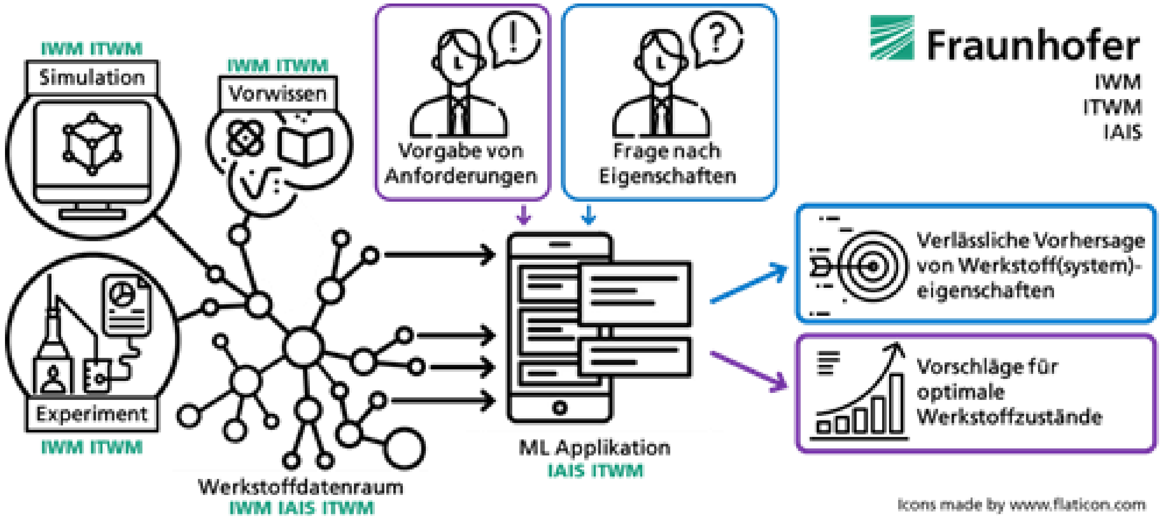
ONLINE-VERANSTALTUNG

Data-based Estimation of Cable Bundle Stiffness

Abschlusskolloquium des Fraunhofer-Konsortiums »UrWerk« zur Entwicklung von unternehmensspezifischen Werkstoff(system)-Datenräumen



Moderation Dr. Michael Luke
Projektleiter »UrWerk«
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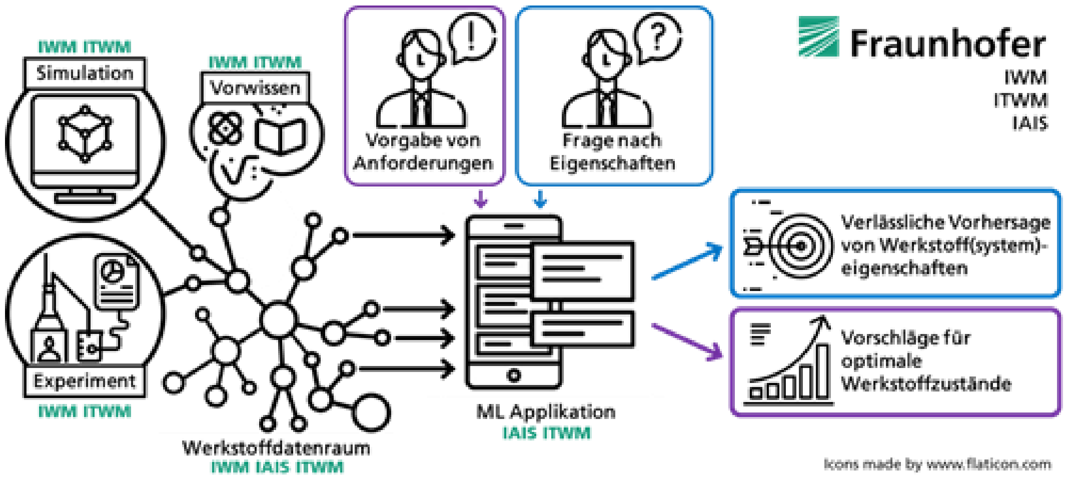
am Fraunhofer-Institut für Werkstoffmechanik IWM

24.November 2022



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MaVo UrWerk - Unternehmensspezifische Werkstoff(system)-Datenräume zur beschleunigten Produktentwicklung

DATA-BASED ESTIMATION OF CABLE BUNDLE STIFFNESSES

Lilli Burger, Vanessa Dörlich, Fabio Schneider, Joachim Linn, Michael Burger

Abschluss Kolloquium – 24. November 2022

Data-based estimation of cable bundle stiffnesses

Agenda

- Data based prediction of effective bundle stiffnesses
  - Introduction of Gaussian Process Regression
  - Model setup
- Validation with bundles from automotive application
- Conclusion and Outlook

Gaussian Process Regression

Data-based approach

Dataset

$$D = \{(\boldsymbol{X}, y)\}, \qquad \boldsymbol{X} = (x_1, \dots, x_N)^T \in \mathbb{R}^{Nxd}, \qquad y = \begin{pmatrix} y_1 \\ \vdots \\ y_N \end{pmatrix}$$

Assumption

$$y_i = f(x_i) + \varepsilon, \qquad \varepsilon \sim N(0, \sigma_n^2)$$

Define function f as a **Gaussian Process** with given mean function m and covariance function k

$$f \sim GP(m, k)$$

Prediction Task

find $y^* = f(x^*)$ for a new datapoint x^*

Gaussian Process Regression

Data-based approach

Conditional distribution can be computed analytically:

$$p(y^*|x^*, \boldsymbol{X}, y) = N(m(\boldsymbol{x}_*) + K_*(K + \sigma_n^2 I)^{-1}(y - M_{\boldsymbol{X}}), K_{**} - K_*(K + \sigma_n^2 I)^{-1} K_*^T)$$

Key prediction equations

Prediction for y_* is the mean value of the conditional distribution

$$y^* = m(\boldsymbol{x}^*) + K_*(K + \sigma_n^2 I)^{-1}(y - M_{\boldsymbol{X}})$$

