RISK.twin
Digitale Zwillinge zum Schutz kritischer Infrastruktur

Hybrid Digital Twin for Critical Infrastructure: Combining Physics-Based Modeling with Data-Driven Predictions

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Motivation

Digital twins are models that link physical objects into digital environments. This can be achieved via physics-based relations or data-driven structures. A Hybrid Digital Twin (HDT) incorporates both approaches for more accurate results. HDTs have major applications in the protection of critical infrastructures like bridges and buildings, because they can predict their behaviour and monitor their structural health in various scenarios[1].

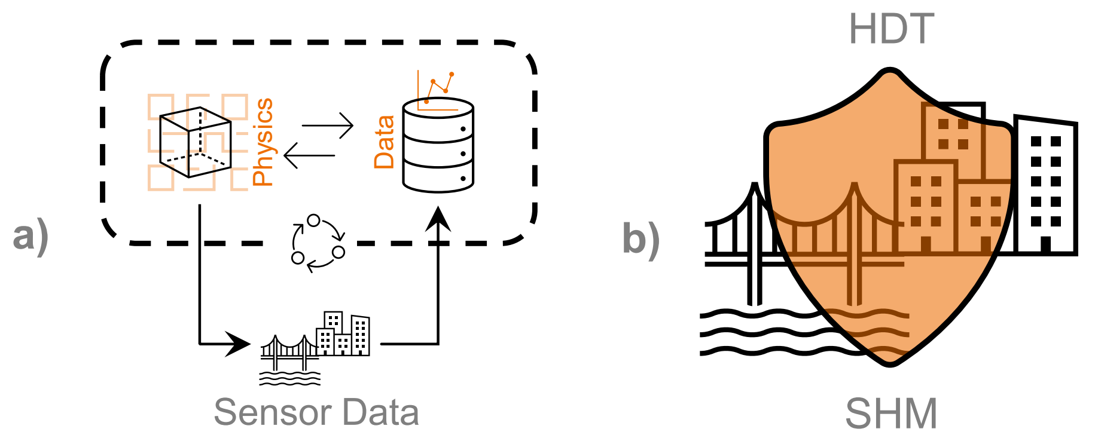

Figure 1 – a) A hybrid digital twin (HDT) implements both physics based and data-driven approaches. b) HDT assists in structural health monitoring (SHM) to protect critical infrastructures like bridges and buildings

Methodology - Approach

HDT integrates state-of-the-art data-driven methods and a complex finite-element model, the physics model is based on the finite element method (FEM). The model parameters are calibrated with sensor information from the real structure. The model is later on optimized to provide a surrogate model which can be used as a virtual twin. This twin is coupled with a data driven digital twin to provide a hybrid digital twin

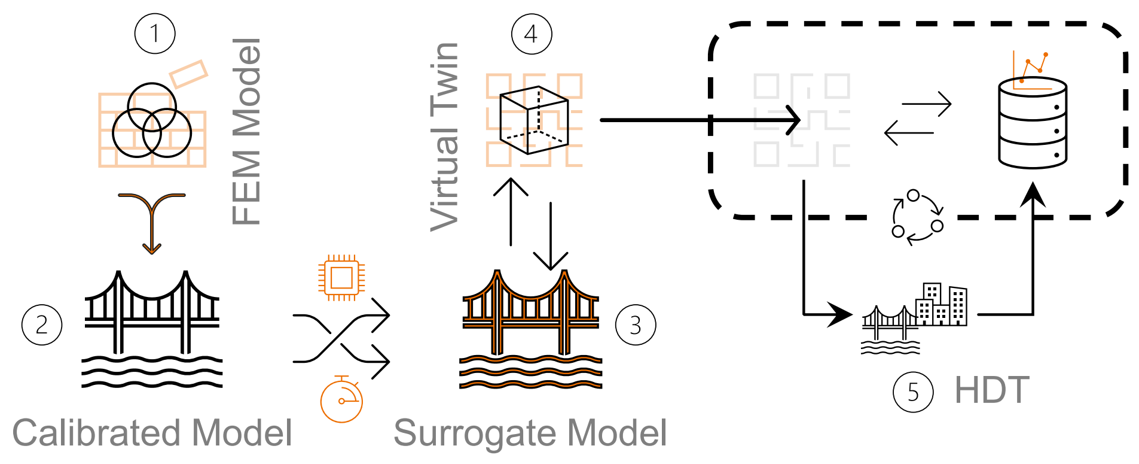

Figure 2 – Proposed approach to develop a Hybrid digital twin starting from a complex FEM model

