Collaborative Research Center

LIFE CYCLE ASSESSMENT OF STRUCTURES VIA INNOVATIVE MONITORING

Technical University Carolo-Wilhelmina - Braunschweig
Germany

SFB 477

Chairman: Prof. Dr.-Ing. U. Peil • Institut für Stahlbau • Beethovenstrasse 51
38106 Braunschweig • Germany • Tel: +49(0)531/391-3379 • Fax: +49(0)531/391-4592
Email: u.peil@tu-bs.de

Vice Chairman: Prof. Dr.-Ing. D. Hosser • Institut für Baustoffe, Massivbau und Brandschutz
Beethovenstrasse 52 • 38106 Braunschweig • Germany • Tel: +49(0)531/391-5441
Fax: +49(0)531/391-4573 • Email: d.hosser@tu-bs.de

Address SFB: SFB 477 • Technische Universität • Beethovenstrasse 51
38106 Braunschweig • Germany
Tel: +49(0)531/391-3362 • Fax: +49(0)531/391-3357
Email: sfb477@tu-bs.de • http://www.sfb477.tu-bs.de

Overview:

The immense number of structures which are in use today requires more attention in the fields of preservation and rehabilitation. The costs for these measures are increasing enormously. Figure 1 compares the trend of the costs invested in new buildings with the costs needed for preservation and rehabilitation and new utilisation.

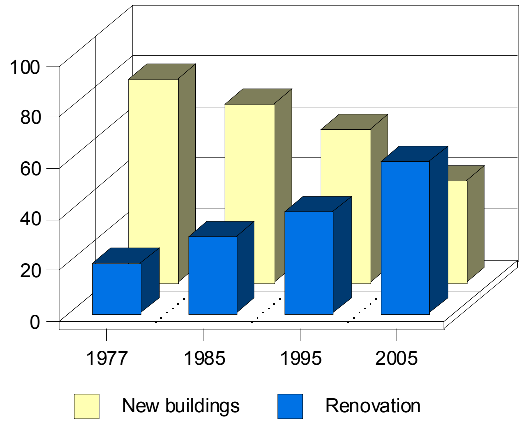


Figure 1: Trends in Building Costs

The overall value of all buildings in Germany will amount to approximately 25000 billion Dollars. Assuming a mean life cycle of about 100 years (optimistically), 2500 billion Dollars are needed year by year for reinvestment. Using appropriate monitoring procedures, the service life of structures can be extended considerably, or they can be rehabilitated and put to new uses in a way which conventional standards would never permit.

It is the aim of the Collaborative Research Center SFB 477 "Monitoring of Structures" funded by the German Science Foundation (DFG) to develop and enhance methods for a precise service life prediction of engineering structures by means of innovative monitoring methods. SFB 477 brings together scientists from the fields civil engineering, surveying, mechanical engineering, electrical engineering and chemistry, and additionally the from the Federal Institute of Physics and Metrology (PTB) in Braunschweig.

To account for the wide scope of engineering structures, the work focuses on projects in the fields structural engineering and landfill sites.

The project is subdivided into the four research fields (A-D) to ensure an efficient collaboration of the particular research projects. A wide scope of topics is investigated: Development of monitoring strategies and procedures on a deterministic and probabilistic basis, measurement techniques, adaptive i.e. smart models which can adapt themselves to a changing system, development of new sensors and, last but not least, the application to real building structures such as bridges, towers, cranes, landfills etc.

Project Field A: *Methods and Strategies*

covers the fundamental aspects of structural monitoring, i.e. the development of the basic principles on which monitoring methods and strategies are to be established. This includes:

☐ Cause, origin and development of damages
☐ Weak points and risk analyses
☐ Damage indicators (symptoms)
☐ Failure paths, fault trees
☐ Limit states
☐ Probabilistic approach, reliability of monitored structures
☐ What monitoring conditions could have provided best for early damage detection?
☐ Economic efficiency of monitoring measures
☐ Development of damage catalogues
☐ Analysis of damages

Project Field B: *Adaptive Models*

concentrates on the development of adaptive models and how they can be validated by means of measurements. The models are used for short and long-term predictions. Different types of models are required, including mechanical (static / dynamic) models, as well as models describing damages as a result of the time depending mechanical, physical, chemical, biological and biochemical processes. The biological models are needed for the description of the behaviour of landfills.

Project Field C: *Measuring Systems, Development and Adaptation*

is concerned with the development, improvement and adaptation of measuring systems and sensors for mechanical, chemical and biochemical processes. An important point is the consideration of reliability and very longterm use of the sensors and the additional equipment under realistic conditions. Up to now, new fibre optical sensors have been developed for the measurement of moisture and chemical attack inside a concrete structure. Sensors to predict the fatigue or damage state, sensors which can be implemented like a bolt into a hole to measure the strains in all directions, and 3D-surveying systems for measurments inside a landfill are under development.

Project Field D: *Testing on Structures*

focuses on realistic measurements on real structures, in which the strategies, methods and sensors developed in the Project Fields A, B, C are tested under realistic conditions.

There are different ways in which the particular research projects are **linked**. Some of the projects deal, for instance, with the development of adaptive models, while others are of a more comprehensive nature. Figure 2 shows the relationships. It appears from this illustration that structural monitoring involves a vertical level assisted by the horizontally oriented methods.

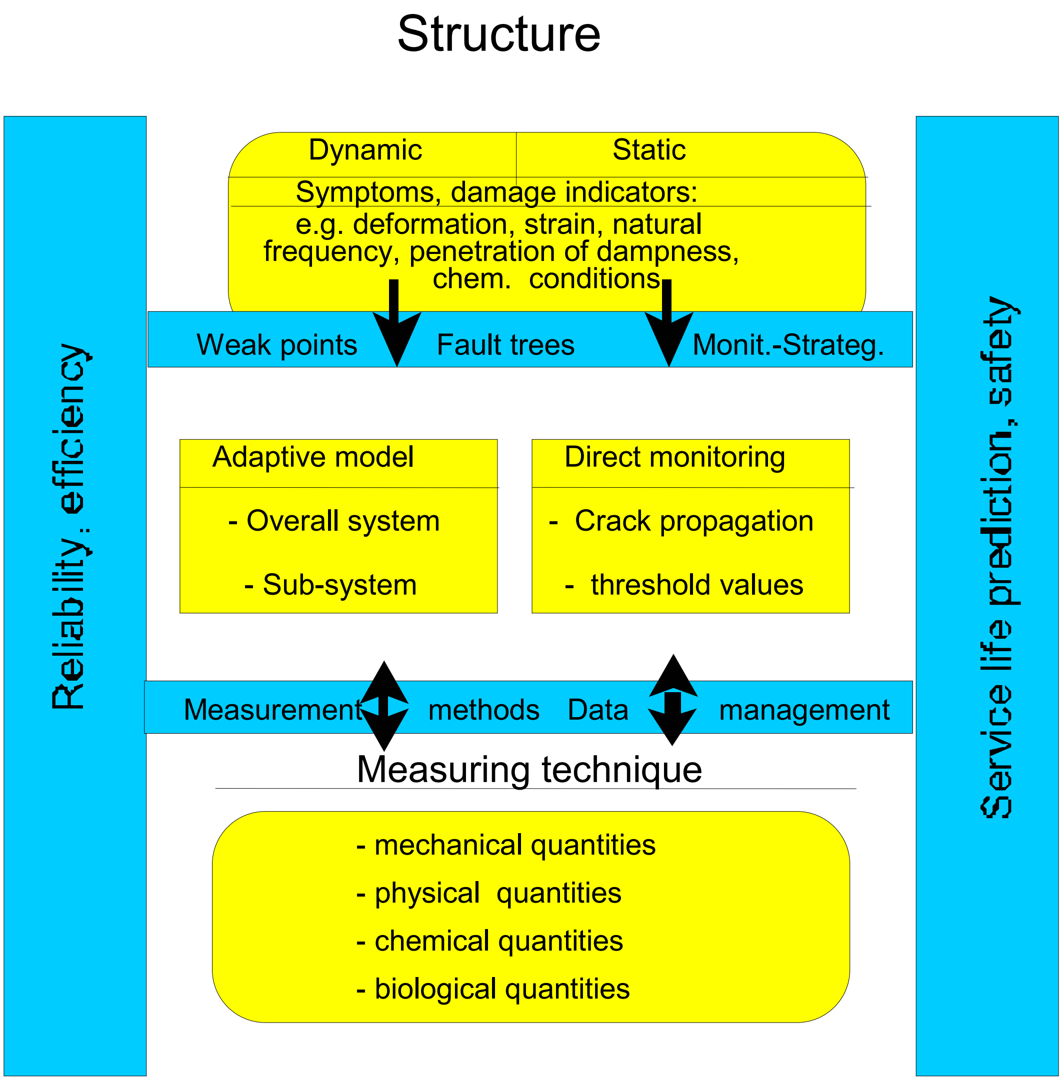


Fig: 2: Projekt Field art projekt linkage

Project Fields

Stand 02/2005

Particular Research Project

A1: Methods for risk and weak-point-orientated assessment and optimization of structural monitoring

Objectives

The aim of structural health monitoring is to recognize negative deviations from planned properties of structures, which can result from built-in faults, system changes or damages, at an early stage. These deviations have to be controlled and the structure, if necessary, has to be repaired or restored. By this means the integrity and serviceability of the structure can be guaranteed for a planned period of use.

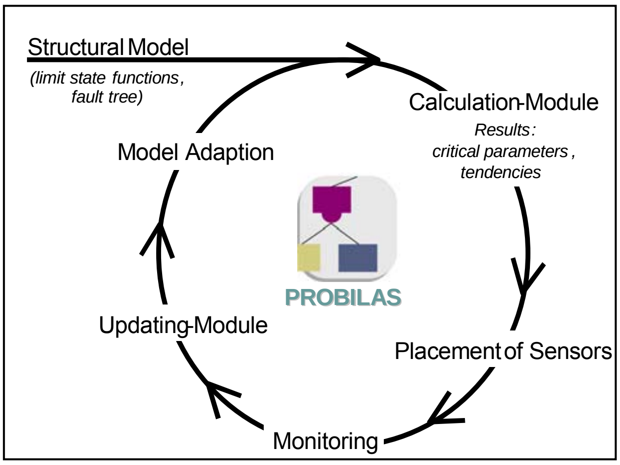
For economical reasons a structure cannot be monitored completely. Therefore it is necessary to concentrate structural health monitoring on critical parts of the structure and on those parameters, he uncertainties of which primarily endanger the structural integrity or serviceability.

The aim of CRC project A1 is to develop methods to identify critical weak points of structural systems and to provide strategies for optimization the of structural health monitoring process. These methods are mainly based on the combination of recognized procedures of reliability and system theory with new concepts and criteria to support decisions about the kind and intensity of monitoring as well as the tolerable measuring errors.

Working Procedure

Finding the optimum monitoring concept is an iterative process. Therefore a structural evaluation circuit has been developed which is shown in figure 1. The necessary calculations and evaluations have to be performed automatically and all information for decisions including proposals of the most favourable solutions have to be presented automatically. Therefore the whole procedure was integrated into the reliability-based system assessment program PROBILAS (PRObabilistic Building Inspection and Life ASsessment).

Fig. 1. Structural evaluation process circuit



The reliability analysis in PROBILAS starts with the help of information from the design phase of the structure. To perform a reliability analysis, PROBILAS requires an analytical or numerical model of the structure. This model has to include all sources of risk, i. e. all relevant failure paths of the structure with all their important parameters. They are discretised in causally connected components and subsystems. These system relations are summarized in logical trees, which combine causes, intermediate events and their consequences. The fault tree, which is the most important input for PROBILAS, regards all possible causal sequences of component and subsystem failures, which would lead to an overall system failure.

For each component limit state equations and their parameters have to be provided by the user. As a rule, these parameters are stochastic and/or uncertain and are described with their statistical distributions. The parameters of the distributions can either be estimated from measurements or be found in the literature. If random variations of an input parameter are small, this parameter can be assumed as deterministic. For simple failure modes the limit state equations can be given in an analytic form. The limit state equations for more complex failure modes are usually given numerically; they are approximated in PROBILAS with the response surface method by using automatically generated numerical results in the failure region.

For the reliability analysis the well-known first/second-order-reliability method (FORM/SORM) is utilized. In these calculations the probability of failure (p_f), the related safety index β ($p_f=\Phi(-\beta)$) and the sensitivity factors (α) can be calculated for all limit state equations, for partial systems representing a possible failure path and finally for the whole system including all failure paths. On the basis of the calculated β-values the failure path with the highest contribution to the probability of system failure can be identified and on the basis of the α-values the parameters with the biggest impact on the failure. Especially these most important parameters of the leading failure path should be investigated further by monitoring an evaluation. This will be proposed by PROBILAS which in addition will give advice how often and how exact these main parameters should be monitored in order to reduce existing uncertainties and to improve the knowledge about the state of the structure.

Changes in the structure, e.g. due to damages or deterioration, would cause a change of the monitored parameters. The newly measured values are used to improve former estimates of the random variables of the limit state equations with procedures of Bayesian updating. After the recalculation of the system with the sharpened stochastic model, the new safety index β or probability of failure p_f can be compared to previous values. This is the basis for further decisions on the safety of the structure and the monitoring process. If the probability of failure increases significantly or if a certain tendency can be observed, PROBILAS will generate a warning signal to alarm the user to take the appropriate measures. If there is no impact on the system reliability, the monitoring of a special parameter can either be stopped or the interval between two measurements can be extended.

A database with predefined limit state functions for usual ranges of application in structural systems is available as user support.

Up to now, the procedures are developed and tested using simple examples of steel structures, concrete structures and landfill sites. Real structures like bridges will be analyzed in the near future.