Prediction variance (uncertainty quantification)

$$\sigma_*^2 = K_{**} - K_*(K + \sigma_n^2 I)^{-1} K_*^T$$

Data-based estimation of effective cable bundle stiffnesses

Gaussian Process Regression

Training data set

$(EI)_i$: eff. Bending stiffness of base cables
$(GJ)_i$: eff. Torsional stiffness of base cables
ρ_i : length density of base cables
r_i : base cable radius
a_C : number of base cables within bundle composition
r_b : bundle radius

$(EI)_B$: eff. Bundle bending stiffness
$(GJ)_B$: eff. Bundle torsional stiffness

GPR

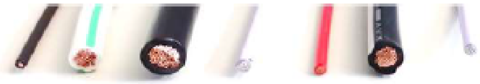
$$y^* = m(\boldsymbol{x}^*) + K_*(K + \sigma_n^2 I)^{-1}(y - M_{\boldsymbol{X}})$$

$$\sigma_*^2 = K_{**} - K_*(K + \sigma_n^2 I)^{-1} K_*^T$$

Data-based estimation of effective cable bundle stiffnesses

Gaussian Process Regression

Training data set



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a_C : number of base cables within bundle composition
r_b : bundle radius

$(EI)_B$: eff. Bundle bending stiffness
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Validation with test data set

$(EI)_i$,$(GJ)_i$,ρ_i ,r_i ,a_C ,r_b

GPR

$$y^* = m(\boldsymbol{x}^*) + K_*(K + \sigma_n^2 I)^{-1}(y - M_{\boldsymbol{X}})$$

$$\sigma_*^2 = K_{**} - K_*(K + \sigma_n^2 I)^{-1} K_*^T$$

$(EI)_B$: eff. Bundle bending stiffness
$(GJ)_B$: eff. Bundle torsional stiffness

Estimation of effective cable bundle stiffnesses

Gaussian Process Regression

- Probabilistic model described by kernel and mean function
- Define process parameter with training step
- Kernel scale parameters for **rational quadratic kernel function** k
- Parameter β for linear/ quadratic **mean function** m
- Noise standard deviation σ_n

Rational quadratic covariance function

$$k(x_i, x_j) = \sigma_f^2 \left(1 + \frac{1}{2\alpha} \sum_{m=1}^{d} \frac{\left\| x_i^{(m)} - x_j^{(m)} \right\|_2^2}{l_m^2} \right)^{-\alpha}$$

with $l_1, \ldots, l_d, \alpha > 0$: (characteristic) length scale and
d: number of predictors

$$f(x) \sim GP(m(x), k(x, x'))$$

Key prediction equations

Prediction for y_* is the mean value of the conditional distribution

$$y^* = m(\boldsymbol{x}^*) + K_*(K + \sigma_n^2 I)^{-1}(y - M_{\boldsymbol{X}})$$

Prediction variance

$$\sigma_*^2 = K_{**} - K_*(K + \sigma_n^2 I)^{-1} K_*^T$$

Prediction of effective cable bundle stiffnesses

Preliminary work

- Probabilistic model, with point estimation and standard deviation as a r
- Machine learning approach suitable for application with few data availa
- Good results expected for bundles within training data base
- Different analysis steps made (Feature tests, sensitivity analysis, differen

Academic bundles

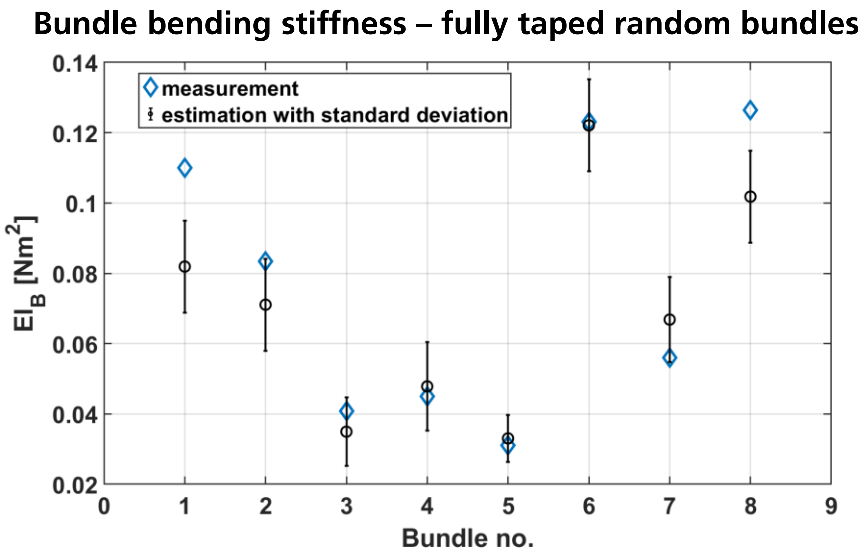
- Effective **bending stiffnesses**
- Training with 80% / test with 20% of the data base

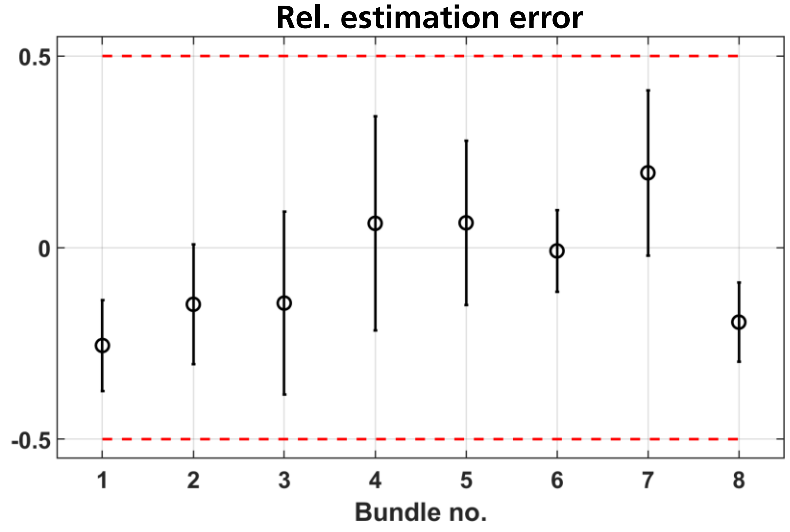
Academic bundles

- Effective **torsional stiffnesses**
- Training with 80% / test with 20% of the data base

