Advancing wind turbine blade end of life assessments with Bayesian model updating

Case study on decommissioned blade

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Motivation

Current practice

- Typical lifespan of turbine blade: 20-25 years
- Around 14,000 blades are decommissioned annually (~50,000 tons)
- Conservative approach to avoid catastrophic failure

The opportunity

- Blade life extension through accurate health assessment
- Reduce waste, operational costs and environmental impact

How to assess the health of aging turbine blades to support life extension?

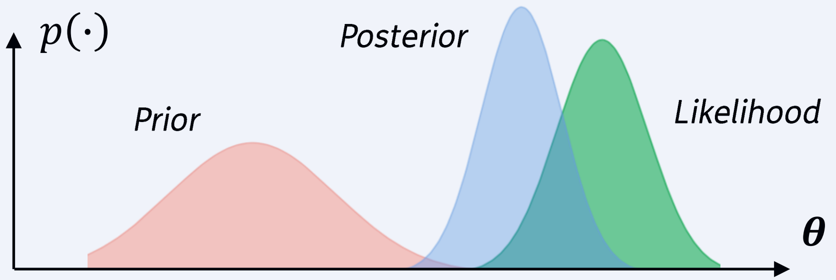
- Bayesian system identification

Bayesian system identification

- Bayesian system identification uses Bayes' theorem to update uncertain model parameters:

Posterior · *Likelihood* · *Prior* · *Evidence*

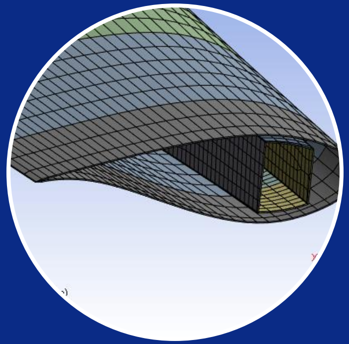
$$p(\boldsymbol{\theta}|\boldsymbol{y}) = \frac{p(\boldsymbol{y}|\boldsymbol{\theta}) \cdot p(\boldsymbol{\theta})}{\int p(\boldsymbol{y}|\boldsymbol{\theta}) \cdot p(\boldsymbol{\theta})\, d\boldsymbol{\theta}}$$



- Performing Bayesian system identification is hard:
  - Complex statistical methods
  - High computational costs
  - Programming skills

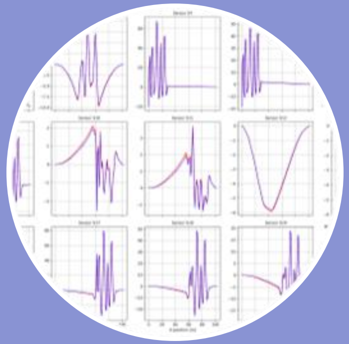
- Then… why doing it?
  - ✓ Theoretically consistent method to integrate measurement data with structural models
  - ✓ Estimates the uncertainties of predictions rather than just giving a 'best guess'
  - ✓ Incorporates knowledge of the structure via the priors

