SHAPE RECONSTRUCTION OF A BENT TAPERED COMPOSITE PANEL BASED ON STRAIN DATA CAPTURED WITH LUNA‘S FIBER-OPTICAL-SENSOR SYSTEM (FOSS)

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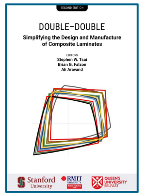
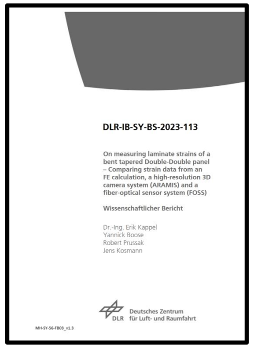
DLR

Storyline/Background

- A demonstrator has been manufactured to show that Double-Double laminates can be elegantly used to adjust a panel's deflection shape (local curvature) to given requirements
- In the examined scenario, the panel's tip is deflected with a certain displacement, while the panel contour has been evaluated in the deflected state.
- Optical measurements were executed to validate the process. See chapter 3 in  Download link: http://web.stanford.edu/group/composites/ebook/book_form_2ed.html

- For validation purposes of a new quasi-continuous fiber-optical strain measurement system from LUNA has been used.
- Fiber-optical sensors were integrated at different levels in the CFRP laminate stack and an additional fiber was attached to the panel's outer surface as well.
- An excellent match between FE-model results and measured strain could be verified
- See open source report :https://elib.dlr.de/199302/


DLR-IB-SY-BS-2023-113

On measuring laminate strains of a bent tapered Double-Double panel – Comparing strain data from an FE calculation, a high-resolution 3D camera system (ARAMIS) and a fiber-optical sensor system (FOSS)

Wissenschaftlicher Bericht

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Robert Prussak
Jens Kosmann

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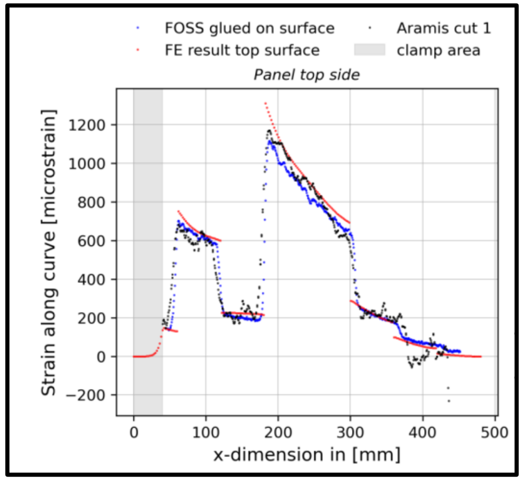
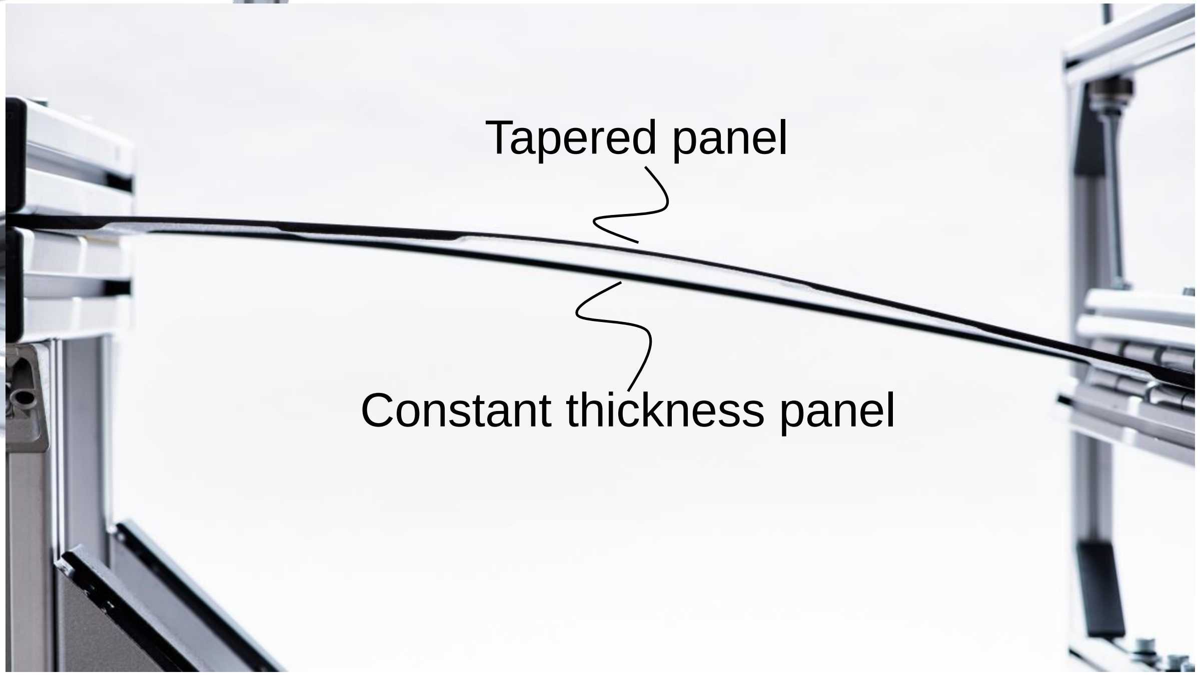
MH-SY-56-FB03_v1.3



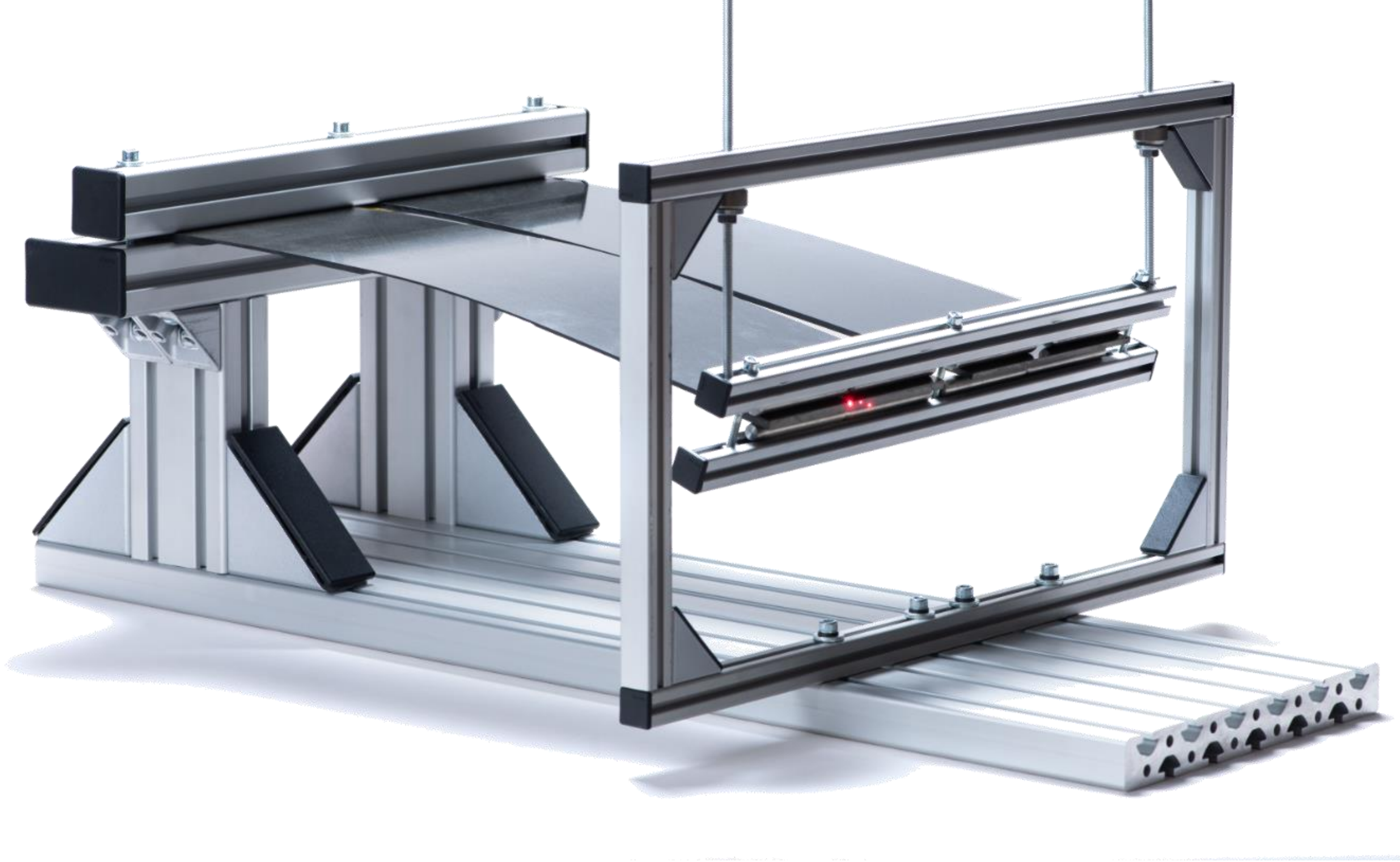
This presentation uses the captured top-surface strain data and shows how this data can be used to reconstruct the panel's bent contour

