Crash Simulation of Additively Manufactured Lattice Structures

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1 Introduction

This paper is a description of the contents of the presentation slide by slide. The presentation is added in chapter 3.

2 Slides summary

Slide 2 — Agenda and structure

The report proceeds by first motivating the use of AM lattice structures and highlighting the specific challenges of crash applications, especially material behavior and geometric complexity. It then details the materials characterization required to inform fracture-capable models and the steps of material card development (characterization–calibration–validation). Next, it outlines efficient simulation workflows, including beam and solid FE modeling as well as mesh-free linear analyses, and demonstrates applications on a crash box and a mega-brace. Finally, it consolidates conclusions and sketches an outlook for future methods integration.

Slides 3/4 — Motivation: Why AM lattice structures?

Lightweighting is a strategic lever to reduce vehicle mass, improve the CO2 footprint, and conserve resources. AM lattice structures offer complex, ultralight geometries with tunable crash performance through control of topology, cell size, and wall thickness. A representative comparison shows that a lattice design with a shell in aluminum can reduce weight from 3.063 kg to 1.767 kg, corresponding to approximately 43% reduction relative to a full solid aluminum casting, while maintaining crash-relevant load pathways. These capabilities position AM lattices as promising candidates for energy-absorbing structures in automotive crash, shown by a crash box, where energy absorption can be improved by 35% using lattice structure design.

Slide 5/6 —Challenges for AM crash parts: material properties

Despite compelling lightweight potential, AM crash parts confront critical challenges that span material behavior (ductility and fracture), design complexity (vast topology and parameter space), and simulation scalability (predictive fracture modeling at reasonable cost). The following sections expand these challenges, beginning with material properties that govern ductility and failure modes and then progressing to design and simulation aspects.

Many current metallic AM materials exhibit insufficient ductility under high-rate, crash-relevant loading, which can trigger brittle failure and compromise structural integrity. Ensuring stable plastic deformation and progressive energy absorption is therefore a primary requirement for crash components made with AM lattices.

Slide 7 — Material property targets and development approach

The primary material target is to avoid brittle failure and achieve high ductility for stable energy absorption, while maximizing strength within that ductility envelope. The development plan involves varying alloy composition, heat treatments, and AM process parameters, followed by systematic mechanical testing (tensile, three-point bending, and high-strain-rate tests) with DIC-based strain-field measurements. Metallography, chemistry, and porosity assessments are conducted to link microstructure and defects to mechanical response, including sensitivity to build orientation and process

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settings. Early bending assessments indicate clear distinctions between brittle and ductile behaviors across candidate materials.

Slide 8 — Comparative test results across alloys/heat treatments
Tensile and three-point bending tests across alloys and heat treatments reveal trade-offs between strength and ductility that are essential for crash performance tuning. Notably, the Al5X1 (AD1) alloy exhibited the lowest strength among the examined materials but demonstrated high ductility, making it promising for crash applications where stable plastic deformation and energy absorption dominate design objectives. These results motivate selecting or tailoring alloys with ductility emphasis while managing strength through local geometry and topology optimization.

Slide 9 — Lattice-level test results and reproducibility
Initial lattice-structure testing demonstrates reproducible force–displacement responses and failure modes, an encouraging prerequisite for both design-of-experiments and model validation. Reproducibility at the lattice level suggests that material, process controls, and geometry are sufficiently stable to support predictive simulation and optimization.

Slide 10 — Designer challenge: complexity of the design space
Selecting the most efficient lattice structure for a target crash application requires navigating a vast design space of topologies, beam diameters, cell sizes, wall thicknesses, and orientations. Implicit geometric modeling is often advantageous over conventional CAD for such complex periodic or graded lattices, but it introduces new toolchains and workflows. Given this complexity, designers benefit from efficient, predictive simulation processes to screen, rank, and refine options rapidly.

Slide 11 — Need for efficient crash simulation methods
Systematic and efficient structural simulations are essential to explore and optimize lattice designs against crash performance objectives. Predictive material models with fracture are key enablers; without them, design iteration risks overreliance on testing, slowing down the adoption of new lightweight technologies. Thus, the focus is on simulation methods that capture ductility, damage, and fracture under relevant loading, while remaining computationally tractable.

Slide 12 — Simulation workflow overview (section introduction)
The simulation workflows encompass both linear screening analyses and nonlinear crash simulations, combining mesh-free methods for rapid ranking with FE-based approaches (beam and tetrahedral models) for fracture-capable prediction. The next slides detail linear-analysis pipelines and their integration considerations, followed by crash-focused FEM workflows.

Slide 13 — Linear-analysis workflow with mesh-free methods
A typical pipeline transforms CAD geometry into an implicit geometry representation, generates a triangulated surface mesh, and performs mesh-free linear analysis. This approach delivers rapid insight into stiffness, load paths, and relative ranking of design variants without the overhead of volume meshing for early concept decisions.

Slide 14 — Integration considerations and focus on FEM
While mesh-free methods are effective at the component or subsystem level, integrating them into full-vehicle FEM environments remains nontrivial. Consequently, the crash-focused portion emphasizes FEM models that can be incorporated into established full-vehicle workflows. IsoGeometric Analysis capabilities exist for crash applications but were not evaluated here specifically for AM lattices.

Slide 15 — FEM workflow for crash: beam and tetra options
For lattice structures, two primary FE representations are used: beam-based models (1D) and solid tetrahedral models (3D). Beam models are easy to mesh and simulate very quickly, making them suitable for screening and design-of-experiments; they can correlate well with tests for beam-type lattices when manufacturing deviations are captured. Solid tetrahedral models are also relatively straightforward to mesh but incur small time steps and higher computational cost; they support fracture prediction via GISSMO and MF-GenYld+CrachFEM. A semi-automatic workflow (using Beta CAE ANSA) converts implicit CAD to a quality tetra mesh, optionally using an intermediate beam model.

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Slide 16 — 3D tetra meshing quality and constraints
Robust tetra meshing was achieved for element sizes above roughly 1.5 mm across the studied lattice geometries. Complex regions occasionally required localized manual cleanup or refinement to ensure mesh quality and stable simulation.

Slide 17 — Predictive simulation methods (section introduction)
To deliver predictive crash simulations, material card development follows a structured pipeline that links characterization to calibration and validation. The subsequent pages detail the test matrix, modeling choices (e.g., damage and fracture models), and verification against coupon and component tests.

Slide 18 — Characterization, card creation, and validation workflow
Comprehensive characterization covers static and highly dynamic tests to capture deformation and fracture, with DIC used to obtain full-field strain data and build-orientation effects explicitly considered. Parameter identification is performed for both deformation and fracture, including the assessment of isotropic versus orthotropic behavior, with targeted LS-DYNA models such as GISSMO and MF-GenYld+CrachFEM. The target outcome is a predictive material card that enables component- and system-level crash simulation with fracture. Validation closes the loop by comparing simulation against samples and small components (e.g., quasi-static or drop tests), including manufacturing effects.

Slide 19 — AM samples and fracture-capable characterization
Numerous AM samples were produced and tested to confirm promising material/process optimizations and to derive stress-state-dependent fracture parameters. Test matrices included multiple materials and build orientations, and high-strain-rate testing was used where appropriate to reflect crash loading. The characterization outputs feed directly into fracture model calibration and subsequent validation steps.

Slide 20 — Calibration: solid-element material card (GISSMO option)
Solid material calibration used 10-node tetrahedral elements (ELFORM=17), starting from first-order tetrahedra with TET4TOTET10 conversion to obtain second-order elements where beneficial. A conservative “worst-case” card was calibrated toward earliest failure to avoid overprediction of punch/bending resistance. Strain-rate effects were not explicitly modeled; a single quasi-static yield curve was adopted for this phase. The GISSMO-based route employed *MAT_PIECEWISE_LINEAR_PLASTICITY (isotropic, consistent with no measured anisotropy) with *ADD_DAMAGE_GISSMO for damage evolution, together with mesh regularization up to a characteristic element length of about 5.5 mm.

Slide 21 — Calibration: solid-element material card (CrachFEM option)
An alternative calibration used LS-DYNA Material Law 48 (MF-GenYld+CrachFEM) to capture advanced fracture phenomena with stress-state dependency. Local mesh refinement was applied near stress concentrators and notches as needed to resolve gradients and fracture initiation. The slide indicates representative hardening and fracture loci, including normal (tension) and shear fracture branches. These data illustrate how the fracture envelope is defined for different stress states.

Slide 22 — Validation of material cards against tests
Validation compared simulated force–displacement responses and fracture patterns against coupon and small-component tests. Both GISSMO-based and MF-GenYld+CrachFEM-based material cards achieved very good correlation to test data, providing confidence that the models can be used for component-level crash prediction.

Slide 23 — Application examples (section introduction)
Two application examples demonstrate the methodology: a drop-tower crash box and a system-level mega-brace. The first focuses on detailed material and fracture modeling in a canonical energy absorber, while the second highlights workflow trade-offs between mesh-free linear analyses and FEM-based crash simulations.