Workflow

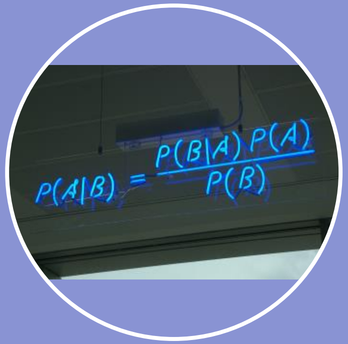


1. Build parametric finite element model

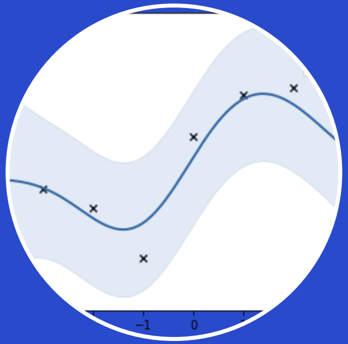
2. Conduct field testing campaign



3. Process measurement data



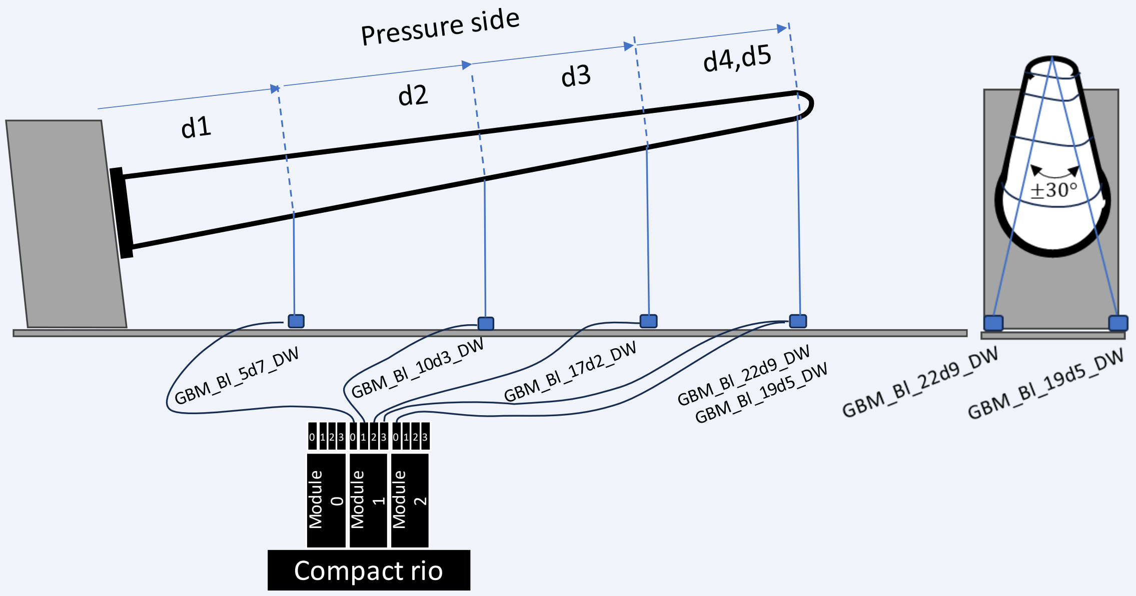
4. Perform Bayesian identification



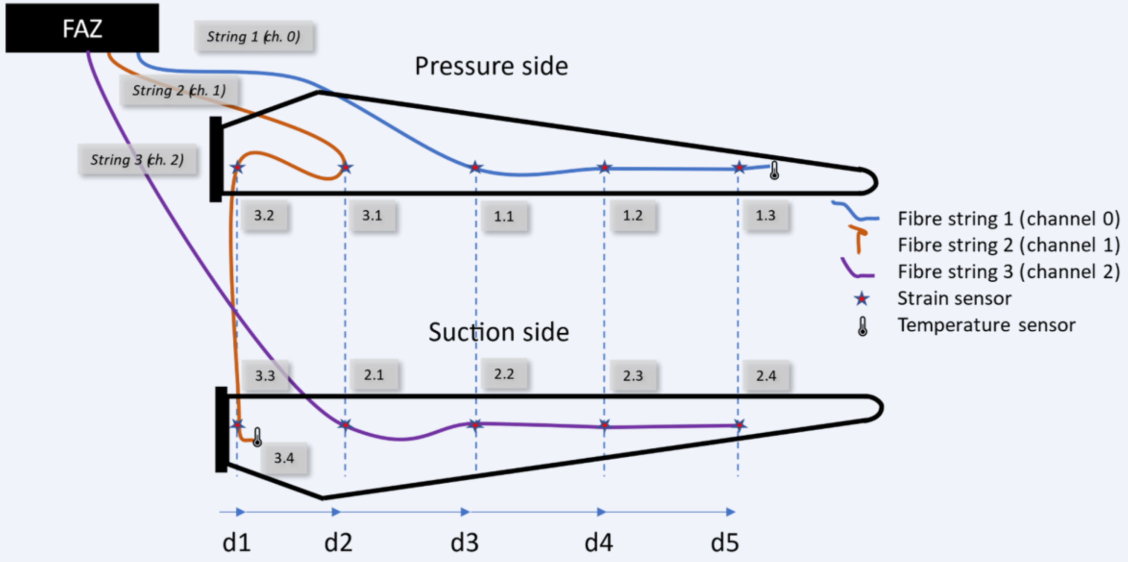
5. Make predictions with updated model

Experimental campaign: Blade

Experimental campaign: Sensors



