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Structural Change Identification at a Wind Turbine Blade using Model Updating

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Motivation

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- Remote location
- Rotor blades: costly and time-consuming repair
- Ice accretion: - Risk of ice throw
  - Undesired loads

➡ Localization and quantification of structural changes using model updating

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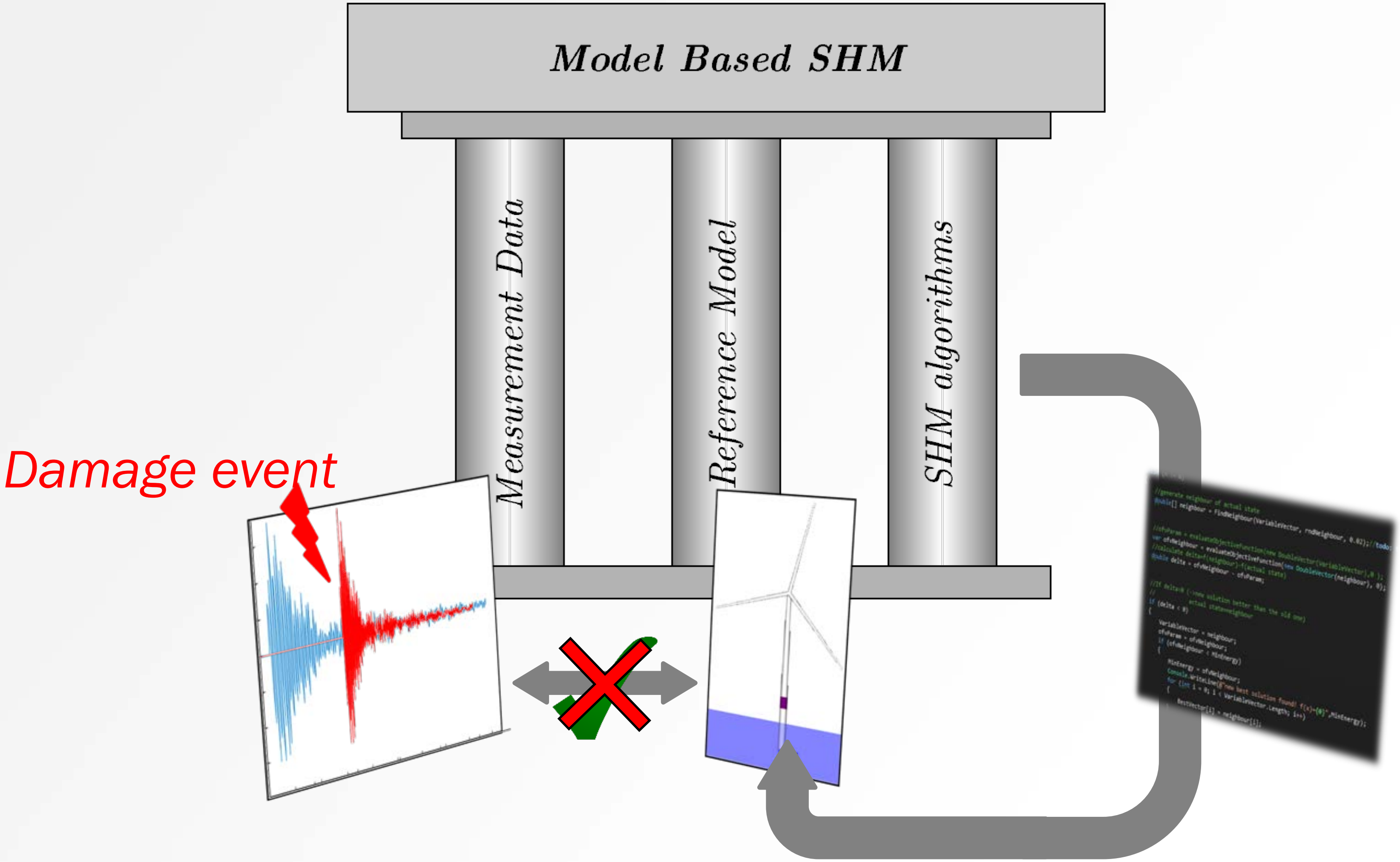
Finite Element Model Updating