Slide 24 — Application example 1: crash box context and testing strategy
Crash boxes play a central role in managing load paths during full-frontal impacts. To represent real load conditions in a controlled setting, a drop-tower test configuration is used with a rigid barrier and a surrogate vehicle or guided impactor, allowing precise control of mass and velocity. This approach isolates the crash box response, facilitating correlation with CAE for both beam and solid representations and for evaluating fracture-capable material cards.

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Slide 25 — Crash box: drop-tower CAE setup and computational cost
The AM lattice crash box tested and simulated measures approximately 240 mm × 63 mm × 63 mm. Two FE representations were constructed: a solid model with on the order of 5,077,310 tetrahedral elements and a beam model with about 2,988 beam elements. The beam model runs in roughly 10 minutes on a laptop for screening, whereas the solid model requires on the order of 6 hours on a high-performance compute node with 48 CPUs, reflecting the cost of resolving fine geometrical features and fracture behavior.

Slide 26 — Crash box: physical drop-tower test
Physical testing provides the force–displacement response and deformation modes used for correlation to CAE, including the onset and progression of local buckling and fracture where applicable. High-speed imaging and post-test inspection support qualitative and quantitative assessment of failure mechanisms.

Slide 27 — Crash box: simulation vs. test and model choices
Simulations using both GISSMO and MF-GenYld+CrachFEM produced good agreement with test force–displacement curves and deformation modes when the hardening curve was scaled by approximately 0.9, indicating sensitivity to modest material strength adjustments. This agreement validates the modeling approach for energy-absorbing AM lattice structures in drop-tower conditions.

Slide 28 — Application example 2: mega-brace (section introduction)
The mega-brace example examines how mesh-free linear analyses can rapidly rank multiple implicit lattice variants against a solid baseline, before committing to more expensive crash simulations. It illustrates the workflow transition from early-stage concept screening to detailed FEM-based assessment.

Slide 29 — Mega-brace: mesh-free linear analyses for variant ranking
Multiple implicit model variants were evaluated (e.g., masses around 1.767 kg and 1.536 kg) against a solid CAD baseline (about 3.063 kg) using a mesh-free solver. These analyses complete within minutes (order of 3–5 minutes) and reveal stiffness and load-path differences sufficient to rank concepts prior to crash modeling. The results demonstrate that mesh-free analysis offers a practically immediate feedback loop for early-stage lattice tailoring.

Slide 30 — Mega-brace: crash analysis setup and runtime
Crash modeling of the mega-brace used tetrahedral elements with typical criteria such as average element outer size of about 4 mm, an average lattice beam size near 3 mm, a minimum element size near 1.5 mm, and a tet collapse limit around 0.2. Resolution guidelines included about five elements along beam length and two layers through wall thickness to capture bending and local failure. Mass scaling around 2e-4 ms and TET4-to-TET10 conversion were applied, implying smaller stable time steps, increased element counts, and longer runtimes; a representative run completed in roughly 34 minutes. Compared to solid structures, lattice geometries impose tighter stability constraints and higher computational cost due to fine features.

Slide 31 — Mega-brace: performance tuning
Lattice structures enable performance tuning, reflected in force/displacement responses for different designs: full solid design vs. two different lattice designs.

Slide 32 — Conclusions and outlook (full content)
Conclusions and outlook (full content) For linear simulations, both solid and beam models are applicable, and small 3D elements are generally manageable at this stage. Mesh-free analysis is applicable at the component or subsystem level and provides efficient early-stage ranking. A key challenge is how to integrate mesh-free analysis results into existing full-vehicle FEM models. For crash simulations, semi-automated beam modeling is feasible for certain lattice types, enabling rapid screening and design-of-experiments that can correlate well with tests for beam-type lattices. For more complex geometries, such as beams with shell surfaces or non-standard joints, manual rework remains necessary. Solid modeling is possible for all lattice types, and semi-automated tetra mesh generation can be used, optionally starting from beam meshes to accelerate model creation. Predictive crash simulation is feasible in LS-DYNA using either GISSMO or MF-GenYld+CrachFEM, with both showing very good correlation to physical tests in the demonstrated cases. However, the computational cost remains high for fine geometrical features, which currently limits routine application in high-volume product programs

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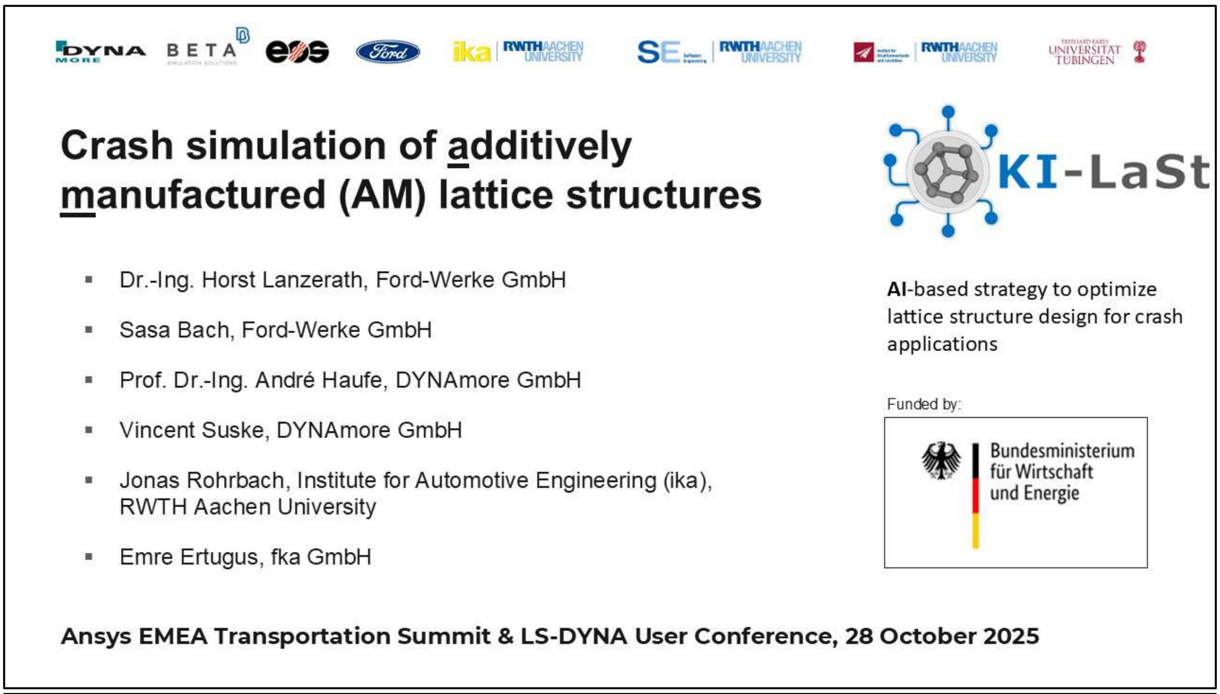
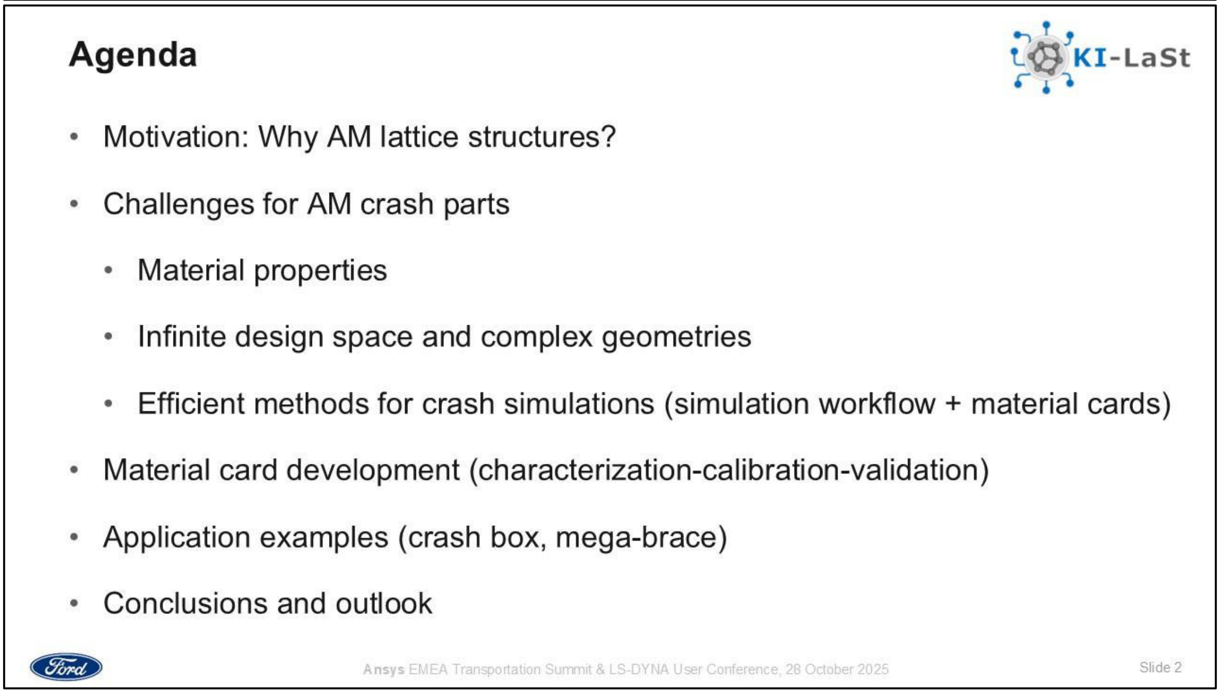
and favors use in niche products and validation-focused runs. IsoGeometric Analysis for crash is available in LS-DYNA but was not evaluated for AM lattices in this work. Looking ahead, mesh-free analysis remains highly effective for linear analyses, and either mesh-free or IGA methods may offer a path to more efficient crash simulation of lattice structures in the future.

