From Micromechanics to Optimal Sensor Positioning in SHM Applications – a Concept Applying a Substructure Technique

Rasoul Najafi Koopas
Chair of Solid Mechanics
Helmut Schmidt University /
University of the Federal Armed Forces
Hamburg, Germany
najafikr@hsu-hh.de

Tim Suchan
Chair of Structural Analysis
Helmut Schmidt University /
University of the Federal Armed Forces
Hamburg, Germany
suchan@hsu-hh.de

Mathias Würkner
Chair of Structural Analysis
Helmut Schmidt University /
University of the Federal Armed Forces
Hamburg, Germany
mathias.wuerkner@hsu-hh.de

Natalie Rauter
Chair of Solid Mechanics
Helmut Schmidt University /
University of the Federal Armed Forces
Hamburg, Germany
natalie.rauter@hsu-hh.de

Wolfgang E. Weber
Chair of Structural Analysis
Helmut Schmidt University /
University of the Federal Armed Forces
Hamburg, Germany
wolfgang.weber@hsu-hh.de

Kathrin Welker
Chair of Mathematical Optimization
TU Bergakademie Freiberg
Freiberg, Germany
Kathrin.Welker@math.tu-freiberg.de

***Abstract*—In order to enhance Structural Health Monitoring of engineering structures, an appropriate modelling of the underlying structures as e. g. bridges or wings is necessary. Amongst other things this includes relevant (pre-)damages as cracks, delaminations, imperfect bonding, etc. which have to be incorporated at the so-called micro- or mesoscale of the structure. However, given the overall dimensions of typical engineering structures a discrete modelling of these (pre-)damages is not feasible at the macro-/structural scale. Thus, a scale-bridging is necessary to capture the structural behaviour. One promising approach to incorporate (pre-)damages at the microscale while maintaining a numerically manageable model of the overall structure is the sub-structure technique which will be used in the current project. Since a Structural Health Monitoring using the aforementioned numerical models strongly relys on useful measurement data it is of tremendous interest to determine the optimal number and the optimal position of the respective sensors. Hence, this topic is also addressed in the current contribution.**

***Index Terms*—SHM, scale bridging, discrete modelling, substructure technique, optimal sensor positioning**

I. Introduction

Structural Health Monitoring (SHM) is a proper means to increase the service life of engineering structures such as bridges or wings. The continuous SHM allows for substantiated conclusions regarding the structure's current health state. With this knowledge an efficient maintenance work can be planned and performed. Beneath the increased service lifetime, the reliability of the structure is increased, too. However, this necessitates an appropriate modelling of the underlying structure.

Especially in civil engineering the health state of a structure, e. g. a bridge, is determined by regular inspections with fixed intervals. The findings are documented in so-called inspection reports and the respective bridge is rated according to the number and severity of the damages, if any. These written statements can be misinterpreted by readers other than the surveyors. Several approaches exist to automatically evaluate such inspection reports, e. g. [3]. However, the authors believe that a continuous monitoring of a structure and the automatic evaluation of the measurement data is more reliable. For this automatic evaluation and for deriving respective maintenance measures, a sophisticated (numerical) model of the bridge is needed. Amongst other things this includes relevant (pre-)damages as cracks, delaminations, imperfect bonding, etc. which have to be incorporated at the so-called microscale of the structure. Although much work has been conducted in recent years to refine material models or to develop numerical methods which are capable of capturing relevant effects at the microscale, there is still a lack in numerically efficient methods and in models incorporating multi-field mechanics.

As can be seen from Figure 1 a discrete modelling of the microscale phenomena such as cracks or the corrosion state is not feasible at the macroscale. This is due to the overall dimensions of typical (civil) engineering structures. Consequently, in order to capture the overall structural behavior a scale-bridging from the microscale to the macroscale is sought. Within this research project the sub-structure technique is applied to incorporate pre-damages, crack initiation and crack propagation at the microscale on the one hand, while on the other hand ensuring a numerically manageable model of the structure at the macroscale. Once such a numerical model exists it allows substantiated conclusions and forecasts regarding the remaining service life with and without maintenance work. However, these conclusions and forecasts strongly depend on the measurement data obtained from the SHM. This necessitates research works to develop criteria for determining the optimal number and the optimal position of the sensors used for SHM.