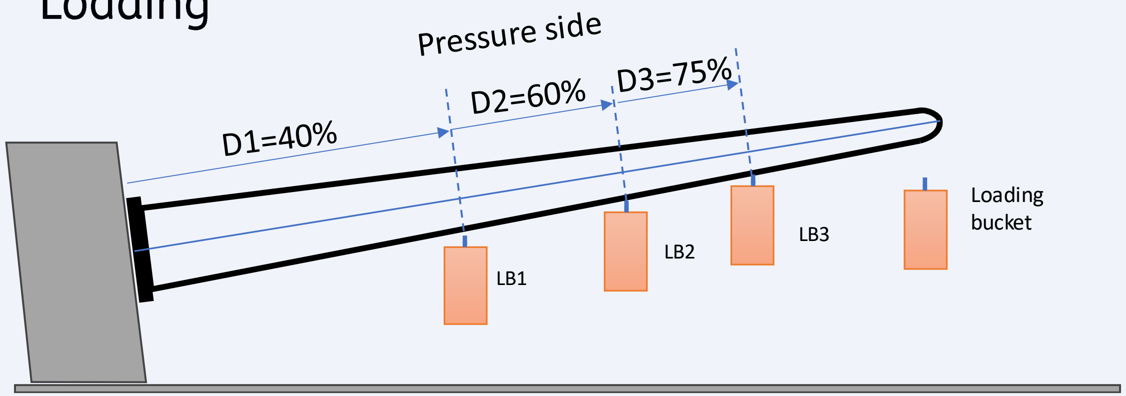
Draw wire locations (DW4 and DW5 at the tip)



Strain gauge locations

Experimental campaign: Load cases

- Loading



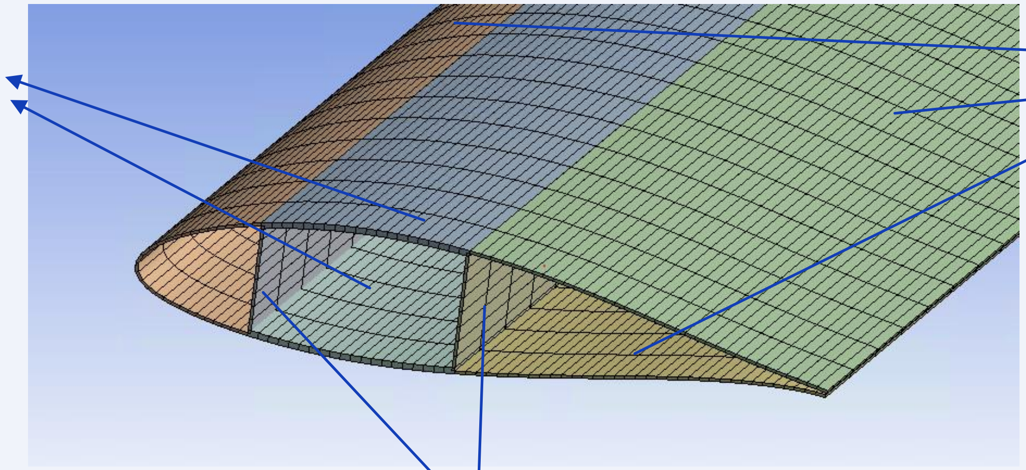
Finite element model (1/2)

- Shell thicknesses are taken from scan
- Assume 3 material groups: shell skin, spar cap, shear web
- Density is manually tuned to match total weight
- No contacts defined in model so fast calculation

