Structural monitoring and identification approaches

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ABSTRACT: The continued use of existing structural systems is, due to environmental, economical and socio-political assets, of great significance growing larger every year. In front of this background we find the necessity to identify the key parameters and procedures to verify and update the knowledge about the present condition of a structure. Monitoring continuously the decisive parameters of a structure provides the quantitative basis for analytical modeling, structural identification and condition assessment in order to ensure the safety of highway bridges with regard to life extension and replacement strategies. In this paper the authors discuss the monitoring system installed on the Colle Isarco viaduct (Italy) and an excerpt of the main results. The paper concludes with a description of the reliability analysis and structural identification procedures.

1 MAINTENANCE AND REPAIR

Engineering structures are designed for special requirements and a defined and limited service life. With regard to the assumed timeframe of utilization, the existing inventory of structures will result in enormous maintenance and rehabilitation costs in future. To a continuously growing degree, we observe an increasing shift from investments in the construction of new infrastructures to the maintenance and lifetime extension of the existing ones. At the time the Federal Republic of Germany owns 36,971 bridges with a road surface area of approx. 27.2 million m² and an estimated asset value of 40 billion € (Metzler, 2004). The Austrian Republic is responsible for approx. 12,000 bridge objects with an area of 7.4 million m² and an asset value of 9.5 billion € (Wicke et al. 2001). In Europe the annual upkeep for bridges amounts from 0.8% to 2.5% of the construction costs. Beside the strategic costs due to the restriction of utilization during preservation, the annual expenditures average out to 10 – 15 € per m² bridge deck area (Bergmeister and Santa, 2004). Considering modified loading requirements, aging of materials and environmental actions, insufficient maintenance and preservation, performance of many of these in-service structures has decayed over the years of utilization and the inherent level of safety may be inadequate relative to current design standards. For the purpose of developing adequate life extension and replacement strategies, issues such as whole-life performance assessment rules, target safety levels and optimum maintenance strategies must be formulated and resolved from a lifetime reliability viewpoint and lifecycle cost perspective. In order to maintain the health of a structure up to a given time into the future, a cost-effective maintenance strategy has to be used (Frangopol et al. 2001). In front of this background we find the necessity to identify the key parameters and procedures to verify and update the knowledge about the present condition of a structure with respect to a number of aspects. A visual inspection may yield a first qualitative, maybe purely intuitive impression. A better judgment would be based on the evaluation of acquired quantitative information.

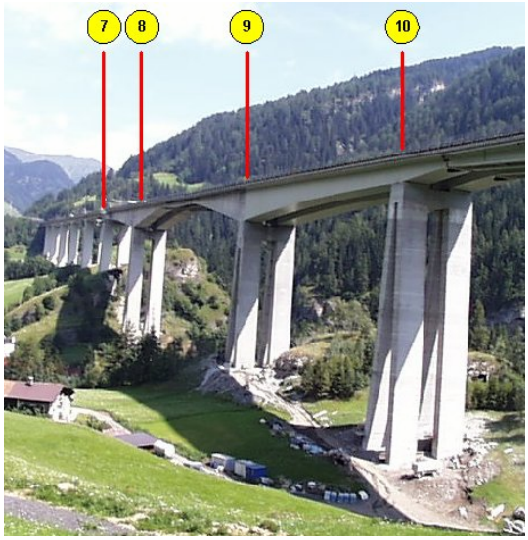


Figure 1. Monitored viaduct Colle Isarco

Recent progress in the development of sensing and data processing technologies combined with material/structure damage characterization have resulted in a significant interest in diagnostic tools to monitor structural integrity and to detect structural degradation. Adequate monitoring techniques provide qualitative and quantitative knowledge that facilitates a more precise condition assessment and efficient maintenance interventions. This paper is intended to give a short outline of the monitoring system installed on the Colle Isarco Viaduct shown in Figure 1. The overall length of the instrumented section of this prestressed concrete structure is 380 m. The maximum height of the box girders near the supports number 8 and 9 is 11 m, having a uniform width of 6 m. The arrangement for each roadbed is approximately 11 m wide. The height of the 4 supporting piles no. 7, 8, 9 and 10 varies between 55 and 68 m. The bridge was built in 1969 and was upgraded through an essential rehabilitation intervention from 1999 – 2001 (Fig. 2).

