Červenka Consulting s.r.o.
Na Hřebenkách 55
150 00 Prague
Czech Republic
Phone: +420 220 610 018
E-mail: cervenka@cervenka.cz
Web: https://www.cervenka.cz

SOFTWARE DOCUMENTATION

VALIDATION AND EXAMPLES MANUAL

Project Result TM04000012-V3

STOchastic **N**ode **E**ditor:

Nonlinear Simulation Boosted by Stochastic Methods for Modelling Physical Damage Supported by Big Data

Written by

Jan Červenka

Ondřej Slowik

Dalimír Stano

Drahomír Novák

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Contents

Executive Summary

This document provides **validation and examples documentation** for the new **software tools** developed as a part of the STONE software co-funded by the research program DELTA-2 funded by Technology Agency of the Czech Republic. The project title was **"A concrete bridge health interpretation system based on mutual boost of big data and physical mechanism".**

The project was an international cooperation between partners in Czech Republic and China:

Cervenka Consulting s.r.o.

Brno Technical University,

Jiangsu Easttrans Intelligent Control Technology Group Co., Ltd.,

Hohai University

The goal of the project was to bridge the knowledge and technology gab in the management of aging infrastructures when numerous concrete bridges have been installed with health monitoring systems, which have collected massive response data of bridge real-time operation and advanced modelling capabilities of modern simulation software.

The data collected from aging structures have the 4V characteristics of big data, providing fundamental support for health interpretation of the bridges. Nevertheless, effective methods to effectively utilize these big data for modelling structural responses and further interpret health condition of a concrete bridge are extremely lacking and difficult to make in practice.

Several software tools have been developed in the project teams in Czech Republic that are further enhanced and applied to infrastructure projects by the Chinese partners in China as well as other countries.

The software result V3 is implemented as the **STONE (STOchastic Node Editor)** module integrated into the **ATENA / SARA** simulation environment. Its primary purpose is to enable **advanced nonlinear simulation of concrete structures**, in which **physical mechanism-based damage and fracture modelling** is systematically combined with **stochastic methods and measured big data** originating from structural health monitoring. This integration allows realistic simulation, assessment, and prognosis of structural behavior under uncertainty, exceeding the capabilities of conventional deterministic analysis.

The document demonstrates that TM04000012-V3 fulfills its intended objectives in three key functional areas:

1. **High-efficiency nonlinear simulation of concrete structures**, including damage and fracture processes governed by advanced constitutive models and verified numerical solvers.
2. **Probabilistic nonlinear analysis**, in which uncertainties in material properties, geometry, loading, and environmental effects are represented by stochastic variables and propagated through nonlinear simulations.
3. **Mutual boost of physical mechanism and measured big data**, enabling calibration, validation, and improved predictive capability of numerical models based on monitoring-derived information.

Validation is performed using a set of **representative benchmark problems, experimental comparisons, and application examples**. These include static and cyclic loading scenarios, shear and punching failure modes, and selected international benchmark studies previously used for blind or semi-blind verification of nonlinear concrete models. The presented results

demonstrate numerical robustness, physical plausibility of damage evolution, and consistency of probabilistic outcomes with observed structural behavior.

In addition to validation, the document provides **practical usage examples** illustrating how the STONE module is applied within the ATENA / SARA framework. These examples demonstrate typical workflows ranging from deterministic nonlinear analysis to probabilistic assessment and prognosis, thereby serving both as verification evidence and as guidance for advanced users.

The results confirm that **TM04000012-V3 represents a validated, practically applicable software outcome**, suitable for advanced assessment of concrete bridges and other concrete structures, particularly in contexts where large volumes of monitoring data are available. The software is ready for use in engineering practice, further research, and future integration into comprehensive bridge health interpretation systems.

1 Introduction

The assessment and management of existing concrete bridges represent a major engineering challenge, particularly in the context of ageing infrastructure and increasing demands on safety, reliability, and serviceability. A large proportion of bridge structures in Europe and worldwide were constructed several decades ago and are currently operating close to or beyond their originally intended design life. At the same time, advances in monitoring technologies have led to the widespread deployment of structural health monitoring systems capable of collecting large volumes of data describing the real-time behavior of bridges under operational and environmental loading.

Despite the availability of extensive monitoring data, the practical utilization of such information for engineering decision-making remains limited. Raw sensor data alone rarely provide direct insight into structural safety, remaining load-bearing capacity, or future performance. Conversely, advanced numerical simulation tools based on nonlinear finite element analysis are capable of realistically modelling damage, cracking, and failure mechanisms in concrete structures, but they are traditionally applied in a deterministic manner and often rely on idealized assumptions regarding material properties, boundary conditions, and loading.

The research project **BRIHIS – A concrete bridge health interpretation system based on mutual boost of big data and physical mechanism** addresses this gap by developing methods and software tools that systematically combine **measured big data** from monitoring systems with **physical mechanism-based numerical models**. The central concept of the project is the *mutual boost* between data and physics: monitoring data are used to calibrate, validate, and update numerical models, while physically based simulations provide interpretation, filtering, and predictive capability beyond what can be obtained from data-driven approaches alone.

Within this framework, the software result **TM04000012-V3** represents a key integrative component of the overall system. It is implemented as the **STONE (STOchastic Node Editor)** module within the ATENA / SARA simulation environment and enables the coupling of advanced nonlinear structural analysis with stochastic methods and probabilistic representation of uncertainties. STONE allows uncertainties in material properties, geometry, loading, and environmental effects to be explicitly incorporated into nonlinear simulations and supports the assimilation of monitoring-derived information into the modelling process.

The primary objective of STONE is to support **probabilistic assessment and prognosis of concrete structures**, including the evaluation of damage evolution, reliability, and future structural performance. By combining nonlinear fracture-mechanics-based modelling with stochastic simulation and data-informed updating, the software extends the capabilities of conventional deterministic analysis and provides a robust basis for decision-making in bridge assessment and management.

This document serves as **validation and example documentation** for the software result TM04000012-V3. It presents the functional scope of the STONE module, its integration within the ATENA / SARA framework, and a set of representative validation examples and application cases. The intention is twofold:

(i) to demonstrate that the software fulfills the objectives defined for the project result V3, and
(ii) to provide guidance and reference examples illustrating its practical use in advanced nonlinear and probabilistic analysis of concrete structures.

2 General Validation of Advanced Nonlinear Analysis

Advanced nonlinear finite element analysis of reinforced concrete structures has been under continuous development for several decades and represents a mature yet still evolving engineering discipline. Its credibility relies on the ability of numerical models to realistically reproduce experimentally observed structural behavior, including stiffness degradation, cracking, redistribution of internal forces, and ultimate failure mechanisms.

Before addressing probabilistic extensions and data-informed model updating implemented in the STONE module, it is essential to demonstrate the **general validity and robustness of the underlying nonlinear analysis framework** used within the ATENA / SARA environment. This framework forms the deterministic core upon which stochastic modelling, Bayesian updating, and monitoring-based calibration are subsequently built.

Validation of nonlinear analysis methods is traditionally performed through comparison with experimental results. In addition to direct comparison with laboratory tests, a particularly stringent form of verification is provided by **blind or semi-blind prediction benchmarks**, in which numerical simulations are performed without prior knowledge of experimental outcomes. Such benchmarks provide an objective measure of modelling capability and help to identify both strengths and limitations of the applied constitutive models and numerical solution procedures.

This section summarizes selected validation results of advanced nonlinear analysis implemented in the ATENA system. The presented examples include internationally recognized benchmark problems focusing on critical failure modes of concrete structures, such as shear failure, punching, cyclic loading, and size effect. These benchmarks establish the reliability, numerical robustness, and physical plausibility of the nonlinear simulation tools that constitute the deterministic backbone of the STONE software module.

2.1 Nonlinear Analysis

Advanced nonlinear finite element analysis (NLFEA) (see Fig. 1) provides a physically realistic representation of the structural behavior of concrete structures by explicitly modelling cracking, crushing, reinforcement yielding, and redistribution of internal forces. Unlike linear or simplified nonlinear approaches, NLFEA [4][5][29] is capable of capturing the progressive damage evolution and failure mechanisms that govern the ultimate and serviceability performance of reinforced concrete members and systems.

The nonlinear analysis framework employed in the ATENA / SARA [16] environment is based on continuum mechanics and fracture-mechanics principles, using constitutive models for concrete and reinforcement [9] (see Fig. 2) that have been developed and refined over several decades. The adopted modelling approach allows the simulation of key phenomena relevant to existing concrete structures (Fig. 3), including tensile cracking with softening (Fig. 4), compressive crushing, shear transfer across cracks, cyclic degradation, and interaction between concrete and reinforcement.

A reliable nonlinear analysis requires not only appropriate constitutive models, but also robust numerical solution strategies. These include incremental–iterative solution schemes, convergence control techniques, and consistent treatment of material softening to ensure numerical stability and mesh objectivity. The implemented methods are designed to provide stable solutions over a wide range of loading scenarios, including monotonic, cyclic, and combined loading conditions.

The credibility of the stochastic and data-supported extensions implemented in the STONE module directly depends on the reliability of this deterministic nonlinear analysis core. For this reason, the nonlinear analysis framework is treated as a validated baseline, whose performance has been extensively examined through comparison with experimental data and international benchmark studies, as summarized in the following subsection.

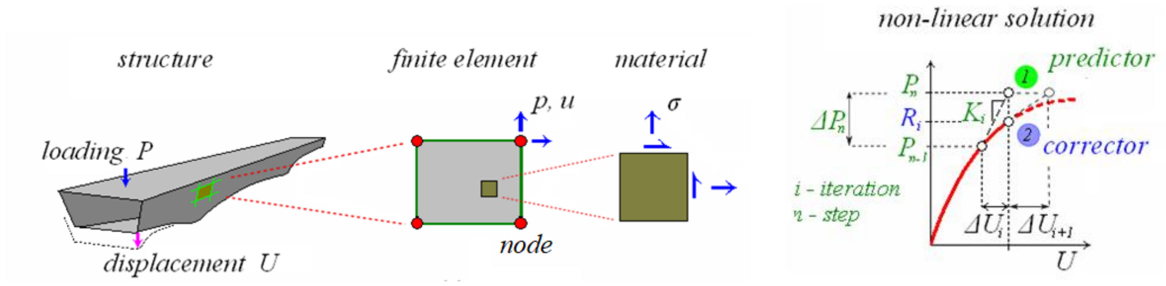

Fig. 1: FEM method in the analysis of bridge structures (left), typical flow of nonlinear iterative solution (right).

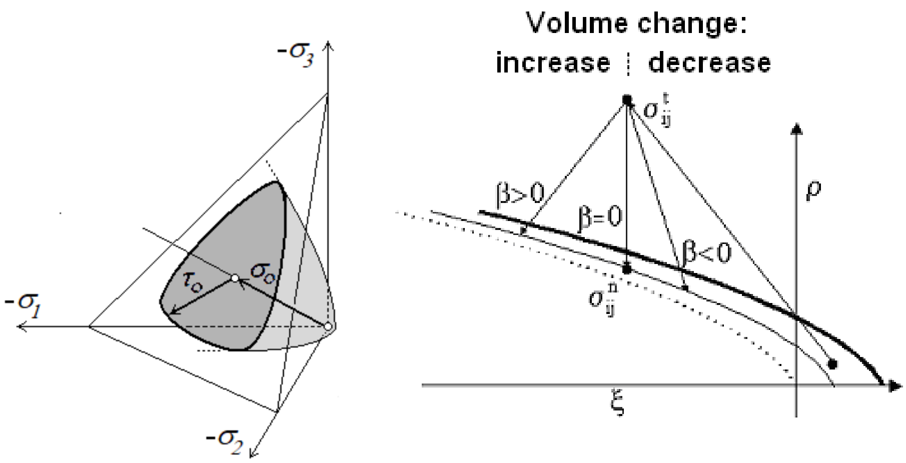

Fig. 2: Concrete failure criterion (left) and non-associated flow in compression behavior modelling (right)

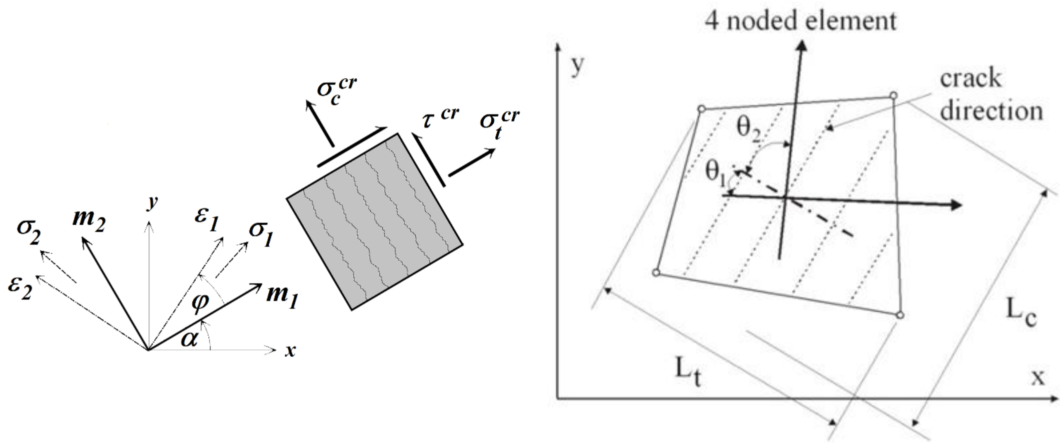

Fig. 3: Typical stress state in concrete finite element with the assumptions on crack band orientation and evaluation.

