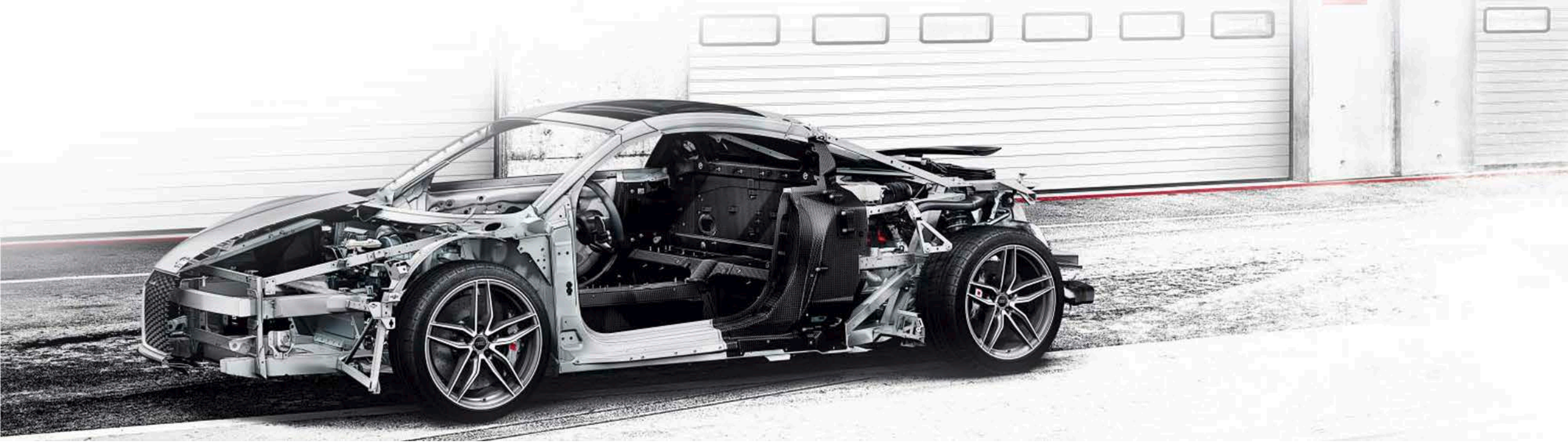

Kurzzeit-dynamische Biegeprüfung: Dehnratenabhängige Biege-Eigenschaften von kohlenstofffaserverstärkten Kunststoffen

T. Schmack | Prof. Dr. F. Walther

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2 Strain Rate Dependent 3-Point Bending Test

3 Estimation of the Maximum Testing Velocity

4 Conclusions

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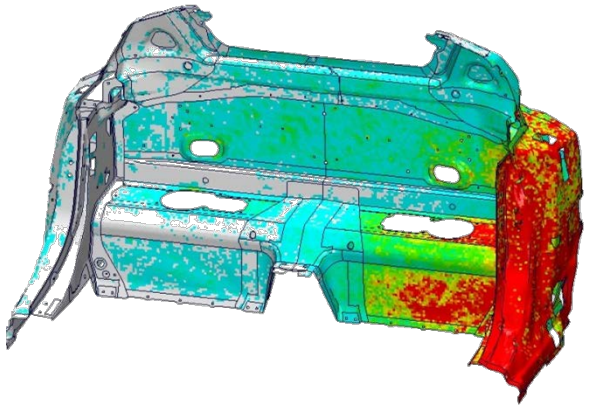
Motivation

Strain rate distribution in the R8 rear panel side-crash

Side-crash

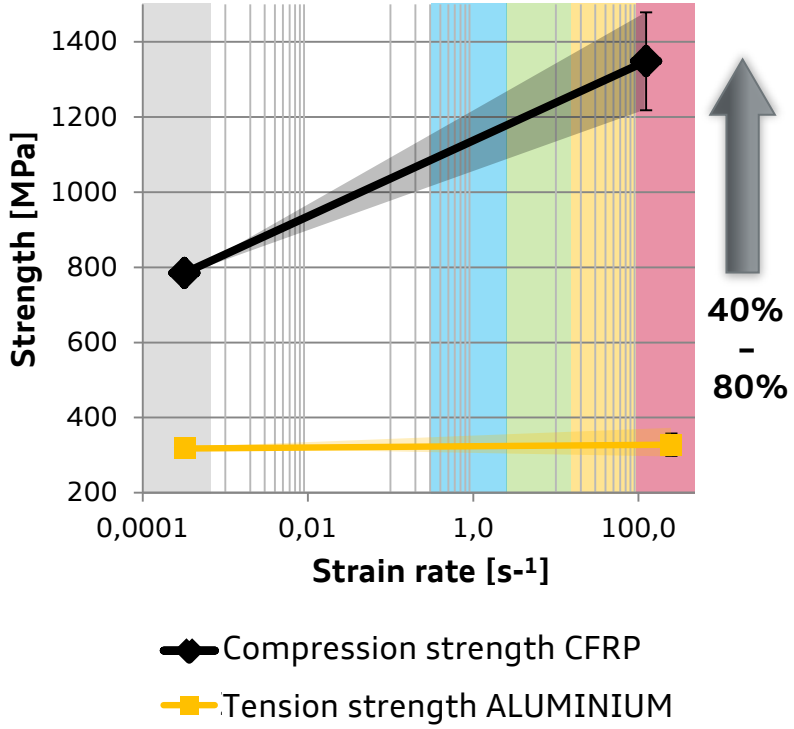
- Compressive load on structural component
- Crash-speed v_{Crash} = 55 km/h
- Strain rate up to $\dot{\varepsilon}$ = 300 s^{-1}

Strain rate distribution from FEM model



- $\dot{\varepsilon}$ = 100 s^{-1} (peaks of 300 s^{-1})
- $\dot{\varepsilon}$ = 10 s^{-1}
- $\dot{\varepsilon}$ = 5 s^{-1}
- $\dot{\varepsilon}$ = 1 s^{-1}

Material Strain Rate Dependency



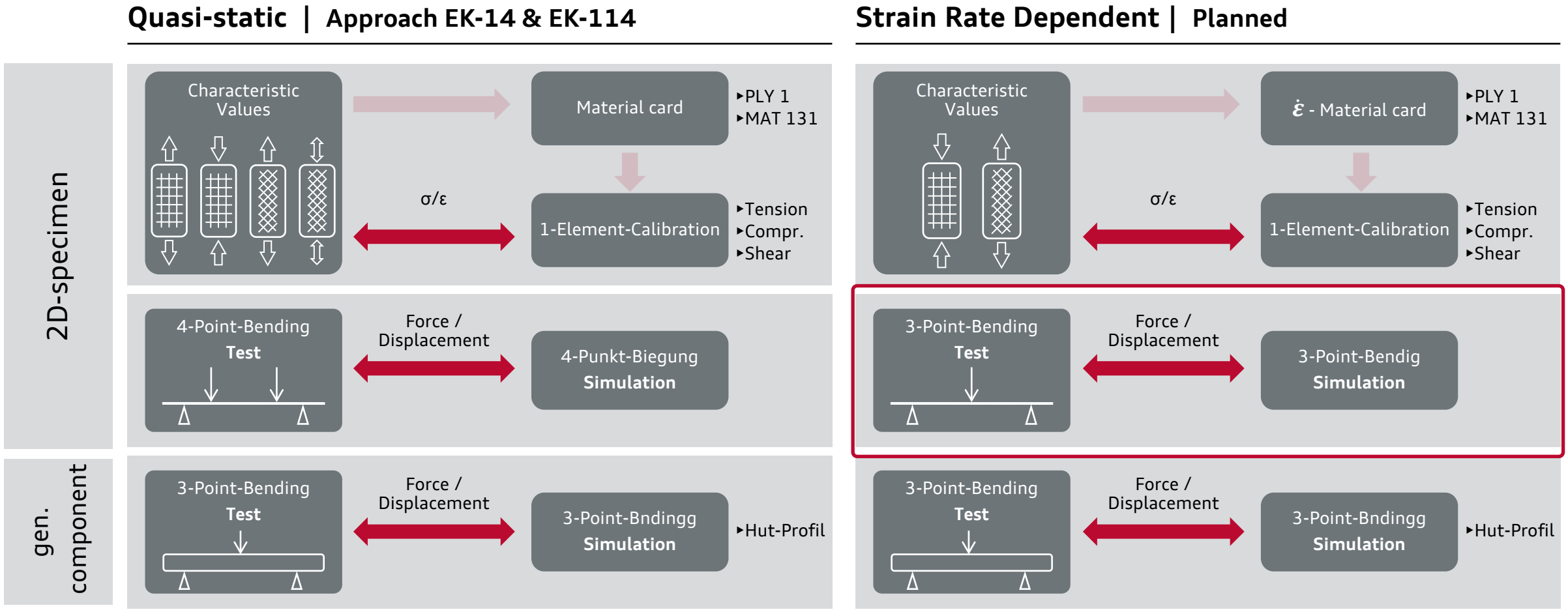
Considering the dynamic strength of the material » **Maximise the use of material**

Reduction of safety factors in the design » **Lightweight potential**

More economical CFRP components » **Costs**

Motivation

Strain rate dependent 3-point bending tests and FEM simulation



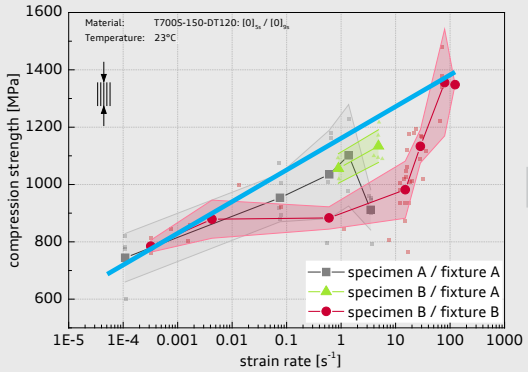
- Similar approach between quasi-static and dynamic material characterisation
- Ensure a realistic and comparable implementation in the Audi process

Motivation

Validation Concept - Strain Rate Dependent 3-Point Bending

Uniaxial Compression | Test

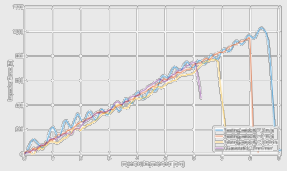
Material properties from uniaxial compression tests



$\dot{\varepsilon}$ - Material Card

3-Point Bending | Test

Strain Rate Dependent Bending Test

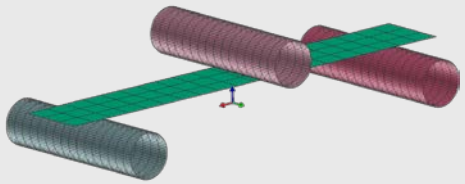


Force-Displacement

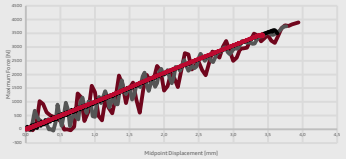
Validation

3-Point Bending | Simulation

Strain Rate Dependent Simulation Model



Force-Displacement



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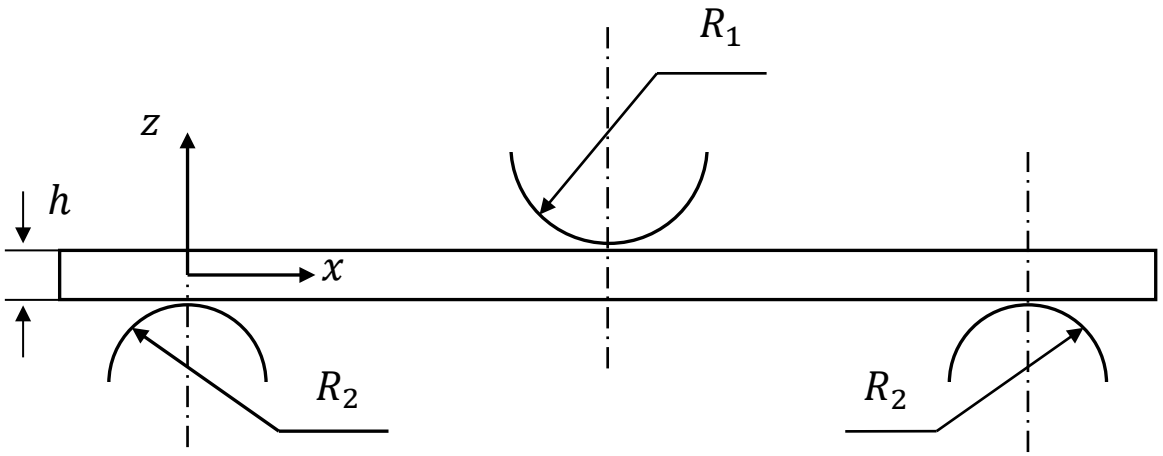
4 Conclusions

Test Setup
Fixture Design

- No accepted standard is available for strain rate dependent 3-point bending tests
- The guidelines provided by the quasi-static norm DIN EN ISO 14125 were used for the fixture design
- Fixture requirements:
  - allowing testing of a wide range of specimens
  - durable
  - light
  - cost effective
  - allowing using strain gauges to measure the load
  - local force measuring near the specimen



Dimension	Value [mm]
R_1	5 ± 0.2
R_2 for $h \leq 3$ mm	2 ± 0.2
R_2 for $h > 3$ mm	5 ± 0.2

» Impactor and supports were designed with a radius of 5 mm

Test Setup
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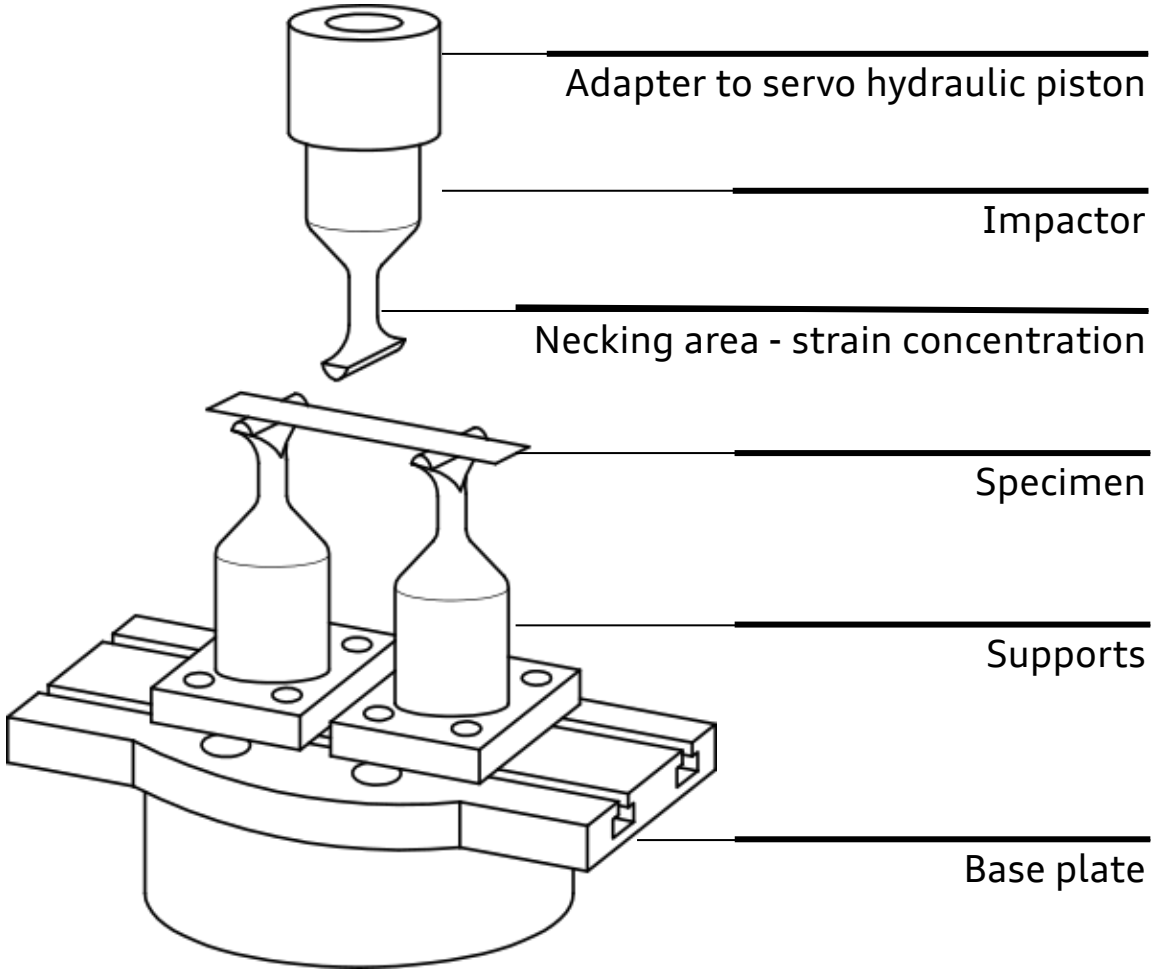