Random bundles

- Eff. **bending and torsional** stiffnesses
- Training with academic bundles
- Test with random bundles





Prediction of effective cable bundle stiffnesses

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Random bundles

- Eff. **bending and torsional** stiffnesses
- Training with academic bundles
- Test with random bundles

Bundle from automotive application

- Validation of eff. bundle **bending** stiffness
- Sensitivity analysis

- Absoluter Schätzfehler: 0,008Nm^2
- Relativer Schätzfehler: 0,133

Prediction of effective cable bundle stiffnesses

Preliminary work

- Probabilistic model, with point estimation and standard deviation as a result
- Machine learning approach suitable for application with few data available
- Good results expected for bundles within training data base
- Different analysis steps made (Feature tests, sensitivity analysis, different model setups,…)

Academic bundles

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Bundle from automotive application

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Bundles from complete door wiring

- …

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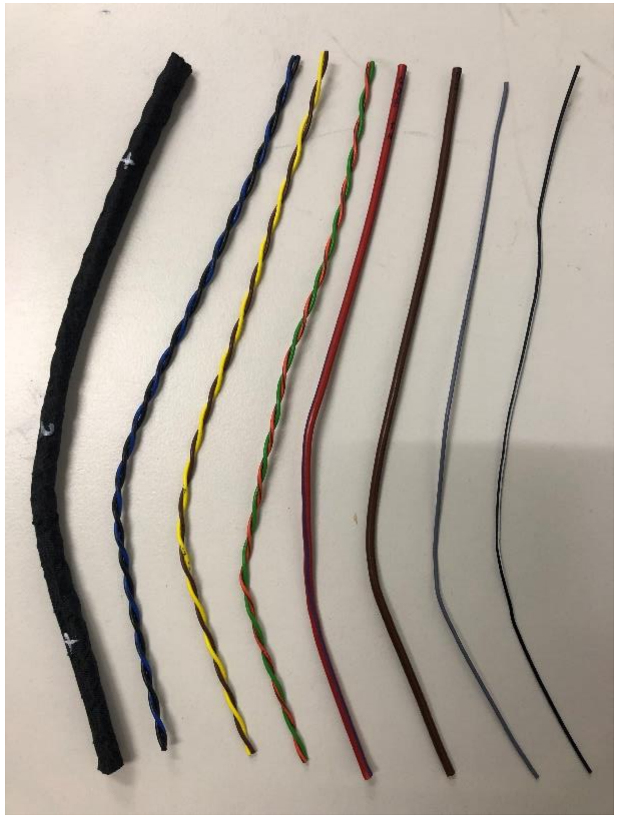
Process Validation with Cable Bundles from Automotive Application

Bundles from complete door wiring

Variant of complete door wiring

- Same condition as it is before assembling (folded and fixed with a rubber band)
- Samples generated by cutting out segments of sufficient length
- After measuring the effective stiffnesses of the bundle the taping has been removed and all base cables were measured
- Twisted pairs are handled as one base cable specimen (cables are not separeted from each other)
- All measured components:
  - 18 different base cables (diameter: 1,3 mm – 1,6 mm – 2,8 mm)
  - 4 twisted pairs
- Measurement techniques:
  - MeSOMICS bending stiffness
  - Standard torsional stiffness



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Process Validation with Cable Bundles from Automotive Application

Bundles from complete door wiring

Bundle no.	half	fully
1	4 base cables, 2 of them are twisted pairs	7 base cables, 3 of them are twisted pairs
2		12 base cables, 4 of them are twisted pairs
3		5 base cables, 1 of them are twisted pairs
4		7 base cables, no twisted pairs