Total parameters: 12

4 parameters from shell skin, spar cap, shear web (4x3=12)

spar cap



shell skin

shear web

Orthotropic Elasticity
Young's Modulus X direction
Young's Modulus Y direction
~~Young's Modulus Z direction~~
Poisson's Ratio XY
~~Poisson's Ratio YZ~~
~~Poisson's Ratio XZ~~
Shear Modulus XY
~~Shear Modulus YZ~~
~~Shear Modulus XZ~~

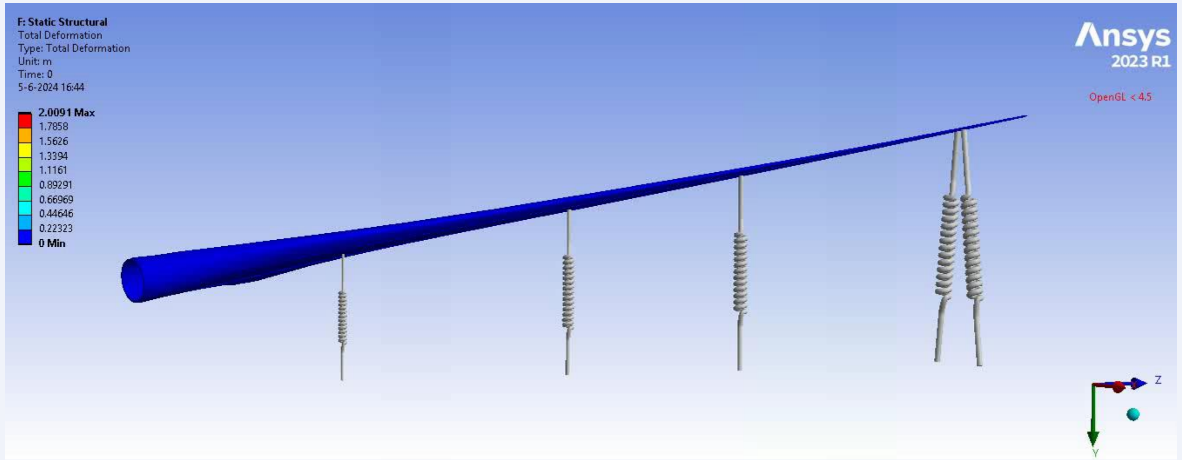
Finite element model (2/2)

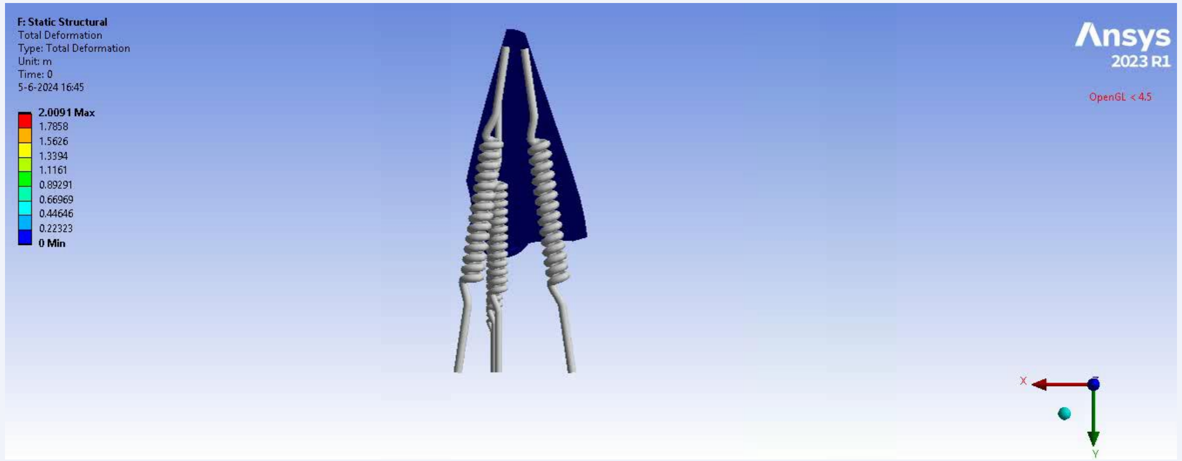
Modifications to match site condition

- Centre line (global coordinates)
- Sensor locations
- Loading locations
- Adding the mass from loading fixture frame
- Adding the mass from loading