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Test Setup
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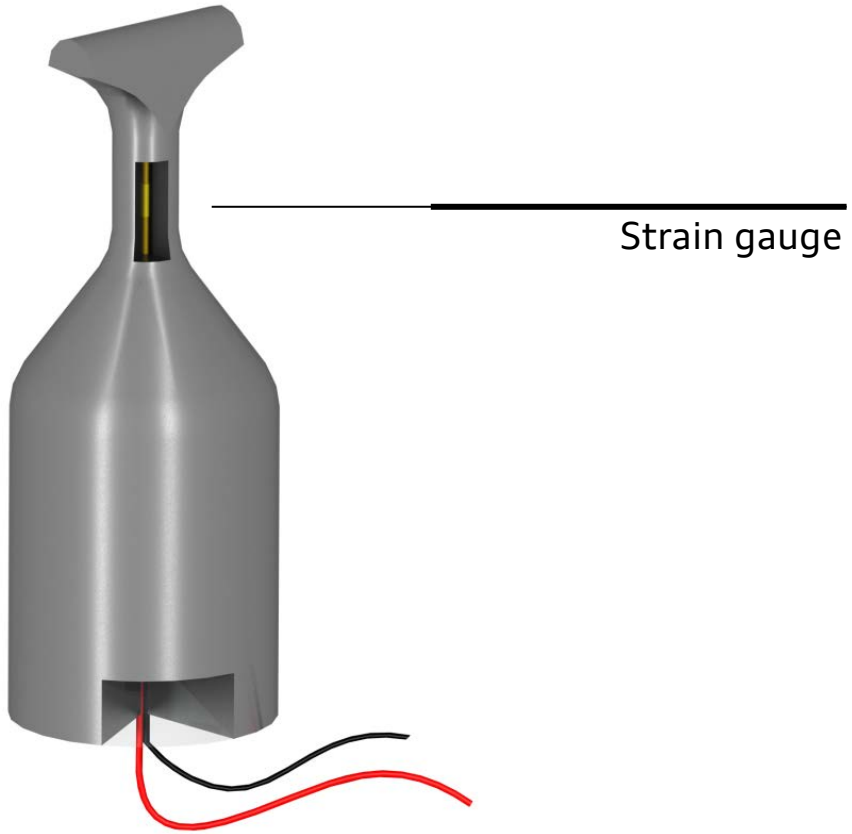
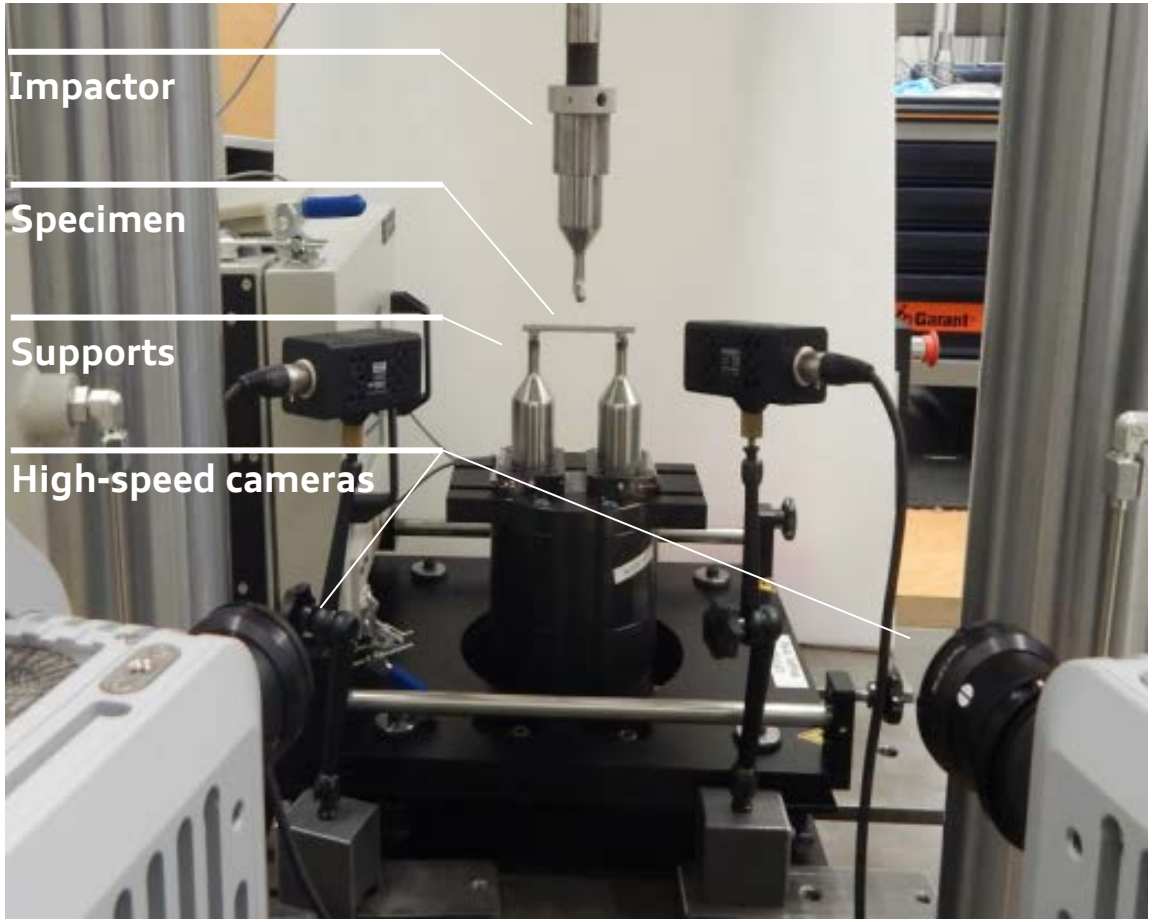


» A strain gauge in the necking area allowed measuring the force near the specimen

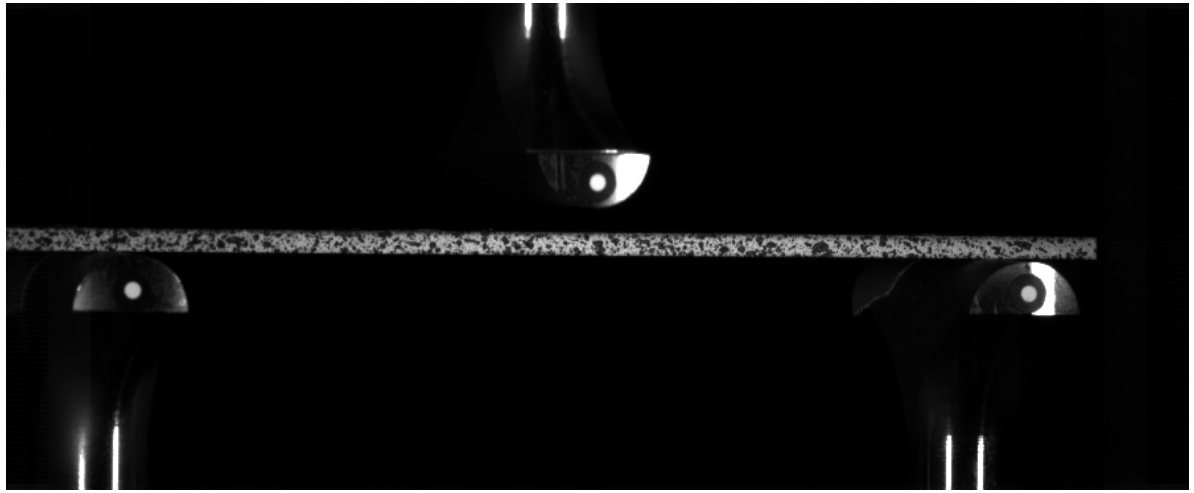
Test Setup
Testing Equipment

Testing Equipment



Large Measuring Volume

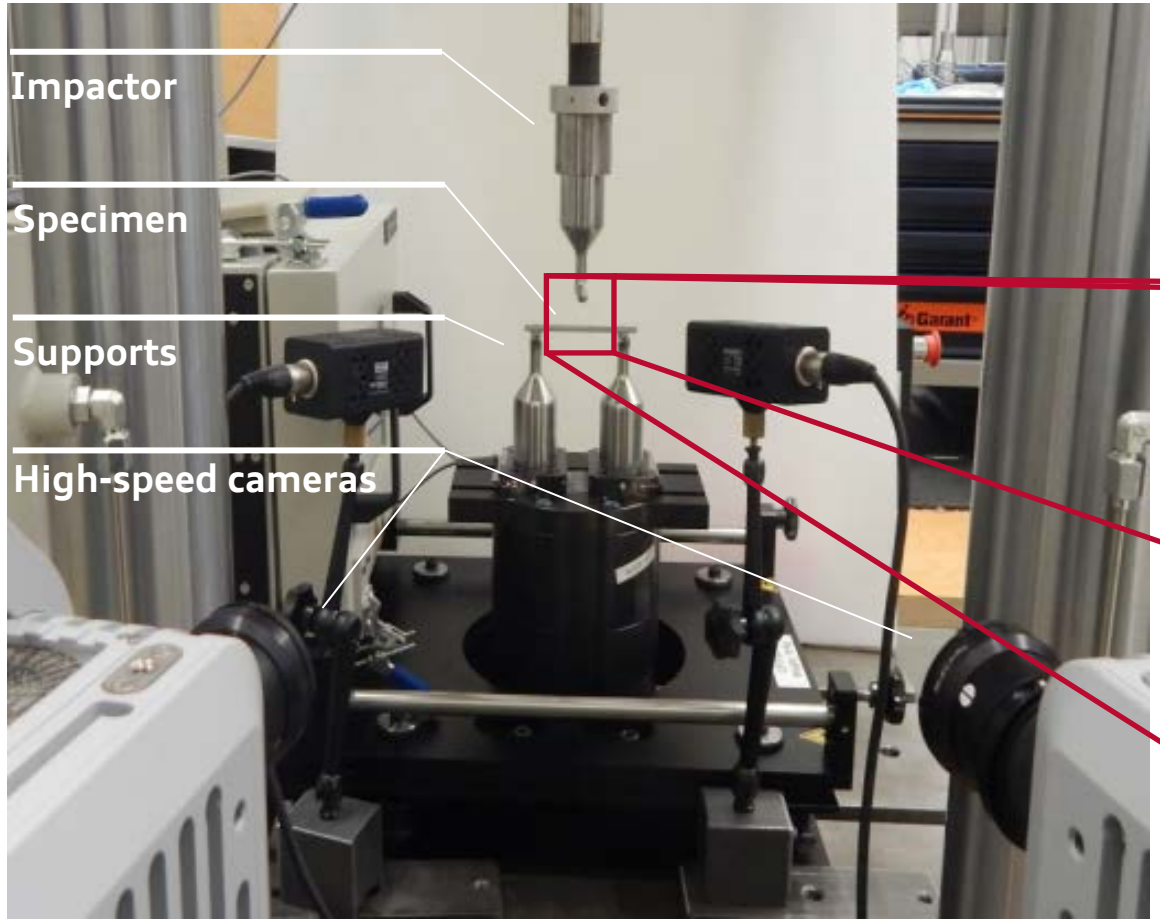
Material:	T700S-150-DT120 $[UD]_{13}$
Temperature:	23 °C
Thickness:	2 mm
Supports Span:	80 mm
Testing Speed:	10 m/s
Record Rate:	36000 fps
Video Rate:	3 fps



» A smaller measuring volume was required to better asses the specimen-impactor detachment

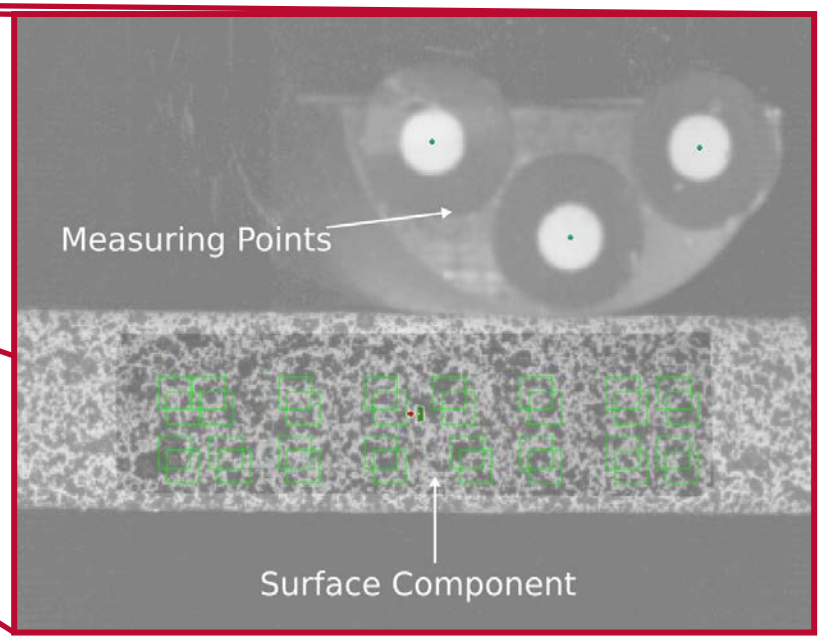
Test Setup
Testing Equipment

Testing Equipment



Small Measuring Volume

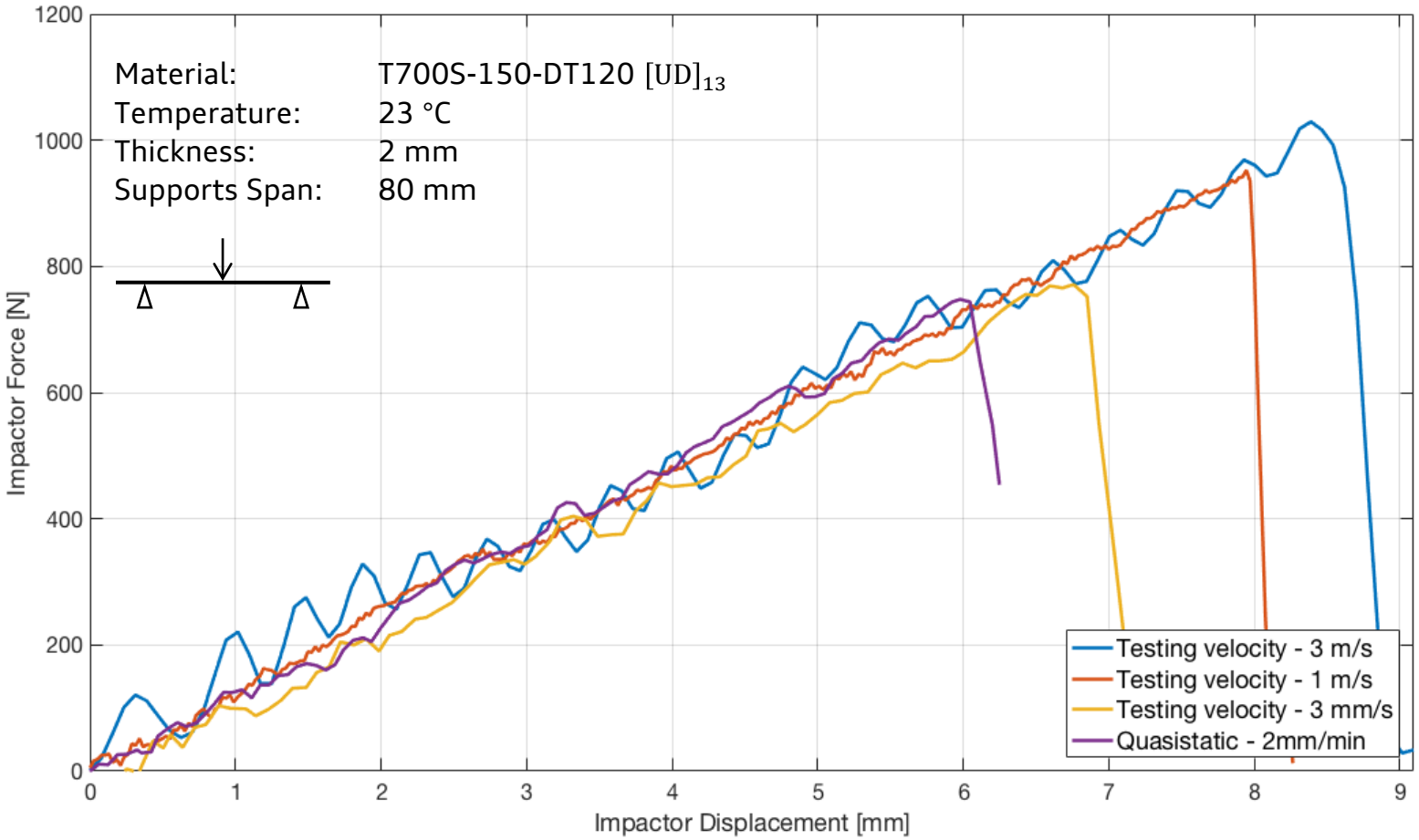
- Measuring points to track the piston velocity
- Surface component used to track the specimen midpoint displacement

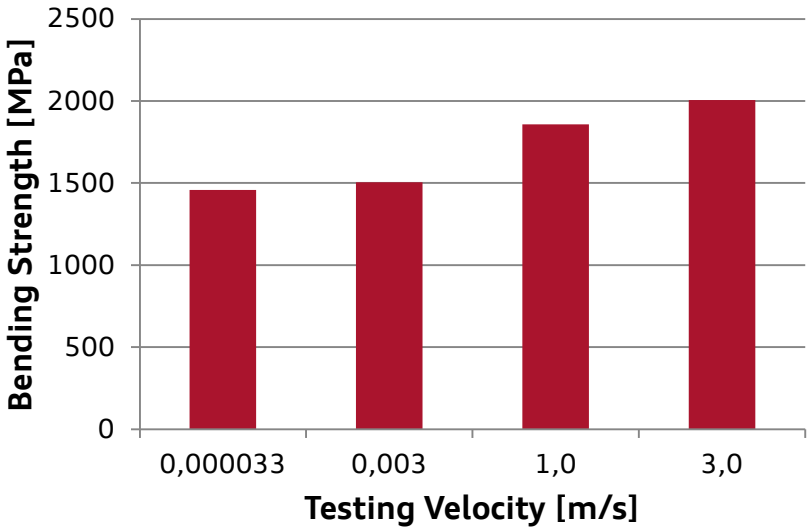


» The small measuring volume allowed tracking the specimen midpoint displacement

Test Results

Strain Rate Dependency in Bending Tests





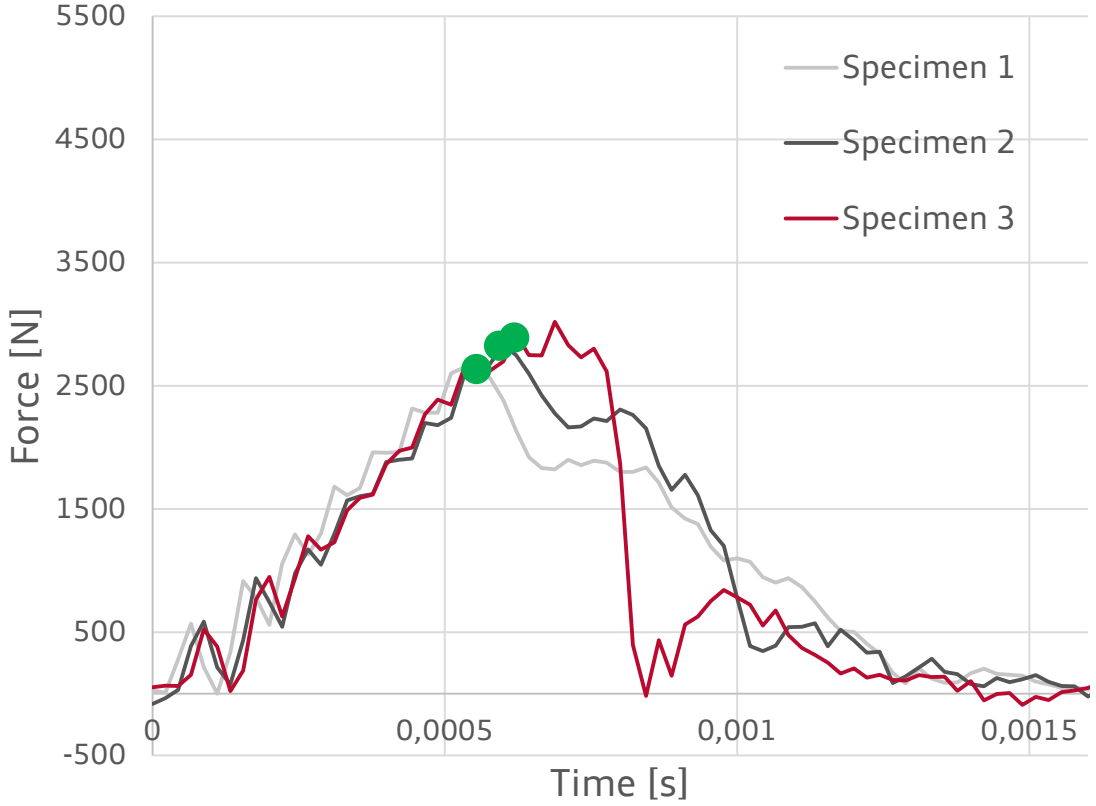
	Force [N]	Displacement [mm]
2 mm/min	748	5.98
3 mm/s	771	6.76
1 m/s	952	7.94
3 m/s	1029	8.39