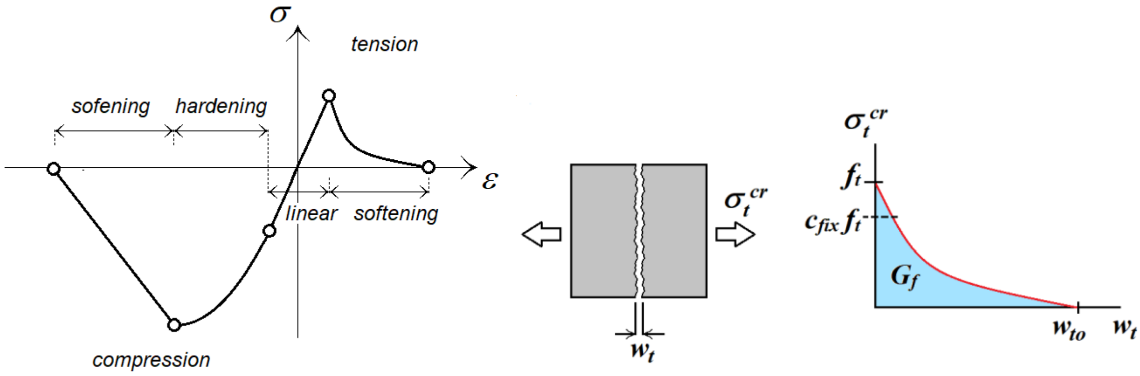

Fig. 4: Uniaxial stress-strain relationship for concrete and the strain softening assumptions in tension based on fracture energy G_f.

2.2 Validation Examples

Validation of nonlinear analysis methods is commonly achieved through systematic comparison of numerical predictions with experimental observations. In addition to direct calibration against laboratory tests, a particularly demanding form of validation is provided by **blind or semi-blind prediction benchmarks**, in which analysts are required to predict structural response and failure without prior knowledge of experimental results.

Over the past decades, the nonlinear analysis framework implemented in ATENA has been repeatedly evaluated in such benchmark studies, covering a broad range of reinforced concrete failure modes. These include shear and punching failure, cyclic loading of columns, size effect in concrete elements, and combined bending–shear behavior. The benchmarks typically assess not only ultimate load capacity, but also stiffness, deformation capacity, crack patterns, and damage localization.

The validation examples summarized in this subsection demonstrate that the nonlinear analysis framework provides physically plausible and numerically robust predictions within the scatter inherent to experimental testing of concrete structures. While prediction uncertainty remains unavoidable due to material variability and modelling assumptions, the results confirm that the employed models achieve a level of accuracy suitable for advanced structural assessment.

These general validation results establish confidence in the nonlinear analysis core that underpins the STONE software module. They form the necessary prerequisite for the subsequent application of stochastic methods, probabilistic simulation, and monitoring-supported model updating presented in the following sections.

This section summarizes additional blind competition results of ATENA software. Verification of simulation models for concrete structures is typically conducted through comparison with experimental data. Interesting insight can be obtained from blind predictions in international competitions, when the experimental results are not known at the time of the analysis. Fig. 5 to Fig. 10 summarizes several such contests and benchmarks in which the authors participated, for more details see Cervenka et. al. (2024) [18]. The overall summary is prodived in Fig. 10, where the predicted strength is normalized by the ratio F_{sim}/F_{exp} with 22 cases from seven benchmark contests displayed on the horizontal axis. The vertical bars represent the prediction scatter, while the author's results are marked in green.

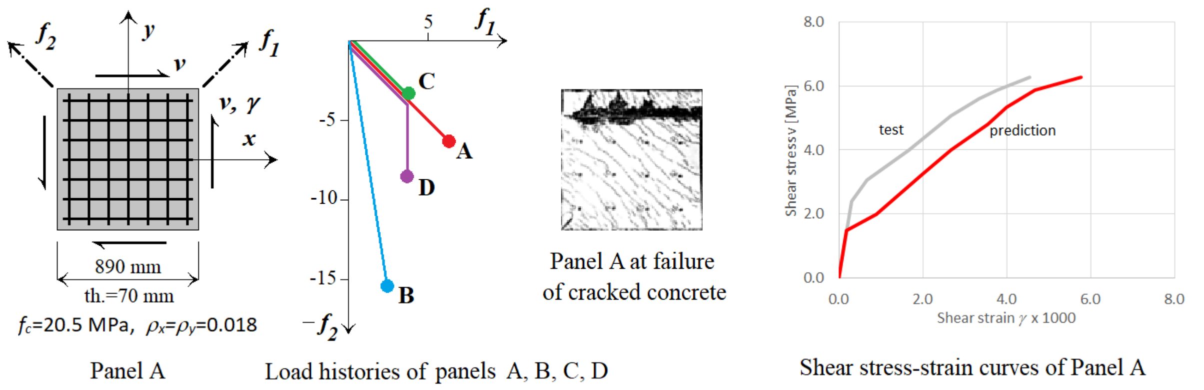

Fig. 5. Reinforced concrete panels, Toronto 1985.

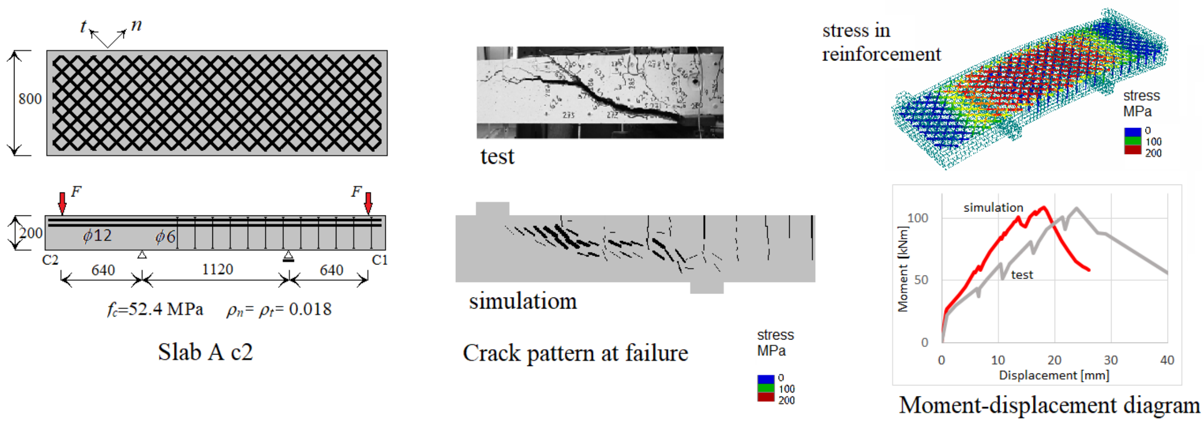

Fig. 6. Reinforced concrete slab, ETH 2005.

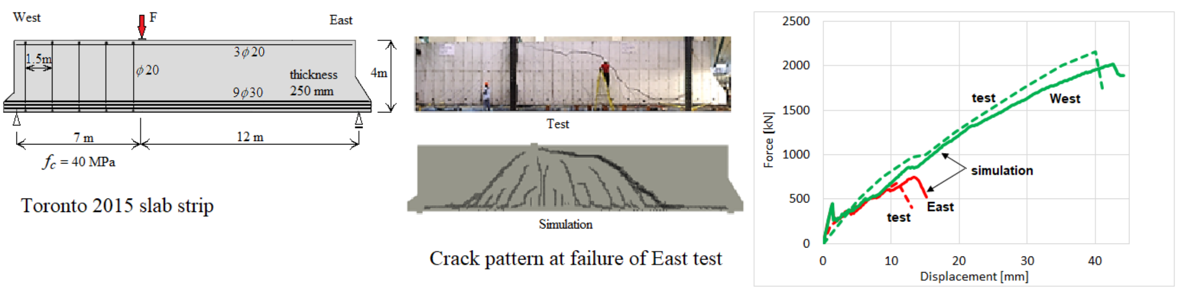

Fig. 7 Shear strength of very thick slab strip, Toronto 2015.

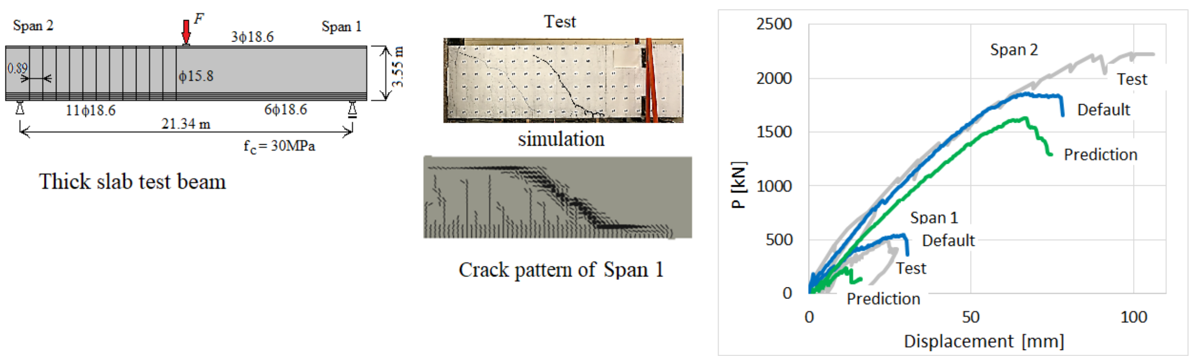

Fig. 8 Shear strength of reinforced concrete foundation, Berkeley 2021.

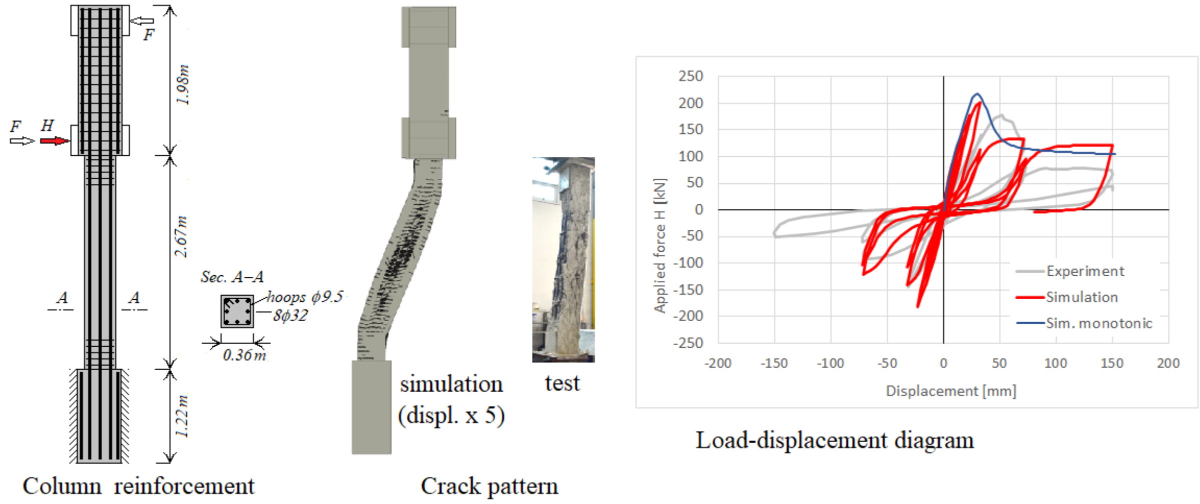

Fig. 9 Cyclic loaded reinforced concrete column.