Deviation between numerical model and measured data

⇒ Quantification of the „difference“ between model and measurement

Modal parameters

- Eigenvalues
- Mode shapes

$$\varrho(\boldsymbol{\theta}) = \|\frac{\omega_m - \omega_s(\boldsymbol{\theta})}{\omega_m}\|_2 + \sum_{i \in \mathcal{Y}} ||\phi_m^i - \phi_s^i(\boldsymbol{\theta})||_2$$

Transmissibility functions

$$\varrho(\boldsymbol{\theta}) = \sum_{i=1}^{n} \frac{\|\boldsymbol{TF}_{xy,i}^m - \boldsymbol{TF}_{xy,i}^s(\boldsymbol{\theta})\|_2}{\|\boldsymbol{TF}_{xy,i}^m\|_2}$$

Minimization of the deviation

$$\min_{\theta} \; \varrho(\theta)$$
$$\text{subject to } c_i(\theta) \geq 0 \; \forall \, i \in \mathcal{I}$$

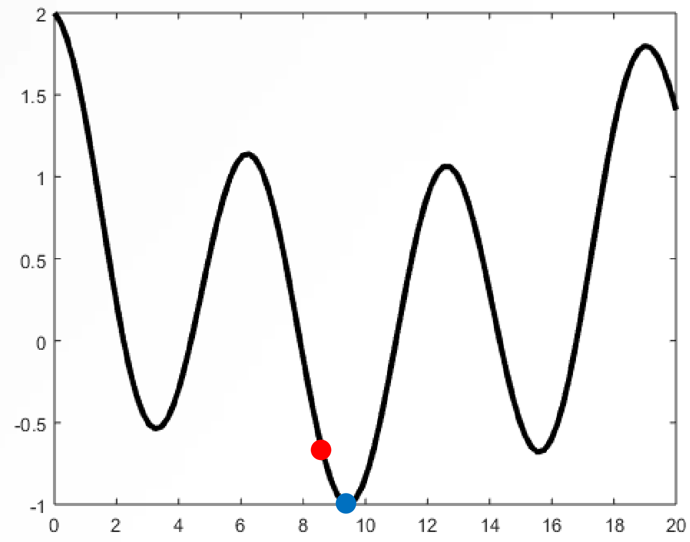
- Nonlinear
- Constrained
- Nonconvex
- Several local minima

Global optimization algorithm:

➡ Simulated Quenching

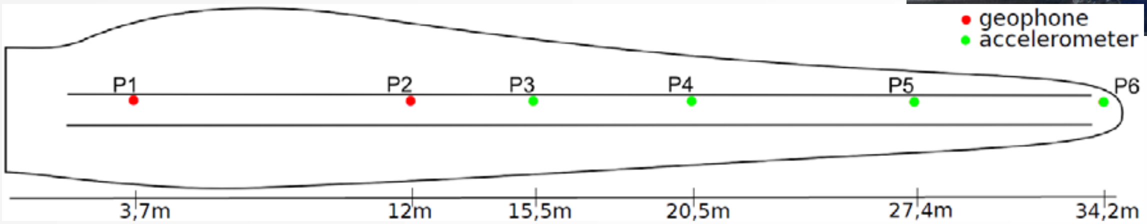
Local optimization algorithm:

➡ Sequential Quadratic Programming

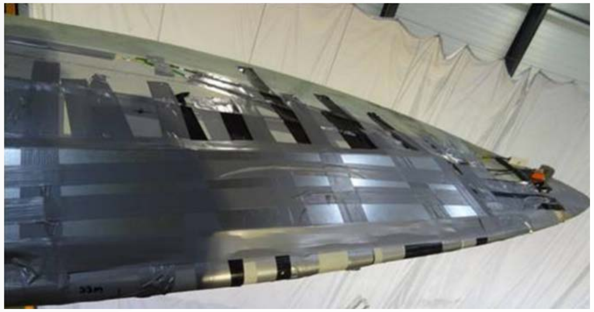


Rotor blade test

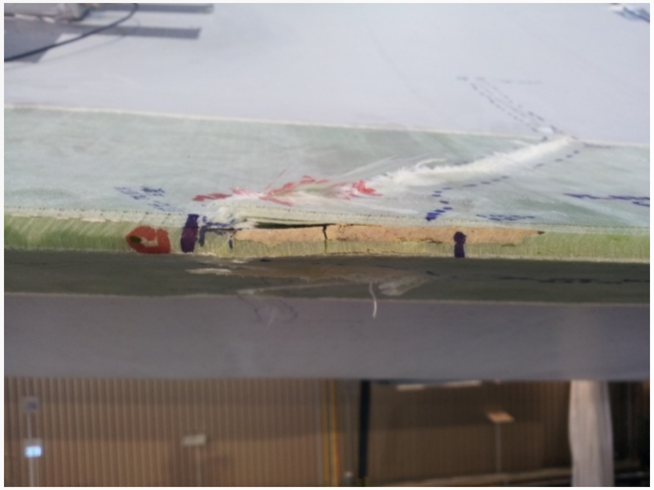
- Hammer excitation
- 12 measurement channels



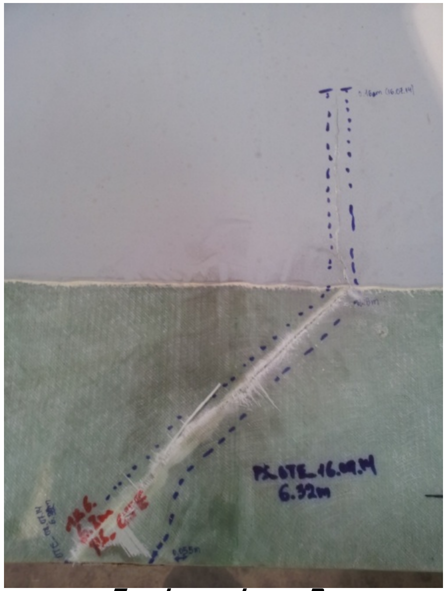
Rotor blade test



- Hammer excitation
- 12 measurement channels
- Ice mass
- Damage



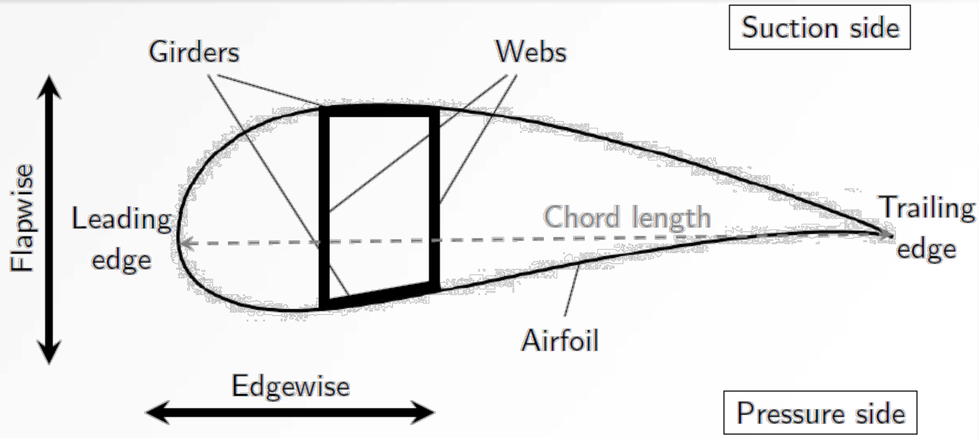
Trailing edge bondline:
Spot of damage initiation



Trailing edge – Pressure Side (outside)