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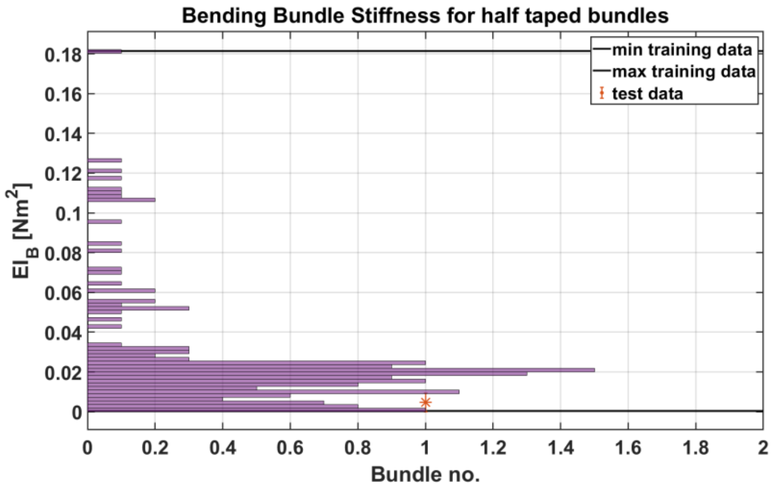
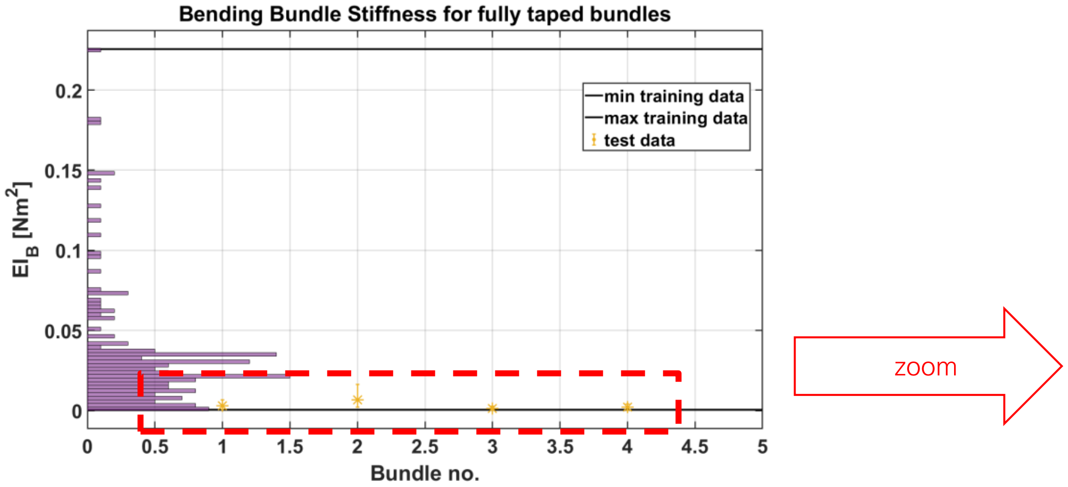
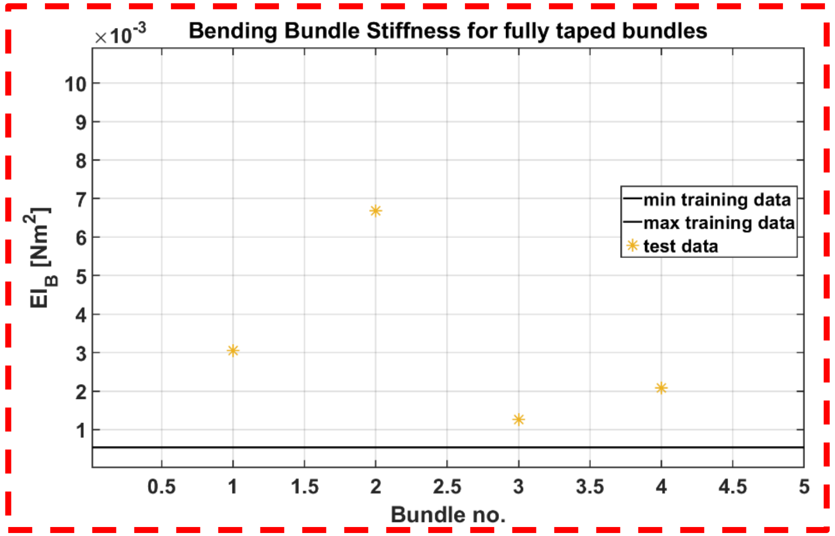
Comparison between Training and Test Data

Effective Bending Stiffness of Test Bundles



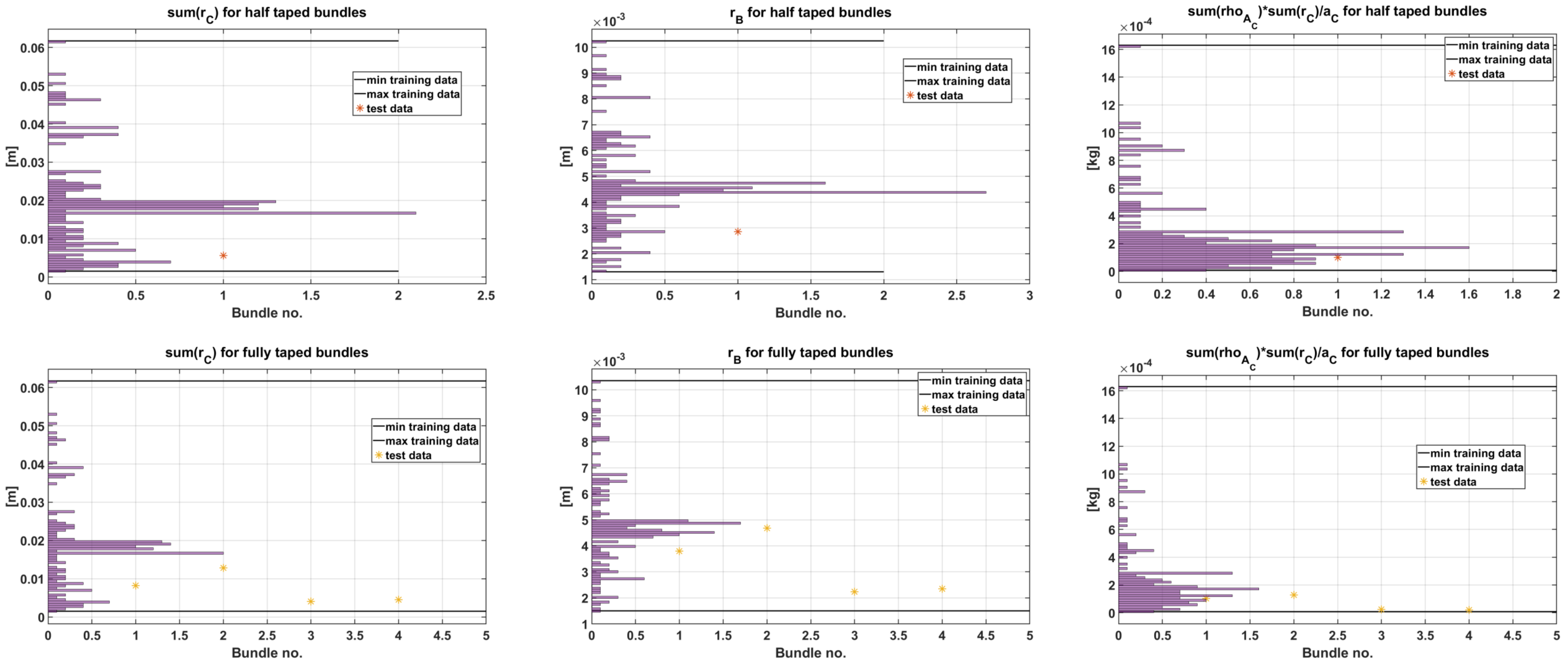




Effective bundle bending stiffness is at the lower boundary of our training data set