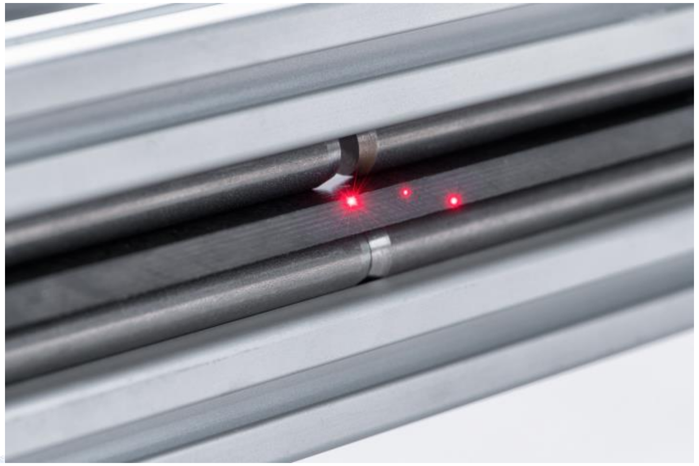
Demonstrator – “How local thickness affects the bent shape of a panel”



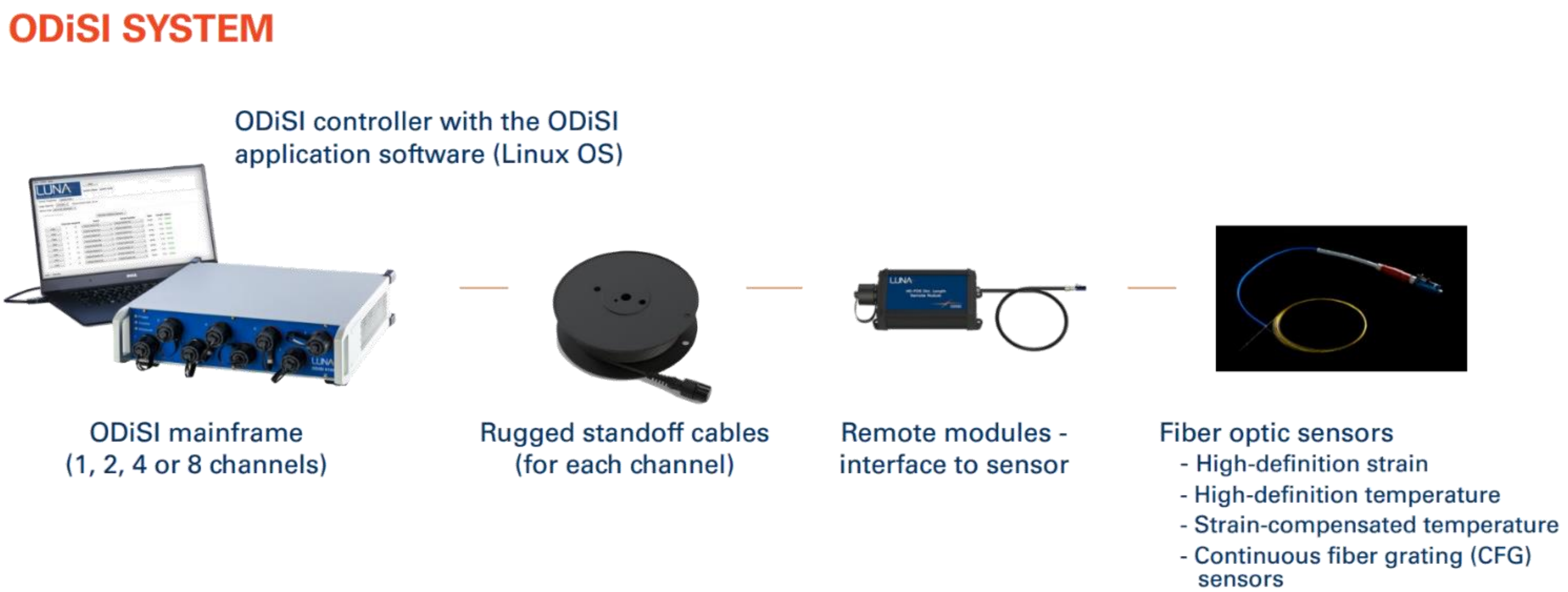
‘Identical tip deflection, different bent profile’

Demonstrator – ‘Integrated fiber-optical sensors in CFRP laminate at different levels in the stack’





LUNA Fiber-optical-sensor-system (FOSS)



For details visit:
https://lunainc.com/product/odisi-6000-series

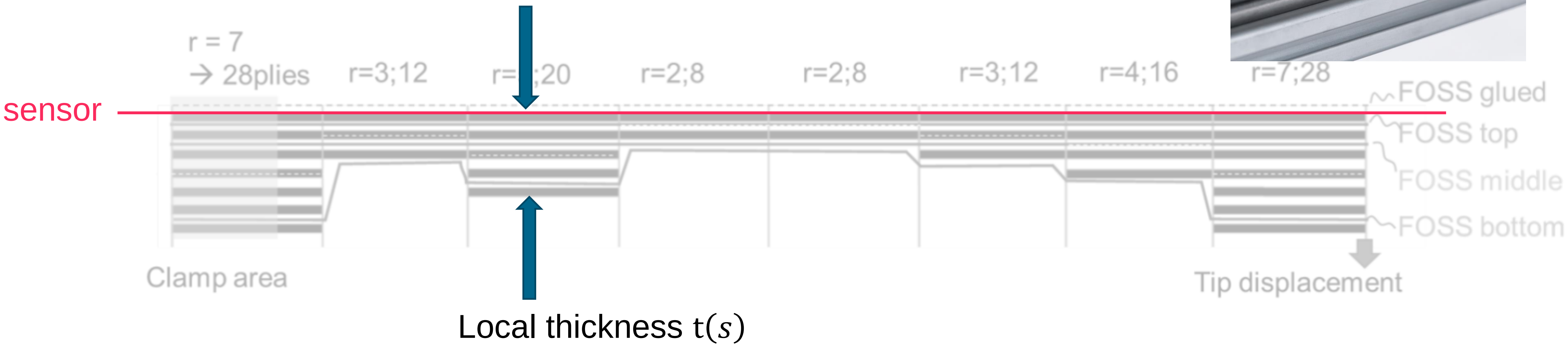
Input information needed

Note:

$\kappa(s) = \frac{\varepsilon_{top}(s) - \varepsilon_{bottom}(s)}{t(s)}$ to blank out mid-plane strain

$\kappa(s) = \frac{\varepsilon_{top}(s)}{t(s)/2}$ only for pure bending, erroneous when mid-plane strain is present

- From FOSS sensor: local axial strain at a certain position, $\varepsilon(s)$
- From Design/ Application pattern: local thickness or defined distance, $t(s)$

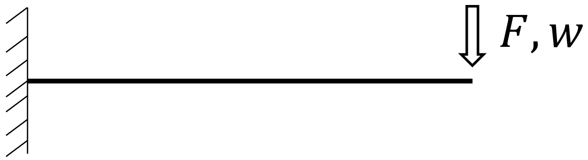


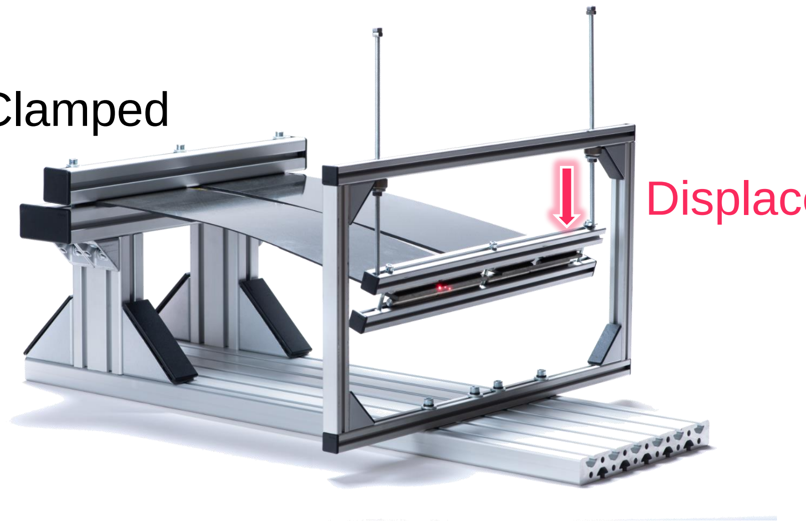
Euler beam basics for demonstrator load case

$$w'' = -\frac{M(x)}{EI} \; with \; M(x) = F \cdot (x - L)$$

- with $w = w' = 0$ follows:
- $w'' = \frac{F}{EI}(L - x)$
- $w' = \frac{F}{6EI}(6Lx - 3x^2)$
- $w = \frac{F}{6EI}(3Lx^2 - x^3)$