Numerical Modeling

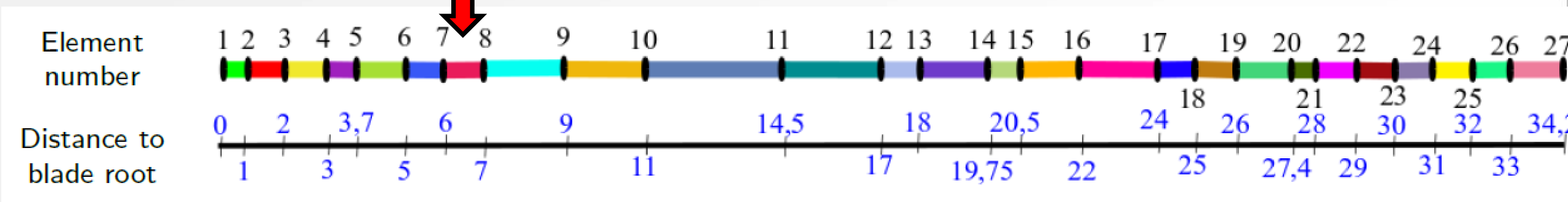
- Rectangular Cross Section
- Known: EI and mass
- 26 Timoshenko beam elements
- Clamping at blade root
- Material damping



	ω_m in Hz	ω_s in Hz	$\pm$ in %	Dir.	MAC
1.	1.069	1.048	2.0	flap	0.99957
2.	1.679	1.726	2.7	edge	0.99747
3.	3.113	3.128	0.5	flap	0.99731
4.	5.643	5.390	4.5	edge	0.99727
5.	6.644	6.811	2.5	flap	0.99847
6.	11.536	11.999	3.9	flap	0.99712
7.	13.140	12.383	5.8	edge	0.99118
$\mathcal{M}$			4.58		0.99682

Numerical validation

Stiffness reduction



$$\min_{\boldsymbol{\theta}} \varrho(\boldsymbol{\theta})$$

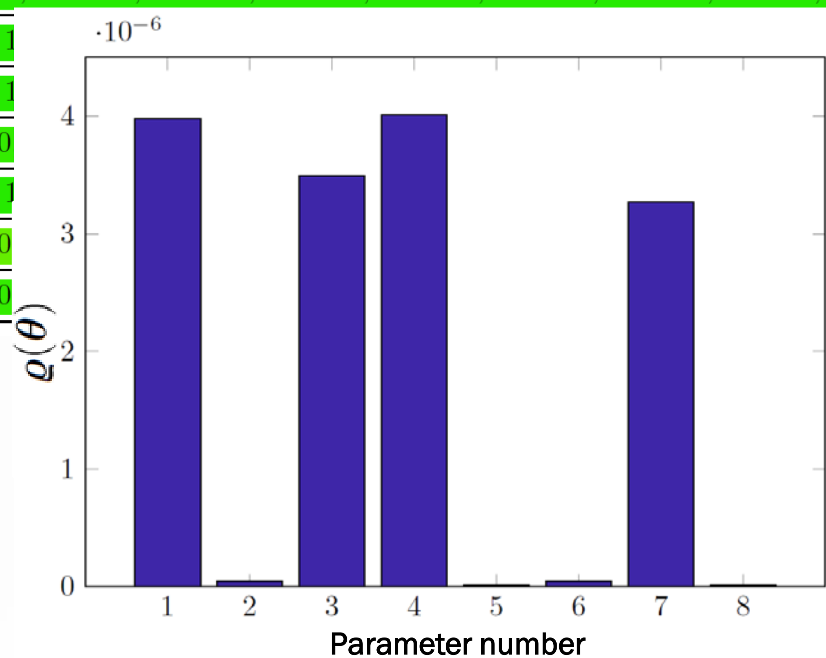
$$\text{subject to} \quad \theta_i \geqslant 0,5 \; \forall \; i \in \boldsymbol{\theta}$$

