BIM based Cyber-physical System for Bridge Assessment

cyberBridge

Project funded by the European Community under the
Eurostars project E! 10925

M8.3 Validation and Verification of the Complete cyberBridge System

Responsible author: Tobias Mansperger
Co-authors: Jan Cervenka, Markus Petschacher,

Status: final
Type: software/pilot
Access: public
Version: 5.0
Date: 10.06.2020

Available for download at
http://www.cyberBridge.eu

Executive summary:

The project cyberBridge develops a new cyber-physical bridge assessment system that will at low cost allow continuous online monitoring and system identification beyond modal analysis on the level of crack propagation and hence considerably improve prognosis of bridge deterioration. A software system was developed both as a product and as a service. Besides selling the system, continuous support and training, partial and complete bridge monitoring services and life cycle prognosis will be offered.

The goal is to radically improve bridge monitoring and forecasting. The main result is an innovative BIM based cyber-physical system for bridge assessment comprising continuous bridge and load monitoring, continuous vehicle load and bridge system identification for global and local crack propagation deterioration, and forecasting using mass simulation and probabilistic methods. It will be provided as a continuous monitoring platform with online evaluation. The automated use of HPC (Cloud/Grid) power allows for deep system identification at any time providing for much better understanding of the deterioration process and the impact of each deterioration event on the reliability of the bridge.

This report contains the evaluation of the developed software products, new monitoring sensors and their application to the three pilot bridge projects.

1 Revision history:

date	author	status	changes
07.04.2020	Tobias Mansperger	draft	First draft version
	Markus Petschacher	draft	Pilot Tiffen added
28.05.2020	Tobias Mansperger	V1	Pilot Esslingen added
09.06.2020	Michael Polter, Fangzheng Lin, Markus Petschacher, Tobias Mansperger	V4	Overview, Funktionalities, Recommendations added
10. 6. 2020	Jan Cervenka	Version 5	Prognosis model, Wonka bridge, further extensions

Table of contents:

1. General

The goal is to radically improve bridge monitoring and forecasting. The main result is an innovative BIM based cyber-physical system for bridge assessment comprising continuous bridge and load monitoring, continuous vehicle load and bridge system identification for global and local crack propagation deterioration, and forecasting using mass simulation and probabilistic methods. It is provided as a continuous monitoring platform with online evaluation. The automated use of HPC (Cloud/Grid) power will allow deep system identification at any time providing for much better understanding of the deterioration process and the impact of each deterioration event on the reliability of the bridge.

The system is able to continuously detecting micro cracks and the deterioration state as well as its changes on a much more precise level and a higher confidence than today's monitoring systems and keeps monitoring costs at about the same level. This is based on several new methods:

1) A new continuous simulation-based system identification method for global and local behaviour identification, using massive Grid/Cloud simulation,

2) Load monitoring systems for identification of individual vehicles and their synchronisation with the bridge behaviour monitored values,

3) Reliable, accurate prediction of the remaining lifespan and retrofit measures on the basis of the deeply identified system and massive Grid/Cloud sensitivity simulations and probabilistic methods

4) BIM, Multimodel and ontology-centred flexible and efficient mass information management and visualization of the results via a 3D bridge navigator enabling improved information and decision-making even for laypersons

5) Improved sensor system layout, modification and tuning process for global and local bridge system identification based on multiple virtual scenario simulations and ontology-based Multimodel information management.

6) Improved sensor network with max 1ms delay.

Target clients and products are:

1) Bridge Owners

Product (2): The cyberBridge system itself, including the system, installing equipment, training people for a fixed period, helpdesk support, consultancy on demand and continuous updates on annual fee basis.

Product (1): Consulting for bridge assessment. In this case, the cyberBridge system will be maintained by the partners. The clients will have full access on all data or only on some selected data depending on the specific

contract. The cyberBridge system will either be explicitly rented or will be offered as part of the consultant contract and price.

2) Monitoring and Assessment Companies

Product (3): The cyberBridge system. The complete system with all hardware and software components will be offered at a fixed price and an annual support as well as update fee. The latter concerns in particular the cyberBridge software components, i.e. the core platform services, the workflow system, the data management and storage system, the public Cloud access, the private Grid, the BIM filter and navigator tools as well as the ATENA extended system and the system identification system, i.e. variation and fit algorithms and strategies.

3. Consultant Companies

This is essentially the same as for Bridge Owners, but the related contract is sub-contracting.

4. To all

Product (4): Education, system identification with cyber-physical systems is a new area in civil engineering, where up to now no courses are offered, except of traditional temporary monitoring and vibration modes fitting, i.e. with a strongly limited amount of parameters. Therefore, the results of cyberBridge will be offered as a new university and industry course by TUD as wells as for the training courses mentioned above.

Most important at the start of the development of the cyberBridge platform was the proper identification of all relevant requirements in accordance with the project scope and objectives, all relevant basic specifications to be used in the development work, with special emphasis on available standards or accepted industry norms, the envisaged users / clients of the system, and the respective practice-oriented usage scenarios. Requirements were defined on the basis of the buildingSMART IDM methodology (ISO 29481-1:2010) to provide for early recognition of all data exchange and interoperability issues as a first substantial step towards Multimodel based information integration. Requirement gathering was thereby split in three separate tasks, namely

(1) computational engineering and system engineering,

(2) monitoring and

(3) ICT system,

in order to work out the most innovative use of the newly emerging technologies in each domain by one partner per task in accordance with the expertise and background knowledge of the partners. Consolidation was performed by TUD as part of Task 1.3. For development of the usage scenarios in task 1.4 the BPMN modelling as recommended by buildingSMART was used.

Additionally, the system architecture was drafted by LAP from end user point of view. Selecting a non-software partner for that task is done on purpose, to avoid technological bias and ensure that end-user needs and wishes are properly addressed. The transformation into a detailed technical software architecture based on the Service Oriented Architecture (SOA) approach was performed by the ICT expert TUD in the WP7.

2 Overview of the system

This section provides an overview of the developed cyberBridge web based structural monitoring and health evaluation system.

2.1 GUI

The GUI guides the user to the workflow and shows the current step in the workflow. On mouseover a description of the workflow step pops up.

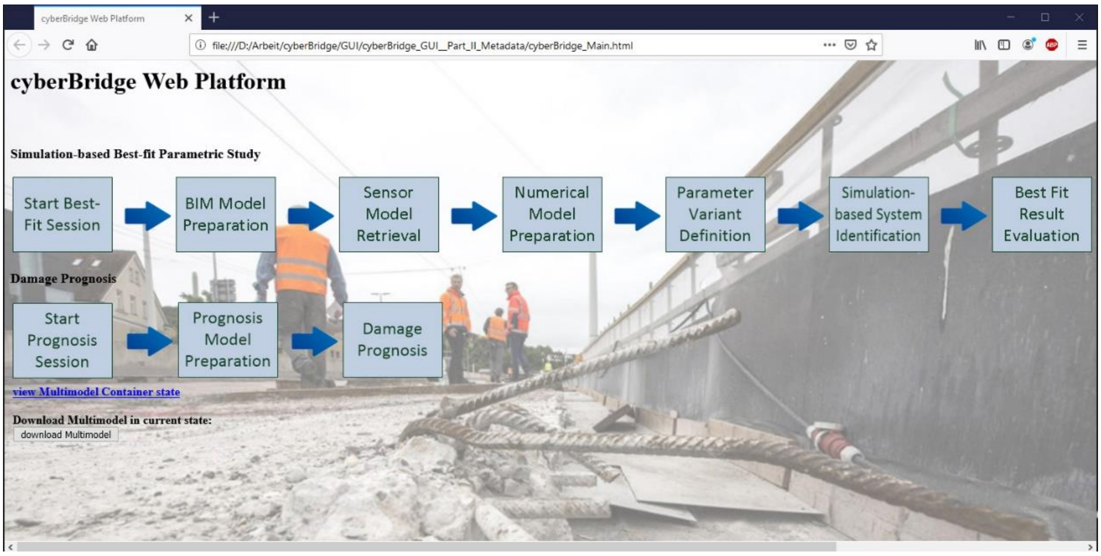

Fig. 2-1: cyberBridge Main Dashboard

For each workflow step, a new wizard opens where the user gets and inputs necessary information for the execution of the step. Each uploaded data is automatically added to the multimodel, which can be downloaded at its current state, no matter where the user currently is in the workflow.