3 Presentation Slides





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Motivation: Why AM lattice structures?

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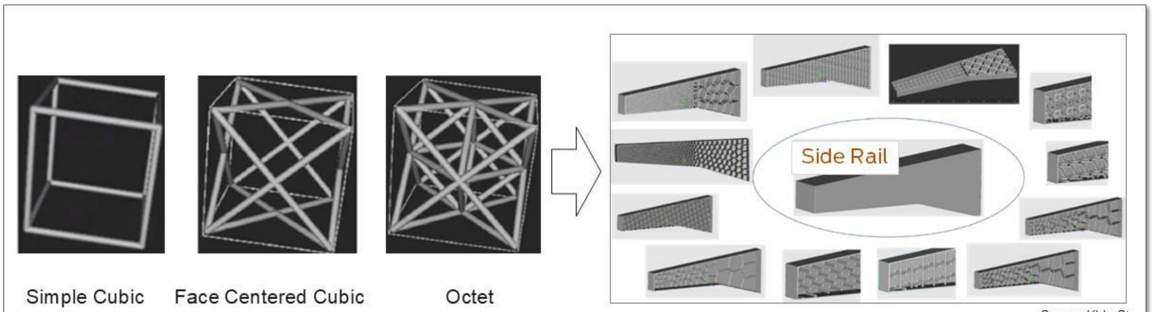
- Lightweighting is a strategic lever to improve vehicle CO2 footprint and reduce resource use
- AM lattice structures allow complex, ultralight part design and tunable crash performance using lightweight materials



Source: KI-LaSt

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Slide 3

Motivation: Why AM lattice structures?

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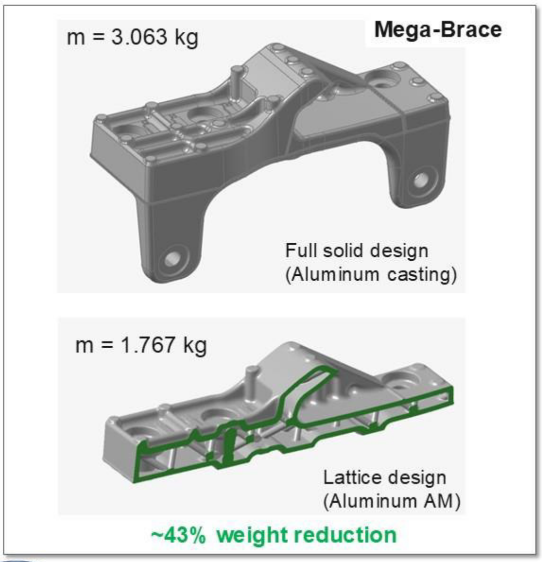

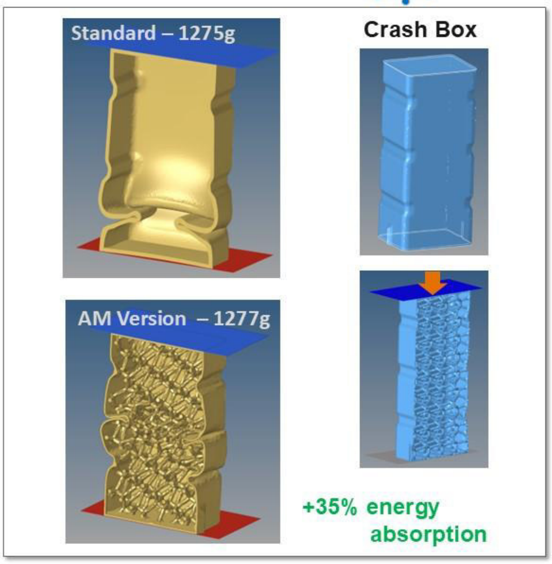

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Slide 4

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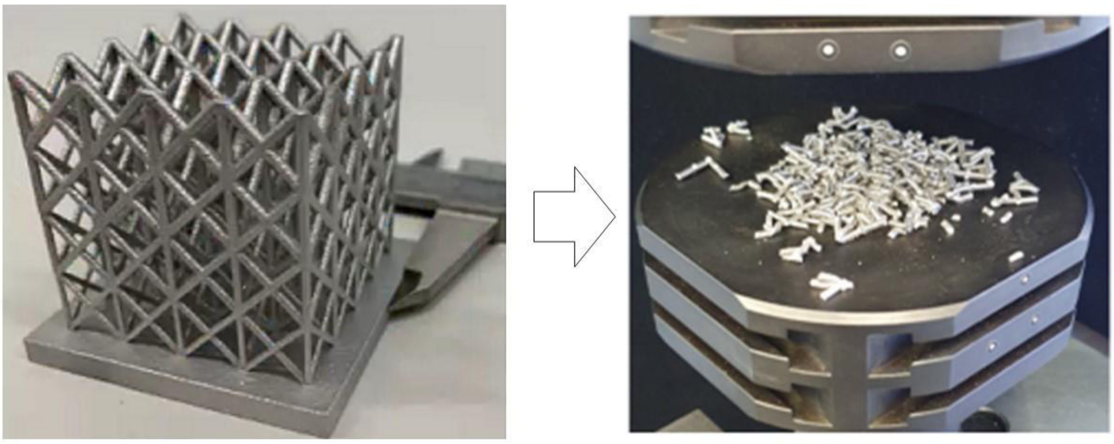
Challenges for AM crash parts

Challenges: material properties

- Many current metallic AM materials exhibit insufficient ductility under automotive crash loads, risking brittle failure and loss of structural integrity



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Challenges: material properties

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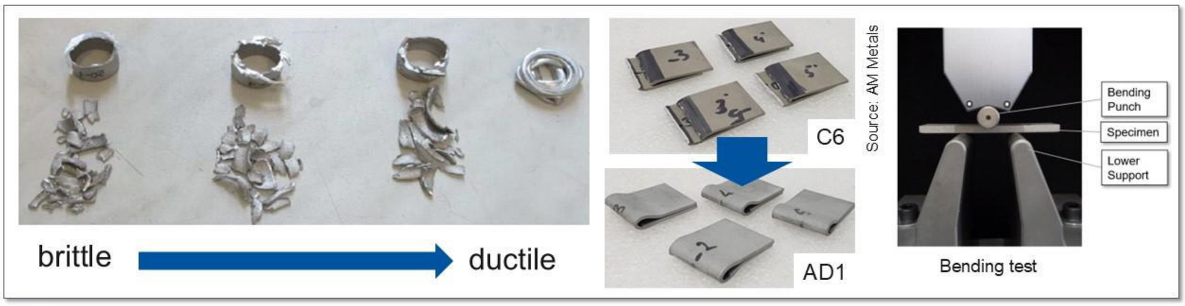
Targets

- Avoid brittle failure; ensure **high ductility** for stable energy absorption in crashes
- **Maximize strength** within the ductility constraint

Development

- Vary alloy composition, heat treatment and AM process parameters
- Mechanical testing (tensile, 3-point bending), high-strain-rate testing, Digital Image Correlation (DIC) strain fields
- Metallography/chemistry and porosity assessment; sensitivity to build orientation and manufacturing process