‘Simple cantilever scenario’





- $F = \frac{3EI}{L^3} \cdot w_{max} \rightarrow \propto E, \propto b, \propto t_{lam}^3, \propto 1/L^3, \propto w_{max}$

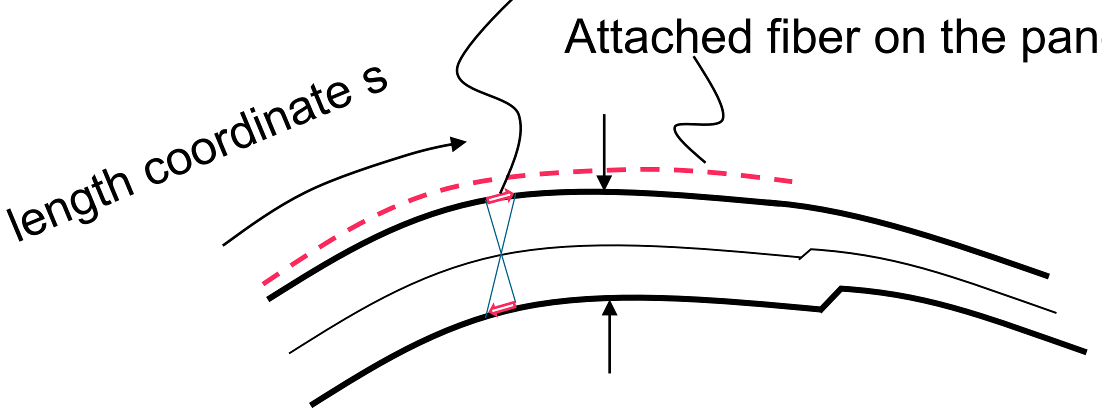
Defined by panel design and displacement scenario

Material selection, For CFRP stacking dependent

Design parameter for optimization

Reconstruction approach

The sensor system provides the local strain at a certain location along its length, $\varepsilon = f(s)$



Laminate thickness t_{lam}=f(s) in zone

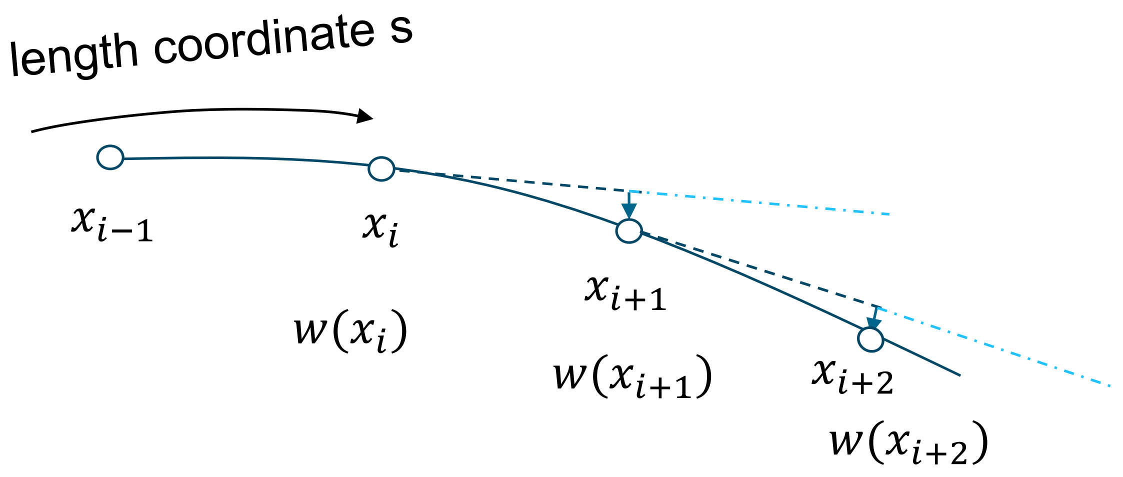
Comment:
When only a single sensor is used, a distinction between mid-plane strain, due to global elongation for example, and bending cannot be executed.
In a pure bending case, a single sensor is sufficient (as in the present demonstrator case)
In a combined load state, a second sensor information is mandatory for the distinction between elongation and bending

Euler beam basics

- $\kappa(s) = \frac{\varepsilon_{top}(s) - \varepsilon_{bottom}(s)}{t(s)}$
- $w'' \approx \kappa$
- $w' = \int \kappa \, dx = \kappa \cdot (x_i - x_{i-1})$
- $w = \int w' \, dx = w'(x_i - x_{i-1})$

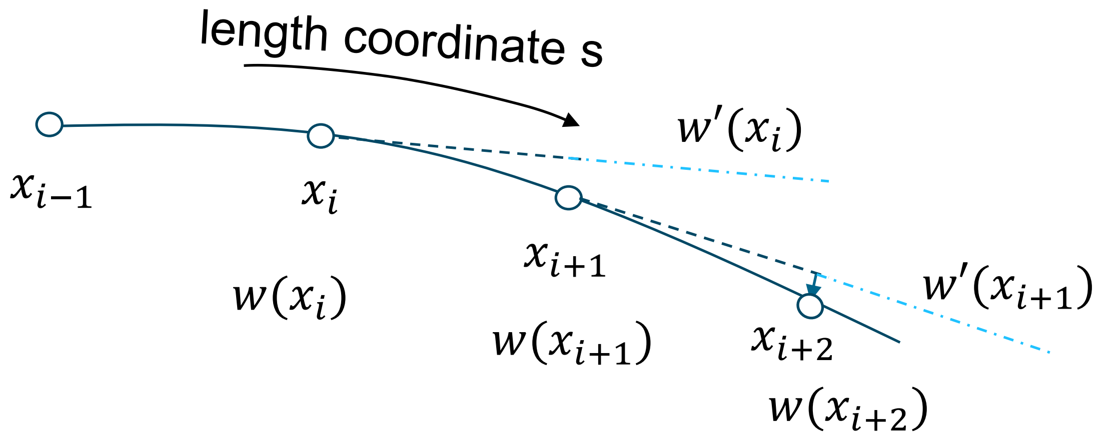
For the bending-only case of the demonstrator

$$\kappa(s) = \frac{2\varepsilon_{top}(s)}{t(s)}$$



Comment:
t(s) refers to laminate thickness in the present example. In a two-sensor setup (tension/compression) t(s) can also be interpreted as sensor distance

Euler beam basics



$$w(0) = w'(0) = w''(0) = 0$$

$$w(x_{i+1}) = w(x_i) + (w'(x_{i+1}) - w'(x_i)) \cdot (x_{i+1} - x_i)$$

$$w(x_{i+1}) = w(x_i) + \left(\frac{\varepsilon_{top}(x_{i+1}) - \varepsilon_{bottom}(x_{i+1})}{t(x_{i+1})}(x_{i+1} - x_i) - \frac{\varepsilon_{top}(x_i) - \varepsilon_{bottom}(x_i)}{t(x_i)}(x_i - x_{i-1}) \right) \cdot (x_{i+1} - x_i)$$