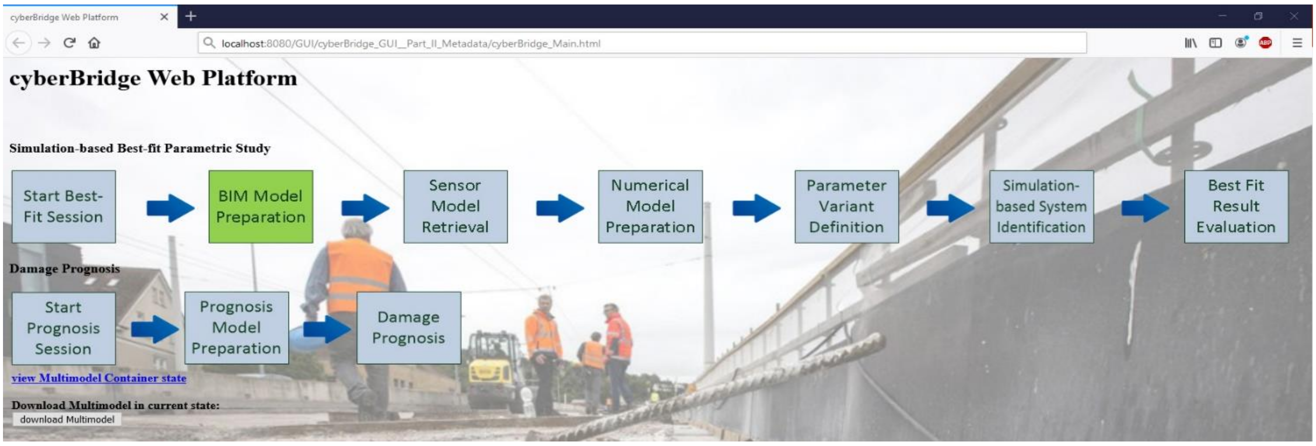

Fig. 2-2: current workflow step – BIM Model preparation

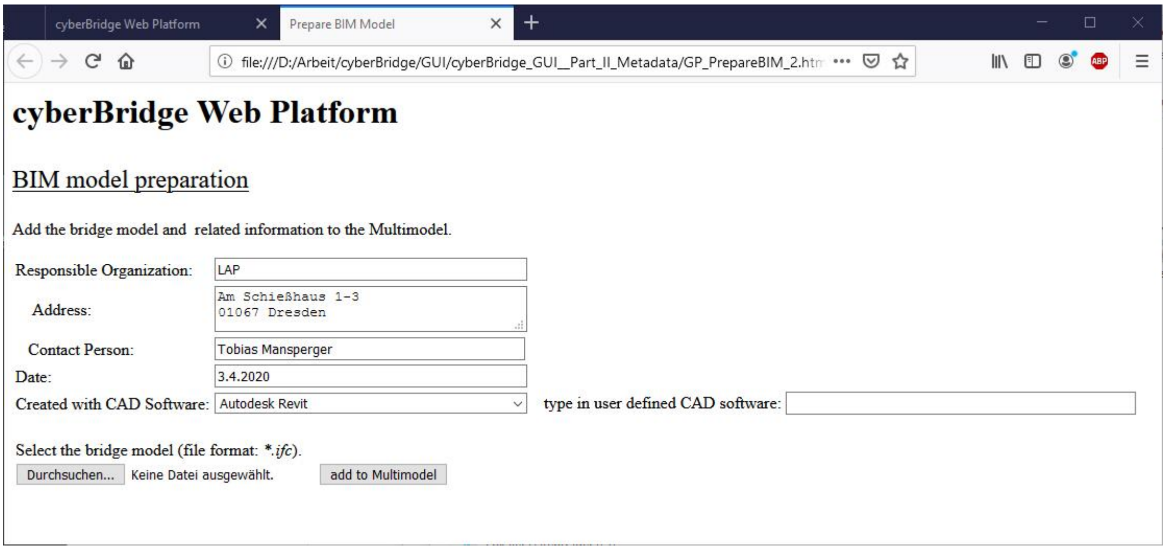

Fig. 2-3: General Project Information

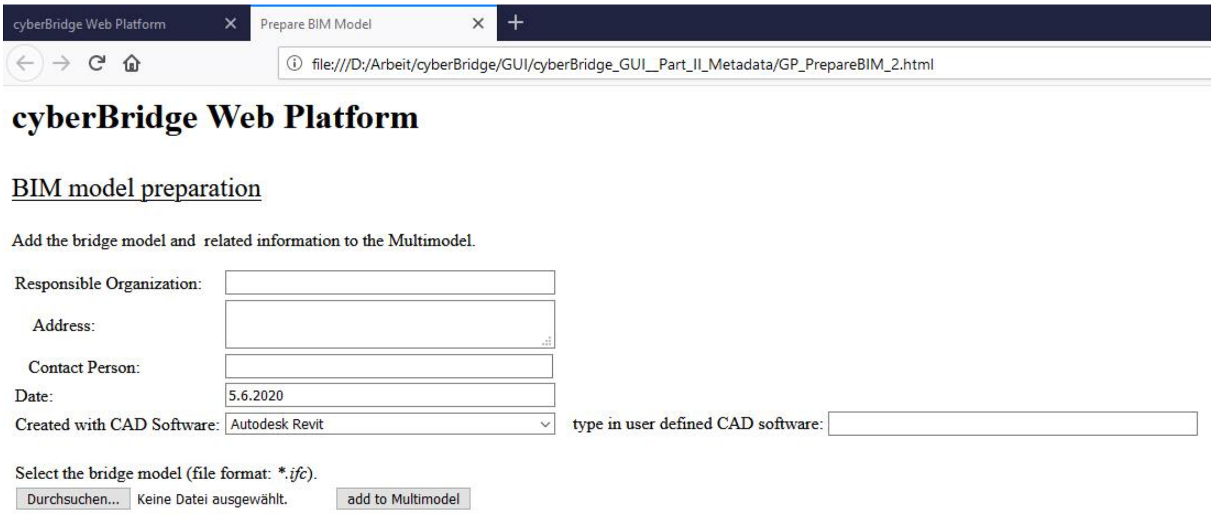

Fig. 2-4: Step 2 – BIM Model Preparation

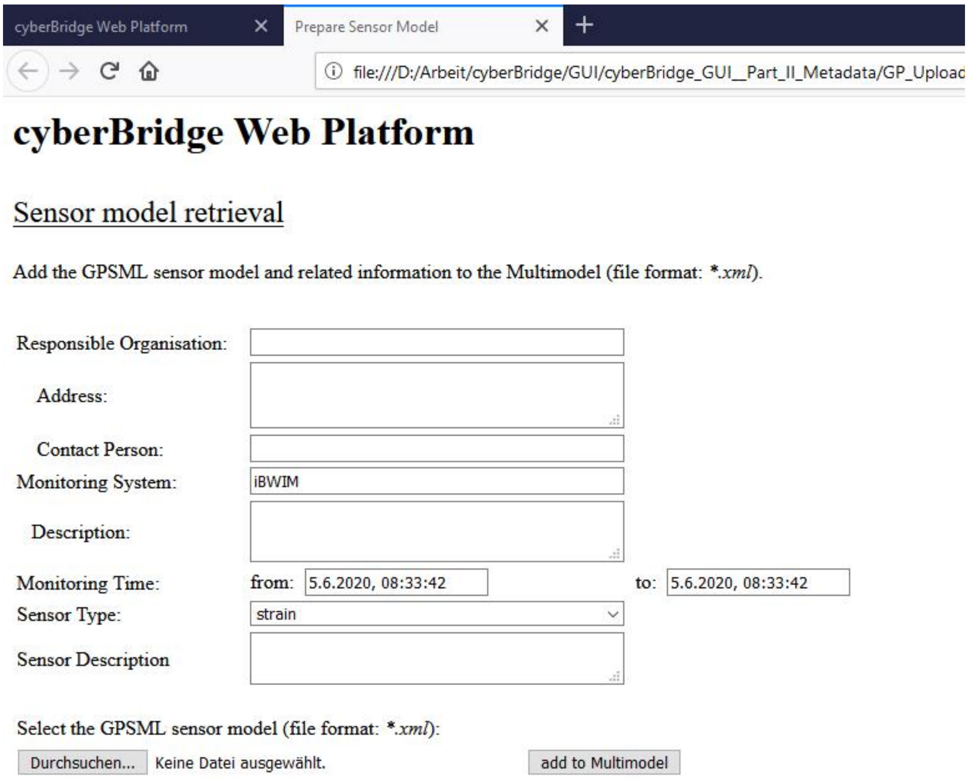

Fig. 2-5: Step 3 – Sensor Model Retrieval

The preparation of the numerical model is the same procedure for both workflows.

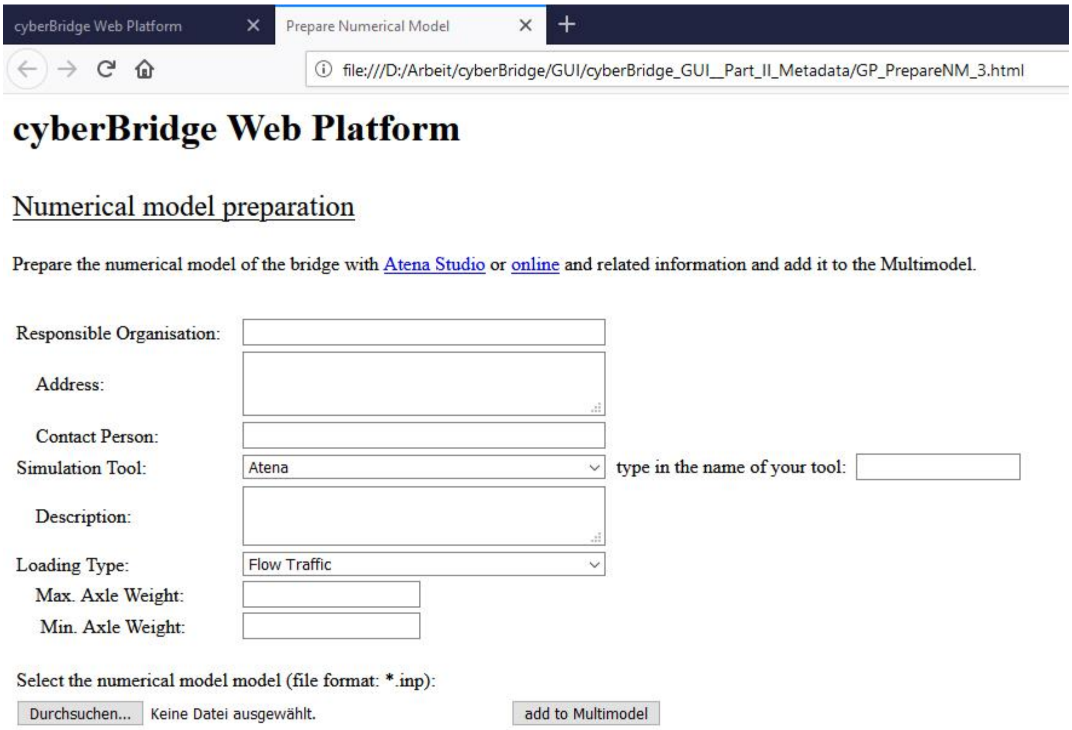

Fig. 2-6: Step 4 – Numerical Model Preparation

In the next step variants have to be defined for an XML-based variation model. The XML schema is provided for download. An online XML Validator is linked to check the variation model against the schema for syntax errors, so model checks don't have to be performed locally. The pre-processor on the Atena Cloud checks for semantic errors.

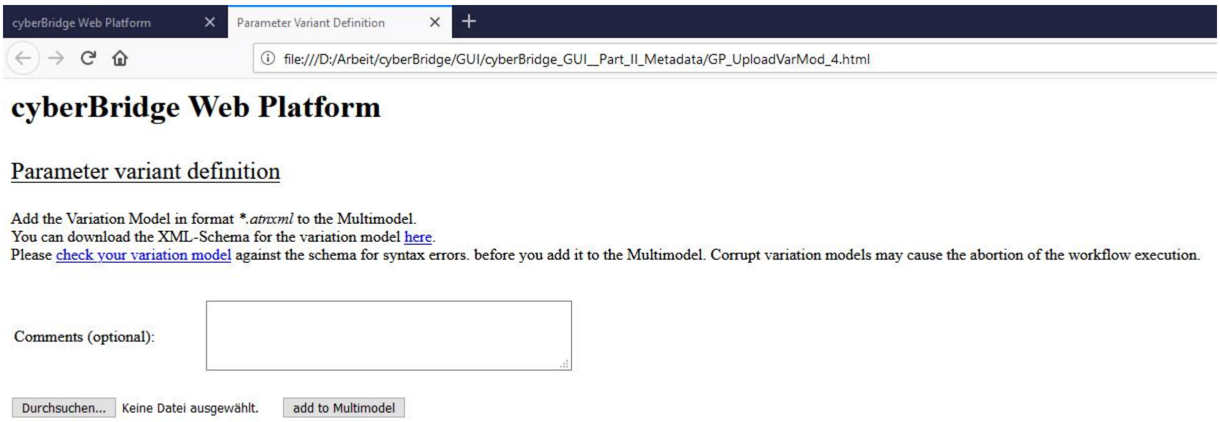

Fig. 2-7: Parameter Variant Definition

Results are automatically added to the multi model as soon as they are available.

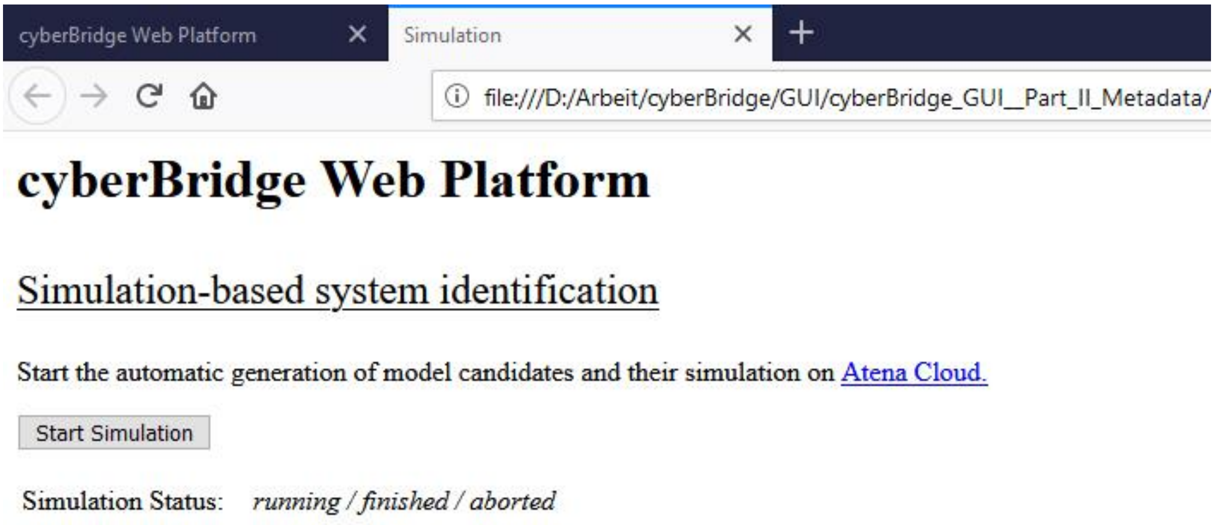

Fig. 2-8: start simulation wizard with link to Atena Cloud (for detailed information) and simulation status

The user can choose to download the complete multimodel of the workflow with all models and results or only get the best fit candidate.

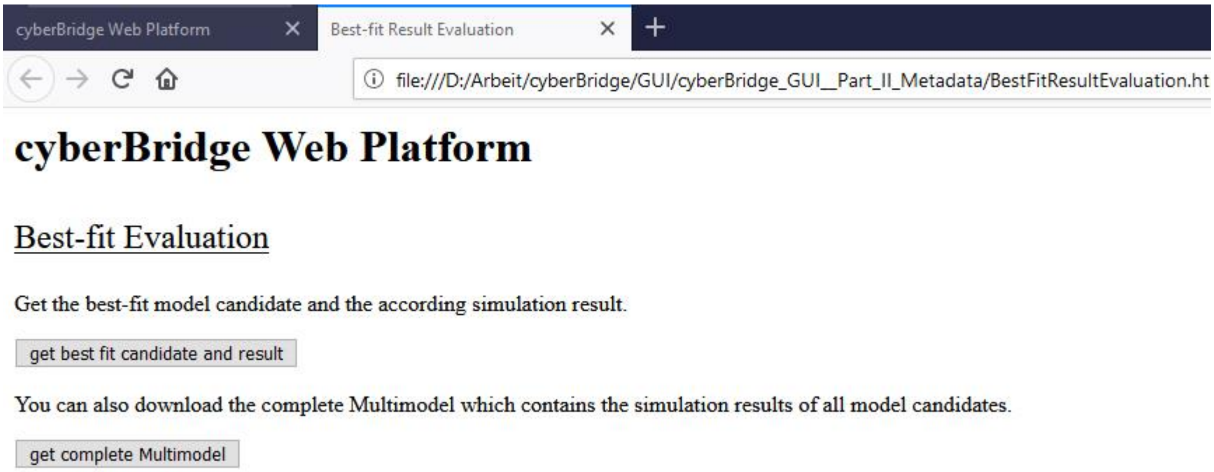

Fig. 2-9: Wizard for downloading results of the workflow execution

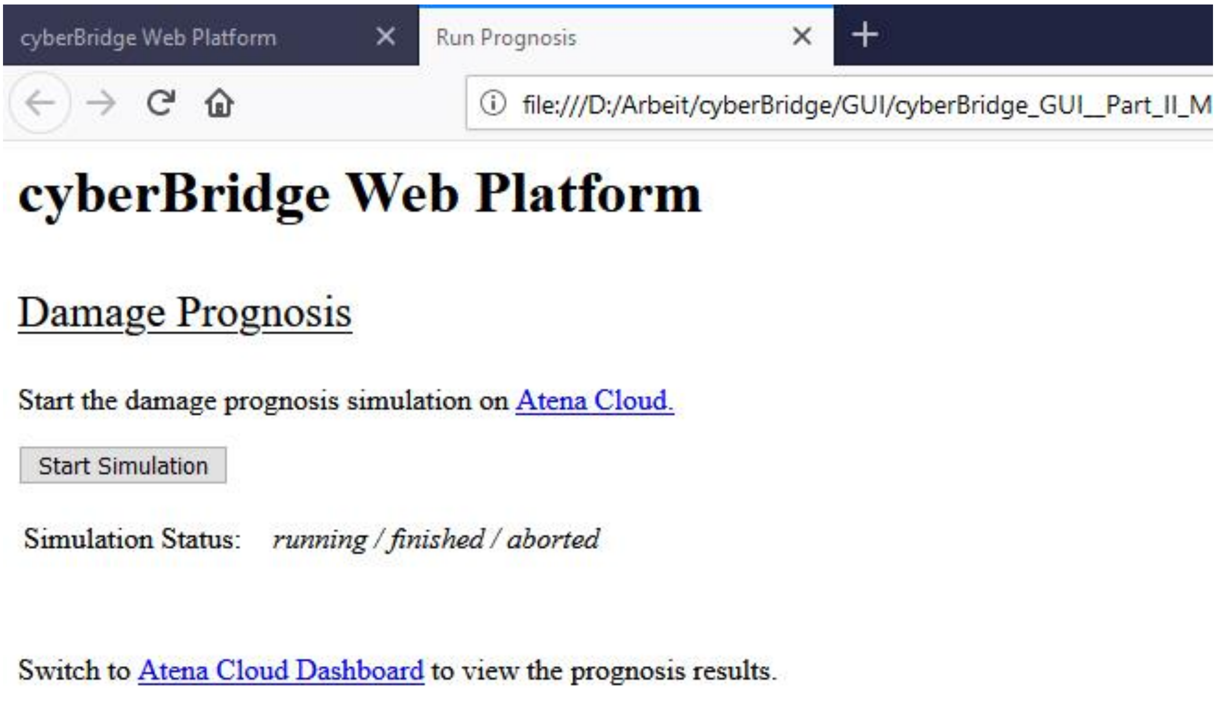

Fig. 2-10: prognosis results panel with link to Atena Cloud where detailed information is provided

2.2 System Identification Tool (TUD)

System identification preparation is done in the workflow steps as described above in Chapter 2.1. The simulation itself is executed on the Atena Cloud.