Comparison between Training and Test Data

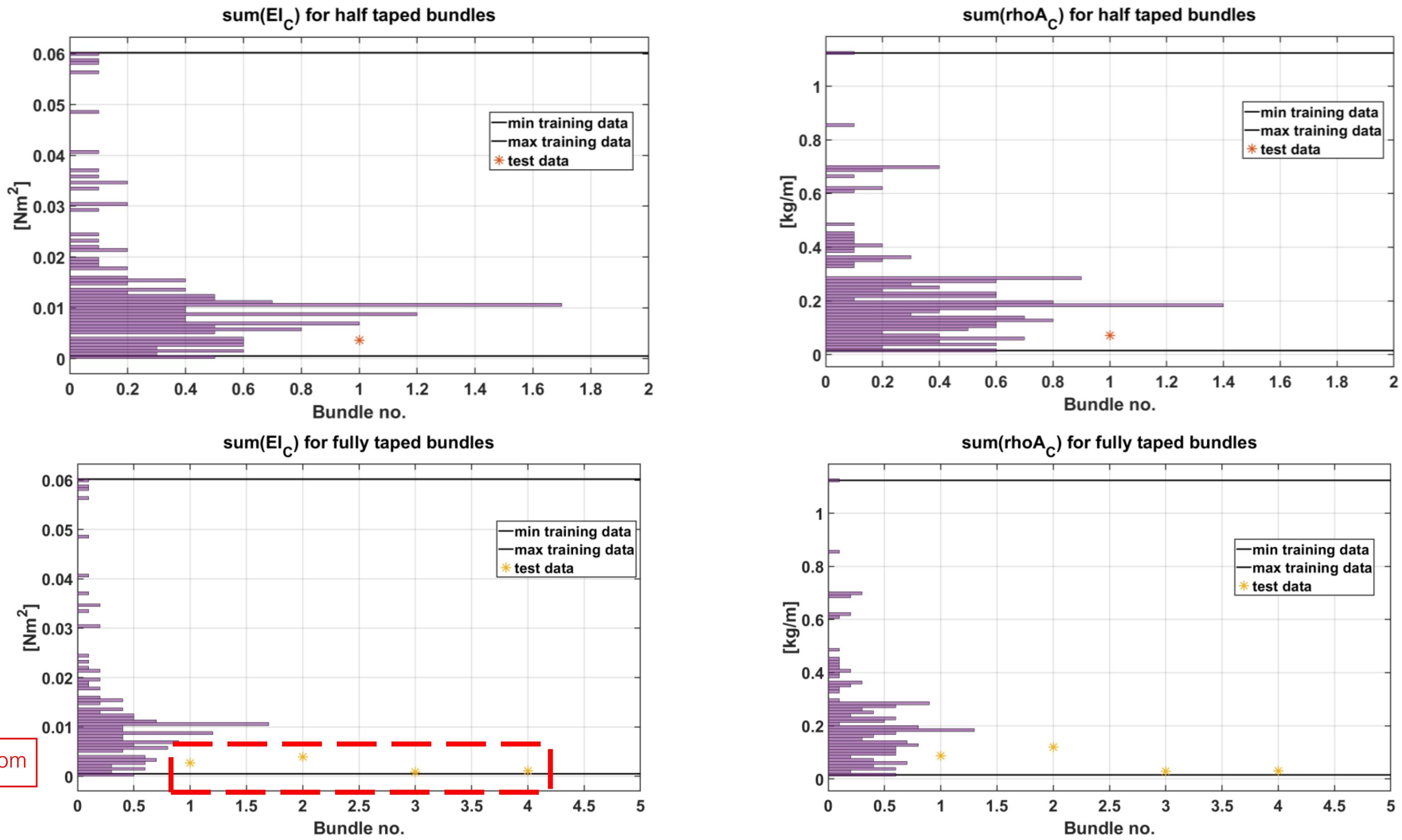
Input Features for Effective Bending Stiffness Estimation of Test Bundles

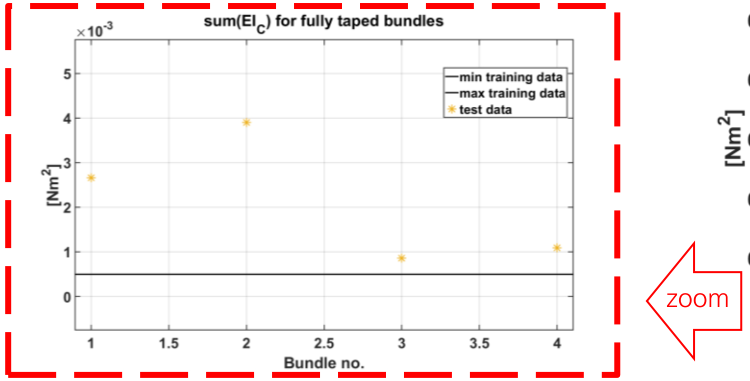


Comparison between Training and Test Data

Input Features for Effective Bending Stiffness Estimation of Test Bundles

- All input features required for effective bending stiffness estimation lie within training data boundaries
- Test bundles are more flexible and consist of thinner base cables than most of the training bundles





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Estimation Results

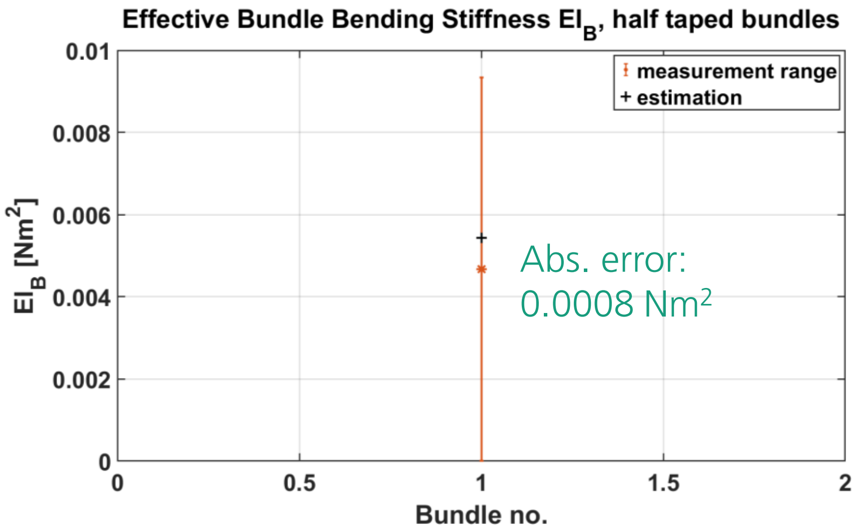
for Effective Bending Stiffness Estimation