Contact:

Univ. Prof. Dr.-Ing. D. Hosser • Institut für Baustoffe, Massivbau und Brandschutz •
Beethovenstraße 51 • 38106 Braunschweig • Tel: +49(0)531/391-5441 • Fax: +49(0)531/391-4573 Email: D.Hosser@tu-bs.de

General description

The prediction of a realistic life cycle and the prolongation of the service life is an important task to reduce costs of civil engineering structures in the future. The precise assessment of the life cycle will become an important challenge.

The project focuses on the prediction of the fatigue life cycle of steel structures under random loading such as bridges, crane ways, towers etc. via monitoring and parallel testing. The theoretical prediction model usually used consists of a load model, a system-transfer model and a damage model. Because the results of one model serve as an input for the next model, the systematic and the random errors of all models flow together and the reliabilities are multiplied. Thus the results of this chain of models are usually unreliable, especially the influence of the uncertain load and damage models controls the reliability of the result.

Since the strains are monitored directly at the critical details, the load model and the system model are not needed anymore, hence the given uncertainties of both models are avoided, see Fig. 1. Consequently an important point is the assessment of critical constructional details which should be monitored.

In a first approach, the measured load histories could now be classified by means of the Rainflow Method. The resulting stress collectives could then be used for common cumulative linear or non-linear damage rules. The result of such life cycle assessment will always be uncertain. To achieve a more reliable prediction, it is essential to avoid the damage model as well.

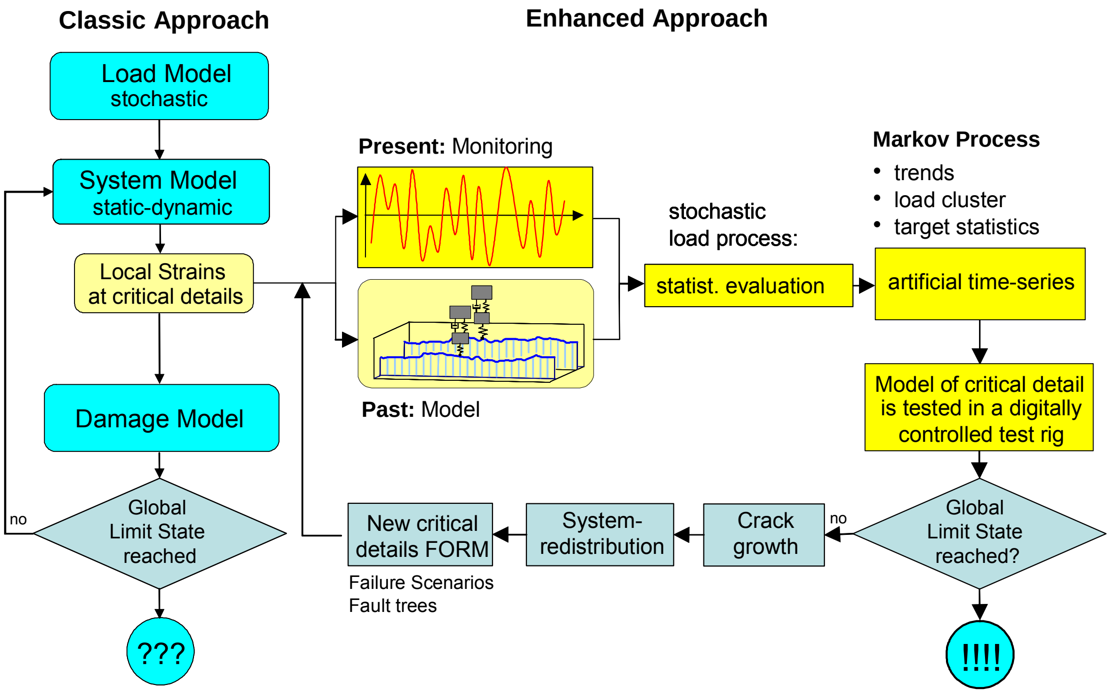


Fig. 1: General procedure

To avoid the damage model, an artificial generated time history is used as an input for a digitally controlled test rig, in which a specimen of the actual constructional detail (or even a part of it) is tested. The monitored time history is reduced, eliminating small i.e. non-damaging stress cycles and breaks of action. The artificial time-series contains the overall statistics of the load process, taking into account the past and the estimated future of the loading situation including e.g. clustering of trucks.

The future trend of the process can be included, using a step by step procedure, testing only a chosen time interval (e.g. 5 years) of the future load process, see Fig. 2. If the specimen survives this time interval, the real detail will survive as well. After having reached the end of the time interval, the same specimen will be tested further with the next artificial strain history, including the latest information about the new trend. If there is a difference between the fatigue states of the specimen and the real constructional detail, the fatigue state must be adjusted before starting the next testing interval. The Markov matrices of both processes have to be subtracted.

Because the damage state of the specimen, loaded by a certain number of cycles, is compared with the same number of cycles for the real structure, there is no need to determine the real damage state. We compare just the cycles. If the fatigue state of the real structure is less than the fatigue state of the specimen, one has to wait for the point in time until the structure has the same damage state as the specimen. The specimen will not be destroyed. After testing, the specimen will be stored close to the structure to assure the same environmental impacts.

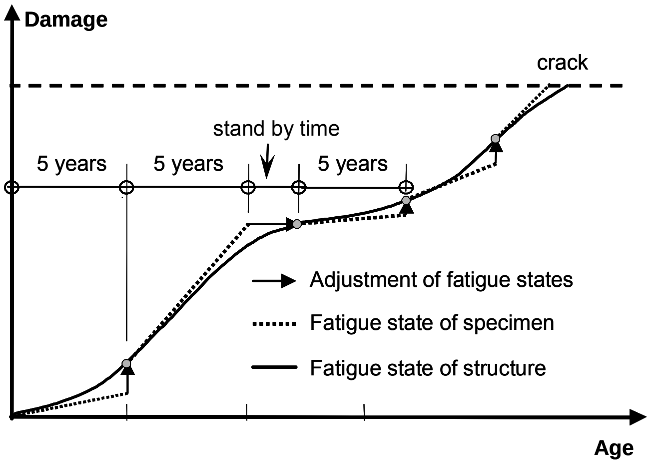


Fig. 2: Adaptive Trend Approximation

If the structure is monitored from the beginning, the procedure is straight forward. To predict the remaining fatigue life of an existing structure, load histories from the past would be required. Since they cannot be monitored in nature, they must be generated.

Due to the consideration of random loads, the proposed method is much more complex than methods that were applied some years ago in air craft engineering. Load histories describing landings and take-offs of special aircrafts are used to test the overall gear construction, e.g. SAE-Histories, TWIST, FALLSTAFF etc.

After the occurrence of the first crack, the system still can carry loads until the global limit state is reached. Due to the crack growth, system-redistribution can occur with new critical points to be monitored.

Validation of the described method is usually impossible because the remaining life cycle of real buildings is very high (much longer than any research project!). To avoid this problem, so called building substitutes (BS) with different weak points are tested under different load histories (narrow and broad-band processes, amplitudes from LCF to HCF) in the laboratory.

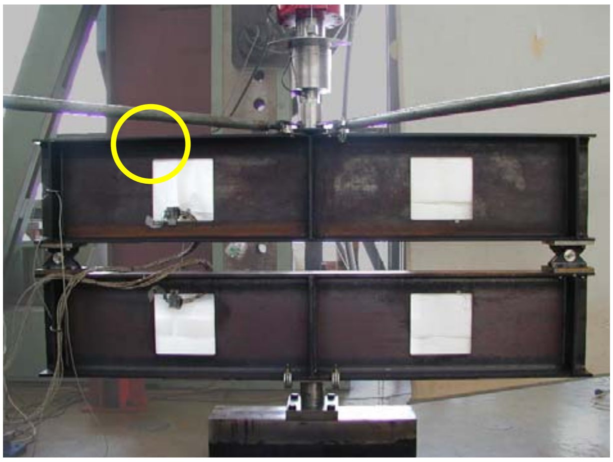


Fig. 3 Test assembly of 2 building substitutes

Fig. 4 Specimens in the test rig

The BS shows details with dimensions which are similar to the real details. These include such fatigue sensitive details as weldings, holes and other notches. Figure 3 shows such a type of a BS under test.

The specimens shown in Fig. 4 represent the notches at the (rounded) corners of the square holes. The specimens are designed such that the principal stresses at the corners of the real structure are nearly identical with those of the specimen. To ensure this, finite-element calculations of the BS and different shapes of specimen are performed.

Results of the investigations show a high reliability of the described procedure.

Contact:

Prof Dr.-Ing. U. Peil • Institut für Stahlbau • Beethovenstr. 51 • 38106 Braunschweig • Germany •Tel: +49(0)531/391-3379 •Fax: +49(0)531/391-4592 •Email: u.peil@tu-bs.de

Aims of the investigations

Welded joints in structures are of special importance regarding the fatigue life since they always introduce a geometric and microstructural inhomogeneity. The basic aim of this research project is the identification of fatigue damage in welds by nondestructive inspection methods. With the micromagnetic testing method, fatigue-related changes in the material characteristics can be localized and quantified so that nondestructively measured quantities can be used as a damage criterion. In connection with the results of other inspection techniques (X-ray diffraction, strain and crack sensors), the fatigue life prediction can be corrected iteratively enhancing its reliability and taking also into account the changing load spectra (adaptive model). “Building Substitutes” (BS) with a butt GMA-weld in a critical position are tested by single-step loading and under load spectra resulting from monitoring of real steel structures (project B3). Parallel to this, specimens with similar weld geometries, microstructures and residual stress distributions are fatigue-tested in the lab under the same load conditions as the weldment of the BS. During this detailed study, the fatigue life of the weld, the important microstructural processes, the behaviour of residual stresses during fatigue, the influence of notches and the mechanical properties of each weld zone can be determined. The results of these tests serve as a growing database for the fatigue life prediction model and also help to improve the micromagnetic testing method.

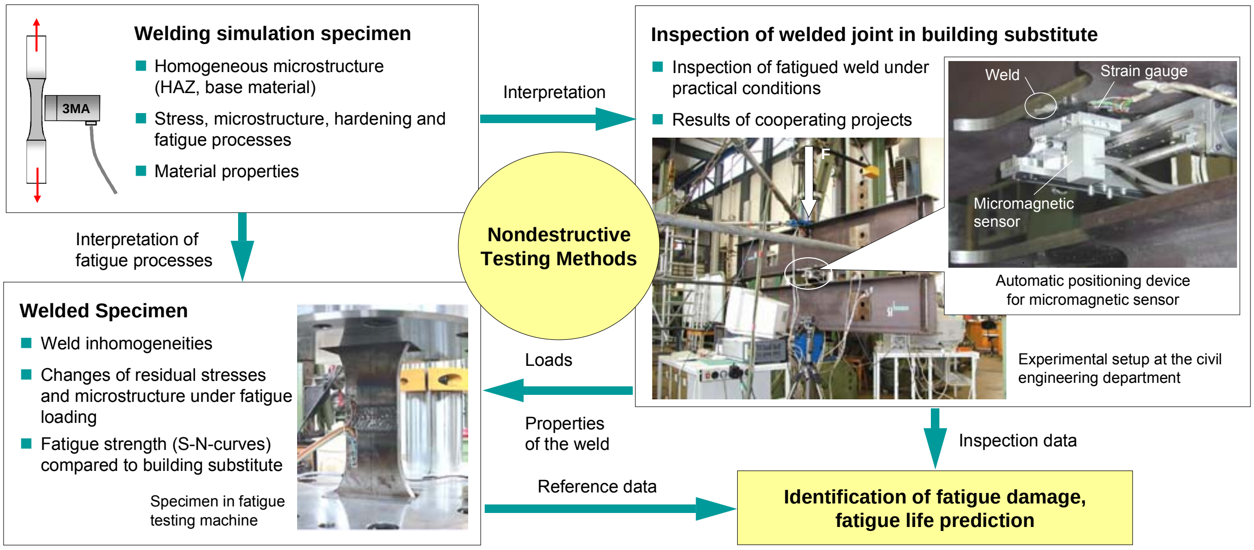


Figure 1 Aims and structure of the investigations of research project B4

Testing Methods

As inspection technique, mainly the micromagnetic testing method is employed (Figure 2). The compact, mobile and easy to handle nondestructive testing (NDT) device contains different magnetic and electro magnetic measurement modules to improve different physical effects. On the base of the magnetic Barkhausen noise, the upper harmonic analyses, the incremental permeability and the multi frequency eddy current technology, 41 parameters can be observed for the material characterisation. Various changes in microstructure, hardness, residual stresses and crack length or –density of a weld could be determined. Therefore the calibration procedure is a very important step: After a selection of the parameters correlating with the target value, the multi parameter regression is used to calculate the effort value. To explain the behaviour of the magnetic parameters and its changes, the effort is to apply alternative (conventional and well known) nondestructive testing methods. In-situ measurements on welding simulation specimens are performed and accompanied by the investigation of macro- and micro-residual stresses and the dislocation density by means of X-ray diffraction and metallographic methods. Additional hysteresis measurements on all specimens with strain gauges give important information about cyclic hardening, softening or creep processes.