Interface to BI

- .inp file is exported from Ansys Mechanical
- PyAnsys modify the parameters in .inp and solve it





Settings of Bayesian system identification

Bayesian inference method

- Variational Bayesian Monte Carlo
- Highly efficient on the number of queries (<200 calls to FE model)

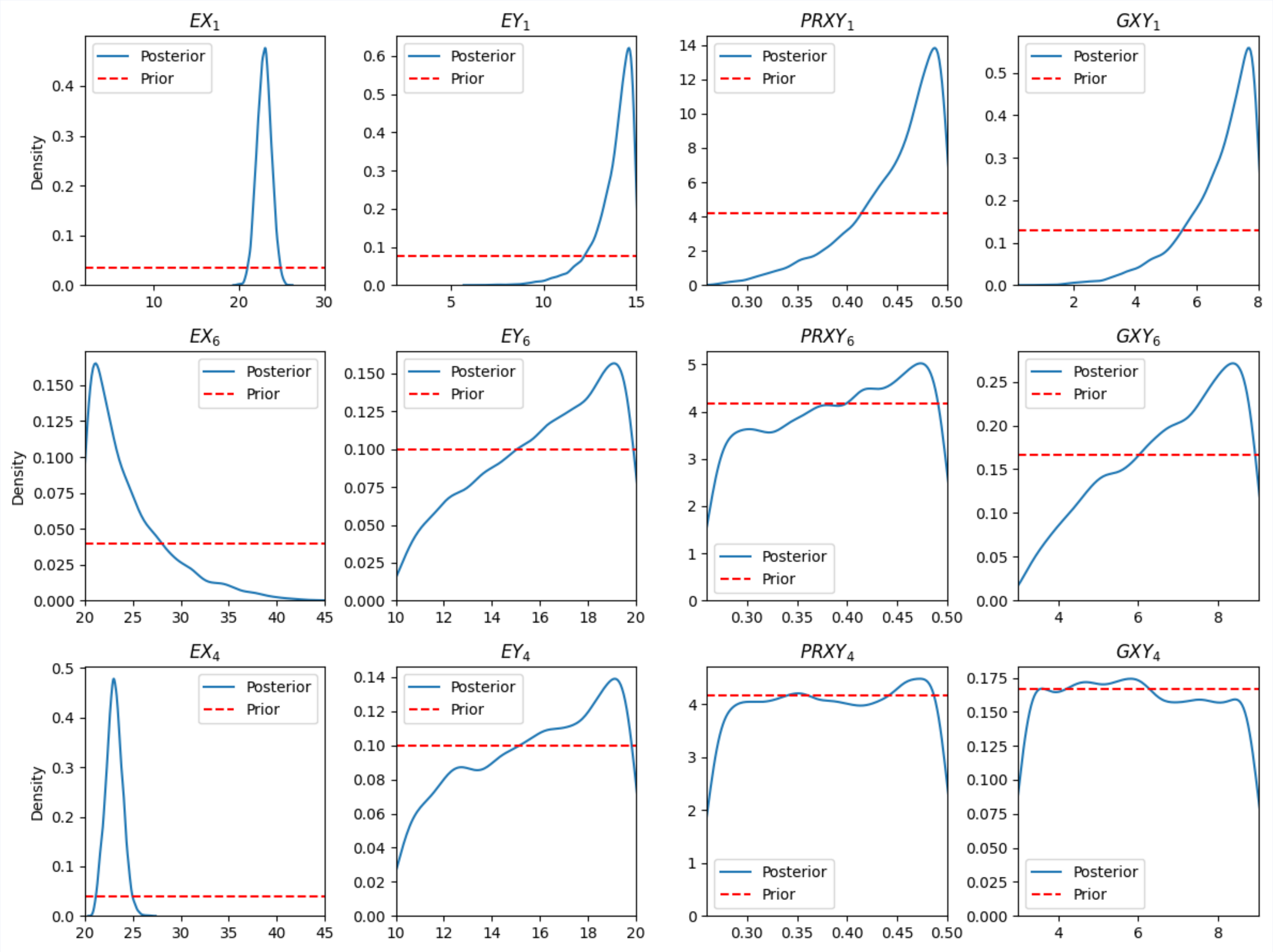
The prior

- Uniform priors for the 12 parameters
- Upper and lower bounds based on engineering judgement