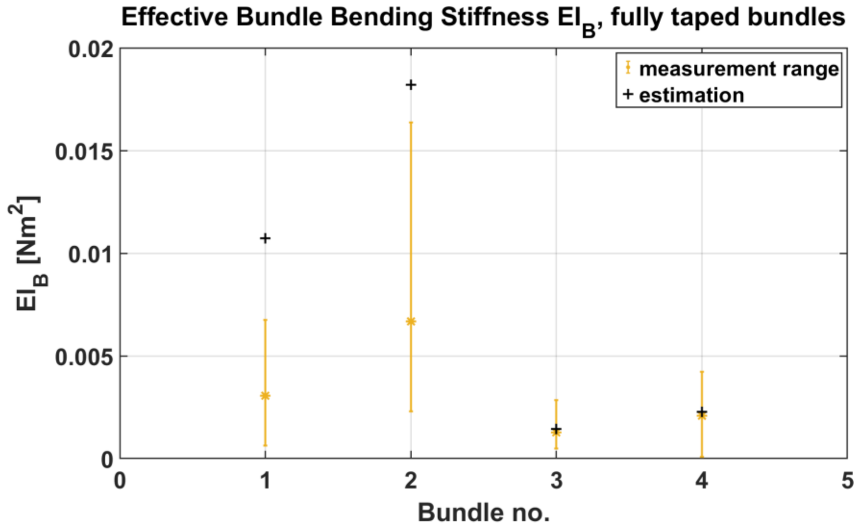
- Comparison of estimated bundle bending stiffness and measured effective bending stiffness
- Additionally, measurement range of test bundles is illustrated, which is quite large

→ Very good result for the half taped bundle

→ Estimated bundle bending stiffness too high for the first two test bundles (but looking at the measurement range, this result isn‘t as bad as it seems…)

→ Very good estimation results for fully taped bundles no. 3 and 4





Abs. error: 0.0077 / 0.0115 / 0.0002 / 0.0002 Nm^2

Estimation Results

for Effective Bending Stiffness Estimation

Bundle no.	Composition	taping	Rel. prediction error for EI_B
1	4 base cables, 2 of them are twisted pairs	half	0.1651
1	7 base cables, 3 of them are twisted pairs	fully	2.5171
2	12 base cables, 4 of them are twisted pairs		1.7235
3	5 base cables, 1 of them are twisted pairs		0.1462
4	7 base cables, no twisted pairs		0.0923

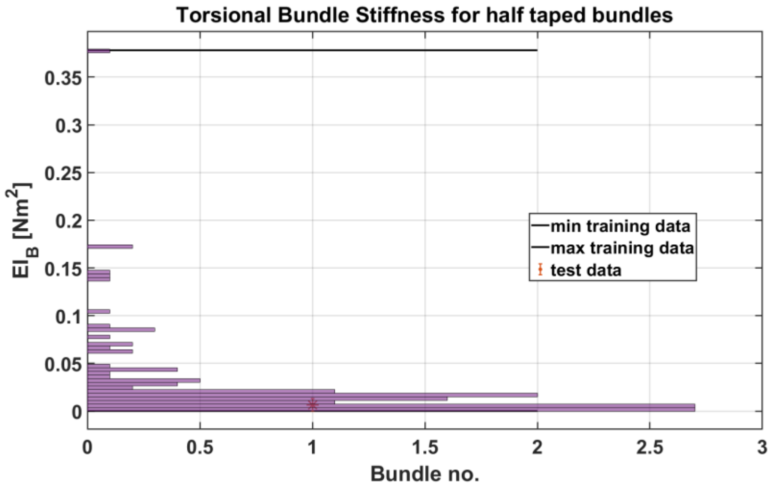
- Most of the effective bundle bending stiffness estimations (3 of 5) lie within the desired 50%-error interval
- Worst estimation result observed for the bundles with the most twisted pairs (bdl. 1 & 2, fully)
- Best estimation result for the bundle without any twisted pair (bdl. 4, fully)

→ The estimation of effective bundle bending stiffnesses works well for bundles, which do not differ widely in their composition and feature values

→ Twisted pairs vary strongly from the ones used for GP training → training data set should be extended

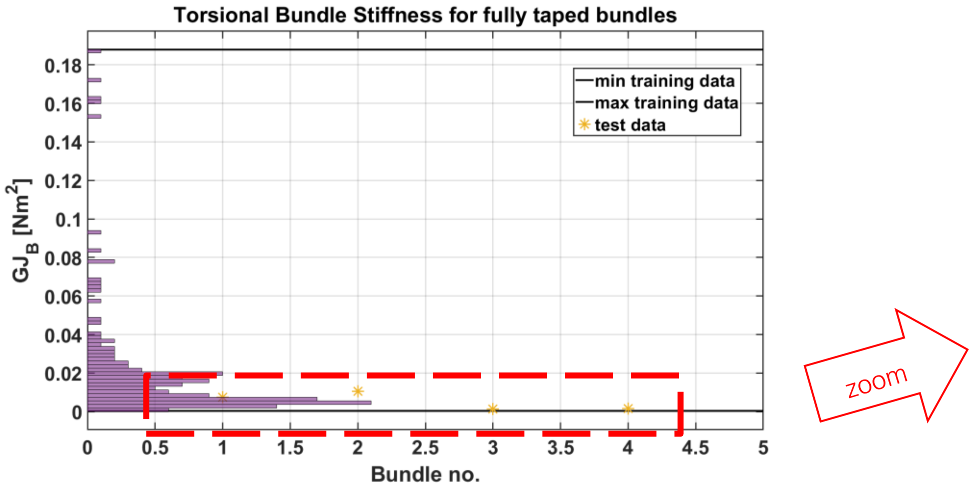
Comparison between Training and Test Data