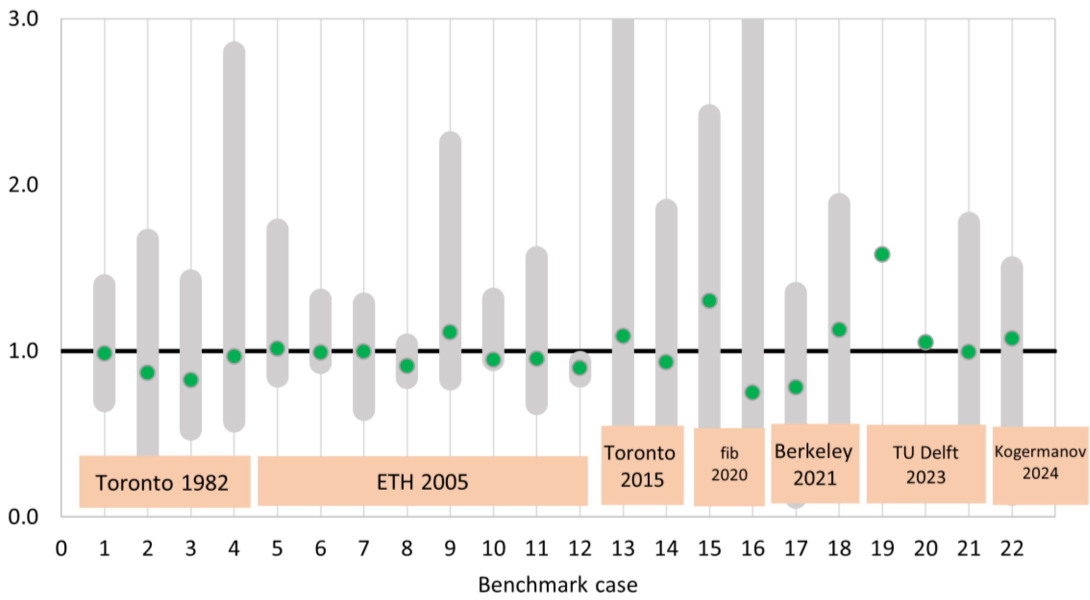

Fig. 10. Benchmark summary.

Over the past 40 years, the engineering community has shown sustained interest in improving simulation tools; however, no clear trend toward reduced uncertainty has emerged. The benchmarks primarily focus on shear or bending strength, and the wide prediction scatter reflects a limited understanding of shear failure. In addition, strength, stiffness, deformations, and crack patterns were also considered in the evaluation.

3 Real Case Validation Examples

Benchmark studies and controlled validation examples provide an essential basis for assessing the reliability of advanced nonlinear analysis methods under well-defined conditions. However, the true value of the methods and tools developed within the project can only be demonstrated through their application to **real engineering structures**, where uncertainties, imperfections, and incomplete information are inherent and unavoidable.

Existing concrete structures operate under complex and often poorly documented conditions. Material properties may differ from design assumptions due to construction variability, ageing, and degradation processes. Boundary conditions and load paths are frequently uncertain, and structures are exposed to a wide range of operational and environmental influences that evolve over time. As a result, structural behavior cannot be reliably assessed using purely deterministic models or simplified analysis approaches.

In recent years, many infrastructure objects have been equipped with monitoring systems that provide continuous or long-term measurements of structural response, such as displacements, strains, temperatures, dynamic characteristics. While these data represent a valuable source of information, their direct interpretation remains challenging. Measured data alone do not provide insight into internal stress states, damage mechanisms, or future structural performance unless they are combined with physically meaningful numerical models and appropriate methods for handling uncertainty.

The research project **BRIHIS** addresses this challenge by developing an integrated set of methods and computational tools that combine:

- nonlinear physical modelling of damage and fracture processes in concrete structures,
- stochastic analysis and uncertainty quantification,
- and the systematic use of large volumes of measured data for model calibration, updating, and validation.

The real case studies presented in this section illustrate how these methods can be applied to practical engineering problems involving existing reinforced concrete structures. The examples demonstrate the interaction between numerical simulation and measured data, showing how physically based models can be used to interpret monitoring results, identify plausible damage mechanisms, and assess the sensitivity of structural response to uncertain input parameters.

The selected case studies cover different types of structures and loading scenarios, including operational loading, environmental and thermal effects, and long-term degradation processes. Each example highlights specific aspects of the developed approach, such as parameter identification, stochastic calibration, or interpretation of complex monitoring datasets. Together, the case studies provide validation of the robustness, flexibility, and practical usability of the methods and tools developed within the project.

Rather than focusing on a single structure or failure mode, the presented examples demonstrate the **generality of the approach** and its applicability across a range of realistic engineering situations. They confirm that the developed methodology provides a consistent and physically meaningful framework for advanced assessment and prognosis of existing concrete structures under uncertainty.

3.1 Small Railway Bridge in the Czech Republic

This case study demonstrates the application of the **STONE (STOchastic Node Editor)** software to the calibration and validation of a nonlinear numerical model of an existing reinforced concrete railway bridge located in the Czech Republic. The example serves as a **validation of the V3 software result**, illustrating the mutual integration of nonlinear physical modelling, stochastic methods, and large volumes of monitoring data within a unified computational framework.

The investigated railway bridge (Fig. 11) exhibits visible damage and cracking that motivated the installation of a long-term structural health monitoring system based on **fiber Bragg grating (FBG) sensors**. The monitoring system provides continuous measurements of structural response under operational loading and environmental effects. These data form the basis for the identification and calibration of uncertain material and structural parameters.

Fig. 11: Railway bridge in Kostomlaty, Czech Republic, showing the observed damages and the installed FBG monitoring system.

A detailed nonlinear finite element model of the bridge was developed in the **ATENA** software (Fig. 13-Fig. 14), capturing the geometry, reinforcement layout, and relevant material behavior of the structure. The nonlinear physical model serves as the deterministic simulation core, capable of reproducing cracking, stiffness degradation, and load-carrying capacity of the bridge.

Due to the large amount of monitoring data, a dedicated **data pre-processing step** was implemented (Fig. 15) to reduce data volume while preserving the essential characteristics of the measured response. This step significantly improves the efficiency and robustness of the subsequent stochastic calibration process.

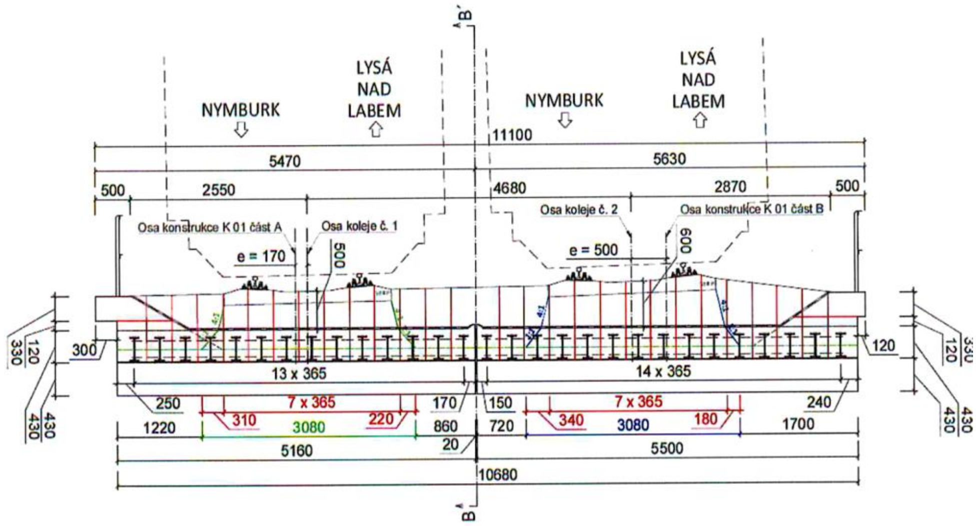

Fig. 12: Crossection of the railway bridge in Kostomlaty, Czech Republic.

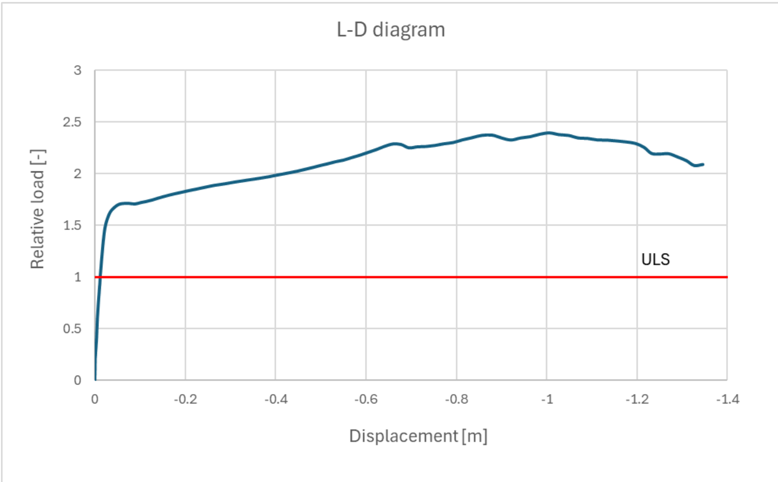

Fig. 13: Load-displacement curve showing the bridge load-carrying capacity of the Kostomlaty bridge.

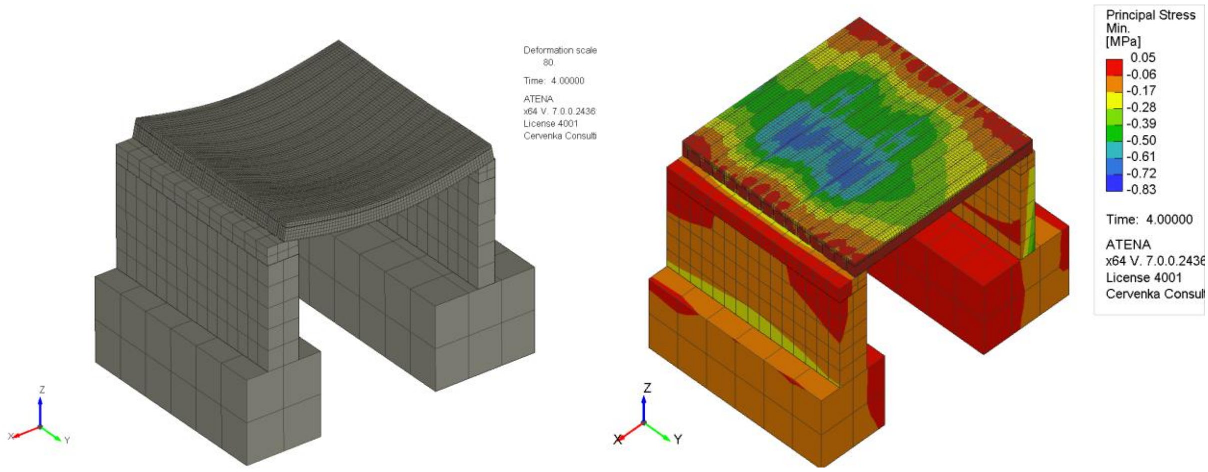

Fig. 14: Kostomlaty bridge numerical model showing the deformed mesh and stresses in the structural elements.

The calibration task was formulated and executed within the **STONE environment**, where individual functional components are represented as interconnected nodes (Fig. 16). The workflow integrates:

- the nonlinear physical model implemented in ATENA,
- stochastic sampling and optimization methods provided by the **FReET** library,
- and the processed monitoring data.

Within this framework, the bridge model was decomposed into several regions with independently identified mechanical properties (Fig. 17). The stochastic optimization procedure searches for parameter sets that minimize the discrepancy between simulated and measured structural response. The results of the optimization process (Fig. 18) demonstrate the capability of STONE to efficiently identify plausible parameter combinations and to quantify uncertainty in the calibrated model parameters.

To further enhance computational efficiency, **surrogate models based on artificial neural networks** were introduced as specialized nodes within the STONE environment (Fig. 20) [6]. These surrogate models approximate selected parts of the nonlinear simulation and enable rapid evaluation of temperature effects and other external influences on the monitored response (Fig. 21), which would otherwise require prohibitively expensive full nonlinear simulations.

This example validates the ability of the **STONE software (TM04000012-V3)** to combine nonlinear physical modelling, stochastic methods, monitoring data, and surrogate modelling within a single, configurable workflow. The results demonstrate that STONE enables effective calibration and interpretation of complex structural behavior under uncertainty, providing a robust basis for assessment and prognosis of existing bridge structures.

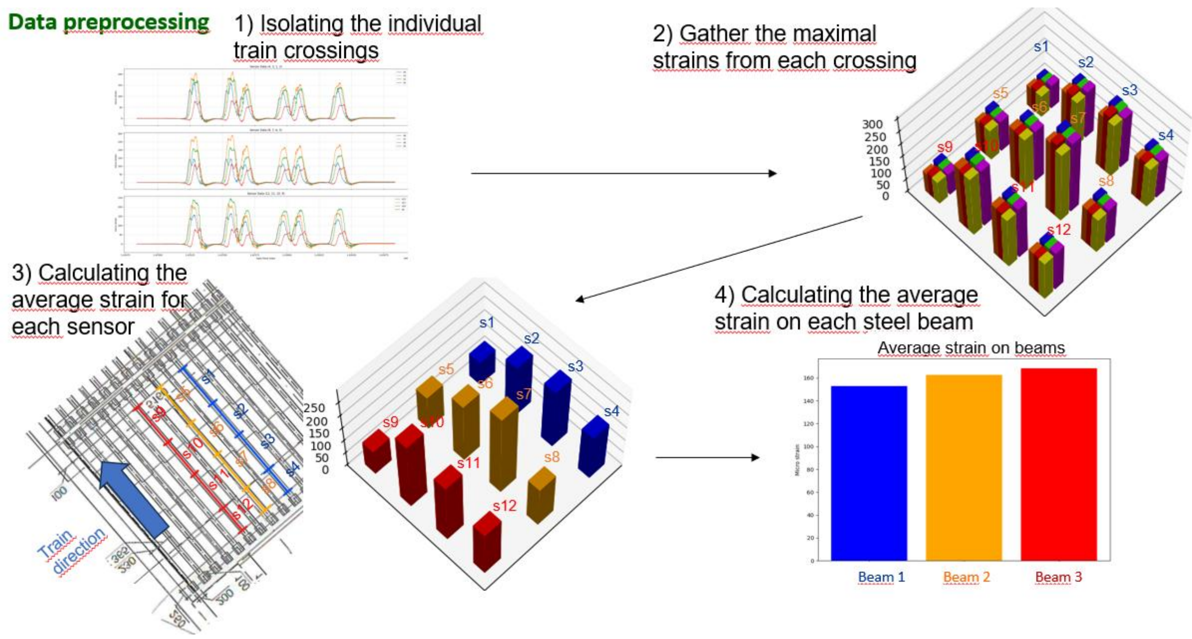

Fig. 15: Pre-processing of the large amount of monitoring data to simplify and increase the efficiency of the optimization strategy.