» The bending strength increased by 38% with increasing testing velocity

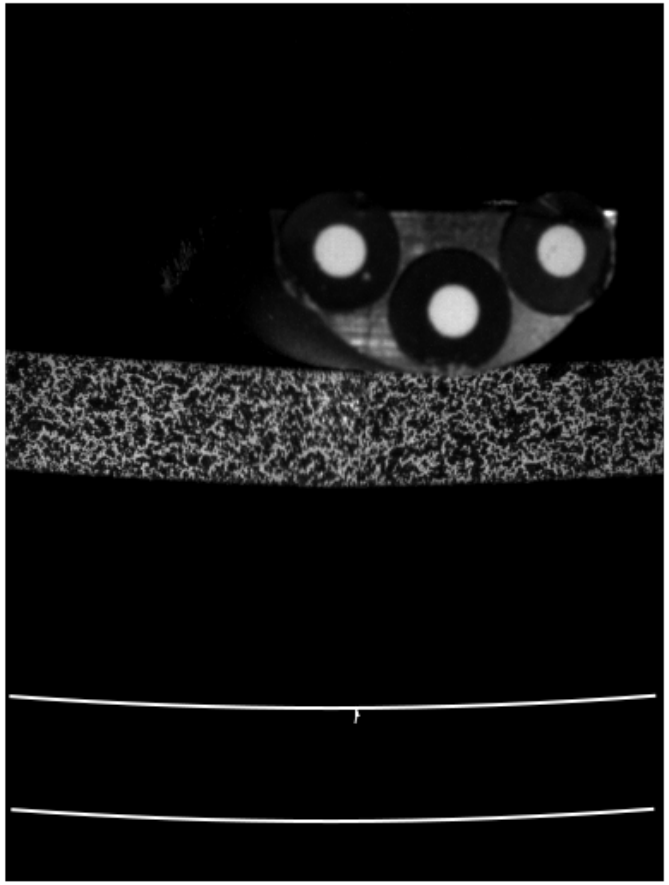
Test Results
Failure Mechanism

Force Time History

- Thickness 3.5 mm
- Support Span 80 mm
- Testing Velocity 5 m/s



Specimen Failure – Fibre Kinking



Test Results
Failure Mechanism

Force Time History

- Thickness 3.5 mm
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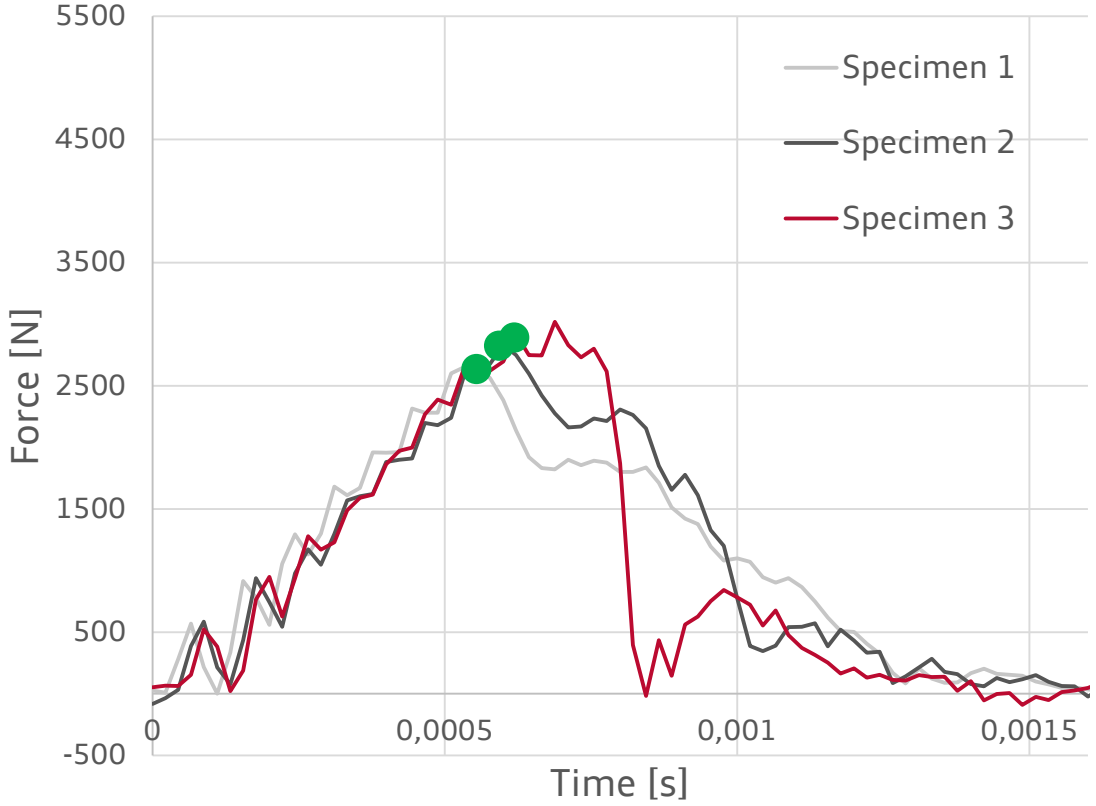
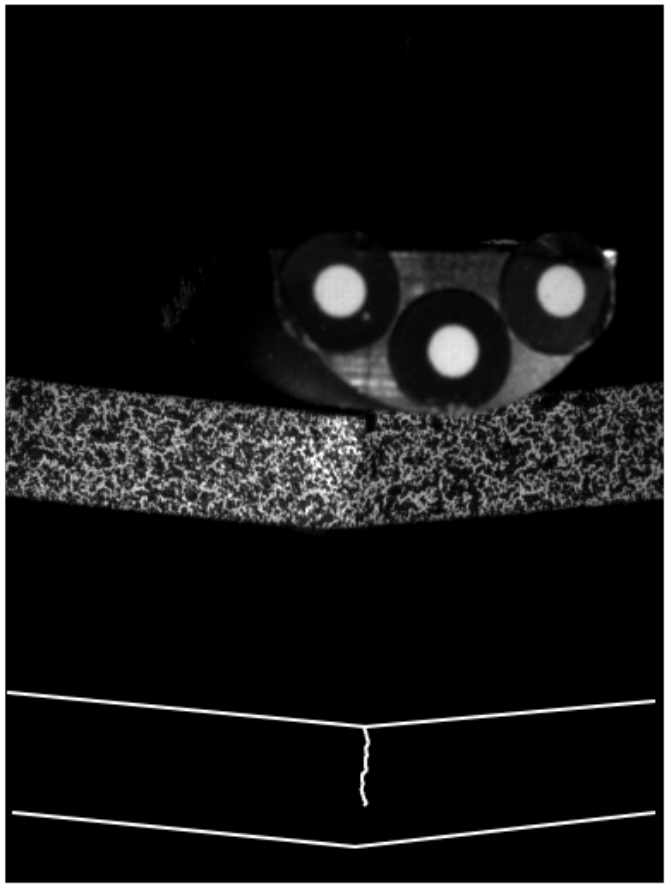


Specimen Failure – Advancing Compressive Failure



Test Results
Failure Mechanism

Force Time History

- Thickness 3.5 mm
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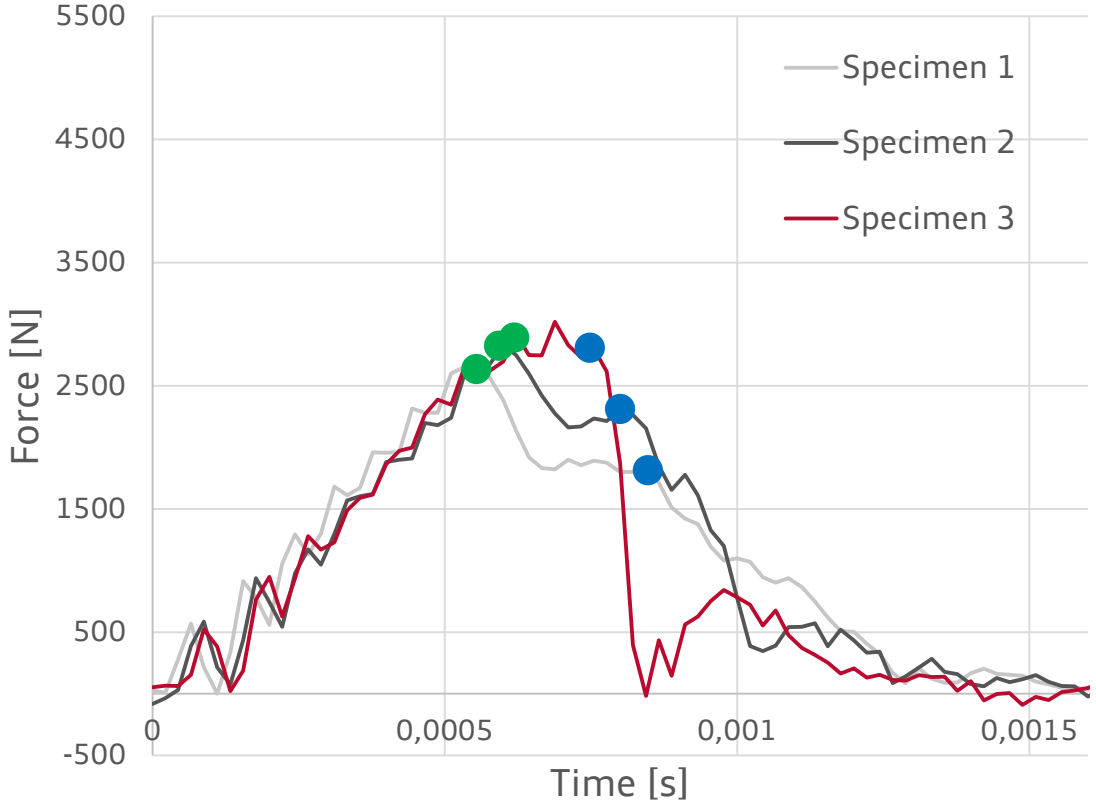
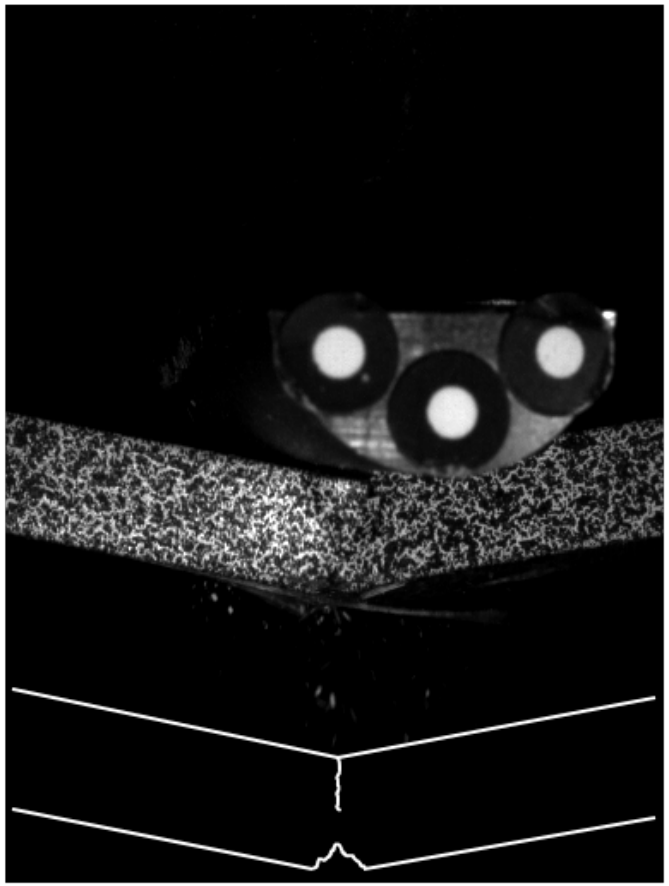
- Testing Velocity 5 m/s