Methodology – Theoretical Framework

Nonlinear Solid Mechanics:
The FEM model is based on a mixed-dimensional formulation of the steel-reinforced concrete. The concrete is described by plastic solid elements, while the steel-reinforcement is modelled using beam theory.

Mortar Method:
This approach allows for the embedding of one dimensional fibers – the steel reinforcement – into three dimensional solid volumes – the plastic concrete –. The governing problem for this coupling is as follows:

$$\delta W^S + \delta W^B - \delta W_c^{1D-3D} + \delta W_\lambda^{1D-3D} = 0$$

Where:

W^S	virtual work from the solid
W^B	virtual work from the beam
W_c^{1D-3D}	coupling interface contribution
W_λ^{1D-3D}	variational form of constraint

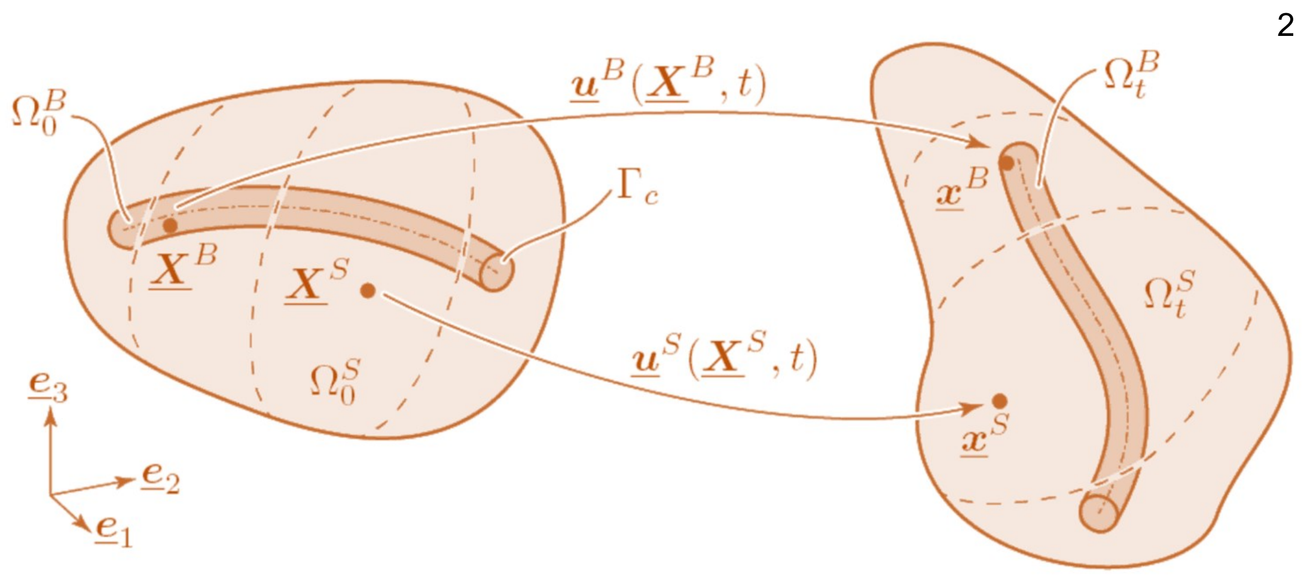

Figure 3 – Embedding of 1D beam element in a 3D solid element using mortar method and mixed dimensional coupling