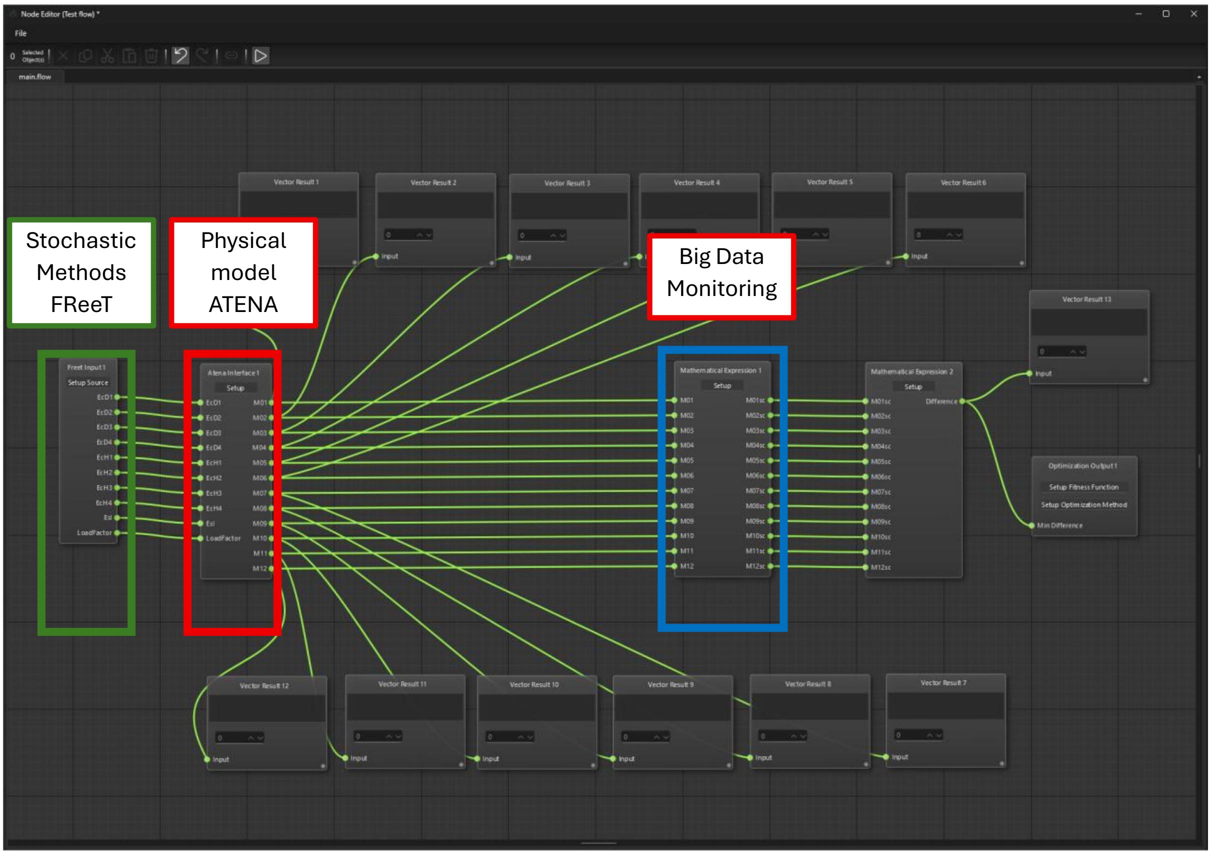

Fig. 16: Implementation of the Kostomlaty calibration and optimization task in the STONE environment with the indicated special nodes for stochastic methods FreeT, nonlinear physical model ATENA and the connection with the monitoring data.

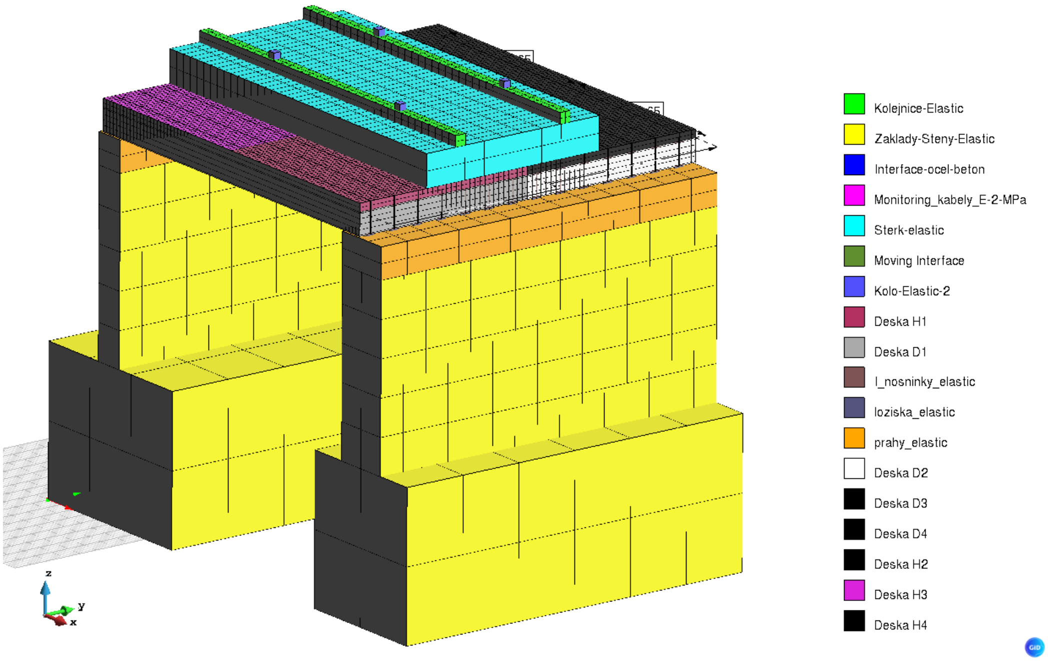

Fig. 17: Numerical model showing the decomposition of the model into several regions, for which the mechanical properties are being identified by the developed STONE software based on the measured data from the installed monitoring system.

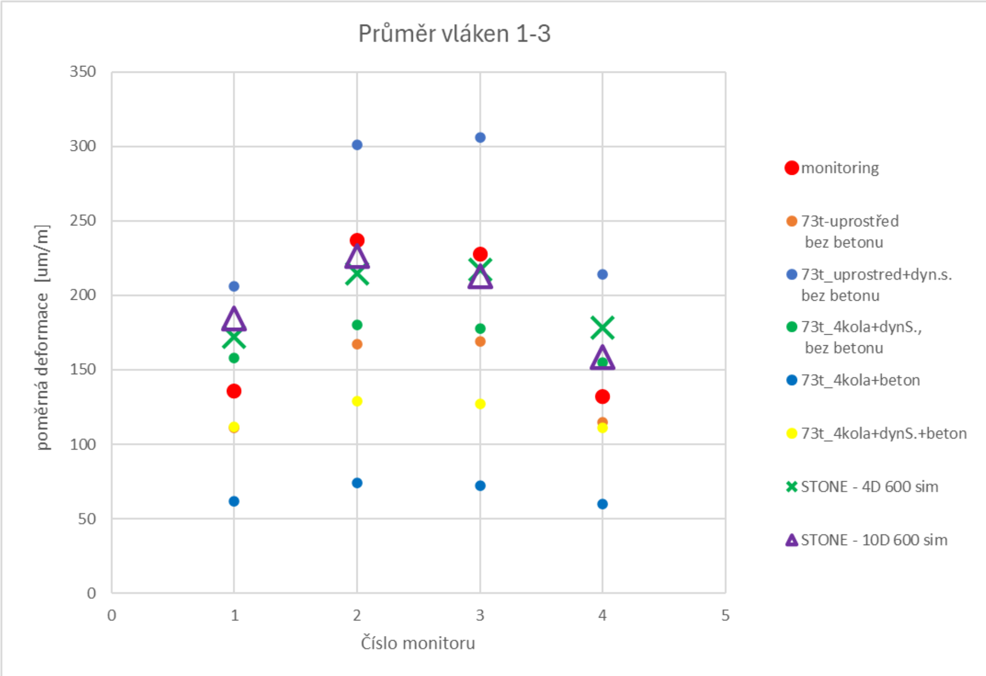

Fig. 18: Result of the stochastic optimization approach implemented in STONE software for the identification of material parameters to match the measured data. Two optimization solutions are denoted by green crosses and purple triangles. The results can be compared also with manual optimization by trial/error approach.

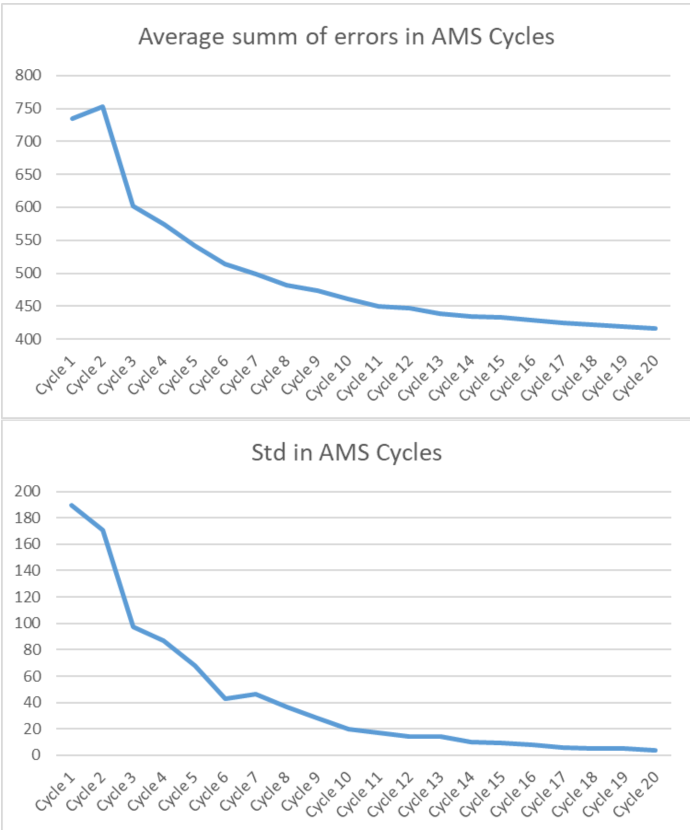

Fig. 19: Evolution of average error and standard deviation in the optimization task of Kostomlaty bridge in the environment of the software STONE.

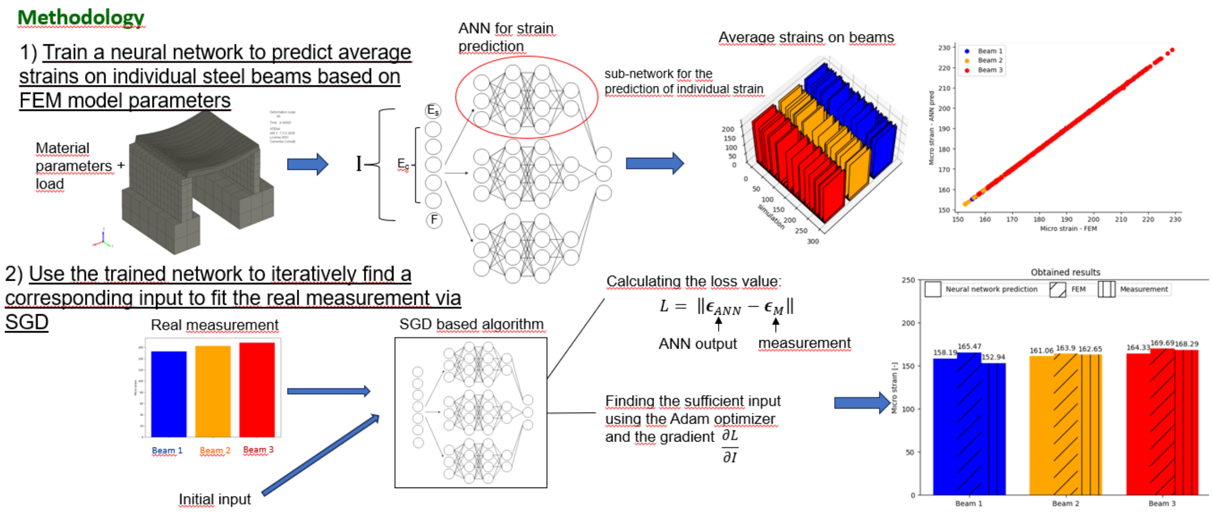

Fig. 20: Methodology of the development of special neural networks nodes for the development of surrogate models to increase the efficiency of the stochastic optimization.

