Data-supported modeling of structural behavior in construction
DataBridge (SNN 134368)

(2020 – 2024)

Final technical report by Noémi Friedman

Introduction, motivation, project objectives

Modern civil engineering design relies heavily on finite element (FE) modeling and design codes. However, once a structure is built, there is often a lack of information on how these design methodologies correspond to the actual behavior of the structure. This is particularly problematic for non-conventional structures that lack well-established design procedures. In reality, structural behavior often deviates from FE model predictions due to uncertainties in the models.

To identify these discrepancies, it is necessary to measure the actual behavior of as-built structures. Collecting and using this data to improve design procedures represents a significant shift in engineering processes. However, the construction sector has been slow to adopt digitalization compared to other engineering sectors. Additionally, continuous data collection via IoT devices can enhance the monitoring of structural health and safety, supporting informed decision-making for critical structures like bridges and hospitals.

The objective of the DataBridge project was to demonstrate the applicability of advanced AI approaches and probabilistic methods in civil engineering. We focused on a set of representative structures—a highway bridge, a footbridge, and non-conventional tall timber structures—to illustrate the following:

- How data-driven models can analyze Structural Health Monitoring (SHM) data, derive effects of environmental conditions, and automatically send alerts when structural behavior deviates from expected norms.
- How design procedures can be reconsidered and FE models improved by Bayesian updating, which helps identify modeling errors.
- How continuous model updating using IoT data can develop a digital twin—a digital representation of the as-built structure—to support continuous, efficient structural health monitoring.

We used uncertainty quantification methods, sensitivity analysis, model-agnostic techniques for feature attribution, Bayesian inversion techniques, and various data-driven modeling techniques such as general polynomial chaos expansion, deep neural networks, mixture density networks, and ensemble tree methods to achieve these objectives.

Collaborative work, project management

We kicked-off the collaboration by a four days seminar, that was held online by Dr. Noemi Friedman (SZTAKI) and Prof. Hermann G. Matthies (TU Braunschweig) in the University of Ljubljana about Bayesian finite element model updating, where we have overviewed already existing methods that could be used in civil engineering.

We had three bigger life DataBridge project meetings, one in Ljubljana and two in Budapest. We also found the possibility to organize smaller DataBridge life meetings merged with other professional occupations (e.g. workshop in Ljubljana, EMI conference in Italy, other international project meetings). We had monthly meetings via video conferences. Individual working groups worked remotely via video links.

The implementation of the research project proceeded exceptionally smoothly. Close and seamless collaboration was established among the project groups from the HUN-REN Institute for Computer Science and Control (SZTAKI) , the Faculty of Civil and Geodetic Engineering, University of Ljubljana (UL FGG), and the Slovenian National Building and Civil Engineering Institute (ZAG).

The collaborative efforts between SZTAKI and UL FGG were further facilitated by the co-supervisement of the PhD work carried out by Blaz Kurent mentored by Noémi Friedman (SZTAKI) and Bostjan Brank (UL FGG). Kurent successfully defended his PhD thesis at the end of 2023.

The DataBridge tasks were divided as follows:

- ZAG performed the measurements on as-built structures;
- SZTAKI with ZAG used big-data and AI methods to pre-process and analyse data, train data-driven models and add model agnostics to deduct the different effects and to find anomalies;
- UL FGG carried out numerical FE modeling;
- SZTAKI and UL FGG with the supervisement of SZTAKI developed a library package for stochastic analysis, sensitivity analysis and uncertainty quantification for buildings and infrastructures using different machine learning techniques;
- SZTAKI, ULL FGG and ZAG jointly developed a procedure for Bayesian updating of numerical models of structures based on vibration measurements.

Changes to the work program

The research project was conducted in accordance with the program outlined in the project proposal. There was one significant deviation from the original plan: Noémi Friedman assumed leadership of the project at SZTAKI right at the beginning of the project period, instead of András Benczúr, who was originally designated for this role. This change was necessitated by András Benczúr's newly acquired leadership of the Hungarian National AI Laboratory (MILAB), which came with substantial responsibilities. Despite this major change, the project proceeded as planned. Noémi Friedman possessed the necessary skills to lead the research group, while András Benczúr remained involved as a senior researcher to provide guidance when needed.