Drucker-Prager Material Model:
This model allows for the simulation of elasto-plastic materials, based on the assumption of small strains (linear kinematics). We use plasticity to capture wearing effects of concrete phenomologically. The yield criterion function for the plastic material is calculated as follows:

$$\Phi(\boldsymbol{\sigma}, c) = \sqrt[2]{J_2(\boldsymbol{s}(\boldsymbol{\sigma}))} + \eta\, p(\boldsymbol{\sigma}) - \xi\, c$$

Where:

$J_2 = \frac{1}{2} s : s$	Second invariant of stress
$s = \sigma - p(\sigma) I$	Deviatoris Stress
$\eta,\ \xi$	Drucker-Prager constants

For stresses outside the yield surface, a return mapping is applied to correct the resulting stresses and elastic strains. The reminder of the strain is assumed to be plastic

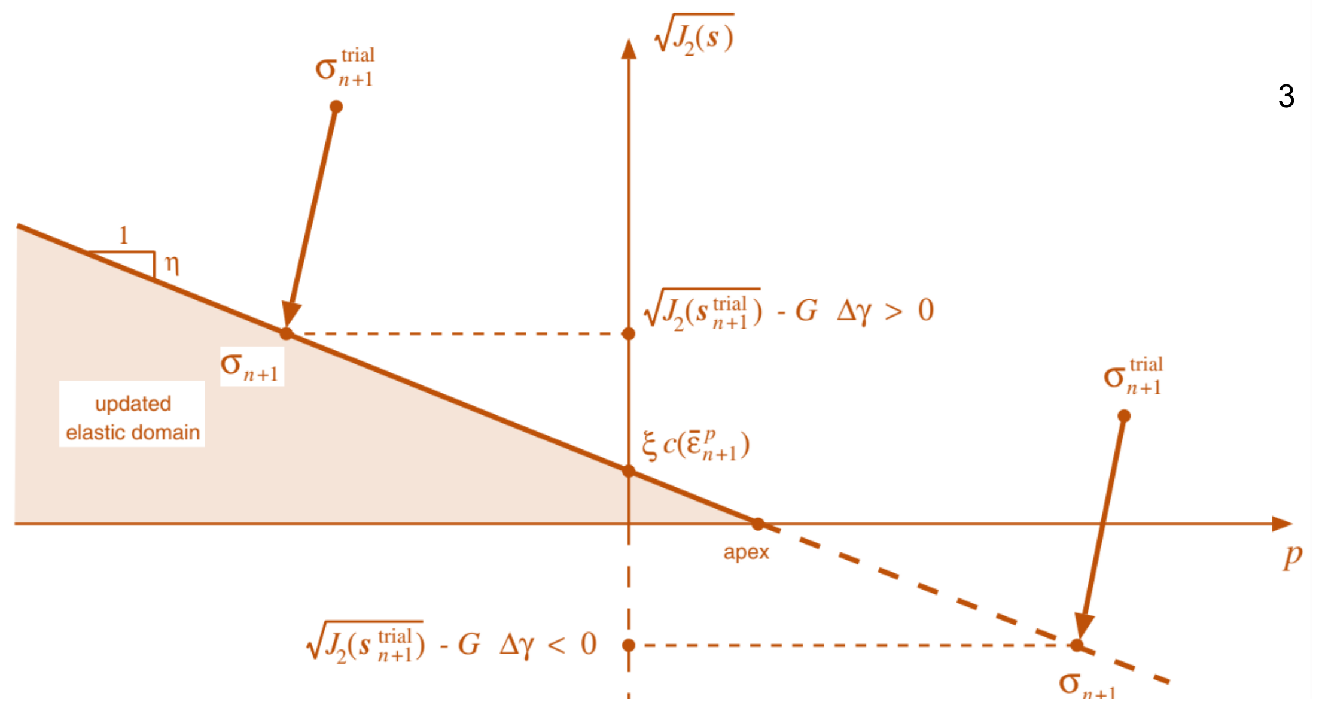

Figure 4 – Simplified yield surface of the Drucker Prager plasticity model along with return mappings for plastic strains

Current Progress (Refer to plan in Figure 2)

1) FEM Model: Implementation of the concrete material model using Drucker-Prager plasticity is achieved on in-house code (4C) [4] and verified using two benchmarks: one for general plasticity applications, and the other for a standard steel-reinforced concrete beam (Figure 6).