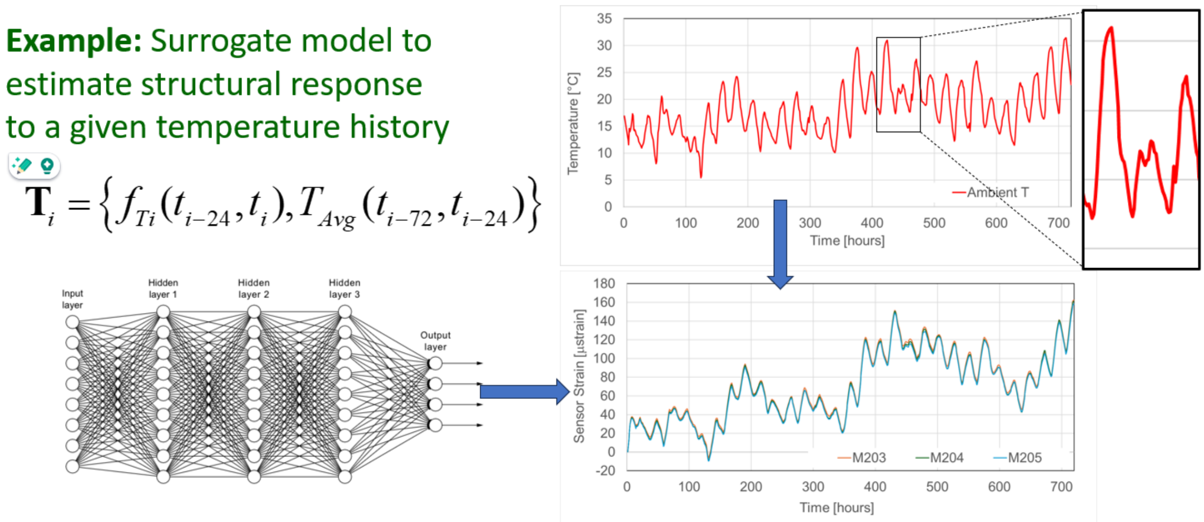

Fig. 21: Surrogate model application using artificial neural networks that is trained to quickly predict and identify the effect of external temperature on the bridge response and monitoring data reading.

3.2 Power House Damage Investigation

This case study presents the application of project results to the investigation of damage mechanisms in a reinforced concrete power house structure subjected to long-term thermal and environmental loading. Unlike the previous bridge example, this case focuses primarily on **thermo-mechanically induced deformation and cracking**, demonstrating the versatility of the project results for different classes of civil engineering structures.

The investigated structure is the **De Cew II power house**, a massive reinforced concrete facility for hydroelectric power generation (Fig. 22). Due to its size, geometry, and exposure to seasonal and operational temperature variations, the structure exhibits complex deformation patterns and cracking that cannot be reliably assessed using simplified analytical approaches.

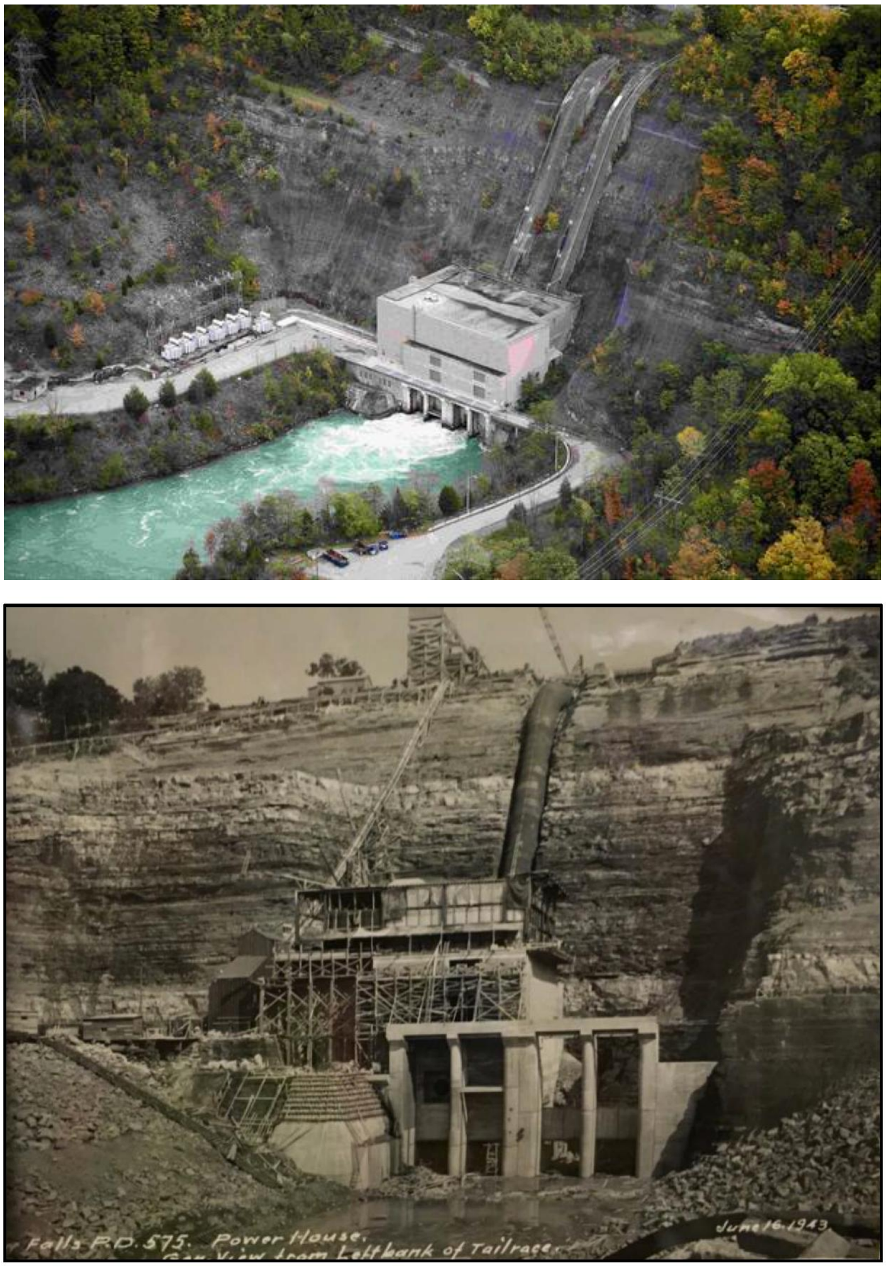

Fig. 22: Photo of the De Cew II powerhouse at present and during the construction.

A detailed three-dimensional nonlinear finite element model of the power house was developed in the **ATENA** software (Fig. 23 to Fig. 24). The model includes the reinforced concrete superstructure as well as relevant parts of the foundation, allowing realistic simulation of structural stiffness, cracking, and interaction between structural components. The nonlinear physical model serves as the deterministic core of the analysis, capable of reproducing temperature-induced stress redistribution and damage evolution.

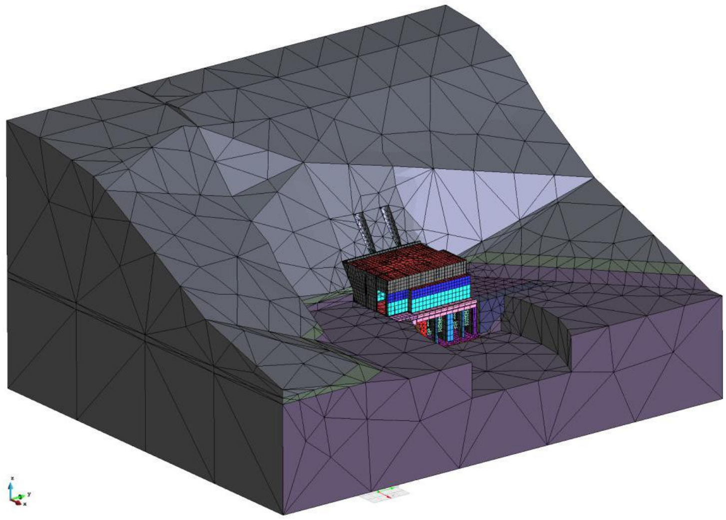

Fig. 23: De Cew II powerhouse numerical model in ATENA software consisting of the reinforced concrete building as well as parts of the foundation.

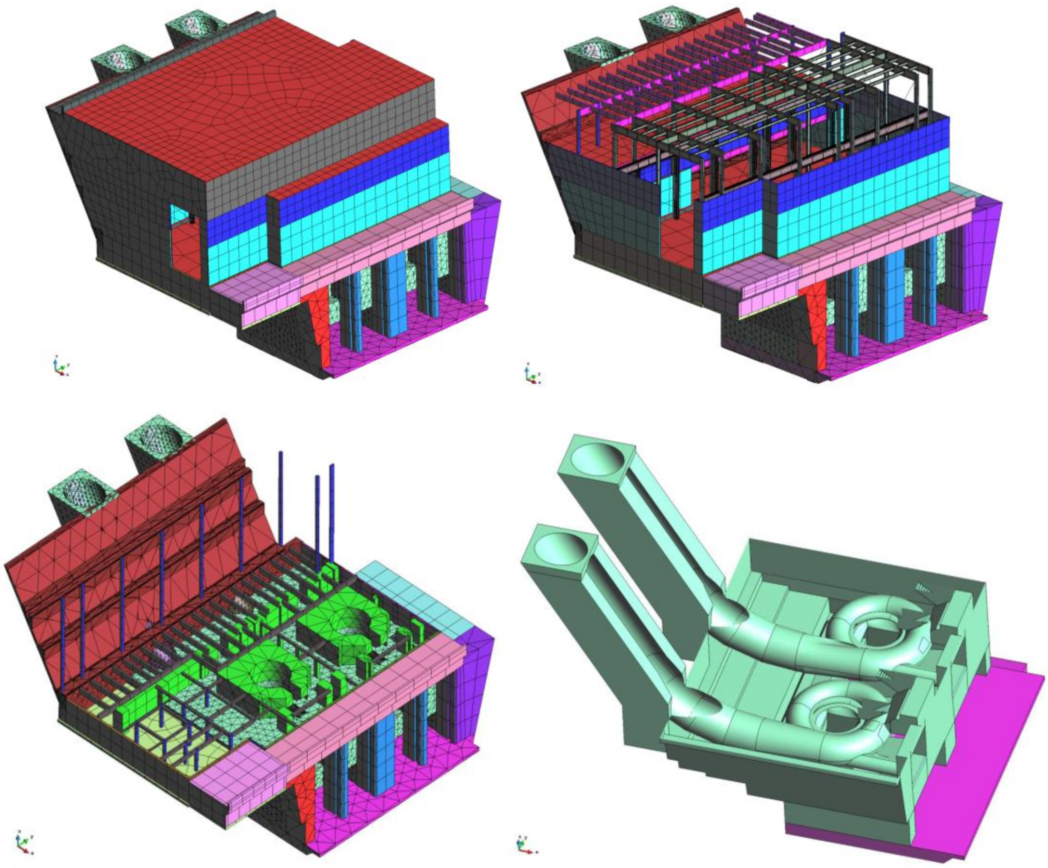

Fig. 24: Details of the interior parts of the numerical model in ATENA software NODE of De Cew II powerhouse.

The structure has been equipped with a monitoring system providing long-term measurements of temperature and displacement at multiple locations and elevations. These data represent a typical example of **large monitoring datasets**, characterized by long observation periods, environmental variability, and measurement noise. Direct interpretation of such data without physical modelling is not sufficient to reliably identify damage mechanisms or predict future behavior.

Within the project terminology, the analysis workflow was formulated as a combination of interconnected software tools representing:

- the nonlinear physical model in ATENA,
- methods for parameter sampling and model updating,
- and measured temperature and displacement data.

The primary objective of the analysis was to identify combinations of material and boundary condition parameters that provide the best agreement between simulated and measured structural response. Comparisons of temperature profiles and displacement evolution at selected locations (Fig. 26 to Fig. 28) demonstrate that the calibrated nonlinear model is capable of reproducing the observed behavior with good accuracy. The resulting simulations also provide detailed insight into crack patterns and damage localization within the structure (Fig. 25), which are not directly observable from monitoring data alone.