Figure 2. Rehabilitation of pillars

2 DURABILITY PARAMETERS

Chloride induced corrosion of the reinforcement is one of the main causes for repair measures to reinforced concrete bridges. The corrosion speed of the depassivated reinforcement depends essentially on the exposure conditions, these are in particular concrete humidity, electrical conductivity of the concrete, temperature and oxygen content in the porewater solution. Before rehabilitation, the pillars of the Colle Isarco viaduct showed high chloride concentrations in the construction concrete as well as extensive corrosion attacks at the reinforcement. The primarily reason had been deicing salts which were transported to concrete surface where they further penetrated into the concrete. Before repair, preliminary examinations were executed to determine the present state of the structure and to identify the instrumentation spots for the sensing elements. This included a visual inspection of the reinforcement, the determination of chloride concentration, carbonation depth, porosity and concrete cover.

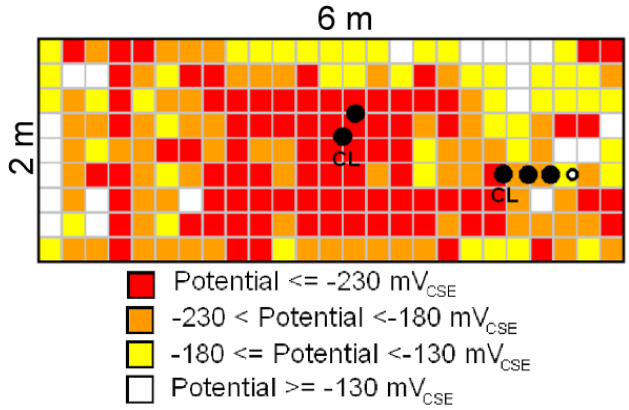


Figure 3. Potential field measurement on column 1, pillar P10

Potential field measurements (referenced to a Copper-Sulphate Electrode) were performed to determine the areas where the reinforcement of the columns is in an active (potential ≤ -230mV$_{CSE}$) or passive state (potential ≥ -130mV$_{CSE}$), see Figure 3.

After rehabilitation of the structure 12 electrochemical multiprobes (Fig. 4) have been installed on 4 selected columns of the Colle Isarco viaduct to monitor continuously the concentration of free chlorides, corrosion current, concrete resistivity, temperature, and electrochemical potentials at different embedding depths. These multiprobes have been developed at the ETHZ, a more detailed description of these sensors can be found in (Schiegg, 2002).

Figure 4. Sensing Multiprobe

The system is in operation since June 2000. The main resume for the monitored period is essentially, that the applied rehabilitation concept (passive cathodic protection) proves to work in the expected way, which means that we observe generally a positive corrosion current flow between zinced mesh (anode) and the reinforcement (cathode). However,

current measurements as a direct indicator of metallic corrosion have to be interpreted carefully.

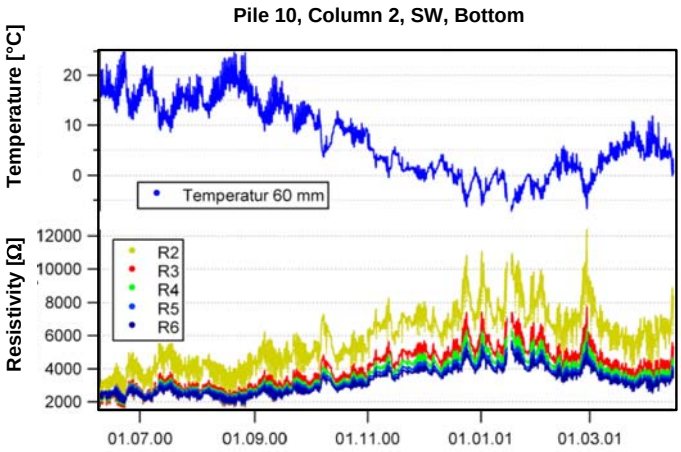


Figure 5. Concrete resistivity and temperature

Figure 6 shows the corrosion current measurements for one instrumentation field on pillar P10. Unlike the other instrumented fields, the cathodic protection in this area was initially not given. However, the system inverted after a while and the zinced mesh finally converted in an anode.

