Development of a Tension Energy Absorber - Progressive Bearing Failure Mechanisms of Composite Bolted Joints

M. Waimer, P. Schatrow, T. Feser, H. Kraft, D. Kohlgrüber
German Aerospace Center (DLR) – Institute of Structures and Design
Stuttgart - Germany

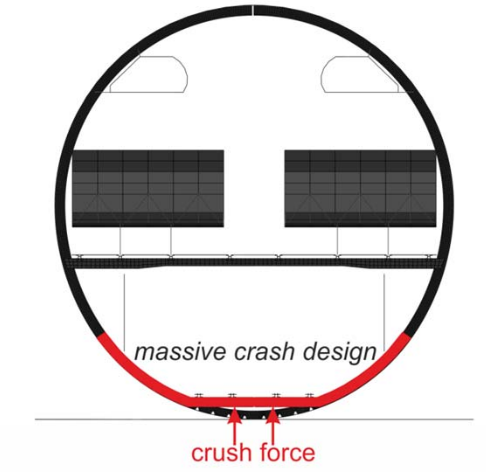
Overview

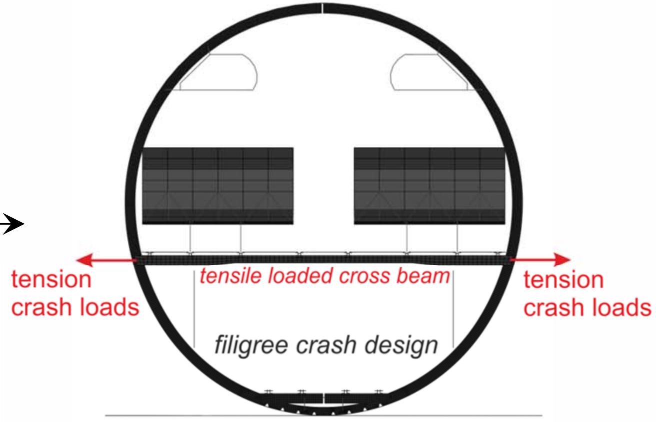
- **Motivation**
  - Crashworthiness for (CFRP) transport aircraft
- **Estimation of the concept capability**
  - Crash simulation at the fuselage section level
- **Tension energy absorber**
  - Design concept for the cabin floor tension crash absorber
- **Concept development**
  - Experiments on coupon level
- **Concept improvement & validation**
  - Experiments on element level
- **Summary & Outlook**

Motivation

Crashworthiness for (CFRP) transport aircraft

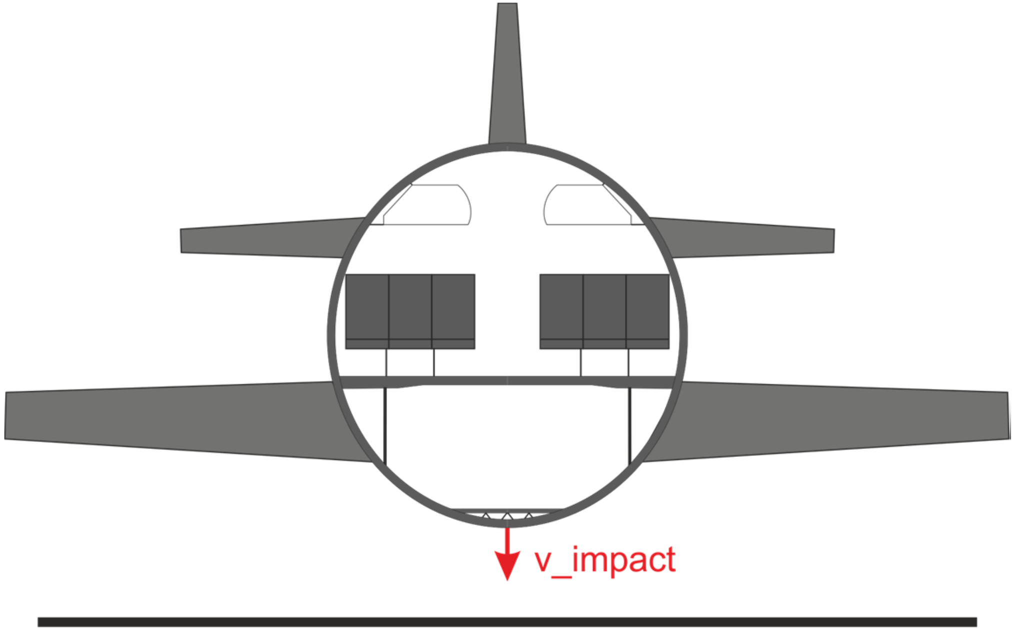
- **Dominant use of carbon fiber reinforced plastics (CFRP)**
  - Partly limited energy absorption (brittle failure behavior)
- **Airworthiness standards/ Special conditions**
  - Equivalent level of safety (compared to metallic A/C)
- **Crash designs for the CFRP fuselage**
  - Tendency to unfavorable structural mass penalty
- **Motivation**
  - Utilization of tension crash loads for energy absorption to reduce the structural mass penalty



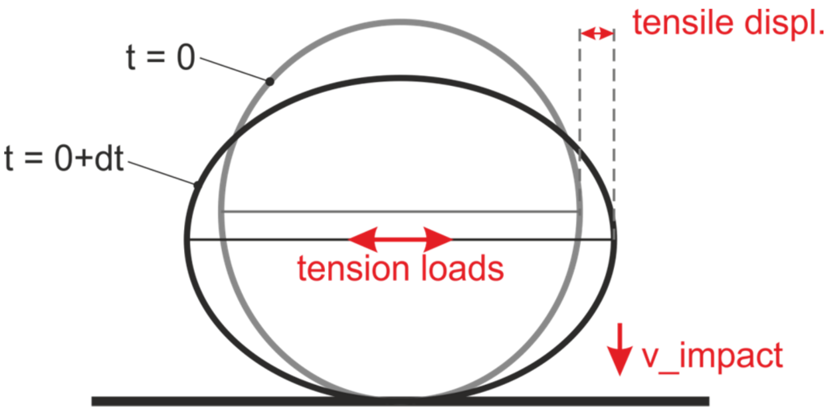


Motivation
Utilization of tension loads for energy absorption

- **Tension loads in a typical crash event (transport aircraft)**
  - 'Ovalization effect'



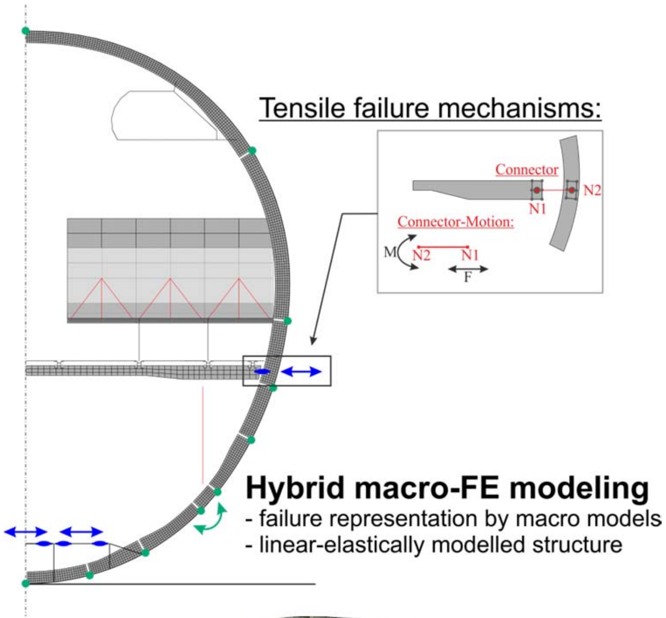
Ovalization of a circular cross section (with transversely stiffened element) impacting on a flat surface:

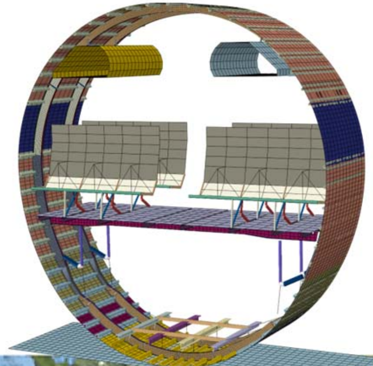


Estimation of the concept capability

Crash simulation at the fuselage section level

- **Development of the overall crash concept**
  - Energy absorption (EA) management
    - EA in the individual structural regions
  - Derivation of required absorber characteristics
    - Failure initiation (trigger) loads [N; Nm]
    - Mean load level of progressive failure for EA [N; Nm]
    - Max. stroke/ bending rotation [mm; degrees]
- **Finite element analysis (FEA)**
  - Hybrid macro-FE modeling approach
  - Fuselage section vertical drop
  - Abaqus/Explicit



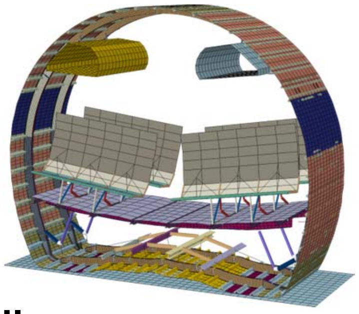


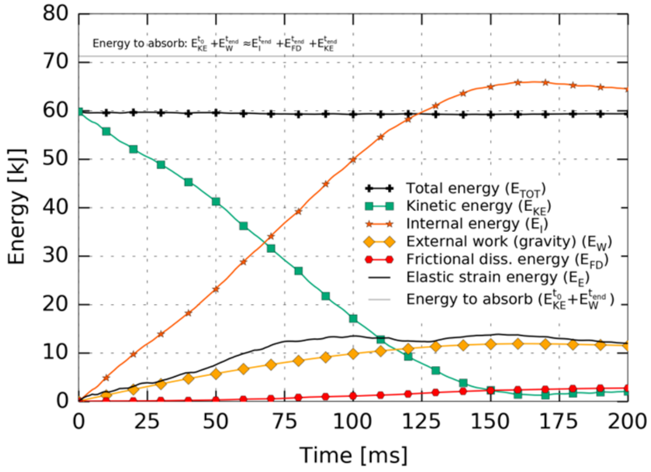
More details in: P. Schatrow, M. Waimer; Crash concept for composite transport aircraft using mainly tensile and compressive absorption mechanisms; CEAS Aeronaut J (2016) 7:471–482