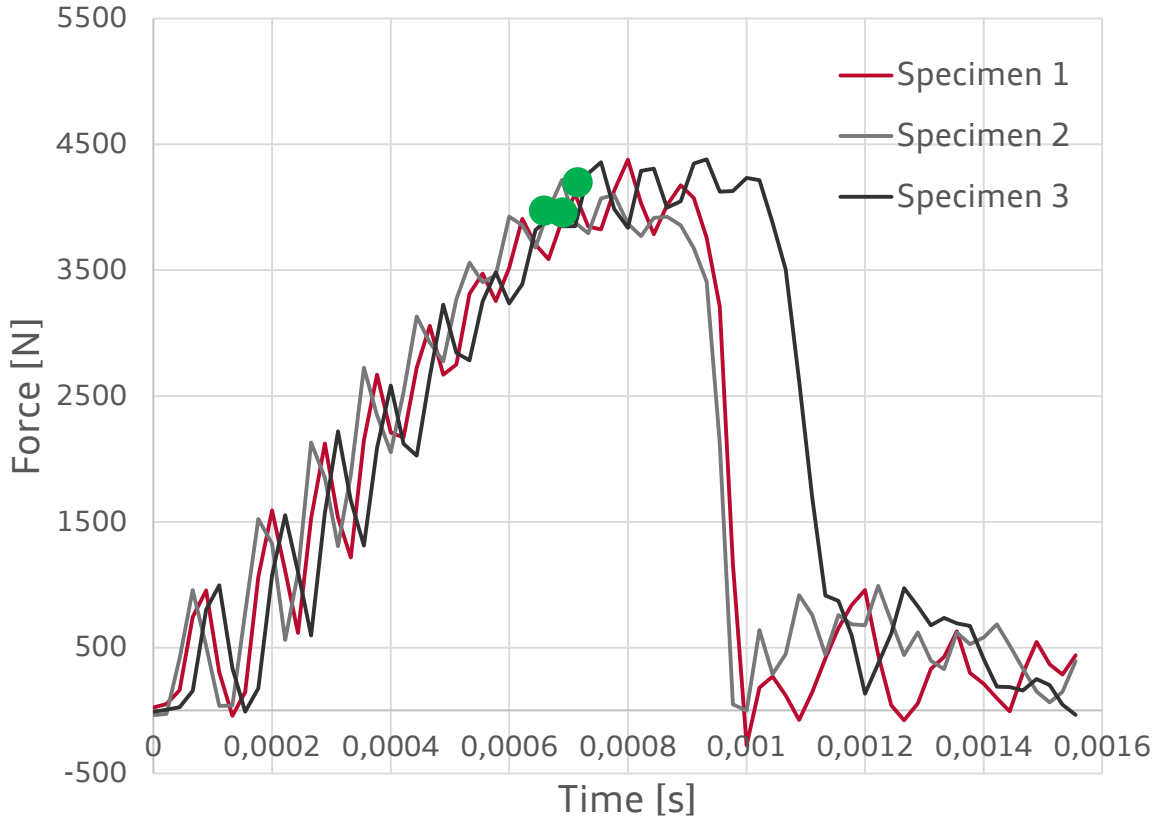
Specimen Failure – Tensile Failure



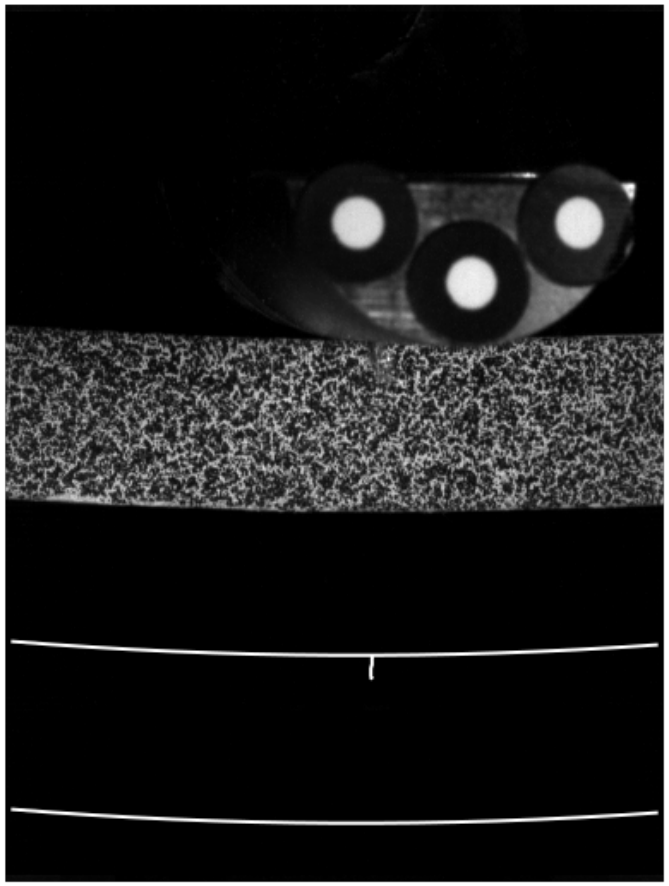
Test Results
Failure Mechanism

Force Time History

- Thickness 5 mm
- Support Span 80 mm
- Testing Velocity 5 m/s



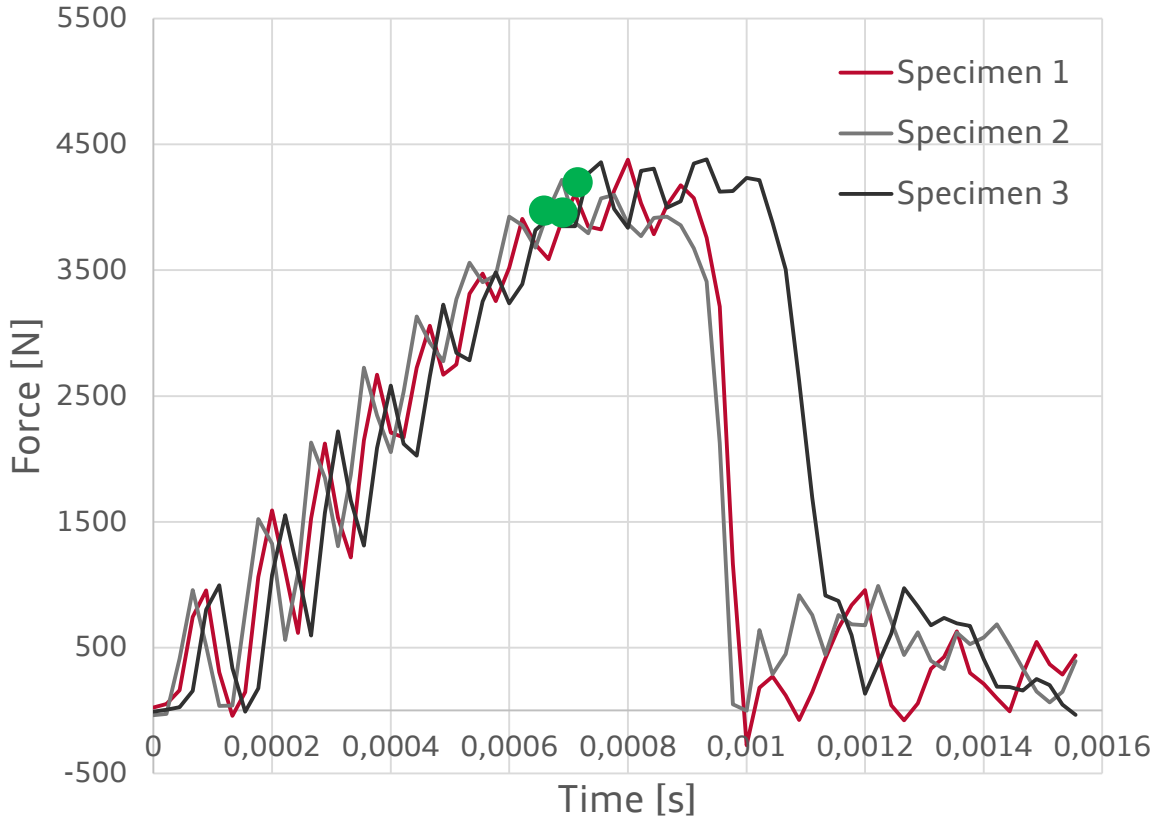
Specimen Failure – Fibre Kinking



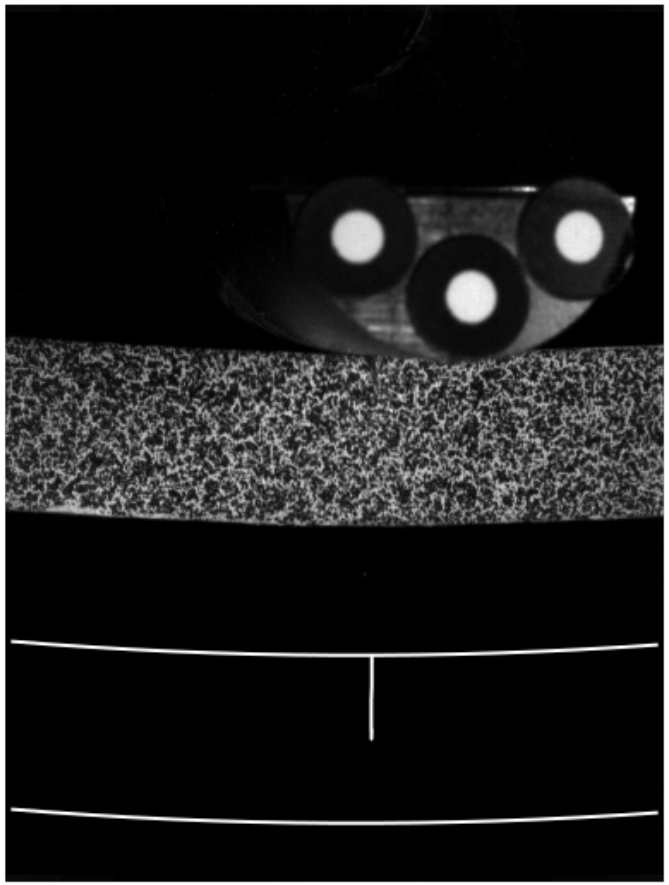
Test Results
Failure Mechanism

Force Time History

- Thickness 5 mm
- Support Span 80 mm
- Testing Velocity 5 m/s



Specimen Failure – Advancing Compressive Failure



Test Results
Failure Mechanism

Force Time History

- Thickness 5 mm
- Support Span 80 mm
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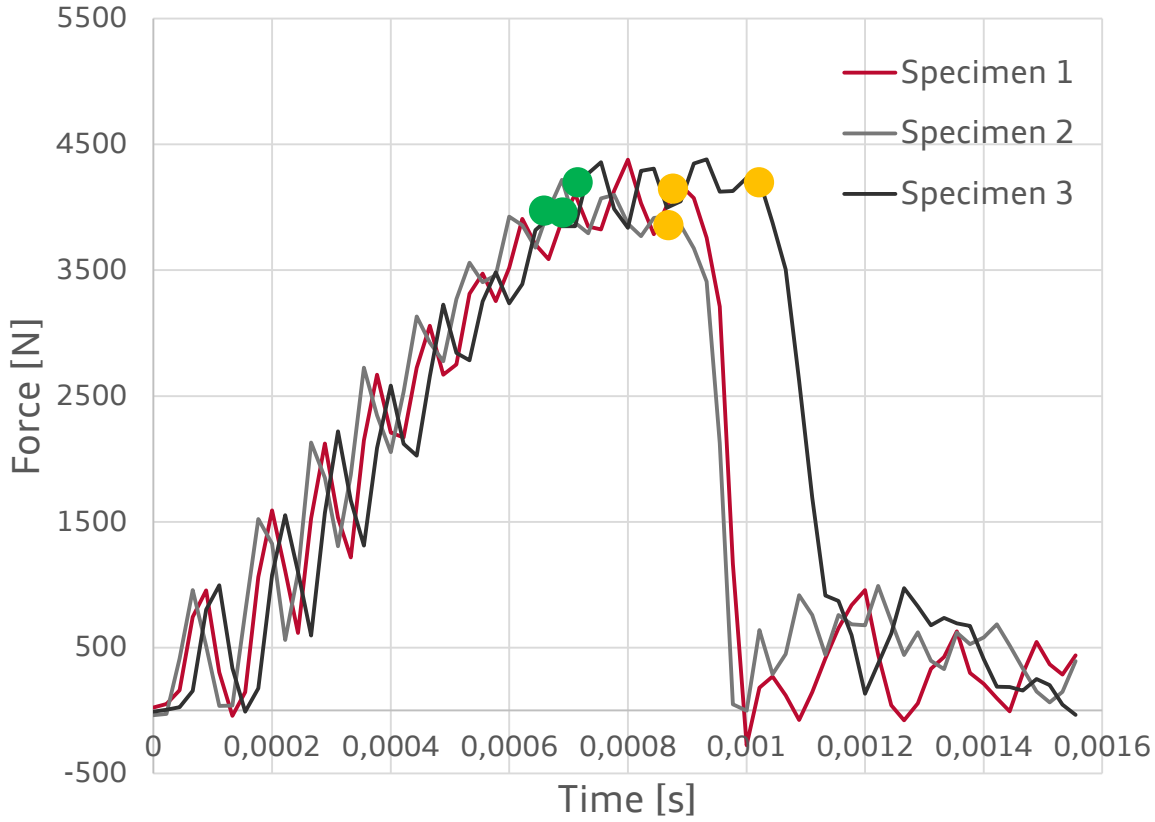
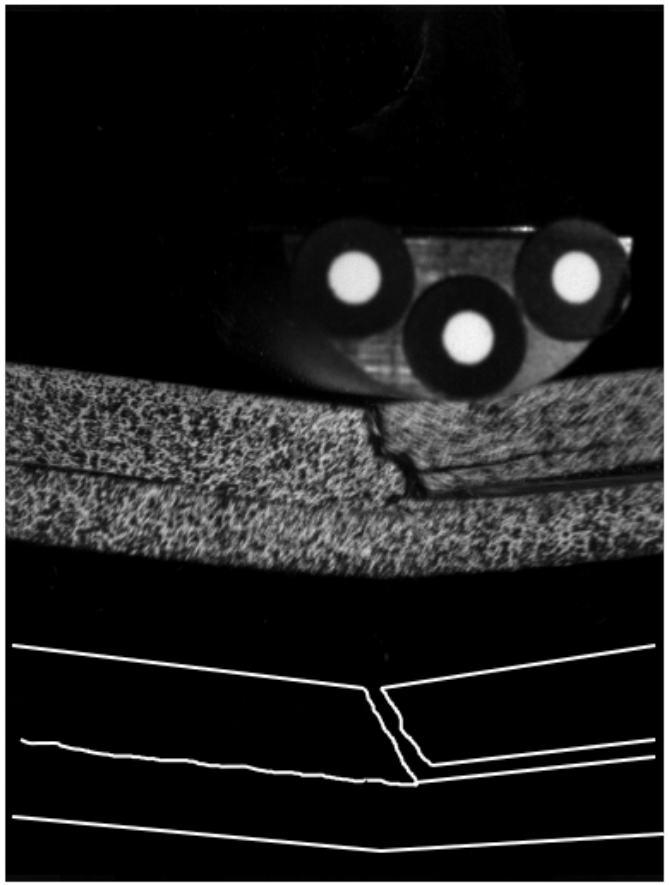


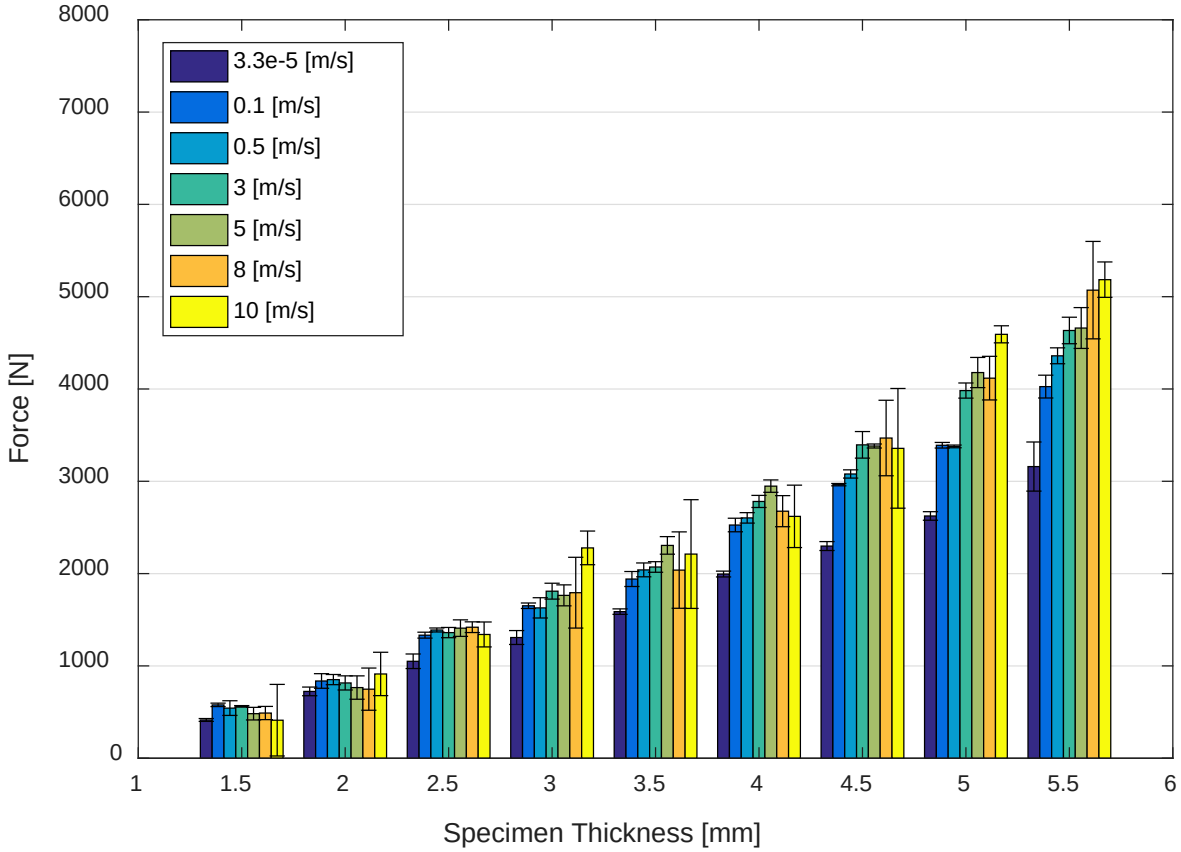
Specimen Failure – Delamination



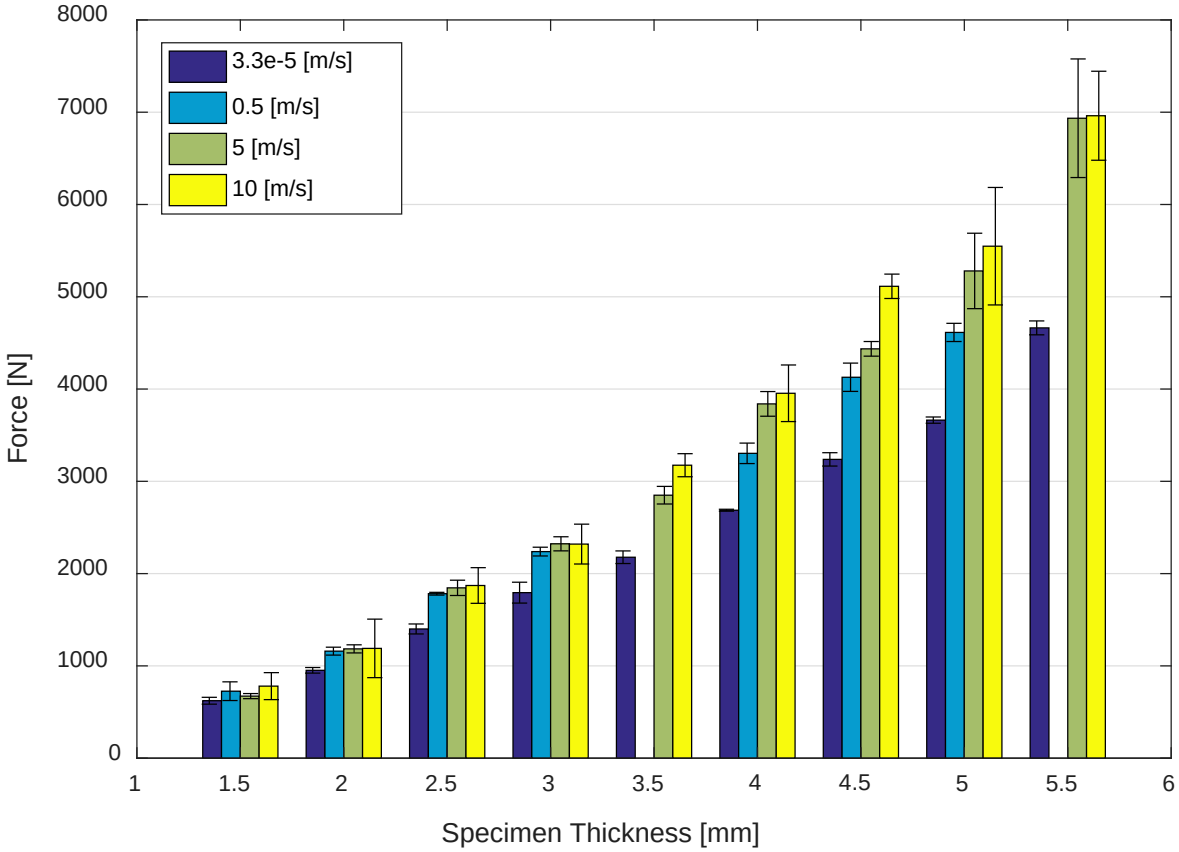
» The maximum force and the maximum midpoint displacement were measured when fibre kinking occurred

