A Hybrid Approach for Prediction of Long-Term Behavior in Concrete Structures

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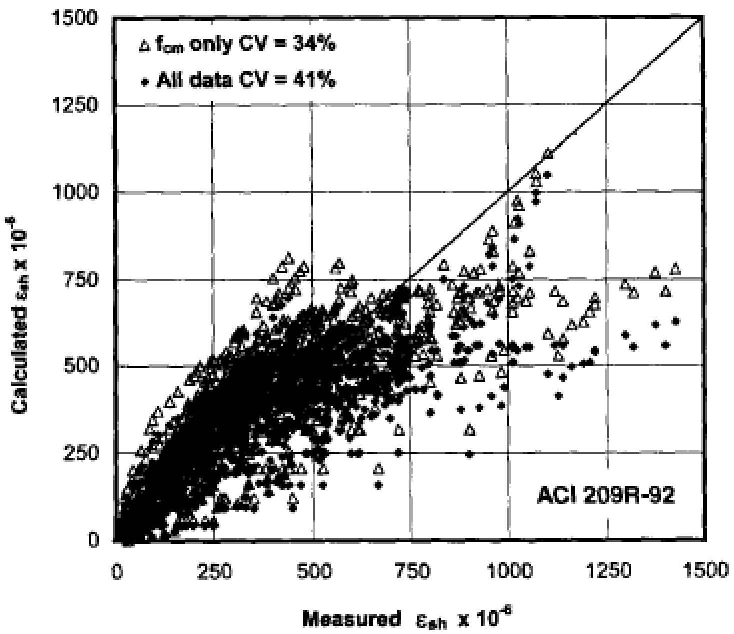
Research Aim

- Create innovative methods to predict the long-term behavior of concrete structures
  - Analytical and/or numerical modeling
  - Machine learning (ML)
  - Data Analytics
  - Structural health monitoring (SHM)

Motivation

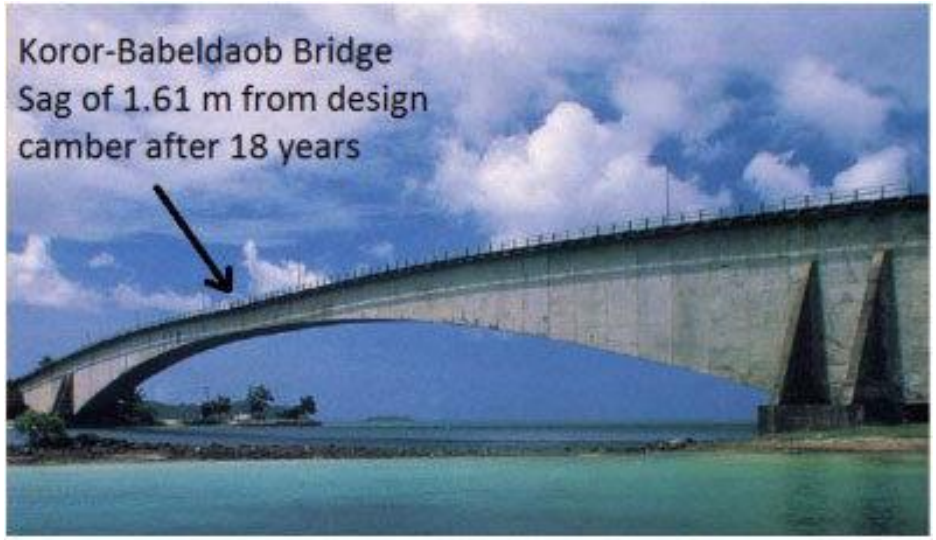
- Concrete structures are ubiquitous in our society
- Lifespans can range multiple decades and may need to be extended
- Long-term time-dependent behavior of concrete is complex to model
  - Creep and shrinkage are stochastic, depend on temperature, humidity, loading
  - Lack of long-term in-situ data



Gardner (2004)

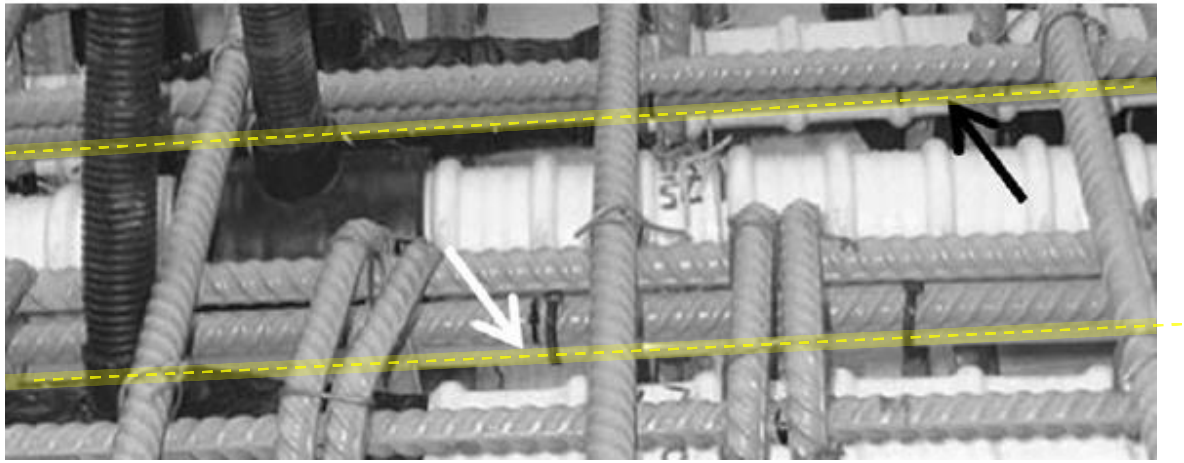
Motivation

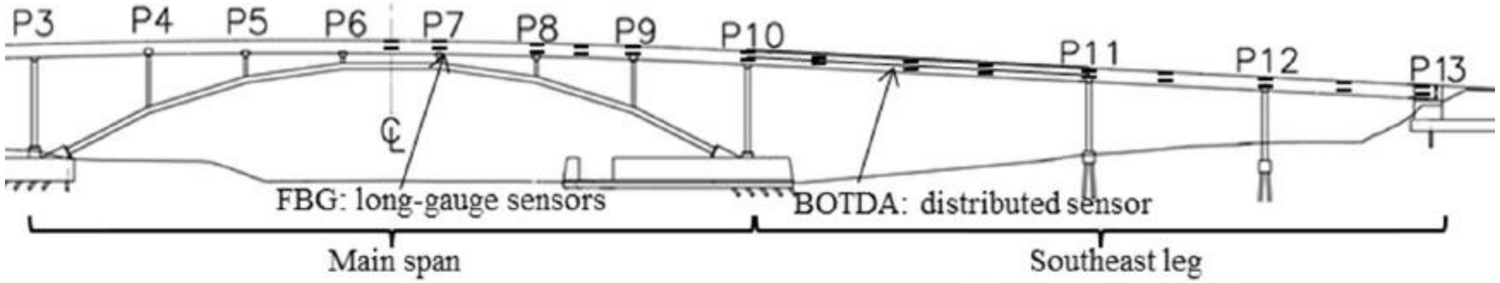
- Poor prediction can lead to limited serviceable life
- Accurate prediction enables the detection of unexpected behavior
  - Degradation processes, changes in boundary conditions, sensor malfunction, etc.