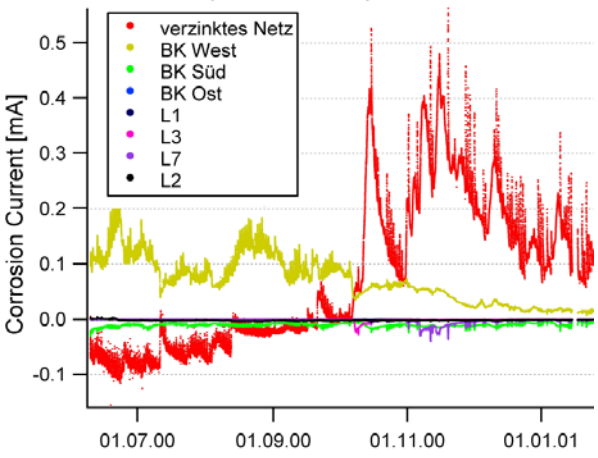


Figure 6. Corrosion current

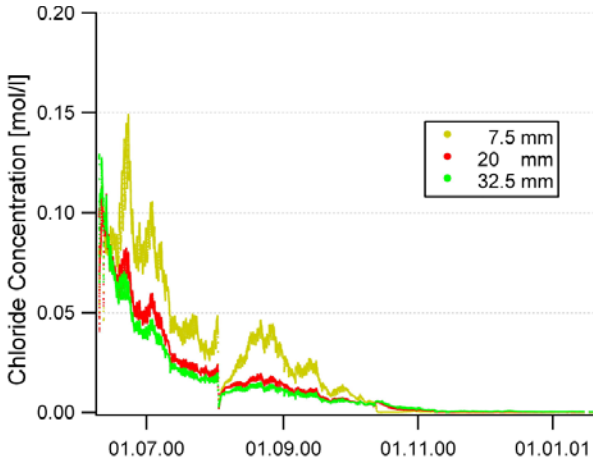


Figure 7. Chloride concentration

The concrete resistivity is generally not significantly influenced by precipitation, whereas the sensors captured drying and hydration of the young shotcrete after rehabilitation. As both concrete resistivity as well as corrosion current are affected by temperature (Figure 5), this influence has to be compensated properly (Schiegg, 2002).

The experience has shown that for this purpose an exacter instrumentation of the temperature distribution would be desirable. The chloride measurements yielded only in part reasonable and stable values as they were, especially at the beginning, influenced by ongoing corrosive processes (Fig. 7).

3 DEFORMATION MONITORING

In the present monitoring system, a network of fiber-optical SOFO sensors (Inaudi, 1999) has been installed for strain and deformation measurements. 96 sensors with a base length of 10 m were installed in the box girders on the concrete surface parallel to the neutral axis in order to determine strains and deformation (Fig. 8). Sensors with a base length of 0.5 m were used to measure the strains of 16 selected prestressing members (Dywidag 32 ST 85/105). Another 24 sensors with a base length of 8 and 10 m were installed on the pillars P7 and P8.

Figure 9 shows the strain and temperature measurements of the instrumented prestressing members in bridge SO for the period of approximately 6 months. By a continuous observation of the strain evolution, eventual prestressing losses and associated failures should be detectable in the domains of both short and long-term stresses. After removing the seasonal component from the time series, the measurements showed no significant trend or deviance. The same evaluation of strain can be made for the 96 sensors installed parallel to the neutral axis on the concrete surface of the box girders as well as for the 24 sensors installed on the piles P7 and P8.

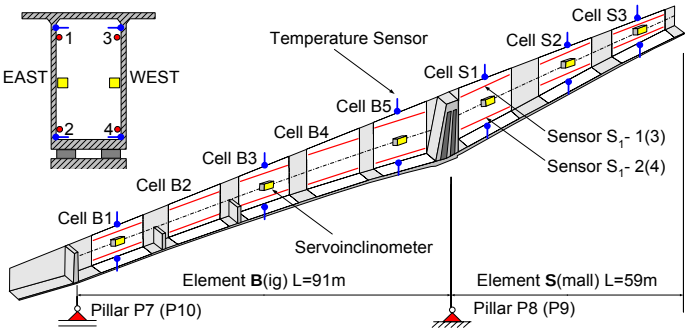
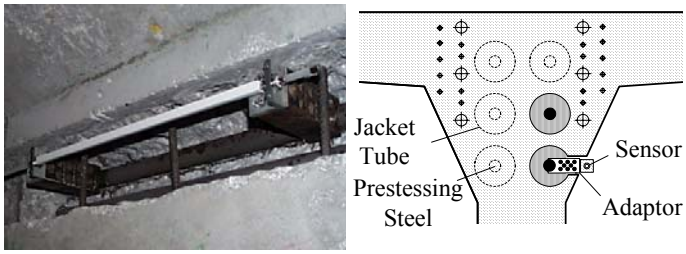