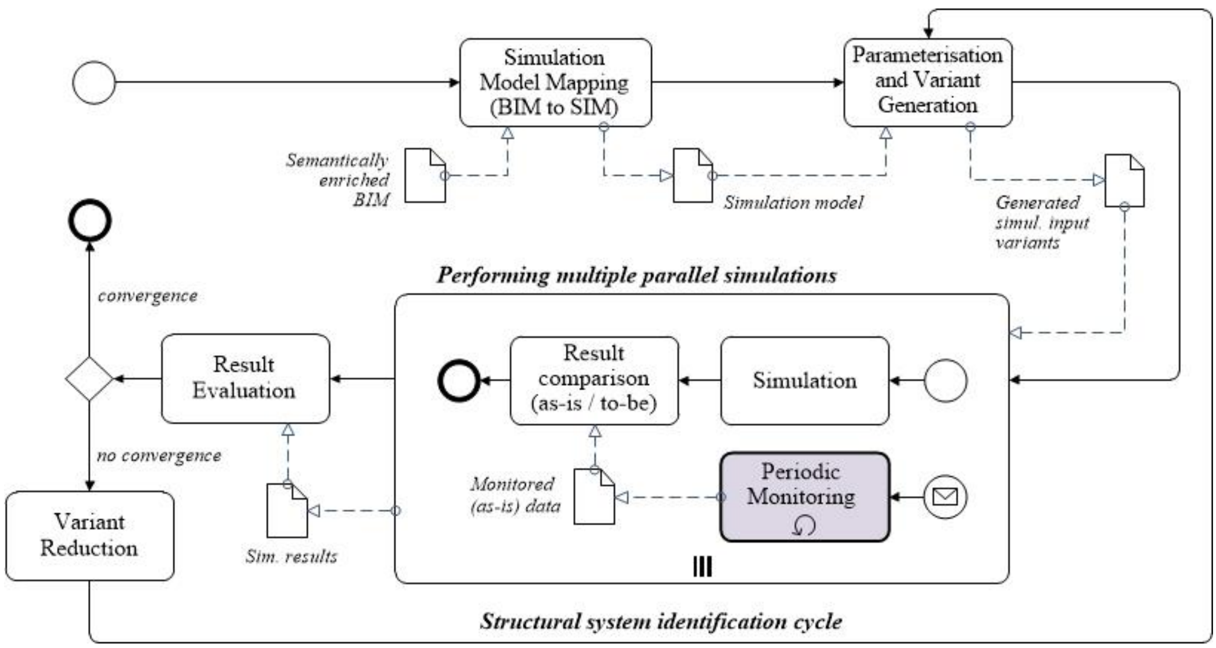

Fig. 2-11: Abstract / Generic System Identification Workflow

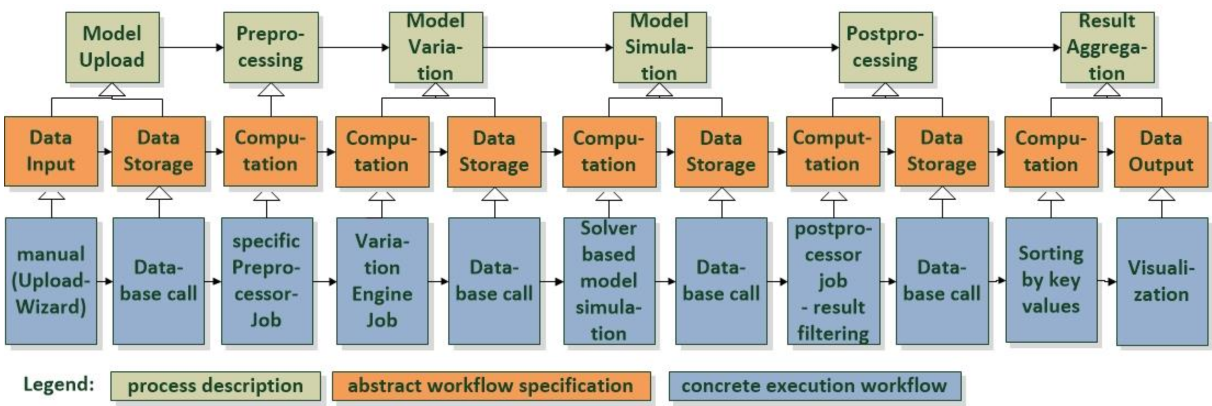

Fig. 2-12: Mapping of the Generic workflow to an executable system workflow

2.3 Prognosis Tool

The prognosis method developed during the project is based on simulation scenarios. These scenarios take into account the uncertainty and fuzziness of the identified model both for the bridge and for the load model and may include retrofitting actions. An assumption regarding the deterioration process is made through appropriate variation of critical and major influencing parameters using a min/max range or even stepped through interval assumptions, in similar manner as applied for the simulation-based system identification in WP4. These deterioration variations are cross-combined with reasonable retrofitting measures, which may also vary in e.g. the applied construction methods and material.

The corrosion and ASR models are implemented in ATENA software [19], using multi-physics approach for mechanics and transport as schematically shown in Fig. (2-13). It predicts induction time and extent of corrosion for chloride ingress, and calculates remaining steel area. The mechanical behavior and concrete cracking is simulated using the fracture-plastic model . It combines plasticity based model for compressive failure and smeared crack model with tensile softening and crack band approach for tension. The reinforcement corrosion is evaluated based on the parameters of the surrounding environment that are specified as a special boundary condition as shown in Fig. 2-14. Fig. 2-14 shows a simple example of a short cantilever whose bottom surface is subjected to chlorides. A mechanical load initiated cracks starting at the bottom surface. For each reinforcement, the closest distance to the surface subjected to chlorides is calculated. The initiation phase as well as all the other corrosion phases as described previously are evaluated assuming a 1D transport process along this closest distance considering also the width of the surface crack. Based on the amount of corrosion the effective reinforcement area is reduced, which can directly affect the load carrying capacity or the deflections of the numerical model. This approach can simulate the effect of structural degradation in a very effective and efficient way.

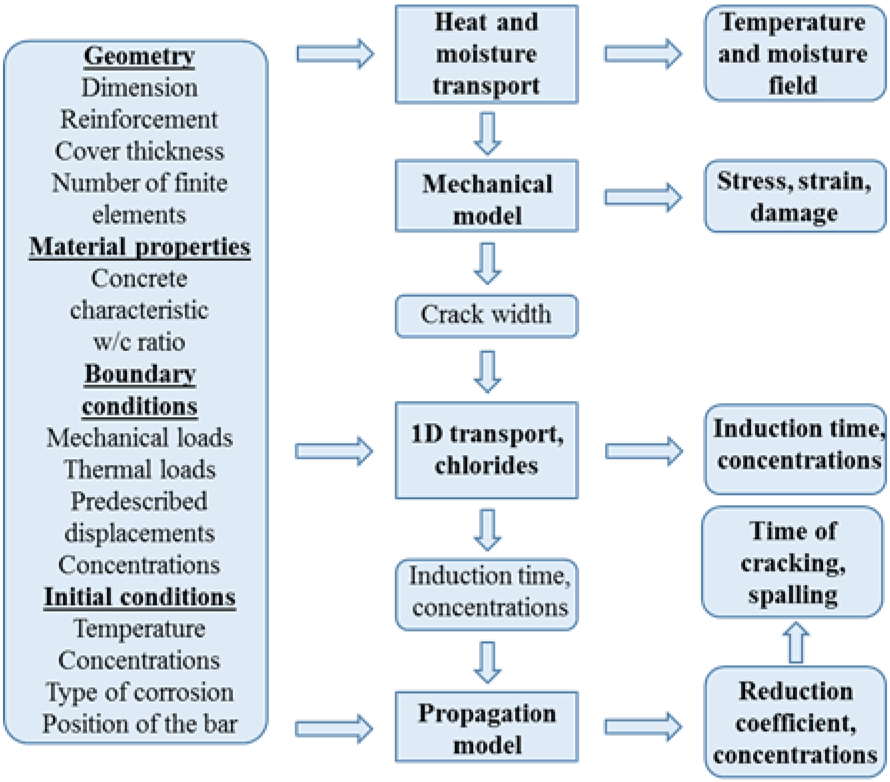

Fig. 2-13: New durability model in ATENA software

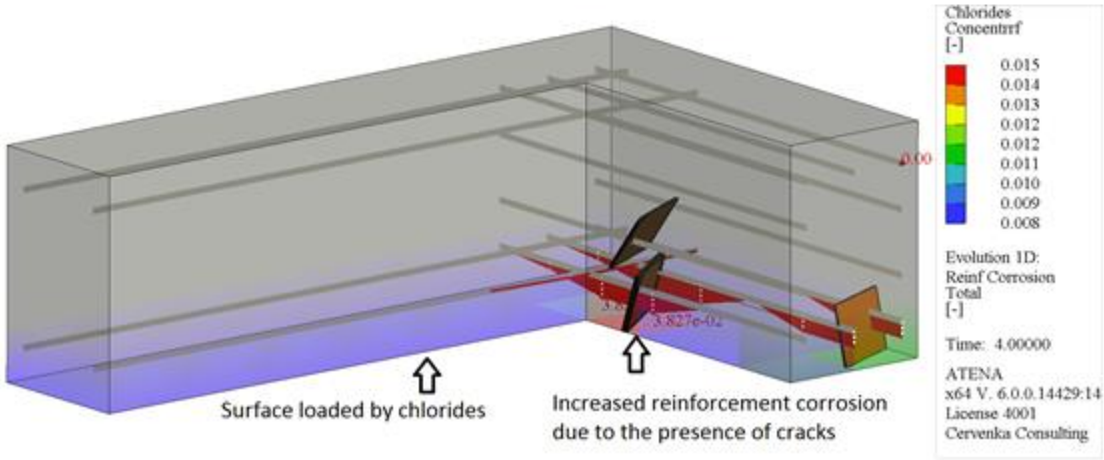

Fig. 2-14: Corrosion modelling in finite element nonlinear analysis

The prognosis modelling can be based on deterministic models using the global safety formats as for instance proposed in [1], but full probabilistic models can be applied as well. The following list provides a summary of features/options for probabilistic modelling for structural reliability prognosis:

(a) stochastic modeling (inputs):
- Direct connectivity to the nonlinear analysis input data
- Friendly Graphical User Environment (GUE)
- 30 probability distribution functions (PDF), mostly 2-parametric, some 3-parametric, two 4-parametric (Beta PDF and normal PDF with Weibullian left tail)
- Unified description of random variables optionally by statistical moments or parameters or a combination of moments and parameters
- PDF calculator
- Statistical correlation (also weighting option)
- Categories and comparative values for PDFs
- Basic random variables visualization, including statistical correlation in both Cartesian and parallel coordinates

(b) probabilistic techniques (solution):
- Crude Monte Carlo simulation
- Latin Hypercube Sampling (3 alternatives)
- First Order Reliability Method (FORM)
- Curve fitting
- Simulated Annealing
- Bayesian updating

(c) response/limit state function (evaluation):
- Numerical form directly connected to the results of nonlinear FE analysis
- Multiple response functions are assessed in same simulation run

The probabilistic approach requires many nonlinear analysis to facilitate the Monte-Carlo sampling approaches. In the cyberBridge platform this is supported by the AtenaCloud web based application, which allows to perform 100-1000s of parallel analyses on the cloud virtual computers.