Challenges: material properties

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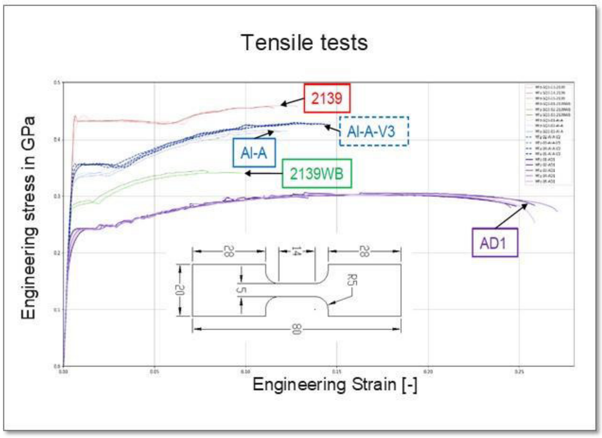
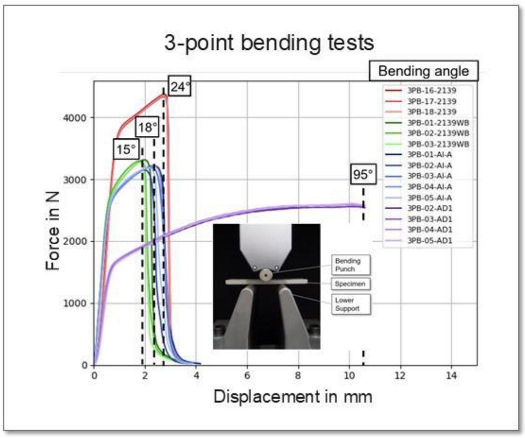
- Tensile & 3-point bending tests across alloys and heat treatments show trade-offs between strength and ductility





The **Al5X1 (AD1)** alloy exhibited the lowest strength among those examined but showed high ductility - promising for crash applications, where energy absorption and stable plastic deformation are critical

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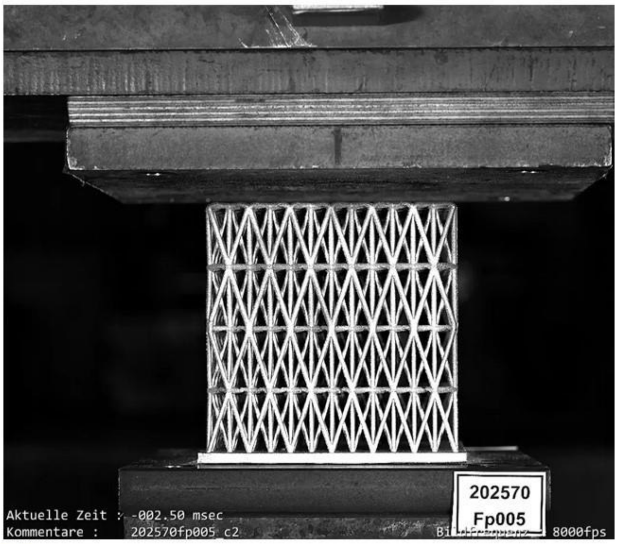
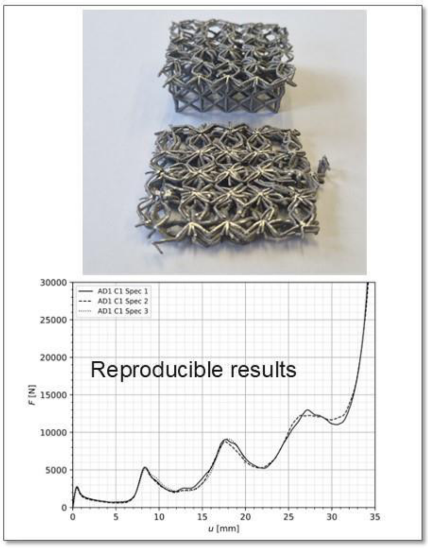
Test results on lattice structure





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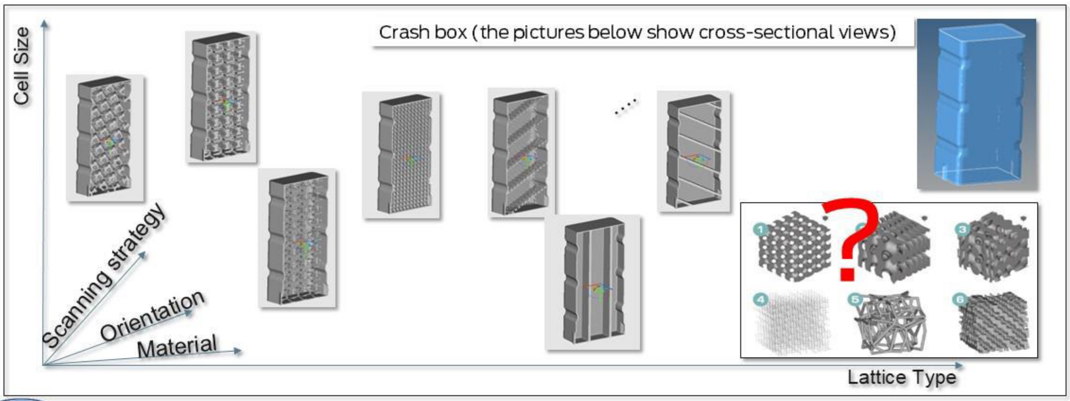
Slide 9

Challenges for designers: complexity

- **Goal:** Identify the most efficient lattice structure for the crash application
  - Vast design space (topologies, beam diameters, cell sizes, wall thicknesses, orientations)
  - Complex geometries (CAD vs. implicit geometric modelling → change of software ?
- **Status:** Difficult for designers to grasp → Efficient **simulation methods** enable decision



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Slide 10

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Challenges: efficient methods for crash simulation

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- Systematic application of structural simulations is essential for lattice structure design exploration and optimization
- Effective **simulation processes** and **predictive material models** are key enablers
- Without effective predictive simulation methods, new lightweight design technology **will not be** introduced into vehicles today

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Slide 11

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Simulation workflow

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Slide 12

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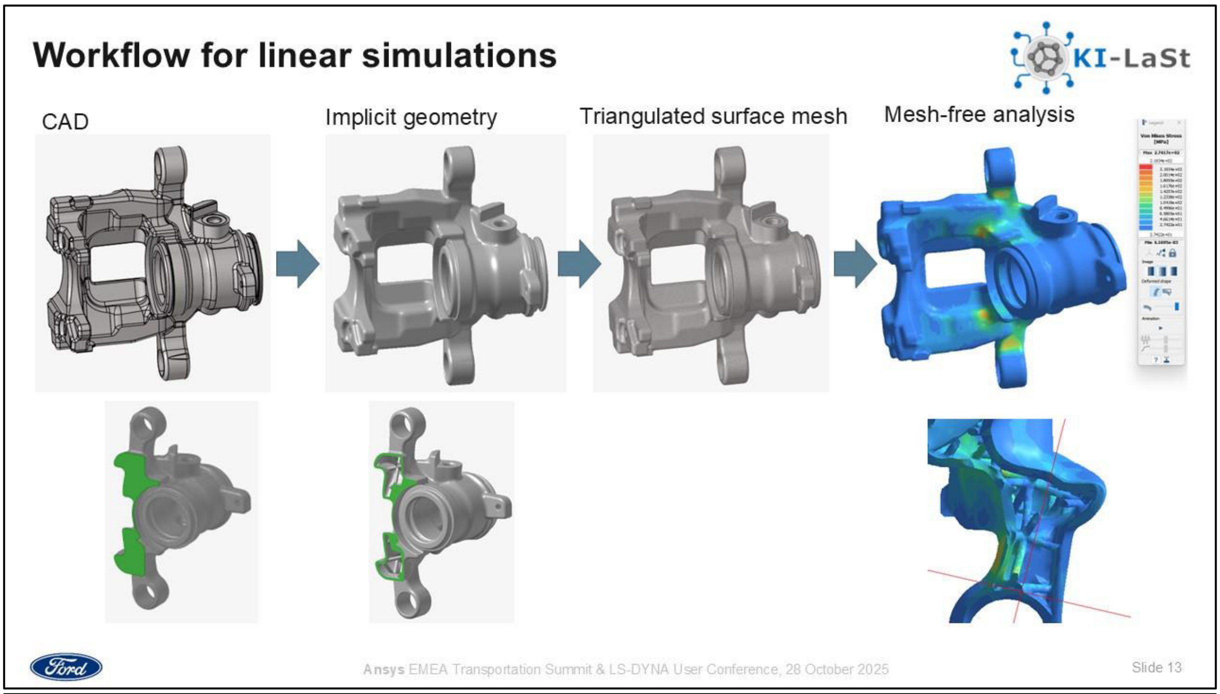

Workflow for linear simulations

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But: How can mesh-free analysis be integrated into a full-vehicle (FEM) model?