R. Wendner, Mija H. Hubler & Z.P. Bažant (2013)

1.1 Streicker Bridge





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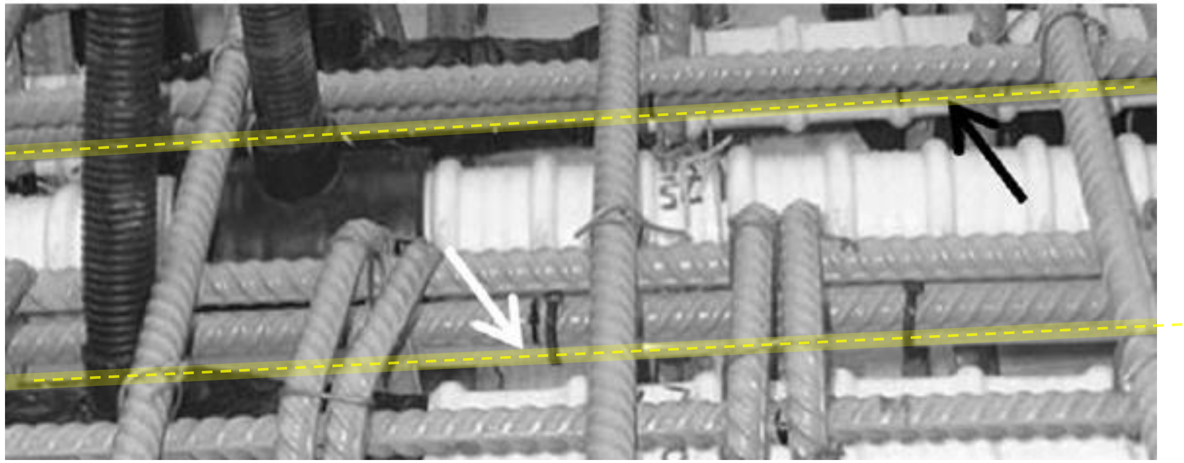
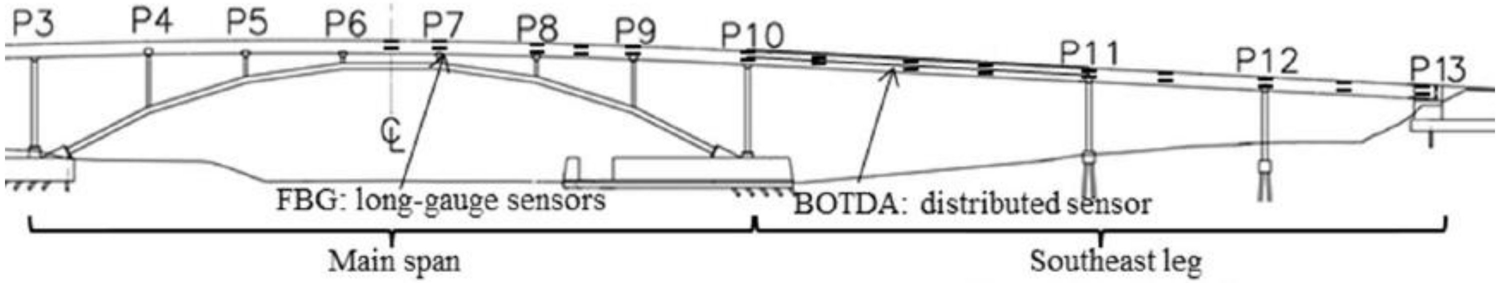
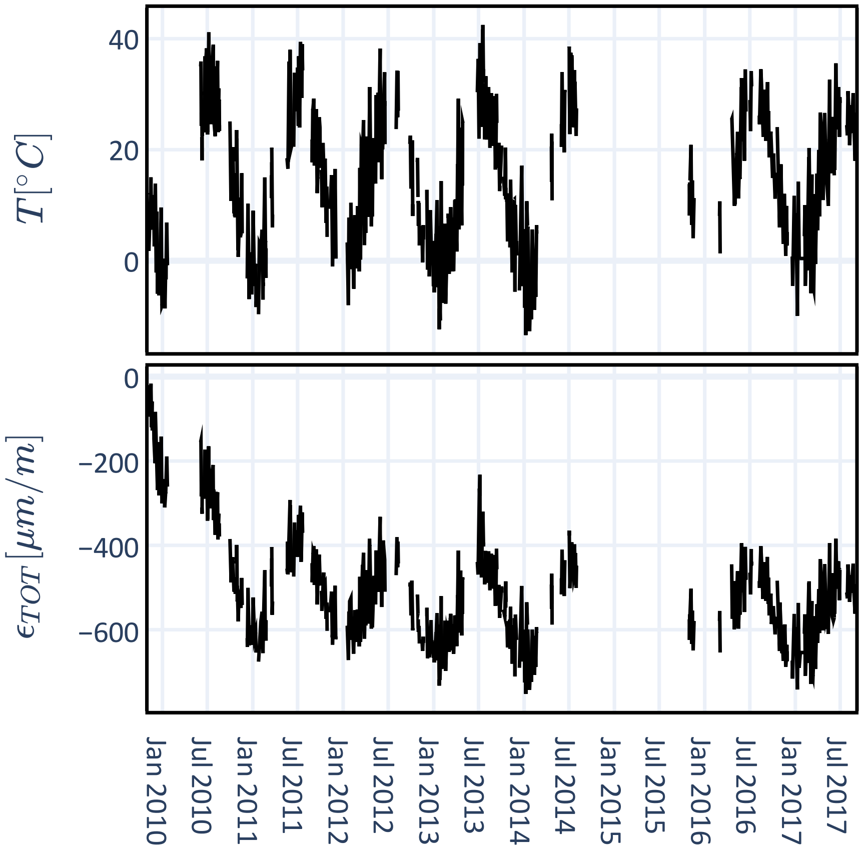






$$\varepsilon_{TOT}^{t} = \varepsilon_{T}^{t} + \varepsilon_{e}^{t} + \varepsilon_{R}^{t}$$