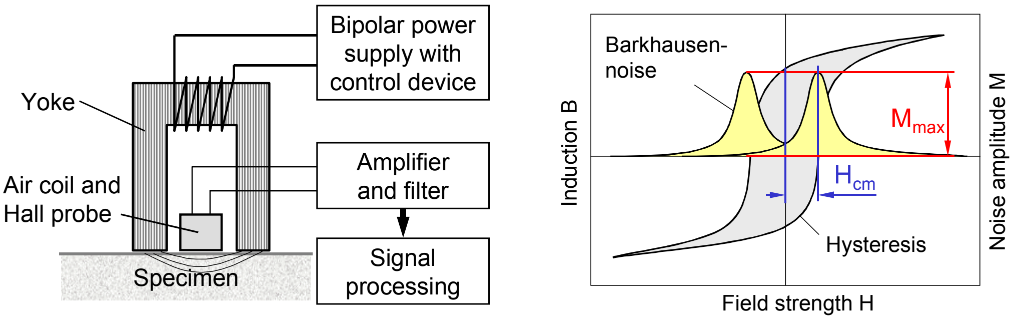


Figure 2 Micromagnetic sensor setup and parameters from Barkhausen noise and magnetic hysteresis

Results

Detailed measurements on butt-welded specimens indicate a relationship between micromagnetic parameters, residual stresses, dislocation density and cyclic creep (figure 3). Especially the Barkhausen noise amplitude (M_{max}) and the residual stress state in the weld toe indicate accumulated fatigue damage *before* the detection of a crack. The increase of cyclic creep shortly before fracture and the drop of M_{max} measured across the weld also indicate the *location of failure* within the welded joint. These results show the feasibility to detect fatigue damage *before* the appearance of cracks.

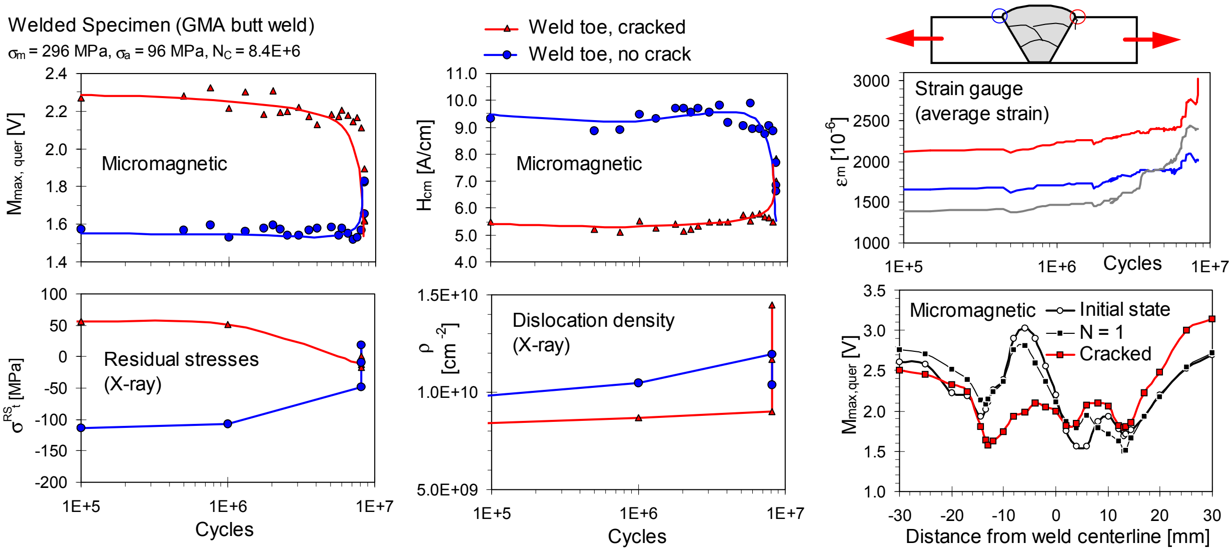
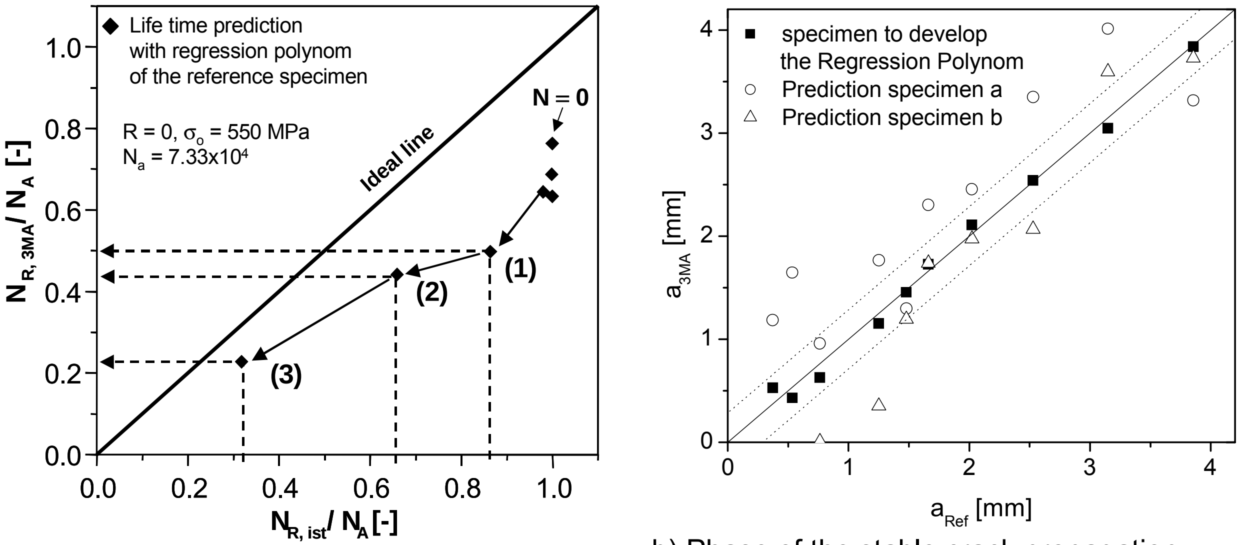


Figure 3 Results of micromagnetic, X-ray and strain measurements on fatigued butt-welded specimen

In Fig. 4 exemplary coarse grain (sealing run, 220 HV) is the result of an attempt to correlate the developed regression equation with prediction of the residual life duration of a sample of the same structural condition. The intersections of the broken lines with the abscissa in Fig. 4a indicate the calculated remaining life time, which one receives, if the characteristic values measured after different life span phases (N/N_A after 13 %, 34 % and 68 % of the incipient crack number of cycles) are inserted into the regression equation.
The accuracy of the prediction becomes higher with the approach to the actual number of cycles by the incipient crack and, as Fig. 4 reveals, the results of the prediction are always conservative. All prognosed residual life times lie below the material value, are thus conservative. In the same way, however, an accomplished evaluation using a sample with the harder final pass structure (350 HV) did not lead yet to the same result. A multiple linear regression (Fig. 4b) led for the phase of the stable crack propagation also to a relatively reliable result, i.e. also for the crack propagation phase the application of the magnetic measuring method seems to be appropriate.



a) Phase up to the incipient crack

b) Phase of the stable crack propagation

Figure 4. Welding simulation specimen, coarse grain, 220 HV

As a conclusion, nondestructive techniques – especially the fast and mobile micromagnetic method – are well suited to detect fatigue damage in different fatigue stages. In future investigations, NDT will be embedded in an improved fatigue life prediction model for cyclically loaded structures.

Contact:

Prof. Dr.-Ing. K. Dilger • Prof. a.D. Dr.-Ing. H. Wohlfahrt • Welding Institute • Langer Kamp 8 • D-38106 Braunschweig • Germany • Phone: +49 (0) 531 / 391 – 78 20 • Fax: +49 (0) 531 / 391 – 58 34 • E-mail: ifs-bs@tu-bs.de

B5: Analysis and Modelling of Chemical and Biological Reaction Processes in Municipal Landfills

Subject

In contrast to usual engineering structures, impact of stress on landfill structures is not time-invariant and not subsequently adjustable (neither can refuse be taken away nor can reaction processes be specifically controlled). As a consequence of physical, chemical and biological activities, the refuse is under constant change and can, therefore, be regarded as a dynamic system.

The chemical and biological activities are part of the risk potential which arises from the way a landfill is operated. Presently, most of the sanitary landfills are operated as partly controlled bioreactors.

Leachates from municipal landfills are regarded as hazardous groundwater pollutants. The contaminants released to the aqueous phase by microbial degradation and chemical and physical processes, percolate through the landfill body and unsaturated environment. Accumulation of aggressive components may cause severe damage to the artificial barrier and drain system of the landfill site. Inhibition of the well-balanced community of refuse degrading micro-organisms may happen as well.

So far no complete model exists which contains bio- and chemo-kinetics, mass transfer from the solid to the liquid phase and transport phenomena in the saturated pore system. Currently, the modelling of pollutant and leachate generation mainly hinges on a deeper understanding of mechanisms of mass release from the solid to the aqueous phase, the biodegradation of organic matter and organic contaminants being involved, as well as on the uncertainty of bio-kinetic parameters.

With regard to the variety of organic matter in landfills, no simple equation or rate constant can adequately describe the rate of biodegradation and the rate of landfill gas generation as well as the temperature development. Therefore, conceptual considerations of chemical and biological reaction processes in landfill ecosystems should be reflected in structured models. Those models are useful for consideration additional details of mixed-culture population dynamics and/or multiple-reaction schemes as a function of environmental factors (e.g.: temperature, pH value or water content of the porous system).

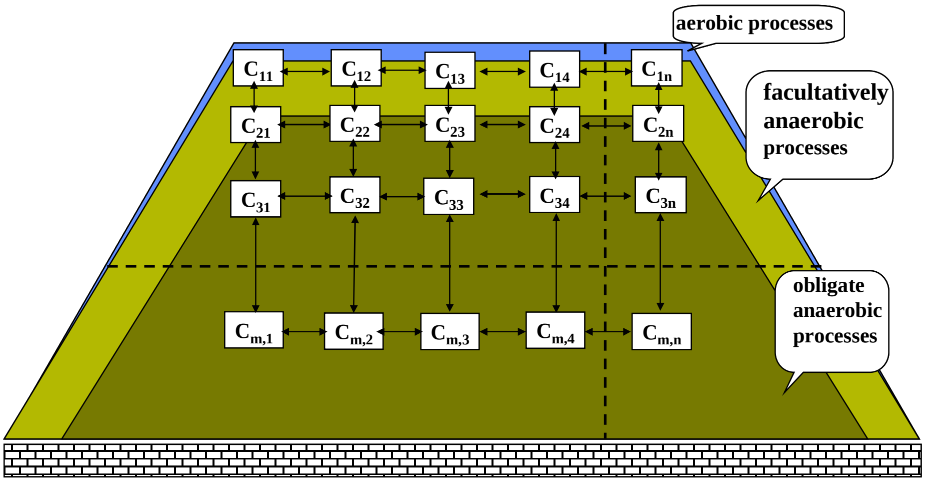


Figure 1: Two-dimensional network of Representative Element Volumes (REV).

Investigations into and modelling of the subject this paper is about focus on the formulation of Representative Element Volumes (Figure 1) characterized by different environmental and bio-kinetic conditions. Further refinements of the model will be focused on the integration of a bio-availability factor, which is observed to control biodegradation in solid-water systems. Additionally, the extension of the REV system to a three-dimensional network is intended.

As for the formulation of bio-kinetics, MONOD type expressions are helpful tools. The application of these expressions requires the analysis of organic compounds, microbial populations being involved as well as the selection of reliable bio-kinetic constants and their dependencies on environmental factors. In Figure 2 the general model structure and the links between the different model modules are depicted.

For the time being, the model allows to calculate local mass changes of organic matter and contaminants as well as local changes and impact of temperature, pH value in a fictitious landfill. Mass transfer of landfill gases from the aqueous phase (saturated area) into the gaseous phase (unsaturated area) is also taken into consideration.

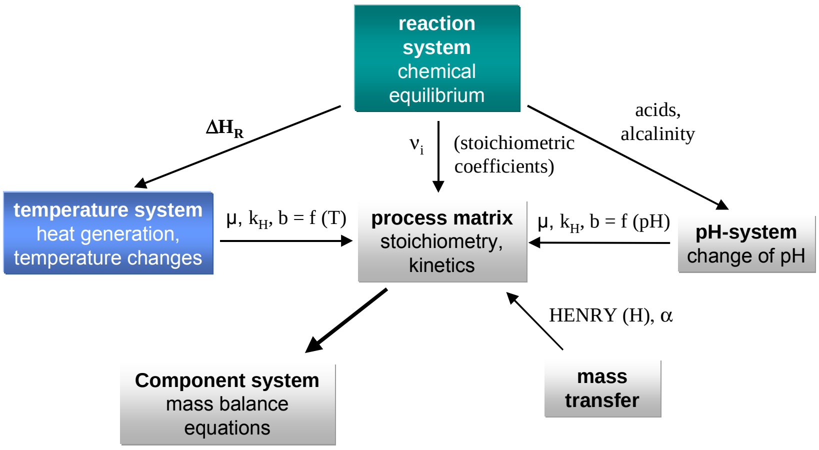


Figure 2: General model structure (μ: specific growth rate, K_S: MONOD constant, b: rate of decay).

According to landfill dominating anaerobic bioprocesses a general model of the conversion of solid organic matter (easily and slowly hydrolyzable) to soluble organic compounds and organic intermediates (e.g. glucose and organic acids) and gases (e.g. CH_4, CO_2, H_2) is formulated. Impacts of environmental factors such as pH and temperature on rate expressions are also been taken into consideration. Further, heat generation and temperature development are simulated as well. The influence of inhibitory effects (e.g. the influence of oxygen concentration on anaerobic conversion processes) on reaction rate has been investigated and implemented into the model utilizing expressions which are of the non-competitive inhibition type. The temporal change of pH value and temperature due to the microbiological activity are compared to an optimum range criterion integrated within the model.
The model equations used to describe the temporal change of organic compounds (substrates) involved are mainly based on Monod kinetics. Close to these kinetics a differential equation system of first order has been formulated:

$$\dot{\mathbf{s}} = \frac{d\,\mathbf{s}}{d\,t} = \mathbf{B}(s) \cdot \mathbf{s} \ , \qquad (1)$$

where ***s*** is the component vector and ***B(s)*** the process matrix, being depended on ***s***. The time integration of the initial value problem in (1) is universally performed by the transfer matrix method.
Usually, in biological reaction processes substrates are converted in constant stoichiometric relations. For modelling purposes, it is advantageous to separate the reaction process into a common reaction rate and individual stoichiometric coefficients. But the separation is not unique; to make it unique, one of the stoichiometric coefficients (usually the stoichiometric coefficient belonging to a limiting substrate) is set to one. The temporal change of the concentration of a substrate is then given as a product of the common reaction rate and the substrate-specific stoichiometric coefficient. The overall formulation is then given by the product of coefficient matrix ***M*** and reaction rate matrix ***R(s)***:

$$\mathbf{B}(s) = \mathbf{M} \cdot \mathbf{R}(s) \ . \qquad (2)$$

The structures of the matrices ***M*** und ***R(s)*** are based on the consideration that all processes are assumed to happen simultaneously. So, whenever there will be a change in environmental conditions (oxic/anoxic, redox-potential, temperature or alkalinity) for instance, the model is able

to describe new resulting processes or processes which tend to vanish slowly.
In Figure 3 and 4 the simulation of time-variant change of gases (CH_4, CO_2 and H_2), acids, cell growth of anaerobic bacteria and the degradation of solid and soluble organic matter (cellulose, acids) during a period of 100 days is represented.