Figure 8. Instrumentation scheme of the box girders

In an advanced evaluation step the strain measurements of this network of sensors build the basis to calculate the displacement and curvature profiles of the 4 instrumented bridges by an algorithm described in (Vurpillot, 1999). Figure 10 shows the observed maximal local deformation over 2 years and the exemplary 24^h deflection behavior for one of the

instrumented bridge structures. In the long term, the 4 instrumented structures showed nearly an identical behavior (Santa, 2004).



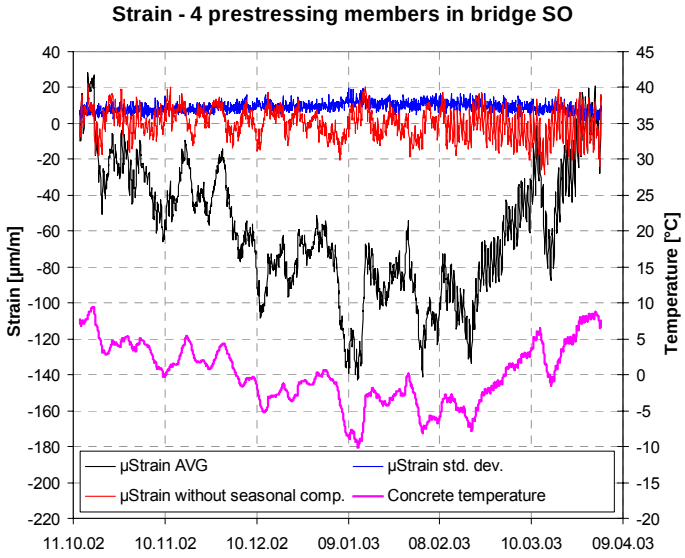


Figure 9. Instrumentation scheme and exemplary strain measurements of the prestressing members in bridge SO

The observed range of vertical deflection accumulates to 16 mm in the midfield (x = 45 m) and 60 mm at the end of the cantilever (x = 150 m). The same calculus concept is applied to the sensor network installed on the piles P7 and P8. Additionally, 10 LVDTS have been installed to instrument the relative displacements between piles and girders on the bearings. Another approach that found application in the present monitoring system was the installation of 36 highly accurate inclinometers (Fig. 8).

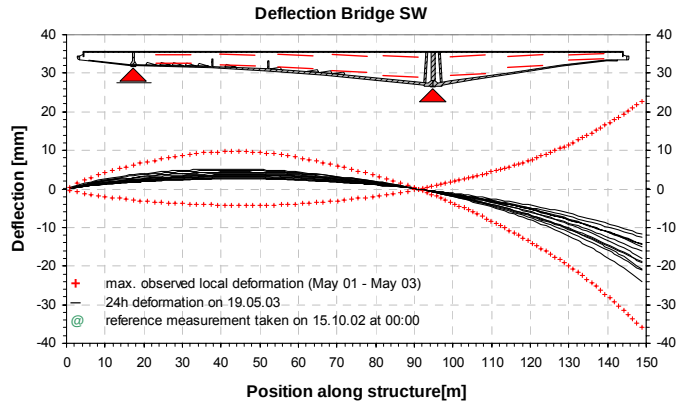


Figure 10. Vertical deflection behavior of bridge SW

On the one hand, these devices complete the fiber optical network with information on the rigid body displacements of the structure. On the other hand, vertical deflections can alternatively be determined by a similar algorithm as adopted for the fiber optical sensor network. In order to separate the influence of thermal gradients in the structure and other agents (traffic, snow, wind, etc.), 96 thermocouples (T-Type, embedment depth 200 mm) have been installed in the girders and another 16 on the piles P7 and P8. The microclimate in the 8 chambers of the viaduct is monitored by transducers for air temperature und relative humidity (Santa, 2004).