$$\theta_i \leqslant 1,01 \; \forall \; i \in \boldsymbol{\theta}$$

$$\sum_i (1 - \boldsymbol{\theta}_i) \leqslant 0,5$$

Numerical validation – Modal Parameters

	$\varrho(\theta)$	Parameter number 1	2	3	4	5	6	7	8	9	10	11	12	13
1	$3,975 \cdot 10^{-06}$	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,000	0,999	1,000	1,00	1,00	1,00
2	$5,032 \cdot 10^{-08}$	1,00	1,00	0,992	0,985	1,001	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
3	$3,494 \cdot 10^{-06}$	1,00	1,00	1,00	1,00	1,00	1							[illegible]
4	$4,007 \cdot 10^{-06}$	1,00	1,00	1,00	1,00	1,00	1							[illegible]
5	$1,510 \cdot 10^{-08}$	1,00	1,00	1,00	0,978	1,001	0							[illegible]
6	$5,032 \cdot 10^{-08}$	1,00	1,00	0,992	0,985	1,001	1							[illegible]
7	$3,272 \cdot 10^{-06}$	1,00	1,00	1,00	1,00	1,00	0							[illegible]
8	$1,496 \cdot 10^{-08}$	1,00	1,00	1,00	0,978	1,001	0							[illegible]



Numerical validation – Transmissibility Functions

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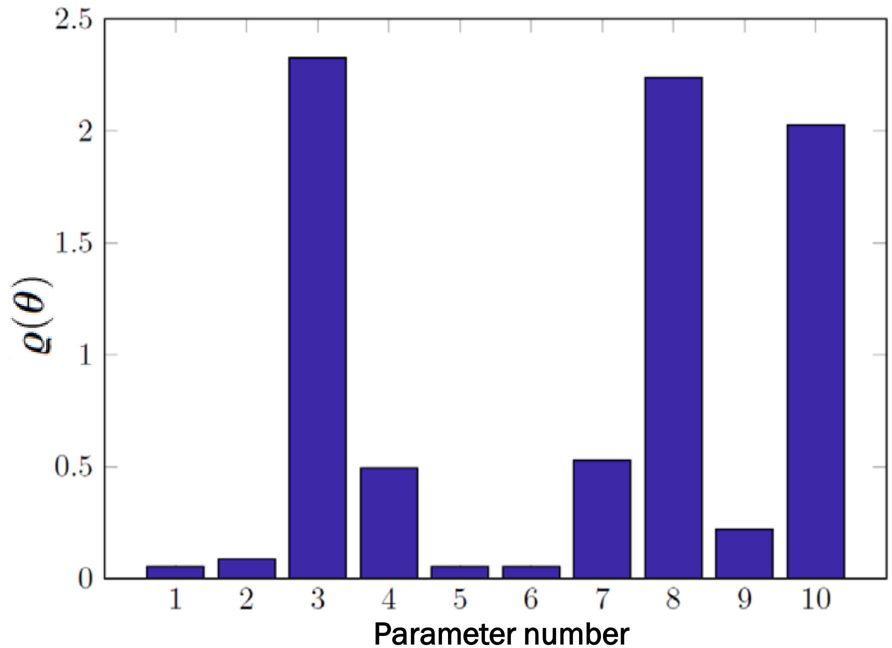
	$\varrho(\theta)$	Parameter number 1	2	3	4	5	6	7	8	9	10	11	12	13
1	0,0537	1,00	1,00	0,996	0,982	1,001	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
2	0,0869	1,00	1,004	0,994	0,982	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
3	2,3264	1,00	1,00	1,00	1,00	1,010	1,010	0,952	1,00	1,00	1,00	1,00	1,00	1,00
4	0,4932	1,010	0,983	1,00	1,00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	0,0540	1,00	1,00	0,996	0,982	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	0,0538	1,00	1,00	0,996	0,982	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	0,5321	1,00	1,00	1,00	1,00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	2,2413	1,00	1,00	1,00	1,00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	0,2233	1,00	1,010	0,987	0,978	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	2,0297	1,00	1,00	1,00	1,00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