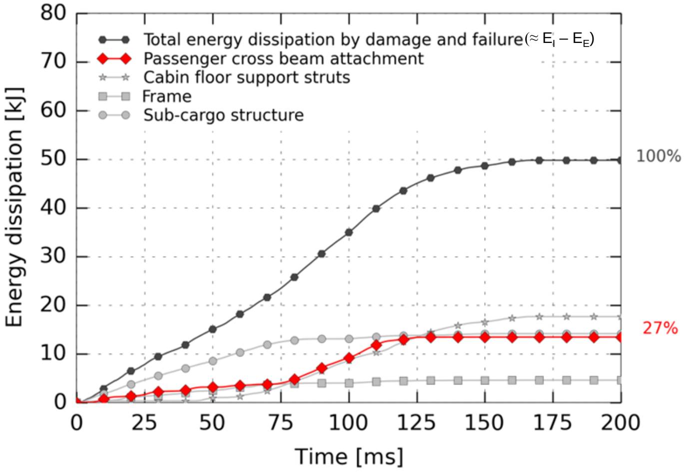
Estimation of the concept capability

Crash simulation at the fuselage section level

- **Simulation results**
  - Energy absorption by tension loads in the cabin floor:
    - 10% - 20% (max. 30%) of total energy dissipation by damage & failure of the total structure
    - depending on structural design & crash load case
  - Exemplary crash load case:
    - Vertical drop: v_i= 30 ft/s
    - 100% pax, 0% cargo loading
  - **Significant potential to absorb energy by tensile loads in the passenger cross beam!**





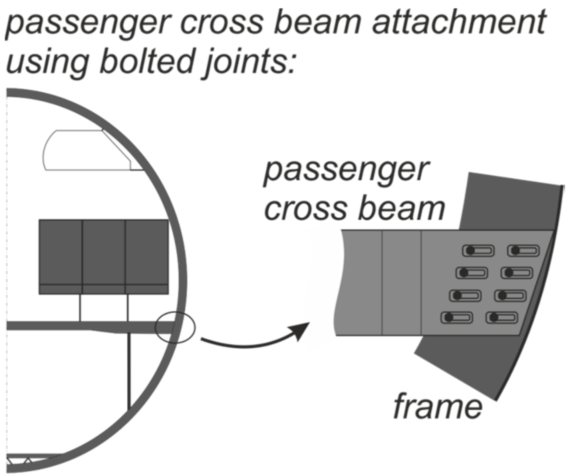


More details in: P. Schatrow, M. Waimer; Crash concept for composite transport aircraft using mainly tensile and compressive absorption mechanisms; CEAS Aeronaut J (2016) 7:471–482

Tension energy absorber

Design concept for the cabin floor tension crash absorber

- **Integration of a tension absorber in the passenger cross beam**
  - By use of the bolted cross beam attachment
  - Energy absorption by progressive bearing failure of the bolted joints
- **Specific design to strictly control the failure process!**
  - Control the direction of bearing failure under various loading conditions
  - Limit the progressive bearing failure to a certain displacement
  - Prevent blockage effects caused by a constrained flow of the debris out of the local crush zone

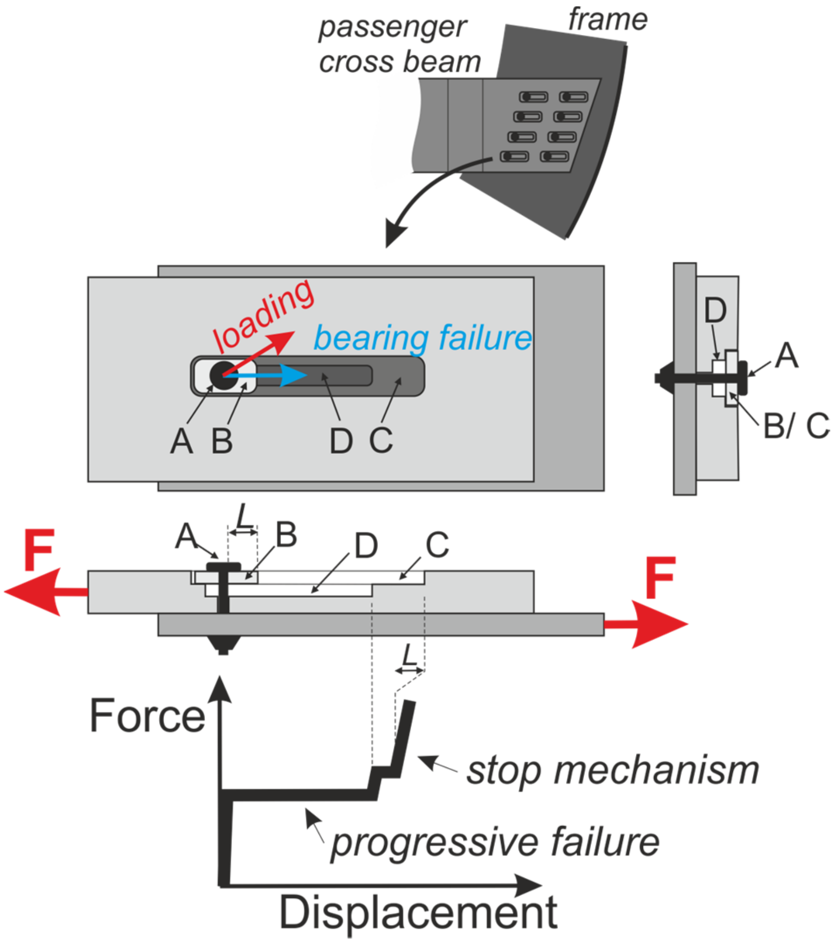


➔ Structural integrity of the cabin floor is a main survivability factor in case of a crash event!

Tension energy absorber

Design concept for the cabin floor tension crash absorber

- **Specific design to strictly control the failure process!**
  - **Bolt (A)**
    - Bolted joint set under regular conditions (pre-stressed)
  - **Washer (B) and Washer notch (C)**
    - Prevent bolt pull-through failure
    - Provide guidance in direction of progressive failure
    - Limit progressive failure to a certain distance
  - **Debris notch (D)**
    - Provide space for flow of the debris out of the local crush zone

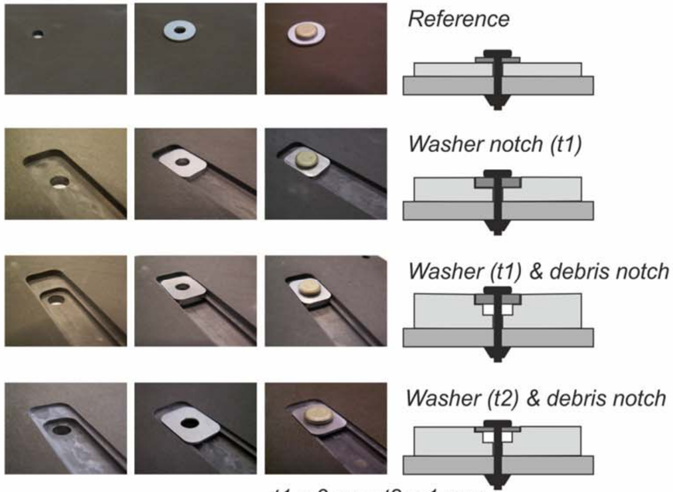


Concept development
Experiments on coupon level

- **Objectives**
  - Identify optimal design solutions for:
    - Force-displacement characteristics
    - Off-axis robustness
    - Limitation of failure process (stop mechanism)
    - Un-constrained debris outflow
- **Experimental test program**
  - Single-bolt specimens (coupon level)
  - Several notch & washer design parameters
  - Loading conditions (v = 5 mm/min, 2 m/s; off-axis: 0°, 10°, 30°)
  - In total, 120 quasi-static and dynamic tests

Washer types

Notch designs

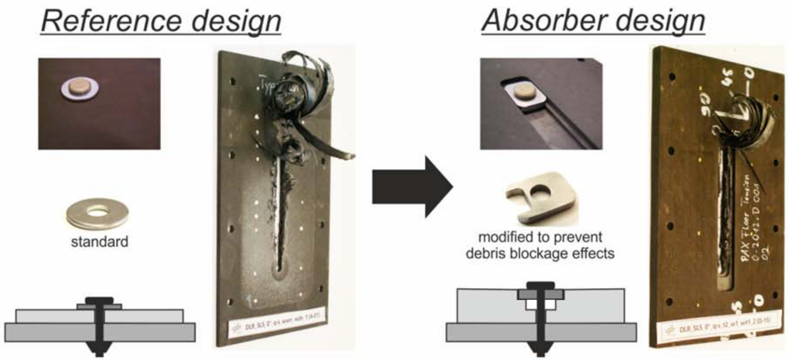


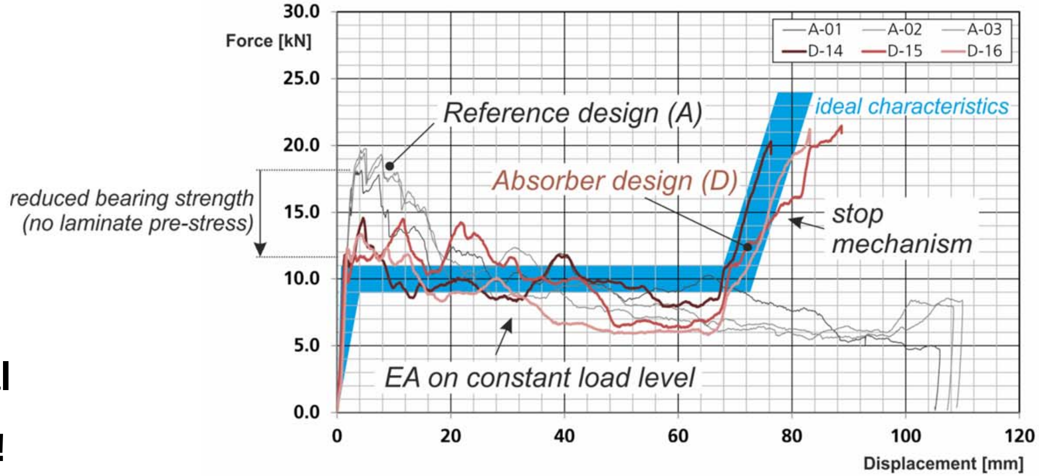
t1 ≈ 3 mm; t2 ≈ 1 mm

Single-bolt specimen (on-axis, off-axis 10° and 30°)