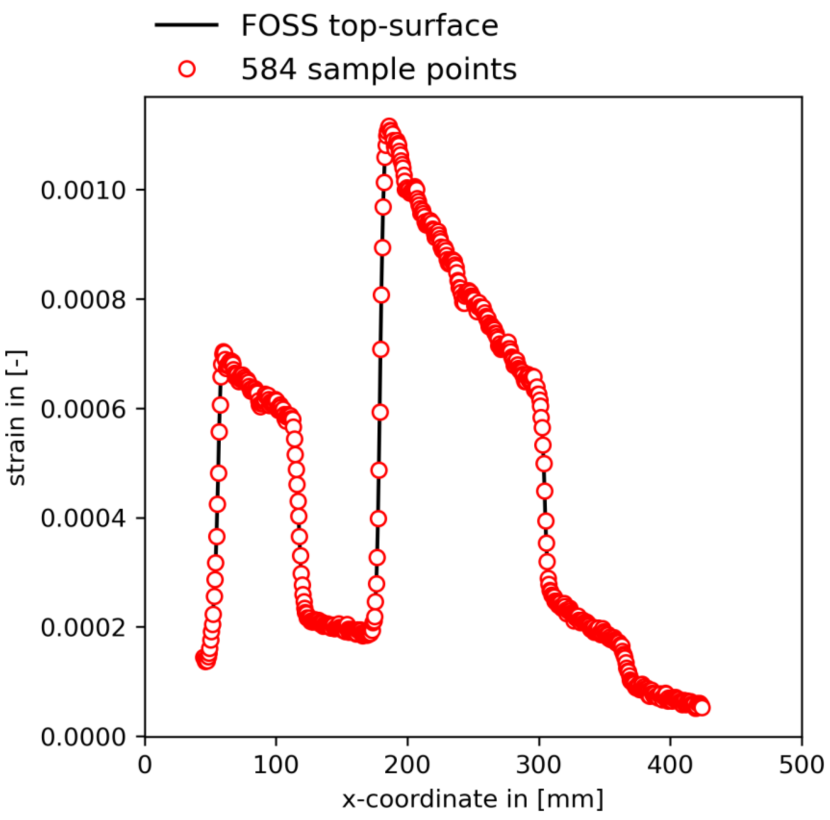
$$w(x_1) = w(x_0) + \left(\frac{\varepsilon_{top}(x_1) - \varepsilon_{bottom}(x_1)}{t(x_1)}(x_1 - x_0) \right) \cdot (x_1 - x_0)$$

Note the FOSS strain data refers to local length coordinate s. When large deformation occurs one must account for this within the reconstruction, as $dx \neq ds$

Effect of sampling

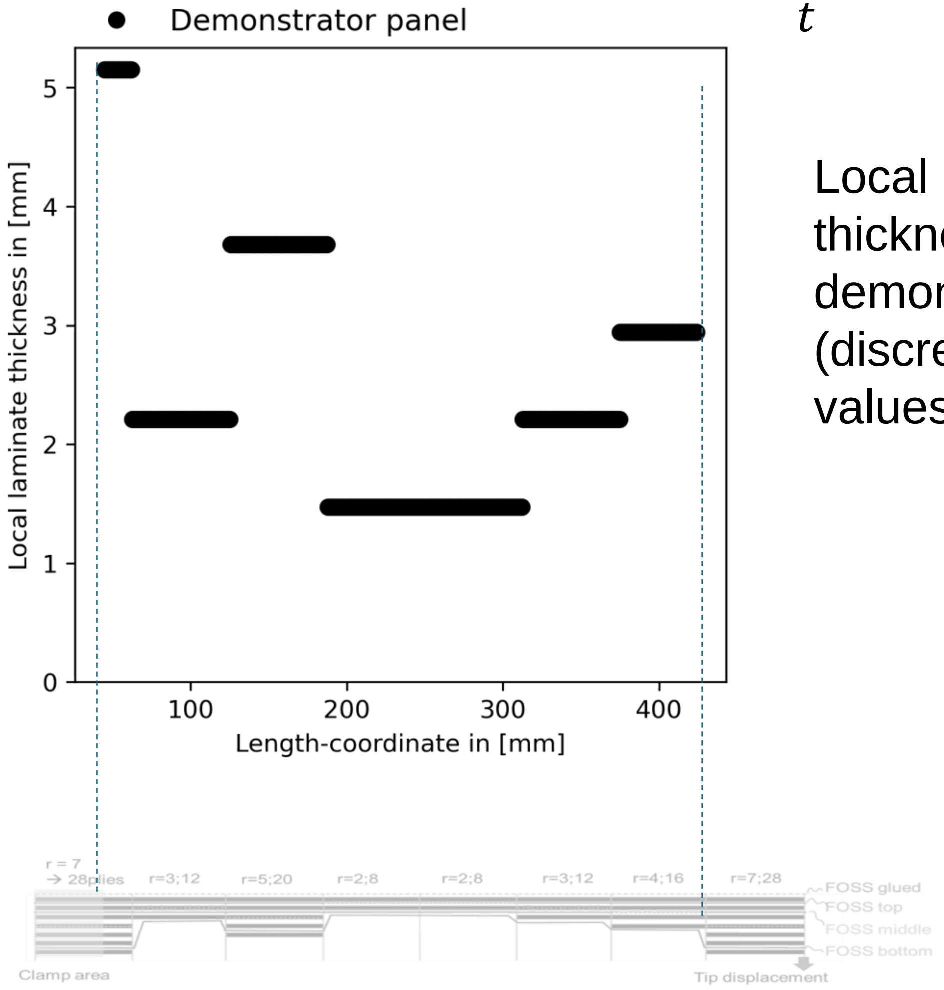
One data point each 0.7mm in average!

- The fiber sensor provides 584 data points along the bent for the tested flex



Strain from FOSS system

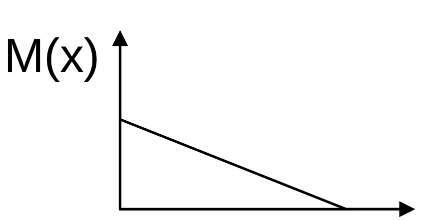
$$\kappa \propto \frac{1}{t} = '\ change\ of\ slope'$$

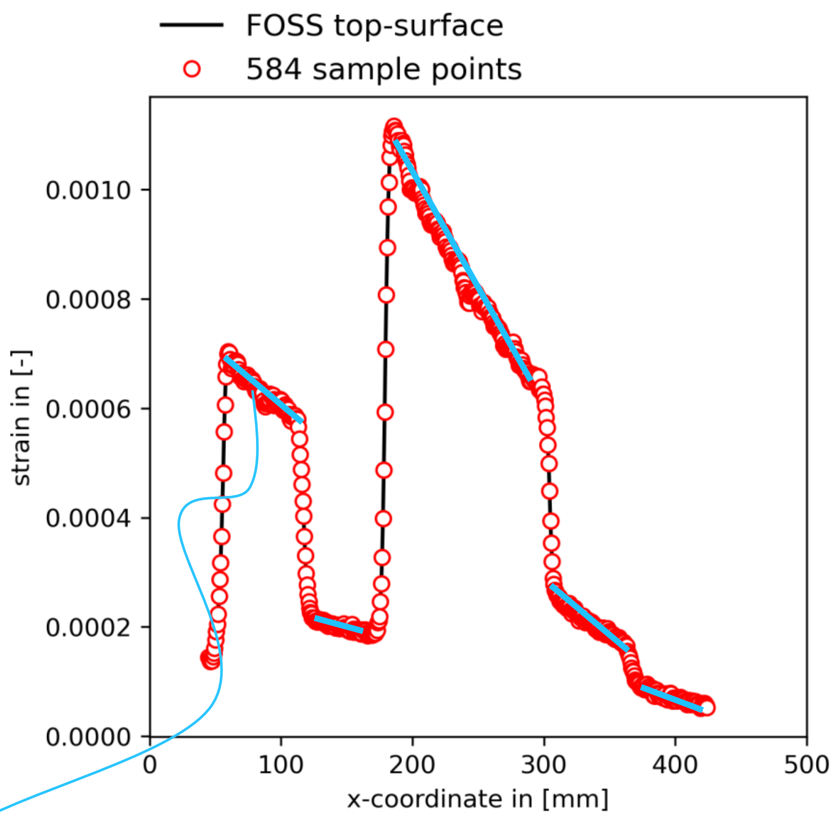


Local laminate thickness of demonstrator panel (discrete/ nominal values)