$$\varepsilon_{T}^{t} = \alpha \cdot \Delta T^{t}$$

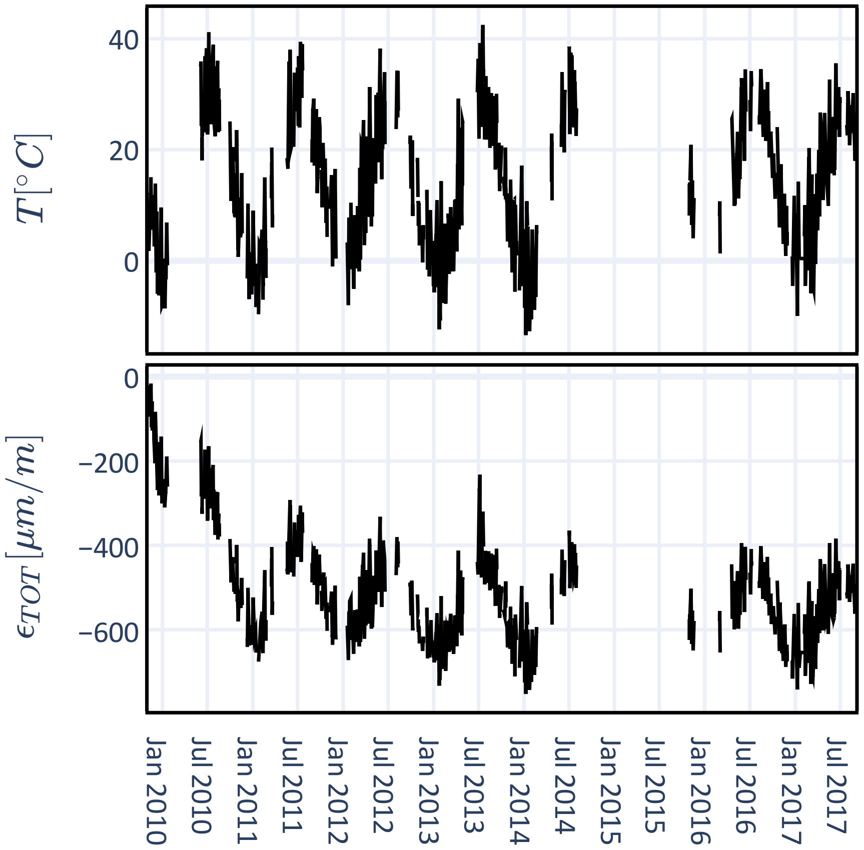
$$\varepsilon_{e}^{t} = \varepsilon_{e,P}^{t} + \varepsilon_{e,T}^{t}$$

$$\varepsilon_{e,T}^{t} = \varepsilon_{e,T}(\boldsymbol{\Delta T^{t,\tau}}) = \varepsilon_{e,T}^{t,\tau}$$

$$\varepsilon_{TD}^{t,\tau} = \alpha \cdot \Delta T^{t} + \varepsilon_{e,T}^{t,\tau}$$

$$\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \varepsilon_{e,P}^{t} + \varepsilon_{R}^{t}$$

1.2 Strain Measurement Modeling



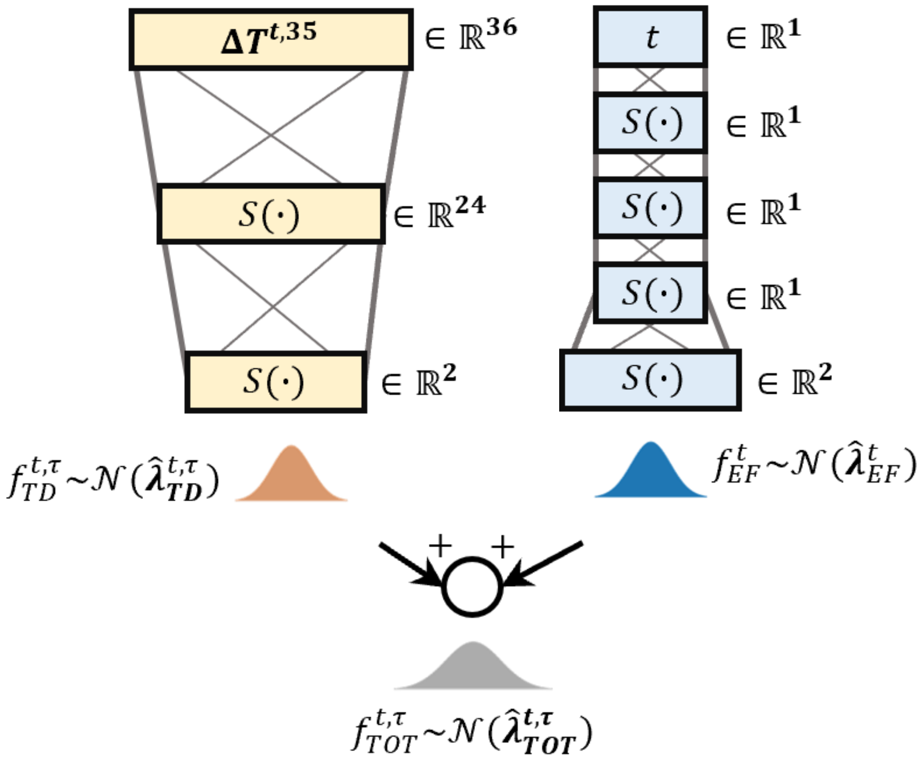
$$\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \varepsilon_{e,P}^{t} + \varepsilon_{R}^{t}$$

$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \delta\varepsilon_{e,P}^{t} + \delta\varepsilon_{R}^{t}$$

$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \delta(\varepsilon_{e,P}^{t} + \varepsilon_{R}^{t})$$

$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \delta\left((1-\chi^{t})\varepsilon_{R}^{t} + \varepsilon_{e,P}'\left(\frac{\chi^{t}}{\chi'}\right)\right)$$

$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \varepsilon_{EF}^{t}$$



$$\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \varepsilon_{e,P}^{t} + \varepsilon_{R}^{t}$$

$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \delta\varepsilon_{e,P}^{t} + \delta\varepsilon_{R}^{t}$$