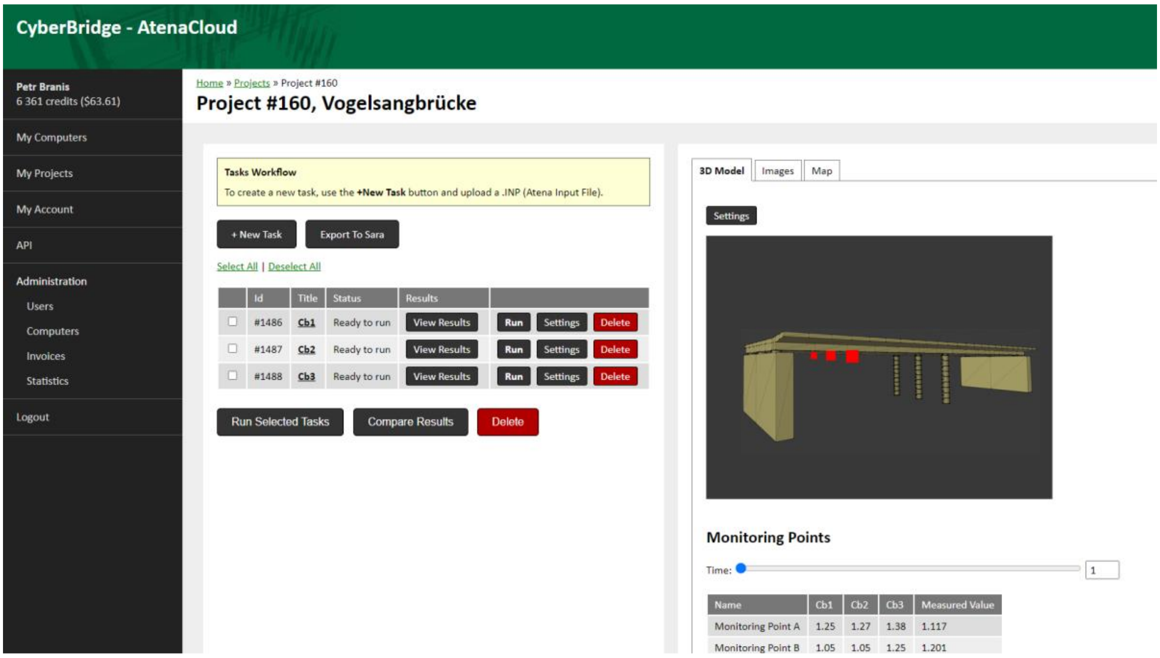

Fig. 2-15: CyberBridge – AtenaCloud platform for online cloud computing

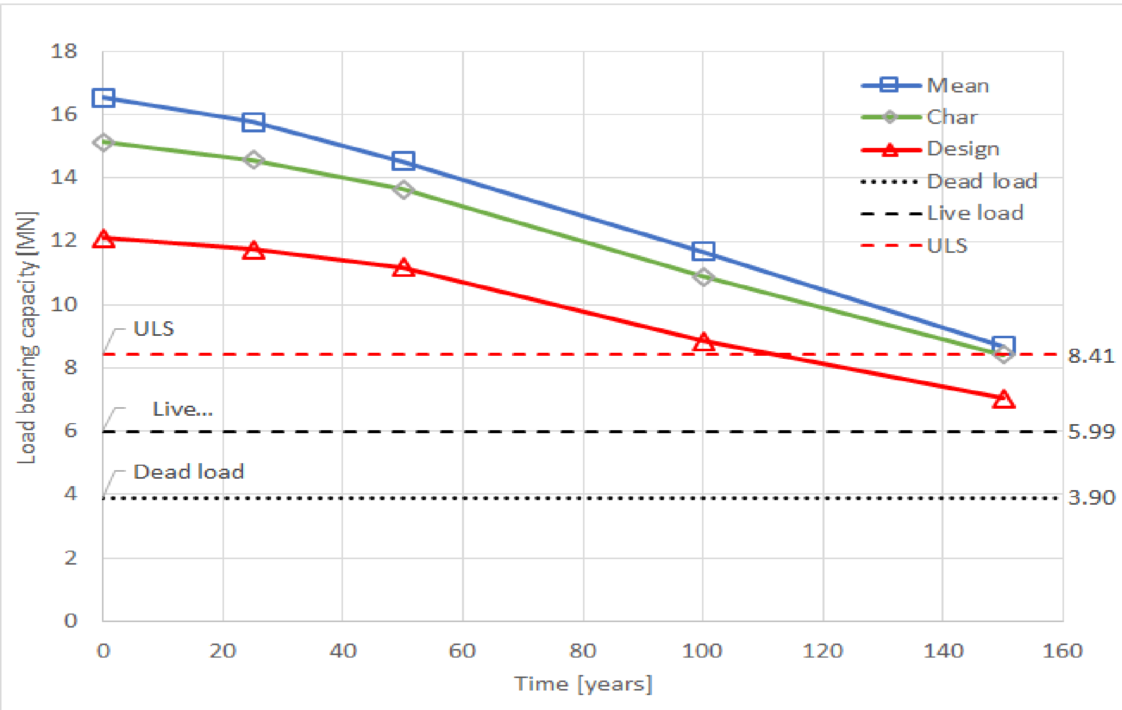

Fig. 2-16: Prognosis of the development of structural reliability of the pilot Vogelsang bridge in 150 years.

3 Validation and verification process

3.1 Wonka Bridge, Czech Republic

The Wonka bridge was the first pilot bridge in the cyberBridge project, where iBWIM monitoring was applied and tested in 2018. The interfaces with the online platform and with the numerical simulation software were tested and verified for the first time. The further improvements of the cyberBridge system were proposed and developed on the basis of this initial pilot project. More details about this pilot project can be found in the report [24], which is dedicated to the description and evaluation of the individual pilot projects.

Fig. 3-1: Wonka bridge in Pardubice, Czech republic

The numerical model was developed in ATENA software as shown in Fig. 3-2. The bridge is modelled by 4512 layered shell elements. The structure near supports and some other details are modelled by hexahedral and wedge solid elements. The pre-stressed tendons are realized by 3022 external cable truss elements, while the conventional reinforcement is introduced by embedded reinforcement within shell elements. The model calibration consisted of three stages. In the first phase the measurements from the bridge load from 2006 were used. In this phase namely the pre-stressing losses in the embedded cables were estimated. The final calibration was done using the iBWIM measurements performed during the cyberBridge project in the time period Aug. – Oct. 2018. The calibration process in described in more detail in the report [24]. During the investigated time period, the bridge was also equipped by an additional monitoring system installed by Bohemian Technology Group company, and it was possible to use this data for additional calibration and validation of the developed models. During the monitoring period it was also discovered that some of the deviators holding the post-tensioning cables inside the box girder are broken, and one of the tendons is therefore not active. This damaged bridge situation was also studied and analysed, and it provided an interesting insight into the capabilities of the developed system to detect and simulate existing bridge damages.

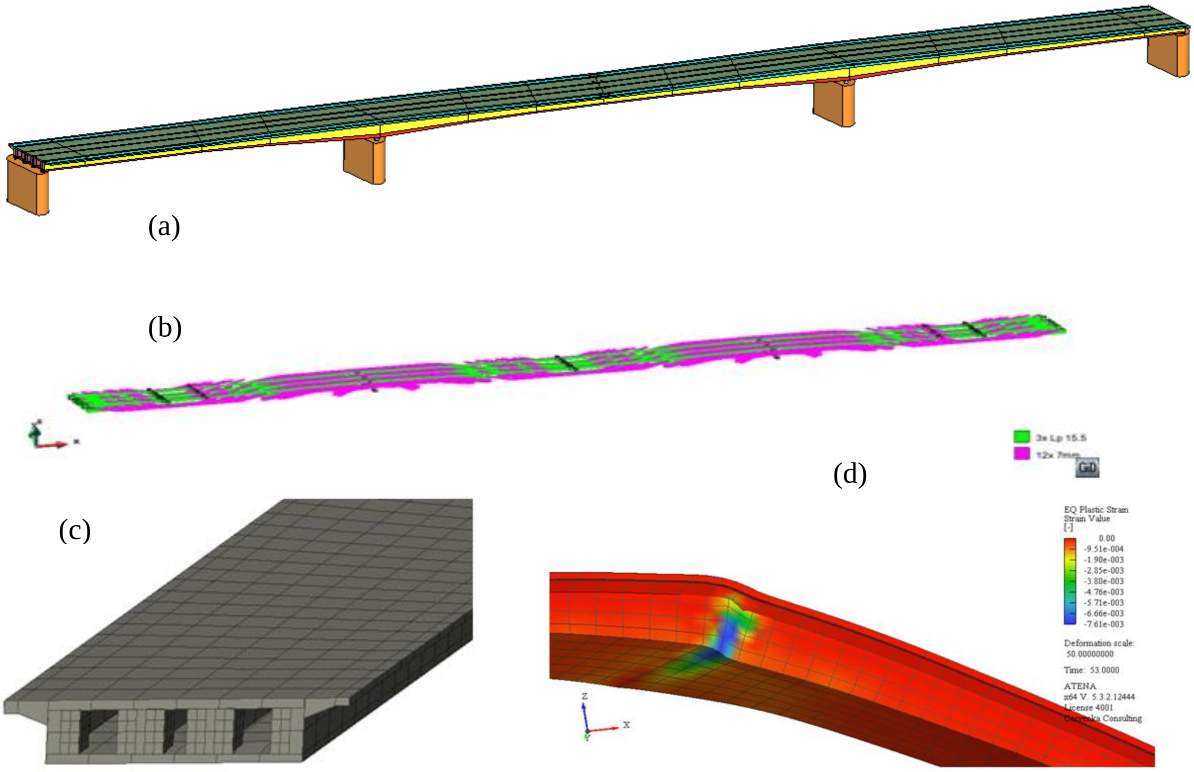

Fig. 3-2: (a) Geometrical model of P. Wonka bridge, (b) geometry of pre-stressing cables, (c) the finite element model of the end segment, (d) failure mechanism at peak load near the right middle support during overloading up to failure

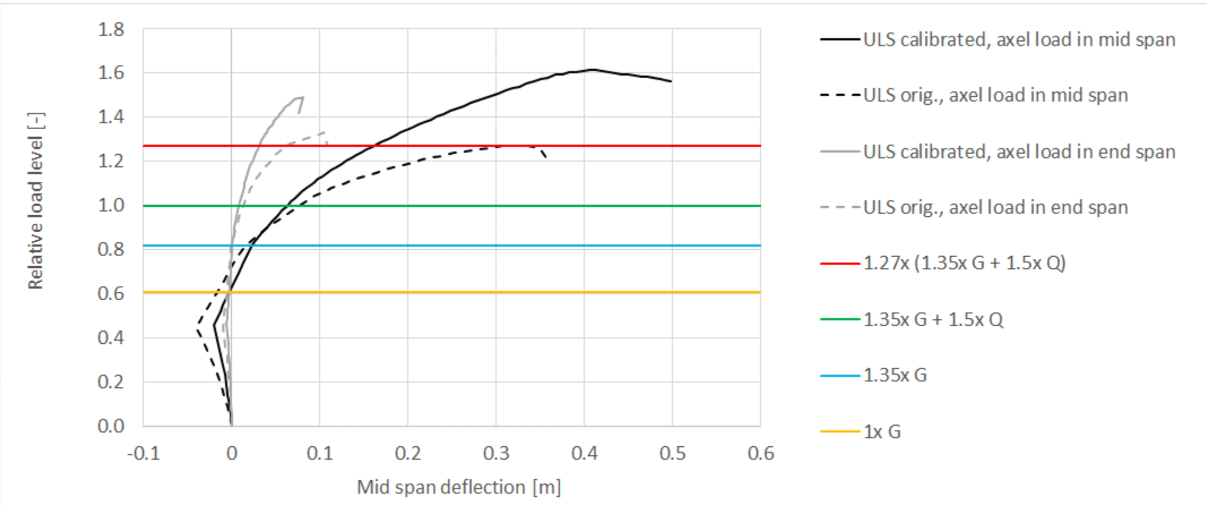

Fig. 3-3: Prognosis of load-carrying capacity of Wonka bridge

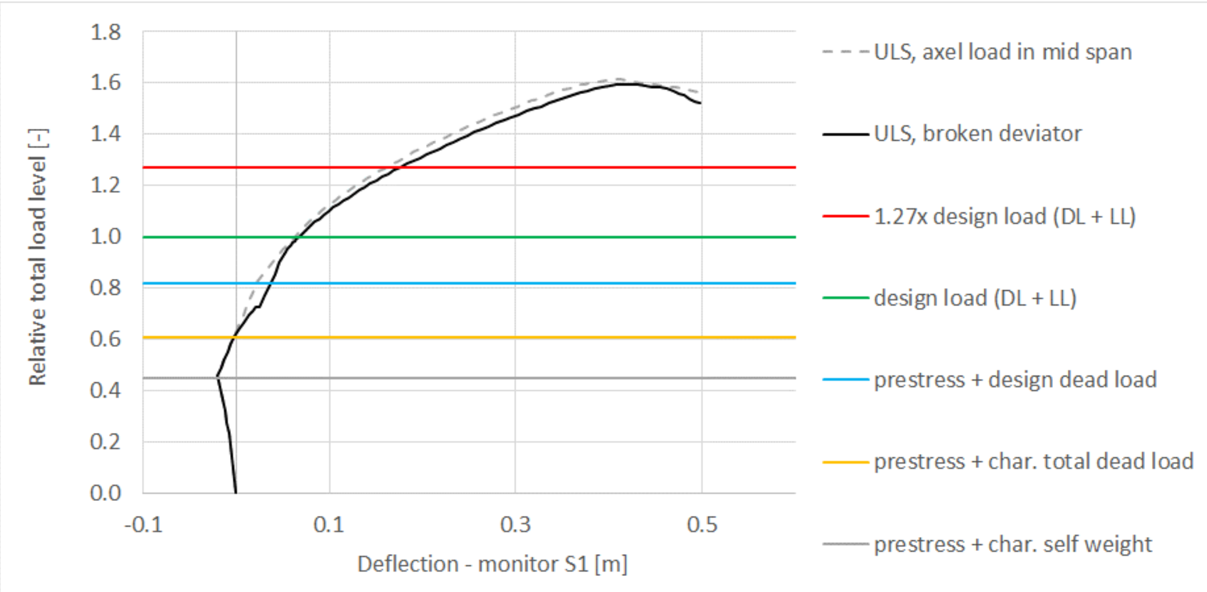

Fig. 3-4: Effect of the deactivated/broken tendon on the Wonka bridge load carrying capacity