This example integrated the thermo-mechanical nonlinear simulation with large volumes of monitoring data in a unified computational workflow. The results show that it was possible to match quite accurately the measured responses, but also **physical interpretation of underlying damage mechanisms**, which is essential for reliable assessment of structural safety and long-term performance.

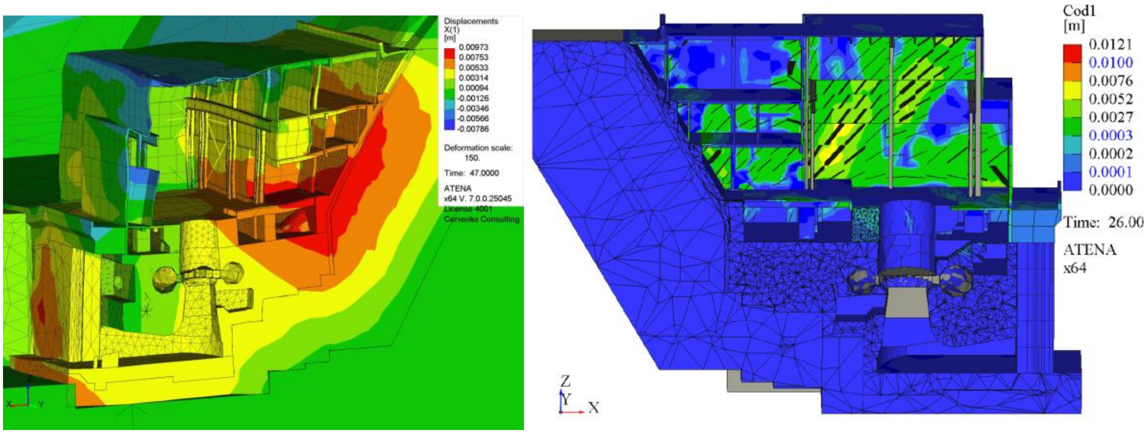

Fig. 25: Typical view of displacement contours and crack damage obtained in the nonlinear simulation.

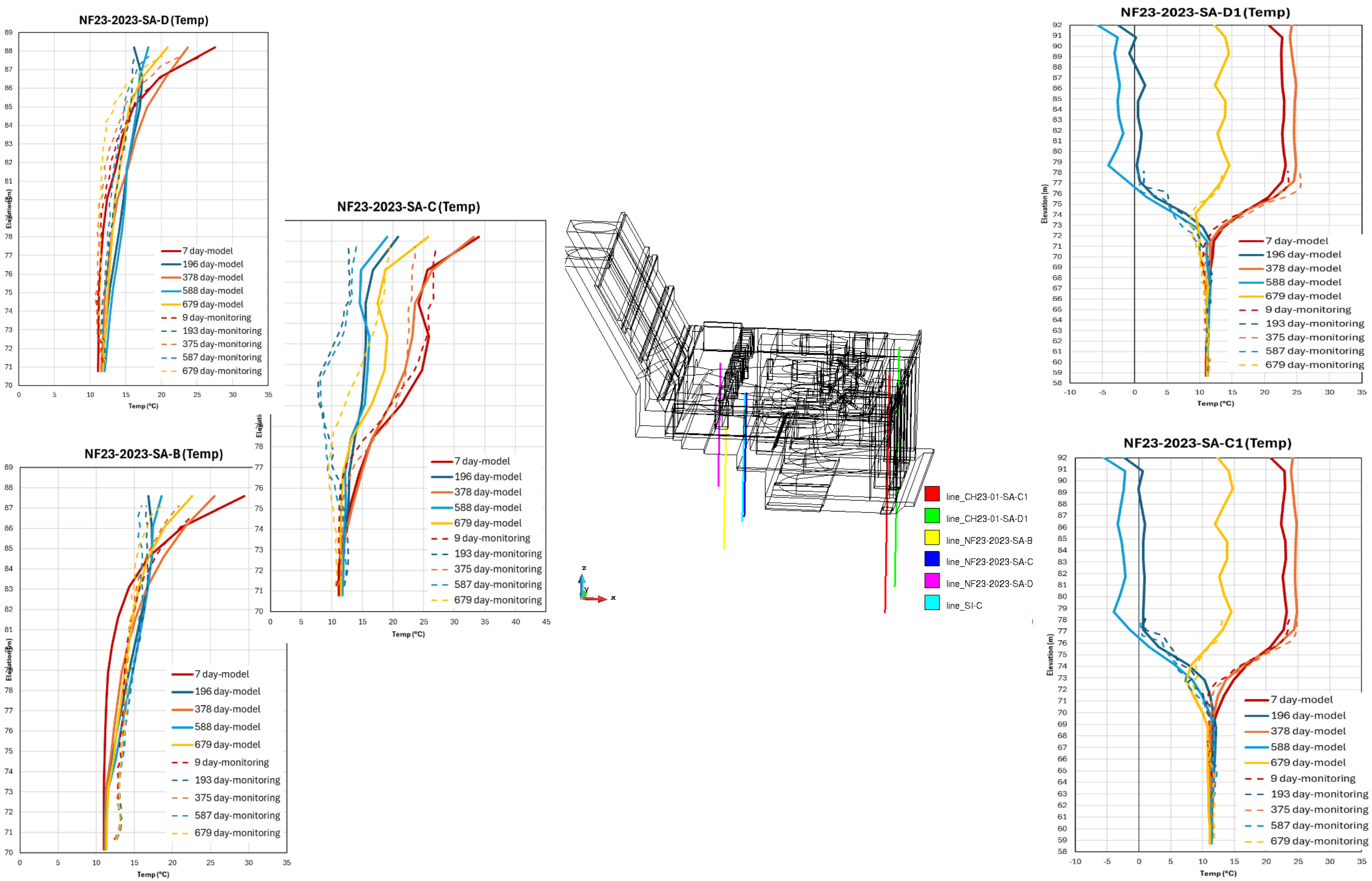

Fig. 26: Comparison of temperature profiles at selected extreme dates in summer and winter (best match jc19).

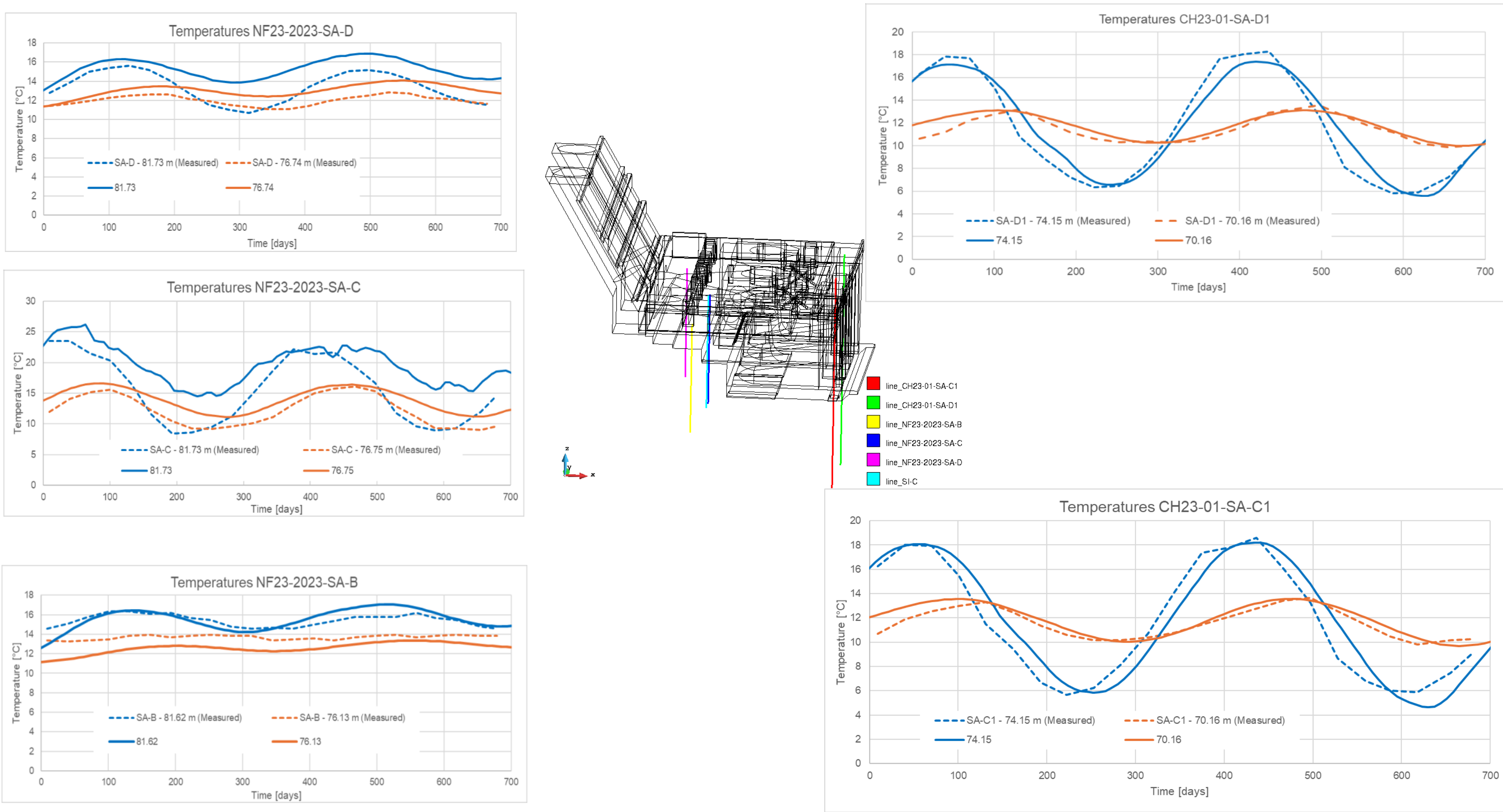

Fig. 27: Comparison of temperature evolution at selected elevations (best match jc19).

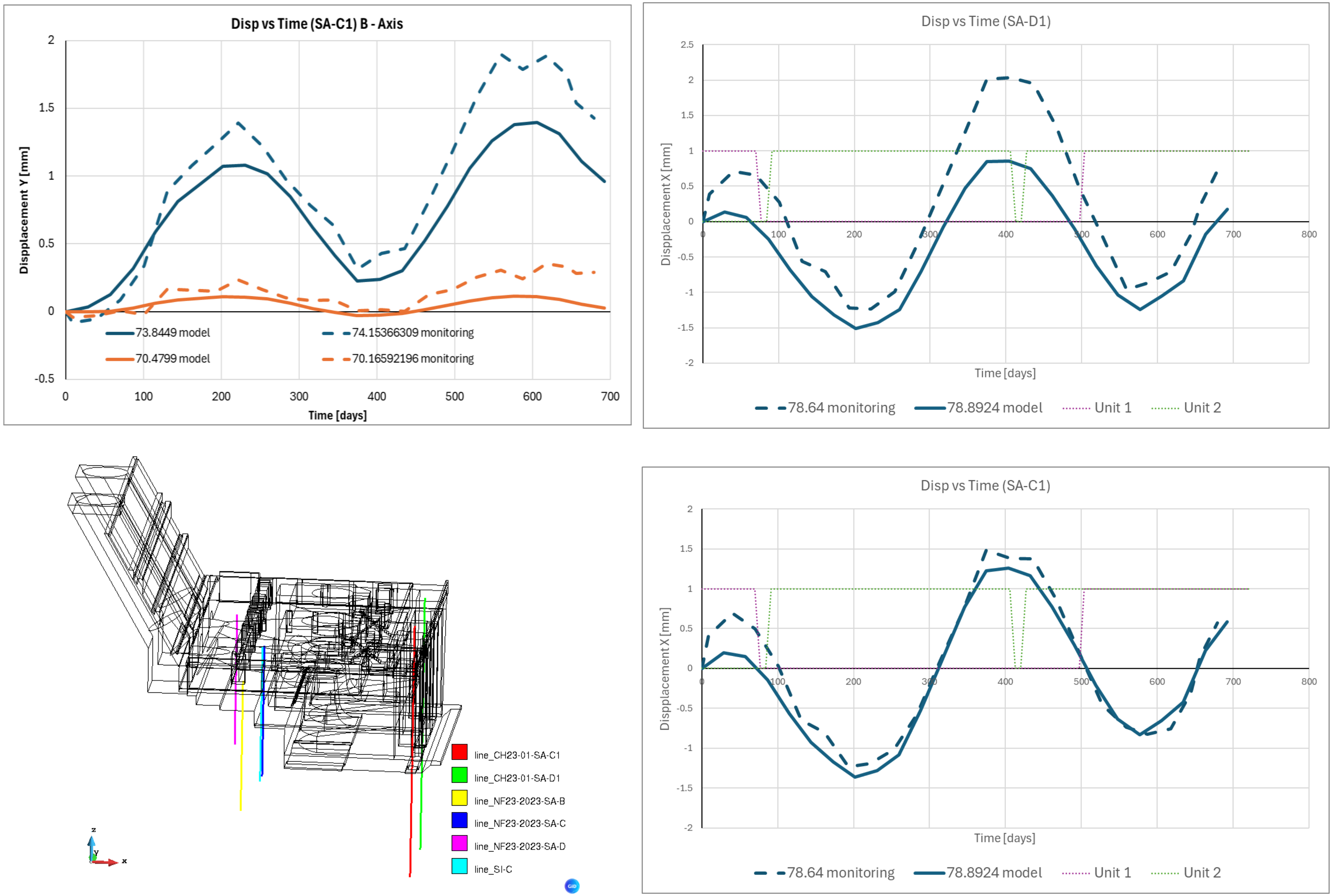

Fig. 28: Comparison of displacements evolution at selected elevations (best match jc32)

3.3 Durability Modelling of Reinforced Concrete Bridge

This case study demonstrates the application of the methods and tools developed within the project to the **long-term durability assessment of a reinforced concrete bridge**, with particular emphasis on chloride ingress, reinforcement corrosion, and their interaction with mechanical damage. The example illustrates the ability of the developed approach to combine **time-dependent material degradation models** with nonlinear structural analysis and to provide **physically meaningful predictions of future structural performance**, supported by comparison with observed damage in the real structure.