Test Results
Maximum Force at Failure

Support Span: 80 mm



Support Span: 60 mm



» The maximum force at failure increases with increasing testing velocity

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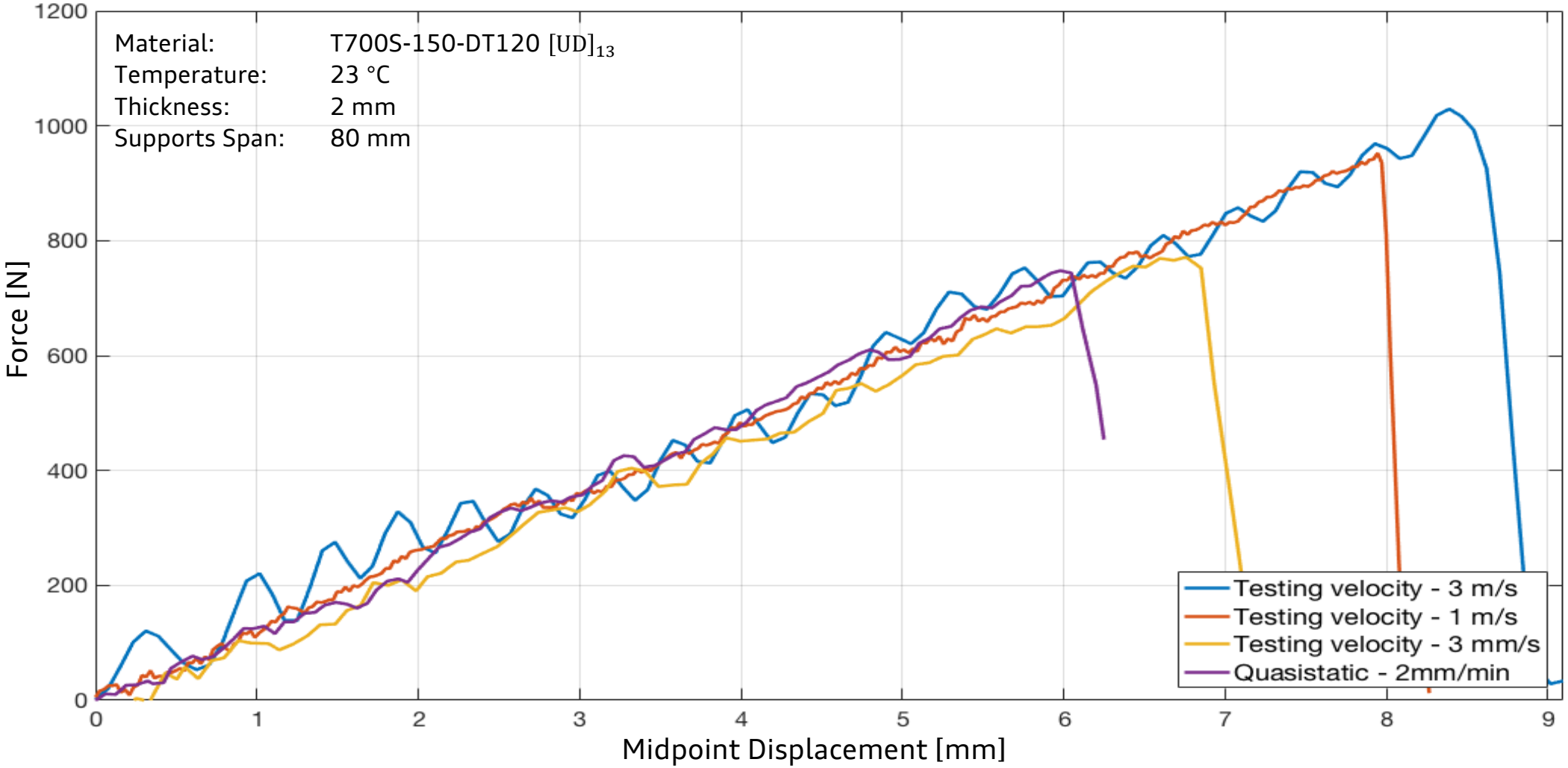
Estimation of the Maximum Testing Velocity

Increasing Vibrations with Increasing Testing Velocity – Force signal



» Increasing Vibration of the specimen with increasing testing speed

Estimation of the Maximum Testing Velocity

Video of the Tests

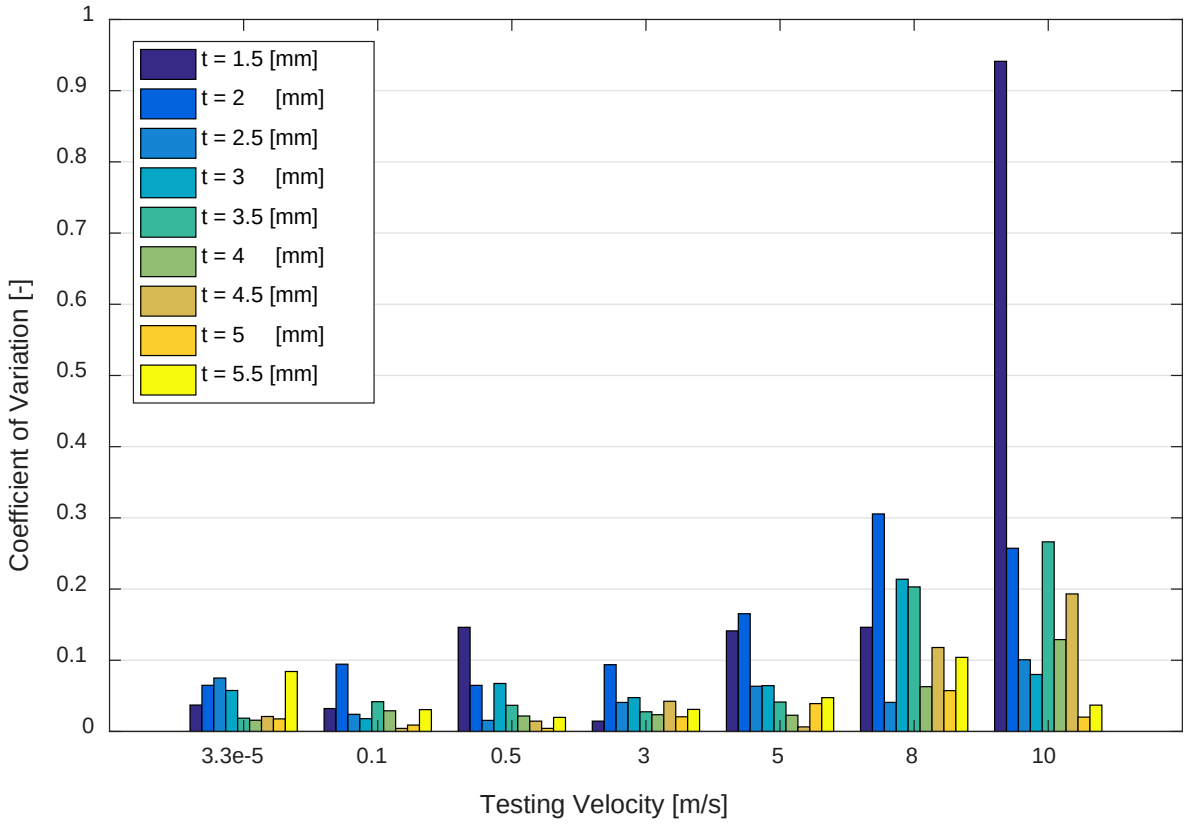
Support Span 80 mm – 10 m/s

Support Span 80 mm – 0.5 m/s

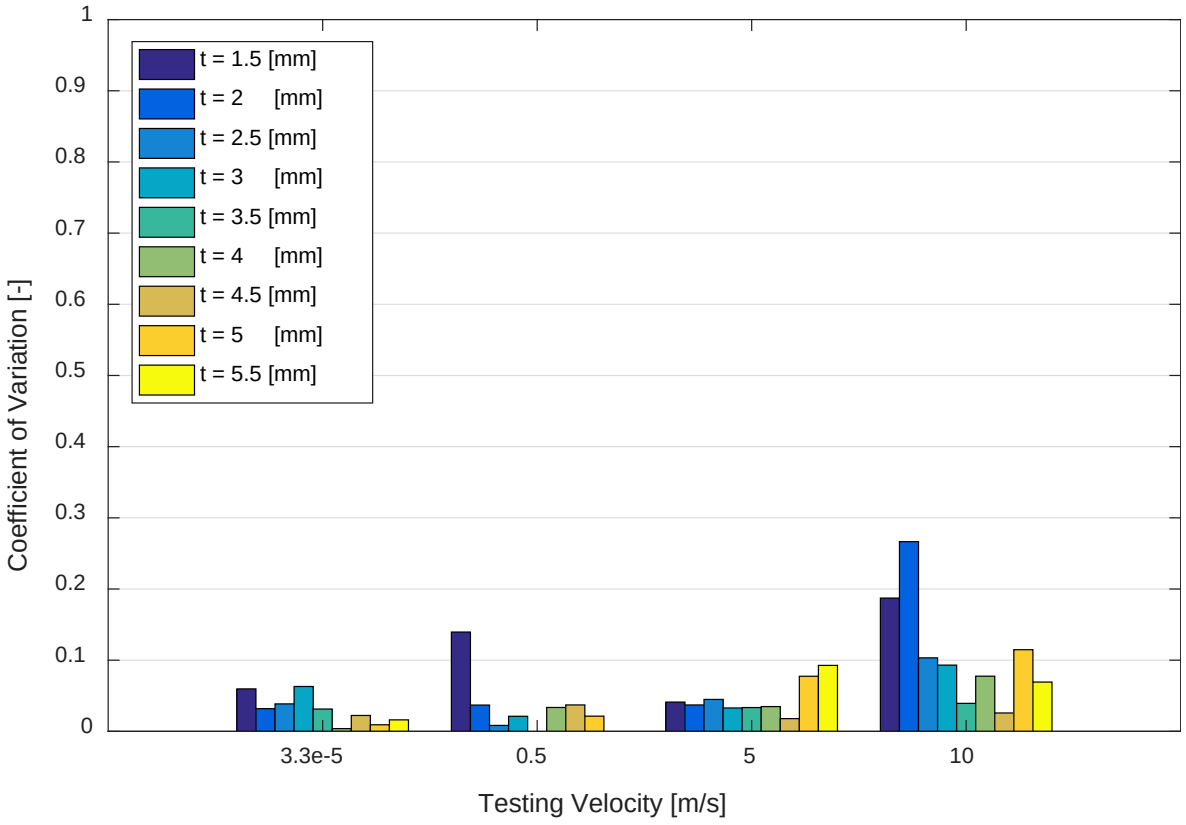
Estimation of the Maximum Testing Velocity

Data Variation with Increasing Testing Velocity – Coefficient of Variation

Maximum Force at Failure – Support Span 80 mm



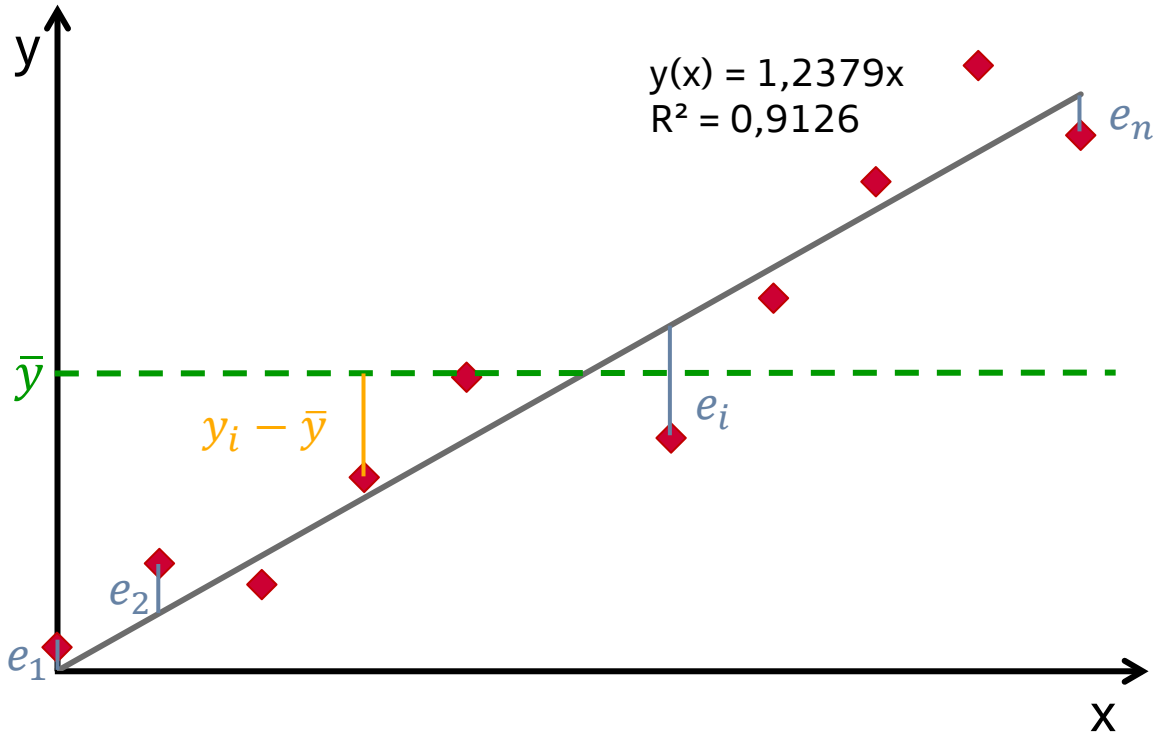
Maximum Force at Failure – Support Span 60 mm



» The increase in the testing velocity results in a higher coefficient of variation

Estimation of the Maximum Testing Velocity

Goodness of Test Results – Coefficient of Determination - R^2



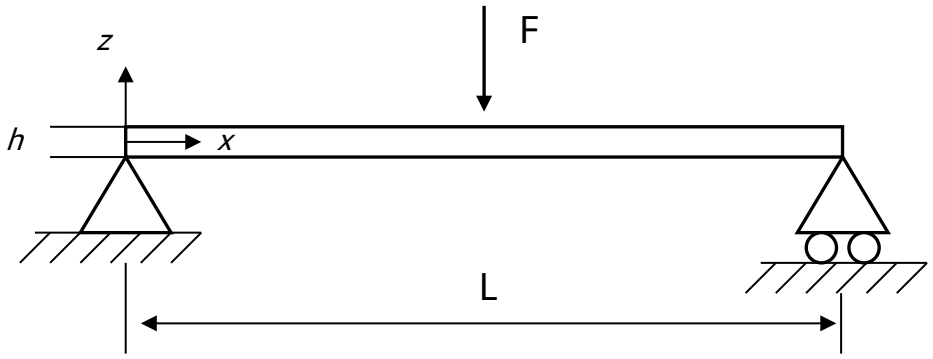
- General point coordinates: $P_i = (x_i, y_i)$
- Linear regression line: $y(x) = mx + b$
- Mean of all y_i: $\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$
- Residual: $e_i = y_i - y(x_i)$
- Residual sum of squares: $SS_{res} = \sum_{i=1}^{n} e_i^2$
- Total sum of squares: $SS_{tot} = \sum_{i=1}^{n} (y_i - \bar{y})^2$
- Coefficient of Determination: $R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$
- R² =]0;1]

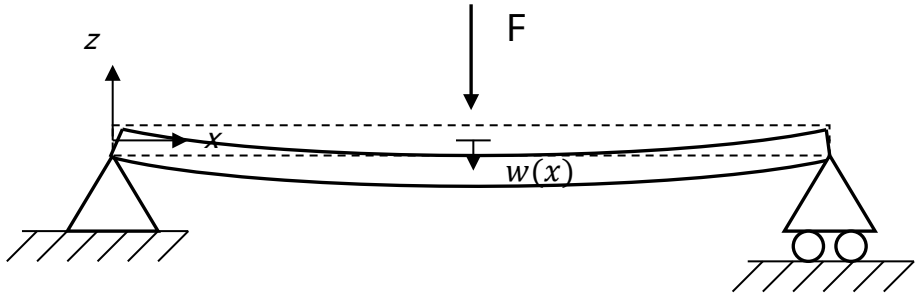
The term $\frac{SS_{res}}{SS_{tot}}$ defines the percentage of the total variation SS_{tot} that is not described by the linear regression. Therefore, the term R^2 defines the percentage of the total variation that is described by the linear regression. If the residual sum of squares SS_{res} is small, the line is a good fit. A high percentage of the total variation in y is described by the variation in x (the line).

» The closer is R^2 to 1 the better the linear regression fits the data set

Estimation of the Maximum Testing Velocity
Specimen Global Stiffness

Simply Supported Beam





Global Stiffness

- From classical beam theory

$$w(L/2) = w_{max} = \frac{L^3}{48(EI)_{beam}} F \rightarrow F = \frac{48(EI)_{beam}}{L^3} w_{max} \rightarrow$$

$$F = K_{beam}\, w_{max}$$

- Global Stiffness

$$(EI)_{beam} = E_b \left(\frac{b\, h^3}{12}\right) \qquad E_b = \frac{12}{h^3\, d_{11}}$$

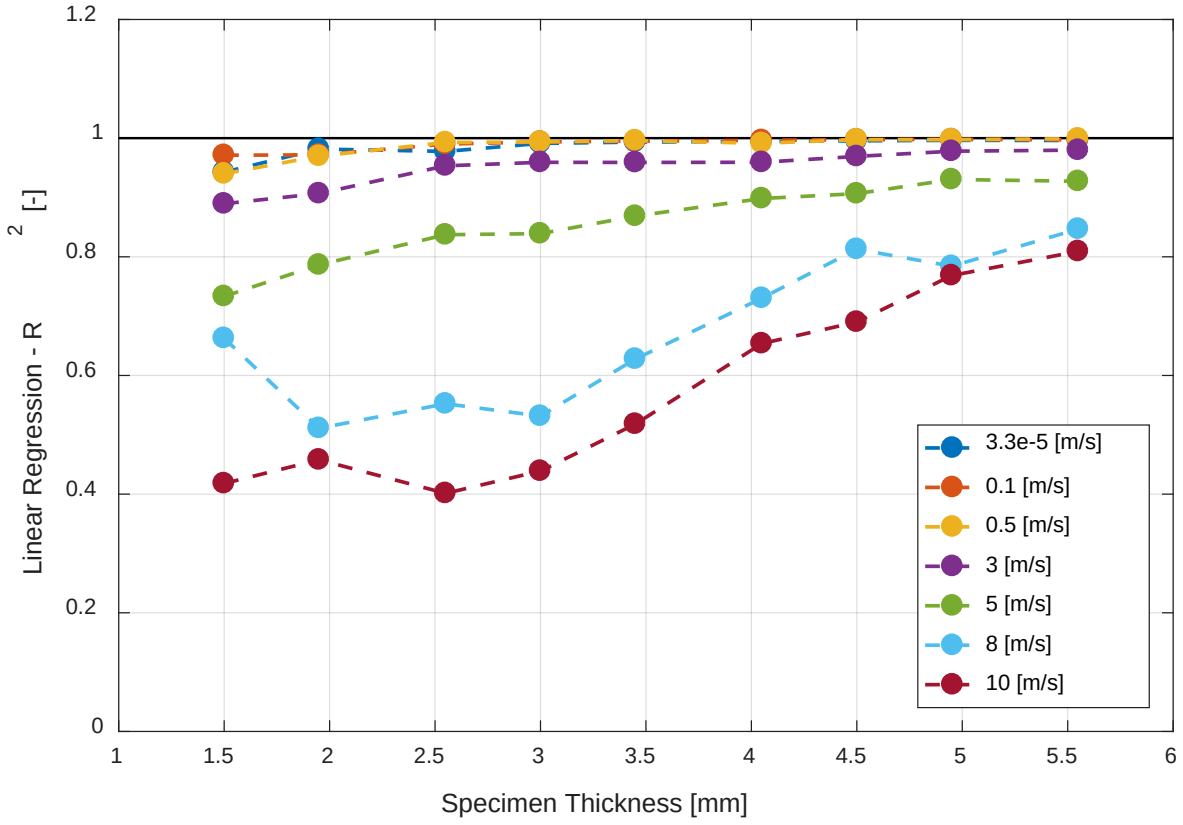
$$K_{beam} = \frac{48\, b}{d_{11}\, L^3}$$