Concept development
Experiments on coupon level

- **Main results**
  - Significant influence of debris blockage effects
    - Requires a specific design (debris notch & washer)
  - Realization of desired absorber characteristics
    - Favorable crush force efficiency
    - Almost constant steady state load level
    - Load increase to stop the failure process
  - Successful validation
    - Off-axis loads up to 30°
- **Experiments on coupon level show the potential to use bolted joints as tension energy absorber!**

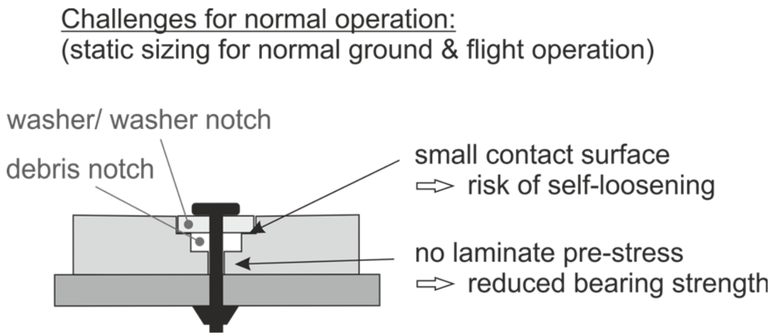


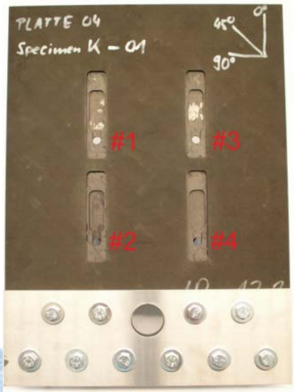


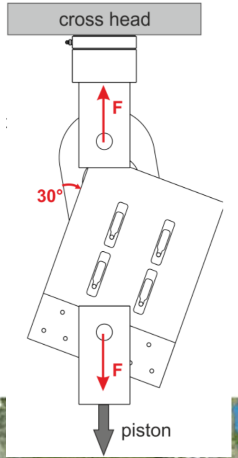
Concept improvement & validation

Experiments on element level

- **Objectives**
  - I. Concept improvements
    - Crash performance vs. normal operational performance (bolted joint)
    - Exp. investigations based on 2-bolt specimens
  - II. Validation of concept
    - Simplified structural joint under complex loading conditions
    - Exp. investigations based on 4-bolt specimens





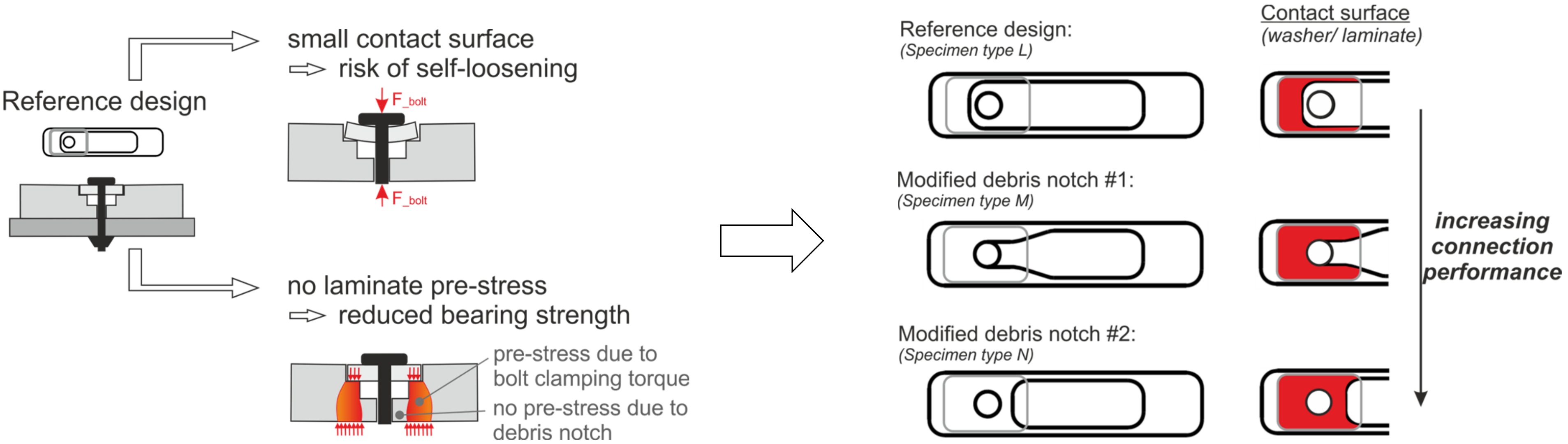


Concept improvement & validation

Element level - Study I: Concept improvements

- **Objectives**
  - Optimal design: Crash performance vs. normal operational performance (bolted joint)

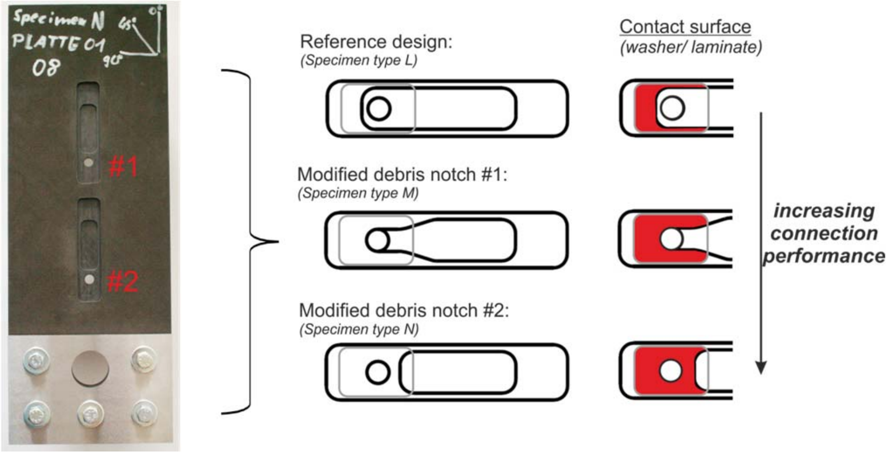
- **Challenges & potential design solutions**



Concept improvement & validation

Element level - Study I: Concept improvements

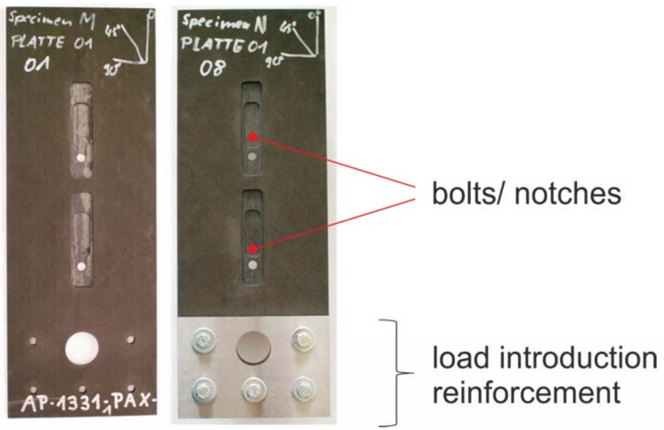
- **Test program**
  - 2-bolt specimens
  - Three different notch designs
  - Two loading rates
    - v = 2 m/s
      - Expected loading rate at the cabin cross beam attachment for typical crash events
    - v = 0.1 m/s
      - Analysis of debris outflow effects for minimum expected speeds (less distinct fragmentation)
  - Three repeat tests per variant

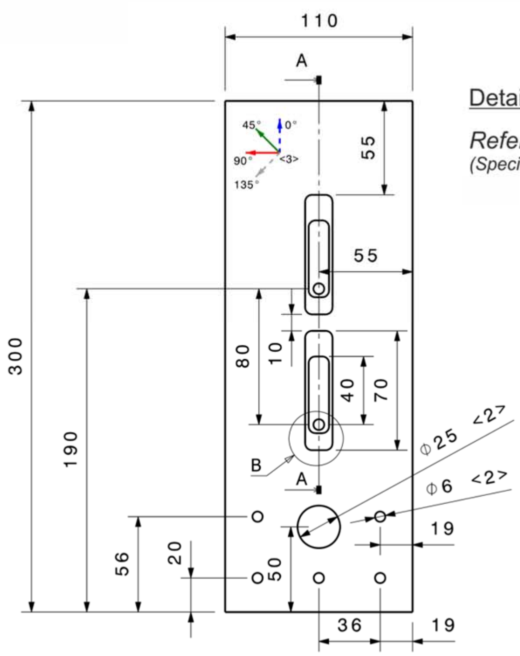


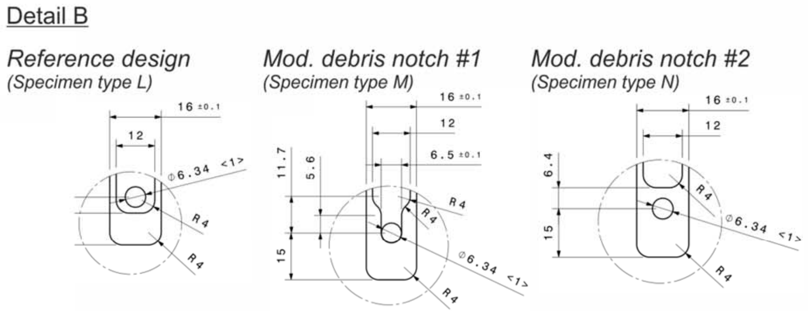
Concept improvement & validation

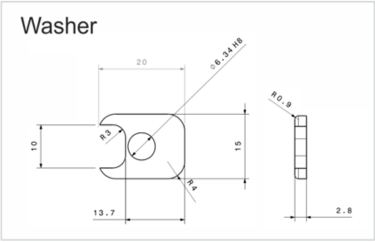
Element level - Study I: Concept improvements