2) Model Calibration: Development of a model calibration method using the FEM model with introduced sensor data. This is achieved by modifying the material parameters to allow for a more accurate structure representation. In this case, we assume the compressive strength and the modulus of elasticity of the concrete as unknowns, and using the displacement and strain from a singular sensor we identify said parameters. Results are shown in Figure 5.

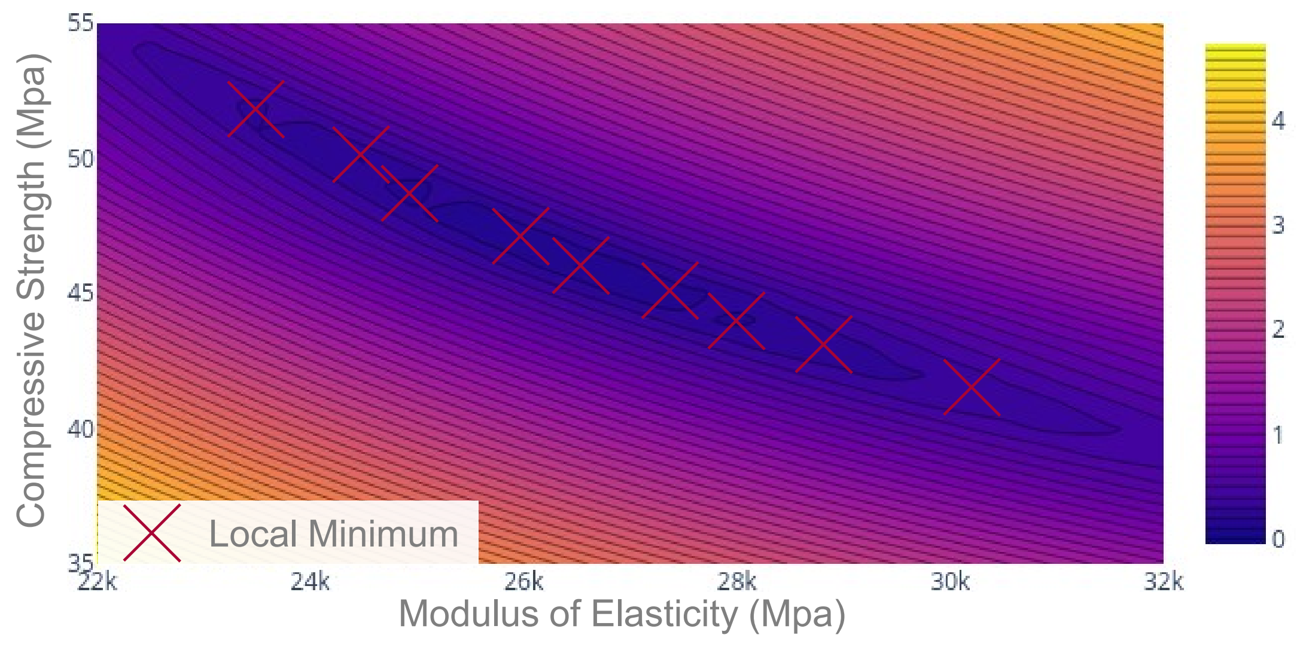

Figure 5 – Mean square error of displacement and strain data at the sensor location based on modifying the compressive strength and modulus of elasticity of concrete in the FEM model.

The complexity of both the materials and the model renders the optimization problem difficult to solve without high level optimizers. However, using the displacement and strain of one sensor is sufficient to optimize two of the structure parameters, and with more data, more parameters can be recovered for more accurate model representation without additional computational expenses.

Figure 6 – Modified 3D model of steel-reinforced concrete beam

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