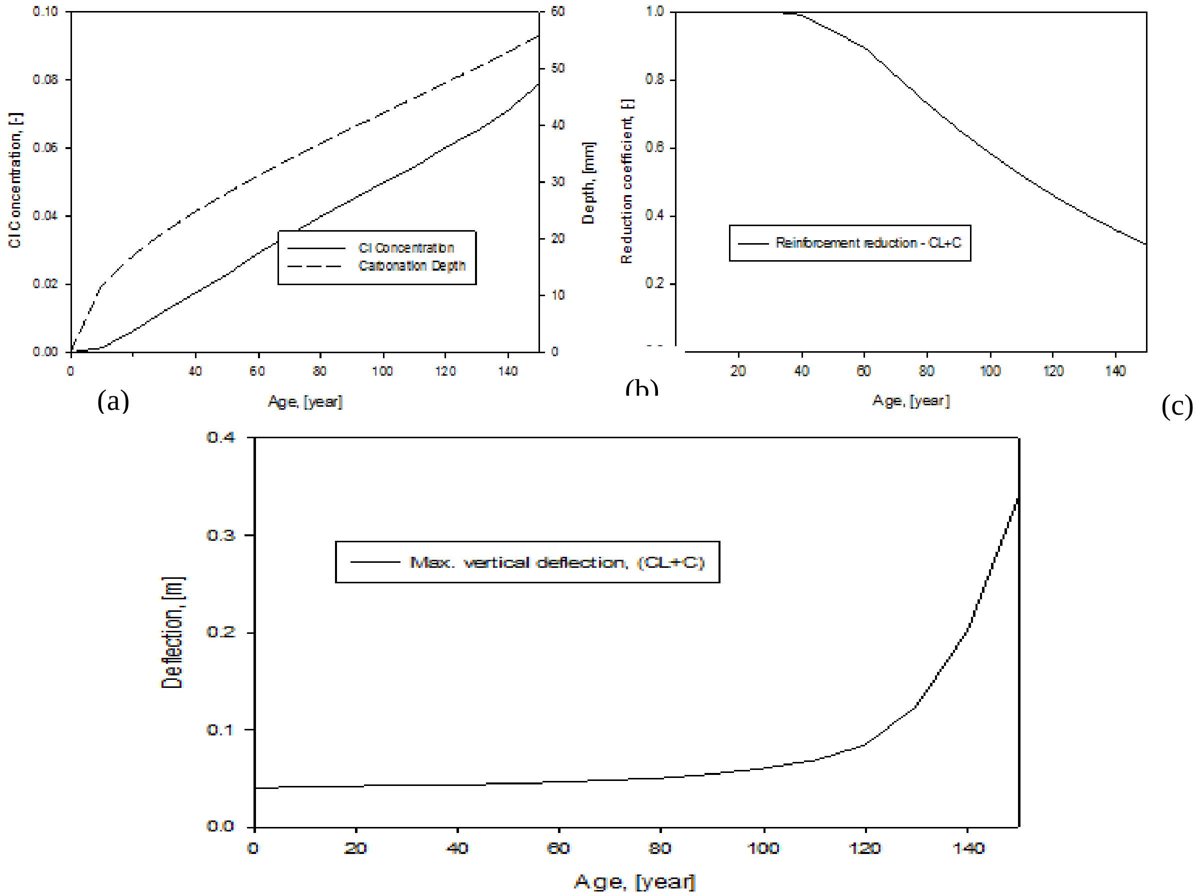

Fig. 3-5: Prognosis of: (a) concentration of chlorides and carbonation at tendon depth, (b) tendon cross-sectional area reduction due to corrosion, (c) deflection increase in time

3.2 Vogelsang Bridge, Germany

3.2.1 Overview

This pilot bridge is a concrete bridge over the Neckar River in the city of Esslingen, Germany. It is a major part of the city's infrastructure with a high impact on the regional traffic. The bridge consists of eight partial structures built in three different construction types. The bridge was built between the years of 1971 and 1973. The total length is approx. 595m and it has a total area of 9,744m² including ramps.

Fig. 3-6: Aerial image of Vogelsangbrücke Esslingen, Germany [source: maps.google.com]

During the last major check, many damages have been detected, that influence the structural safety, the safety to traffic and the durability. Due to the damages, refurbishment is urgently needed.

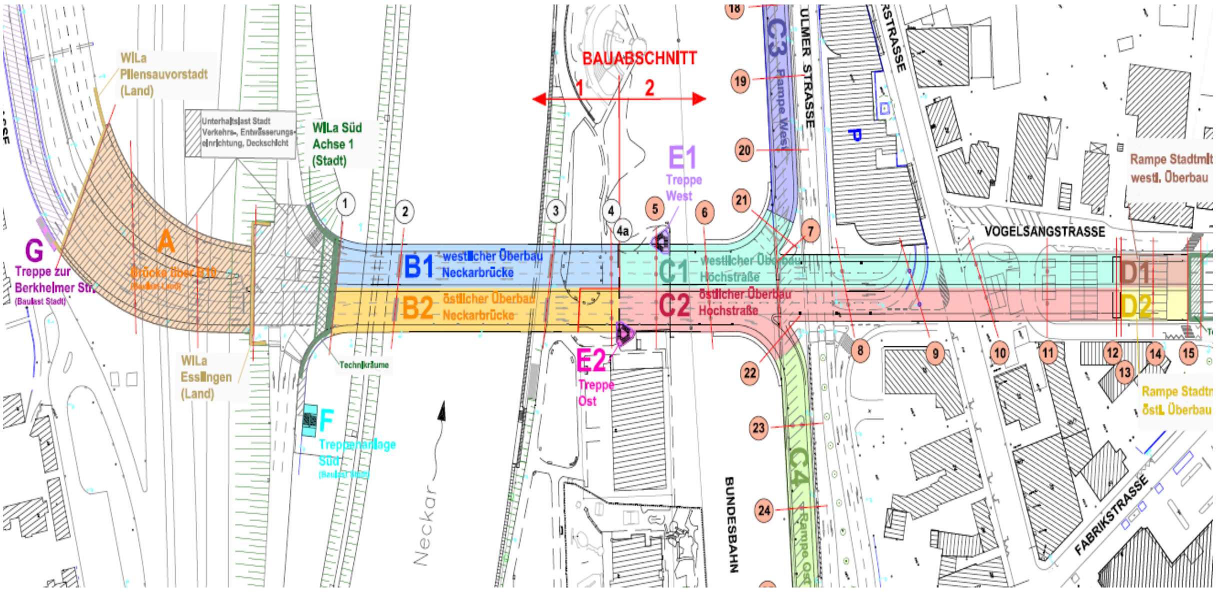

Fig. 3-7: Plan view on the Vogelsangbrücke with its different structures

Beyond that, tendons prone to stress corrosion cracking have been used for the prestressing of the Vogelsangbrücke, which may lead to spontaneous failure of the structure. In a previous feasibility study, a concept was developed, that allows further use for 15 to 20 years by partial strengthening combined with a continuous monitoring system.

3.2.2 Monitoring

The approach bridge building D turned out to be ideal for the installation of an iBWIM monitoring system as it has short spans and is easy to access. Although the approach bridge is not under the focus by the client as it is a not-prestressed concrete construction, results from building D are important to learn about the loading of the entire bridge and the deterioration of the concrete structure, which can be extrapolated to the main bridge as well.

One BWIM was used for each lane; each BWIM has a sensor ensemble consisting of one laser rangefinder; five strain gauges arranged in a row transverse to the road; and two strain gauges which are placed on either side of the row. The gauges in the row perform the actual measurement; the two adjacent gauges are used for triggering a measurement and estimating the speed of the vehicle; the laser rangefinder is used to detect and localise the vehicle axles. The spatial arrangement of sensors is shown below.

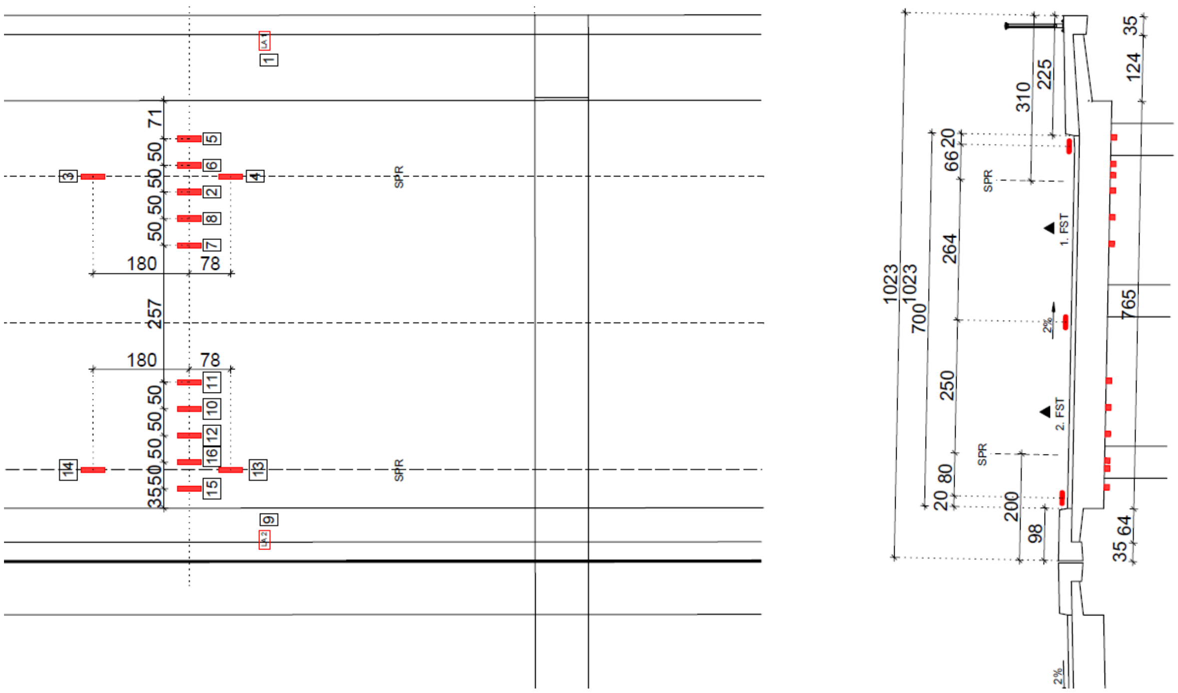

Fig. 3-8: Distribution of strain sensors.

Fig. 3-9: View of the installed sensors

Various results were gained which are very valuable for the durability assessment of the entire bridge including the other parts like the main river bridge. Major results like the number of heavy vehicles (trucks) crossing the bridge, the typical gross weight of the trucks, typical length of the trucks and number of axles and their weight were identified. Furthermore, the probability distribution of the loading events very calculated.

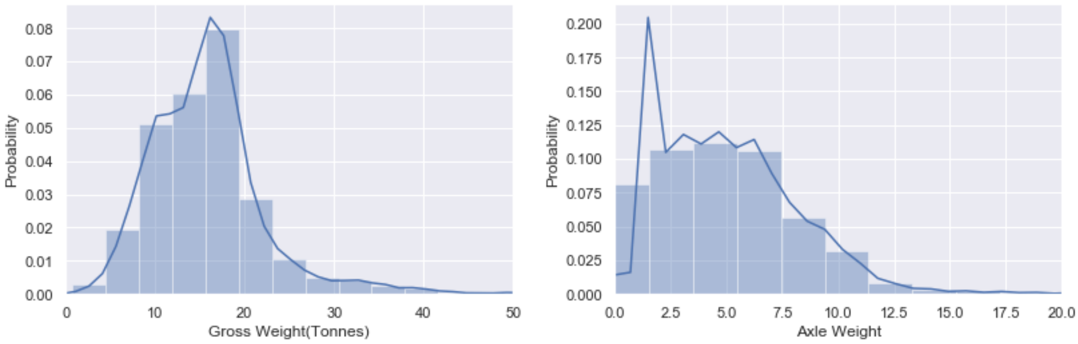

Fig. 3-10: Distribution of gross weight and axle weight of vehicles

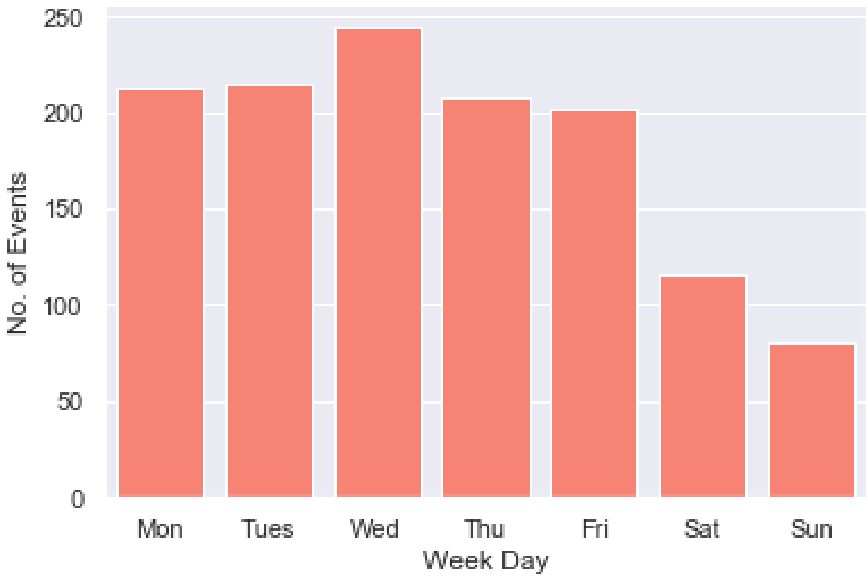

Fig. 3-11: Number of daily events corresponding to weekdays

3.2.3 Simulation

A numerical model was created in the ATENA software. Just one half of the bridge was modelled because of symmetry and connecting between two slabs in the middle of the bridge was neglected. For meshing was used hexahedra quadratic mesh sized as 0,5 m. Bridge is supported by nine steel plates fixed to bottom surface of the slab and each steel plate has constraint for middle point. Bridge is 27 m long and first span in 13,2 m and second span is 13,8 m. Height of the slab is 0,6 m and width of one slab is 9,5 m. The reinforcement was modelled for robustness and durability calculations.