In the precedent work [23] of some of the authors the general methodology for solving the aforementioned tasks was introduced. In the current contribution recent advances as well as the next scientific steps are described.

Based on the precedent motivation the outline of this contribution is as follows: Section II gives an overview of the discrete crack modelling at the micro- and mesoscale including crack growth due to traffic loads of a bridge. A methodology for incorporating this damage state at the macro-/structural scale is described in Sec. III. This scale-bridging allows for substantiated investigations regarding the optimal sensor positioning at a given bridge. The approach used within the project dtec.SHM is introduced in Sec. IV. Finally, a summary is provided in Sec. V.

II. Micro- and mesomechanical modelling of (pre-)damaged structures

The adequate modelling of (pre-)damaged materials constituting engineering structures is of high scientific and practical interest. This includes modelling crack initiation and crack propagation [12], [13], [21] as well as a proper modelling of the (steel) reinforcing's corrosion state [20]. Depending on the aggregates used for the concrete mixture, stress corrosion cracking may occur [19]. An approach for adequately dealing with stress corrosion cracking phenomena is presented in [10].

Regarding the (pre-stressed) reinforcing of infrastructure buildings, such as e. g. bridges, several uncertainties exist. These are not limited to the current damage state but also extend to the actual cross-sectional area as well as the spatial distribution of the so-called interfacial transition zone (ITZ) between the reinforcing and the surrounding host material. Several approaches exist to describe the influence of the ITZ to the propagation of acoustic waves [24], [25] which are used in SHM applications.

In this work the focus for the numerical modelling of damage on the microstructural level lays on different fracture simulation methods to simulate and predict the crack propagation in a multiphase material such as concrete. Initially, four widely used fracture simulation methods are evaluated, comparing their computational expenses and implementation complexities within the Finite Element (FE) framework. This comprises the intrinsic Cohesive Zone Model (CZM) using zero-thickness cohesive interface elements (CIEs), the Standard Phase-Field Fracture Modelling (SPFM) approach, the Cohesive Phase-Field Modelling (CPFM) approach, and an innovative hybrid model. The hybrid approach combines the CPFM fracture method with an application of the CZM within the interface zone. Within the context of concrete the Finite Element model is characterized by three phases, namely inclusions, matrix, and the interface zone. An example of a detailed modelling of an emerging crack utilizing different modelling approaches is provided in Figure 2.

The in-depth analysis of these modelling techniques reveals that the CPFM approach stands out as the most effective computational model in case the thickness of the interface zone is not significantly smaller than that of the other phases. In materials like concrete, which contain interfaces within their microstructure, the interface thickness is notably small when compared to other phases. This leads to the hybrid model standing as the most authentic finite element model, utilizing CIEs within the interface to simulate interface debonding.

A significant finding from this investigation is that the CPFM method is in agreement with the hybrid model when the interface zone thickness is not excessively small. This implies that the CPFM fracture methodology may serve as a unified fracture approach for multiphase materials, in case the interface zone's thickness is comparable to that of the other phases. For an indication of the interface's thickness it is referred to [16]. According to the measurement results presented therein, an interface thickness of 40% of the aggregate's radius might be a good first estimation.

Following this, the modelling approach on the microstructural level can serve as the basis for the incorporation of Neural Networks to predict the structural response at small scales for different damage scenarios. This is required in a subsequent step for the scale transition. Current literature demonstrates the effectiveness of new deep-learning-based surrogate models for fracture analysis in homogeneous and composite materials, e. g. [1], [2], [22]. Within this project a spatiotemporal UNet-based surrogate model is proposed, which is capable of predicting the homogenized stress-strain curve and final crack pattern of concrete microstructures. For this, a specially designed pipeline is developed to interpolate the FE data to a regular grid with high accuracy, eliminating the need for complex surrogate frameworks like Graph Neural Networks and making it possible to implement neural operator learning on the current model to increase accuracy for future development.