During the project, some members of the project group changed, but this also didn’t affect the implementation of the project, as the leading members (Noémi Friedman at SZTAKI, Bostjan Brank at UL FGG and Uros Bohinc at ZAG and SZTAKI) remained the same.

There were minor modifications to the budget, mainly involving small allocations. E.g. the cost of equipment for the project increased slightly due to COVID-19, but the discrepancy was covered by the funds originally allocated for travel expenses for in-person meetings, which had to be held online because of the pandemic. Another change was made due to budget allocated for assuring open access of our last submitted journal paper. Due to the long reviewing process, we have decided to prolongate the project with 6 months so that we can spend this money for its designed purpose, but unfortunately the paper is still under review (though the first reviewed version was already resubmitted last year.

Work performed

The work was structured into three scientific work packages (WPs).

Most of the **measurements** were carried out in the framework of **WP2 led by ZAG**. Besides general synthetic toy models [1] the project tested and showcased the new methods developed on the following civil engineering structures: a) three tall timber buildings [2-8] with a special attention on a building in Glasgow (YOKER) [3] b) the Ravbarkomanda highway bridge [9-11] c) a general earth fissure problem [12] d) a steel frame toy structure of medium size (2m x 2m x 4m) built in ZAG for this project [13] e) a footbridge in Ljubljana [13]. The vibration test results of the tall timber buildings were provided by another European project, DYNATTB. The synthetic data of the earth frissure problem was generated by University of Padova. All the other measurements − vibration test of the two bridges and the toy structure, and the long-term continuous SHM testing of the Ravbarkommanda bridge − were designed and collected by ZAG.

All synthetic data received from physics-based simulation models (generated from FE models) as well as data from the vibration test of as-built structures were pre-processed and analyzed with a joint work between the three institutes **in WP3**. We used exploratory data analysis before further processing the data. From the vibration data we derived modal properties, eigenvalues and egienfrequencies of the structures as well as the corresponding uncertainties in the form of distributions representing the confidence in these measured values.

SZTAKI with the assistance of ZAG and UL derived different-purpose data-driven models:

- Linear regression, ensemble tree models, deep neural networks, convolution networks, long-short-term memory models (LSTM) extended with model-agnostic methods **to analyze SHM data (**see e.g. [9-11]).
- Generalized Polynomial Chaos Expansion (gPCE) and ensemble tree methods **to develop a surrogate model of the Finite Element (FE)** analysis using synthetic data generated by the FE code (see e.g. [2-8, 12, 13].

Derivation of the best applicable models were derived with the help of cross validation techniques.

In WP 4 stochastic modelling and model updating were carried out for many analyzed models. UL FGG prepared **FE** numerical **models** of all the structures (except the earth fissure model, that was developed by Padova University).

SZTAKI developed a stochastic framework for the uncertainty quantification and sensitivity analysis of the structural responses of civil engineering structures, to see how the uncertainties of the exact values of different design parameters or parameters describing ageing processes can influence the building behavior, how the initial, a-priori uncertainties propagate through the model. With the leadership of SZTAKI the update procedure of simulation models based on measured data of modal properties was also developed within a collaborative work with UL FGG.

The developed codes of the stochastic framework can be wrapped around a deterministic FE codes. The **wrapper and the tools have been tested** on simple toy models and several FE models (three timber buildings [2-8], the earth fissure model [12] and the pedestrian bridge [13]).

SZTAKI succeeded in developing **a novel updating framework using modal data** with the help of the generalized inverse **mixture density model which is capable of an online update procedure of the FE model.** Such analysis can be extremely helpful in developing an efficient structural health monitoring system. The procedure was only tested for the one-time update of the FE model of the Yoker building allowing a comparison between the already published methods and the newly developed one [6]. Unfortunately, we had no IoT data available yet to test the online updating capabilities of the model.

We have used Sobol global sensitivity measures for optimal sensor placement, and we have investigated how to take into account model errors on simple toy examples, on a cantilever example.