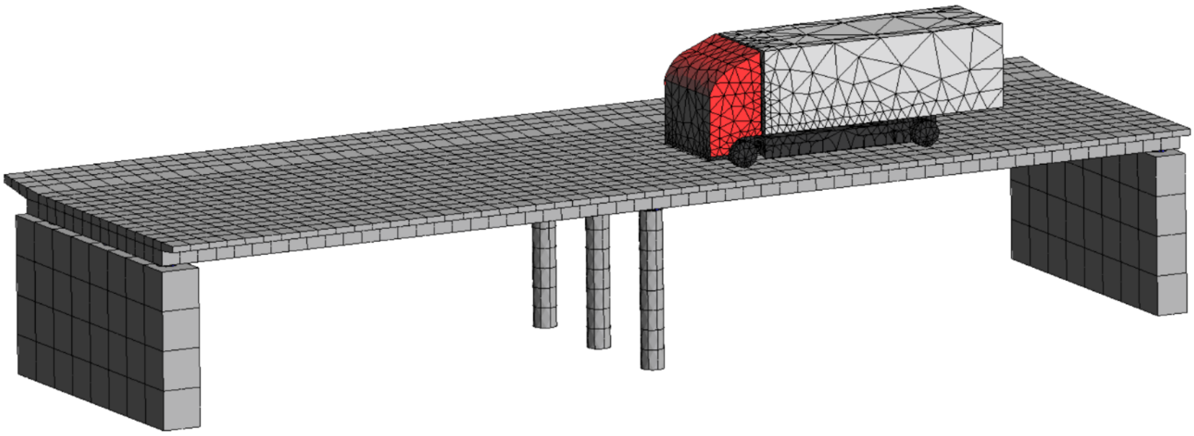

Fig. 3-12: Numerical model of the bridge with moving truck and shown mesh

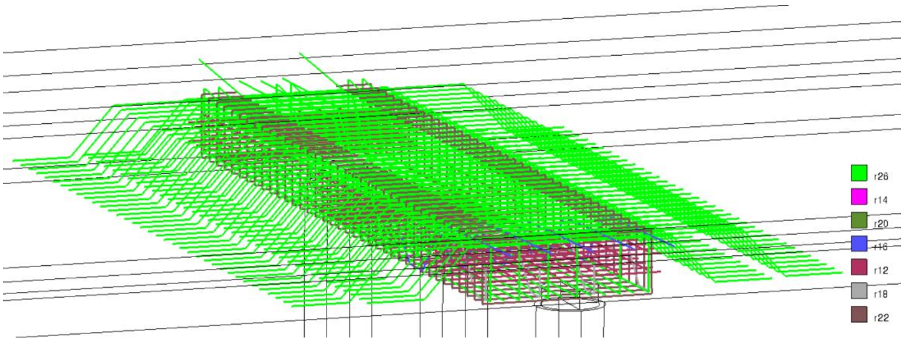

Fig. 3-13: Detail of reinforcement above the middle columns.

The model was loaded by the dead load of the structure and live loads. Live loads were increased to provoke cracking of the concrete. After cracking, the live load was reduced and a rolling truck was applied on the bridge. Results show the typical bending shape and stress distribution of a two-span slab.

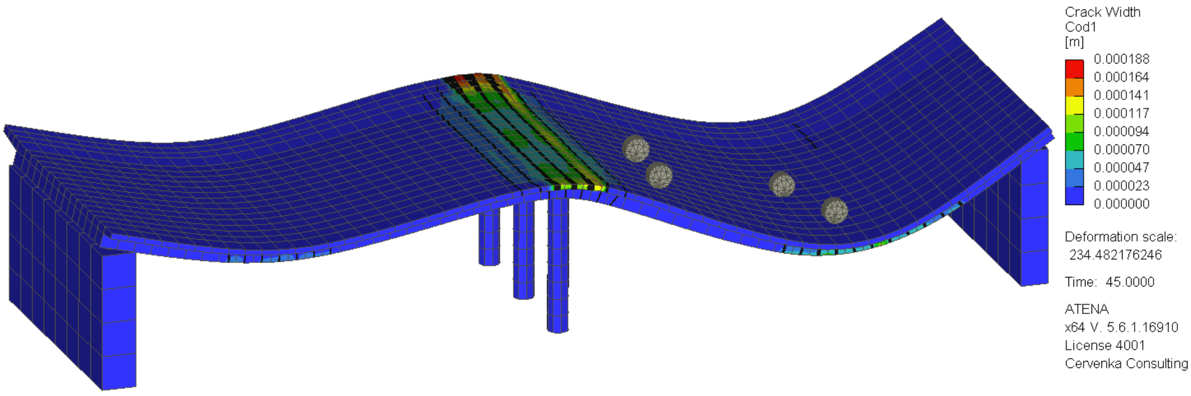

Fig. 3-14: Crack width of the concrete caused by a single truck

3.2.4 Prognosis

A durability prognosis was performed to predict the lifetime of the bridge due to environmental actions, the proceeding of passivation of the concrete and corrosion of the reinforcement.

Results of reinforcement corrosion prognosis show on the one hand the influence of reinforcement corrosion on the lifetime of the bridge and on the other hand the failure mode of the bridge due to reinforcement corrosion. Reinforcement on the upper surface of the slab in the support area is most likely to be weakened by corrosion. This leads to increasing rotations and decreasing hogging moments in that area. As a result, the sagging moment in midspan increases until failure of the structure.

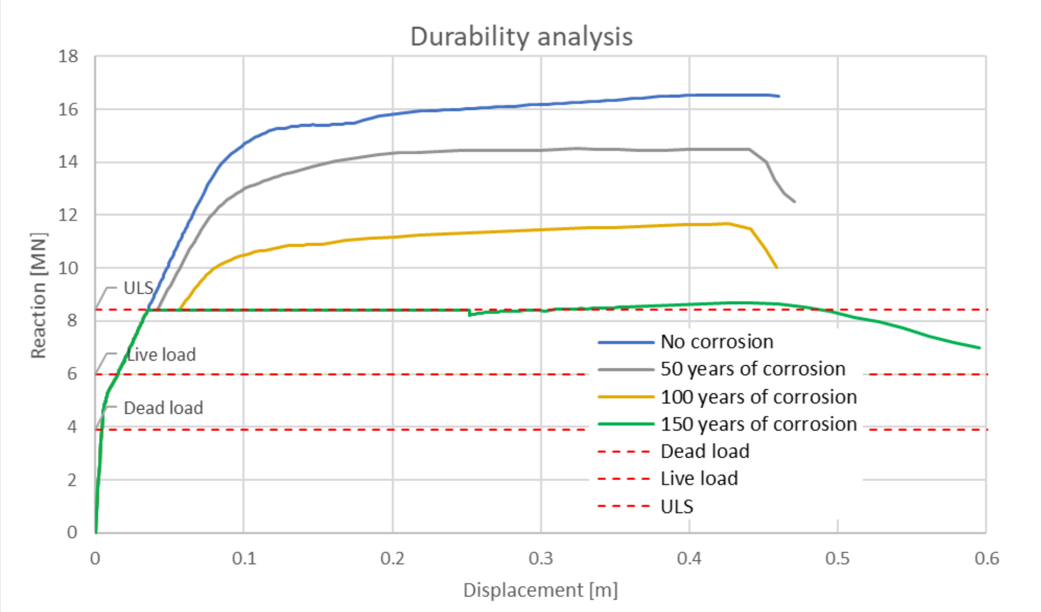

Fig. 3-15: Influence of corrosion on the load bearing capacity

3.2.5 Conclusions

The results of the durability studies show a much higher remaining lifetime of the bridge, than previously estimated with less sophisticated methods. Considering Building D alone, the remaining lifetime can be exceeded to approximately another 50 to 60 years from now instead of 15 to 20 years previously predicted. The results also show that chlorides have a great impact on the deterioration of the structure. Therefore, it is very important that the sealing underneath the wearing surface is in good condition so chlorides cannot intrude the concrete.

Ongoing deterioration will lead to great deformations and visible damages especially in the support area of the bridge including spalling of the concrete cover. Typical for a not-prestressed concrete structure the bridge has a very good preparatory behaviour.

Apart from that a monitoring system, especially the iBWIM Method on bulding D is a very good measure to monitor the traffic on the bridge. Knowing the loading of the bridge in real time is very valuable for the monitoring of the other building parts C and D which are prone to stress corrosion cracking. As the spontaneous cracking of tendons may lead to a collapse without any advance notices, it is very important to know the behaviour of the bridge very well, so that minor changes of gauge signals can be interpreted correctly and the correct measures can be taken.

3.3 Tiffen Bridge Austria

This third pilot bridge was mainly used for the verification of the developed monitoring systems and sensors. To verify that the iBWIM installation at Tiffen is functioning properly we conducted a series of "sanity" checks. We check the system at various points on the signal chain; because of the sequential nature of processing, the later stages, of course, rely on the previous stages to provide high quality data. Given the distributed nature of the system these are grouped into Measurement and Analysis tests. The Measurement tests test the sensors and on-site embedded hardware. The quality of the signal and the system's ability to packet it into discrete events are tested. The Analysis tests assess how well the remote system can model the data, and whether the inferred values, e.g. speed and weight, are plausible.

Verification of Measurements

3.3.1 System Uptime

One novel aspect of the Tiffen installation was its reliance on solar and battery power. Our first test is to assess how well the system could operate through the winter months. As detailed elsewhere, the solar and battery capacity proved insufficient. A pattern emerged where the system would operate for a few days until it had exhausted its stored power, then shut down for typically two days until the solar module had restored stored power to the necessary level. This pattern can be seen in the time history of recorded traffic events.

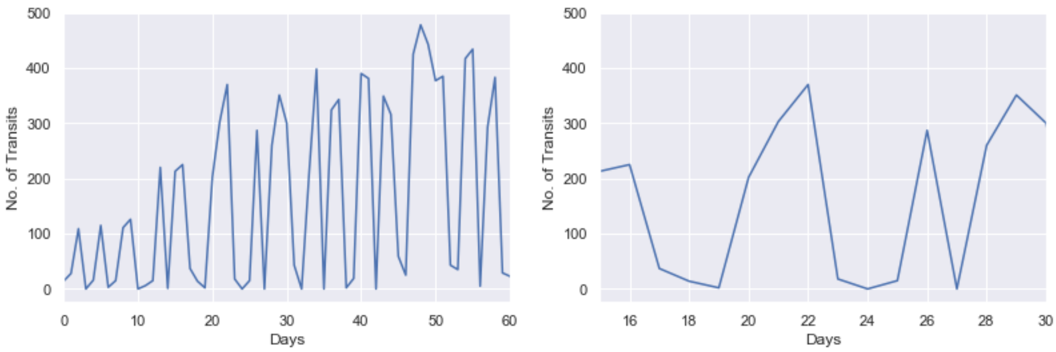

Fig. 3-16: Time history of events from Tiffen; whole period (left) and detail (right).

3.3.2 Parsing

The sensors monitor a bridge continuously; however, we are interested in discrete events. The embedded hardware must monitor sensors and decide when an event begins and ends. The relevant portion of the data is then extracted, packaged and passed to the remote system for analysis. Our second test is whether the embedded system can extract records of a plausible length, typically between 1 and 2 seconds. In fact all the recorded events fall into this range.

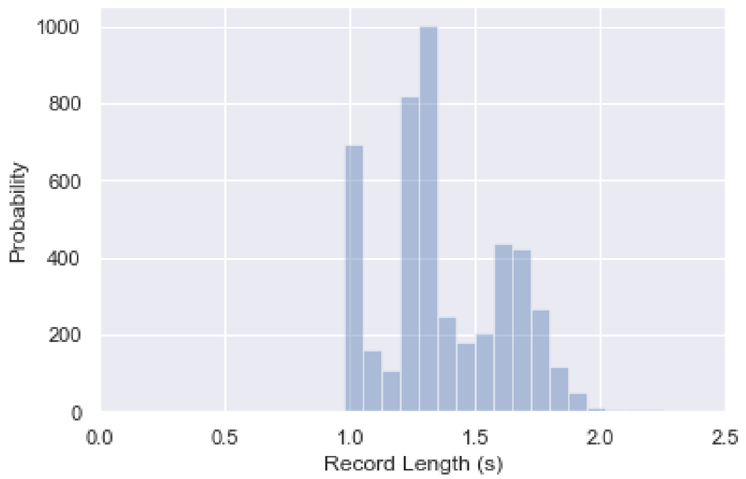

Fig. 3-17: Duration of packets for traffic events.