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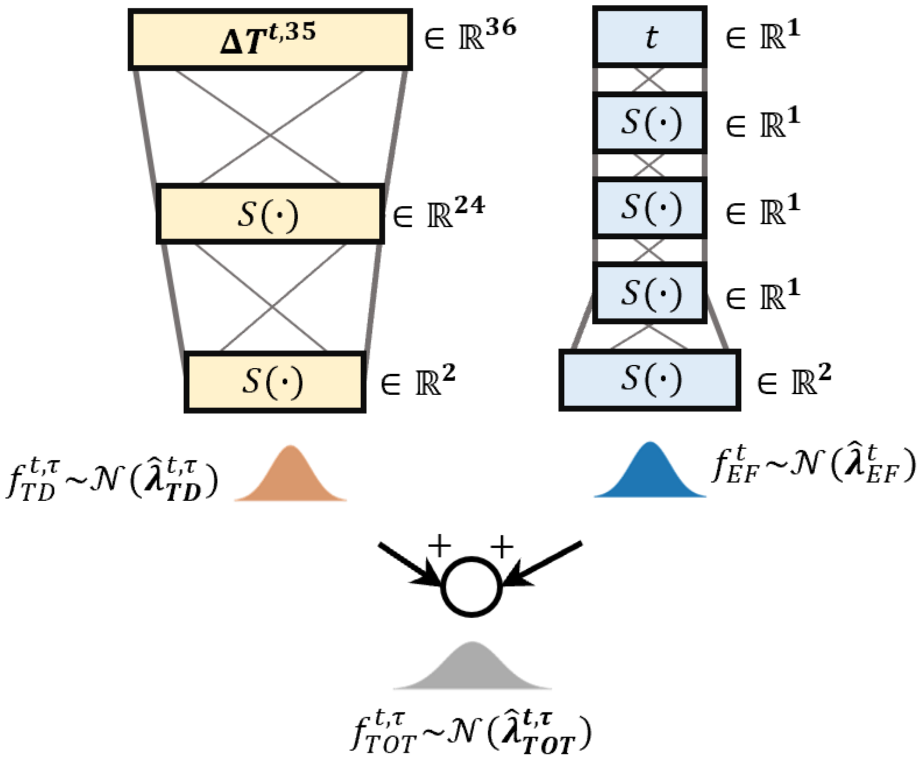
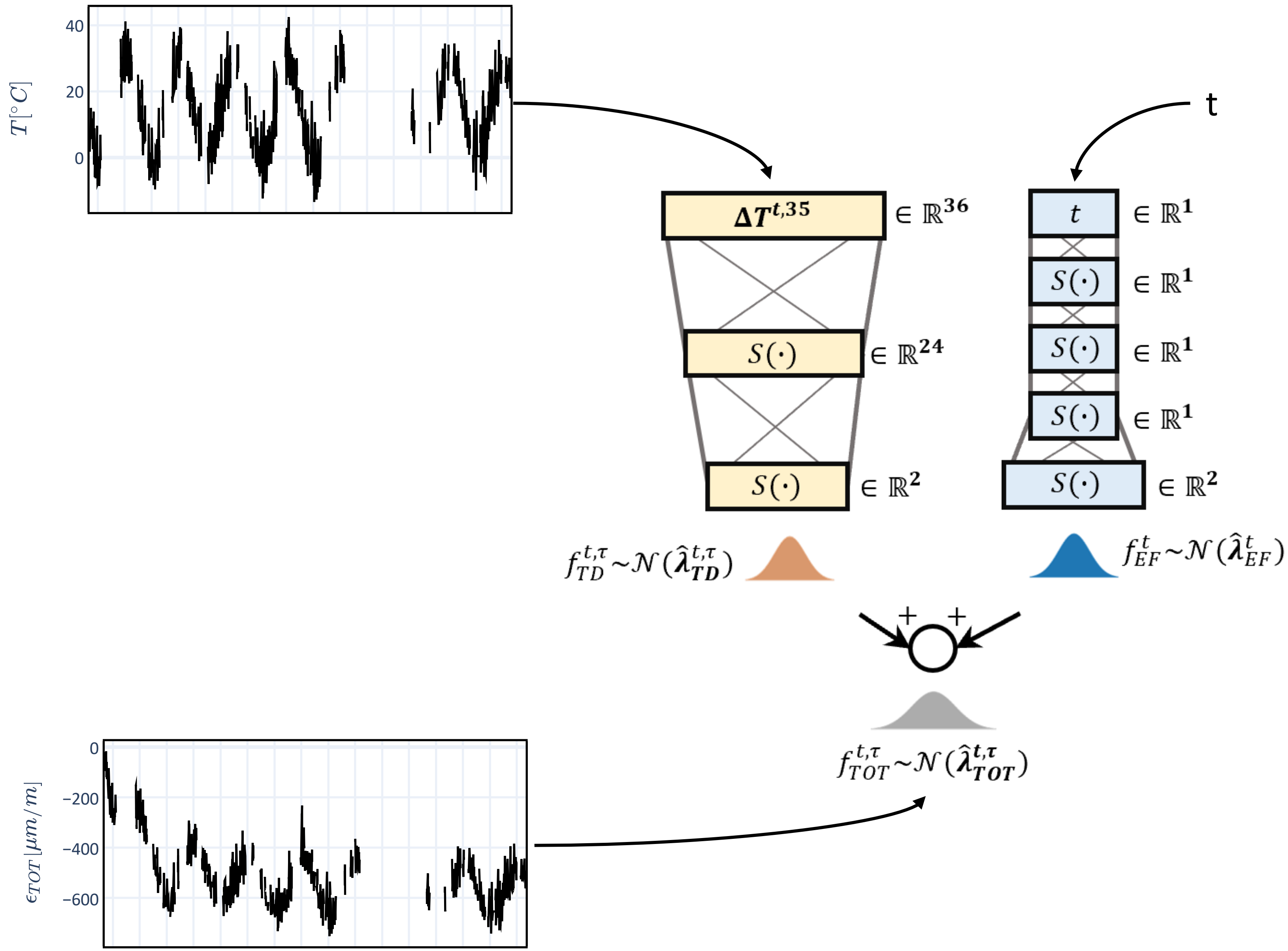
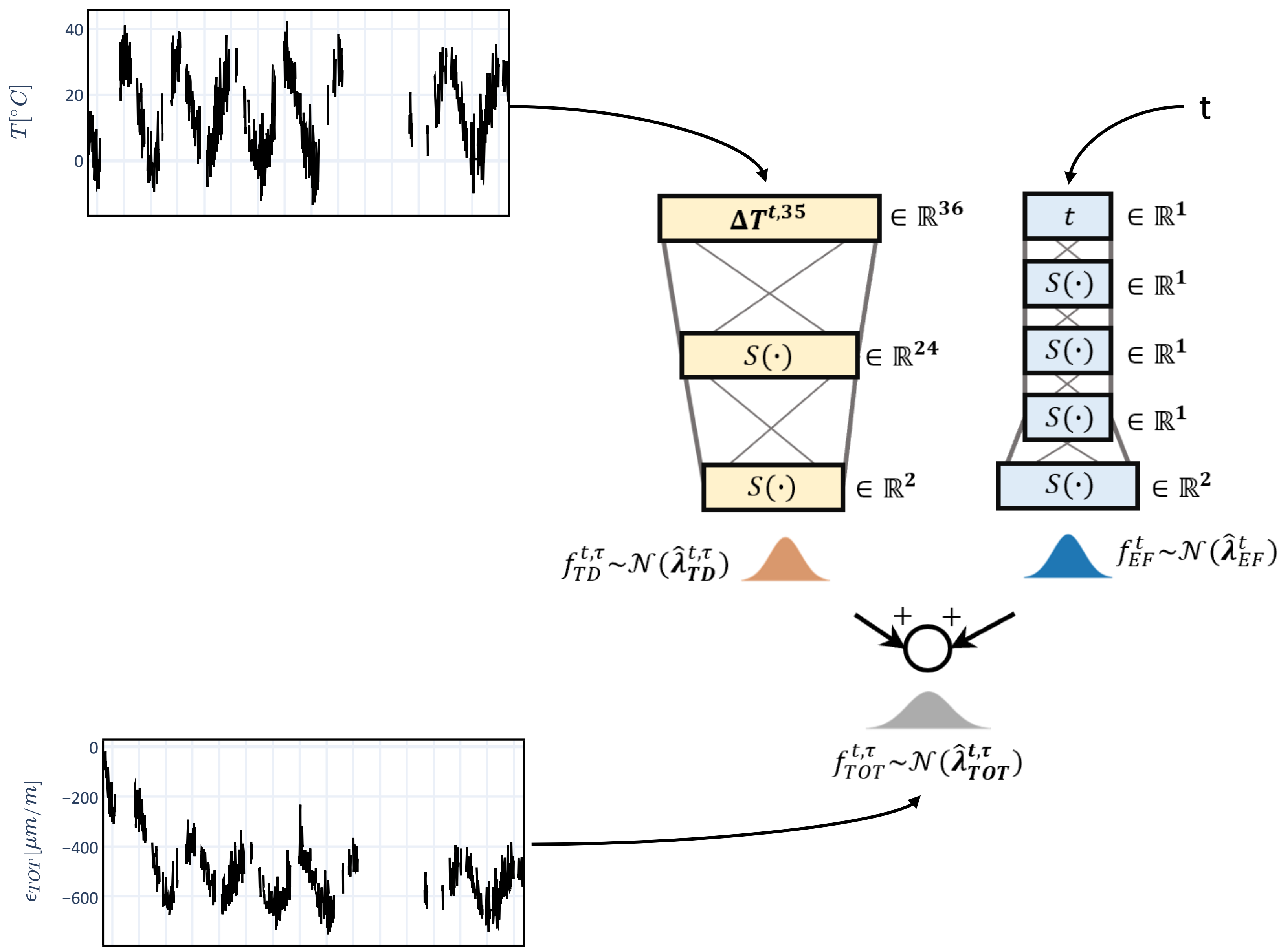
$$\delta\varepsilon_{TOT}^{t,\tau} = \varepsilon_{TD}^{t,\tau} + \varepsilon_{EF}^{t}$$