» The beam global stiffness depends on the specimen layup, the support span and the specimen thickness and width

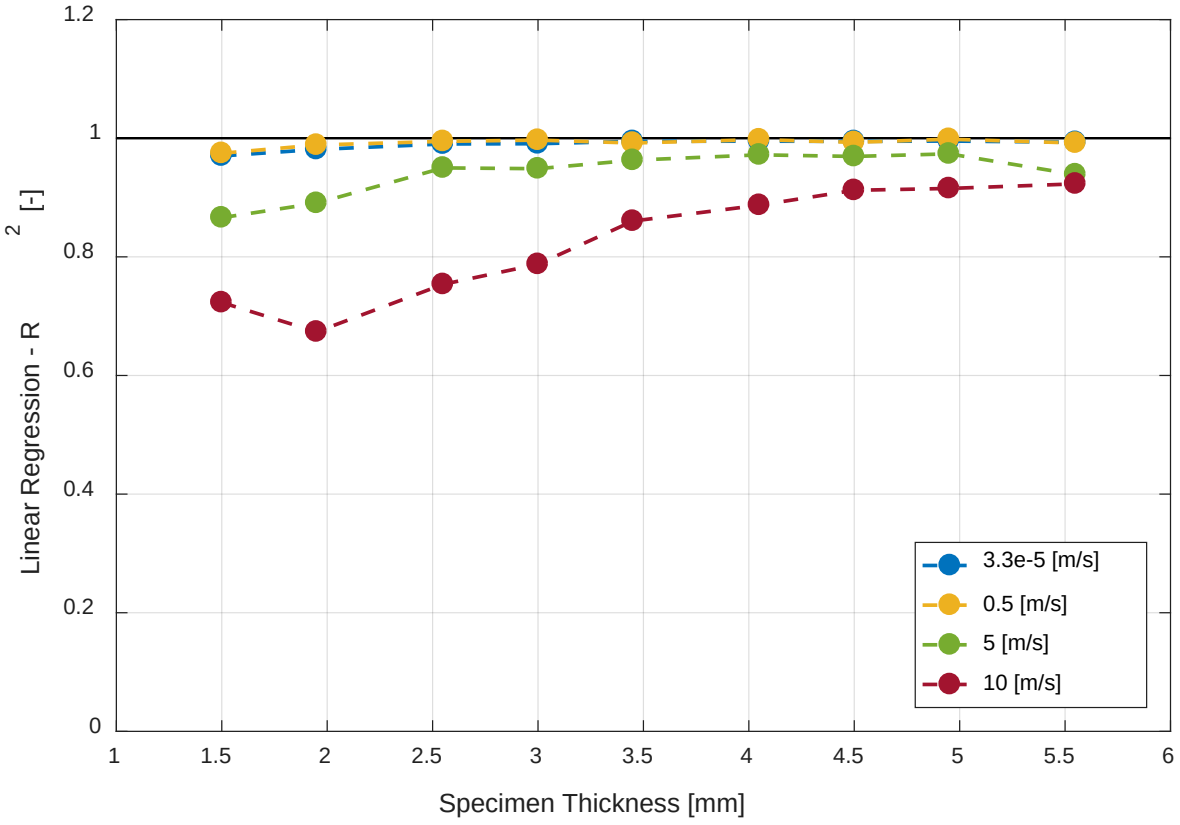
Estimation of the Maximum Testing Velocity

Coefficient of Determination R^2 vs. Specimen Thickness

Support Span 80 mm



Support Span 60 mm

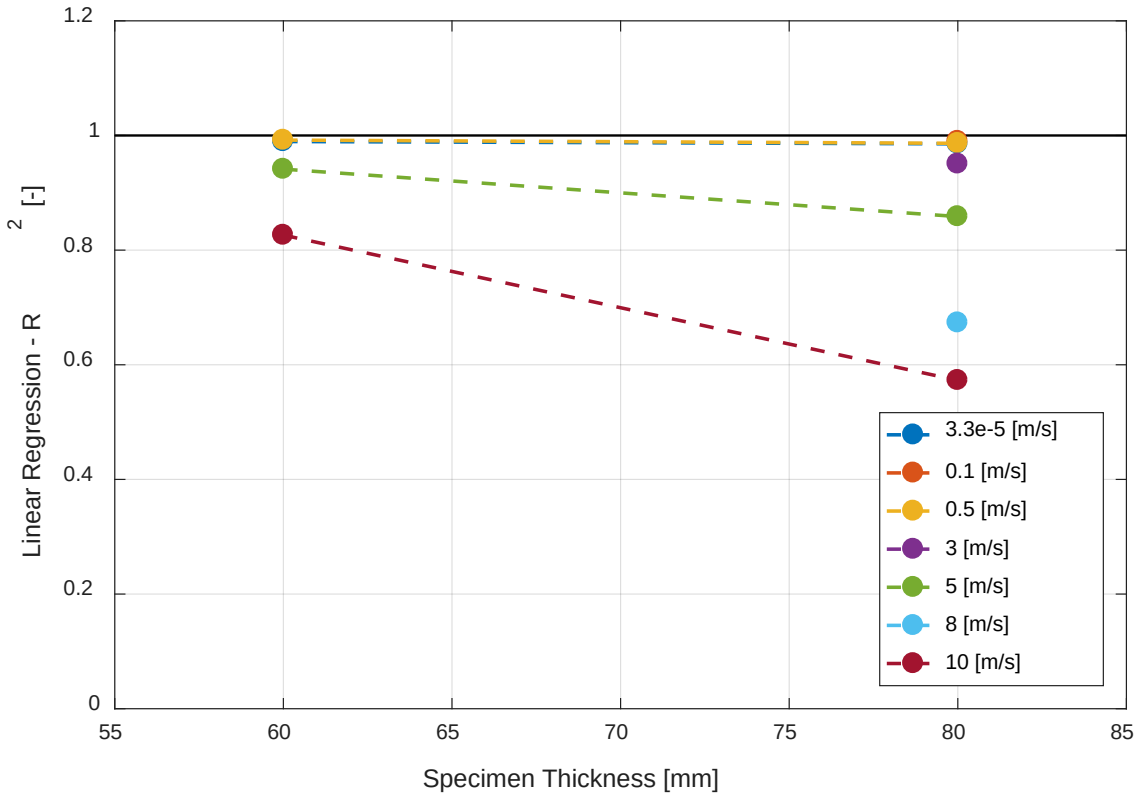


» R^2 increases with increasing specimen thickness

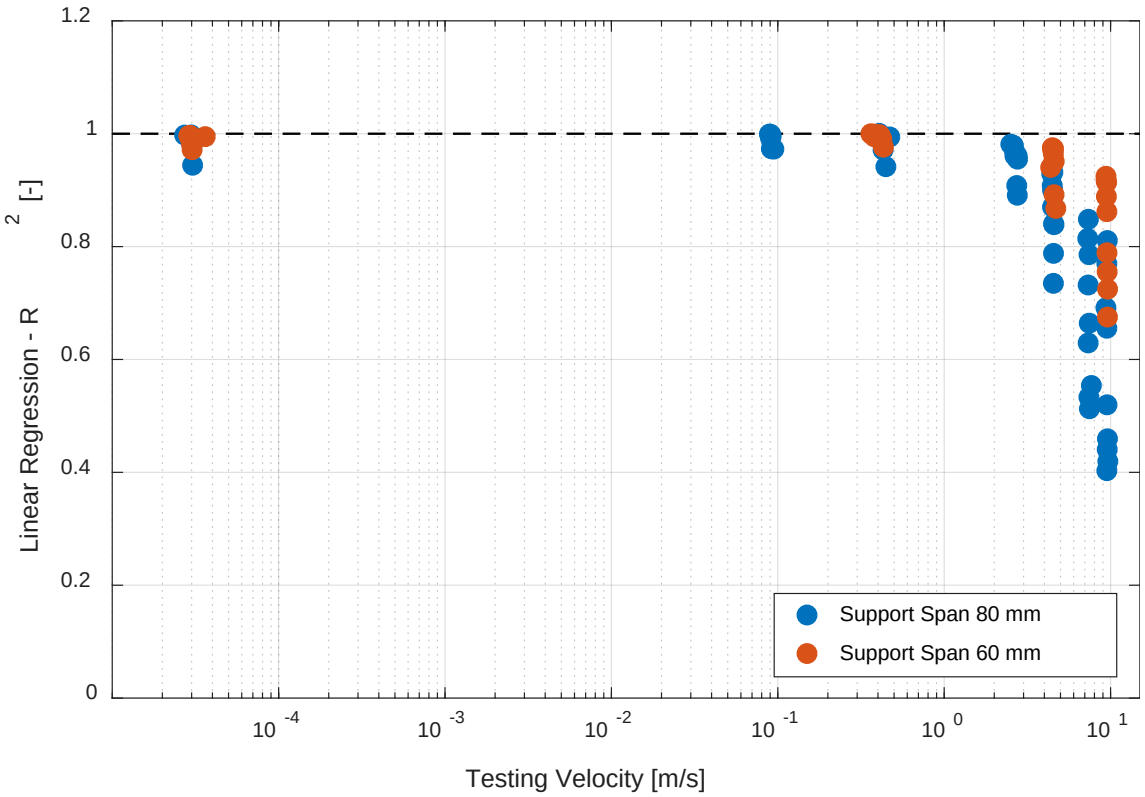
Estimation of the Maximum Testing Velocity

Coefficient of Determination R^2 vs. Support Span and Testing Velocity

Effect of the Support Span



Effect of the Testing Velocity

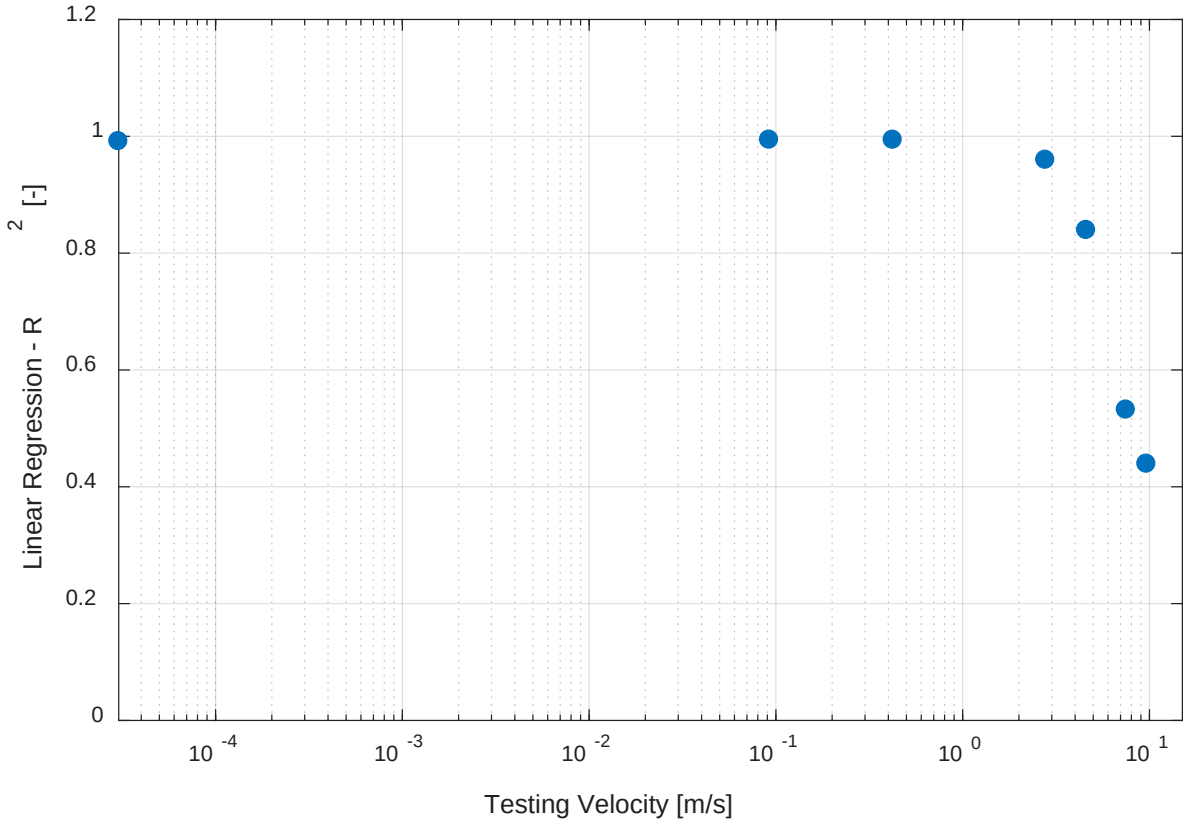


- With the support span of 60 mm higher R^2 are obtained
- R^2 decreases with increasing testing velocity

Estimation of the Maximum Testing Velocity

Fitting Curves – Coefficient of Determination R^2

Support Span 80 mm – Thickness 3 mm



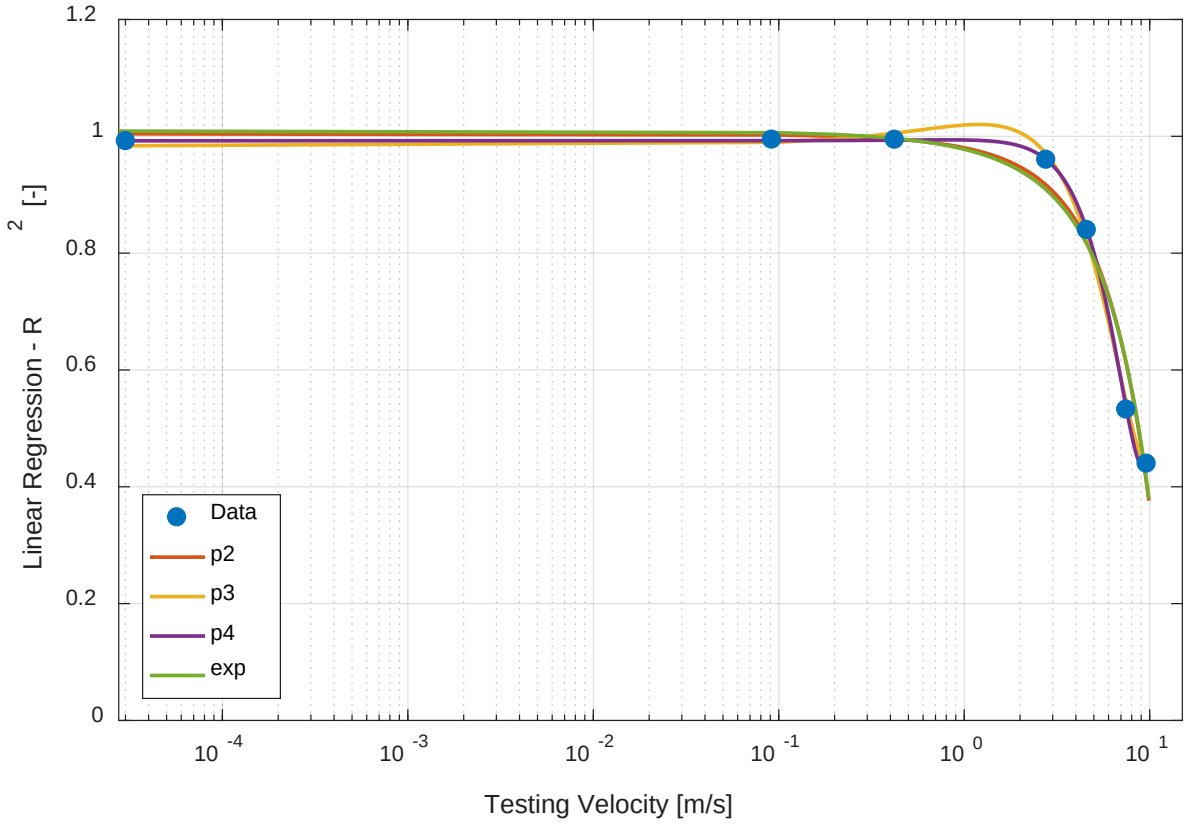
Fitting Laws

- Interpolation of data required to find the testing velocity for any value of R^2
- Fitting laws considered
  - Polynomial: $p(x) = p_1\, x^n + p_1\, x^n + \cdots + p_n\, x + p_{n+1}$
  - Exponential: $f(x) = a\, e^{bx} + c\, e^{dx}$