With respect to cell growth, the assumption is made that all cells are suspended in the aqueous phase. Initial values were estimated from monitoring data which had been made available by a municipal landfill owner near the town of Braunschweig. Here, average biomass concentrations of 0.4 – 1.0 kg m^{-3} were found. The initial environmental conditions for process simulation are assumed to be in the optimum range. Furtheron, the reaction system (REV) in this case is assumed to be closed; no mass or heat transfer into and out of the cluster is allowed. The consideration of mass and heat exchanges between two or more clusters as well as the influence of physico-chemical processes controlling the bioavailability of nutrient substances are part of present investigations and simulations.

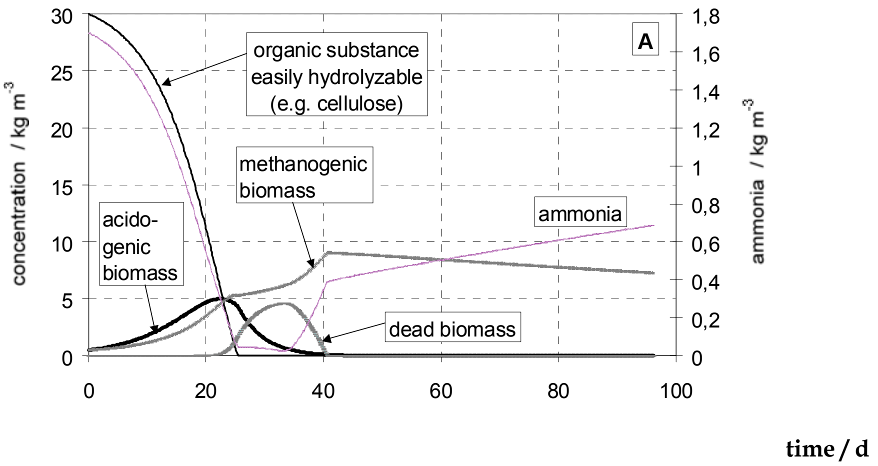


Figure 3: Simulation of hydrolysis of polymer organic matter, bacterial growth and death as well as consumption and generation of ammonia. Initial mass of easily hydrolyzable polymer organic matter: 30 kg/m^3 waste.

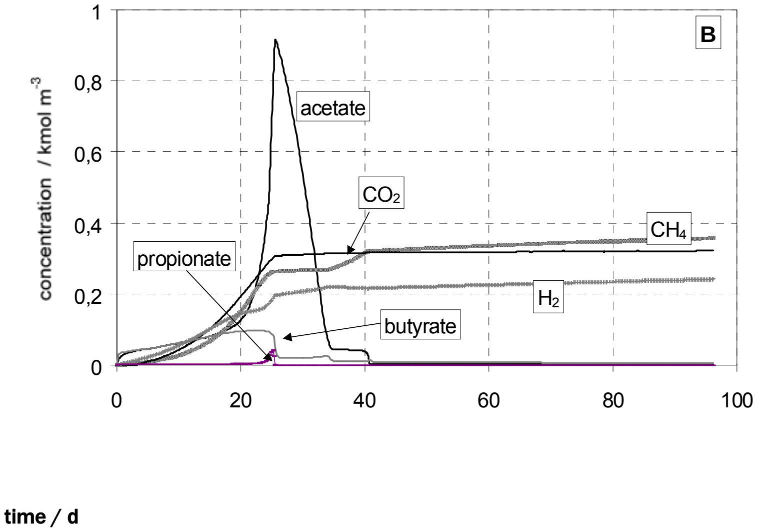


Figure 4: **Simulation generation of organic acids and landfill gases.**

B5: Analysis and Modelling of Chemical and Biological Reaction Processes in Municipal Landfills

Objective:

Identification and location of relevant chemical and biological reaction pathways responsible for degradation of organic matter and pollutant generation.
Prediction and measurement of the distribution and correlation of rate influencing environmental parameters.
Prediction of landfill stability and long-term behaviour.
Development of a model based landfill monitoring.

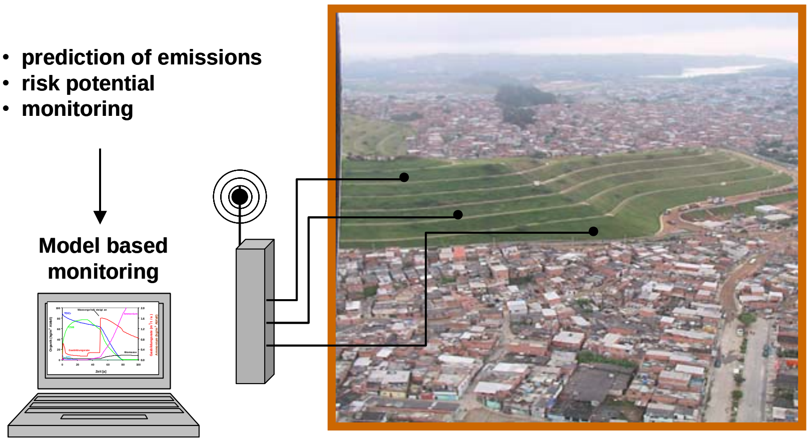


Figure 5: landfill risk management referred to as model based monitoring.

Solution:

Analysis and identification of main chemo- and bio-kinetics.
Analysis and description of main transport processes.
Coupling of transport and bio-kinetics.

Contact:

Prof. Dr.-Ing. D. C. Hempel, PD Dr. A. Haarstrick • Institut für Bioverfahrenstechnik • Gaußstr. 17 • 38106 Braunschweig • Tel: +49(0)531/391-7654 • Fax: +49(0)531/391-7652 • Email: d.hempel@tu-bs.de, a.haarstrick@tu-bs.de

Lifetime prediction and phenomena in landfills

Landfills are capsuled constructions serving the purpose to separate waste depositions from the surrounding environment. During operation and aftercare the embedded waste is exposed to various physical effects, which induce flow processes of leachate and landfill gas, heat transport and mechanical deformation. In many cases large quantities of organic matter exist inside the landfill body and are subjected to biochemical reaction processes.

So far there are hardly any reliable computer models available to analyze the physical processes in landfill bodies over a long period of time. In many cases observations of emissions and experience values are employed to get an approximate estimation of the long-term landfill evolution. Therefore, the development of capable analytical models for the investigation of processes inside of landfills is of great importance.

As illustrated in Fig. 1, many different factors of influence play an important role in the landfill behavior. Obviously, waste degradation and landfill emissions are strongly related. Reaction processes depend on environmental conditions like temperature, pH-value and substrate concentration. Transport is driven to a certain extent by the production of gas and leachate. Waste degradation affects pore geometry and distribution and leads to changing hydraulic parameters like porosity and permeability.

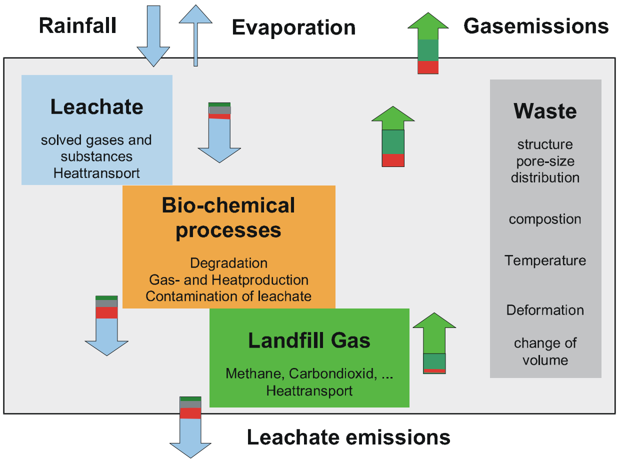


Fig. 1: Phenomena in landfills

Landfills are composed of a variety of inorganic and organic components, among which biodegradation occurs under proper conditions. Landfill gas and leachate may accumulate and pollute the environment, if barriers are missing or insufficient. This research project deals with the development and application of a multiphase flow and transport model for the analysis of processes inside of landfills:

Analysis of temperature distribution.
Aerobe and anaerobe degradation of organic substances in the deposit and its development in time.
Balance of components of leachate, gas, and organic substances in the deposit and their temporal and spatial distribution.
Flow processes of fluids in porous media.
Deformation resulting from degradation in the deposit.

Multiphase flow and multicomponent transport processes

The basic equations for multiphase flow and transport in porous media are known from literature. The 3-D transport equation is obtained by mass conservation in a control volume. The control volume is referred to as the Representative Elementary Volume (REV) and is the smallest homogeneous model unit. For every component mass conservation is formulated and applied as model equation on the macroscopic level.

Storage/Evolution Advection Diffusion/Dispersion Sources/Sinks

$$(A_c \cdot z)_{,t} \quad + \quad \mathrm{div}\,(A_u \cdot z) \quad + \quad \mathrm{div}\,(A_\lambda \cdot \mathrm{grad}\; z) \quad + \quad q(z) \quad = \quad 0 \; .$$

The advective transport coefficients are governed by using a generalized Darcy law for multiphase flow. To describe the interaction between various fluid phases as well as capillary forces empirical approaches are applied. Diffusive transport due to concentration gradients is described by Fick's law. Temperature is considered to be equal for all phases, what is a proper assumption for characteristic flow velocities in landfills and consistent with local thermodynamic equilibrium.

Local mass balance and reaction kinetics

The model equations describing the temporal change of organic compounds (termed as substrates) are mainly based on Monod kinetics, according to which a set of differential equations have been formulated.
The temporal change of the substrate concentrations s is described by the product of the common reaction rate matrix R(s) and the substrate-specific stoichiometric coefficient matrix M. The derived process matrix B(s) contains all information necessary for the mathematical description of transient reaction processes including biochemical substances, biomass and temperature development. Sources and sinks ŝ are related to global transport of mass and energy.

$$\mathbf{B}(\mathbf{s}) = \mathbf{M} \cdot \mathbf{R}(\mathbf{s}) \;, \qquad \dot{\mathbf{s}} = \mathbf{B}(\mathbf{s}) \cdot \mathbf{s} + \hat{\mathbf{s}} \quad .$$

All processes are assumed to happen simultaneously in the boundary region between solid and fluid phases of the microscopical pore structure of the embedded waste. Whenever there is a change in environmental conditions – oxic/anoxic, redox potential, temperature or alkalinity – the model is able to describe new resulting processes or vanishing processes in an adaptive way.

Numerical schemes

The numerical solution of the strongly nonlinear and coupled transport and reaction equations can be obtained using an adaptive 3D model. The weak form of the model equations is discretized by means of a finite element method in space domain. Integration in time is done with an implicit Eulerian scheme. Numerical stabilization of the spatial discretization is obtained by applying the fully upwinding method. The interaction of global transport and local reaction is considered implicitly. The resulting overall model is able to investigate global and local sensitivities with respect to characteristic processes and parameters.
Results

The rate of degradation of cellulose in a locally closed system is solely dependent on initial values of the substrates and conditions. Temperature and pH-value are controlled by heat release and the actual concentration of available substrates. Figure 2 shows the evolution of substrates for the case that initial values correspond with conditions of experiments in landfill simulation reactors. The described degradation model is compared to the model from literature that only captures the evolution of temperature and organic substance while landfill gas is just a product. The more detailed model, which is developed in cooperation with project B5 considers complex coherencies of more than 20 substrates, biomasses and temperature, see Fig 2.

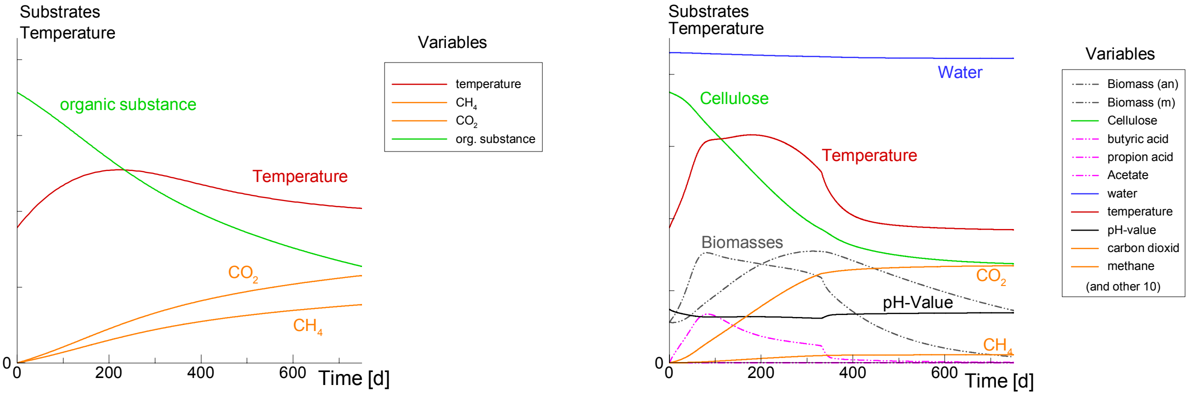


Fig. 2: Comparison of models: Model from literature (left) and own model (right)

For practical use and coupling with 3-D transport models the detailed model has to be reduced to the most characteristic degradation processes and variables. Conducting sensitivity analysis main reactions and substrates may be identified and implemented into a separate model. In Fig. 3 results obtained by applying the reduced model are represented. Here, hydrolysis, acetogenesis and methanogenesis are considered to be the most important reaction processes.

