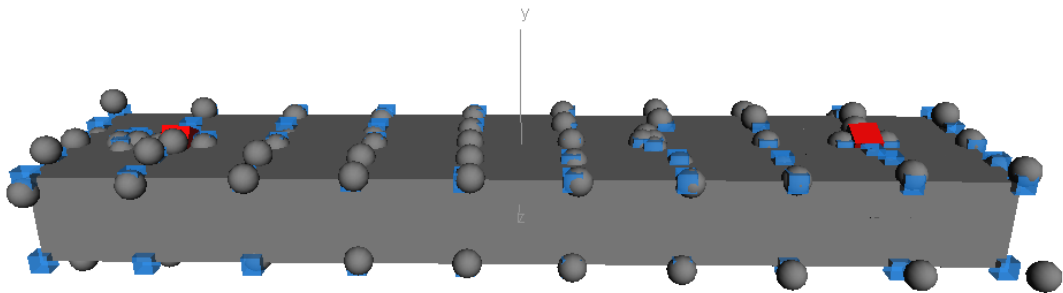
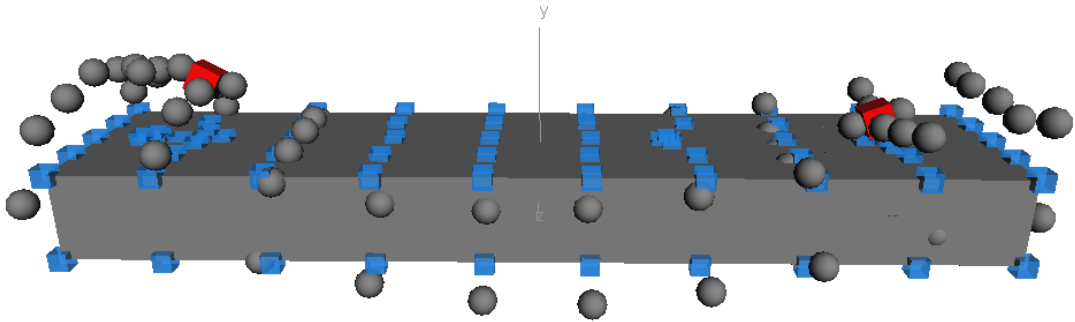
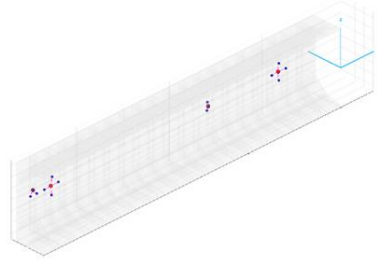
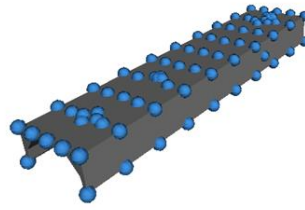
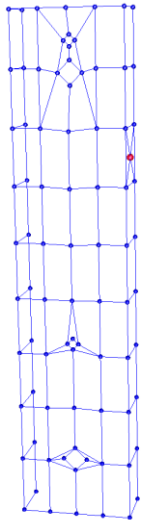
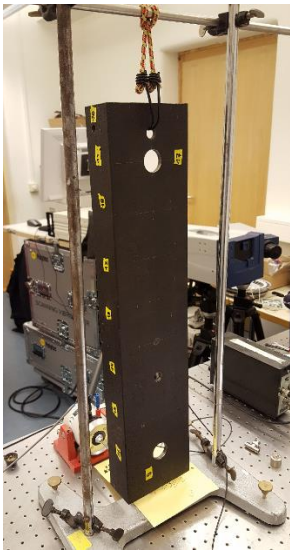


**Figure 18:** Crank shaft, DoF approx. 100,000 and 500,000





**Figure 19:** Car body, DoF approx. 100,000 and 1,000,000



**Figure 20:** Elastic body of a truss based on measured data gained from ME-Scope