Therefore, we focus on **FEM models**

Note: **IGA** (IsoGeometric Analysis – different from "mesh-free analysis") crash capabilities exist in LS-DYNA but were not evaluated here for AM lattices

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Slide 14

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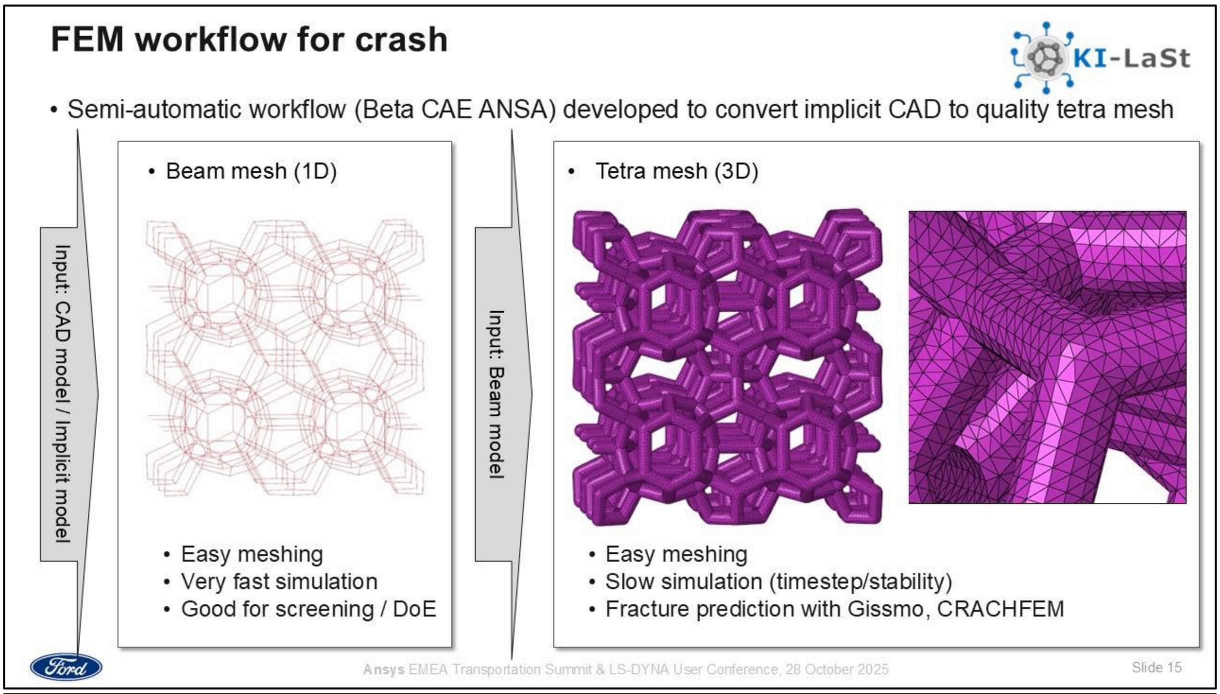

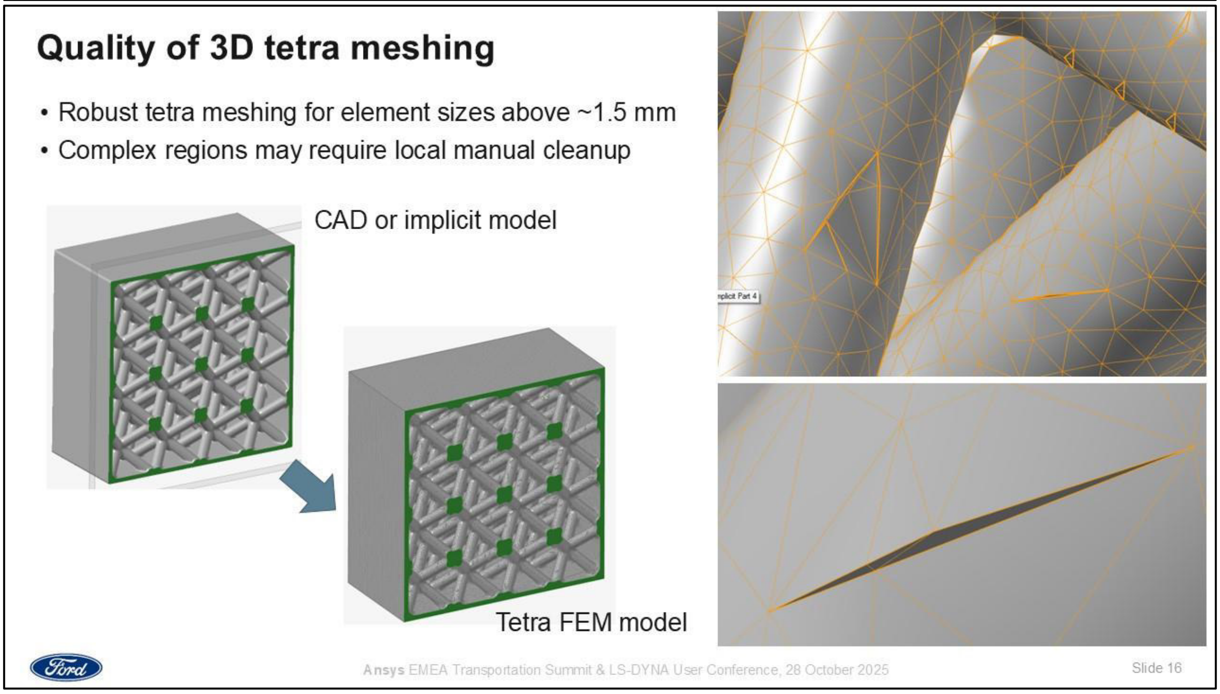

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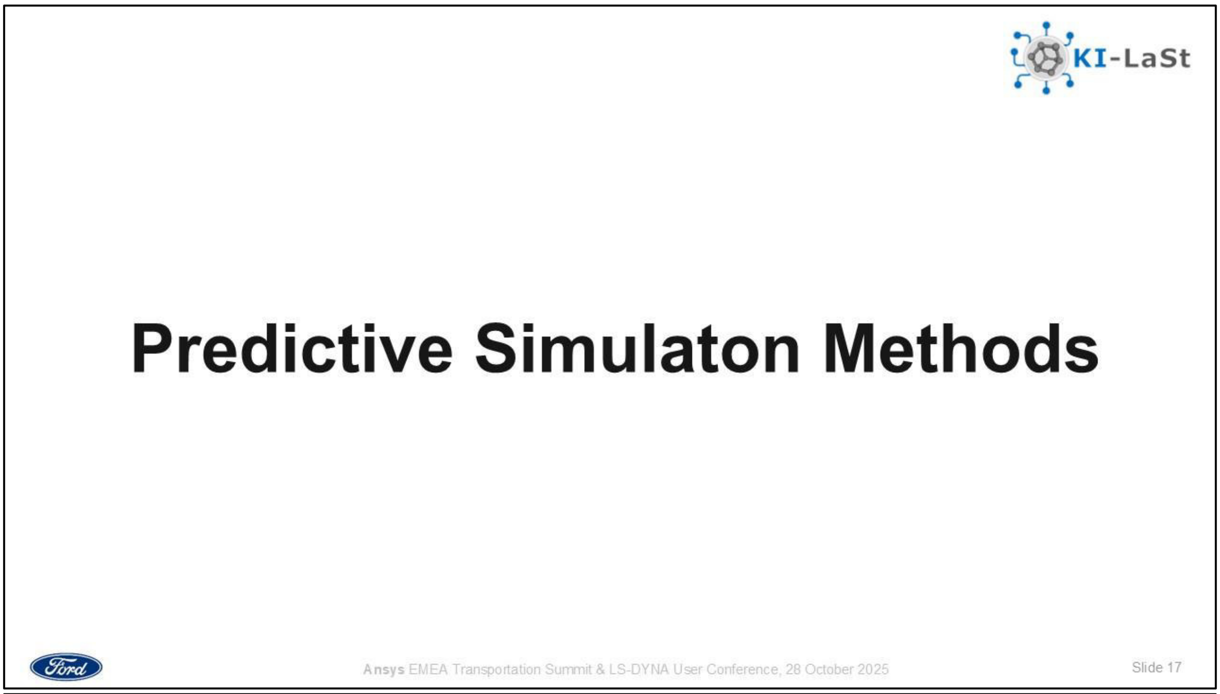