Strain data and thickness distribution

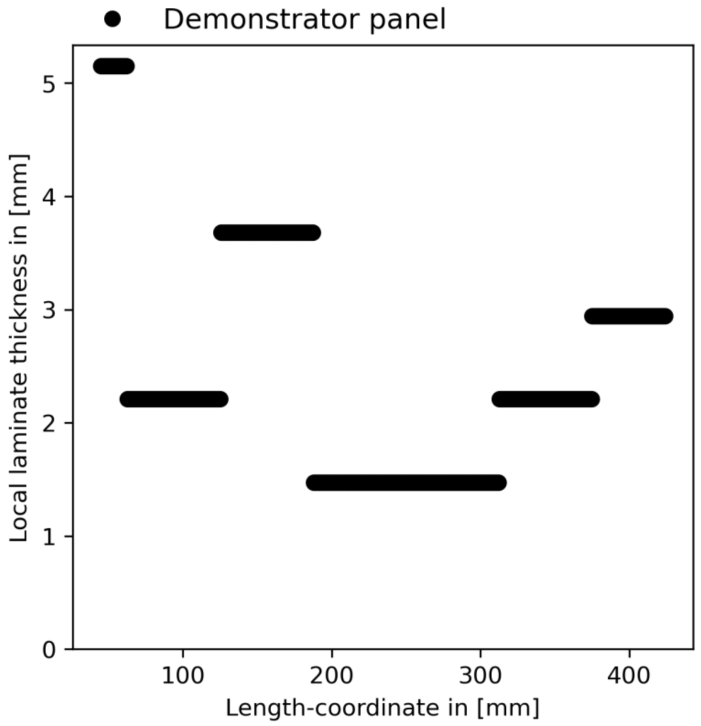
$$w'' = -\frac{M(x)}{EI} \; with \; M(x) = F \cdot (x - L)$$





$$w'' = \frac{F}{EI}(L - x)$$

$$\Delta w'' \propto \frac{1}{t^3}$$



Strain/Curvature decreases linearly with x

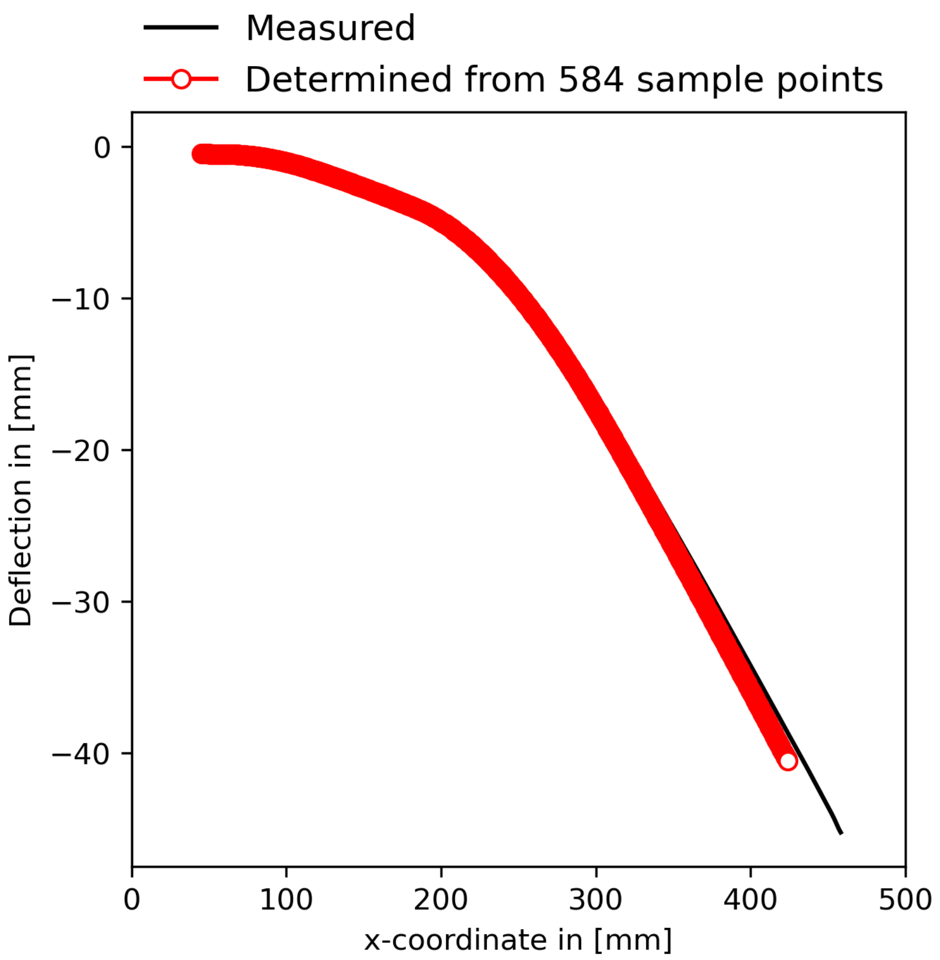
Slope of decrease proportional to $1/t_{lam}^3$

DD laminate repeat values r: [3,5,2,2,3,4]

tlam=4*r*t_{ply}

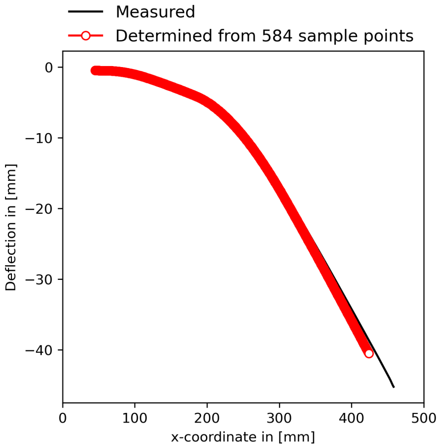
$1/t_{ply}^3$: [0.09, 0.02, 0.31, 0.31, 0.09, 0,04]

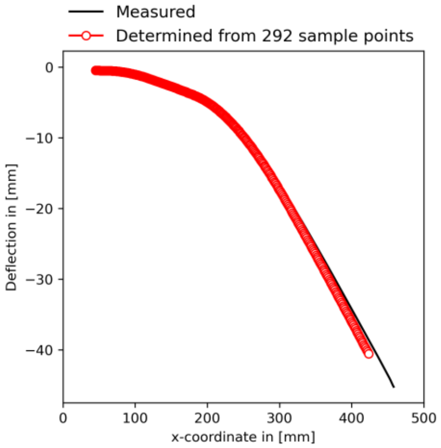
Shape reconstruction – Full data set

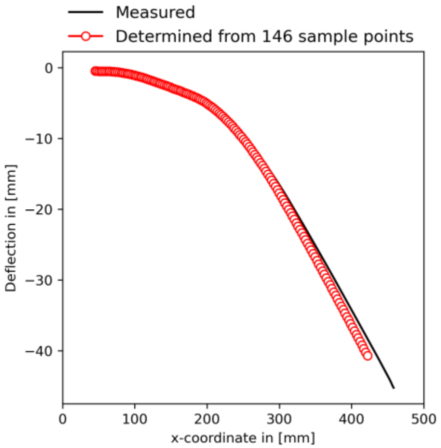


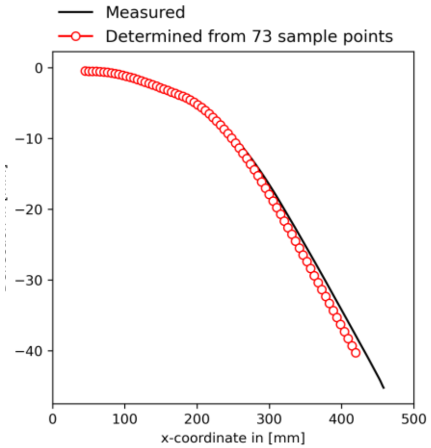
- The shape reconstruction works fine when the full strain dataset is used.

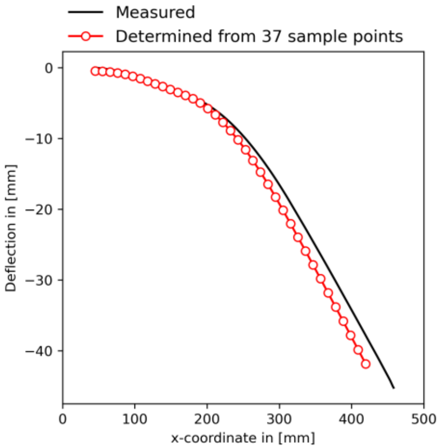
Shape reconstruction - Effect of sampling