Main scientific achievements

Explainable AI model for subtracting effect of environmental conditions tested on a viaduct

The usability of AI methods for civil engineering structures was first tested on the Structural Health Monitoring (SHM) data of the more than 45 years old reinforced concrete Ravbarkomanda viaduct, a highway bridge in Slovenia. Weather station data, traffic data, temperature sensors and data from strain gauges were used for the analysis. Following some correlation analysis as well as the visualization of the data and cleaning it, the main target was to develop an explainable machine learning model capable of separating the effects of the weather and traffic conditions on the structural behaviour of the bridge. behaviour such as the changes of the frequencies of prestressed cables and the changes of the strains in the main beams and the cantilever of the structure. In this way, we obtained the basic values of the measurable bridge behavior. Deviation from this value may indicates damage. We published the results at a European conference [9], and on a Hungarian event “HIDASZ napok” organized for bridge experts from academy and industry (HIDASZ napok) and published it in its special edition [10].

Demonstrating the use of probabilistic approaches in civil engineering

As a first step preliminary digital twins were developed in the form of FE models based on best engineering judgement predicting the dynamic properties of the structures. The second step was to carry out ambient and/or forced vibration tests. Then the FE model was changed to a probabilistic setting considering all the model uncertainties (of design/modeling parameters and of material/geometrical properties). By optionally replacing the FE model with a computationally significantly less expensive proxy model can facilitate the further demanding steps. For the proxy modelling of modal properties we have tackled the problem caused by frequency switching [3]. One important aspect of the probabilistic modelling is to quantify how the parameter uncertainties propagate to the quantity of interest, e.g. the dynamic characteristics of the structure and the influences of the different uncertain parameters. The final step is the updating of the model by updating its uncertain parameters using Bayesian updating based on the measured modal properties, its inherent uncertainties due to the measurement errors and the prior uncertainties of the model parameters. With the help of the updating, we came to interesting conclusions about the stiffnesses of individuals structural elements, which has considerable practical value. In the case of tall wooden buildings (where there is still much unknown about the functioning of individual parts of the structure) with the methods used, we were able to estimate the stiffness of individual structural elements, and in the case of steel frames, the stiffness of (screwed) joints. We have published the results in journal papers [1][3][5][8][12] (where [5] is still under review), in lectures at conferences [2][4][6] [14], and at workshops and a PhD [7].

We have developed a new framework to take advantage of IoT sensor data and do the updating in an online manner using Mixture Density Network Model representing a generalized inverse of the structural model. [6]. We prepared a digital twin model for the footbridge and the steel toy structure based on ambient vibration measurements, a surrogate model and Bayesian updating. The new online updating technique is planned in the future to be tested for these structures, that will adapt to each measurement and will be used for long-term monitoring of the condition of the bridge. We presented the preliminary results at a conference [13].

Modeling of multi-storey cross-laminated timber buildings for vibration serviceability

With the help of the above-described model updating techniques, we have in detail addressed the vibration serviceability of multi-storey timber buildings. After ZAG has prepared a detailed finite element model for three different high timber buildings, SZTAKI used uncertainty quantification and Bayesian model updating to improve these models and to be able to accurately predict modal properties for a trustable vibration serviceability checking. Findings obtained from studying three multi-storey timber buildings are summarized and discussed [8]. Two of the buildings (of seven and eight storeys) consist entirely of cross-laminated timber (CLT), while the third is a five-storey hybrid CLT-concrete building. With the probabilistic framework, influential modeling parameters as well as the sources of modeling error were identified. This allowed for conclusions to be drawn about the in-plane shear stiffness of the constructed walls (whose higher value causes the natural frequencies to increase by up to 25%), the soil deformability (which may cause the natural frequencies to drop by up to 20%), and the perpendicular-to-the-grain deformation of floor slabs (which may lead to an overestimation of a fundamental frequency by up to 8%).

Dissemination of project results

At the start of the project, Boštjan Brank (UL FGG), Noemi Friedman (SZTAKI) and Hermann Matthies (TU Braunschweig) organized a 4-day webinar on the topic "Bayesian (finite element) model updating".

Research results were presented at conferences (also as invited lectures) and in international, Hungarian and Slovenian research journals. We were also invited to present our developed methods in other professional events such as the workshop in Hamburg "Digital Bridge" organized for doctoral students at the Helmut Schmidt University in Hamburg, and the HIDASZ napok 2023 (days of bridge engineers 2023), and we were invited by other industrial and academical partners to collaborate (FÖLDTANI intézet, UNITEF, Közút). Within the framework of the DATABRIDGE project we also initiated new collaborations with the University of Twente, University of Split, University of Granada. Our collaborative work on the Ravbarkommanda bridge made it even to the Slovenian media [15].