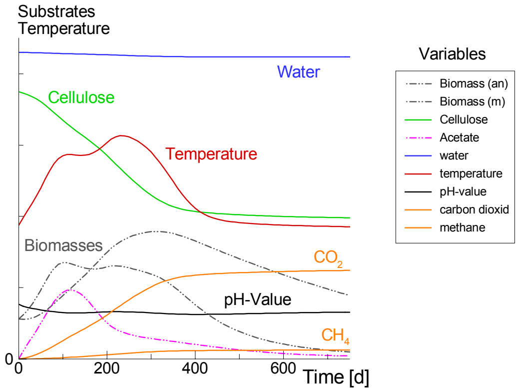


Fig. 3: Reduced model

Comparing Figs. 2 and 3, the evolution of substrates of the reduced model is very similar to the detailed degradation model. It follows that reduced degradation models may be accurate enough for a coupling of local reaction with global transport.

In many cases, realistic simulations of coupled transport and reaction processes in landfills are only possible on the basis of multidimensional analysis. The developed model allows the calculation of arbitrarily shaped two-dimensional structures with the adaptive, iso-parametric element concept. The possibilities of the model are demonstrated with the represented two-dimensional landfill section, utilizing symmetries to the vertical boundaries, see Fig 4.

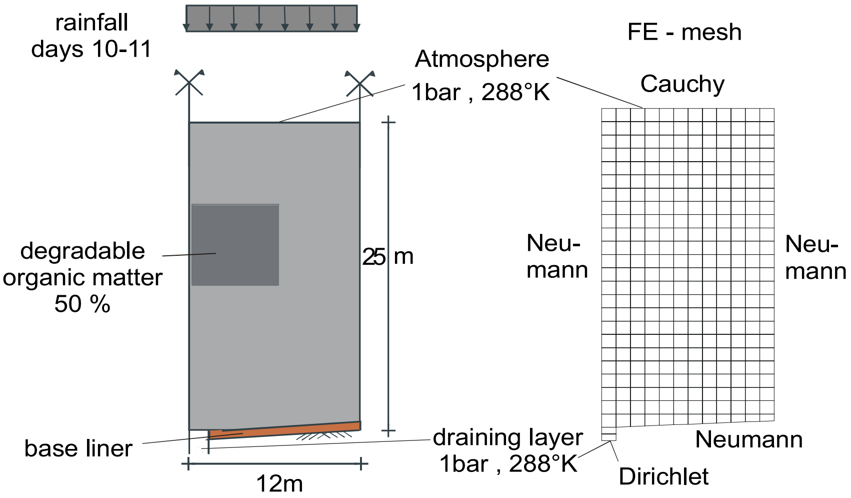


Fig. 4. Geometry and FE-mesh of landfill segment

This is an example of a common landfill section. At the beginning the pore space is filled to 60% with water and to 40% with landfill gas. Degradable organic substance is concentrated to 50% in the solid phase of the characterized subsection. Degradation of organic matter follows the reduced degradation model.

Since the landfill body is not yet sealed above, rain water – modeled as sources in the top level element layer – can penetrate the waste. At the lower boundary an inclined base liner with special Neumann boundary conditions and a drainage layer with Dirichlet boundary conditions are modeled in such a way that leachate can flow off only in the area of the left-hand side. The simulation period amounts to 50 days during which a rainfall event occurs on days 10-11.

Fig. 5 shows the saturation of the gaseous phase in the pore space. Mobile water flows downward unimpaired and accumulates over the bottom liner and the drainage layer. For water saturations less than 40% the water phase is nearly immobile. With penetration of rain water the gas saturation decreases and the liquid phase is mobile again. With the degradation of organic substances the produced landfill gas flows out of the characterized subsection into the remaining area and hinders water penetration into the subsection. The water preferentially flows around the area instead, reaching here nearly full saturation.

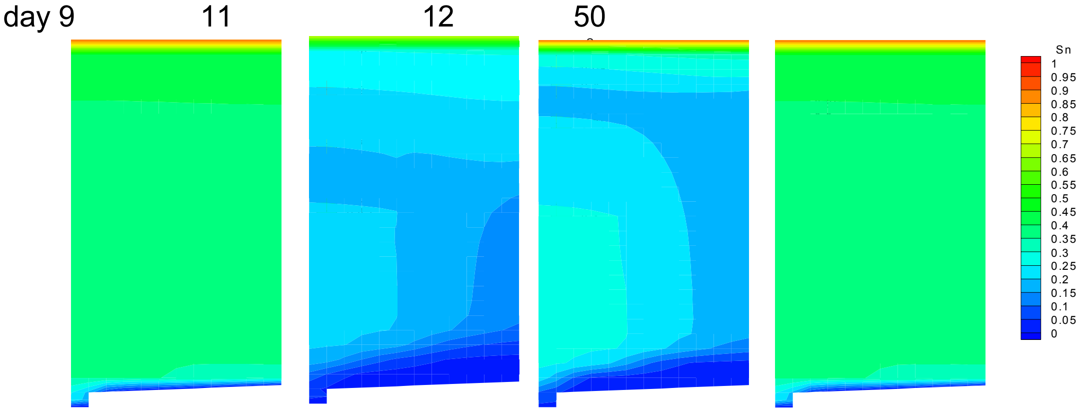


Fig. 5: Evolution of gas phase saturation

Contact:
Prof. Dr.-Ing. D. Dinkler • Institut für Statik • Beethovenstr. 51 • D-38106 Braunschweig
Tel:+49(0)531/391-3667 • Fax:+49(0)531/391-8116 • eMail: statik@tu.bs.de

B9: Adaptive model for the prognosis of durability during the monitoring of concrete structures

Objectives

Most durability models for concrete structures are based on design data and do not consider measured performance criteria of the structure. Such models must already consider the unknown actions during the life time at the time of structural design. Uncertainty is unavoidable. A reliable prognosis of durability and remaining service life during the utilization of a structure requires actual information about the behaviour of the structure and a simulation model which is able to treat this information. An adaptive simulation model that improves its accuracy itself by the use of measurable data is needed. So the durability will become a property that can be monitored. There is another advantage of such an adaptive algorithm. Unlike a non-adaptive algorithm, the properties of the uncorroded concrete structure need not be known very accurately. So the expensive and time consuming determination of inital data for the simulation can be shortened. It is the long-term object of the part-project B9 of the DFG collaborative research center SFB 477 to develop and to test such an adaptive durability model for the monitoring of concrete structures.

Methodology

The adaptive model is based on the software system TRANSREAC (transport and reaction). TRANSREAC combines the calculation of chemical reactions by a thermodynamic algorithm, transport processes within a structure and corrosive effects. TRANSREAC was not an adaptive model so far. The algorithm was extended and connected with data from in-situ measurements.
To test and validate the adaptive model reinforced concrete testing structures are used, exposed to real climatic conditions, acid, sulfate, chloride and ammonium solutions. The structures are prestressed to ensure realistic stress situations and cracks. It is an important experimental feature of the research project that we do not immerse small, non-loaded, non-cracked specimens in aggressive solutions, but work with 3 tons testing structures, fabricated, cured and loaded under practical conditions. One of the testing structures is shown in Fig. 1a. It is equipped with moisture and chemosensors (developed by part-project C1), thermocouples and commercial available multi-ring electrodes and corrosion sensors. The environmental climatic data are automatically recorded. The climatic data, the cement composition, the concrete mixing properties, the composition of the aggressive solutions and the sensor signals are input data for the adaptive simulation. The corrosion behaviour of this structures is simulated. The calculated and measured data are compared and the function of the adaptive algorithm is checked. The results of the durability model (loss of surface mass, expansion, loss of strength, rise of cracks as a result of chemical processes, corrosion of the reinforcement, etc., all time and space dependent) are input data for other part-projects of the collaborative research center, in particular for the safety analysis located in the part-project A1.

B9: Adaptive model for the prognosis of durability during the monitoring of concrete structures

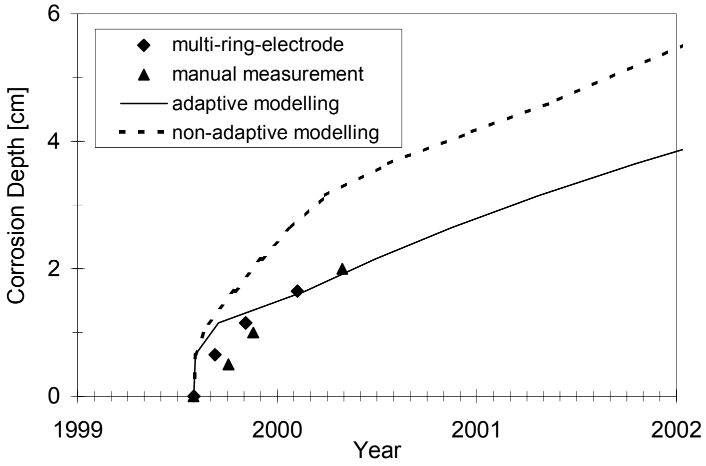


Fig 1a: Left: concrete testing structure with test regions for aggressive solutions

Fig 1b: Right: measured and calculated corrosion depth by the non-adaptive and the adaptive algorithm in the case of acid attack

Results

First we concentrate on the acid attack. After one year the corrosion depth amounted to about 2 cm. It was possible to use a multi-ring electrode to monitore the corrosion depth. This electrode measures the impedance that showed a significant decrease in the corroded zone. Fig. 1b shows the adaptive and non-adaptive prognosis of the corrosion depth in comparison with the experimental results. It could be shown that it is possible to prognosticate an acid attack with more accuracy and only crude approximations of the initial data by an adaptive modelling

Contact:
Prof. Dr.-Ing. H. Budelmann • Dr.-Ing. F. Schmidt-Döhl • Institut für Baustoffe, Massivbau und Brandschutz • Beethovenstr. 52 • D-38106 Braunschweig • Germany • Tel: +49(0)531-391-5405/-5419 • Fax: +49(0)531-391-8179 • Email: H.Budelmann@tu-bs.de/F.Schmidt-Doehl@tu-bs.de

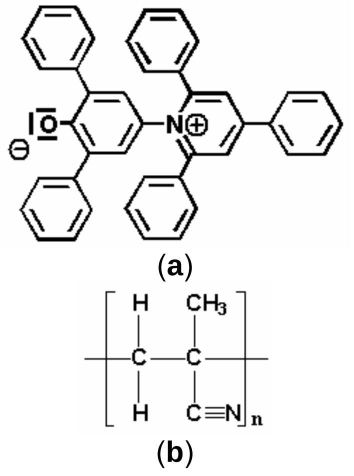
Objectives

Commercial available fiber-optical sensors for monitoring concrete structures are known for mechanical damage processes, e.g. fiber-bragg-grating as strain sensor. Contrary to this there are no commercial measurement systems for monitoring chemical attacks on concrete structures. An important factor for chemical processes in concrete is humidity, since water is the transport medium of all ions in concrete and participates in nearly all chemical reactions. In healthy concrete the pH should be around 13. The majority of chemical attacks on concrete result in a decrease of pH. Therefore most chemical processes in concrete can be characterized by humidity and pH. For some important attacks on concrete the concentration of damaging ions has to be measured, too, e.g. chloride induced electrical corrosion. Therefore the development of an *in-situ* monitoring system for chemical attacks on concrete structures, which is the aim of this research project in collaboration with project C1b, requires an interdisciplinary work of researchers in the fields of photonics, organic chemistry and civil engineering. The research in this project is divided into the synthesis of suitable sensor materials for the different parameters to be monitored and the development of a fiber-optical monitoring system, which sensor probes are designed to be able to include any of the synthesized sensor materials. The application of the sensors under real test conditions is done in collaboration with other research groups of the collaborative research center.

Methodology of Synthesis of Sensor Materials

The sensor materials used for detection of various chemical parameters inside of concrete consist of an indicator dye embedded into a suitable polymer matrix. The optical properties of the dye, i.e. refraction, absorption or fluorescence, are influenced by changing conditions in the concrete. Light transmitted through the sensor material is changed in intensity, phase or polarity and these optical changes are detected by a spectrometer. The polymer used as matrix material has to be permeable to the species which is monitored e.g. water or various ions (Cl^-, Mg^{2+}). The various material systems have to be tested on long term stability against the basic conditions inside the concrete (pH 11-13), high optical quality and dependency on temperature changes.