III. Scale-bridging by means of substructure technique

Bridge dimensions by several orders of magnitude differ from the dimensions of the bridge's microstructure and cracks, if any. As an example, it is referred to Figure 1 and Figure 2. Thus, modelling a bridge including its microstructure within one single FE model is not appropriate since the microstructural details would dramatically increase the FE model size. In practical applications such FE models can hardly be calculated due to a lack of computer memory space and computation time. A promising alternative is applying model order reduction techniques. Examples for physical subspace methods are modal subspace methods, the Krylov subspace method, and the so-called Guyan reduction, cf. [4],

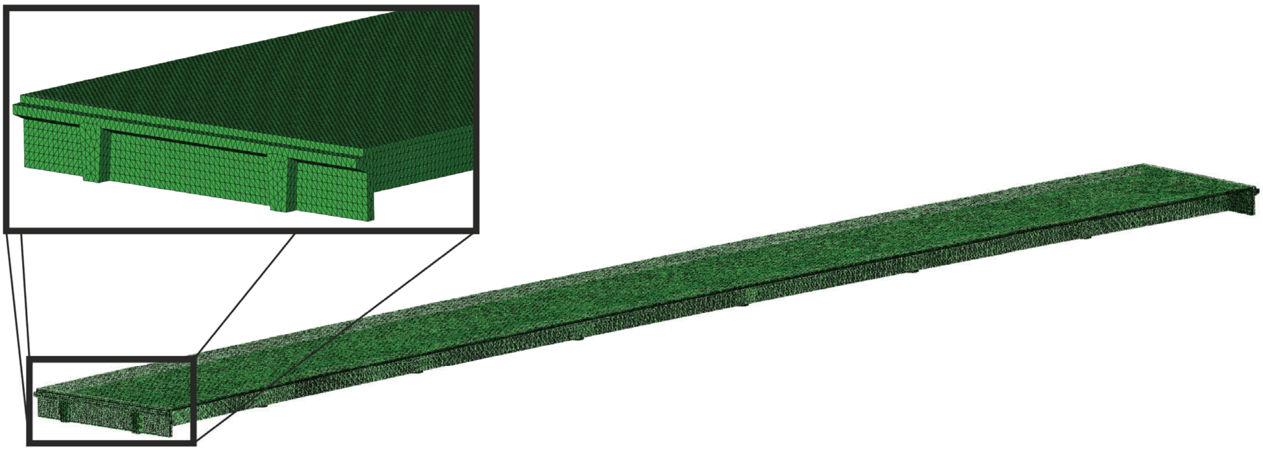

FIGURE 1. FE MODEL OF ONE SUPERSTRUCTURE OF THE BRIDGE STADER STRASSE, HAMBURG, GERMANY. CALCULATIONS ARE PERFORMED USING ABAQUS®

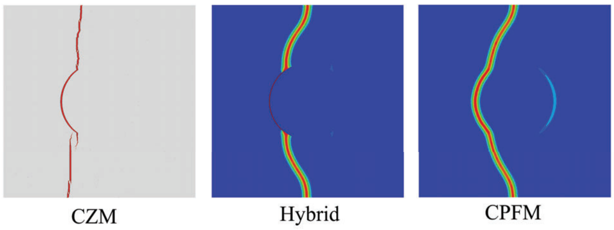

FIGURE 2. EXAMPLE FOR MODELLING OF A DISCRETE CRACK AT THE MICRO-SCALE WITH DIFFERENT FRACTURE SIMULATION METHODS, TAKEN FROM [14].

[5]. Other model order reduction techniques do not take into account the underlying physics. One example is the proper orthogonal decomposition [11]. However, main characteristics of the underlying mechanical system still need to be captured.