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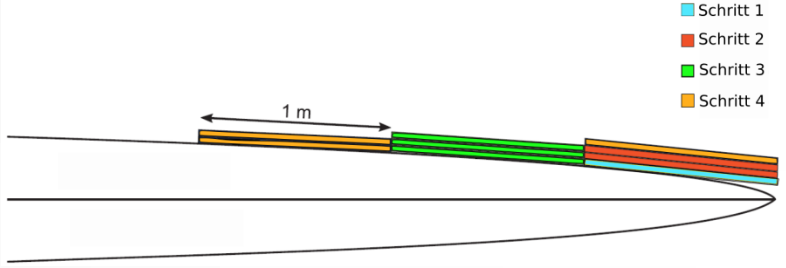
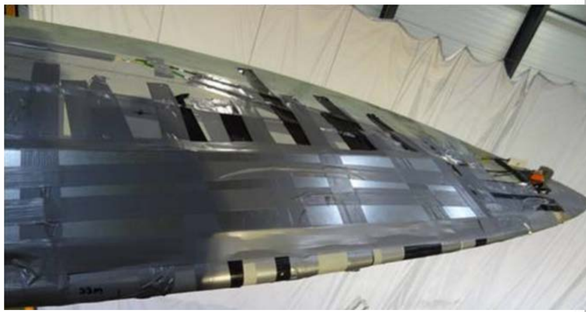
Ice accretion



- 4 steps
- Variation of density
- Optimization problem: $\min_{\boldsymbol{\theta}} \varrho(\boldsymbol{\theta})$

$$\text{mit } \theta_i \geqslant 0,99 \; \forall \, i \in \boldsymbol{\theta}$$
$$\theta_i \leqslant 1,75 \; \forall \, i \in \boldsymbol{\theta}$$



- Step 3: 14,4kg at 32m-33m and 33m-34m

Ice localization – Modal Parameters

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	$\varrho(\theta)$	Parameter number 1	2	3	4	5	6	7	8	9	10	11	12	13
1	0,0165	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,093	1,224
2	0,0199	1,00	1,00	1,00	1,00	1,00	1,00	1,029	1,077	1,046	1,00	1,00	1,00	1,00
3	0,0167	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,990	1,190	1,197
4	0,0199	1,00	1,00	1,00	1,00	1,00	1,00	1,040	1,170	1,111	1,00	1,00	1,00	1,00
5	0,0197	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,062	1,103	1,024	1,00	1,00
6	0,0196	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,020	1,113	1,051	1,00	1,00
7	0,0166	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,126	1,200
8	0,0199	1,057	1,147	1,023	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
9	0,0168	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,004	1,231	1,158
10	0,0200	1,082	1,023	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
11	0,0165	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,093	1,224

- Correct Localizations in runs 1, 3, 7, 9 und 11
- Verification using objective function value
- Ice localization using modal parameters is possible