- **Specimen design**
  - 2-bolt specimens
  - Three different notch designs
  - Material:
    - HiTape AS7 12k / RTM6
  - Lay-up:
    - quasi-isotropic
    - t = 8.1 mm (65 plies)
  - Bolt:
    - ANSI B18.3 (d = 6.4 mm)







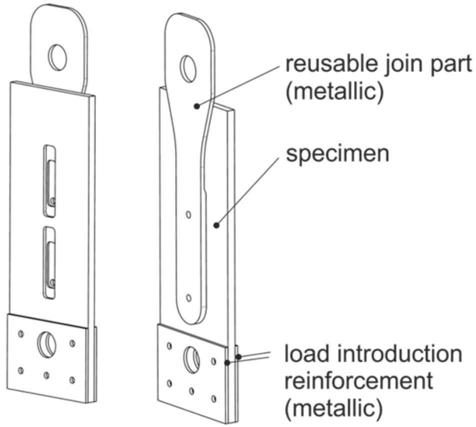


dimensions in [mm]

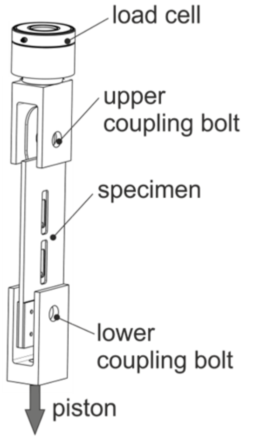
Concept improvement & validation
Element level - Study I: Concept improvements

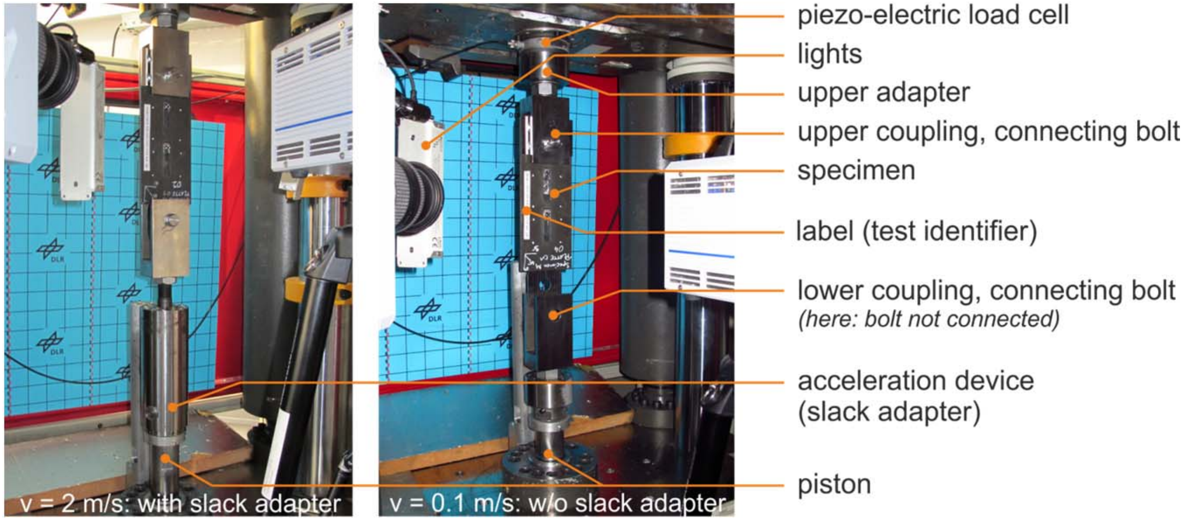
- **Test setup**
  - High-speed testing machine
    - Instron VHS PLS100/20M
    - Loading rates: 0.1 m/s; 2 m/s
  - High-speed cameras
    - FASTCAM SA-Z
    - FASTCAM-APX RS 250K
  - Transient recorder (KRENZ PSO 8200)
    - f_sampling (0.1 m/s) = 50 kHz
    - f_sampling (2 m/s) = 1 MHz
  - Measured variables
    - Force (piezo-electric load cell)
    - Displacement (piston, digital image corr.)

Specimen assembly:



Test setup (schematic):

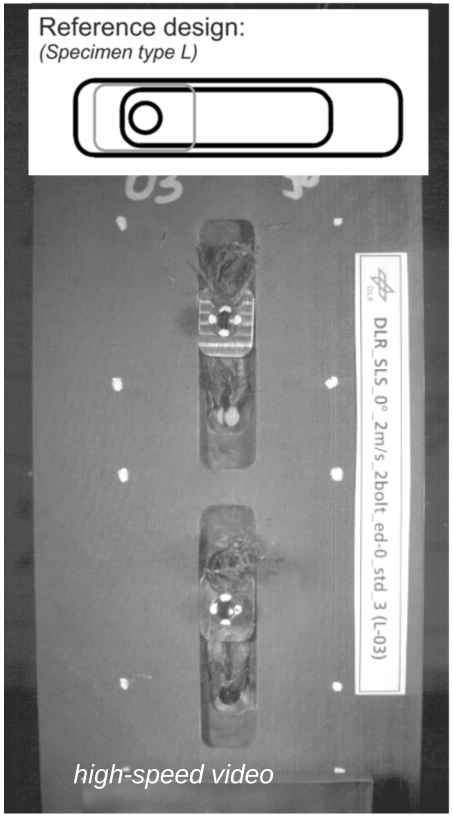


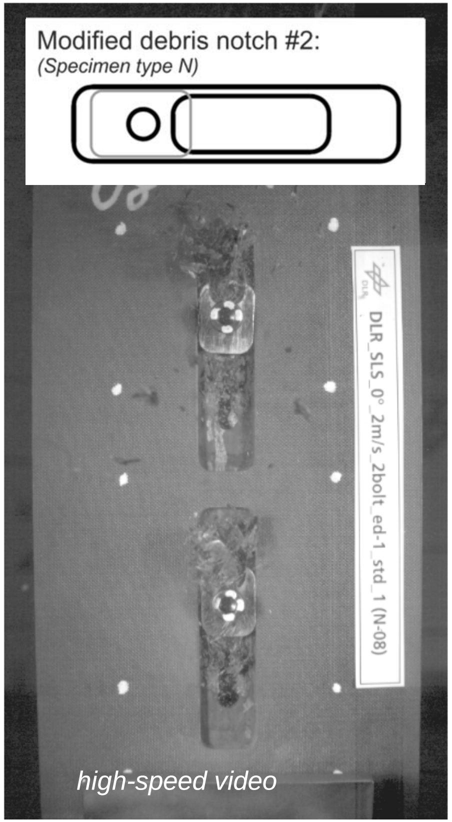


Concept improvement & validation

Element level - Study I: Concept improvements

- **Test results**
  - Exemplary test sequences

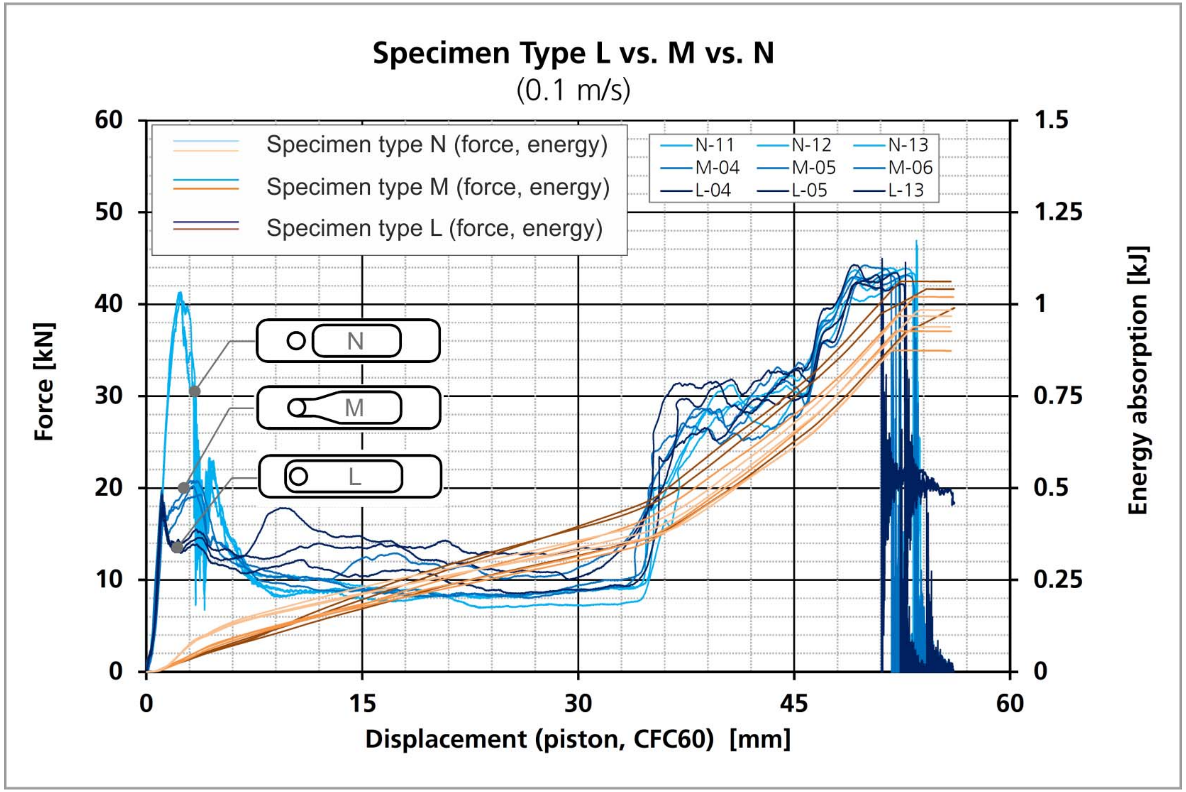




Concept improvement & validation

Element level - Study I: Concept improvements

- **Test results**
  - Influence of notch designs
    - Significant influence on failure initiation load level
  - Selection of concept depending on the design philosophy
    - Crash performance vs. normal operational performance
  - Selection of concept ‘M’ for further testing activities