Data generating process

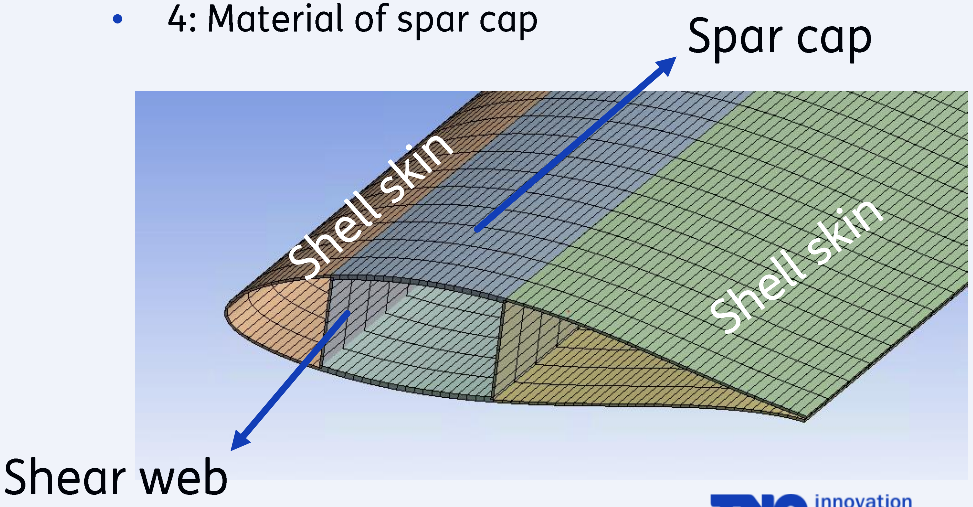
- $x_{meas} = x_{FE}(\theta_{true}) + \epsilon_{model} + \epsilon_{meas}$
- Measurement and model uncertainty as zero-mean Gaussian noise