Due to the extensive successes of the data-driven methods for civil engineering structures developed in the project we were invited to organize a minisymposia in the ECCOMAS MSF 2023 and 2024 conferences and to organize a summer school and seminar on Bayesian updating and Digital Twinning by the ESREL organization, which will be held in the late spring of 2024 (29-31 May).

Limits of the project, outlook

Even after the completion of the DataBridge project, our collaboration persists. Our successful research work opened the gate towards new research questions. Currently, we are actively engaged in a new HORIZON project "BUILDCHAIN BUILDing knowledge book in the blockchain distributed ledger" (project, link: www.buildchain-project.eu/) that has evolved from the foundations laid by DataBridge. UL FG- G, SZTAKI and ZAG, were the initiators of the preparation of the project for the Horizon Europe call. In this new project we have the possibility to elaborate on ideas that could not be addressed in the DataBridge project such as data management, using digital logbooks, integrating digital twinning procedures with Building Information Models (BIMs), and the special issues of the historical buildings. Furthermore, we are jointly supervising a new doctoral student, Tomislav Franković, at UL FGG, who will rather focus on steel structures. Our collaboration extends beyond formal projects as well; we are continuing to develop the research initiated during the DataBridge project. Moreover, we are in the process of planning further large-scale international research projects.

The new aspect that we are currently working on is how to generalise our updating procedure to be able to investigate the accuracy of standards. We have proposed using measurements of several similar buildings and updating in a joint manner the input parameters of the models of the different buildings. The elaborated procedure is now being tested on a one-time joint update of two tall timber buildings.

Impacts

Scientific Impacts - Advancement in Structural Health Monitoring, development of Digital Twin Technology: The project has significantly advanced the field of structural health monitoring by AI tools and data models, which enhance the accuracy and efficiency of damage prediction in infrastructure, the support of decision making in maintenance. **Innovation in Structural Identification:** By combining in-situ measurements, efficient numerical models, and probabilistic methods, the project has pushed the boundaries of modern structural identification, contributing new knowledge and methodologies that can be applied across the construction industry.

Economic Impacts - Cost Savings in Maintenance, Enhanced Infrastructure Longevity: The implementation of advanced monitoring techniques and digital twins can lead to substantial cost savings in the maintenance of infrastructure. Early detection of potential issues allows for timely interventions, reducing the need for extensive and expensive repairs. By accurately predicting and mitigating structural damage, the project helps extend the lifespan of infrastructure, resulting in long-term economic benefits and more efficient use of resources.

Social Impacts - Improved Public Safety, Increased Public Trust, Preservation of Cultural Heritage: Enhanced monitoring and maintenance of critical infrastructure lead to safer buildings and facilities, thereby protecting the public from potential hazards and failures. Demonstrating the application of advanced technologies in infrastructure management can increase public confidence in the safety and reliability of their environment.

Summary, self-assessment

The research project was executed in accordance with the program outlined in the project proposal, with no major deviations. The majority of the program was successfully realized as part of the research project. Collaboration between UL FGG, ZAG, and SZTAKI was strong and consistent throughout the project. Even after the completion of the DataBridge project, we continue to work together both formally, within the framework of the BUILDCHAIN project and through joint mentoring of doctoral students, as well as informally by further developing the research initiated in the DataBridge project. Additionally, we are jointly submitting new proposals for Horizon Europe projects.

All changes in the composition of the project team for UL FGG and ZAG were promptly reported to the project administrator. It proved extremely beneficial to have a diverse group of researchers with different educational backgrounds, including civil engineering, mechanical engineering, physics, computer science, and informatics. This multidisciplinary team ensured competence across all areas covered by the project.