4 RELIABILITY ANALYSIS

Accompanying to the measurement activities, the monitored structure was analyzed with SARA (Novák et al. 2004), a software package based on the 2D nonlinear FE program ATENA (Červenka et al. 2001) and the probabilistic reliability analysis tool FREET (Novák et al. 2002). The used probabilistic LHM-algorithm has the advantage of using only a small number of samples to achieve a significant reliability statement. Statistical parameters like standard deviation, coefficient of variation and distribution type regarding the recommendations by CEB, fib, RILEM etc. are assigned in SARA. Since in reality there are interactions between the random parameters it is important to consider this when simulating the real behavior, a feature supported in SARA by the formulation of correlations between material parameters. For the reliability analysis of a structure it is further necessary to choose certain observation points within the structure. In the nonlinear simulations the relationships between the applied line load and the structure specific values like stress, strain, displacement etc. are captured at the defined monitoring points. In this way we obtain the ultimate load and post-peak behavior. The bridge girder failed for the deterministic investigation typically next to the middle support.

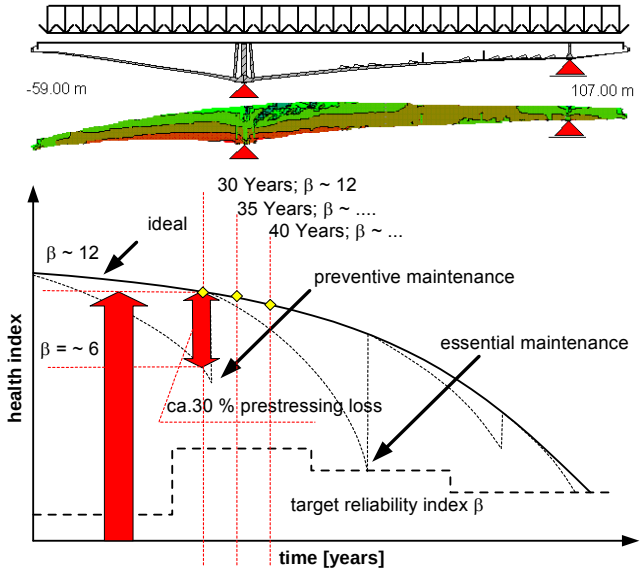


Figure 11. Lifetime, reliability and maintenance

The results of the randomized problems (10-100 samples) calculated in ATENA are returned to SARA studio, where the statistical and sensitivity analysis are carried out with the help of the program module FREET (Novák et al. 2002). Therefore the statistical response values and the authoritative influence parameters due to the sensitivity analysis are known in the monitoring points after the probabilistic analysis with SARA. A detailed description can be found in (Strauss, 2003).

5 IDENTIFICATION ALGORITHMS

Health monitoring as described above provides statistical information (e.g. deflections). An inverse FEM problem can be considered: what statistical parameters should be used to reproduce monitored random responses? A primary key problem in practical utilization is an identification of material model parameters. Parameters like fracture energy, tensile strength etc. cannot be always determined by experiments.

Based on these ideas the following two approaches are worked out to use monitoring data for the evaluation of material properties and consequently degradation processes in existing structures.

5.1 *Sensitivity based approach*

The approaches for identification can be based on statistics updating using sensitivity factors α_i evaluated for each random variable.

$$\vec{\alpha} = \alpha_{M_i,k} \qquad k = 1...n; \quad k = Ec, ft, fc... \tag{1}$$

The software package SARA can perform a sensitivity analysis, based on nonparametric rank-order correlation (Pukl et al. 2003). For every monitoring point sensitivity factors of the parameter included in the vector ***X,*** are calculated. The algorithm determines the differences of the mean values of the output concerning the simulation obtained from vector ***X*** and the observation ***Y***, see Figure 12.

$$\Delta m_{M_i} = m^{Y}_{M_i} - m^{X}_{M_i} \tag{2}$$

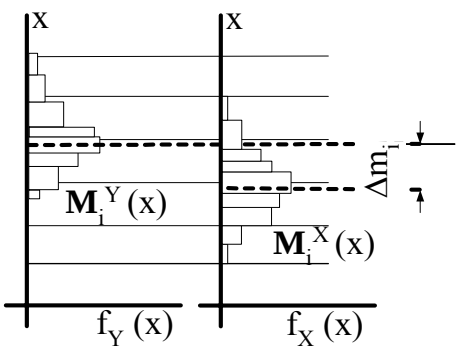


Figure 12. Differences of the mean values of the output at a monitoring point

The main target however, is to create an efficient procedure that changes the input data of the simulation in order to achieve that the simulated output data agree with the observed data. An efficient method seems to be the utilization of the sensitivity factors α_i in the correction process. The difference of the mean values of the output data are divided according to the sensitivity factors. This formulation allows the utilization of the dominancy of the sensitivity factors in the updating process of the input (Eq. 3-5). Sensitivity factors describe the influence of the input data on the simulation output.