Results: Posterior distribution vs Prior

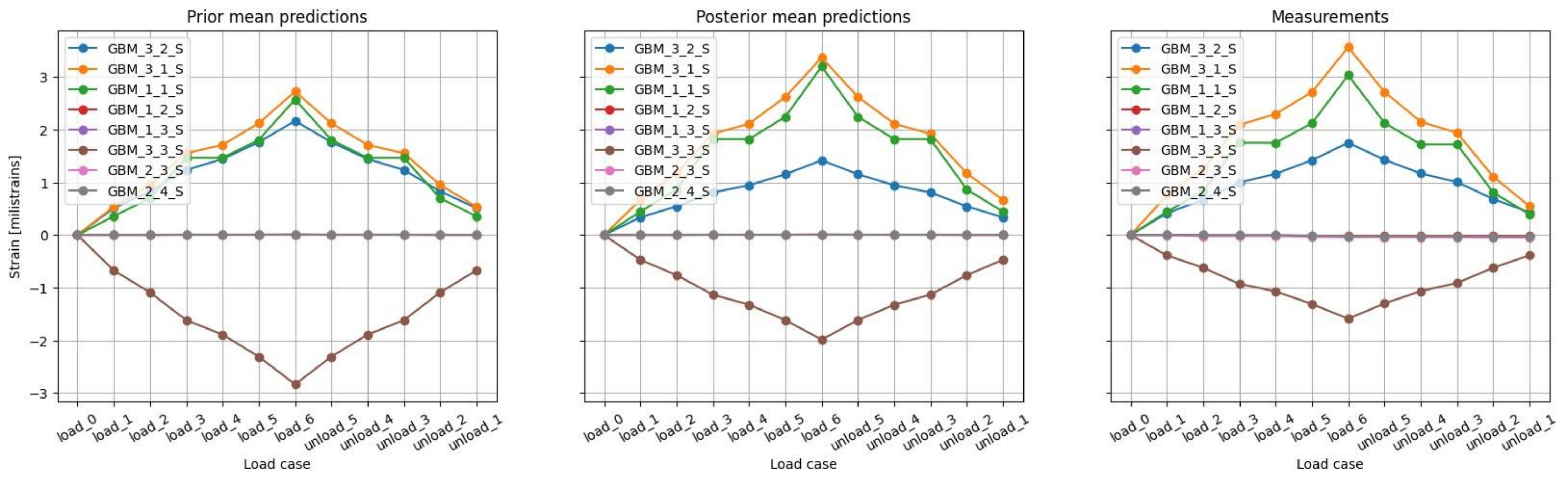


- EX, EY [GPa]: Young's modulus in X, Y directions
- GXY [GPa]: Shear modulus in XY plane
- PRXY: Poisson ratio in XY plane

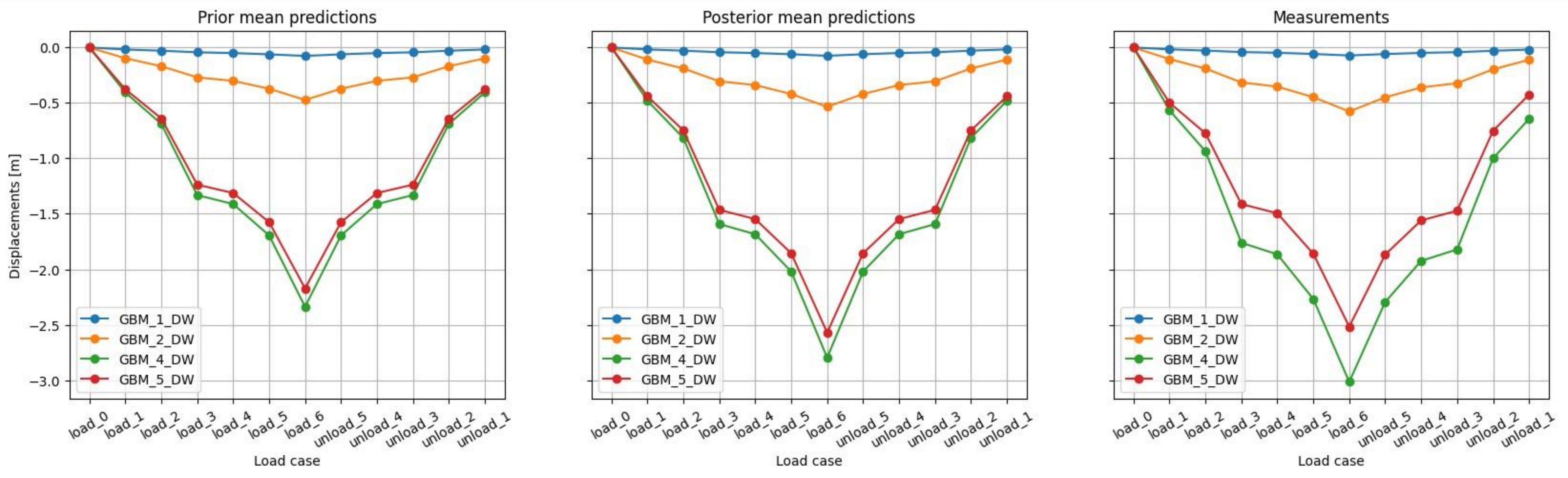
- 1: Material of shell skin
- 6: Material of shear web
- 4: Material of spar cap



Results: FE response w/ updated model (fit to data)



Results: FE response w/ updated model (prediction)



Conclusions

Results

- Developed and validated a Bayesian workflow for blade assessment
- Responses with updated FE model match experimental data, both for fitting and predictions

Short term goals

- Compare updated parameters with coupon tests
- Propagate the uncertainty in updated parameters to predictions (posterior predictive distribution)

Future directions

- Extend methodology to handle operational conditions and dynamic measurements
- Develop framework to translate parameter updates into remaining life predictions

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