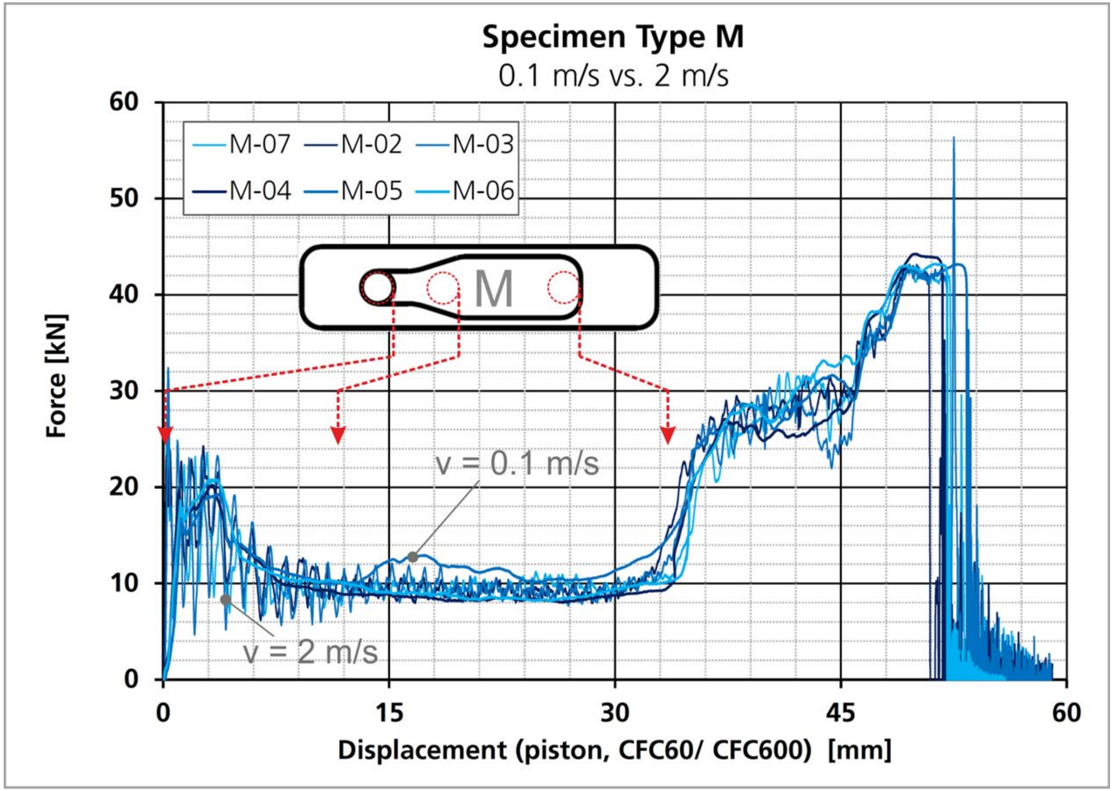


Concept improvement & validation

Element level - Study I: Concept improvements

- **Test results**
  - v = 0.1 m/s vs. v = 2 m/s
    - Here exemplarily: Concept ‘M’
  - Similar force-displacement characteristics
    - Progressive failure at a reduced loading rate (0.1 m/s): No tendency to blockage effects which might be caused by less distinct fragmentation

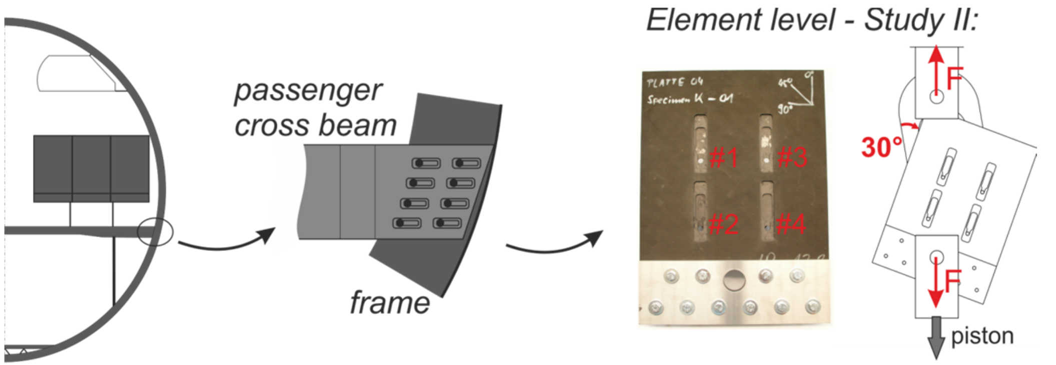
(Blockage effect: A constrained flow of the debris out of the local crush zone in front of the bolt that can lead to bolt failure due to high compaction of the debris)



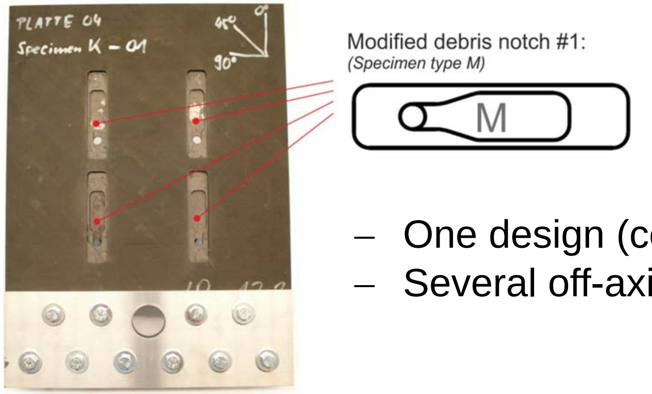
Concept improvement & validation

Element level - Study II: Concept validation

- **Objectives**
  - Concept validation
    - Simplified structural joint (4-bolt specimen)
    - Complex loading conditions



- **Test program**
  - 4-bolt specimens
  - Off-axis loading: 0°, 10°, 20°, 30°
  - Dyn. loading rate: v = 2 m/s
  - Three repeat tests per variant

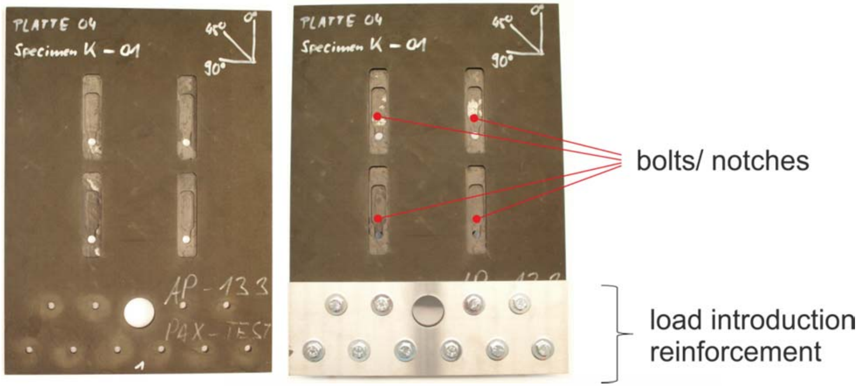


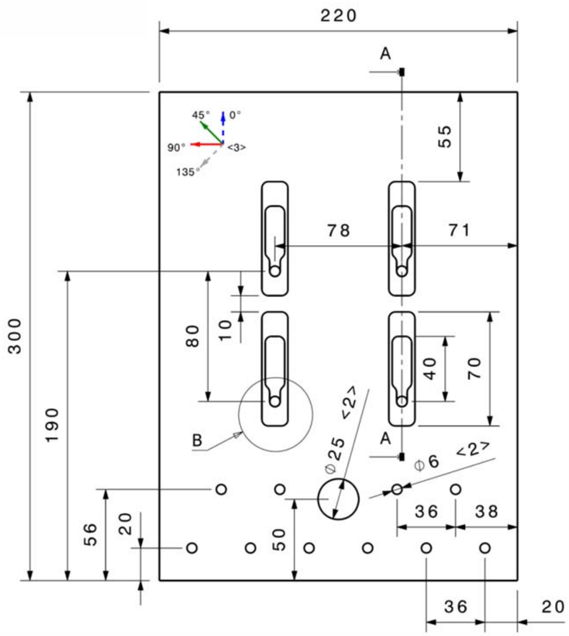
- One design (concept ‘M’)
- Several off-axis loading conditions

Concept improvement & validation

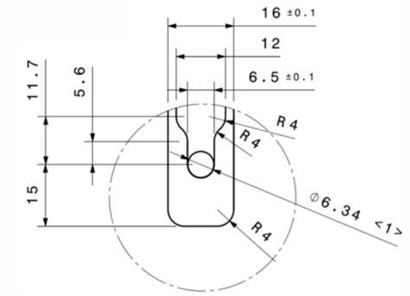
Element level - Study II: Concept validation