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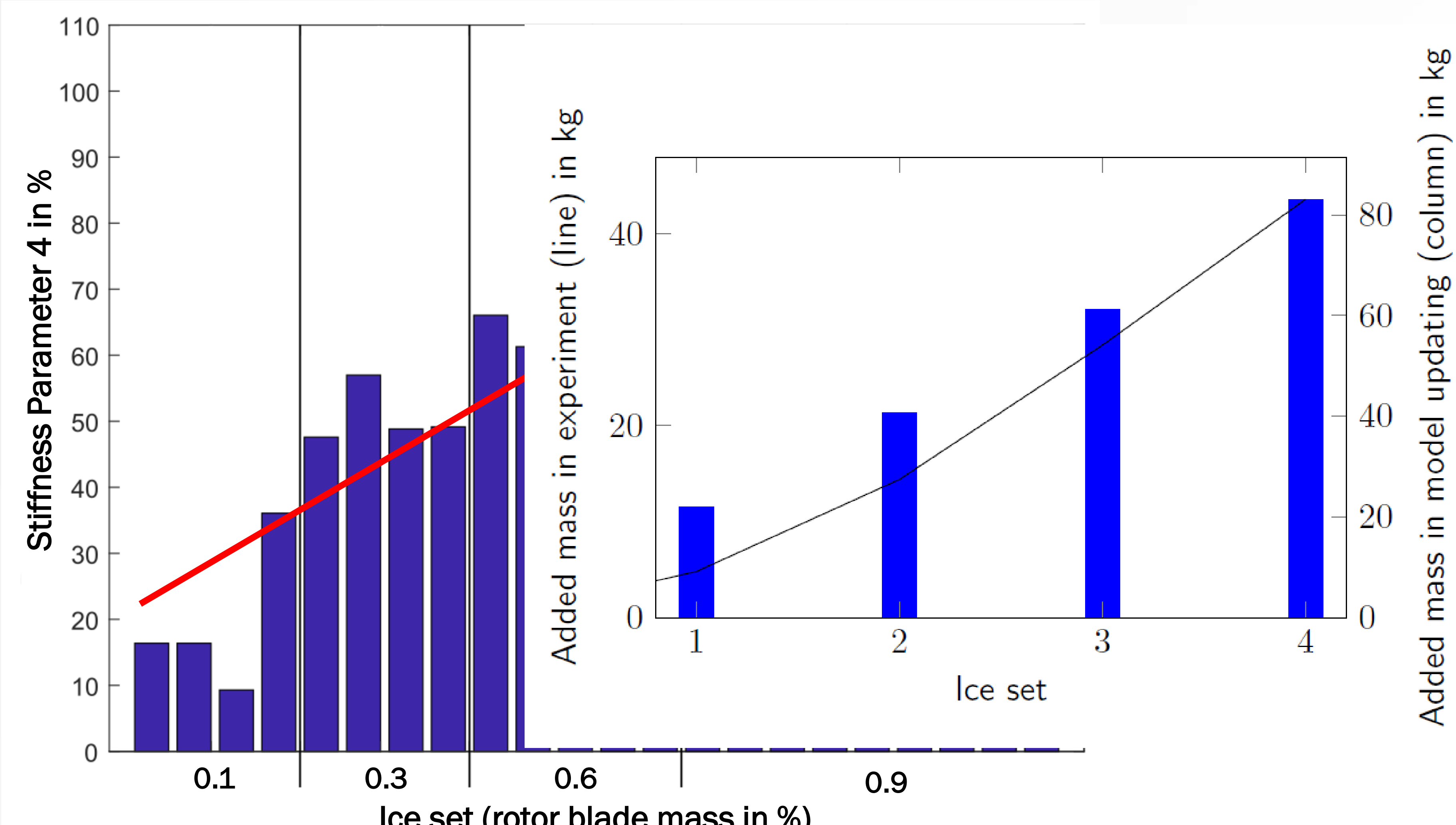
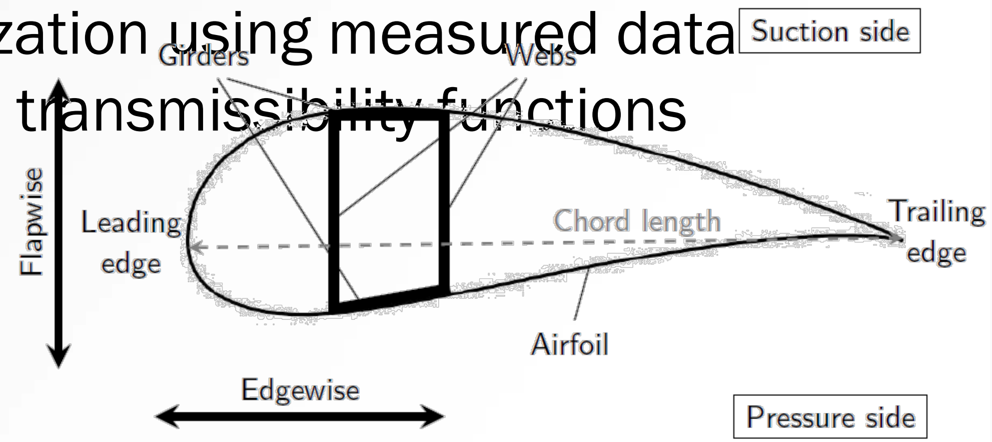
Ice quantification – Modal Parameters



Conclusion

- Updating in numerical examples
  and for ice quantification successful
- Minimization using global two-step optimization algorithm
- No success for damage localization using measured data
- Modal parameters superior to transmissibility functions



Outlook

- Investigate more advanced metrics for model updating
- Application to changing conditions (in situ)

Thank you for your attention!

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