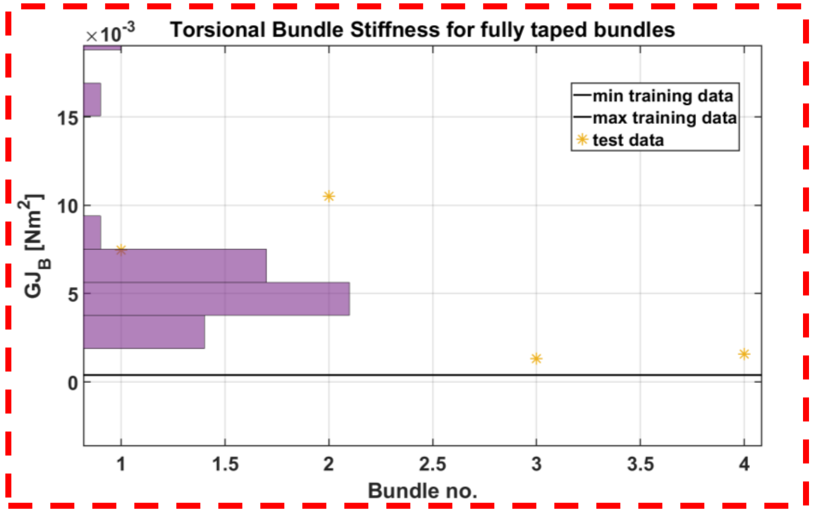
Effective Torsional Stiffness of Test Bundles



Effective bundle **torsional** stiffness is at the lower boundary of our training data set.

Two test bundles are very torsional elastic compared the training bundles.





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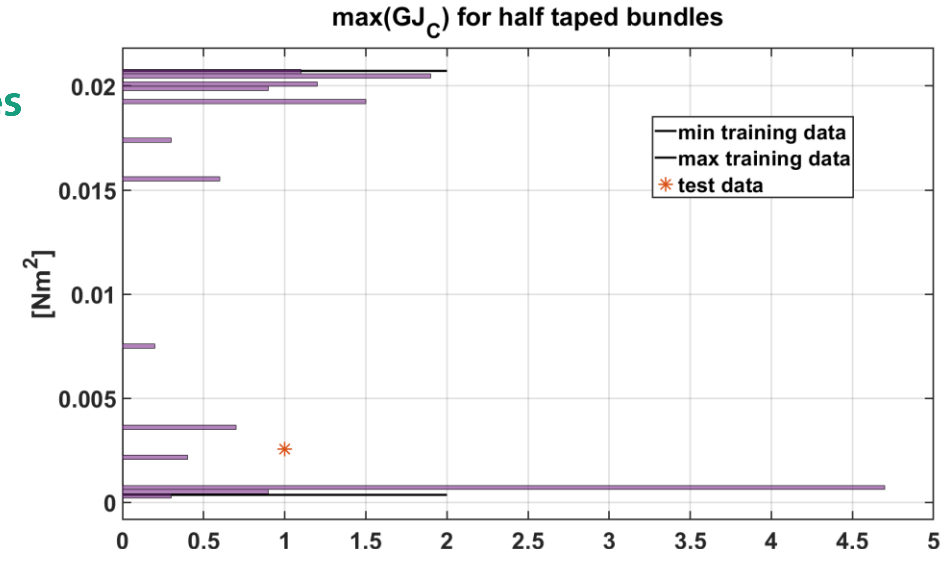
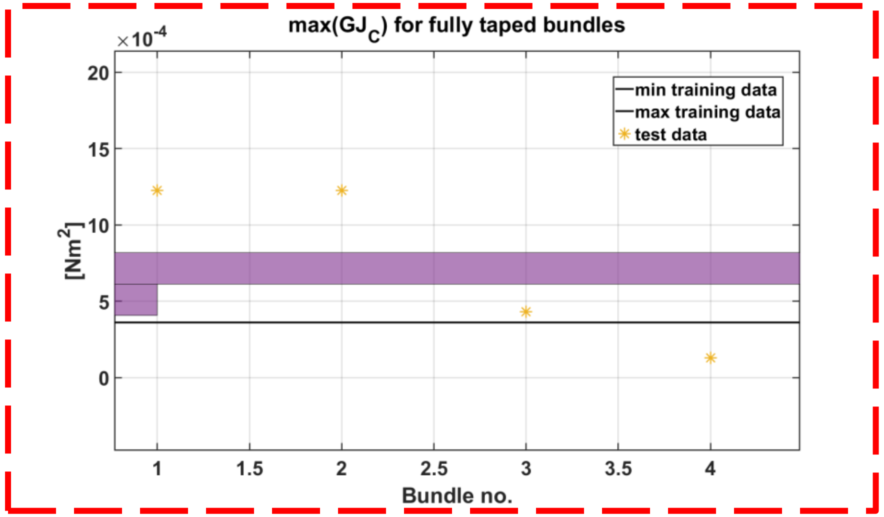
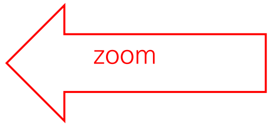
Comparison between Training and Test Data