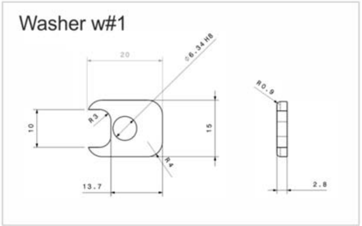
- **Specimen design**
  - 4-bolt specimens
  - Debris notch: Design concept ‘M’
  - Material:
    - HiTape AS7 12k / RTM6
  - Layup:
    - quasi-isotropic
    - t = 8.1 mm (65 plies)
  - Bolt:
    - ANSI B18.3 (d = 6.4 mm)





Detail B (Design concept ‚M‘)





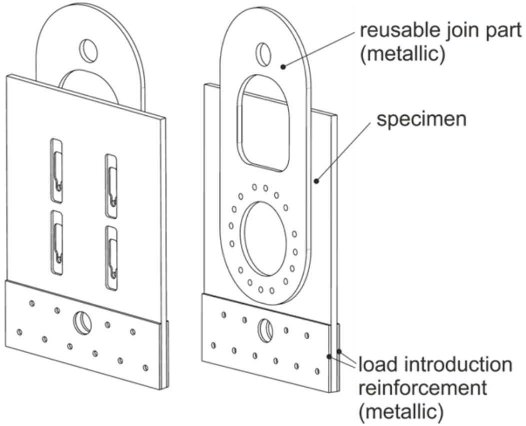
dimensions in [mm]

Concept improvement & validation

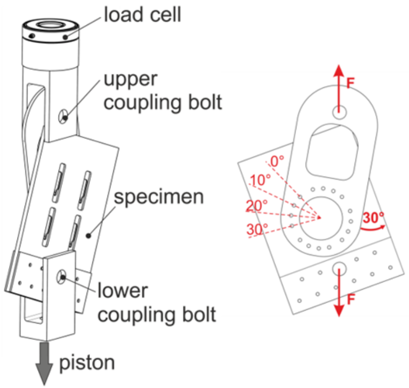
Element level - Study II: Concept validation

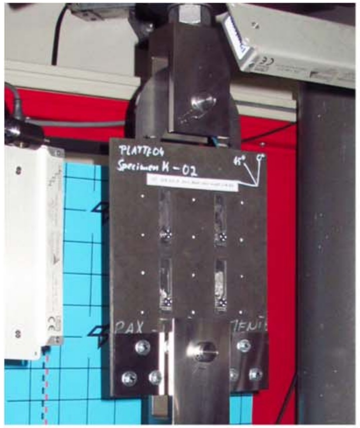
- **Test setup**
  - High-speed testing machine
    - Instron VHS PLS100/20M
    - Loading rate: 2 m/s
  - High-speed cameras
    - FASTCAM SA-Z
    - FASTCAM-APX RS 250K
  - Transient recorder (KRENZ PSO 8200)
    - f_sampling (2 m/s) = 1 MHz
  - Measured variables
    - Force (piezo-electric load cell)
    - Displacement (digital image correlation)

Specimen assembly:



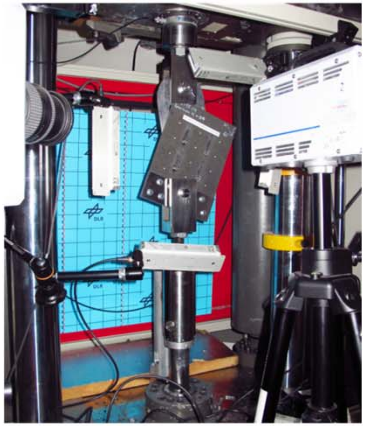
Test setup (schematic):