References

[1] Landi, F and Marsili, F and Friedman, Noémi and Croce, P (2021) gPCE-Based Stochastic Inverse Methods: A Benchmark Study from a Civil Engineer's Perspective. Infrastructures, 6 (11). ISSN 2412-3811 10.3390/**Infrastructures** 6110158

[2] KURENT, Blaž, FRIEDMAN, Noemi, BRANK, Boštjan. On (Bayesian) finite element model updating of civil engineering structures by using modal features. V: IBRAHIMBEGOVIĆ, Adnan NIKOLIĆ, Mijo **ECCOMAS 2021**. Sarajevo: Faculty of Civil Engineering, 2021. Str. 9-11.

[3] Kurent, B and Friedman, Noémi and Ao, W K and Brank, B (2022) Bayesian updating of tall timber building model using modal data**. Engineering Structures**, 266. ISSN 0141-0296 10.1016/j.engstruct.2022.114570

[4] B. Kurent, N. Friedman, B. Brank: Bayesian updating of a multi-storey timber building, **EMI 2023 International Conference**, Palermo, Italy August 27-30, 2023

[5] Kurent, B and Friedman, N and Alosio, A and Pesca D and Tomasi R. and Brank, B: Bayesian model updating of eight-storey CLT building using modal data, submitted to the **Probabilistic Engineering Mechanics Journal** on the 2nd of November 2023, the paper **is still under review**.

[6] N. Friedman, B. Kurent, A Urbanics, R. Alekszier, B Brank, Online Calibration of the Dynamic Model of a Tall Timber Building by Mixture Density Deep Neural Network , in Proc. Of the 6th International Conference on Multi-scale Computational Methods for Solids and Fluids, **ECCOMAS MSF 2023**, June 25-27, Sarajevo, Bosnia Herzegovina, pp 170-171, ISBN 978-9958-638-73-2

[7] KURENT, Blaž. Probabilistic Modelling and Model Updating of Tall Timber Buildings: **doctoral dissertation**. Ljubljana: 2023 (supervisors: B. Brank, N. Friedman).

[8] Kurent, B., N. Friedman, and B. Brank. "Modelling of Multi-Storey Cross-Laminated Timber Buildings for Vibration Serviceability." **Buildings** 14.3 (2024): 689.

[9] N. Friedman , Z. Tasci, U. Bohinc and J. Kalinc, The 8th European Congress on Computational Methods in Applied Sciences and Engineering, **ECCOMAS Congress 2022**, 5-9 June 2022, Oslo, Norway, "Machine Learning for Explainability of Structural Health Monitoring Data of a Viaduct"

[10] N. Friedman, A. Urbanics, Z. Tasci, U. Bohinc: Megépült építőmérnöki szerkezetek szenzoradatainak felhasználása, Hídász Napok 2023 Előadásainak Gyüjteménye, http://www.hidak.hu, ISSN 2732-026X, **Lánchíd füzetek**, Első Lánchíd Bt. pp241-252, 2023.

[11] N. Friedman, Z. Tasci, U. Bohinc, Jan Kalin, Machine learning for explainability of structural health monitoring data of a viaduct, The 8th European Congress on Computational Methods in Applied Sciences and Engineering, **ECCOMAS Congress 2022**

[12] Li, Y and Friedman, Noémi and Teatini, P and Benczúr, András, ifj and Ye, S (2022) Sensitivity analysis of factors controlling earth fissures due to excessive groundwater pumping. **STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT**, 36. pp. 3911-3928. ISSN 1436-3240 10.1007/s00477-022-02237-8

[13] T. Frankovic, N. Friedman, U. Bohinc, B. Brank, Examples of Deterministic and Stochastic Model Updating for Steel Structures, in Proc. Of the 6th International Conference on Multi-scale Computational Methods for Solids and Fluids, **ECCOMAS MSF 2023**, June 25-27, Sarajevo, Bosnia Herzegovina, pp 170-171, ISBN 978-9958-638-73-2

[14] A. Stanic, M. Nikolic, N. Friedman, H. G. Matthies, Stochastic Identification of Material Parameters in Dynamic Fracture, in Proc. Of the 6th International Conference on Multi-scale Computational Methods for Solids and Fluids, **ECCOMAS MSF 2023**, June 25-27, Sarajevo, Bosnia Herzegovina, pp 43-45, ISBN 978-9958-638-73-2

[15] Izobraževanje, gradbeništvo in hrana: To umetna inteligenca dela že danes - siol.net