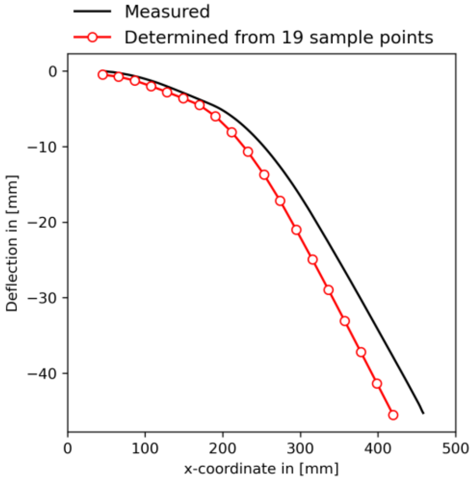


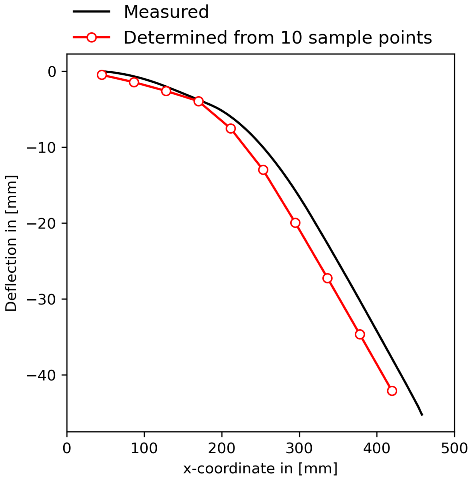






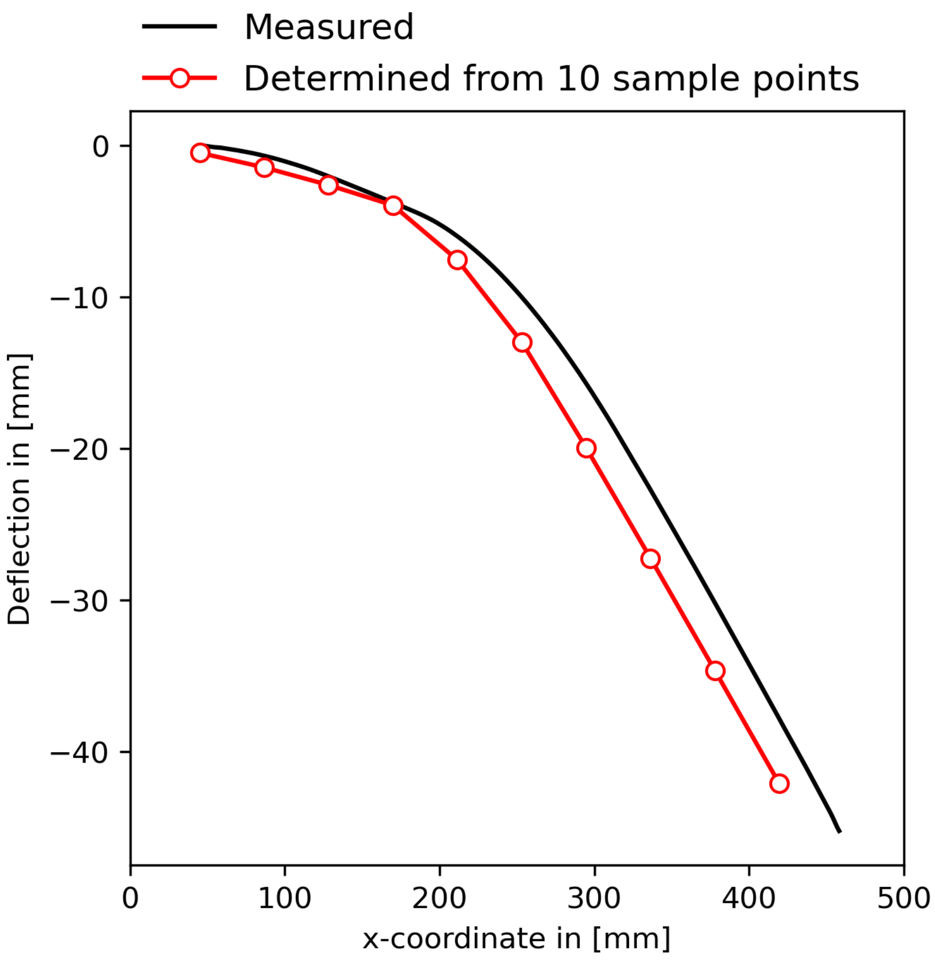






Observations:
Total deviation increase with decreasing number of points used from the data set

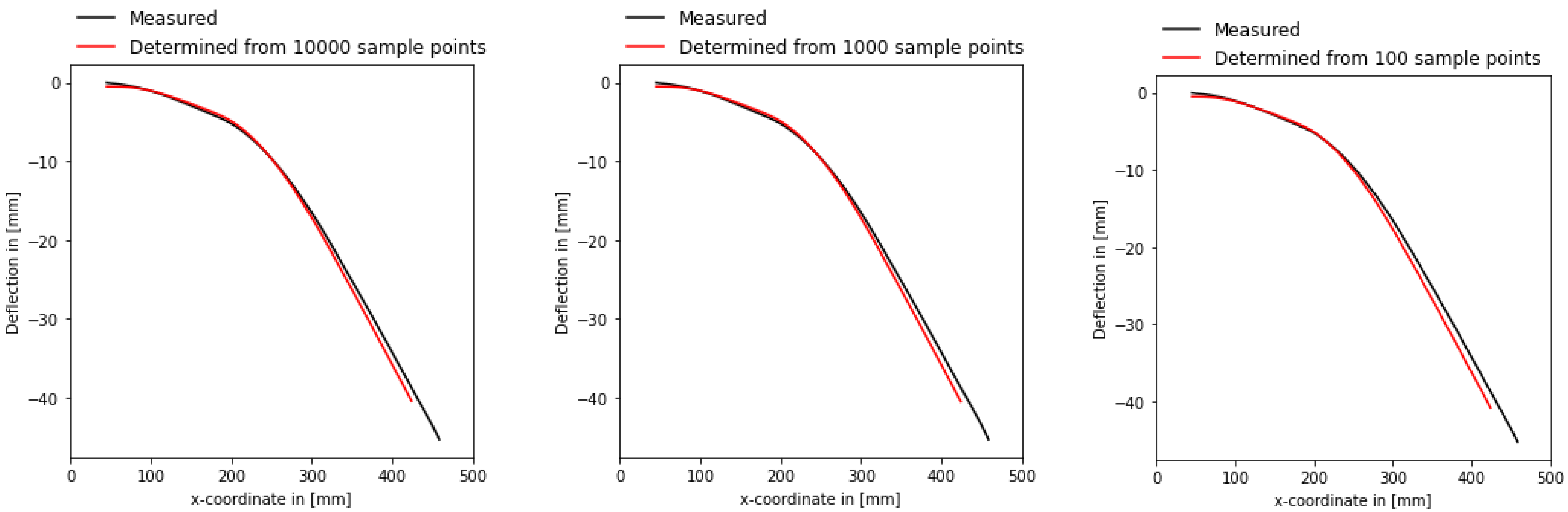
Effect of sampling – ‚issue low sample rate‘



Due to the calculation scheme (integral), deviations sum up, as the deflection of point i is determined based on the deflection of point $i-1$ + the slope at i, times the distance between the points i and $i-1$.

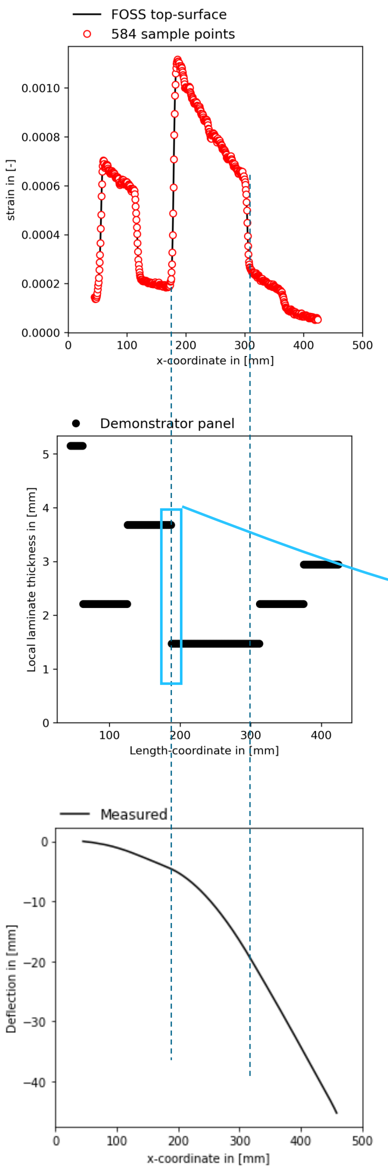
There is no correction mechanism, as the strain data is linked to the slope calculation, only.