Moisture Sensor



(**a**)

(**b**)

Figure 1: Reichardt's Dye (**a**) and poly(methacrylonitrile) (**b**)

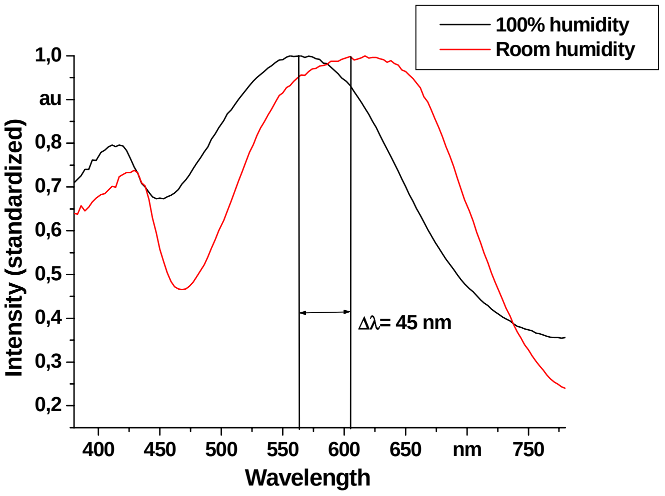


Figure 2: Absorption spectra of Reichardt's dye at two different water concentrations

For detection of moisture content inside of concrete structures a solvatochromic dye, the pyridinium phenolat betain Reichardt's dye (Figure 1a), is embedded into a polymer matrix consisting of poly(methacrylonitrile), a polymer with moderate hydrophilicity (Figure 1b).
This ensures a limited absorption of water by the polymer generating reproducible moisture dependent conditions in the vicinity of dye molecules. A new synthesis was developed to produce the polymer with a defined size and a narrow distribution in chain length leading to a better processability. An increase in water content leads to a continuous hypsochromic shift in the absorption spectrum (Figure 2). The dye is embedded into the polymer as guest/host – system. There is work in progress to link the dye covalently to the polymer ensuring an uniform concentration of the dye all over the polymer and preventing its leaching.

pH-Sensor

The measurement of pH in concrete is very important for a comprehensive evaluation of stability and corrosive damage in reinforced concrete. It is therefore of great interest to develop a pH-sensor that is capable of indicating a decrease of basicity in the pore solution. In order to use an all-optical setup we synthesized an indicator dye that covers the relevant pH-range from 7 to 11. It shows a colour change from yellow ($\lambda_{max,01}$ 462 nm) to red ($\lambda_{max,02}$ 530 nm). The absorption spectra show a constant absorption of the system at 482 nm, i.e. the isosbestic point of the dye (Figure 3).
This internal reference makes it possible to determine the pH-value quantitatively by using only one type of indicator.

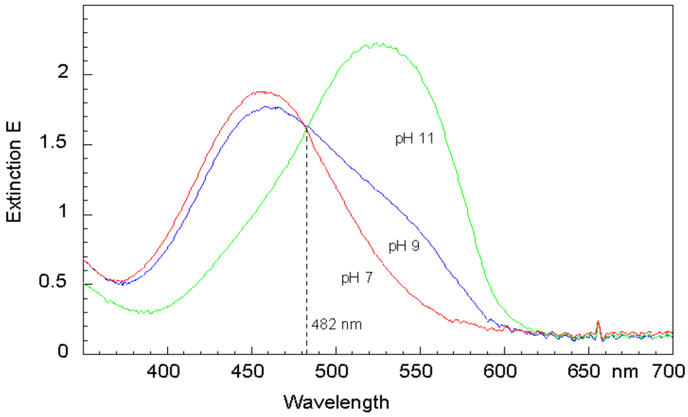


Figure 3: pH dependence of the absorption spectrum of a carbohydrate foil.

Chloride Sensor

All known optical chloride sensors are restricted to neutral and acidic pH. Chloride ions cause electrochemical corrosion even in high alkaline environment of reinforced concrete. Therefore chloride sensitive dyes are investigated which are usable under these conditions. Trimethine dyes form so called *J*–aggregates (Figure 4) under the influence of different salts, solvents and in alkaline media (hydroxide ions). The resulting color change from monomer to *J*-aggregate is again detected via a spectrometer.

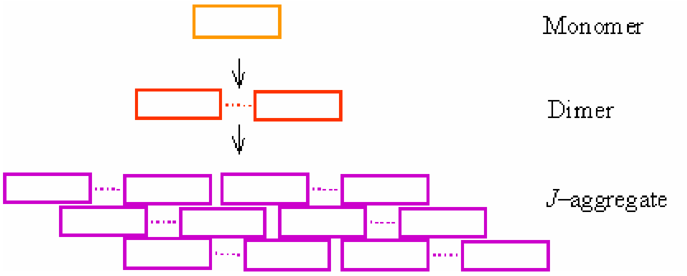


Figure 4: Principal Scheme of *J*–aggregation (simplified)

Methodology of System Development

For monitoring concrete structures the synthesized sensor materials are incorporated in a fiber-optical planar transmission sensor (Figure 5). The sensor is fabricated by coating the end-face of a fiber with silver in a vacuum chamber. The metallized fiber is glued onto a suitable substrate, whereas the glue encapsulated the silver mirror. Afterward a slit is cut through fiber and glue, which is filled with sensor material. The dimensions of the slit depend upon the cutting process. By cutting the fiber in normal plane of fiber axis, two perfectly aligned and fixed fibers are created without any adjustment techniques. The fibers are protected on their complete length by glue against the aggressive environment of concrete.

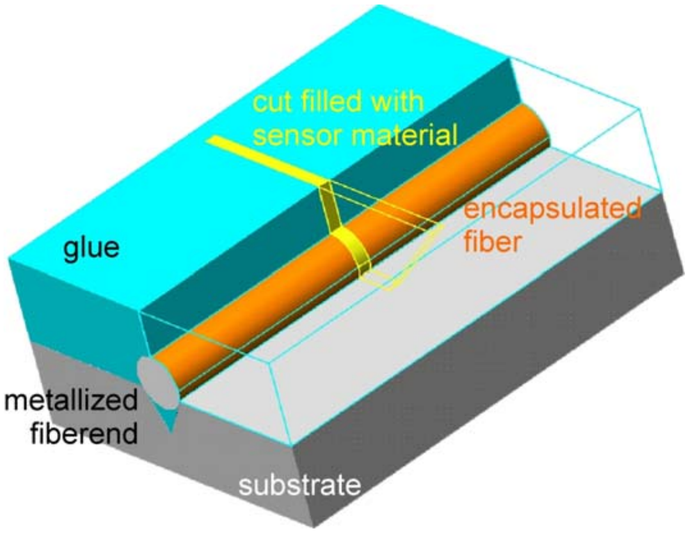


Figure 5: schematic planar transmission sensor

The planar transmission sensors are read out by the measurement system depicted in Figure 6. As a light-source a halogen lamp with a continuous spectrum in the visible range is used. The light is guided through a 3 dB-coupler to a broadband fiber switch, which aligns input and output fibers. After passing the planar transmission sensors the light is guided back to the switch and then through the 3 dB-coupler to a microspectrometer, which records the resulting absorption spectrum. A computer controls the optical system and analyzes the spectral data. The measurement data can be sent via internet to a monitoring center, which in turn can control a large number of *in-situ* monitoring systems.

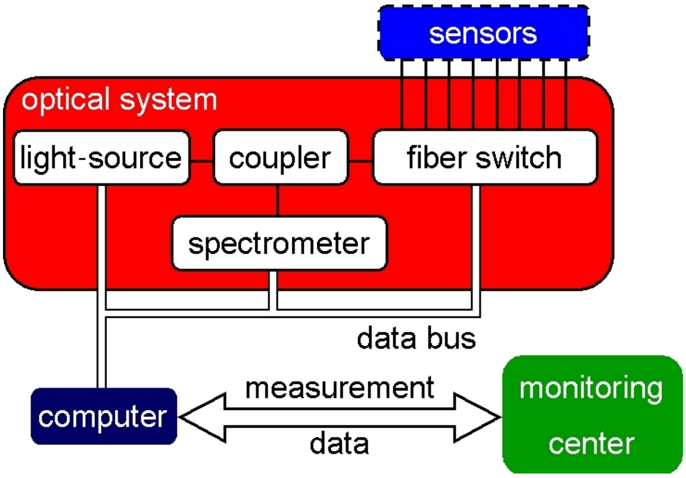


Figure 6: measurement system

Contact:

Dr. H.-H. Johannes • Inst. f. Hochfrequenztechnik • Schleinitzstr. 22 • 38106 Braunschweig • Germany • Tel: +49(0)531/391-2006 • Fax: +49(0)531/391-2045 • Email: h-h.johannes@tu-bs.de

Prof. W. Kowalsky • Inst. f. Hochfrequenztechnik • Schleinitzstr. 22 • 38106 Braunschweig • Germany • Tel: +49(0)531/391-2001 • Fax: +49(0)531/391-2045 • Email: w.kowalsky@tu-bs.de

Crack detection by means of piezo arrays

The monitoring of large areas of steel structures is still essentially accomplished by visual inspection. Regions that are considered as critical are usually examined additionally by non-destructive testing methods after having been checked visually. With not statically loaded structures, e.g. railway bridges, cranes and crane tracks, reactors with changing internal pressure, towers and masts, you have to pay attention especially to fatigue cracks since these can limit the load-carrying capacity directly. Sudden crack initiation can also appear in connection with buildings exposed to chemical attacks (stress corrosion in chemical reactors, blast furnaces, etc.). The visual detection and also the detection by means of non-destructive testing methods is not easy to perform everywhere and sometimes even impossible, e.g. hardly accessible structures at huge heights, the inner regions of reactors or welded box girders. Sometimes structures have to be monitored continuously to prevent damages. In such cases the above-mentioned visual inspection at certain intervals is not possible.

Fig.1**: Possible structures for application of piezo arrays**

If the position of the crack can be anticipated relatively exactly, there are a number of established methods for automated crack monitoring. The situation becomes more difficult if the crack position cannot be predicted precisely, for example, if in a plane structure the crack occurs at an arbitrary point due to local micro notches caused by stress corrosion.

Within the scope of the subproject C6, the detection of cracks is approached in a different manner. The steel structure that is to be investigated is forced to vibrate by piezoelectric patches. At the same time, piezo patches are also used as sensors.

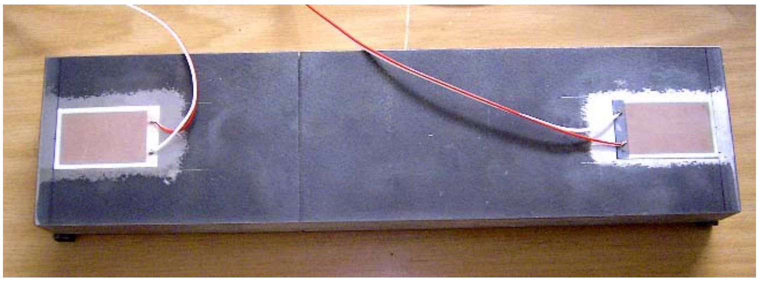


Fig.2**: Steel plate with two applied piezo patches**

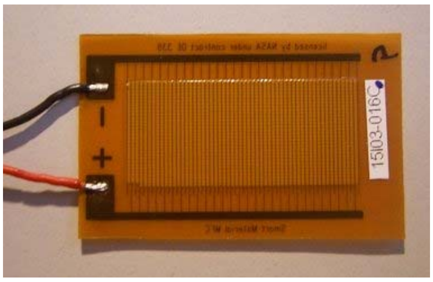
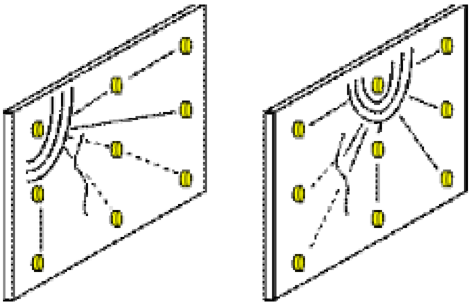


Fig.3**: Piezo patch (NASA LaRC)**

By means of appropriate electrical control, the piezo elements can act as sensors and also as actuators: one patch works as a sensor while all other patches are used as sensors. Then the roles change. If this procedure is applied to all piezo elements, it is possible to determine the position and the size of the cracks because the change in the structure modifies the answer signals. By activating multiple actuator piezos with a phase difference it is possible to obtain a directivity of the signal (use of the interference effect) as it is known from radio antennas in the short wave range. In this way, a larger coverage of the signal can be archieved.



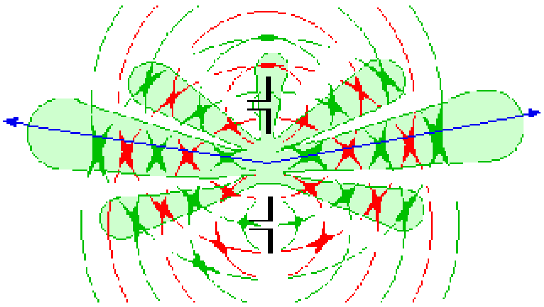


Fig.4**: Principle of the piezo array** Fig.5**: Interference effect**

In the current period of the SFB 477, general experimental investigations are the focus of interest. Especially with regard to the sensitivity and the reproducibility the following aspects are considered:

- Influence of the steel plate thickness
- Influence of the temperature and changing load on the measurements
- Type of cracks, influence of a possible dovetailing of the crack borders with natural cracks
- Geometry of the specimens (also hidden cracks, e.g. under overlapping plates)
- Connection of the piezo patches to the steel structure

Beyond that different types of signals are used for stimulation. Investigated are, for example, a sine wave with continuously changing frequency, white noise or single impulses.
The experimental work is accompanied by theoretical analysis. Investigated are different wave forms as well as their propagation. In this context the influence of the boundary conditions has to be mentioned.

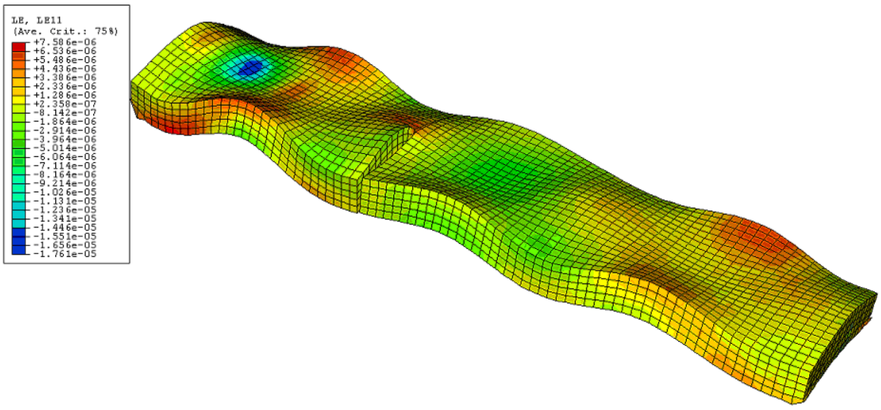


Fig.6**: Plate with crack and asymmetrical lamb wave**

The aim of this theoretical work, on the one hand, is to better interpret the results of the measurements, and, on the other, to create better computer models that can act as reference models for real buildings. Particularly with regard to existing structures where the initial state cannot be determined experimentally, the creation of computer models is of great importance.