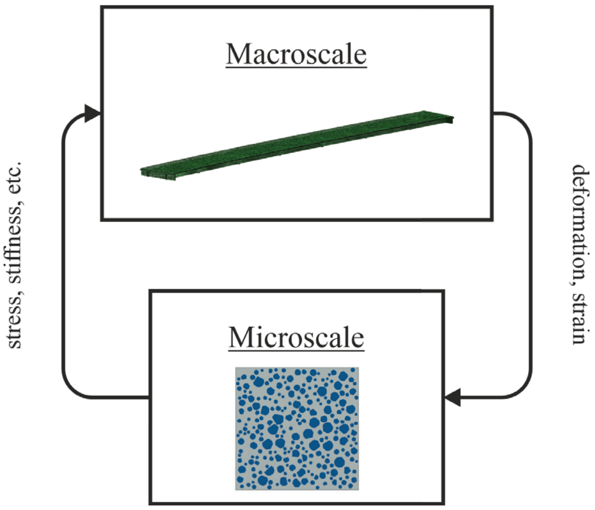

FIGURE 3. SKETCH OF SCALE BRIDGING USING SUBSTRUCTURE TECHNIQUE, INSPIRED FROM [6].

Another possibility to reduce the computational costs is to use scale transition approaches as e. g. the FE^2 technique [17]. Herein, the basic concept is to generate two different FE models to deal with the different scales of the model: (i) the so-called microscale model, as it was described in Sec. II, takes into account the microstructural aspects as e. g. aggregates, ITZ, degradation (e. g. corrosion state), and cracks (if any); (ii) the so-called macroscale model describes the global, i. e. structural, behaviour and takes into account e. g. the loading conditions and the bearing conditions at the structural scale. In classical homogenization approaches both scales are related to each other in such a way that the average of the mechanical work on the microscale is equal to the mechanical work on the macroscale. This condition is known as the Hill-Mandel condition [7], [8].
In this contribution the focus is set on the FE^2 approach, a sketch of which is given in FIGURE 3. Within this approach at each integration point of the macroscale model a microscale model has to be calculated. This microscale model consists of a so-called representative volume element (RVE), i. e. a volume element comprising the representative characteristics of the micromodel in the vicinity of the respective integration point at the macroscale. A detailed 3D FE model of a bridge will have at least several thousands of finite elements, see FIGURE 1. Thus, considering a RVE for each integration point may still lead to an unacceptable effort with respect to the computational cost. As an alternative, a subregion which is affected by the global loading conditions in a special manner can be identified and subsequently can be used to apply the FE^2 method. If it is necessary to assign different RVEs to different integration points at the macroscale, the additional computational cost has to be taken into account. Only for the special case that linear elasticity is assumed and that each integration point is characterized by an unique RVE, six calculations of a microscale model should be sufficient. These calculations refer to six boundary value problems on the microscale which are characterized by linear independent

strain states on the macroscale (three extension strain states and three pure shear strain states). With these problems the effective (homogenized) elasticity tensor on the macroscale can be determined.

The boundary condition for the FE models at the microscale will be determined from an initially calculated macroscale model. For doing so, the deformation gradient or the strain are evaluated. After the microscale model(s) have been solved the results will be used to obtain macroscale quantities such as the tangent stiffness or the stresses by means of an averaging approach. Subsequently, these macroscale quantities are used to start a new iteration process on the macroscale model. Based on the evaluation of macroscale quantities such as displacements or velocities, in a next step optimal sensor positions can be identified from the numerical model. The respective procedure is described in the next section.

IV. Optimal sensor positioning at the structural scale

In engineering disciplines, such as e. g. aircraft engineering or wind engineering, the (micro-)sensors are optimised to be positioned within the respective material during the production process of the structure [9], [18]. However, in the project dtec.SHM focus is set on determining the remaining service life of already existing structures. Thus, sensors preferably need to be fixed at the surface of the material (i. e. steel-reinforced or pre-stressed concrete).

It is desirable to place the sensors in locations that provide the most information about damage and impact to the structure. It is not assumed that the location of the damage is known a priori. A non-negligible challenge in optimising sensor placement is the large number of possible locations. For practical applications the accessibility of the possible positions to place the sensors also needs to be taken into account. Determining the number and placement of sensors is essential for cost-efficient monitoring of the structure and for minimizing the amount of data. This is to be done in such a way that each sensor provides added value in terms of information about the condition of the structure. The problem can be solved numerically with the help of optimisation methods.