Estimation of the Maximum Testing Velocity

Fitting Curves – Coefficient of Determination R^2

Support Span 80 mm – Thickness 3 mm



Fitting Laws

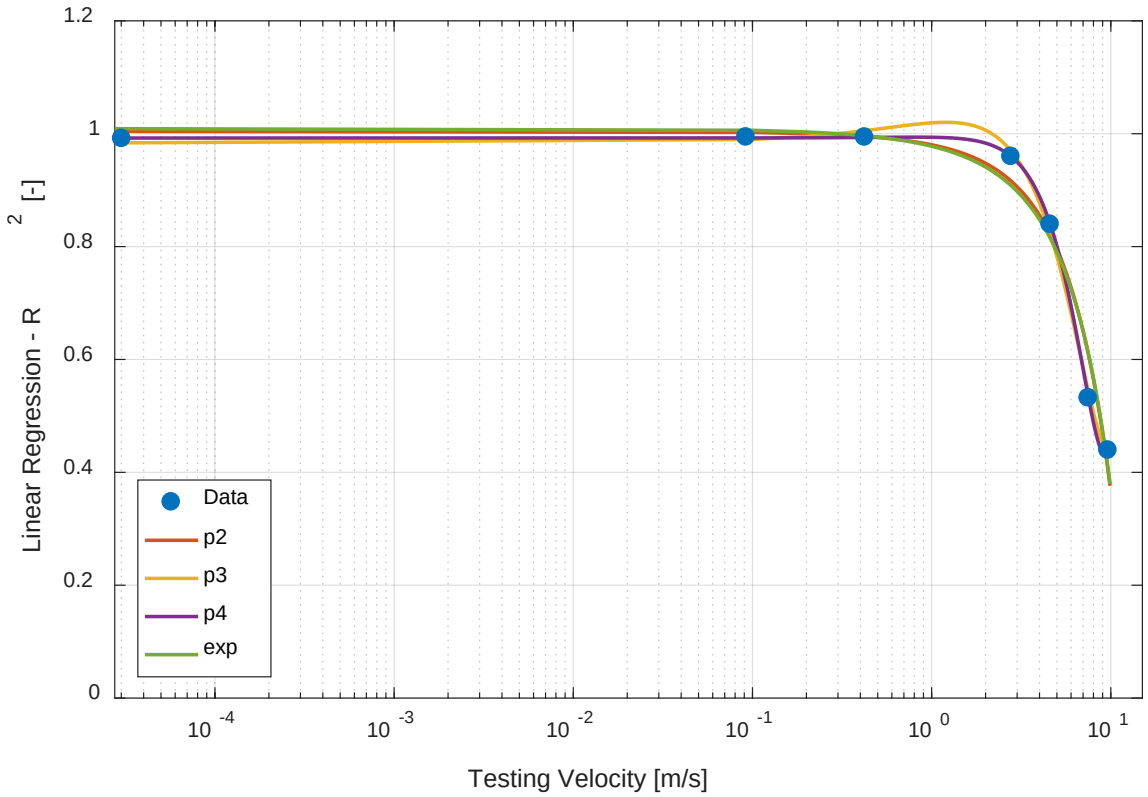
- Interpolation of data required to find the testing velocity for any value of R^2
- Fitting laws considered
  - Polynomial: $p(x) = p_1\, x^n + p_1\, x^n + \cdots + p_n\, x + p_{n+1}$
  - Exponential: $f(x) = a\, e^{bx} + c\, e^{dx}$

» Fitting laws allow determining the testing velocity for a choosen R^2

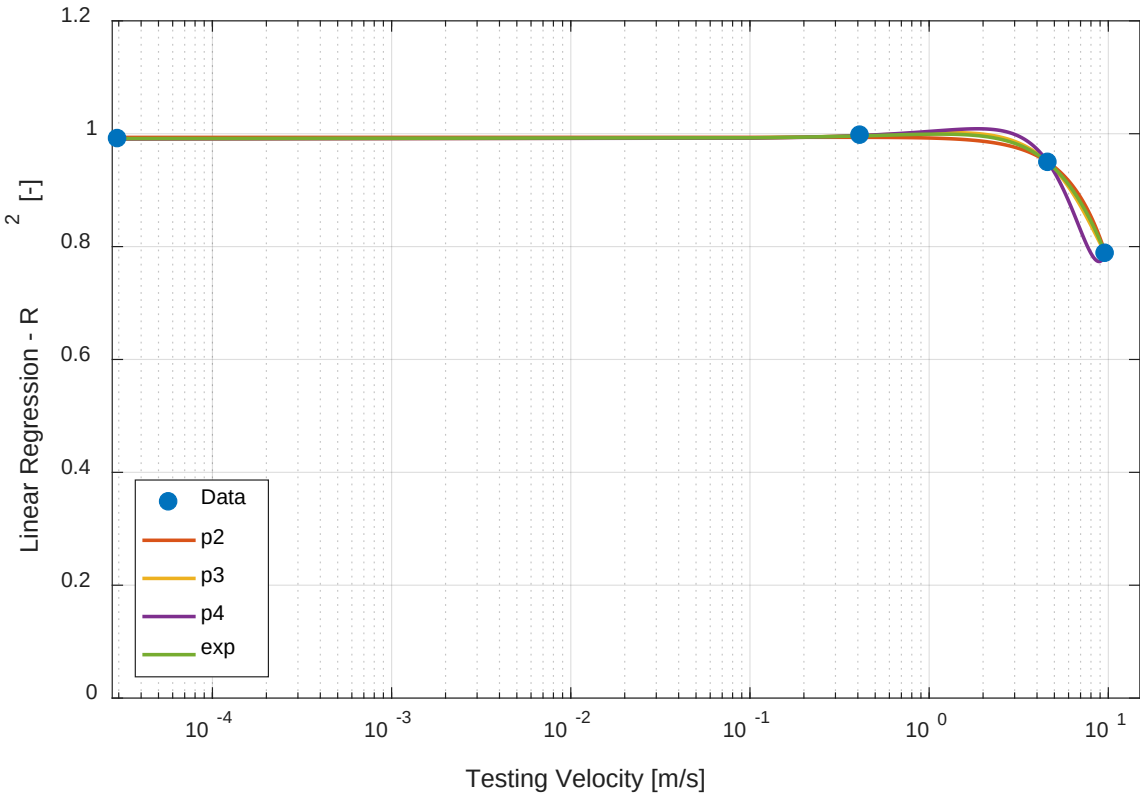
Estimation of the Maximum Testing Velocity

Fitting Curves – Coefficient of Determination R^2

Support Span 80 mm – Thickness 3 mm



Support Span 60 mm – Thickness 3 mm

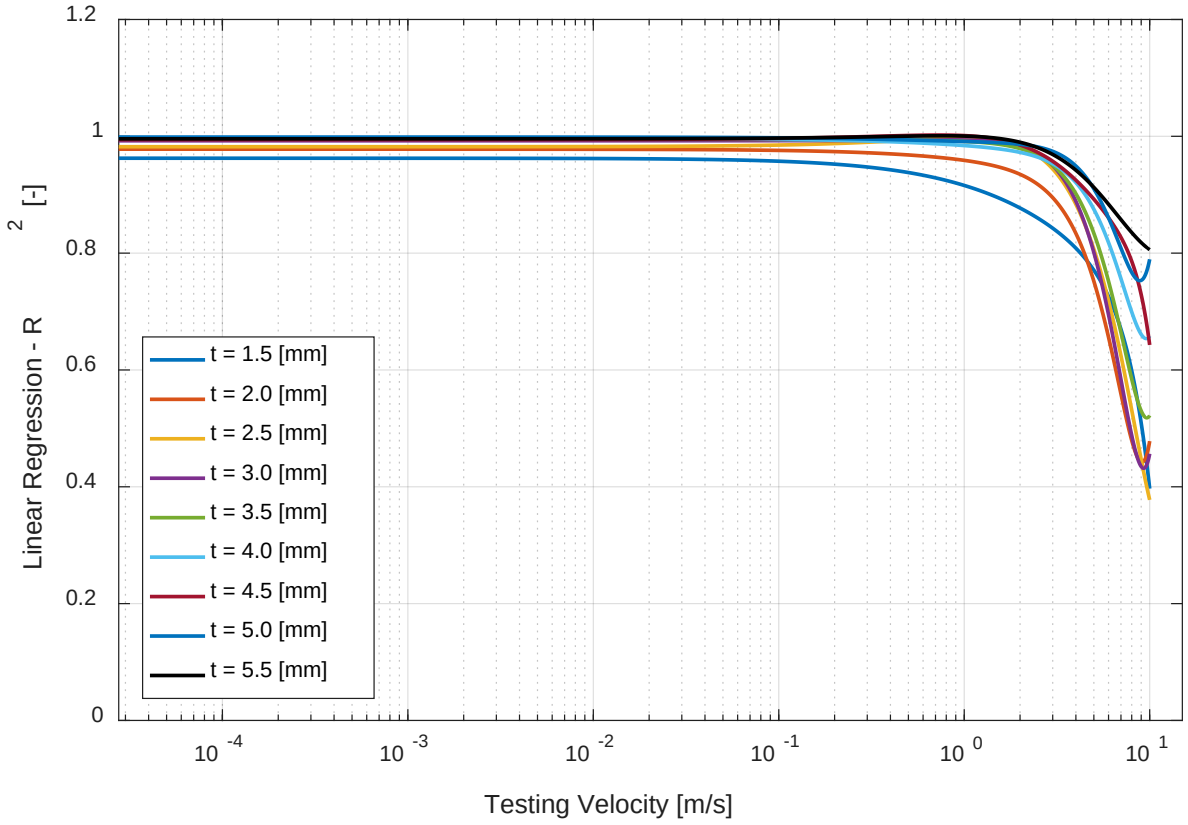


- The 4th order polynomial was used to fit the data for the 80 mm support span
- The exponential curve was used to fit the data for the 60 mm support span

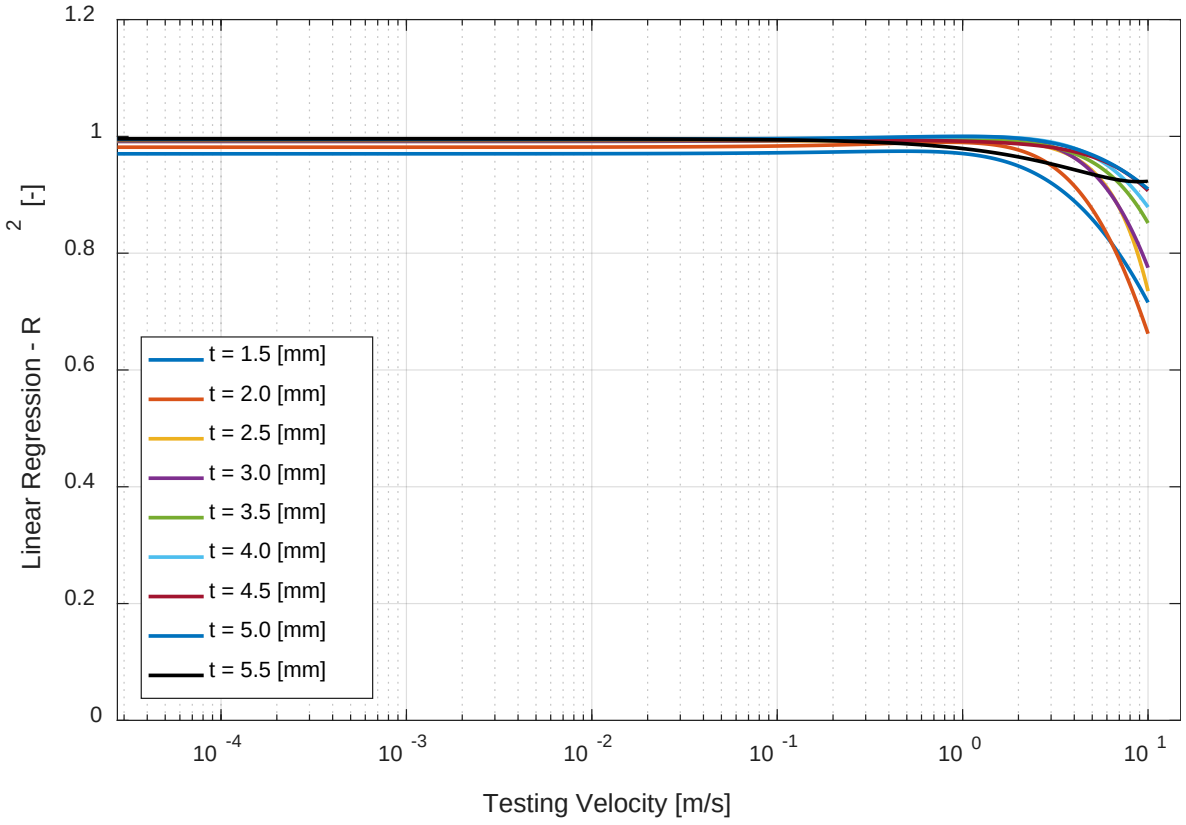
Estimation of the Maximum Testing Velocity

Fitting Curves

Support Span 80 mm



Support Span 60 mm

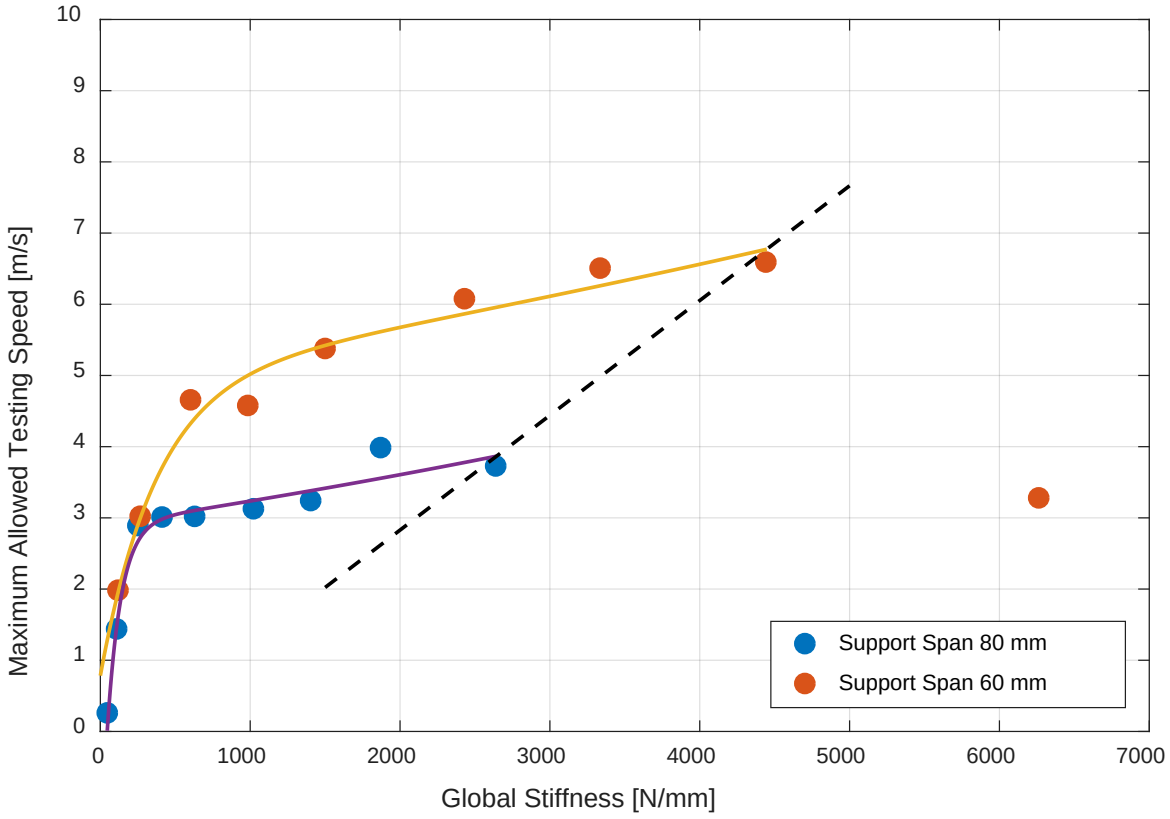


» Fitting curves were used to determine the R^2 -testing velocity behaviour for to each specific test configuration

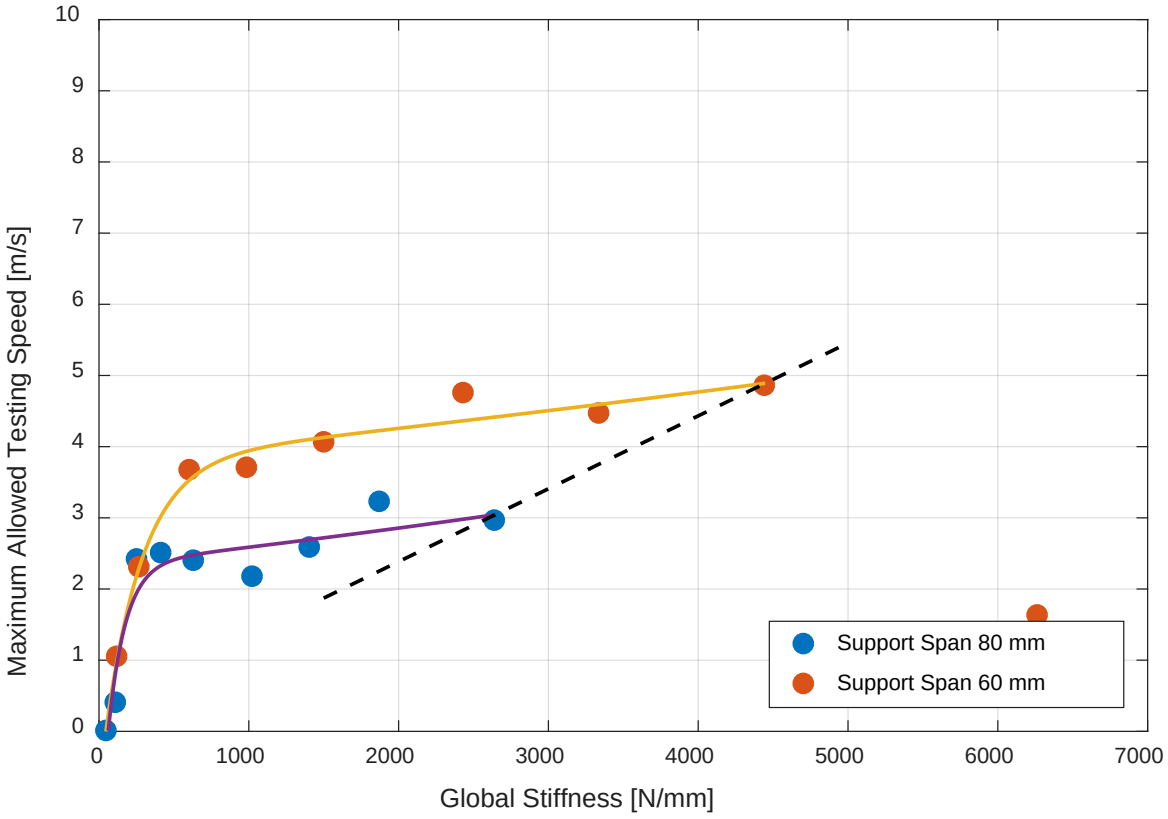
Estimation of the Maximum Testing Velocity