on-axis: 0°

off-axis: 30°

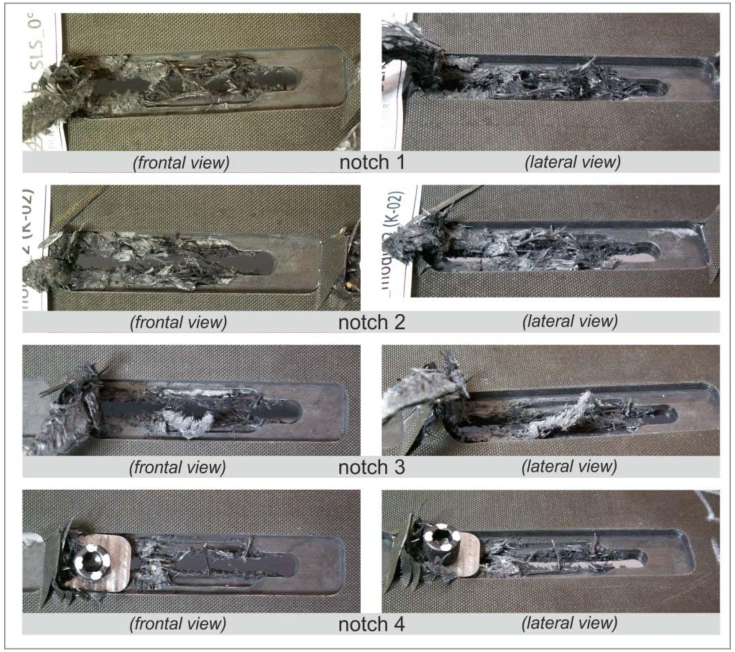


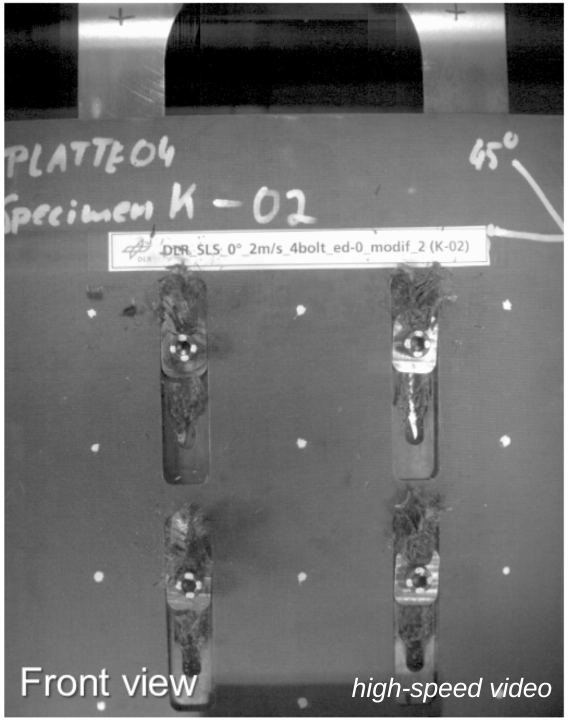
overview test setup

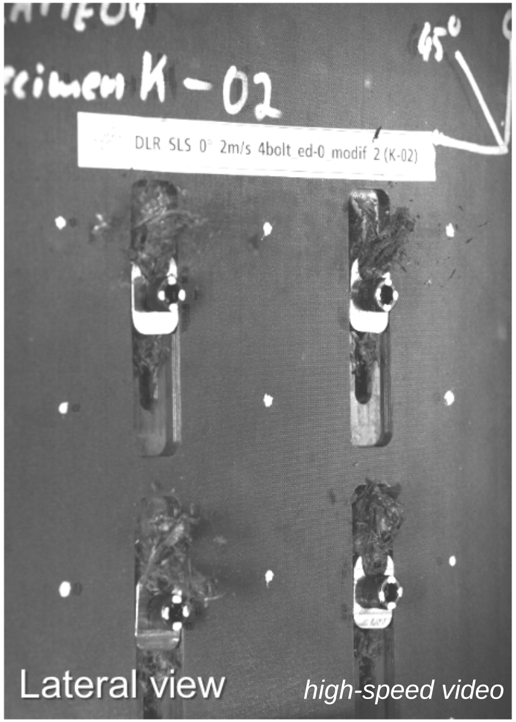
Concept improvement & validation

Element level - Study II: Concept validation

- **Test results (0° on-axis)**
  - Test sequence & post-test pictures



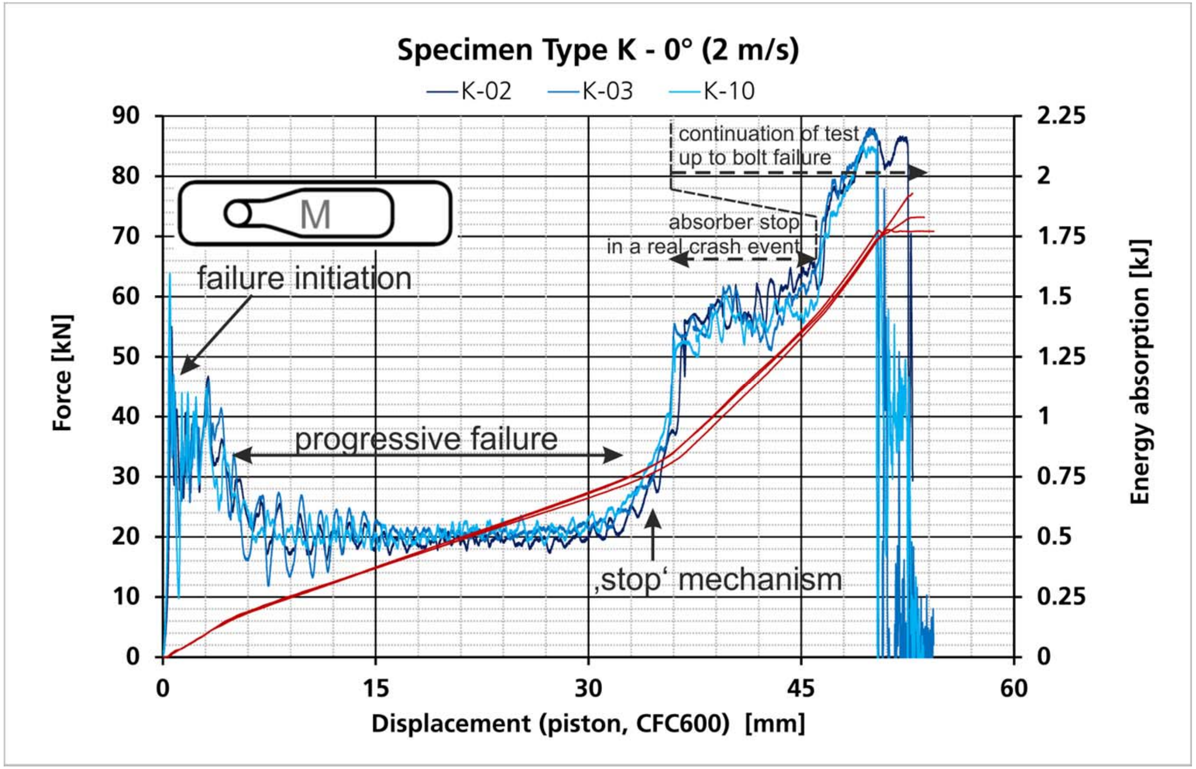




Concept improvement & validation

Element level - Study II: Concept validation

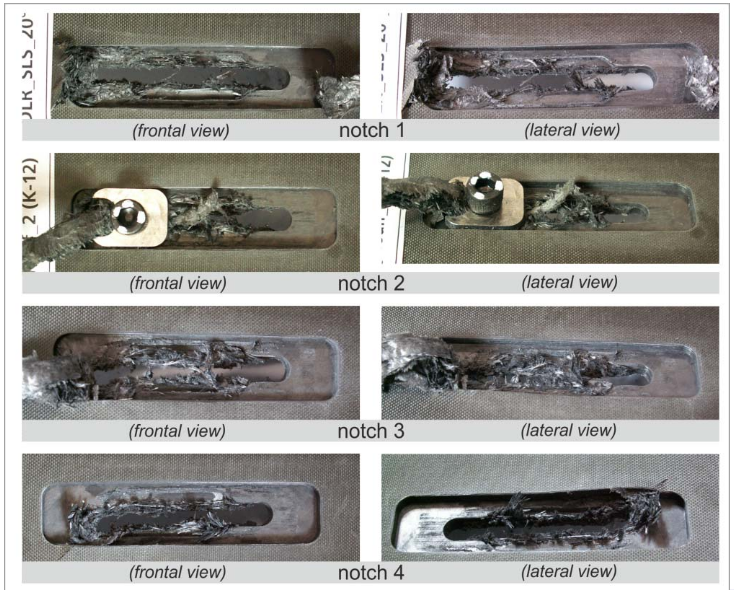
- **Test results (0° on-axis)**
  - No blockage effects
    - Non-constraining flow of the debris out of the local crush zone
  - Good force-displacement characteristics
    - Almost constant load level during progressive failure
    - But increased failure initiation load, resp. reduced crush force efficiency (notch design concept ‘M’)
    - Sufficient ‘stop’ force level

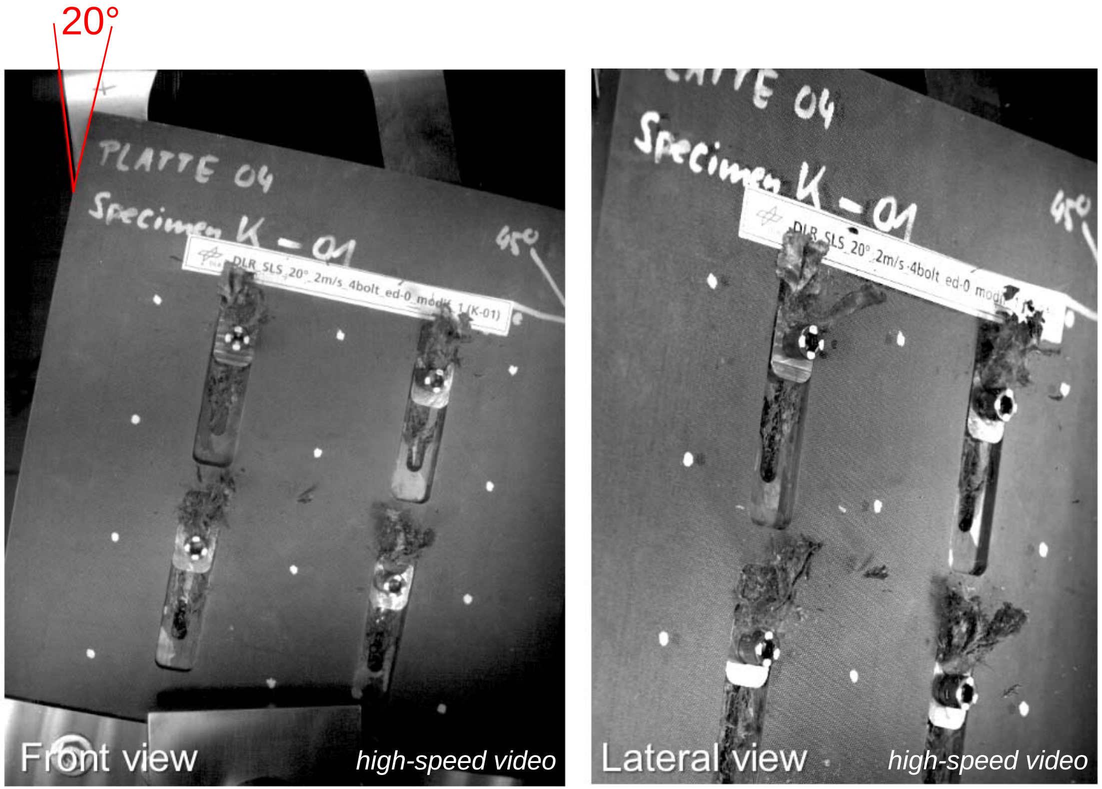


Concept improvement & validation

Element level - Study II: Concept validation

- **Test results (20° off-axis)**
  - Test sequence & post-test pictures
    - Off-axis robustness!

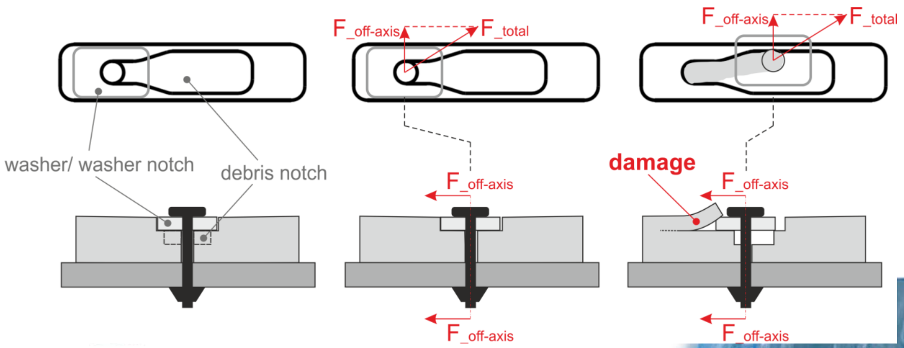


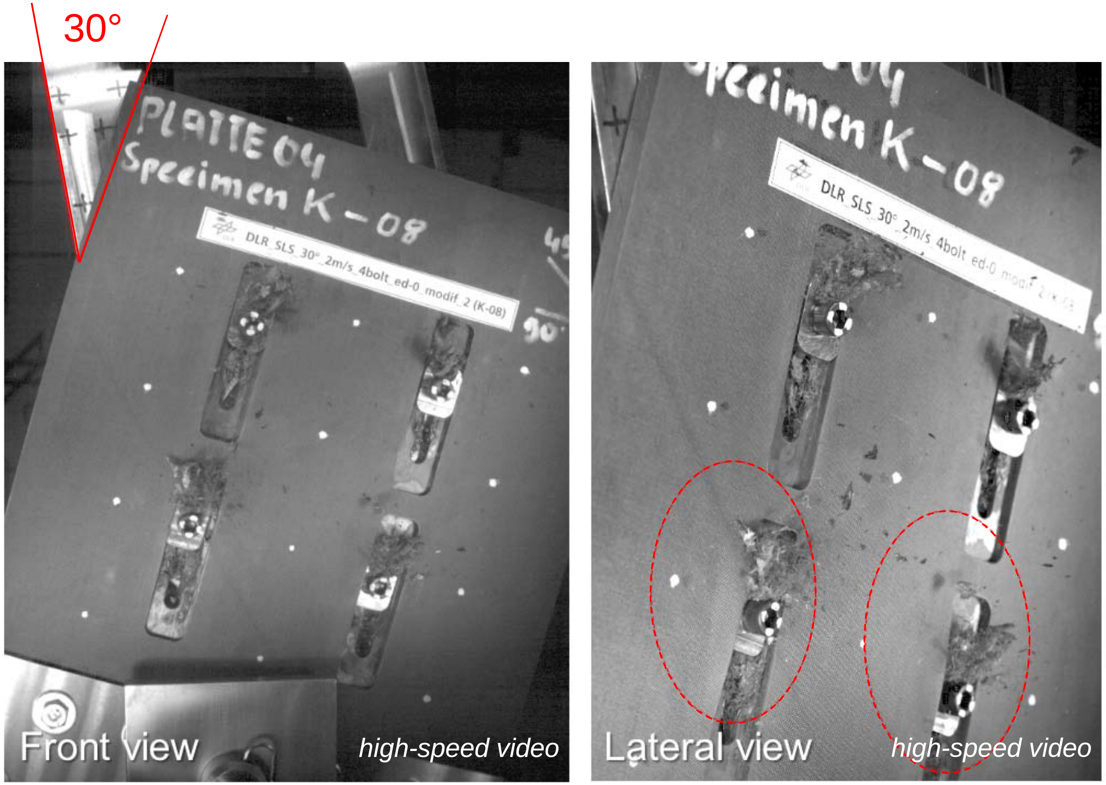


Concept improvement & validation

Element level - Study II: Concept validation

- **Test results (30° off-axis)**
  - Test sequence
    - Limited robustness for off-axis > 30°
    - Damage of lateral notch edges caused by the off-axis load
    - Bolt still guided along the desired failure direction!