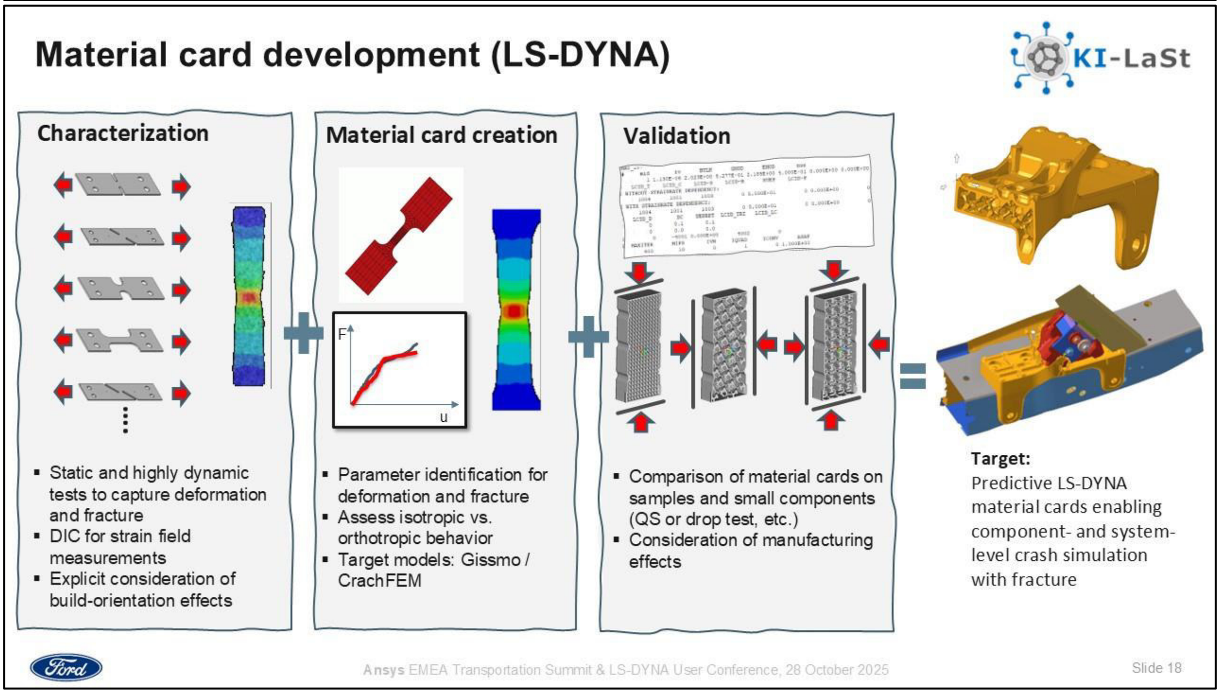

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Additive manufacturing: samples and characterization

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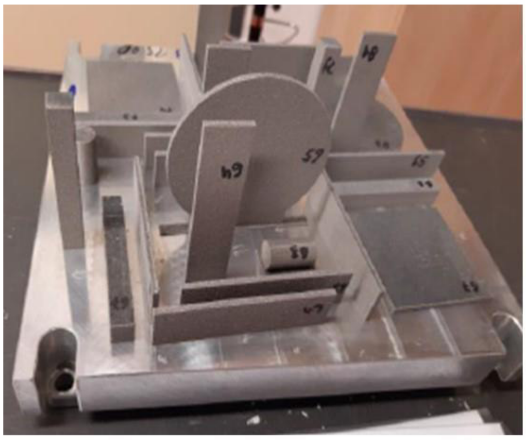
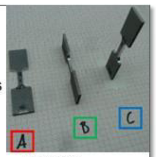
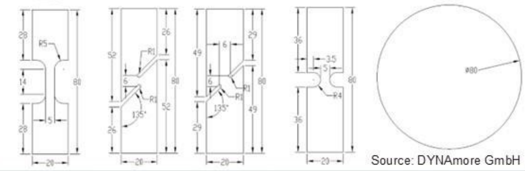
- Numerous samples were produced by AM and tested to validate promising material optimizations
- Goal: derive parameters for crash material cards, including stress-state-dependent fracture prediction



- Multiple materials tested
- Build orientation considered
- Tests to extract stress-state-dependent fracture parameters
- High-strain-rate testing





Source: DYNAmore GmbH

	Small tensile test MFz	0° shear test 00Sz	45° shear test 45Sz	R4 notched tensile test R4Fz	Punch test Ds	
Quasi-static	3	3	3	3	3	
Directions	A, B C	A, B C	A, B C	A, B C	A, C	
Dynamic	3 x 3 velocities	0	0	0	0	
Directions	A	-	-	-	-	
No. of coupons	9+9	9	9	9	6	Sum: 51

Calibration of material cards – Solid elements

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- The solid material card was calibrated under the following conditions:
  - Element formulation: **10-node tetrahedron** elements (**ELFORM=17** in LS-DYNA; 1st order with **TET4TOTET10** conversion to 2nd order)
  - A "worst-case" card was calibrated to earliest failure, ensuring conservative punch/bending predictions
  - Rate effects: no explicit strain-rate dependence; a single quasi-static yield curve was used.
  - **A.) LS-DYNA + Gissmo**
    - Base law: *MAT_PIECEWISE_LINEAR_PLASTICITY (isotropic; no measured anisotropy)
    - Damage: *ADD_DAMAGE_GISSMO (Gissmo damage model)
    - **Mesh regularization** up to characteristic element length of 5.5 mm

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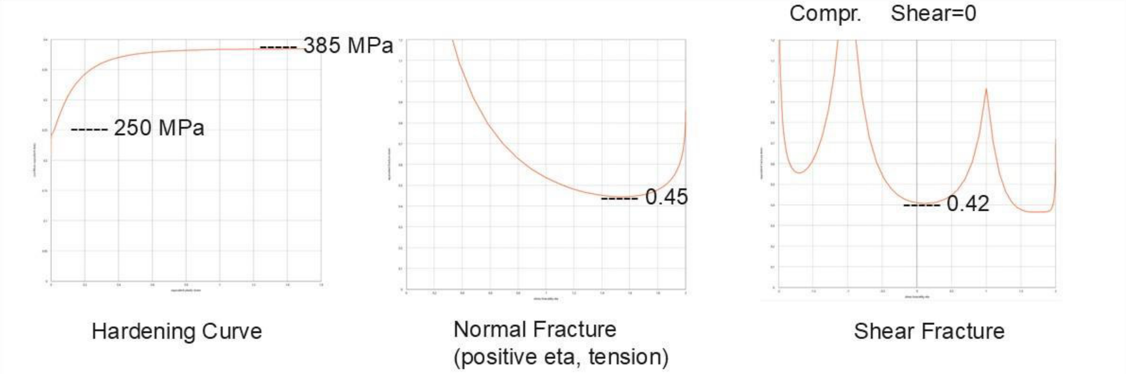
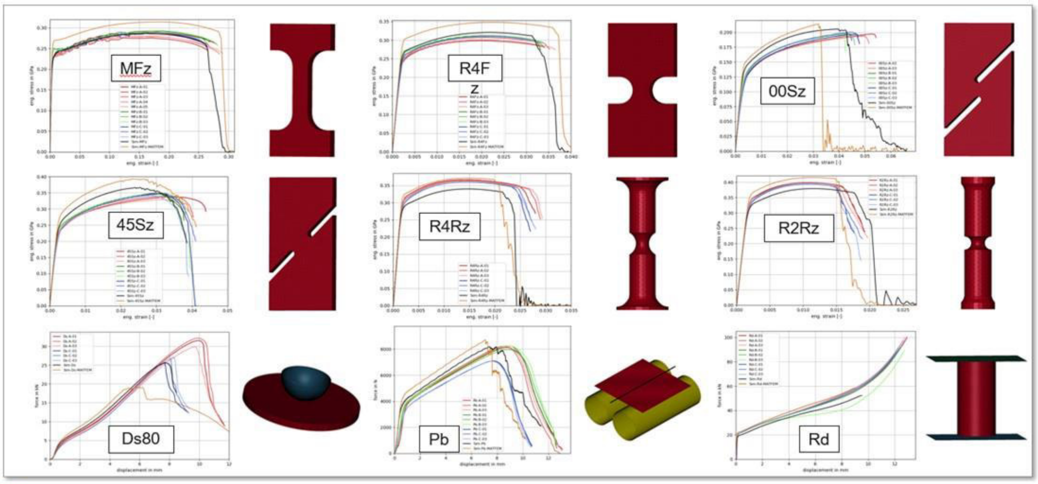
Calibration of material cards – Solid elements

- **B.) LS-DYNA + CrachFEM**
  - Material Law 48: MF-GenYld+CrachFEM for advanced fracture modeling
  - Local mesh refinement near stress concentrators/notches as needed



Validation of the material cards

- Compare simulated force–displacement responses & fracture patterns against coupons and small components
- Outcome: very good correlation for both **Gissmo** and CrachFEM