3.3.3 Signal noise

The signal packets include a "front porch", i.e. a portion of the signal before the first effects of the vehicle are evident. This portion typically lasts around 200 samples (0.25s) and gives us useful data to measure the offset and background noise of the signal. If we define the Signal to Noise ratio as the ratio of the signal maxima to the standard deviation of background noise, most events have SNRs of above 40dB. We conclude noise is not a significant issue.

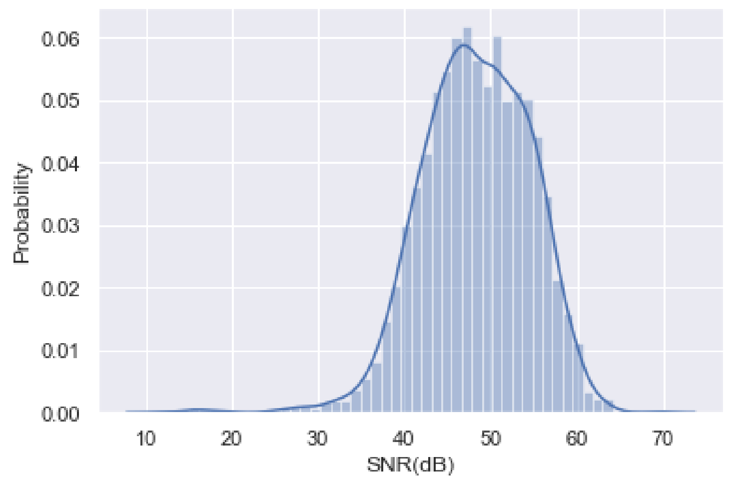

Fig. 3-18: Distribution of estimated signal to noise ratios.

3.3.4 Offset

The mean value of the front porch is also useful for measuring the bias of the signal. We calculate the ratio of average value of the front porch to the signal maxima. The distribution of ratios, Fig. 3-19 shows that 95% of signals have ratios less than 17.5%. This is a cause for some concern and must be accounted for in subsequent calculations.

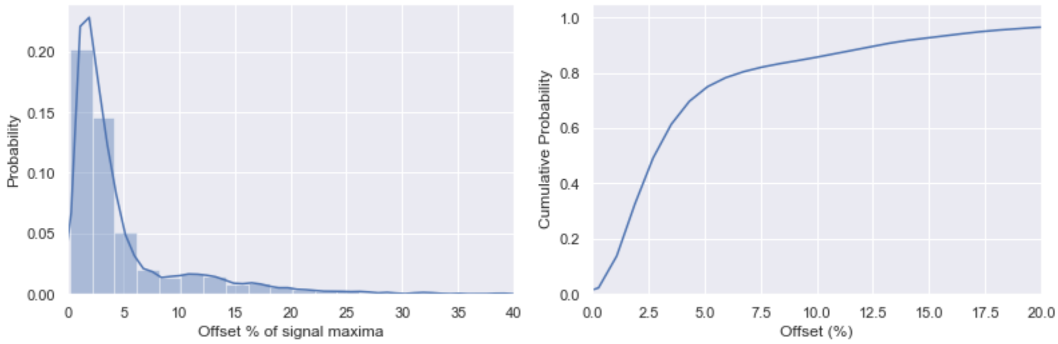

Fig. 3-19 Offset as a percentage of signal maximum; probability distribution (left) and cumulative distribution (right).

3.4 Verification of Analysis

3.4.1 Quality of Fit

iBWIM infers the parameters of interest by fitting a model of the measured strain signal. The better the fit, the more accurate the parameter estimates. When it fits the model, the algorithm also records the quality of the fit, defined in terms of mean square error. Fig. 3-20 shows the distribution of the quality metric and it's cumulative distribution. The distribution has relatively long tails, even so 95% of events have quality metrics below 22 and 99.5% have metrics below 29.

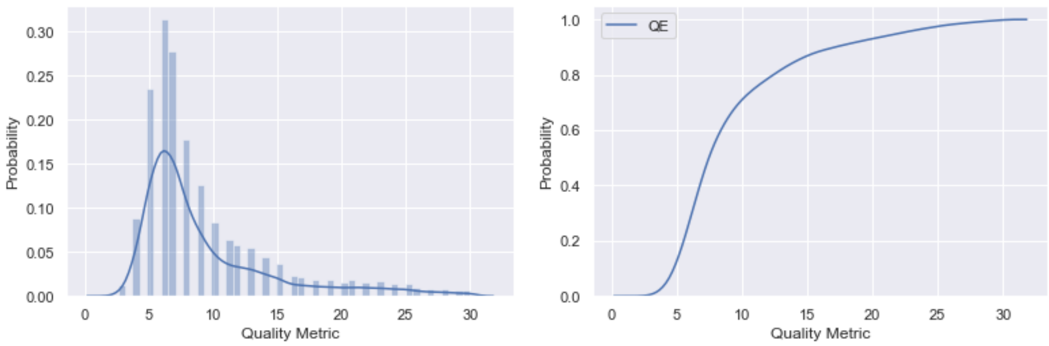

Fig. 3-20 Quality of fit metric; probability distribution (left) and cumulative distribution (right).

3.4.2 Gross Weight

The distribution of Gross Vehicle Weights is shown in Fig. 3-21. We defined any estimate below 0T or above 60T as being implausible. Of the 10811 transits, no negative weights were estimated and only one estimate of more than 60T was recorded. We conclude the weight estimation is performing plausibly.

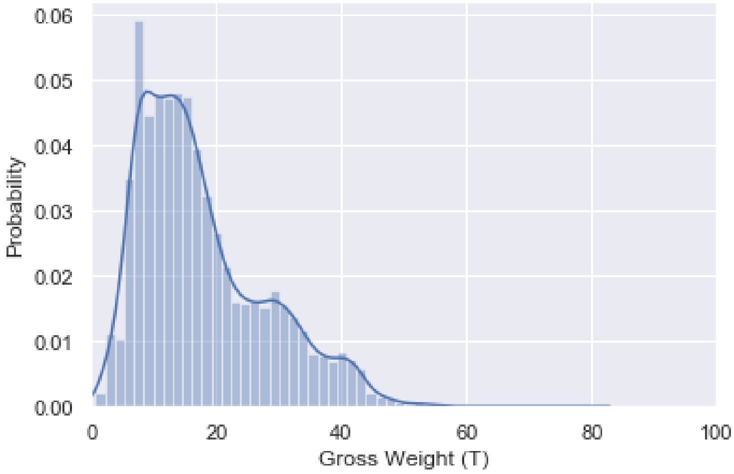

Fig. 3-21 Distribution of Gross Vehicle Weights.

3.4.3 Speed

The speed of the vehicle is inferred from the signal delay between two strain sensors. The Tiffen bridge is free from congestion and has a speed limit of 100km/h, though given that the bridge les on a curve we would expect heavy goods traffic to be travelling significantly more slowly. The distribution of estimated speeds, Fig. 3-22, shows most vehicles travelling at around 80Km/h with no heavy vehicles travelling above 130Km/h or below 20Km/h. We conclude the speed measurements are plausible.

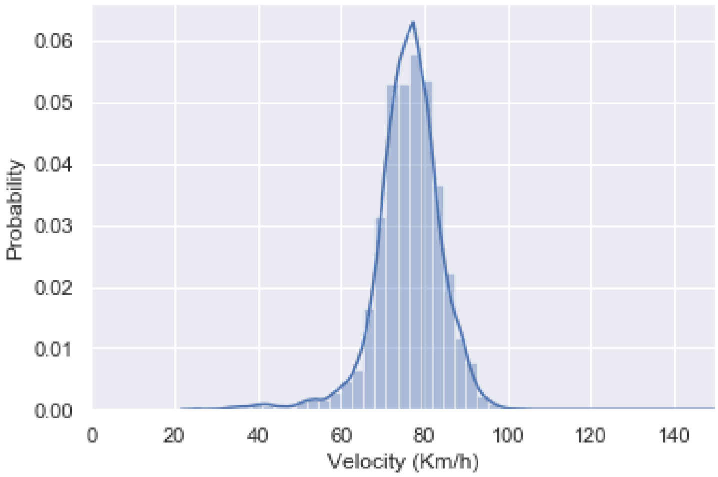

Fig. 3-22 Distribution of measured vehicle speeds.

3.4.4 Vehicle Classification

The algorithm performs a classification vehicle type according the estimated dimensions and axle distribution of the model. If the distribution does not fit any of our defined categories, the vehicle is categorised as unknown. In our data set of 10811 vehicles, 225 were classifed as unknown. This is an acceptable error rate.

4 Assessment of the achieved functionalities

4.1 Monitoring Functionalities

The iBWIM system met the requirements of the other project partners: the installations provided accurate and reliable measurements over the test period. Statistics extracted from the measurements gave plausible models of the traffic loading patterns.

The improved signal processing hardware and software gave visibly improved signals. This improved the performance of the estimation components, i.e. model fitting, later on the signal chain, giving more reliable and accurate estimates of vehicle speed, weight and axle load distribution.

Furthermore, work on a particularly egregious bridge that was not included the original project proposal allowed the development of signal processing software that could be applied to the test bridges—albeit with less dramatic improvements.

The solar module prototype developed for the project was a partial success. The power provided by the cell and the power storage were insufficient to maintain operation throughout the winter. This has provided valuable design data not only for hardware design, but also for software strategies for dealing with power outages.

4.2 Simulation Variation

The antxml schema facilitates the (semi-) automatic procedure of model variant generation and improves the efficiency of simulation in ATENA cloud. Possible damage values are estimated appropriately to satisfy the accuracy threshold in engineering practices and to evade overfitting effectively.

Variants are automatically generated on AtenaCloud from the numerical master model and the variation model; hence the users are relieved from creating numerical model variants manually, which also prevents human errors.

After simulation, variants are stored in a Multimodel utilizing the delta method to reduce storage space consumption.

4.3 System identification tool

The ATENA cloud platform is developed on the basis of cloud services and provides the needed environment for the mass simulation approach for the system identification. Local efforts are strongly reduced due to the generation and subsequent automated simulation of model variants which are both completed in the ATENA cloud.

Simulation results can be exported in csv files directly from AtenaCloud, which enables convenient data processing in succeeding system identification runs.

A method to get the best-fit result after simulation of all variants is provided by Atena Cloud and adapted by the BIMgrid platform for direct download by the user in the last workflow step (Best Fit Result Evaluation – see Fig. 4-2 below).

Screenshots and brief explanation of the GUI as well as benefits for the end users are explained in Report M7.3 [22].

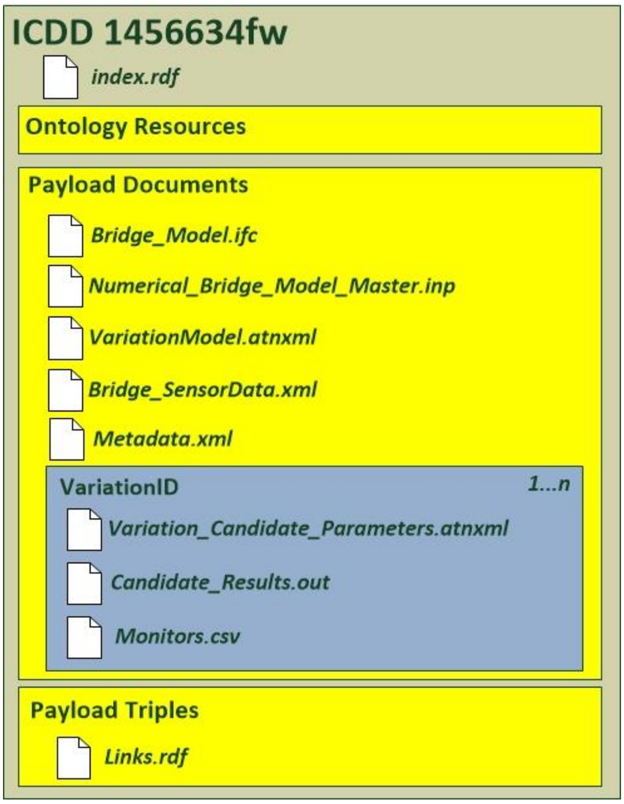

Fig. 4-1: Principal *structure of the cyberBridge multimodel*

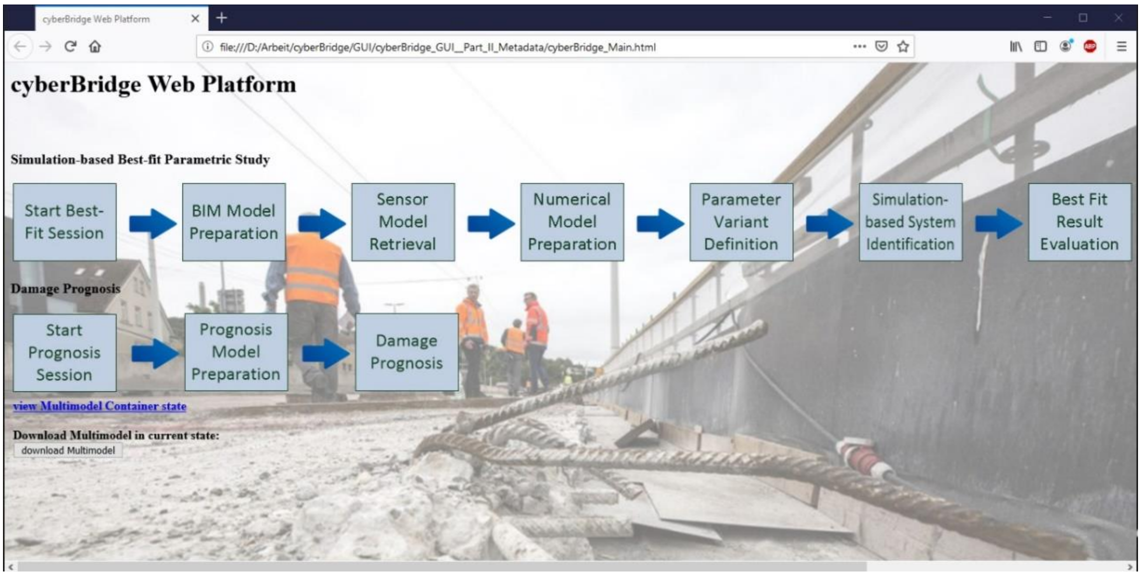

Fig. 4-2: *cyberBridge main dashboard.*

4.4 Prognosis Tool Functionalities CER

The developed prognosis tool is efficiently supported by the previous functionalities of the cyberBridge platform. The key element is the existence of the calibrated material models using the monitoring results, variation methods and the system identification tool. This allows the efficient and accurate applications of the durability models for prognosis of the structural health, reliability and load carrying capacity. The key functionalities and features of the developed prognosis system can be summarized as follows:

- Calibrated numerical model
- Efficient and validated durability models
- Efficient and validated nonlinear structural and material models
- Efficient methods and sampling approaches for probabilistic modelling
- Cloud computing for parallel deterministic or probabilistic analysis

The typical outcome of the prognosis model is for instance the time prognosis of the structural strength as shown for the Vogelsang bridge pilot project in the figure below.