Durability-related degradation processes, such as chloride penetration and carbonation, represent one of the most critical threats to the long-term safety and serviceability of reinforced concrete bridges. These processes evolve over decades and are strongly influenced by environmental exposure, material properties, crack development, and structural response under mechanical loading. Reliable assessment of durability therefore requires an integrated modelling approach that accounts for both **transport phenomena** and **mechanical damage evolution**, as well as validation against observed structural condition.

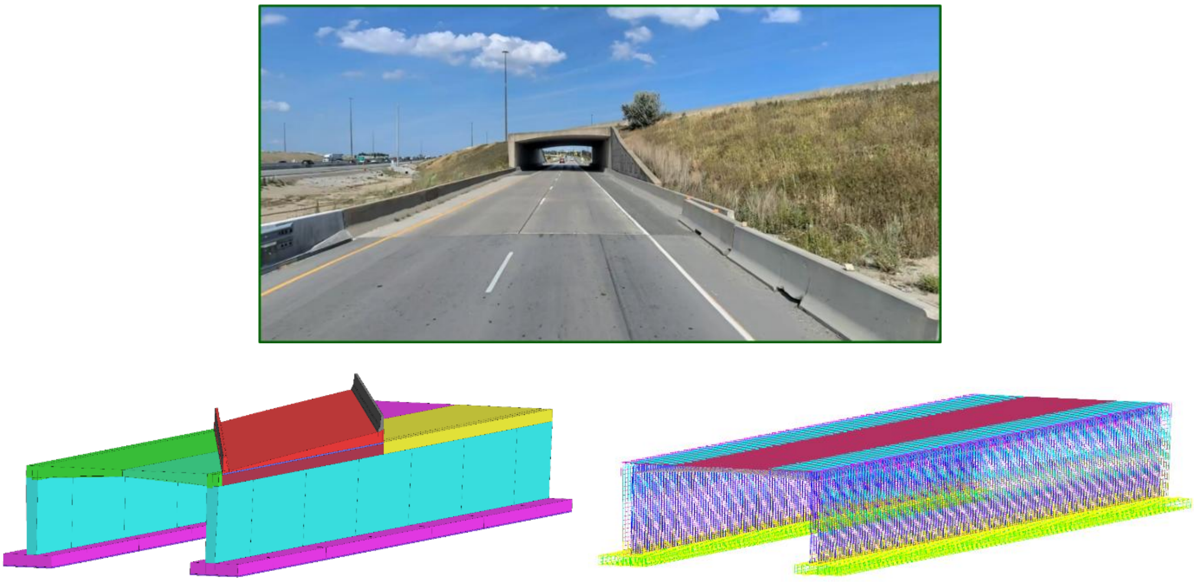

Fig. 29: View of the investigated highway bridge and the used numerical model for long term durability modelling.

In this study, the investigated highway bridge (Fig. 29) was analyzed using a coupled modelling strategy that combines:

- a **one-dimensional transport model** for chloride ingress and carbonation,
- and a **three-dimensional nonlinear mechanical model** of the reinforced concrete structure.

The transport model simulates the penetration of chlorides into concrete as a function of time and environmental conditions. The resulting chloride concentration at the reinforcement depth is then used as input for modelling the initiation and progression of reinforcement corrosion. These effects are subsequently introduced into the nonlinear mechanical model, where corrosion-induced expansion leads to cracking, spalling, and stiffness degradation of the concrete.

The nonlinear mechanical behavior of the bridge, including cracking and damage evolution, was simulated using advanced constitutive models for concrete and reinforcement (Fig. 30 - Fig. 32). The modelling approach explicitly accounts for the interaction between mechanical loading, shrinkage and creep effects, and corrosion-induced damage. This interaction is particularly important, as existing cracks significantly accelerate chloride ingress, while corrosion-related cracking further modifies the mechanical response of the structure.

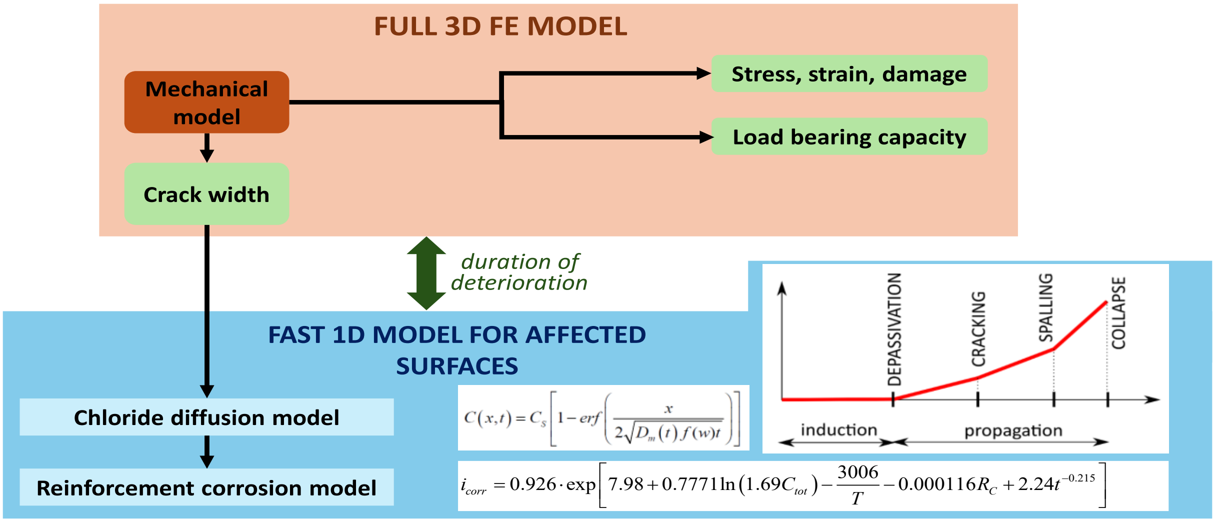

Fig. 30: Schema of the used durability model consisting of 1D model used for chloride ingress that is applied in full 3D nonlinear physical damage modelling.

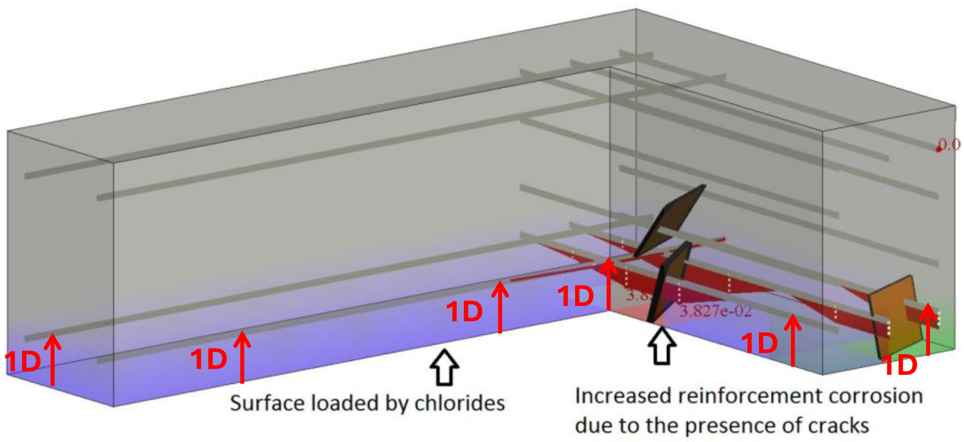

Fig. 31: Visualization of the interaction of 1D chloride ingress model and the 3D mechanical model for concrete damage simulation.

A key part of the validation process was **the matching of the simulated damage patterns and crack widths with observations from the real structure**. The evolution of cracking and damage during the early-age period and the subsequent operational phase of the bridge is shown in Fig. 32 to Fig. 35. The calculated crack locations, orientations, and crack widths exhibit good agreement with observed behavior obtained from inspections and monitoring, providing confidence in the physical consistency of the applied models and in the calibration of material and durability-related parameters.

Based on the calibrated and validated model, long-term simulations were performed to predict the future development of damage and corrosion over the expected service life of the bridge (Fig. 36 to Fig. 37). These predictions account for the coupled effects of environmental exposure, mechanical loading, and material degradation, and provide insight into the likely progression of cracking and reinforcement corrosion over time.

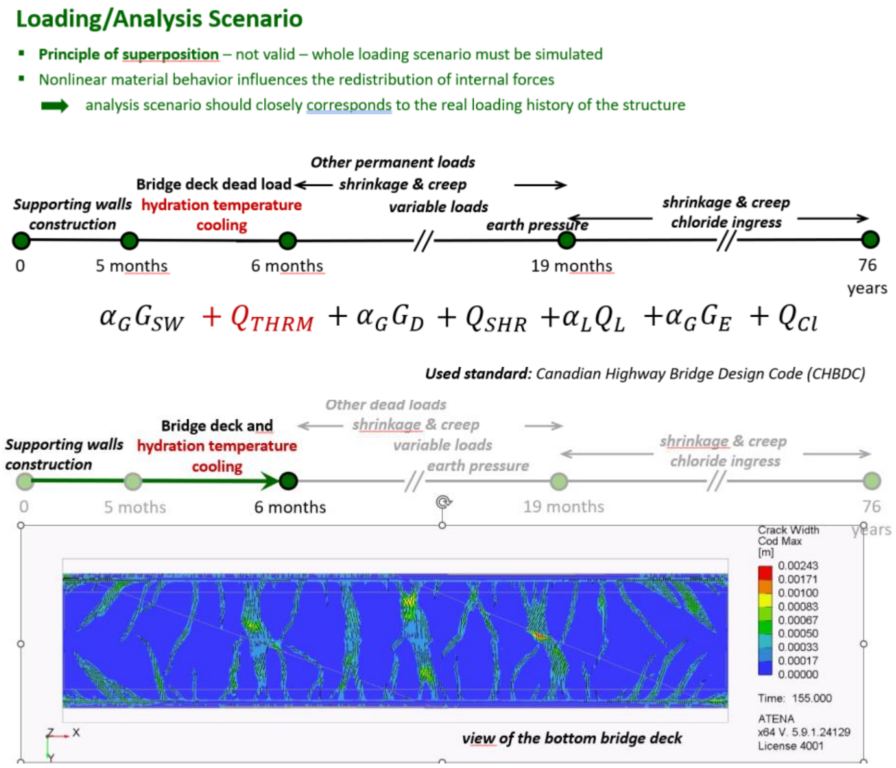

Fig. 32: Concrete deck cracking and damage evolution during the early age concrete maturing and shrinkage.

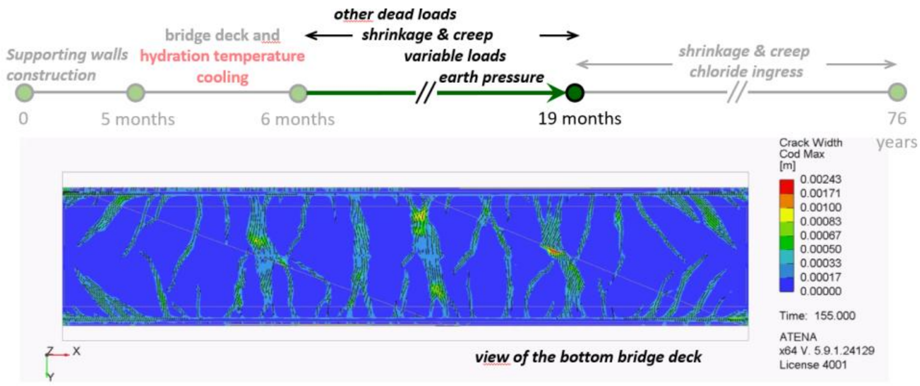

Fig. 33: Concrete deck cracking and damage evolution during the 19 months period after the bridge construction, namely due to shrinkage and creep.