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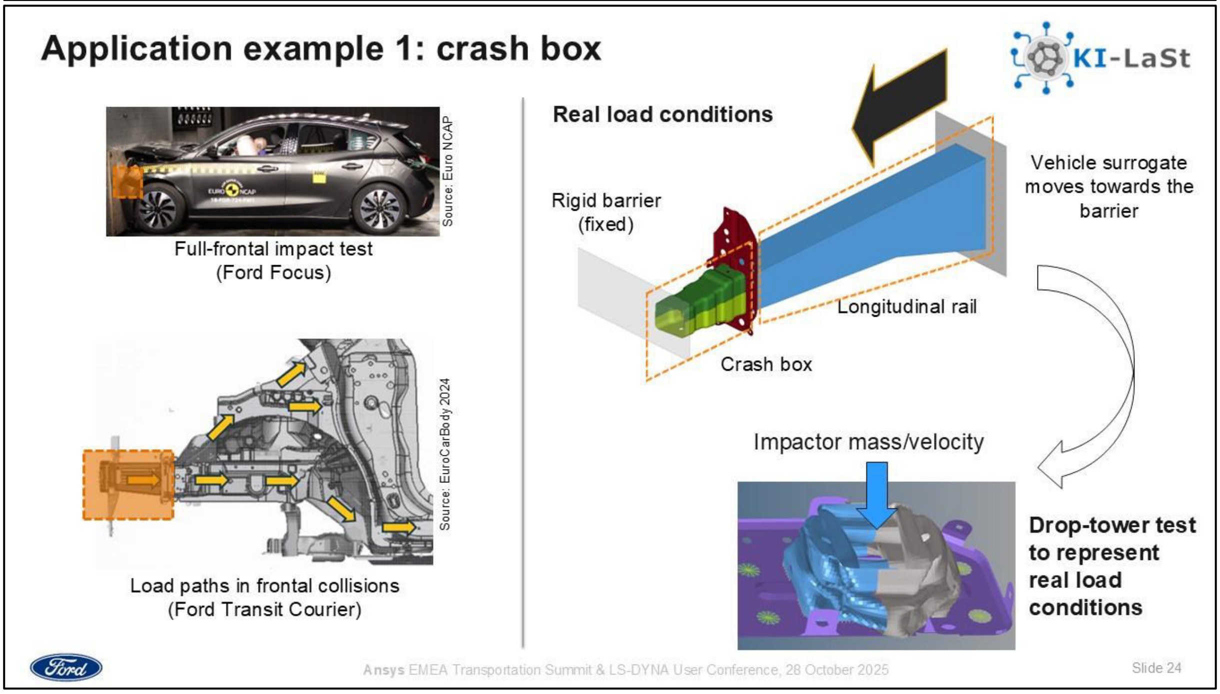

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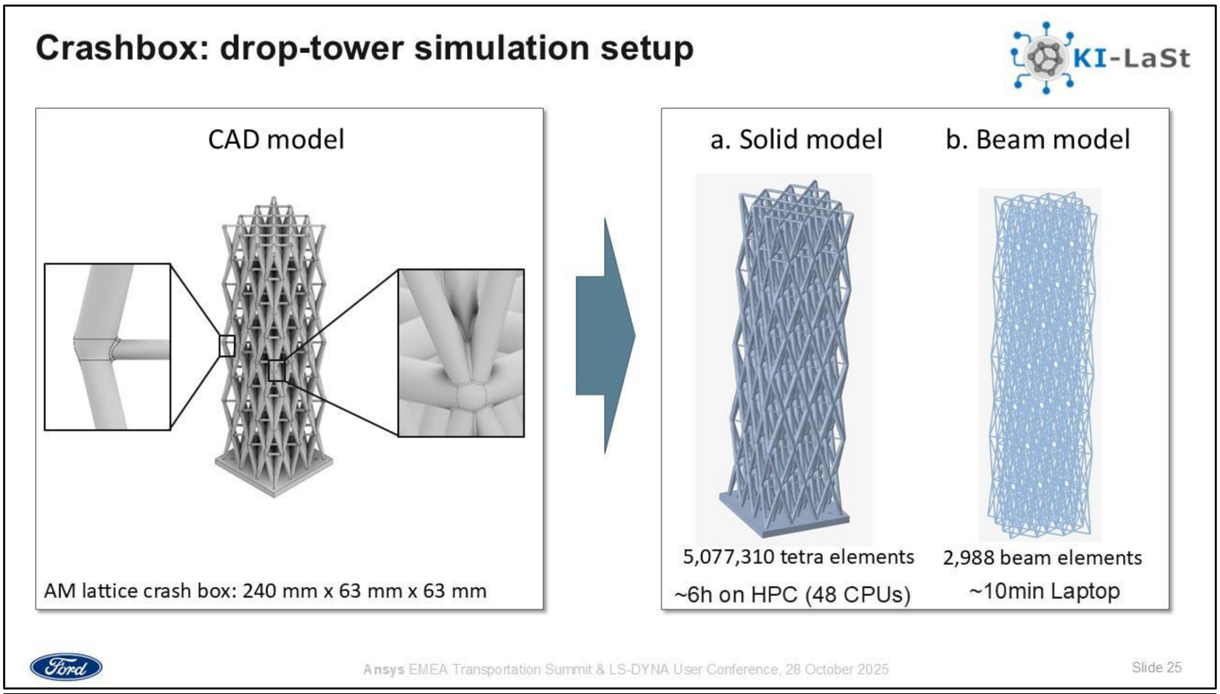

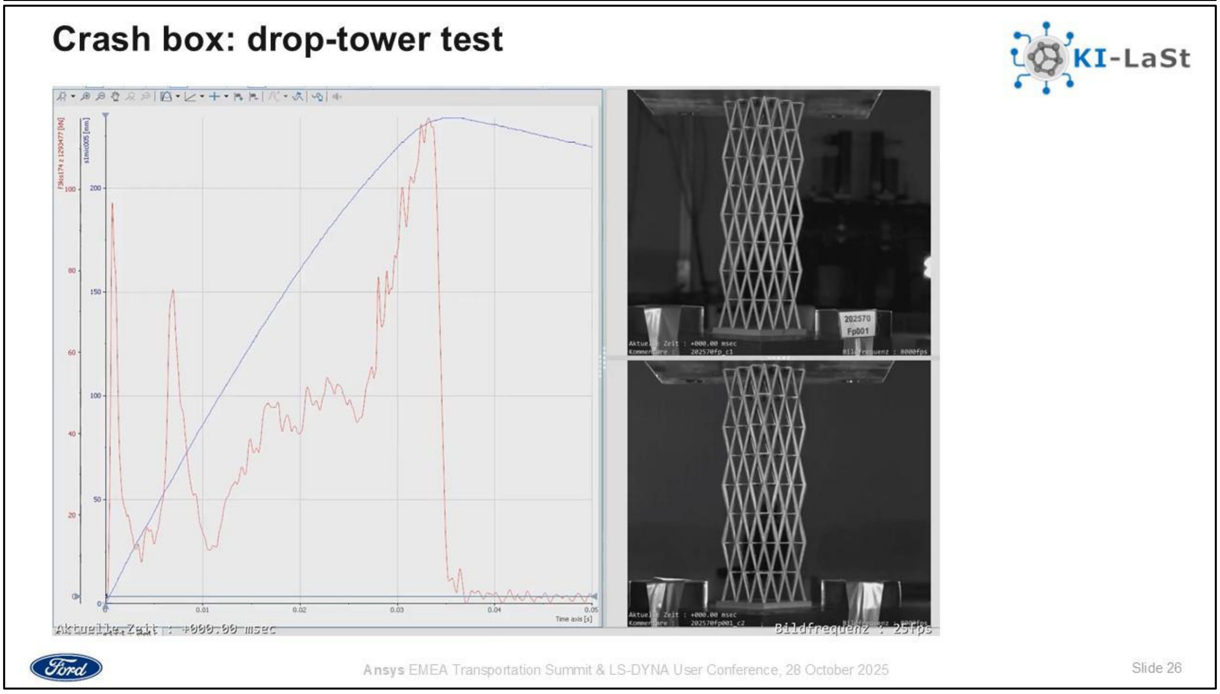

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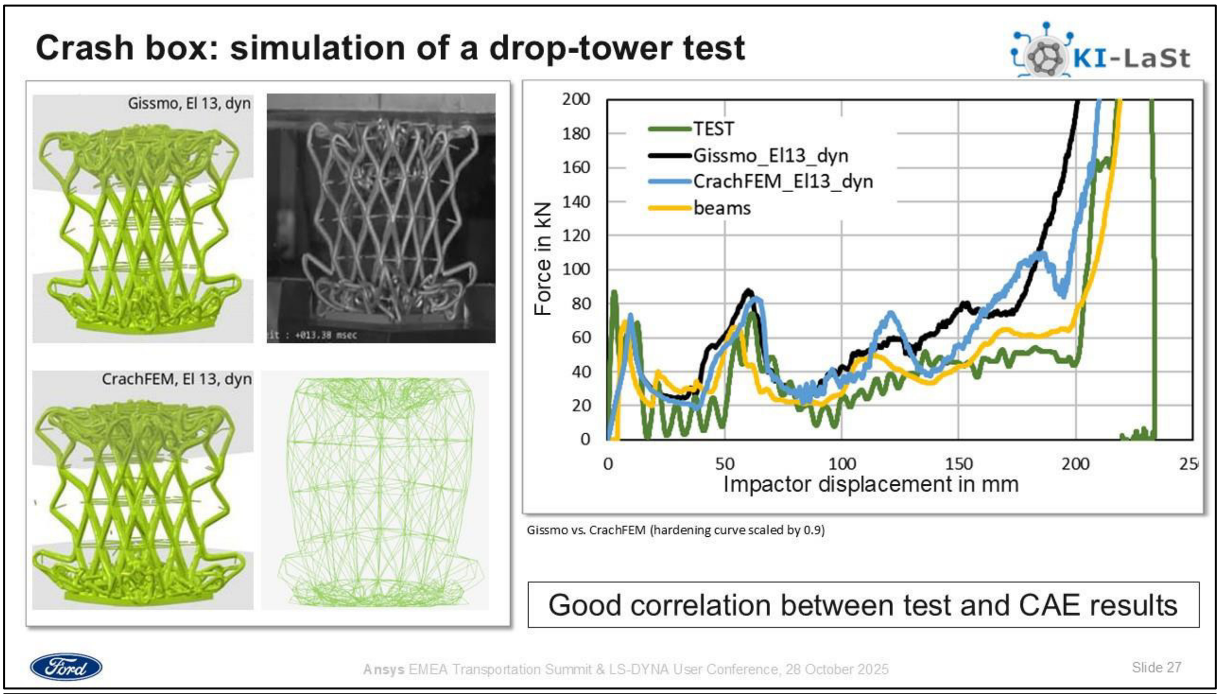