Fitting Curves

$R^2 \geq 0.95$



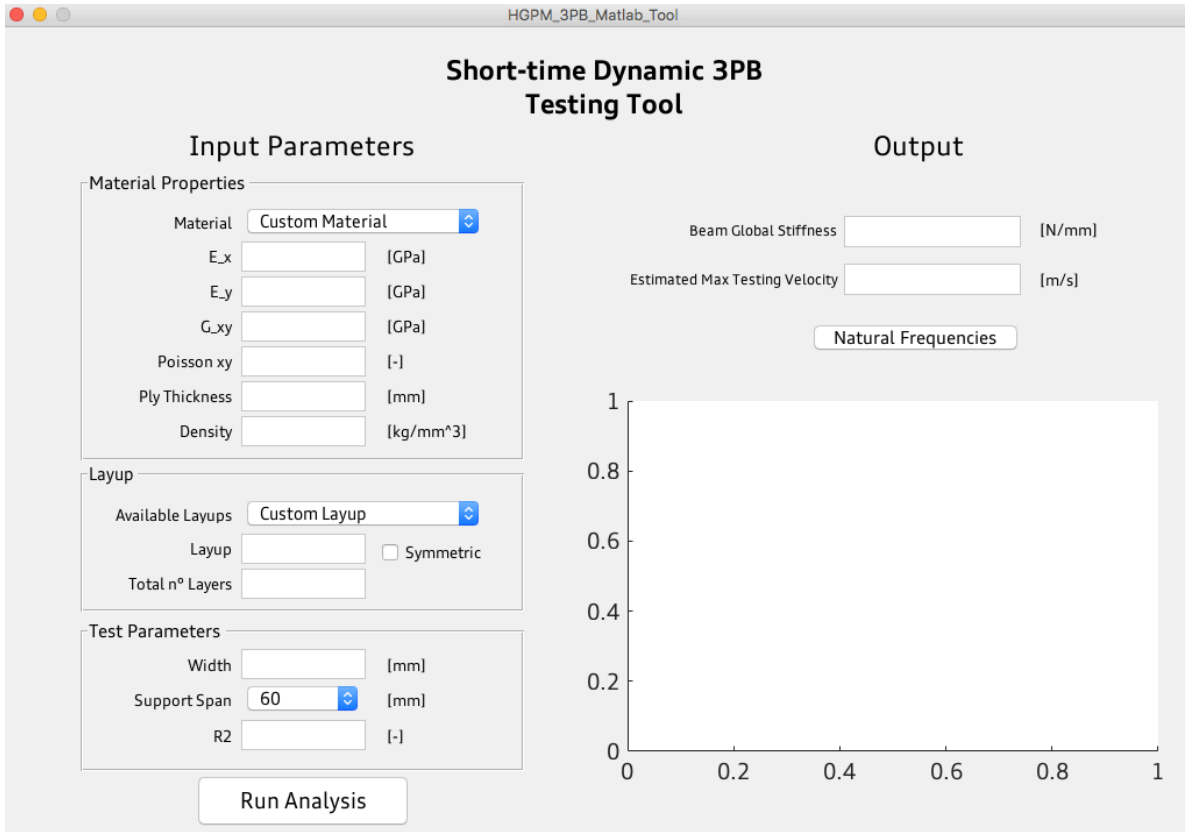
$R^2 \geq 0.97$



» For a specific value of R^2 the maximum testing velocity is estimated as a function of the specimen global stiffness

Estimation of the Maximum Testing Velocity
Matlab Tool

Matlab GUI



Input Parameters

- Material properties
  - chosen from the material database
  - custom material for user defined properties
- Layup
  - built-in layups: UD, $[0/90]_{nS}$, $[45/-45]_{nS}$, $[45/-45/0/90]_{nS}$
  - custom layup for user defined layers orientation
- Additional parameters are the specimen width, the support span and the target R^2

Output Parameters

- Beam global stiffness
- Estimated maximum velocity
- Natural frequencies

HGPM_3PB_Matlab_Tool

Short-time Dynamic 3PB Testing Tool

Input Parameters

Material Properties

Material	CF-T700-DT120	
E_x	132	[GPa]
E_y	6	[GPa]
G_xy	3.5	[GPa]
Poisson xy	0.32	[-]
Ply Thickness	0.15	[mm]
Density	1.52e-06	[kg/mm^3]

Layup

Available Layups	UD	
Layup	Leave Blank	☐ Symmetric
Total n° Layers	25	

Test Parameters

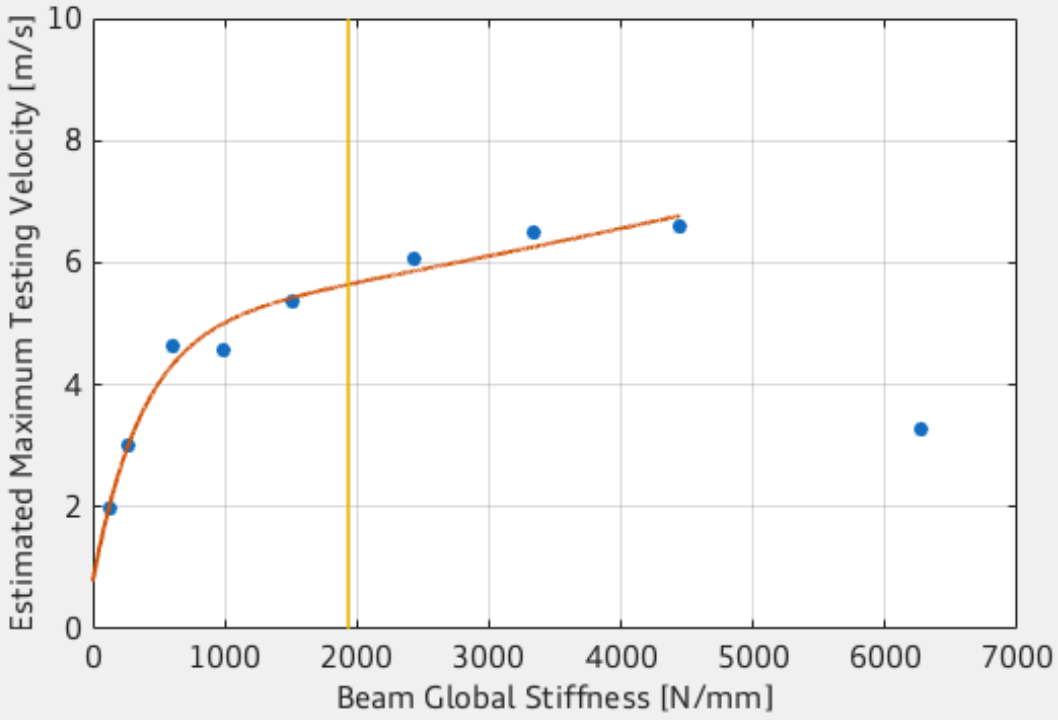
Width	15	[mm]
Support Span	60	[mm]
R2	0.95	[-]

Run Analysis

Output

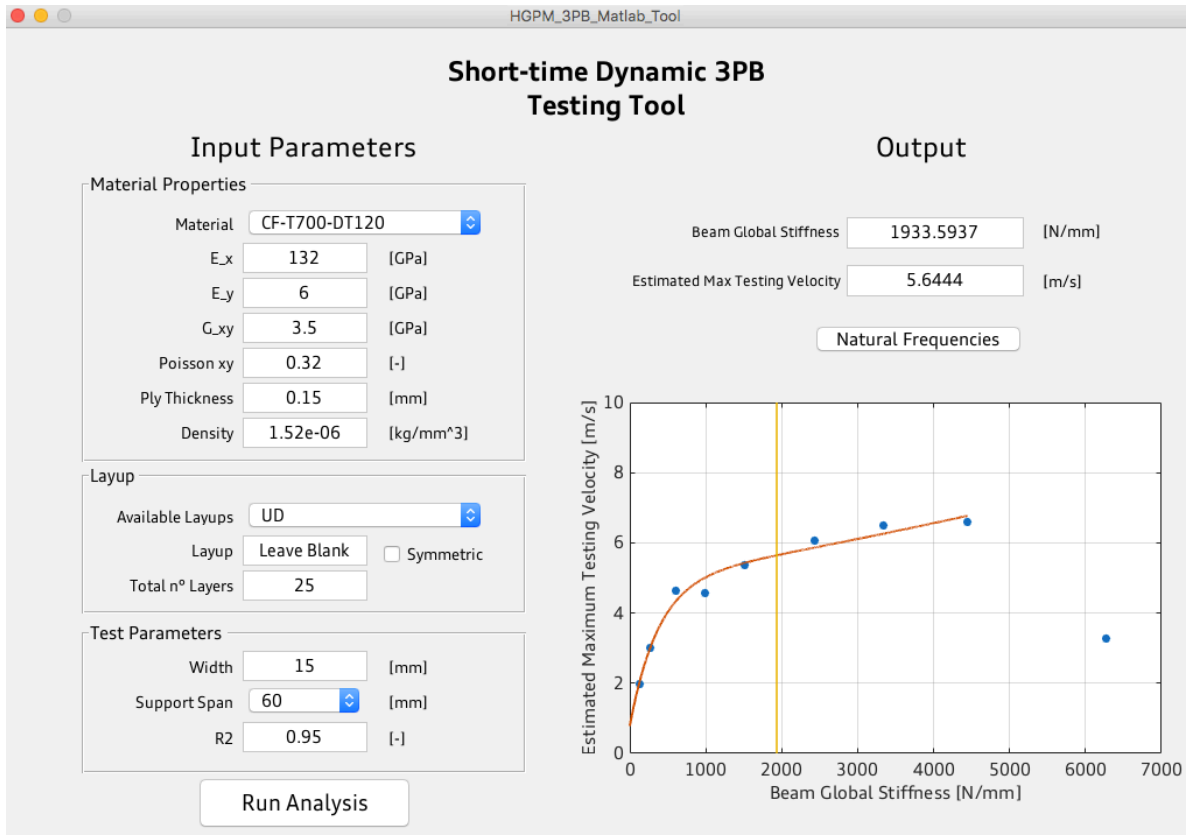
Beam Global Stiffness	1933.5937	[N/mm]
Estimated Max Testing Velocity	5.6444	[m/s]

Natural Frequencies



Estimation of the Maximum Testing Velocity
Matlab Tool

Matlab GUI



Input Parameters

- Material properties
  - chosen from the material database
  - custom material for user defined properties
- Layup
  - built-in layups: UD, $[0/90]_{nS}$, $[45/-45]_{nS}$, $[45/-45/0/90]_{nS}$
  - custom layup for user defined layers orientation
- Additional parameters are the specimen width, the support span and the target R^2

Output Parameters

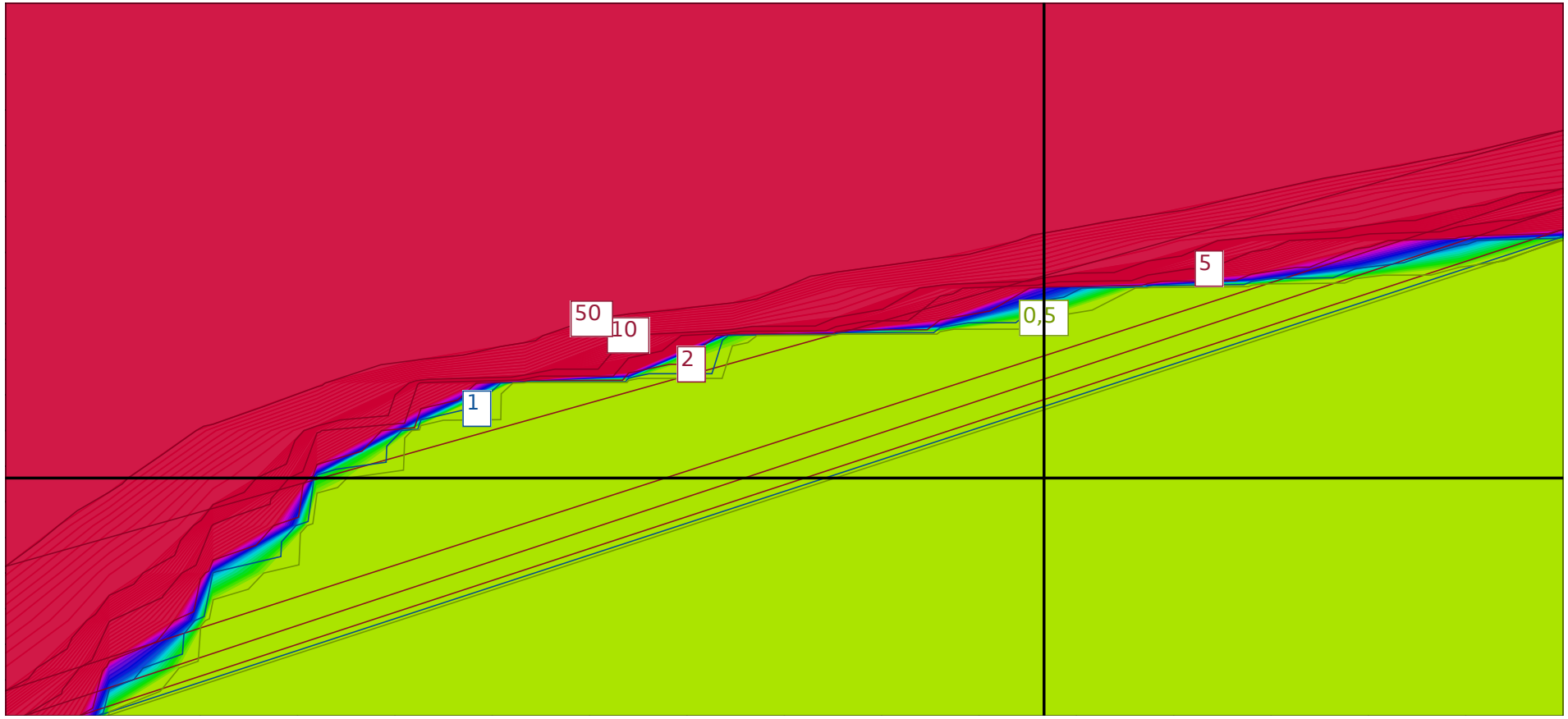
- Beam global stiffness
- Estimated maximum velocity
- Natural frequencies

» Method obtained to get reliable experimental results

» Must be validated through additional tests

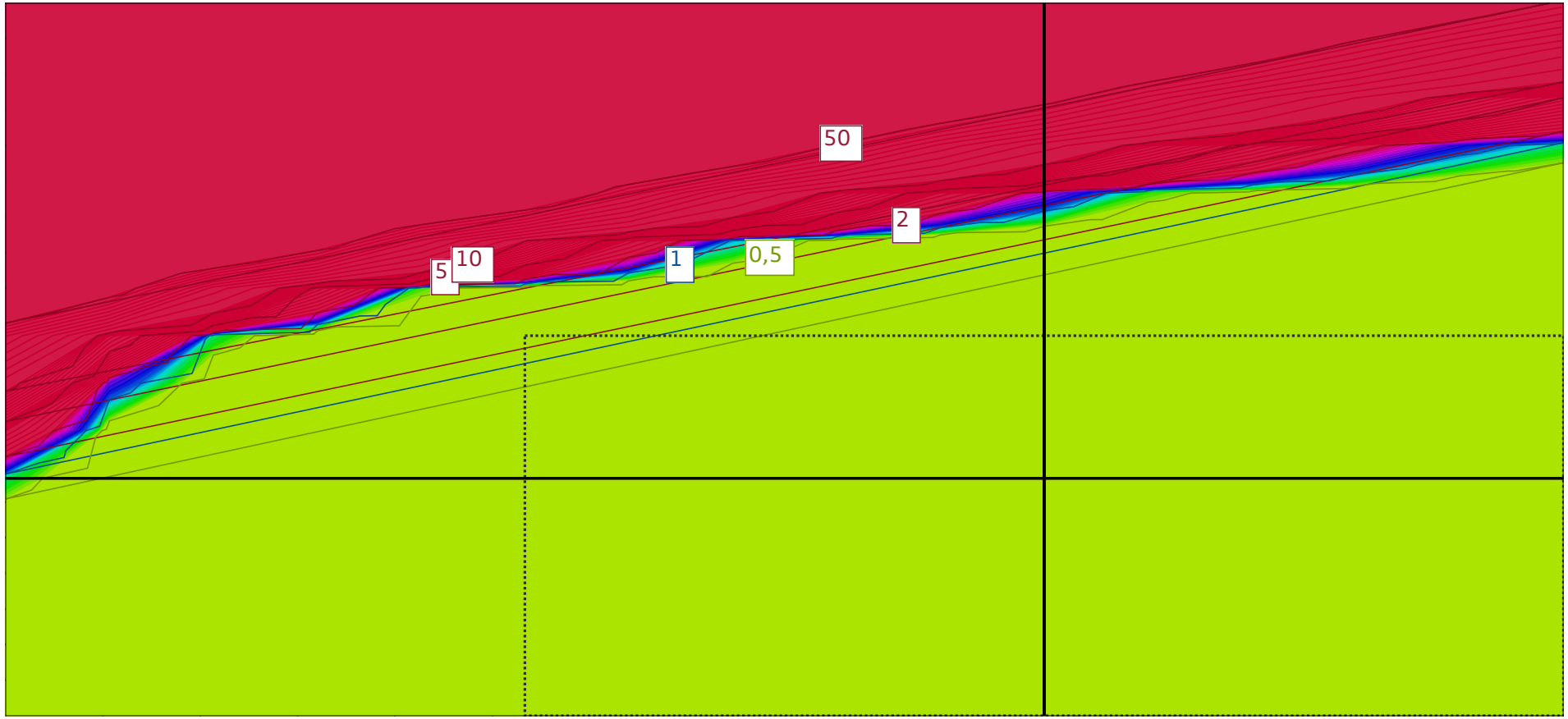
Reliable Test Window | Taguchi Method

Support Span 80mm



Reliable Test Window | Taguchi Method

Support Span 60mm



Reliabel process window by optimizing R^2, CoV und Fracture Stress

Table of Contents

1 Motivation

2 Strain Rate Dependent 3-Point Bending Test

3 Estimation of the Maximum Testing Velocity

4 Conclusions

Conclusions & Next Steps

- The 3-point bending fixture was successfully designed following the DIN EN ISO 14125 guidelines
- The combination of strain gauges and digital image correlation allowed characterising the strain rate dependent tests in terms of force-midpoint displacement curves
- An increase in maximum force at failure and maximum displacement at failure with increasing testing velocity was observed
- A MATLAB tool was implemented allowing the estimation of the maximum testing velocity below which low variation in the test results is expected

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- Compare the results with FEM-Simulation and summarize in a journal publication

Vielen Dank!