$$\Delta\alpha_{M\,i,k} = \Delta m_{Mi} \cdot \alpha_{Mi,k} \tag{3}$$

$$\Delta X^{\,mean}{}_k = -1 \cdot E[\,\Delta\alpha_{Mi}\,]_k \cdot F \tag{4}$$

$${}_{new}X^{\,mean}{}_k = X^{\,mean}{}_k + \Delta X^{\,mean}{}_k \tag{5}$$

The calibration factor F is responsible for the step length of the algorithm. The range of F can be chosen heuristically between [0;2] according to the nonlinearity of the defined problem. After repeated iteration repetition the distances of the simulated mean values to the monitored mean values become smaller (Eq. 5). The convergence criterion for the iteration process can be established by controlling the error of observed monitoring and simulation responses.

In the second phase of the identification process the standard deviations are adjusted. The process is similar as in the case of the mean values (Eq. 6-9).

$$\Delta std_{M_i} = std^{\,Y}_{M_i} - std^{\,X}_{M_i} \tag{6}$$

$$\Delta\alpha_{M\,i,k} = \Delta std_{Mi} \cdot \alpha_{Mi,k} \tag{7}$$

$$\Delta X^{\,std}{}_k = -1 \cdot E[\,\Delta\alpha_{Mi}\,]_k \cdot F \tag{8}$$

$${}_{new}X^{\,std}{}_k = X^{\,std}{}_k + \Delta X^{\,std}{}_k \tag{9}$$

In general, at the initial iteration steps the differences of the mean values are reduced and the differences of the standard deviations are increased. This seems to be a weak point of the identification of the standard deviation. But after capturing the mean value within an accepted error, however the differences of the standard deviations start to reduce also.

The process described above will be carried out in iteration steps. From several examples we can draw the conclusion that the input quantities of the simulations can capture the stochastic models of the real material parameters after several iterations.

5.2 *Neural Network based Identification*

A sophisticated identification technique using artificial neural networks in combination with stochastic training of the networks can be used as an alternative to the previous approach, see Figure 13. The main ideas of the approach are described in (Novák, 2003). From generated basic random variables and the corresponding random response the first two statistical moments of can be obtained. This set of data

can then be used for training of a suitable type of neural network.

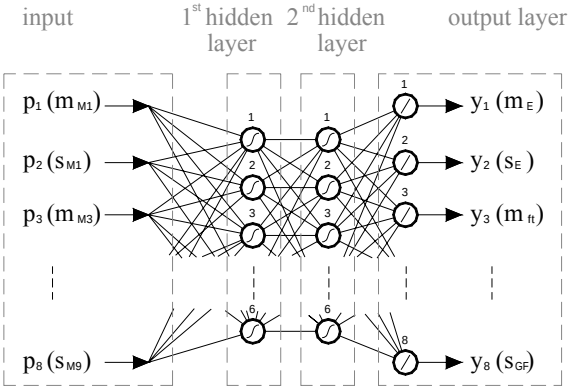


Figure 13. Scheme of neural network used

Once the network is trained it represents an approximation, which can be utilized in an opposite way: For given experimental displacements in monitoring points, which are random as well, to provide the best possible set of material model parameters.

6 CONCLUSION

The present contribution is intended to outline the instrumentation concept of the Colle Isarco viaduct on the Italian Brennero highway A22 and to discuss the main results and experiences gained by the authors. Accompanying to the measurement activities, the monitored structure has been analyzed with SARA. The probability distribution functions for the basic input variables are obtained from stochastically models and, related to the present monitoring program, from the comparison with the recorded structural monitoring data. Comparison and combination of measured and analytically modeled behavior is useful to calibrate and tune the mechanical and numerical model assumptions in order to facilitate analytical prediction and to support decision-making for maintenance and repair interventions.

Two approaches of probabilistic response identification have been suggested. The first approach utilizes sensitivity factors and a statistics control process which can provide good results using a few iterations. The advanced neural network based identification seems to be a complex and powerful technique but requires a larger number of structural response calculations for neural network training.

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