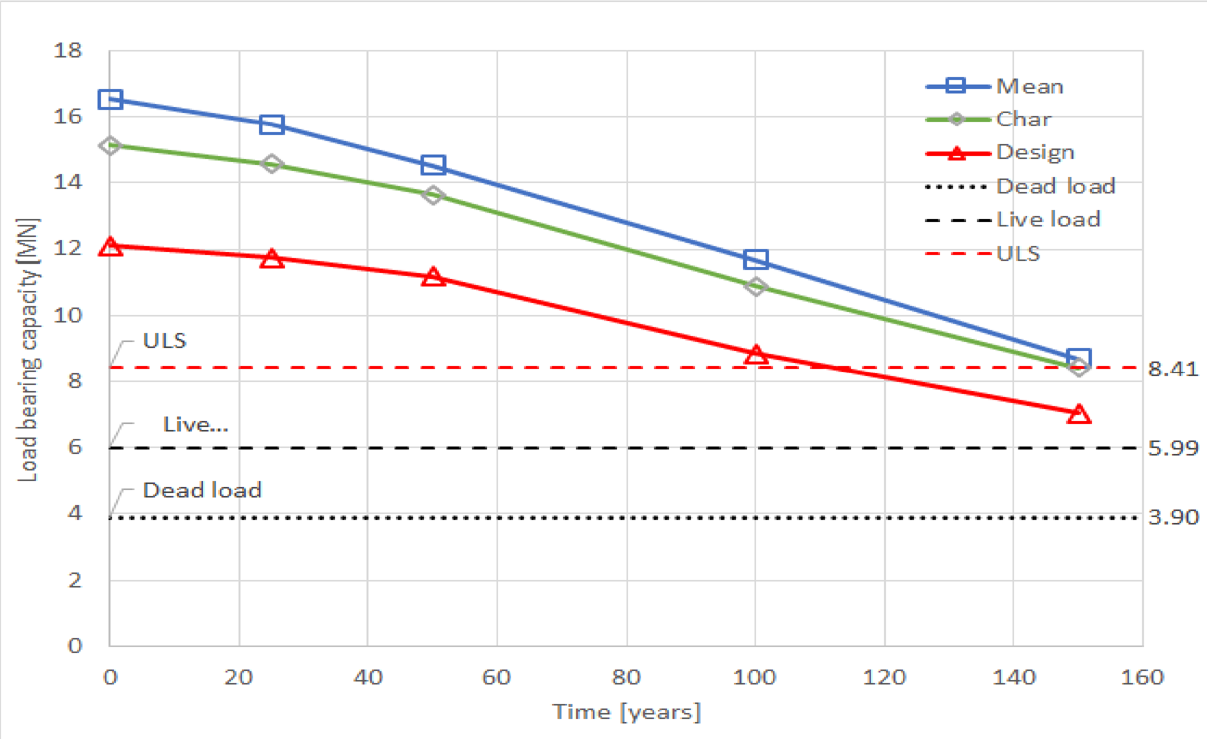

Fig. 4-3: Prognosis of structural health development

4.5 Data Management

All data created during the cyberBridge workflow is stored consistently in multimodels (one multimodel is persistently used per workflow run; the structure of the multimodels is strictly defined as shown on the figure above and explained in previous reports).

Benefits of multimodel use:

- compliant to the ISO 21597-1 standard that is expected to be supported by an increasing number of tools in the future, hence providing for long-term compatibility
- clearly defined data interoerability between tools and users
- as needed just-in-time transparent information delivery

5 Scope and marketing potential

5.1 Scope

CyberBridge brings bridge monitoring and forecasting to another level. It is an innovative BIM based cyber-physical system for bridge assessment comprising continuous bridge and load monitoring, continuous vehicle load and bridge system identification for global and local crack propagation deterioration, and forecasting using mass simulation and probabilistic methods. I is as a continuous monitoring platform with online evaluation. The automated use of HPC (Cloud/Grid) power allows deep system identification at any time providing for much better understanding of the deterioration process and the impact of each deterioration event on the reliability of the bridge.

The system is capable of continuously detecting micro cracks and the deterioration state as well as its changes on a much more precise level and a higher confidence than common monitoring systems and keeps monitoring costs at about the same level. This is based on several new methods:

1) A new continuous simulation-based system identification method for global and local behaviour identification, using massive Grid/Cloud simulation,

2) Load monitoring systems for identification of individual vehicles and their synchronisation with the bridge behaviour monitored values,

3) Reliable, accurate prediction of the remaining lifespan and retrofit measures on the basis of the deeply identified system and massive Grid/Cloud sensitivity simulations and probabilistic methods

4) BIM, Multimodel and ontology-centered flexible and efficient mass information management and visualization of the results via a 3D bridge navigator enabling improved information and decision-making even for laypersons

5) Improved sensor system layout, modification and tuning process for global and local bridge system identification based on multiple virtual scenario simulations and ontology-based Multimodel information management.

6) Improved sensor network.

5.2 Marketing Potential

5.2.1 Bridge Owners

During the cyberBridge project various very powerful tools have been developed. These tools are very valuable for bridge owners, as they bring bridge monitoring and lifetime prognosis to another level. As shown in the pilots, the knowledge of the real traffic load on the bridge monitored be the iBWIM method enables much better prognosis, than state-of-the-art prognosis based on design load models given by design codes. Bridge owners are enabled to gather much better informations about status quo of the bridges and about the actual remaining lifetime of their structures. This is very important for investment planning and decision-making.

5.2.2 Monitoring and Assessment Companies

The work carried out by PSP under the auspices of cyberBridge has improved the marketability of our bridge monitoring systems for monitoring and assessment companies in three ways.

First, by improving the general performance of the system, with the new digital bus and improved signal processing, we have extended the range of bridges to which the system can be applied. Bridge Weigh in Motion systems work best on short, rigid, modern bridges, and performance drops to unacceptable levels when these conditions are not met. By improving the quality of the desired signal components, we can apply iBWIM to bridges that would have, hitherto, been considered unsuitable. This greatly widens the potential market of the iBWIM system.

Secondly, by developing the solar module we have made the iBWIM system almost independent of support infrastructure (with the exception of mobile telephone network coverage). This means the system can be applied to many small bridges in remote locations where the required infrastructure would be prohibitively expensive. Again, this greatly widens the range of bridges to which we can apply the system.

Thirdly, with the development of improved signal processing hardware and novel, smart sensors, we have extended the iBWIM system so that it can now carry out structural health monitoring. The loading of a bridge is closely linked to the the structural health of that bridge and it is logical that SHM systems should also monitor traffic. However, from a signal processing viewpoint, SHM and BWIM systems have quite different design requirements: high sampling rates for BWIM versus long term stability for SHM. The new digital bus and smart sensors make it feasible to combine these tasks without compromising accuracy. While the first two contributions have incrementally improved our potential market, the development of hybrid BWIM and SHM systems opens up an entirely new market sector.

These three developments which have been facilitated by CyberBridge make the iBWIM system a product that will offer monitoring and assessment companies the opportunity to expand their market to include bridges that would otherwise have to be manually inspected.

5.2.3 Consulting Companies/Bridge Engineers

In present, bridge engineers spend a lot of time on calibration of numerical models to match them with sensor data from a monitoring system. Bridge engineers usually build numerical models that are on the safe side for the design process or for recalculation of an existing structure. Models are always a simplification of the reality and hence they have a certain fuzziness. For following up measured data, the numerical models have to be created differently. For this particular task, the model has to be as precise as possible, including possible existing damages in the structure that are not known yet. This process is very time consuming and thus costly.

The ATENA software enables bridge engineers to build a very detailed model of the structure, compared to other structural analysis software. Especially for concrete structures, which behave very complex when they reach high load levels, ATENA gives a very good picture of the reality. It has proven many times to be one of the best programs to predict failure of structural elements in large-scale material or construction-type tests. As ATENA is able to calculate very detailed and complex numerical models very precisely, it is even more important to find the model to match the reality.

The system identification tool automates this process, by creating numerous variants of the structure. The tool calculates all variations and finds the best fit automatically. Hence, it enables the bridge engineer to interpret the behavior of the bridge much faster and hence much more cost efficient.

6 Recommendations for further extensions

Many novel tools, sensors and methods have been developed during this project, and they were successfully tested and validated on the 3 pilot bridges as presented in Section 3. This development however is opening new possibilities and indicating promising directions for further research and development.

This section therefore summarizes some of the most interesting directions and possibilities for new development and extensions of this novel structural health monitoring system.

(1) In the area of the monitoring, the new sensor for deflection measurement using accelerometers was developed and successfully validated on the Vogelsang bridge, but there is still a room for further improvement of the sensor accuracy.

(2) As a direction of further extensions of this project, the developed detection method for damage development can be correspondingly adjusted and employed for damage development (seeFig. 6-1). This idea is conceived based on tow conditions: 1) the bridge monitoring system is capable to deliver continuous monitoring service for a longer term (e.g. years or decades months); 2) new cracks will appear in a longer term and can be observed through bridge inspection or other approaches. The procedure of damage modelling in the input files of ATENA should be improved, so that the damage effects from both old and new cracks are represented in the input files. Adopting the traffic loads of test or real-time vehicles, damage detection can be executed in this way.

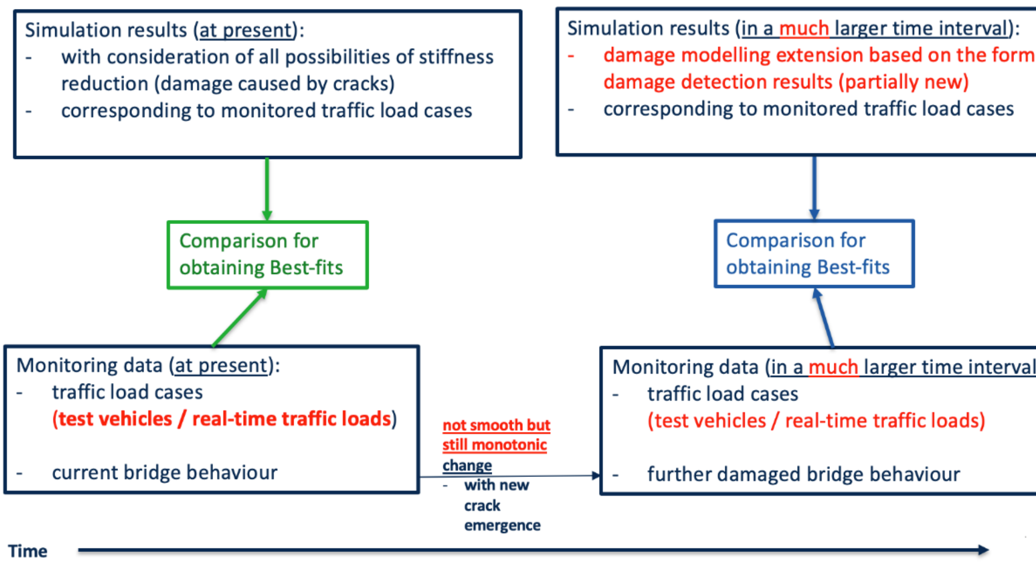

Fig. 6-1: Damage identification conception considering damage development in a longer time

(3) The system identification tools still requires significant support of an expert engineer and fully automated identification is not possible. This is still an open and very active area of research, where the future advances in UI technologies can bring surprising methods and tools for further advancement.

(4) In the prognosis models, it would be extremely useful to develop and implement models for corrosion prediction of prestressing tendons, which are usually located in pipes or ducts with possible access by various fluids. The current durability models are difficult to apply in these situations.

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Acknowledgements

This document was created within the Eurostars project cyberBridge E!10925. The financial support of the Eurostars program and national funding agencies in Czech Republic, Germany and Austria are greatly appreciated.

The partners in the project are:
Cervenka Consulting s.r.o. . CER
Petschacher Software und Projektentwicklungs GmbH. PSP
Leonhardt, Andrä und Partner, Beratende Ing. VBI AG..LAP
Institut für Bauinformatik, TU Dresden..TUD

This report owes to a collaborative effort of the above organizations.

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