$\Delta T^{t,35}$
$\in \mathbb{R}^{36}$
$S(\cdot)$
$\in \mathbb{R}^{24}$
$S(\cdot)$
$\in \mathbb{R}^{2}$
t
$\in \mathbb{R}^{1}$
$S(\cdot)$
$\in \mathbb{R}^{1}$
$S(\cdot)$
$\in \mathbb{R}^{1}$
$S(\cdot)$
$\in \mathbb{R}^{1}$
$S(\cdot)$
$\in \mathbb{R}^{2}$
$f_{TD}^{t,\tau} \sim \mathcal{N}(\hat{\boldsymbol{\lambda}}_{TD}^{t,\tau})$
$f_{EF}^{t} \sim \mathcal{N}(\hat{\boldsymbol{\lambda}}_{EF}^{t})$
+
+
$f_{TOT}^{t,\tau} \sim \mathcal{N}(\hat{\boldsymbol{\lambda}}_{TOT}^{t,\tau})$

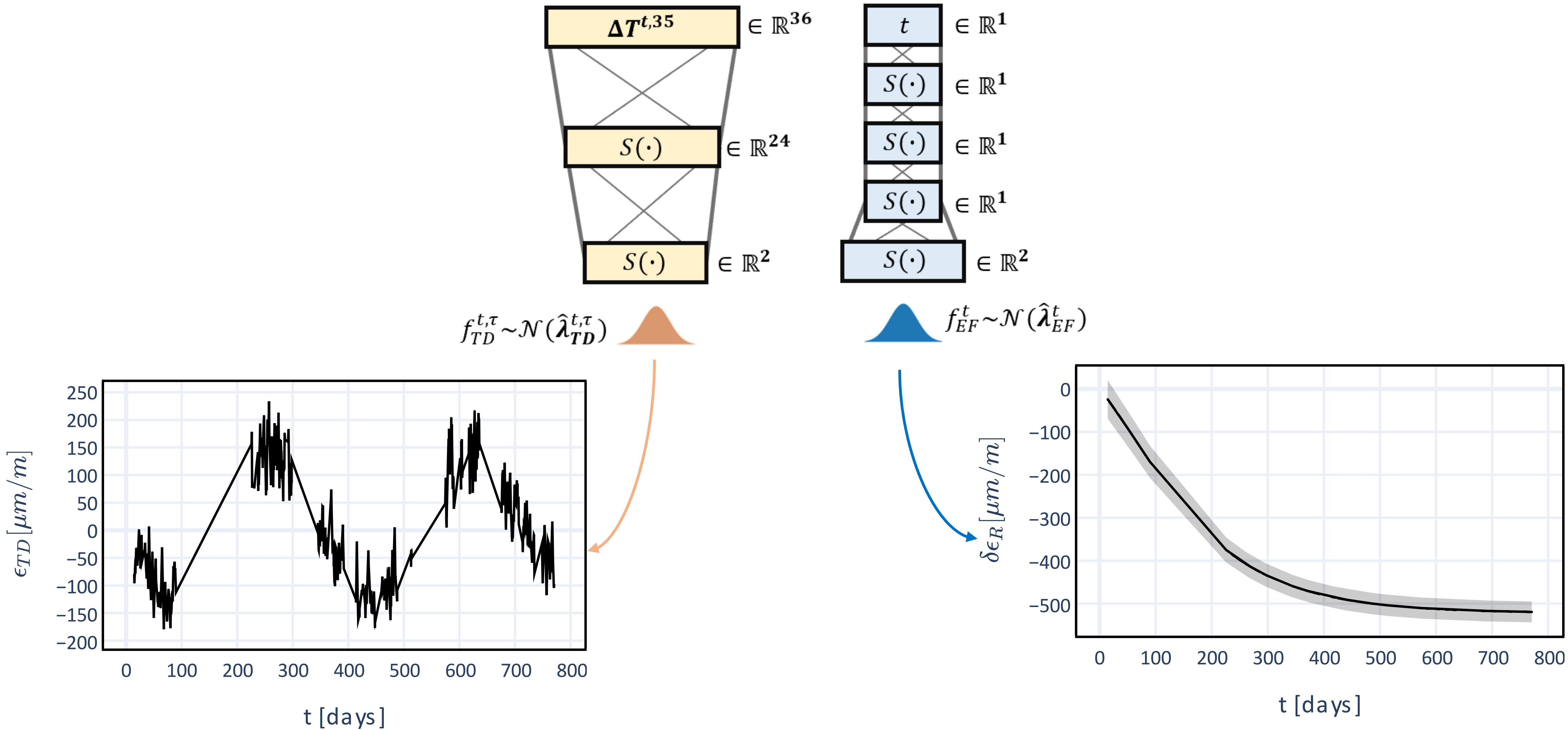
2.1 PNN: Architecture



2.1 PNN: Architecture



2.2 PNN: Strain decomposition



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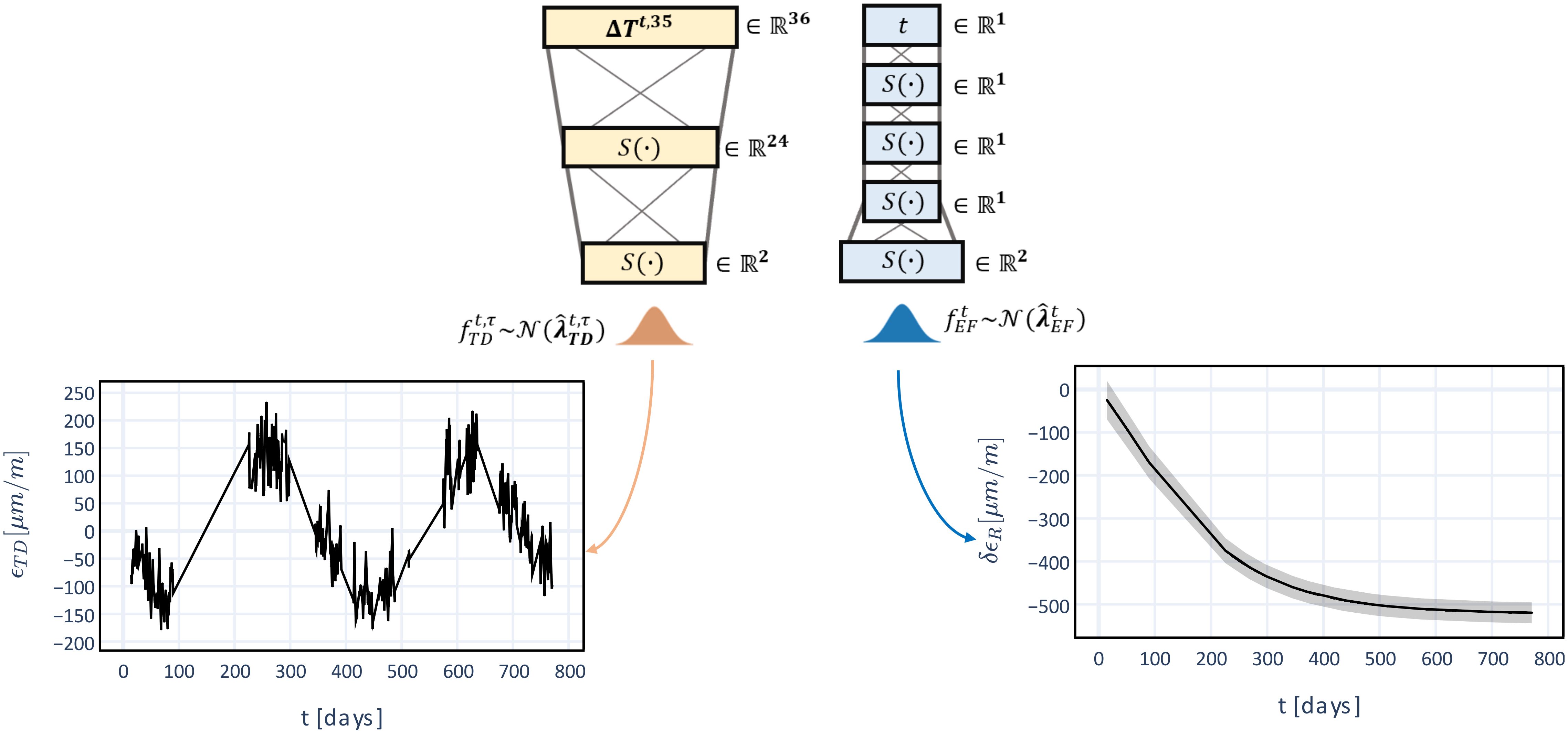
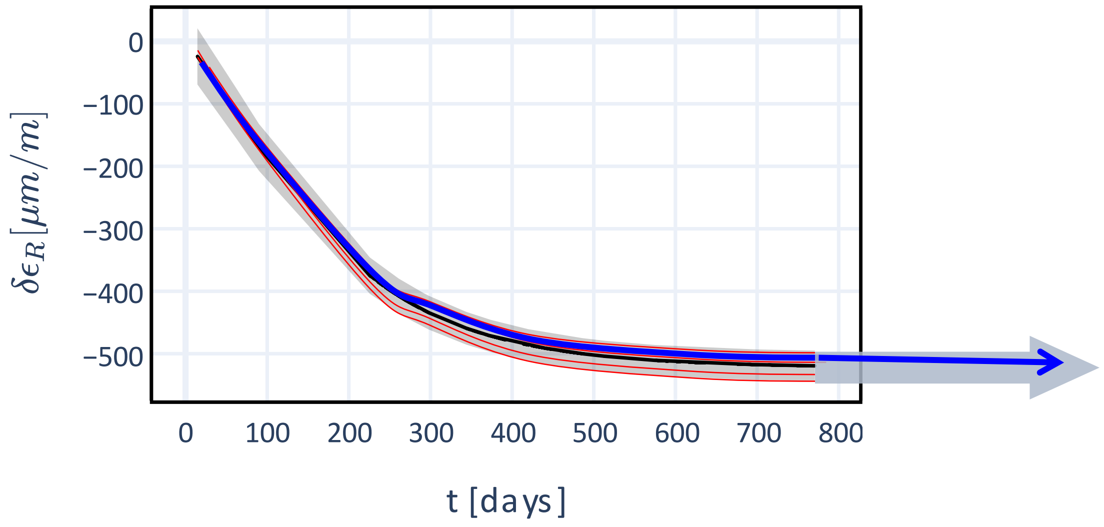


2.3 PNN: Code model functions

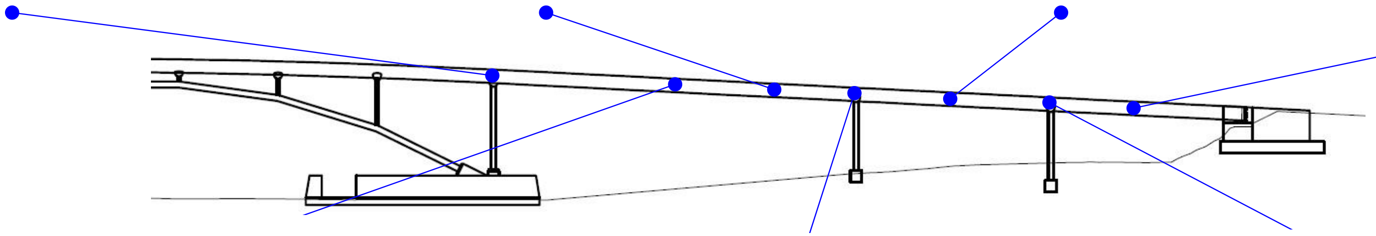


$$\varepsilon_{E+T}^{t} = a \cdot \left(1 - e^{-\frac{t-t'}{b}}\right) + c \cdot \left(\tanh \sqrt{\frac{t-t_0}{d}}\right)$$