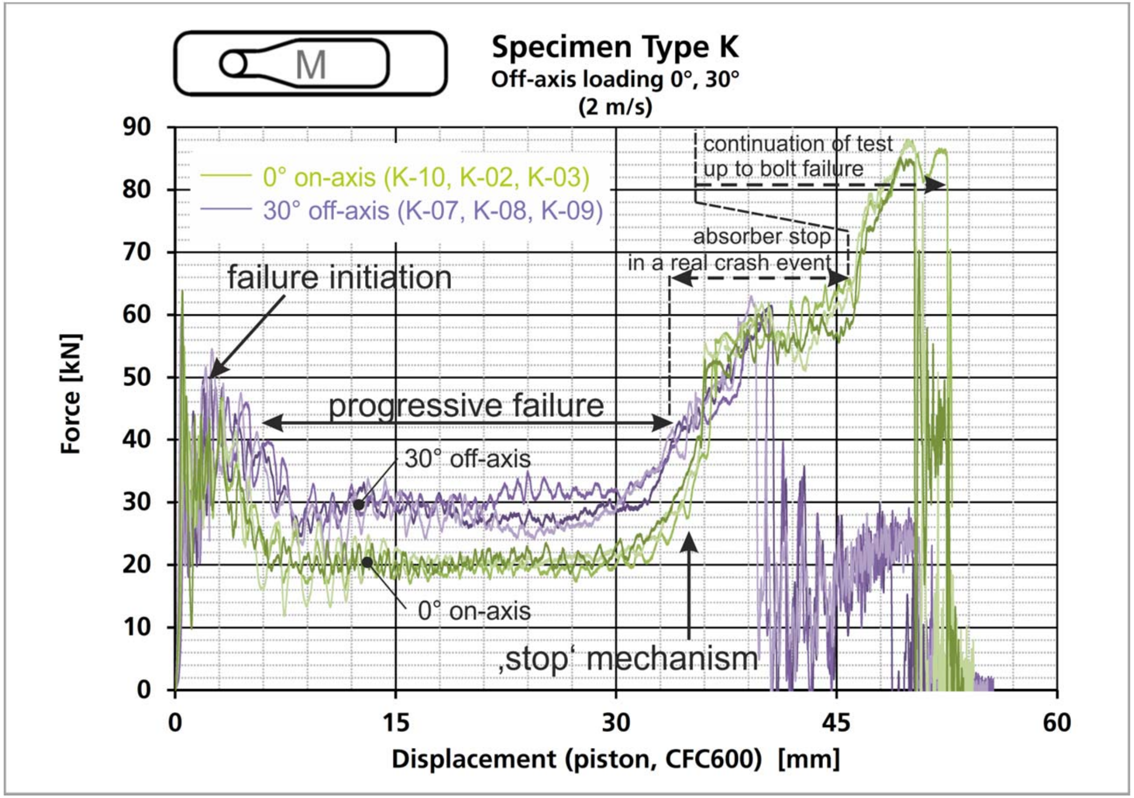




Concept improvement & validation

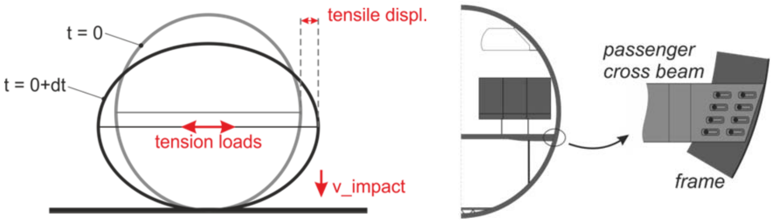
Element level - Study II: Concept validation

- **Test results (0° vs. 30° off-axis)**
  - Good force-displacement characteristics of 30° off-axis compared to 0° on-axis:
    - Similar failure initiation load level
    - Increased steady-state load level
    - Similar load level of ‘stop’ mechanism

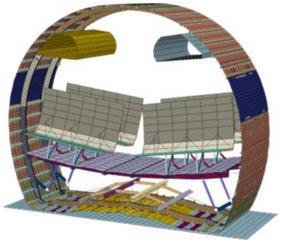


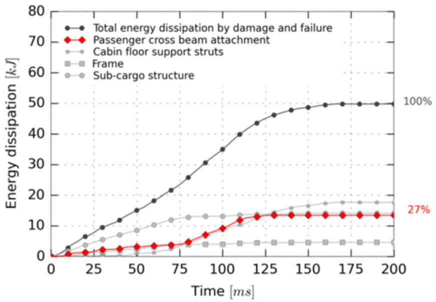
Summary & Outlook

- **Scope of research**
  - Novel crash design based on tension energy absorption by progressive bearing failure of the bolted passenger cross beam attachment



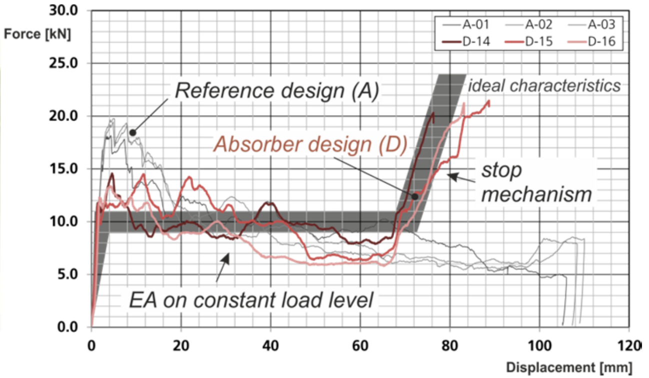
- **Estimation of the concept capability**
  - Favorable results based on FEA at the fuselage section level
  - Energy absorption by tension loads in the cabin floor:
    - 10% - 20% (max. 30%) of total structural energy dissipation
      - depending on structural design & crash load case



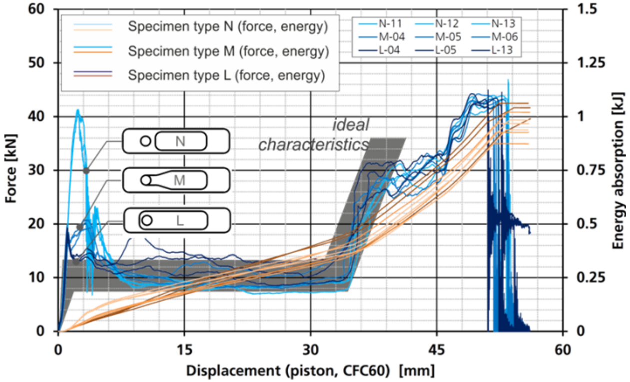


Summary & Outlook

- **Concept development**
  - Coupon level (1-bolt specimens)
    - Objectives: General feasibility, crash performance, etc.
    - Outcomes: Design for favorable absorber characteristics

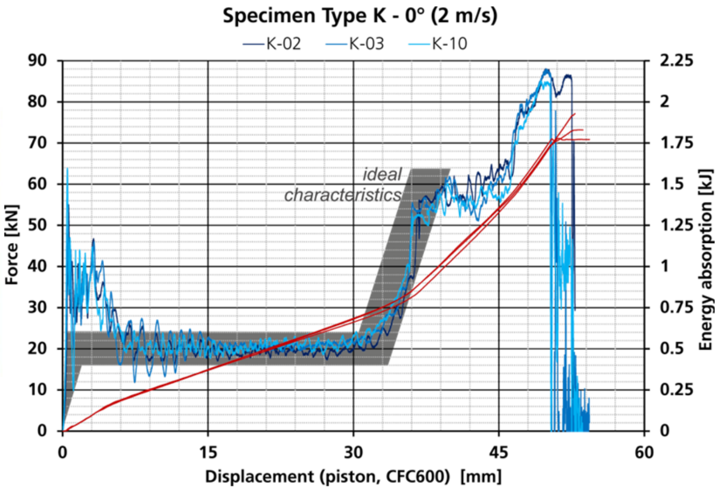


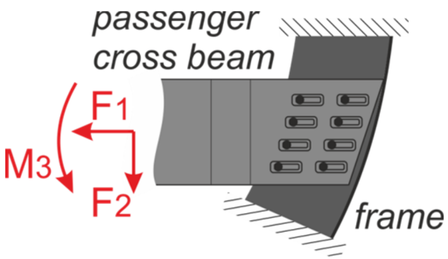
  - Element level (2-bolt specimens)
    - Objectives: Optimal design as a compromise between crash performance and normal operational performance
    - Outcomes:
      - Concepts for different design philosophies (N, M, L)
      - Concept validation for diff. loading rates (0.1 m/s, 2 m/s)



Summary & Outlook

- **Concept validation**
  - Element level (4-bolt specimens)
  - Objectives: Validation under complex loading conditions
  - Outcomes:
    - Successful validation of concept
    - Identification of max. off-axis robustness
      - Presented design: Robustness limited to < 30° off-axis
- **Outlook**
  - Research work is planned to be continued
    - On the next level of complexity (detail level)
    - Taking into account specific designs of frame and cross beam





Thank you for your attention!

Acknowledgements

The research leading to these results was accomplished in the framework of the 4th aeronautical research program of the German Federal Ministry for Economic Affairs and Energy (BMWi), as part of the LuFo-IV project FUGE (TENOR).

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Corresponding Author

Dr. Matthias Waimer
matthias.waimer@dlr.de
+49-711-6862-648

DLR Institute of Structures and Design
Pfaffenwaldring 38-40
70569 Stuttgart - GERMANY