Contact:
Prof Dr.-Ing. U. Peil • Institut für Stahlbau • Beethovenstr. 51 • 38106 Braunschweig •Germany •
Tel: +49(0)531/391-3379 •Fax: +49(0)531/391-4592 •Email: u.peil@tu-bs.de

C7: Determination of inherent fatigue damage in steel structures by means of the lock-in thermography

Objectives

During the last years sophisticated tools and methods have been developed for the life time prediction of dynamically loaded structures. Most of these methods use a phenomenological approach and are either based on more elaborated estimation techniques of the loading history or on a better prediction of the structural response. So far only few methods exist that allow for a quantitative determination of the actual damage state within dynamically loaded structures.
The starting point of the subproject C7 is the fact that fatigue damage is closely related to the initiation and propagation of short cracks and microplastic zones. The underlying micromechanical damage processes have been investigated intensively during the last decades and recently more and more models have been developed that predict micromechanical damage processes. Up to now only very few attempts have been made to incorporate micromechanical damage into engineering lifetime models. One obstacle is that micromechanical damage processes can so far - at least with limited technical and economical means - only hardly be determined within real structures.

The aim of the subproject C7 is therefore:

a) The development, validation and application of a measurement method for structural fatigue based on lock-in thermography. The method allows for an in-situ observation of micromechanical damage processes.

b) The formulation and validation of an engineering lifetime-prediction model based on micromechanical damage processes.

The project’s long-term vision is the determination and quantitative interpretation of physical damage at critical hot spots of cyclically loaded structures.

Procedure

Under laboratory conditions, e.g. at smooth specimens with a polished metal surface, the initiation behaviour of microcracks can be studied via visual microscopes, electron-scanning microscopes, x-ray based measurement techniques, acoustic emission etc. The application of these methods to real structures is difficult or even impossible, since either polished surfaces are necessary - which can not be realized afterwards without destroying the surface-close micromechanical damage indicators - or the testing equipment is simply not usable for in-situ measurements. For the sake of the interpretability of the results a picture-based method is preferable.
For the non-destructive testing of structures, e.g. delaminations cracks, corrosion etc., the lock-in thermography has been extensively used during the last years and applications have been reported from many different fields. The method uses a pixel-wise correlation between a periodic activation (lamps, ultrasonic, mechanical stress, electric circuit etc.) and the pixel response of the infrared-sensitive array of a thermo-camera. The aim of the subproject C7 is the application and the further development of the lock-in method for the visualization and quantification of micromechanical damage phenomena as microcracks and microplastic zones.

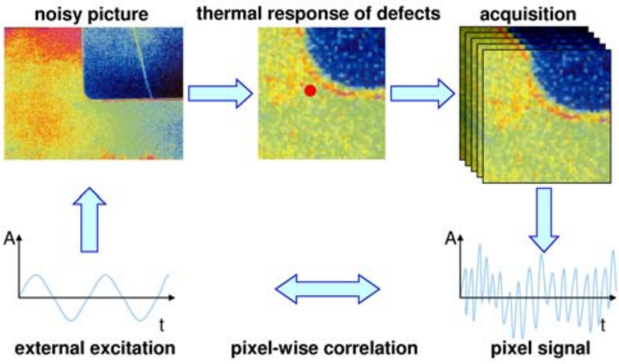


Fig. 1: Principle of the lock-in thermography

The underlying work-principle of the lock-in thermography is shown in figure 1.

An excitation with a certain frequency is applied to modulate the thermal behaviour of a test specimen. For the application of the lock-in method for non-destructive testing it is necessary that the defects within the specimen lead to disturbances in the thermal response of the defect areas compared to the undamaged surrounding. Depending on the chosen excitation the defect areas show a disturbed transmission behaviour (thermal excitation) or heating/cooling of the critical points (mechanical or ultrasonic excitation). Normally the differences in the thermal response of defect and non-defect areas are small and hardly detectable directly by radiometric measurements. However using the lock-in technique very small temperature differences can be detected. This requires that the thermal excitation is synchronized with the image acquisition rate of the infrared camera. Then the thermal response observed with the infrared camera can be correlated with the excitation frequency, so that noise, thermal background reflection etc. can be filtered out.

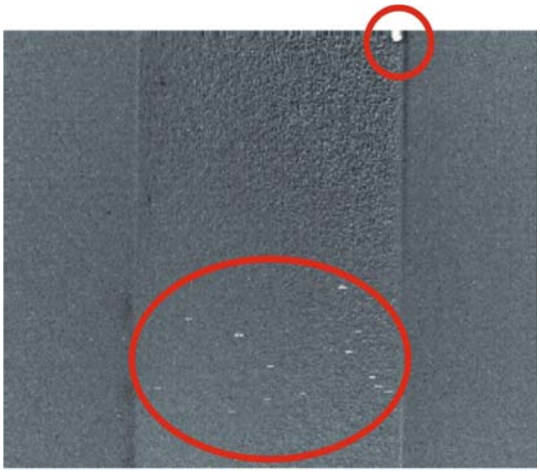


Fig. 2 Phase picture with ultrasonic excitation at 20 kHz; Amplitude modulation of 1 HZ

Both online lock-in correlation techniques during the measurement and offline lock-in correlation techniques are available. For modern array-based infrared cameras the lock-in correlation is commonly applied pixel-wise to a set of successive frames. The results of the operation are two single pictures which contain information about the phase and the amplitude of the thermal answer of each pixel with respect to the excitation. For defect recognition especially the phase picture is interesting, because it is almost free of disturbing effects as thermal background reflection, varying emission properties, temperature drifts etc.

If very high excitation frequencies are used – e.g. for ultrasonic excitation – a direct lock-in correlation can not be realized due to the limited frame rate of the camera. Therefore a slow amplitude modulation of the high frequency signal has to be used for the lock-in correlation. Figures 2 and 3 show examples where the lock-in thermography has been applied to short-crack detection during Low Cycle Fatigue (LCF) tests. The tests were performed in a laser-extensometer-controlled push-pull machine on specimens with a quadratic cross-section of 10x10 mm2 and a maximum strain rate of 12 ‰.

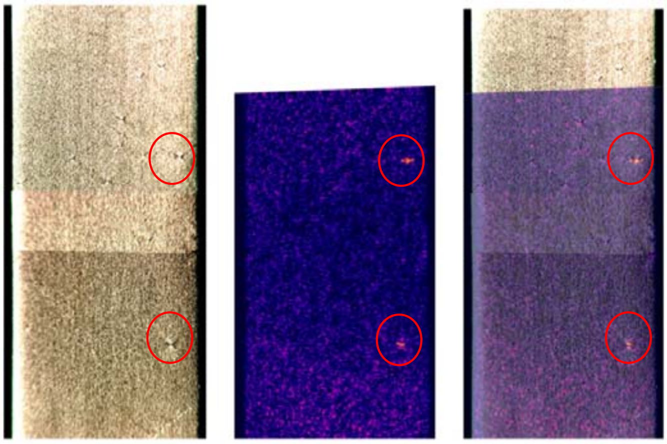


Fig. 3: Microscope picture, phase picture and superposition; LCF probe, mechanical excitation with 100 N/mm^2 stress-amplitude

The LCF test have been stopped when short cracks of approximately 100 µm to 500 µm could clearly be observed on the surface and both, light-microscopic pictures and lock-in pictures have been made of the specimen. Figure 2 shows the results of the lock-in pictures using a mechanical excitation applied with in the push-pull machine. For the lock-in measurements the LCF-test were interrupted and a sinusoidal loading with a stress amplitude of 100 MPa and a frequency of 1 Hz has been used as mechanical excitation for the lock-in procedure. The method revealed clearly the larger cracks on the investigated surface. One aim for the subproject C7 is to investigate if smaller cracks can also be distinguished using a special microscope objective and if it is possible to distinguish active e.g. propagating cracks from non-active cracks.
Figure 3 shows the phase picture of the surface with an ultrasonic excitation of 1000 W. The ultrasonic frequency of 20 kHz has been amplitude-modulated with 1 Hz. The ultrasonic excitation also revealed smaller cracks which can clearly be distinguished in the phase picture of the surface.

Work program

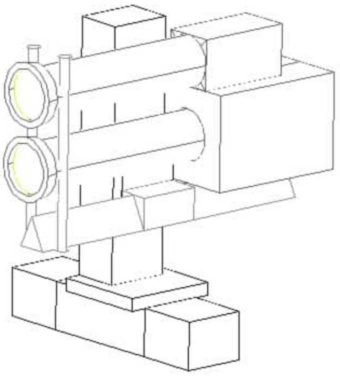


Fig. 4 Schematic view of the camera module

A new experimental setup will be installed which allows for an in-situ observation of microcrack initiation and propagation during fatigue tests in a dynamic push-pull machine. The full setup consist of a three-axis positioning system, an infrared camera with microscope objective, a long-distance microscope and additional hard- and software for data acquistion and processing. The camera module will be integrated the testing maschine. Figure 4 shows a schematic overview of the additional camera module, which will be fully installed in 2005. Both High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) tests will be performed on especially designed polished steel probes of the german steel-grade S355. During the fatigue tests the microcrack initiation and propagation will be observed simultaneously with the long distance microscope and the infrared camera. For the lock-in procedure the performance of different excitation sources and alternative data processing methods will be extensively tested. Further tests are planed on probes with different surface preparations, notched specimens, welded specimens and on the different building substitutes used within the SFB 477. The formulation of an engineering life-time prediction model is part of the next funding period.

Contact

Prof. Dr.-Ing. T. Ummenhofer • Institut für Bauwerkserhaltung und Tragwerk • Pockelsstr..3 • 38106 Braunschweig • Germany • Tel: +49(0)531/391-2501 • Fax: +49(0)531/391-4502 • Email: t.ummenhofer@tu-bs.de

Objective

Municipal solid waste (MSW) has been and will be disposed of in suitable landfills. Due to steadily increasing requirements on environmental protection, the technical design and execution of landfills (Fig. 1) became more and more costly and complicated. The basic idea of modern landfills is that of a capsule. By this the waste shall be separated from the surrounding soil, water and air and liquid gaseous emissions should be kept back. The structure “landfill” has to operate as long as a serious pollution of the environment has to be expected.

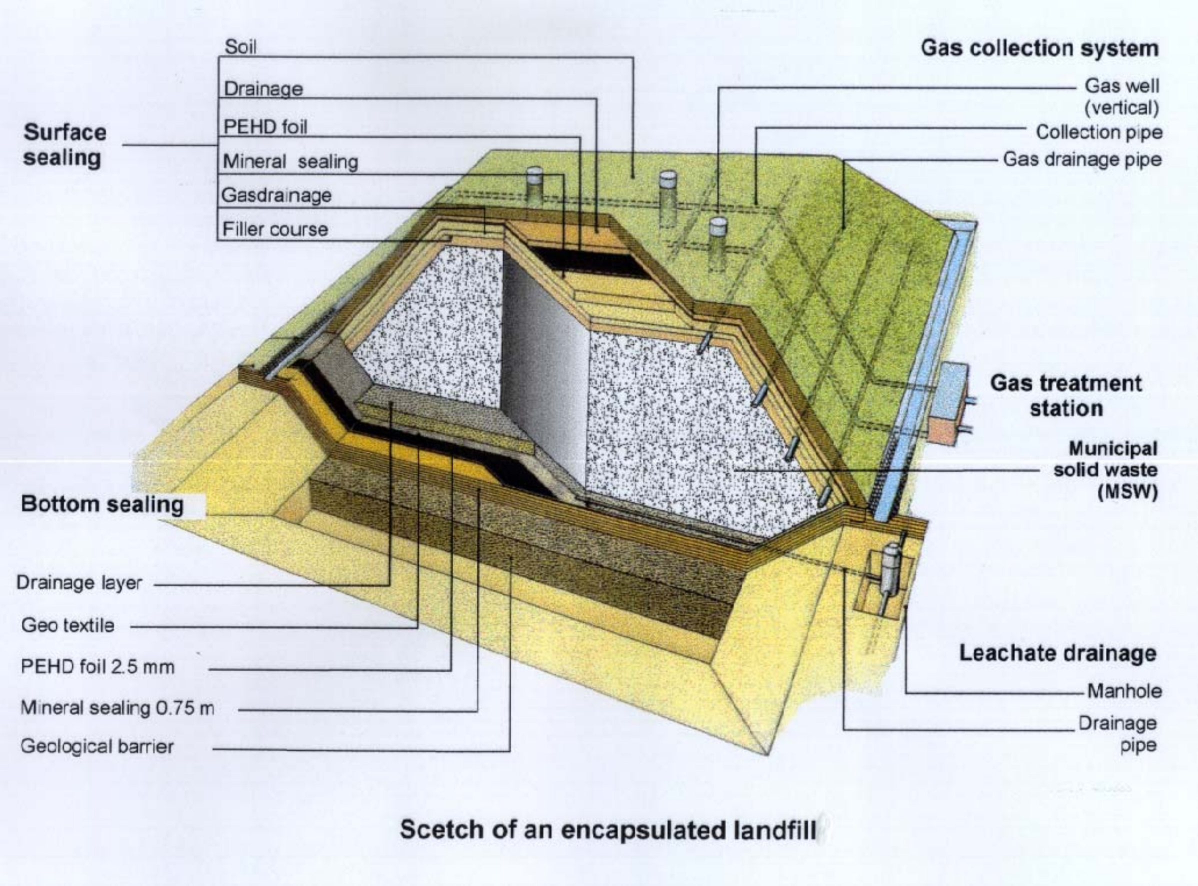


Fig. 1: Sketch of MSW-landfill construction

The capsule and the incorporated structures, such as gas and leachate collection systems, manholes, pipes etc., are subjected to stress in view of various influences:

mechanically,	e.g. load of the waste, movements and settlements
physically,	e.g. temperature
bio-chemically,	e.g. digestion and decomposition processes, dissolution

These stress factors vary with time and they can hardly be influenced after the waste has been disposed of and compacted.