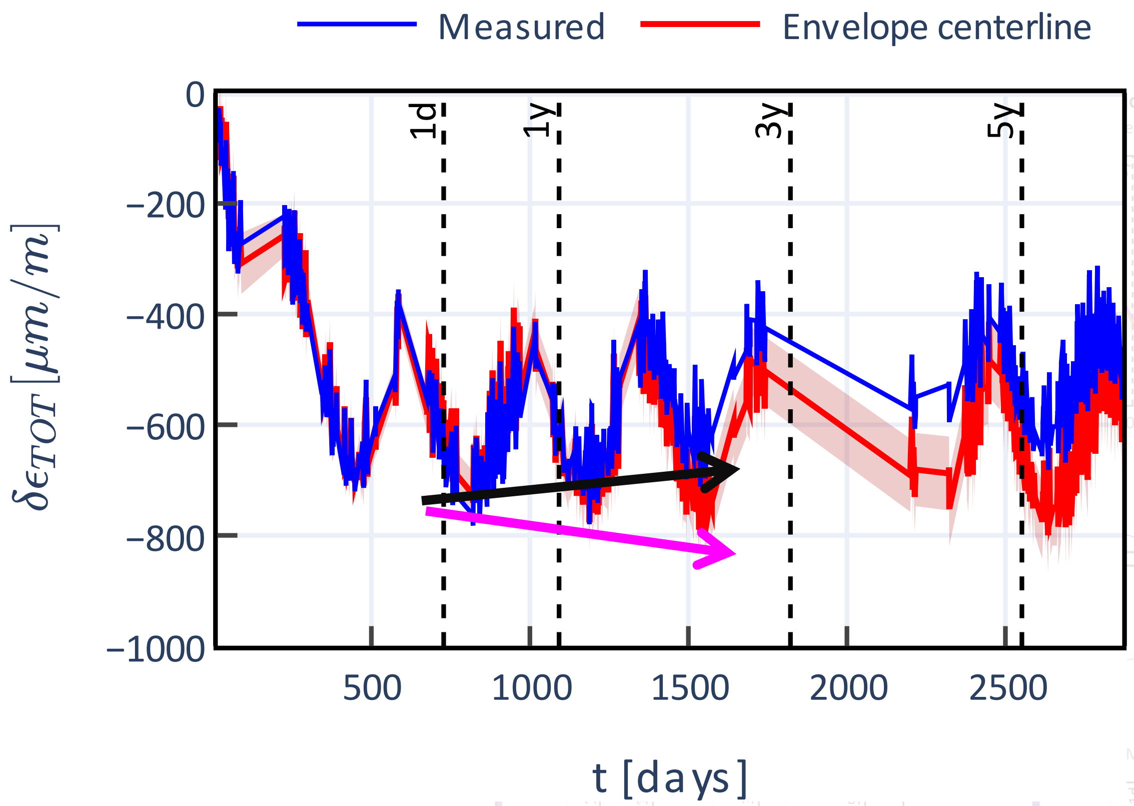
3. Results: Multiple models

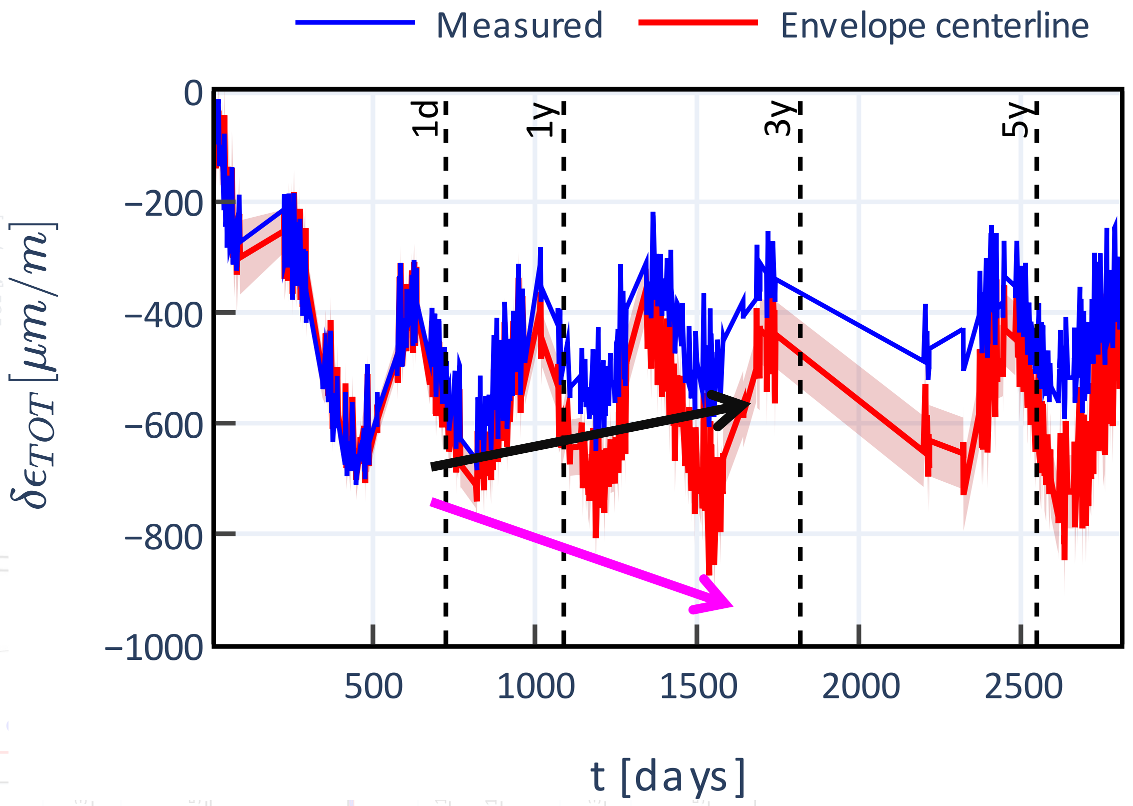
E+T ACI CEB B4 Measured

3. Results: Prediction envelope

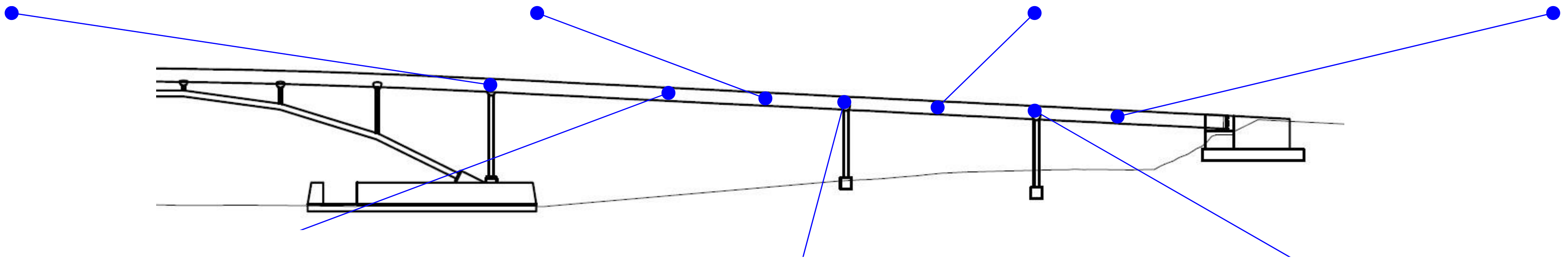


3. Results: Prediction envelope





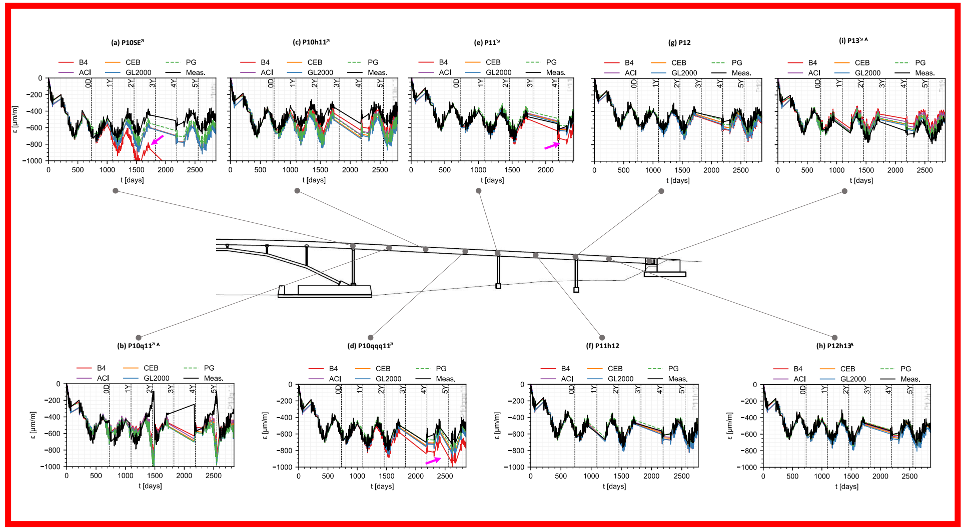
3. Results: Prediction residuals

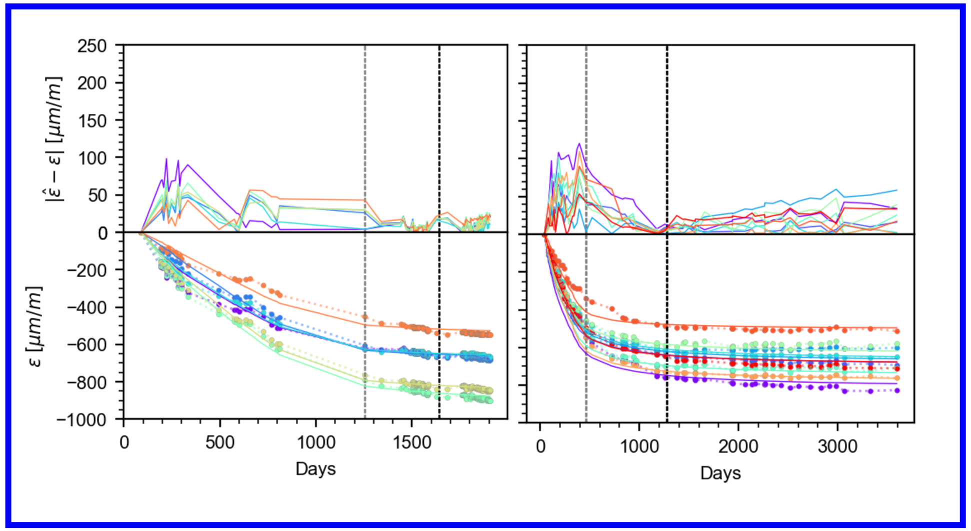


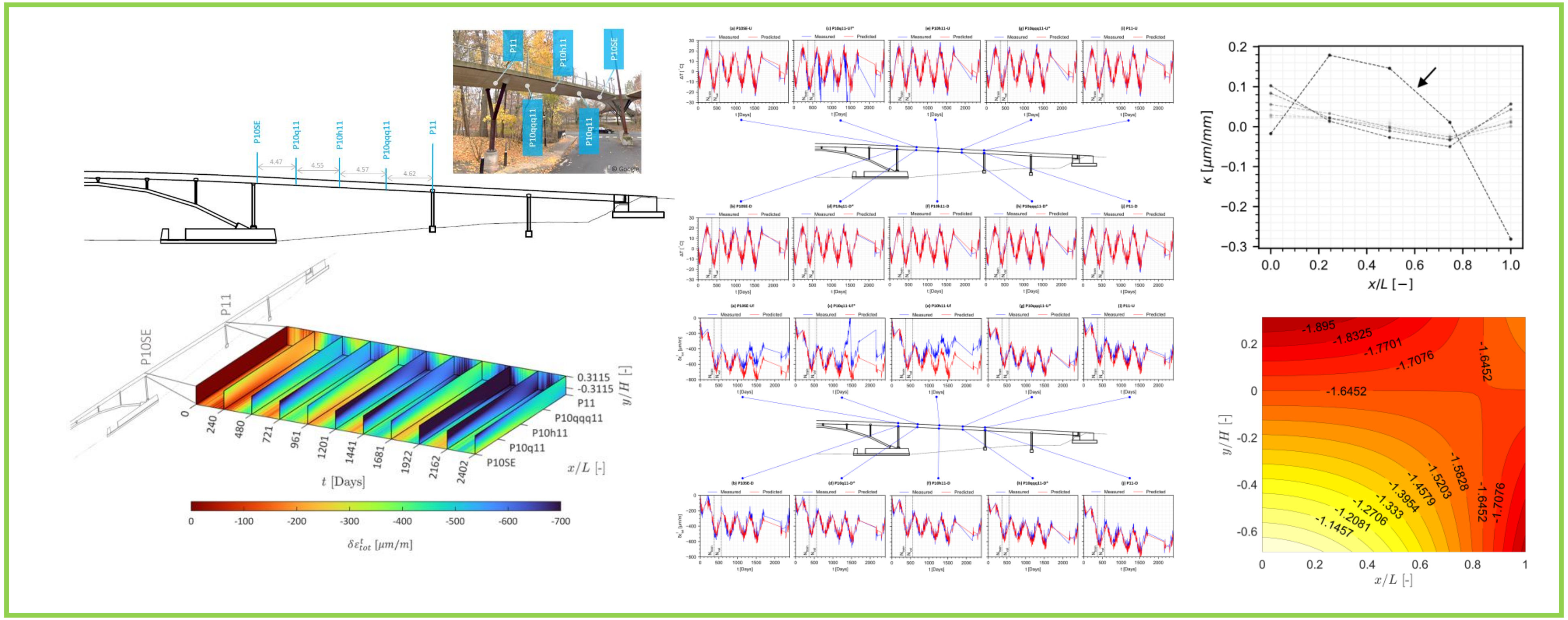
4. Conclusions

- By combining
  - SHM
  - Probabilistic ML
  - Strain modeling
  - Domain specific functions
- We can:
  - Motivate the machine-learning model architecture
  - Decompose the total strain into temperature and time-dependent components
  - Predict structural response envelopes multiple-years ahead
  - Detect both sudden and gradual anomalies

5. Ongoing work







Acknowledgements

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- Princeton University
- Vivek Kumar, Hiba Abdel-Jaber

Thank you!

Questions? :D