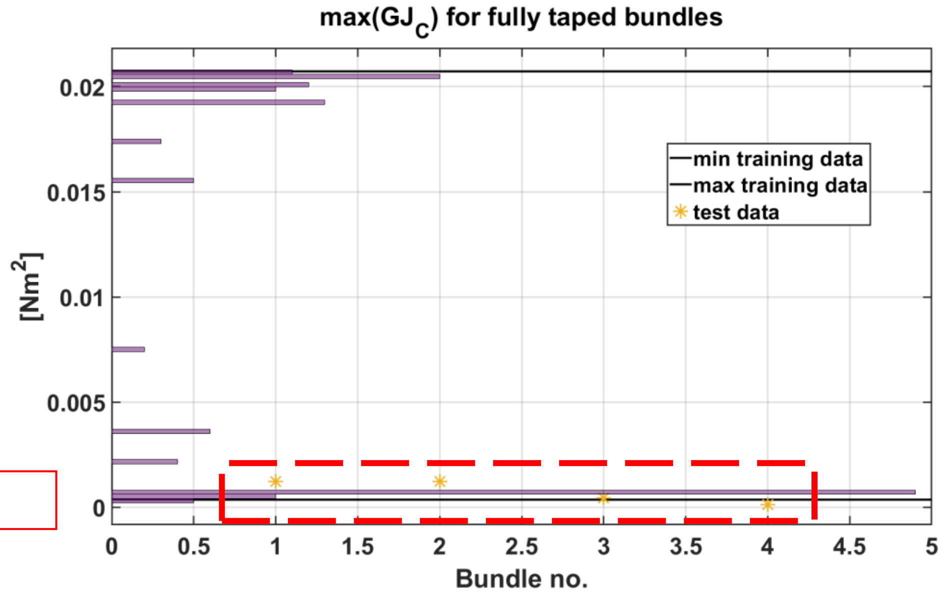
Input Features for Effective Torsional Stiffness Estimation of Test Bundles

- One important process feature – max. torsional stiffness of all base cables – is too low compared to the training data set









Estimation Results

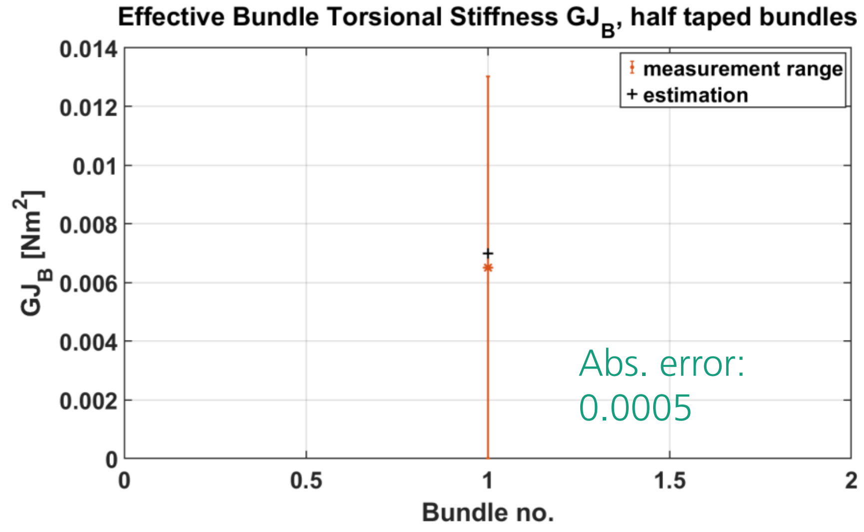
for Effective Torsional Stiffness Estimation

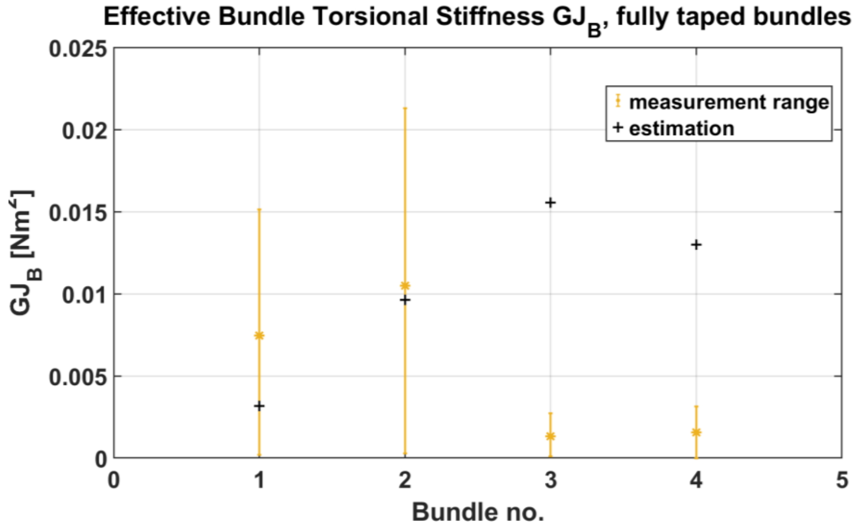
- Comparison of estimated bundle torsional stiffness and measured effective bending stiffness
- Additionally, measurement range of test bundles is illustrated

→ Very good result for the half taped bundle

→ Very good result for the first two fully taped test bundles

→ Estimated effective bundle bending stiffness too high for bundle no. 3 and 4 (fully taped)





Abs. error: -0.0043 / -0.0009 / 0.0142 / 0.0114 Nm^2

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Estimation Results

for Effective Torsional Stiffness Estimation

Bundle no.	Composition	taping	Rel. prediction error for EI_B	Rel. prediction error for GJ_B
1	4 base cables, 2 of them are twisted pairs	half	0.1651	0.0741
1	7 base cables, 3 of them are twisted pairs	fully	2.5171	-0.5766
2	12 base cables, 4 of them are twisted pairs		1.7235	-0.0823
3	5 base cables, 1 of them are twisted pairs		0.1462	10.6790
4	7 base cables, no twisted pairs		0.0923	7.2419

- Base cables in bundle 3 and 4 are too torsional elastic compared to bundles from training data set → bad estimation results, as expected → training data set should be extended

Conclusion and Outlook

- Successful usage of well-sorted data downloaded from ontology
- A ML algorithm is developed, analyzed and trained for the estimation of effective bundle stiffnesses
- The ML algorithm is successful for bundles, which do not differ widely in their composition and feature values

Outlook

- Data set extension (bundles with twisted pairs, thin and more flexible base cables,…)
- Further customized measurement campaigns
- Model setup modifications, new features and additional ML training

Vielen Dank für Ihre Aufmerksamkeit!

Kontakt

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