The analysis further enabled evaluation of the **load-carrying capacity and structural reliability** under various scenarios of material degradation and corrosion parameters (Fig. 38). These results demonstrate how uncertainty in durability-related parameters can significantly influence long-term structural performance and highlight the importance of integrating degradation models into nonlinear structural assessment.

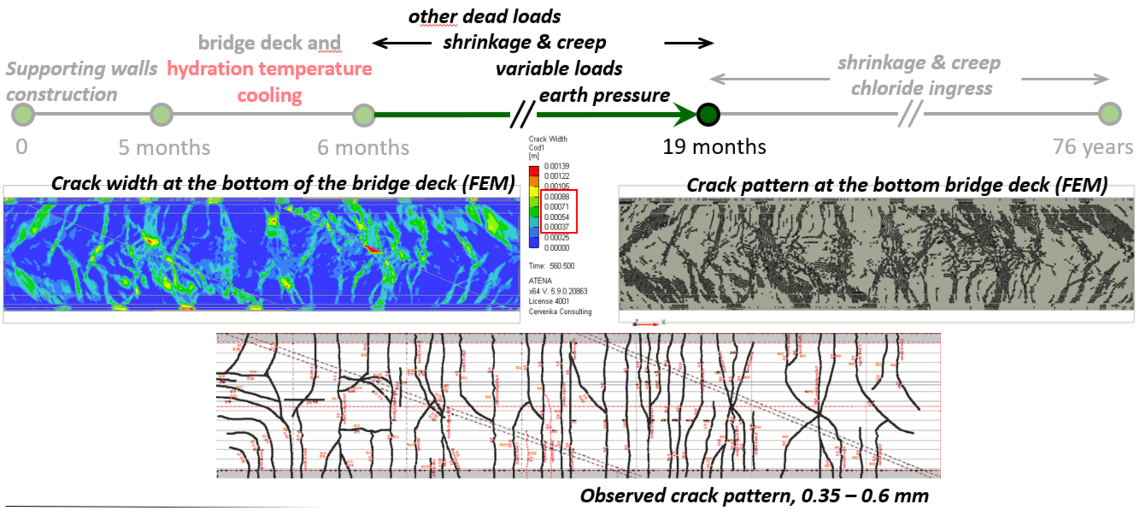

Fig. 34: Concrete deck cracking and damage evolution during the 19 months period after the bridge construction and the calculated response matching with the observed crack pattern and widths.

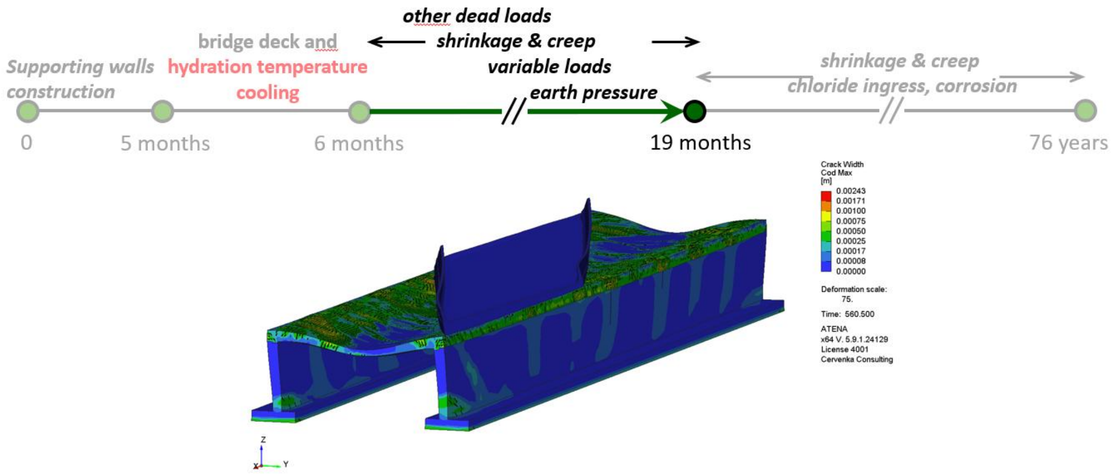

Fig. 35: Overall bridge deformation and crack pattern after 19 months after the bridge construction.

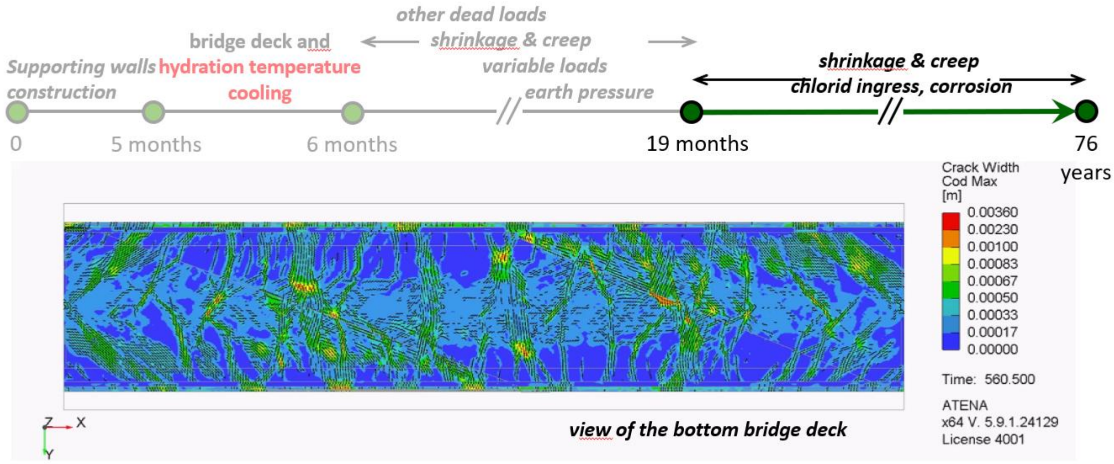

Fig. 36: Predicted future bridge deck cracking and damage evolution in 76 years after the bridge construction.

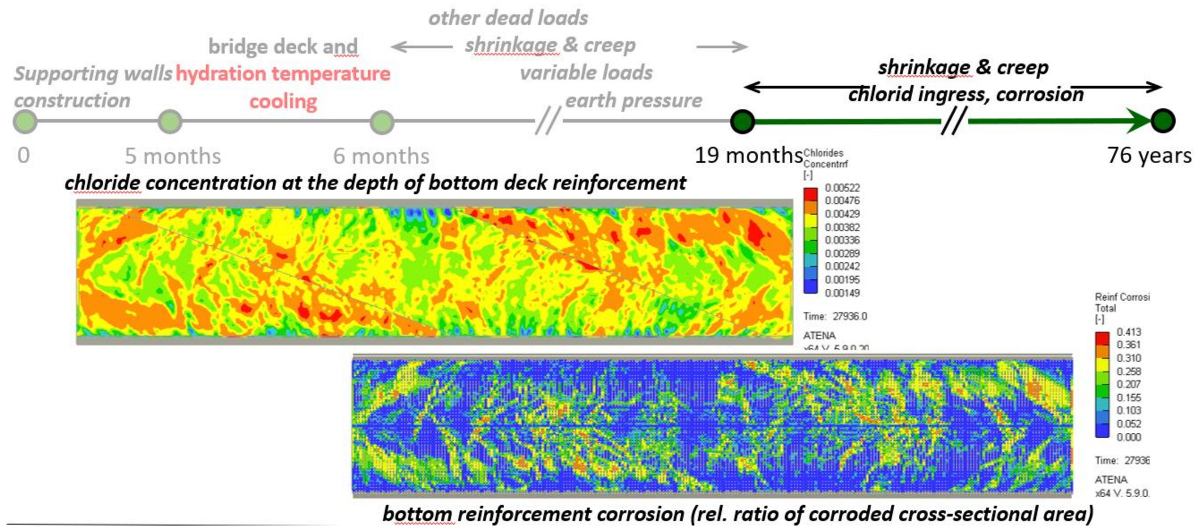

Fig. 37: Predicted future bridge deck chloride concentrations at reinforcement depth and resulting reinforcement corrosion after 76 years of bridge life.

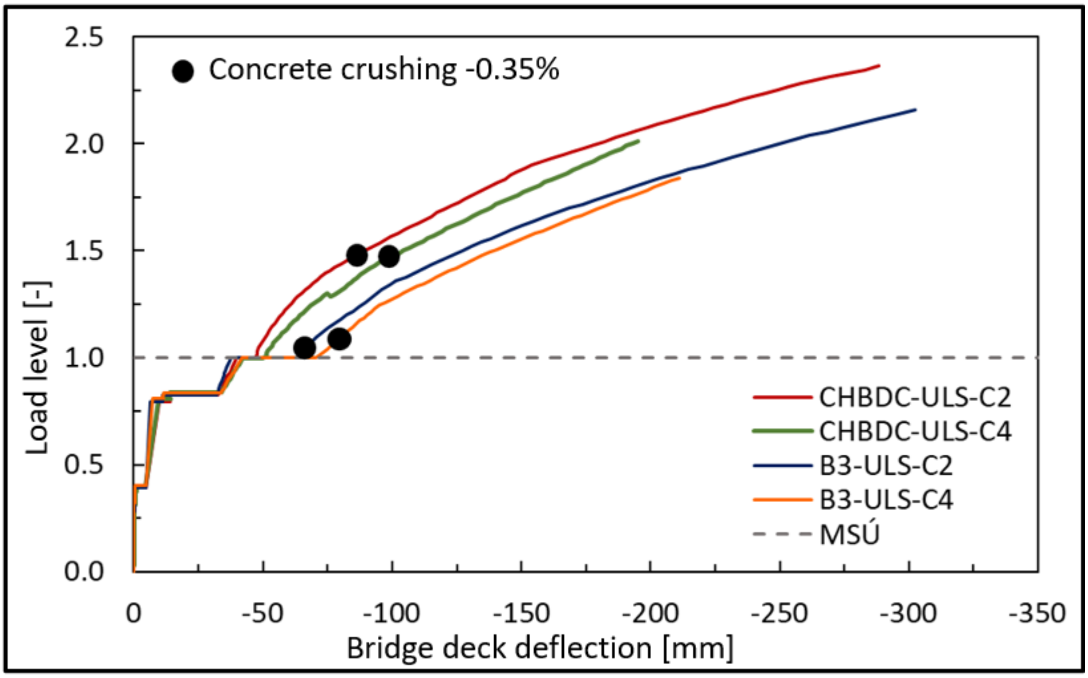

Fig. 38: Calculated load displacement curves and bridge load-carrying capacity for various scenarios of corrosion parameters and shrinkage and creep models.

This example validates the capability of the developed project methodology to **combine durability modelling, nonlinear damage simulation, comparison with observed damage, and long-term prognosis** within a unified computational framework. It demonstrates that the tools developed in the project are suitable not only for assessment of current structural condition, but also for **prediction of future performance and remaining service life**, which is essential for informed decision-making in bridge management and maintenance planning.

4 Conclusion

This document has presented the validation and example-based verification of the software result **TM04000012-V3**, developed within the research project *“A concrete bridge health interpretation system based on mutual boost of big data and physical mechanism”*. The objective of the document was to demonstrate, through representative examples, that the methods and tools developed in the project form a reliable and practically applicable framework for advanced assessment of reinforced concrete structures under uncertainty.

Validation was carried out at multiple levels. First, the underlying **nonlinear physical modelling framework** was shown to be robust and well validated through comparison with experimental data and international benchmark studies. This deterministic core provides the necessary foundation for the application of stochastic methods and data-supported model updating.

Second, the real case validation examples presented in **Sections 3.1–3.3** demonstrated the applicability of the developed approach to realistic engineering problems. The small railway bridge case confirmed the ability to calibrate nonlinear structural models using large volumes of monitoring data and stochastic optimization techniques. The power house investigation demonstrated the integration of thermo-mechanical effects and long-term monitoring data for interpretation of complex structural behaviour. The durability modelling example illustrated the coupling of transport processes, corrosion-induced damage, and nonlinear mechanical response, including validation through comparison with observed crack patterns and crack width data and subsequent long-term prognosis of structural performance.

Together, these examples demonstrate that the developed methods enable consistent integration of **physical mechanism-based modelling**, **stochastic analysis**, and **measured data** within a unified computational workflow. The approach supports not only the interpretation of current structural condition, but also physically meaningful prediction of future behaviour and remaining service life.

The results presented in this document confirm that the software result **TM04000012-V3** fulfills its intended objectives and represents a **validated and practically applicable software outcome**. The developed tools are suitable for use in engineering practice, advanced structural assessment, and further research, particularly in applications involving existing infrastructure with available monitoring data.

In summary, the project has successfully delivered an integrated framework that advances the state of the art in structural health interpretation of concrete bridges and related structures, providing a solid basis for informed decision-making in infrastructure management and maintenance planning.

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