A first step to determine the sensor positions on a structure, e. g. a bridge or a building, is to set up a numerical model that should represent the structural behaviour of it. This can be performed by an optimisation approach that adjusts the local or global material parameters such that the measurement data and the results from numerical simulation are matched.

Then, one can employ optimal experimental design, which is a well-established technique to design and improve experimental setups in order to increase the accuracy of parameter identification in terms of a suitable optimality criterion in view of measurement errors. A problem, in which the parameter to be determined is the location of damage, needs to be modelled by the deviation from the material parameters. Measurements of the state can be made by a series of sensors. However, measurement errors have to be considered at some point. An approach for automatically detecting sensor malfunctions from measurement data is presented in [15]. The overall aim is to optimise the position of the sensors such that the changes in measurements to changes in the material parameters are maximized. This can be realized with the help of the Fisher-information matrix. The approach for determining the optimal positioning of a sensor (network) is sketched in Figure 4.

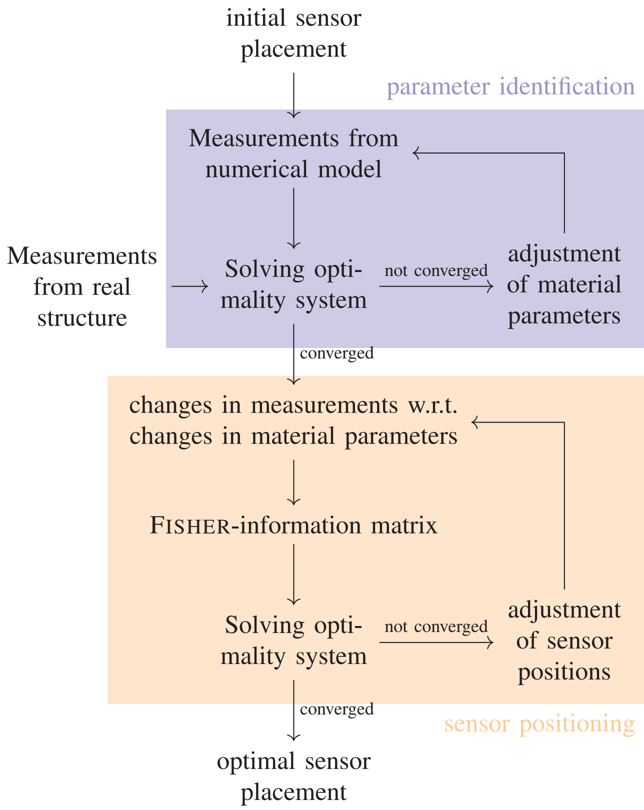

Figure 4. Sketch of the concept and procedures of the optimal design of experiments and the parameter estimation procedure to determine optimal sensor positioning.

V. Summary

To deal with the challenges arising when planning, performing, and evaluating Structural Health Monitoring for e. g. bridges a three-step-approach is suggested. This approach includes (i) an adequate modelling at the microscale, (ii) a scale transition to the macroscale including numerical analyses at this macroscale, and (iii) based on the obtained findings an optimal positioning of the single sensors of a SHM sensor network.

At the microscale, several models have been developed by the authors. These models allow determining or capturing the effects of e. g. corrosion or crack initiation and propagation. With respect to the crack initiation and propagation, the Cohesive Phase-Field fracture model turned out to be a very effective approach for modelling these effects if the material combinations lead to comparable thicknesses of interfacial transition zones of the single constituents as it is the case for

e. g. bridges. The detailed knowledge of the material behaviour at the microscale is transferred to the macroscale by means of the FE^2 approach. To foster the numerical efficiency of the calculations at the macroscale, only those subregions of the structure are incorporated in the FE^2 approach which are highly loaded or/and which show existing or propagating cracks.

Furthermore, the procedure for the optimal positioning of sensors was described. Two optimisation problems are required. The first is used to build a numerical model which behaves similar to the structure and yields the associated material parameters. By perturbing these material parameters in a second optimisation problem, it is possible to maximize the effect of changes in material parameters—which are used to model the damage—on the changes in sensor signal. Thus, an optimal position for sensors can be obtained.