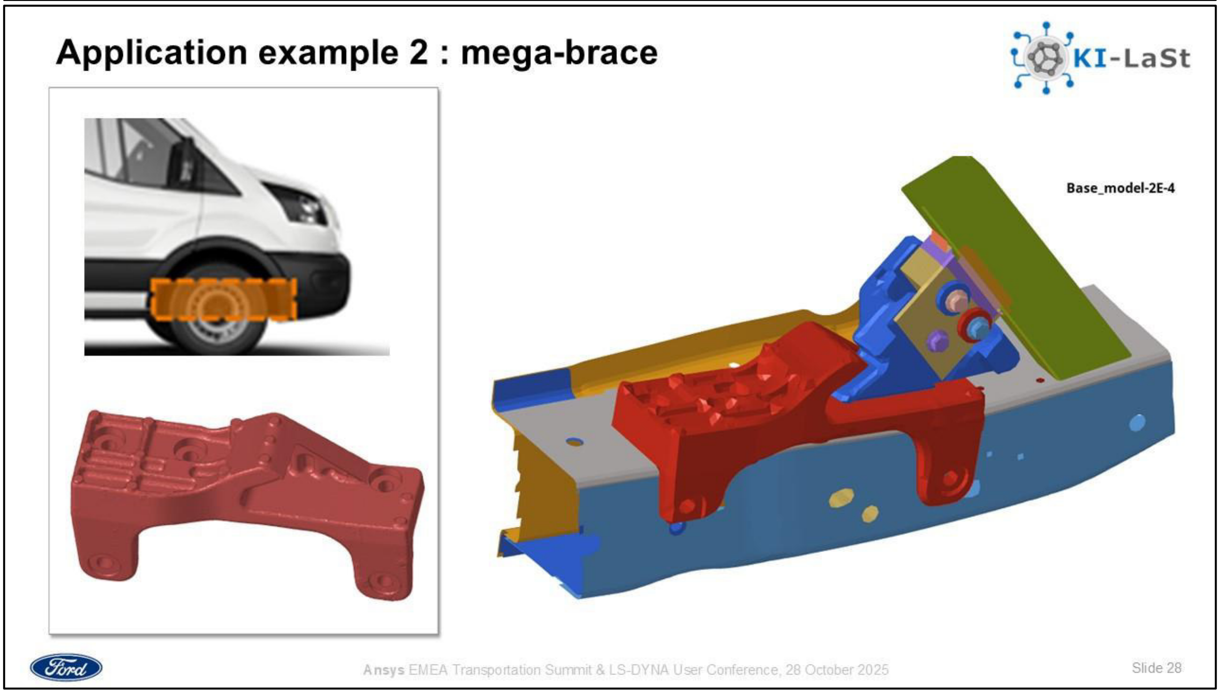

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Mega-brace: linear analyses (mesh-free methods)

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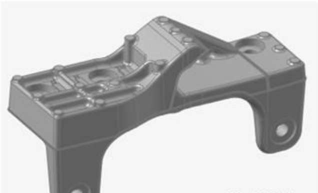
- Mesh-free analyses deliver fast linear analyses suitable for early-stage ranking

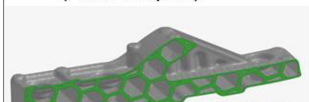
Solid CAD model



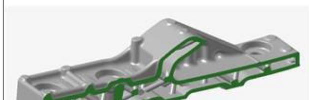
m = 3.063 kg

~5min

Implicit model variants (Altair Inspire)



m = 1.536 kg

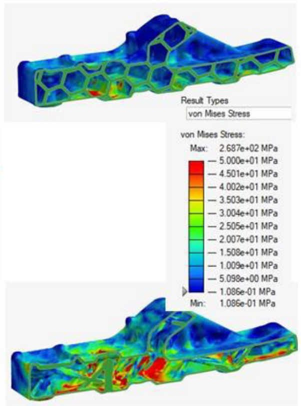


m = 1.767 kg

CAE

~3min

Simulation results (Altair Simsolid)



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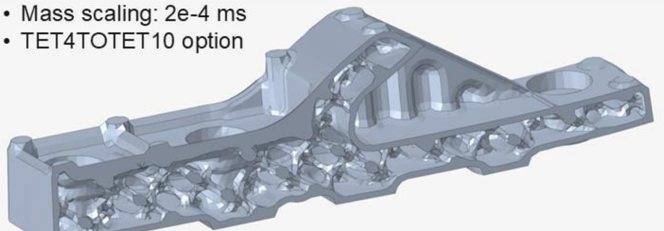
Mega-brace: crash analysis – system-level test

KI-LaSt

- Mass scaling: 2e-4 ms
- TET4TOTET10 option



→ 34 min simulation runtime

Criteria	Given input
Average element outer size	4 mm
Av. element lattice beam size	3 mm
Minimum element size	1.5 mm
Element type	Tetrahedral
Tet collapse	0.2
Elements along beam length	5 elements
Layers through wall thickness	2

For lattice structures (compared to solid structures):

- Much smaller elements
- Higher number of elements

⇒

- Smaller time step requirement for stability
- Longer simulation runtime

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Results Animation: base solid vs. Lattice design-01

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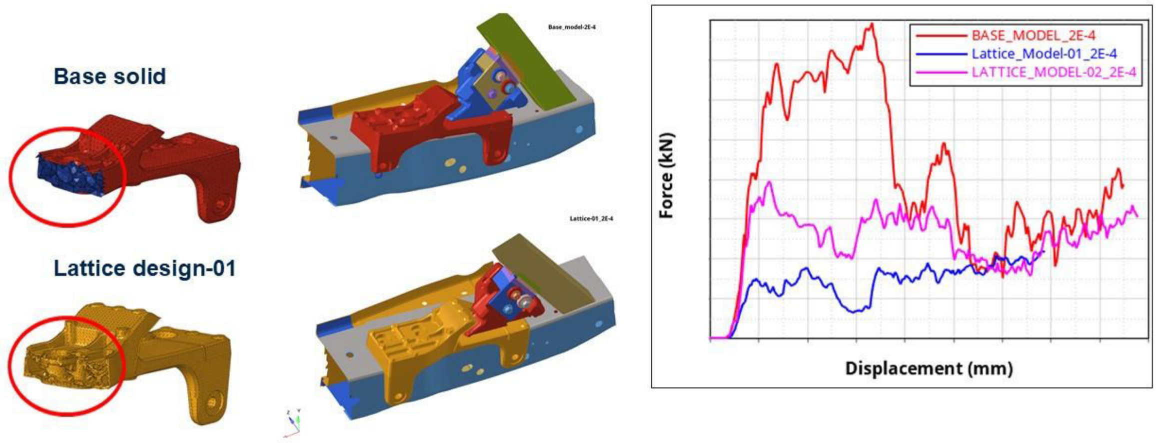
- Lattice structures enable performance tuning



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Conclusions

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Linear simulations

- Solid or beam models are applicable (small 3D elements are usually not a problem)
- Mesh-free analysis is applicable for component- or subsystem level
- Challenge: how to integrate into existing full-vehicle FEM models?

Crash simulations

- Semi-automated beam modeling is possible for some lattice types
  - Beam models provide rapid screening (for DoE) and can correlate well with tests beam-type lattice
  - For more complex geometries (e.g. beams with shell surfaces) → manual rework is necessary
- Solid modeling is possible for all lattice types
  - Semi-automated tetra mesh generation is possible (optionally starting from beam meshes)
  - Predictive crash simulation is feasible in LS-DYNA with Gissmo or MF-GenYld+CrachFEM
  - But: computationally intensive for fine geometrical features
  - → not yet suitable for high-volume product development; suitable for niche products and validation runs.
- IGA for crash is available in LS-DYNA, but has not been evaluated for AM lattices in this work

Outlook

- Mesh-free analysis is highly effective for linear analyses
- Mesh-free or IGA methods may provide a path to efficient crash simulation of lattice structures.

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4 Acknowledgements

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