Effect of sampling – adding artifical data points via interpolation

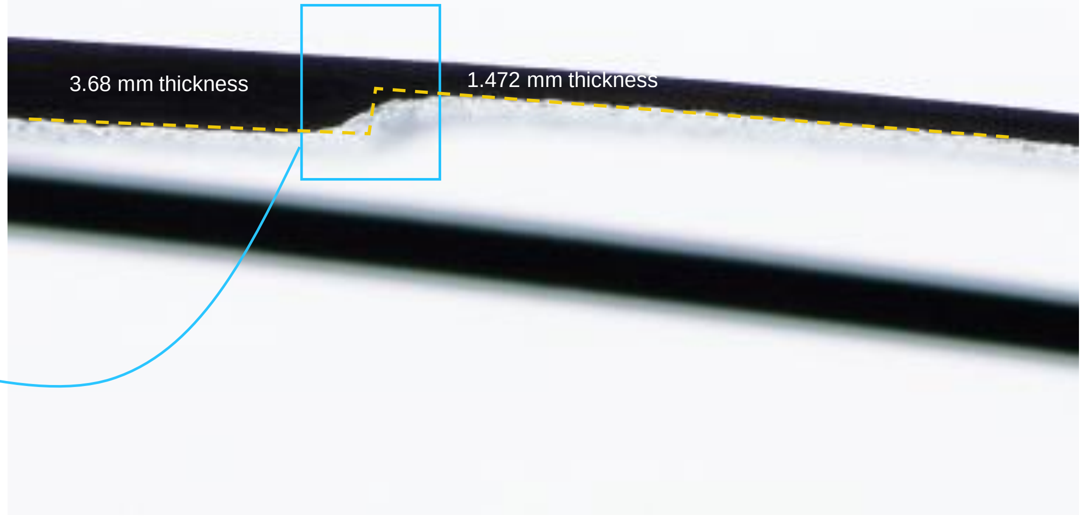


The original strain data set consists of 584 points. Adding additional data points using interpolation operation in Python for example, allows for increasing the number of data points.
The plots above shows, that the effect on the accuracy is limited.

Assessment/ comment – ‘real laminate thickness’



Laminate thickness transition (blue box) in a manufactured part is not a discrete step (dashed line). Instead one observes a rather smooth transition zone. This effect is not covered in the presented reconstruction scheme.

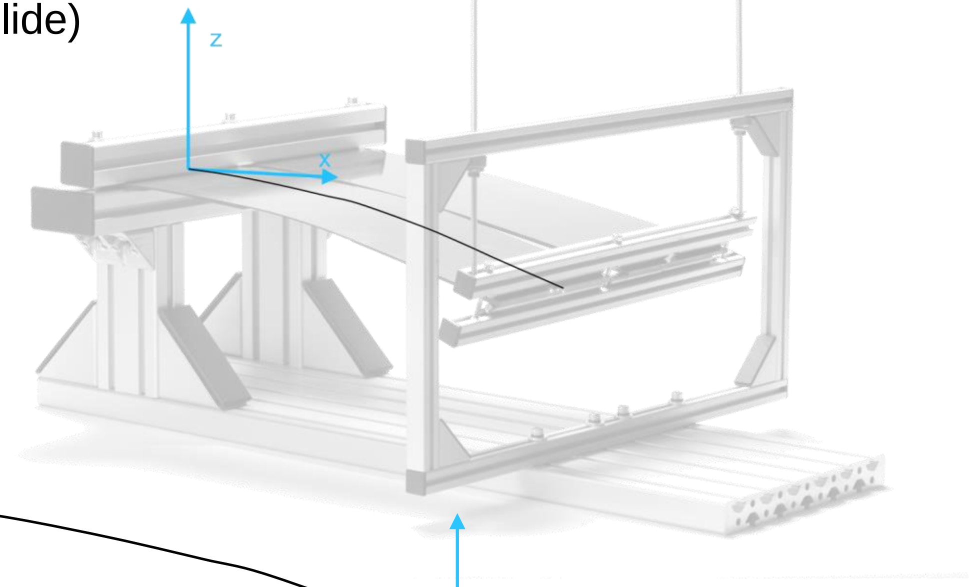


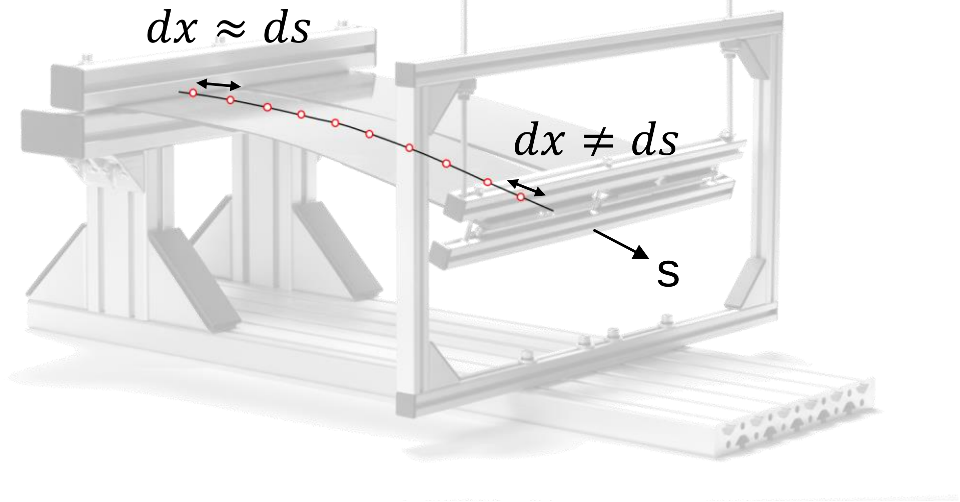
Note:
A single-sided tool concept has been used to for manufacturing the CFRP panel

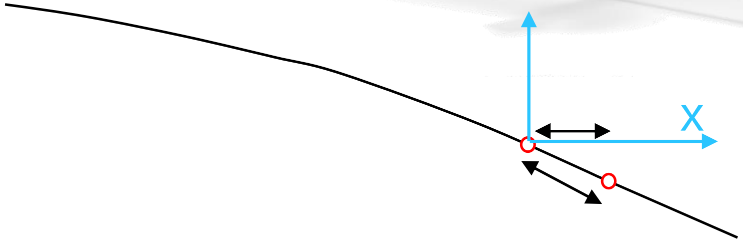
For the panel at hand, the transition-zone length is estimated to 4 mm. In combination with a data-point density of 0.7 mm, one must assume, that 5 - 6 curvature values are determined erroneous. Due to the integration procedure along the fiber those erroneous curvatures induce slight deviations of the local slopes, which sum up to the observed total deviation.

Assessment/comment – For large deformation $x \neq s$

Comment: Displacements usually refer to a cartesian coordinate system. The distance between two sensor data points refers to the local sensor length s. As long as the sensor is aligned parallel to the x axis everything is fine. However, when the displacements become large, as for the flex-panel at hand, one needs to consider that the local sensor coordinate s is not aligned to the cartesian system anymore. Thus, $ds \neq dx$. This effect can be captured (simple approach) by considering the local slope, as for example presented hereafter. If not captured, this effect leads to increased deviation in large-deformation scenario (see the effect of the correction on next slide)