Acknowledgement

This research work is funded by the project 'SHM – Digitalisierung und Überwachung von Infrastrukturbauwerken'. This project is funded by dtec.bw – Digitalization and Technology Research Centre of the Bundeswehr. dtec.bw is funded by the European Union – NextGenerationEU.

Natalie Rauter and Wolfgang E. Weber expressly acknowledge the financial support of the research work on this article within the Research Unit 3022 – Ultrasonic Monitoring of Fibre Metal Laminates Using Integrated Sensors by the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)).

References

[1] Z. Chang, Z. Wan, Y. Xu, E. Schlangen & B. Šavija, "Convolutional neural network for predicting crack pattern and stress-crack width curve of air-void structure in 3D printed concrete, Engineering Fracture Mechanics, vol. 271, pp. 108624, 2022, doi: 10.1016/j.engfracmech.2022.108624.

[2] Y. Chen, T. Dodwell, T. Chuaqui & R. Butler, "Full-field prediction of stress and fracture patterns in composites using deep learning and self-attention", Engineering Fracture Mechanics, vol. 286, pp. 109314, 2023, doi: 10.1016/j.engfracmech.2023.109314.

[3] D.-C. Feng & W.-J. Wang & S. Mangaluthu & Z. Sun, "Condition Assessment of Highway Bridges Using Textual Data and Natural Language Processing- (NLP-) Based Machine Learning Models", Structural Control and Health Monitoring, vol. 2023, pp. 9761154, 2023, doi: 10.1155/2023/9761154.

[4] R. W. Freund, "Model reduction methods based on Krylov subspaces", Acta Numerica, vol. 12(2), pp. 267–319, 2003, doi: 10.1017/S0962492902000120.

[5] R. J. Guyan, "Reduction of stiffness and mass matrices", AIAAJ, vol. 3(2), pp. 380–380, 1965, doi: 10.2514/3.2874.

[6] E. W. C. Coenen & V. G. Kouznetsova & M. G. D. Geers, "Multi-scale continuous-discontinous framework for computational-homogenization-localization", Journal of the Mechanics and Physics of Solids, vol. 60, pp. 1486–1507, 2012, doi: 10.1016/j.jmps.2012.04.002.

[7] P. Suquet, "Elements of Homogenization for Inelastic Solid Mechanics". In: E. Sanchez-Palencia & A. Zaoui (eds), "Homogenization Techniques for Composite Media", Springer, Berlin,vol. 272, 1987, pp. 193-278, doi: 10.1007/3-540-17616-0_15

[8] R. Hill, "Elastic properties of reinforced solids: Some theoretical principles", Journal of the Mechanics and Physics of Solids, vol. 11, pp. 357-372 doi: 10.1016/0022-5096(63)90036-X

[9] J. N. Haus, L. Rittmeier, T. Roloff, A. Mikhaylenko, S. Bornemann, M. Sinapius, N. Rauter, W. Lang & A. Dietzel, "Micro-Oscillator as Integrable Sensor for Structure-Borne Ultrasound", Engineering Proceedings, vol. 10(1), pp. 81, 2021, doi: 10.3390/ecsa-8-11313.

[10] C. Kandekar, A. Ravikumar, D. Höche & W. E. Weber, "Mastering the complex time-scale interaction during Stress Corrosion Cracking phenomena through an advanced coupling scheme", Computer Methods in Applied Mechanics and Engineering, vol. 428, pp. 117101, 2024, doi: 10.1016/j.cma.2024.117101.

[11] G. Kerschen, J.-C. Golinval, A. F. Vakakis & L. A. Bergman, "The method of proper orthogonal decomposition for dynamical characterization and order reduction of mechanical systems: an overview", Nonlinear Dynamics, vol.41 (1–3), pp. 147–169, 2005, doi: 10.1007/s11071-005-2803-2.

[12] R. N. Koopas, N. Rauter & R. Lammering, "Two-Dimensional Mesoscale Finite Element Modeling of Concrete Damage and Failure", Applied Sciences, vol. 13, pp. 8971, 2023, doi: 10.3390/app13158971.

[13] R. N. Koopas, N. Rauter & R. Lammering, "Two-dimensional meso-structural simulation of concrete fracture by the implementation of zero-thickness cohesive interface elements", PAMM, vol. 22(1), pp. e202200020, 2023, doi: 10.1002/pamm.202200020.

[14] R. N. Koopas, S. Rezaei, N. Rauter, R. Ostwald & R. Lammering, "Comparative analysis of phase-field and intrinsic cohesive zone models for fracture simulations in multiphase materials with interfaces: Investigation of the influence of the microstructure on the fracture properties", preprint, 37 pp., doi: 10.48550/arXiv.2311.16826, 2024.

[15] A. Liebert, W. Weber, S. Reif, B. Zimmering & O. Niggemann, "Anomaly Detection with Autoencoders as a Tool for Detecting Sensor Malfunctions", 2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS), pp. 01–08, 2022, doi: 10.1109/ICPS51978.2022.9816908.

[16] V. A. Matonis, "The interfacial stresses in particulate composite systems", Polymer Engineering and Science, vol. 9(2), pp. 100–104, 1969, doi: 10.1002/pen.760090205.

[17] L. Mester, V. Klempt, F. Wagner, S. Scheerer, S. Klarmann, I. Vakaliuk, M. Curbach, H.-G. Maas, S. Löhnert & S. Klinkel, "A Comparison of Multiscale Methods for the Modelling of Carbon-Reinforced Concrete Structures", In: A. Ilki, D. Çavunt & Y. S. Çavunt (eds), "Building for the Future: Durable, Sustainable, Resilient", fib Symposium 2023. Lecture Notes in Civil Engineering, vol. 350, Springer, Cham.

[18] M. Rottmann, T. Roloff, N. Rauter, L. Rittmeier, M. Sinapius & W.E. Weber, "A numerical study on planar gradient acoustic impedance matching for guided ultrasonic wave detection", Journal of Vibration and Control, vol. 30(3-4), pp. 697–710, 2024, doi: 10.1177/10775463221149764.

[19] G. Schacht, M. Käding, G. Bolle & S. Marx, "Konzepte für die Bewertung von Brücken mit Spannungsrisskorrosionsgefahr", Beton- und Stahlbetonbau, vol. 111(2), pp. 85–94, 2019, doi: 10.1002/best.201800087.

[20] M. Shariati, W. E. Weber & D. Höche, "Parallel simulation of the POISSON-NERNST-PLANCK corrosion model with an algebraic flux correction method", Finite Elements in Analysis and Design, vol. 206, pp. 103734, 2022, doi: 10.1016/j.finel.2022.103734.

[21] T. Suchan, C. Kandekar, W. E. Weber & K. Welker, "Crack propagation in anisotropic brittle materials: From a phase-field model to a shape optimization approach", Engineering Fracture Mechanics, vol. 303, pp. 110065, 2024, doi: 10.1016/j.engfracmech.2024.110065.

[22] G. Wang, L. Zhang, S. Xuan, X. Fan, B. Fu, X. Xue & X. Yao, "An efficient surrogate model for damage forecasting of composite laminates based on deep learning", Composite Structures, vol. 331, pp. 117863, 2024, doi: 10.1016/j.compstruct.2023.117863.

[23] W. Weber, N. Rauter, R. Lammering & K. Welker, "Räumliche Auflösung des Schadenszustandes aus mechanischer und mathematischer Sicht", In: D. Schulz et al. (eds), "dtec.bw-Beiträge der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg (Band 1)", 2022, pp. 281–286, doi: 10.24405/14565.

[24] W. Weber, U. Reuter & B. W. Zastrau, "An approach for exploring the dynamical behaviour of inhomogeneous structural inclusions under consideration of epistemic uncertainty", Multidiscipline Modeling in Materials and Structures, vol. 9(1), pp. 81–99, 2013, doi: 10.1108/15736101311329179.

[25] W. Weber & B. W. Zastrau, "Non-plane wave scattering from a single eccentric circular inclusion-Part I: SH waves", Journal of Theoretical and Applied Mechanics, vol. 49(4), pp. 1183–1201, 2011.