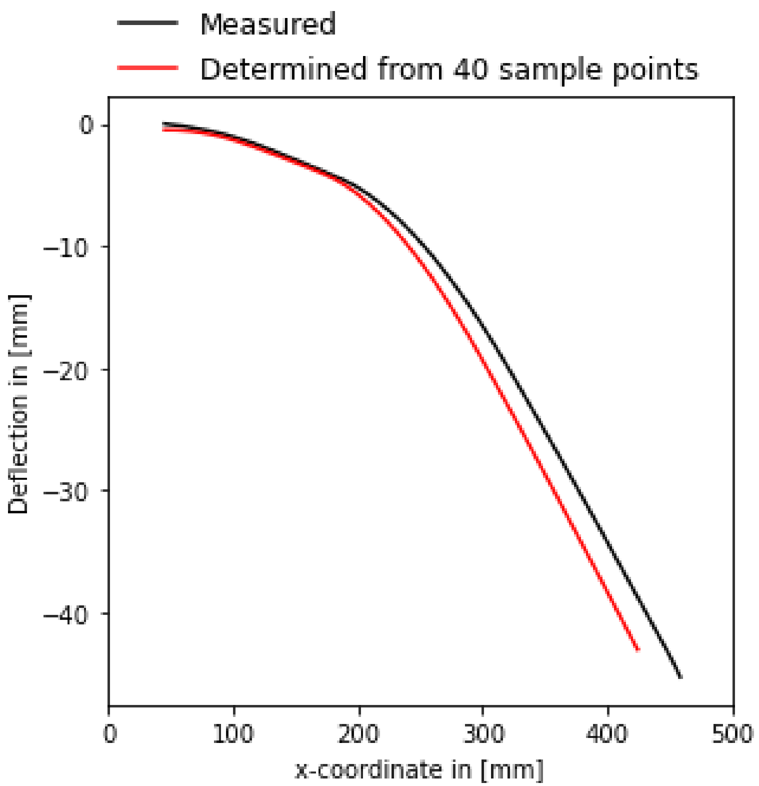


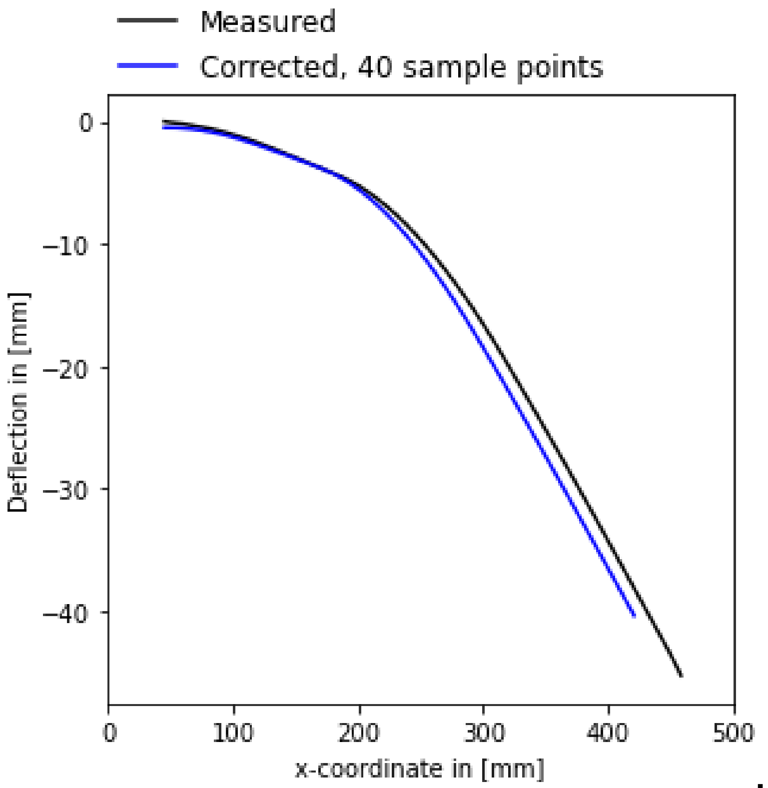


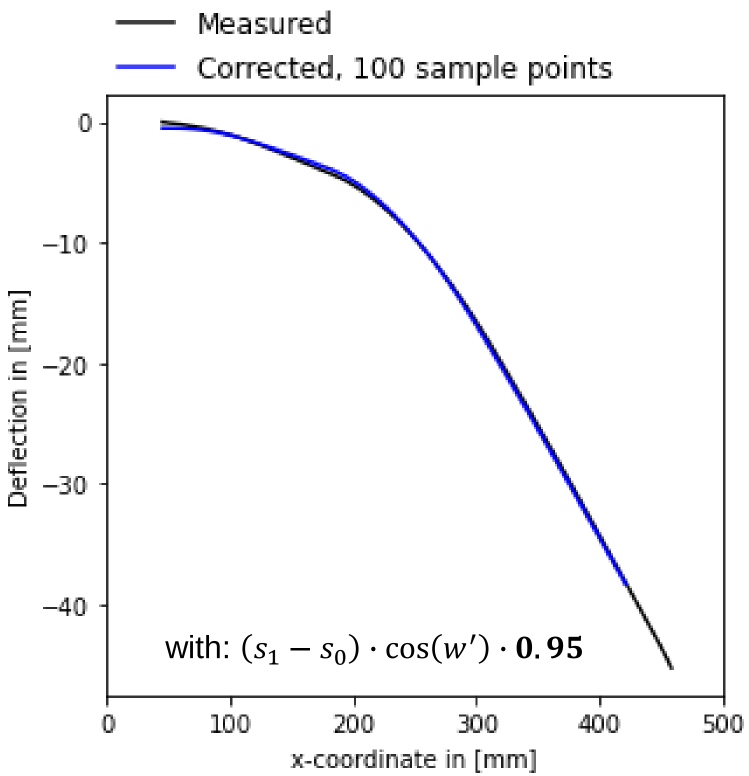
$$w(x_1) = w(x_0) + \left(\frac{\varepsilon_{top}(s_1) - \varepsilon_{bottom}(s_1)}{t(s_1)} (s_1 - s_0) \right) \cdot \underbrace{(s_1 - s_0) \cdot \cos(w')}_{x_{eff}}$$

$$x_{eff} = f(s, w')$$

Assessment/comment - large displacements $x \neq s$







40 data point used

100 data point used + empirical scale of slope contribution with factor 0.95

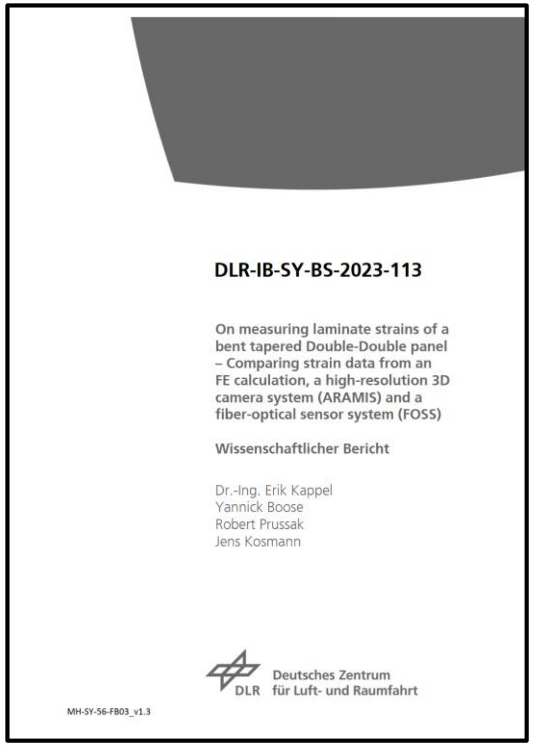
Conclusions

- A single attached fiber-optical sensor (FOS) allows for a high-quality shape reconstruction of the bent shape of a tapered Double-Double flex panel in a tip-displacement cantilever scenario
- The system provides an average data point density of 0.7 mm for the panel at hand
- The effect of sampling has been demonstrated for the flex panel example at hand.
- Due to the incremental formulation (integration) within the strain-based shape-reconstruction calculation, one observes that total deviations sum up along the fiber length. Deviations increase when sample size is reduced, as local curvature effects remain uncaptured.
- The FOS-system (FOSS) provides local strain at a certain length-location. For the shape reconstruction task, in the regarded pure-bending scenario, it is mandatory to have a single fiber attached to the part. However, knowing the local laminate thickness is a prerequisite to transfer strain into curvature, which is needed for the shape reconstruction.
- If mid-plane strain superpose the bending deformation, it is mandatory to have two fibers attached to the part, while the local fiber distance must be known.
- When displacements are large, the discrepancy between the local fiber coordinate s and the cartesian coordinate system x, y, z needs to be taken into account, in order to improve the reconstruction result.
- It is essential to cover high-curvature regions adequately in order to achieve a high-quality reconstruction. The present study focuses on a equidistant sample-point distribution. More advanced selection strategies potentially can help to improve the reconstruction quality for low-number of points, for example when those sample points a predominantly located in regions with high-curvature and local curvature changes.

Sources

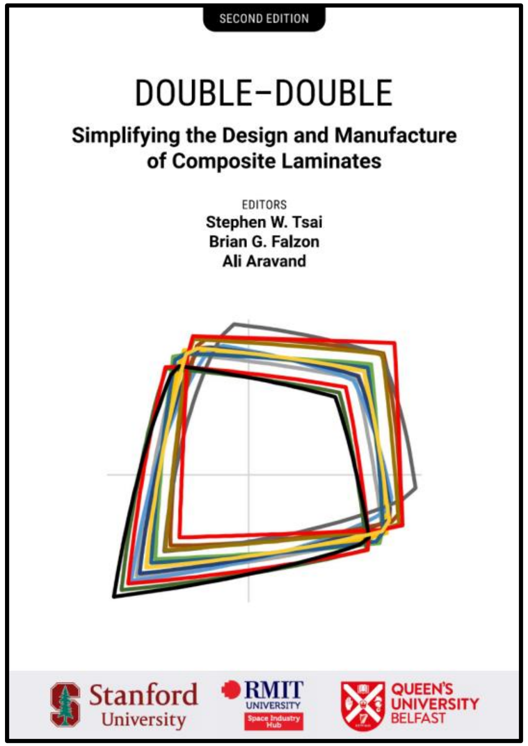
- Strain measurement using FOSS

https://elib.dlr.de/199302/



- Contour analysis of the bent flex panel (Chapter 3)

http://web.stanford.edu/group/composites/ebook/book_form_2ed.html



Impressum

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