The produced liquids and gases may deteriorate directly the construction material and may have negative impact on the environment. Besides this the transformation of solid waste particles into leachate and gas will form voids, which in turn will cause considerable settlements and may even result in a collapse of the cap structure.

Based on this knowledge an after care period of the landfill is prescribed. The needed lifespan as well as the best monitoring system is widely unknown at present. Many investigations have been done on a laboratory scale, mostly dealing with single influencing factors only. The complexity of interaction processes in landfills has so far hardly been investigated.

Therefore the following main topics will be investigated in order to define the length of the after care period of landfills:

emissions (quantity, quality, duration),
mechanical behaviour of waste.

After the study of the mechanisms of emissions and mechanical behaviour as “independent” points, the results will be fit together in the last phase of the research work.

Emission and hydraulic behaviour

The first topic concerns mainly the location and frequency of measurements. This includes besides others the development of new measuring devices. Recently gained results of discharge and run off measurements of drainpipes indicate, that the rate of leachate varies considerably along the drain pipe (Fig. 2). Furthermore the measuring system allows detecting damages in the top cover system.

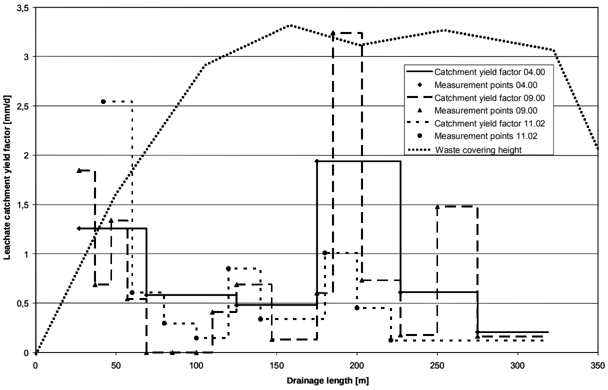


Fig. 2: In-situ measurements of intake rates of leachate with regard to the length of a drainpipe. (This is not the accumulated run off!)

The hydraulic properties of waste are investigated in laboratory scale. Therefore the construction of the large scale oedometers was modified in order to measure permeabilities under different loads. The results show the high influence of tip density on the hydraulic conductivity (Fig. 3). An increase in density of about 27 % leads to a reduction in permeability of about 400 %.

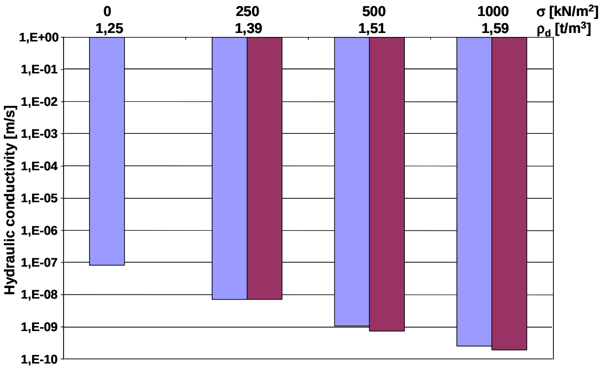


Fig. 3: Changes in vertical hydraulic conductivity as a function of compaction

As a result of compaction of waste the differences between vertical and horizontal permeability in landfills might be of several magnitudes. Therefore a new measuring device is in construction to determine the horizontal flow under different loads.

Starting with models available from literature and own research work, a mathematical model for the water balance of landfills is developed, which is adapted stepwise by means of the results from the in-situ measurements. The model EWA is similar to the well known HELP-model, with the main difference that the properties of the waste are better implemented.

Mechanical behaviour

As far as the mechanical behaviour is concerned, the shear strength, settling, deformations inside and outside the landfill etc. will be investigated particularly with regard to bio-chemical stability of wastes. This concerns tests and measurement in situ and in laboratory scale.

Measuring equipment of various sizes is partly available. This is needed in order to determine the scale effect prior to real experiments. Large scale apparatus for measuring the shearing strengths as well as tensile strengths of wastes are remained and a new triaxial cell to investigate the stress-strain behaviour was developed (Fig. 4).

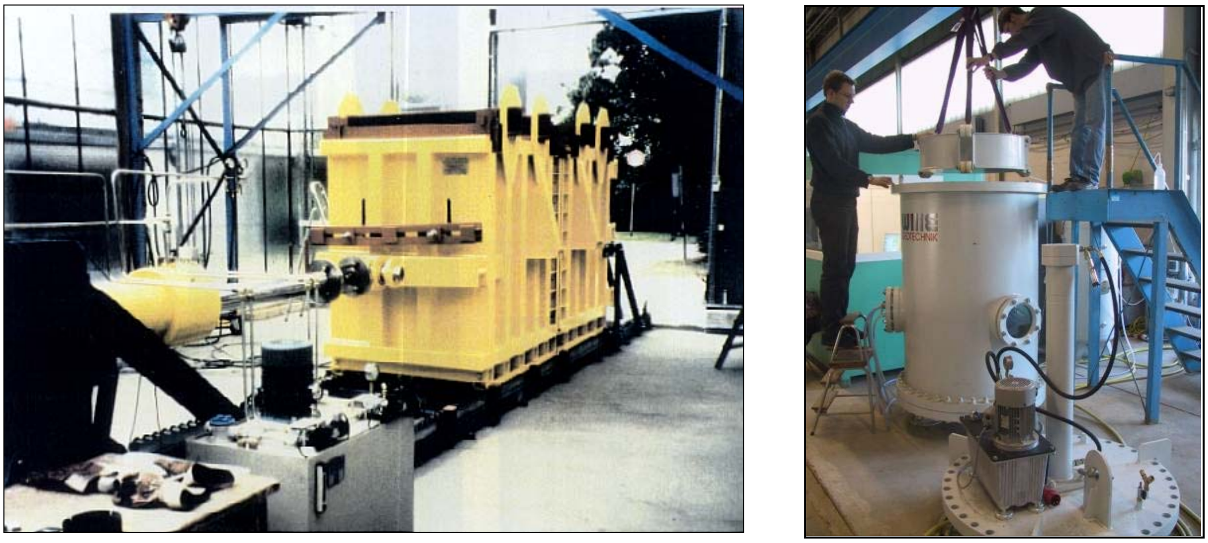


Fig. 4: Large scale laboratory testing devices: tensile test rig and triaxial cell

Laboratory tests to identify the vertical settlement of waste under different loads are conducted in large-scale oedometers (diameter 23 to 60 cm). In this context, the main goal of the research is also to assess the influence of water on the settlement behaviour. The first results of the tests show that for municipal solid waste the consolidation theory based on soil mechanics is not universally valid.

The main emphasis will be laid since the second phase of the D1-Project on the investigation of the mechanical behaviour of the waste with regard to its bio-chemical stability. This is because very little is known on the deformation of landfills, particularly that inside the waste body, which consequently will alter the emissions and the possibility of slope failures or even large slides of the total landfill. According to this in-situ deformation measurements take place and a new inclinometer probe for the landfill use was developed as well (Fig. 5). Inclination measurements are to be performed without extra pipes to direct and centre the probe. Existing gas shafts can be utilized for this purpose. This allows measurements to be conducted without destroying the surface cap, and it reduces the costs of measurements, since new pipes need not be installed.

Furthermore, it is possible to measure pipes that have already been deformed over time, supplying more information on landfill movement (Fig. 6).

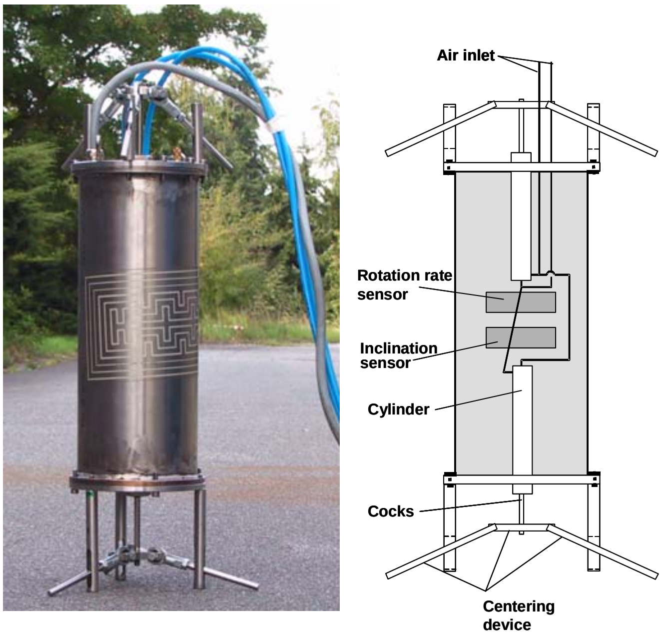


Fig. 5: Inclinometer probe

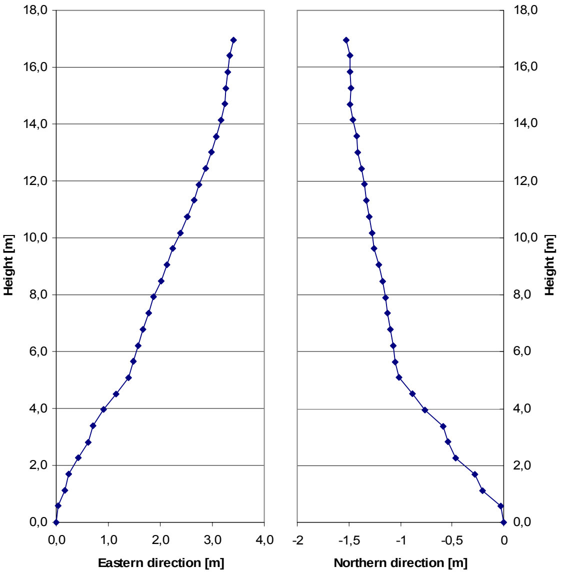


Fig. 6: Horizontal deformation of a gas shaft

At present, knowledge about the physical behaviour of landfill bodies is still insufficient. More precisely, no information is as yet available on the connection between the mechanical strength and the hydraulic behaviour, which is why precise conclusions concerning the deformation behaviour cannot be drawn. Such data are important for the serviceability of the technical equipment installed in landfill sites and to avoid the worst case scenario of slope failures.
Therefore the project D1 has developed different measurement devices to monitor the emission and mechanical behaviour of landfills. The in-situ measurements on leachate discharge, vertical and horizontal deformation are completed by laboratory tests for the physical fundamentals. Along with the modelling of the biochemical and physical (transport processes and mechanical behaviour) behaviour, a prediction model on the long-term behaviour of landfills will be developed. The long-term goals of the research are:

Definition of the different phases of landfill operation,
Monitoring of critical parameters in all phases,
Reducing the measurement effort to the necessary minimum.

These envisaged works could be done only in close cooperation with other the projects of SFB 477.

Contact:
Dr.-Ing. K. Münnich • Prof. Dr.-Ing. K. Fricke • Dipl.-Ing. J. Bauer • Leichtweiss-Institute for Hydraulic Engineering – Department of Waste Management• Beethovenstr. 51a • 38106 Braunschweig • Tel: +49(0)531/391-3969 • Fax: +49(0)531/391-4584 • Email: k.muennich@tu-bs.de • klaus.fricke@tu-bs.de • ja.bauer@tu-bs.de

Objectives

Structures have to provide for long-term use to be able to meet economic and ecological requirements. If the life of existing structures is to be extended, but also for maintenance and improvement strategies, the safety and serviceability of a structure has to be guaranteed throughout its residual life (whole-life performance assessment). Assessments made for the residual life of a structure, e.g. when based on state analysis for a given time, often do not supply data with the required degree of reliability. Accompanying monitoring is a method that furnishes much more exact results.

The condition of tendons needs to be assessed on the basis of the following questions: Where exactly are the tendons located? What is the present tensile force? Is there any damage? Are there any fractures? Can protection against corrosion still be guaranteed? Is there any corrosion activity? If so, how was it caused? There are also a number of additional questions, but they are of minor importance. In this project strains are determined for tendons. For the purpose of strain determination, this project uses several fiber optics measuring methods commercially available, as well as a magnetostrictive method that has been developed within this project. Only the last one is dealt with here. New microwave techniques for corrosion assessment and fracture localization are also developed.

1. Monitoring the Prestressing Force

Magnetoelastic measuring for determination of the local prestressing force of the prestressing steel makes use of the fact that the shape and characteristics of the magnetic hysteresis loop of a ferromagnetic material change gradually and in proportion to the normal tensile stress of the tendon (Figure 1). The measuring facility with magnetoelastic coil sensors conceived by the iBMB for this purpose has been developed to such an extent that the measuring method can be employed for on-line monitoring of up to 8 coil sensors by multiplexing (Figure 1).

Figure 2 shows the changes of the magnetic properties while a tendon was prestressed. The results are standardized in order to obtain a better comparability. The tendon consists of several cold drawn wires. This kind of prestressing steel shows the following characteristics under increasing stress:

- a continuous decrease of the magnetic characteristics and
- a continuous increase of the negative slope of all curves.

The magnetic characteristics do not show any hysteresis no matter if the stress gradient is positive or negative. Due to the shape of the curves, stress measurement is a quite easy task. The calibration of the sensors can be made in a loading machine or on site.

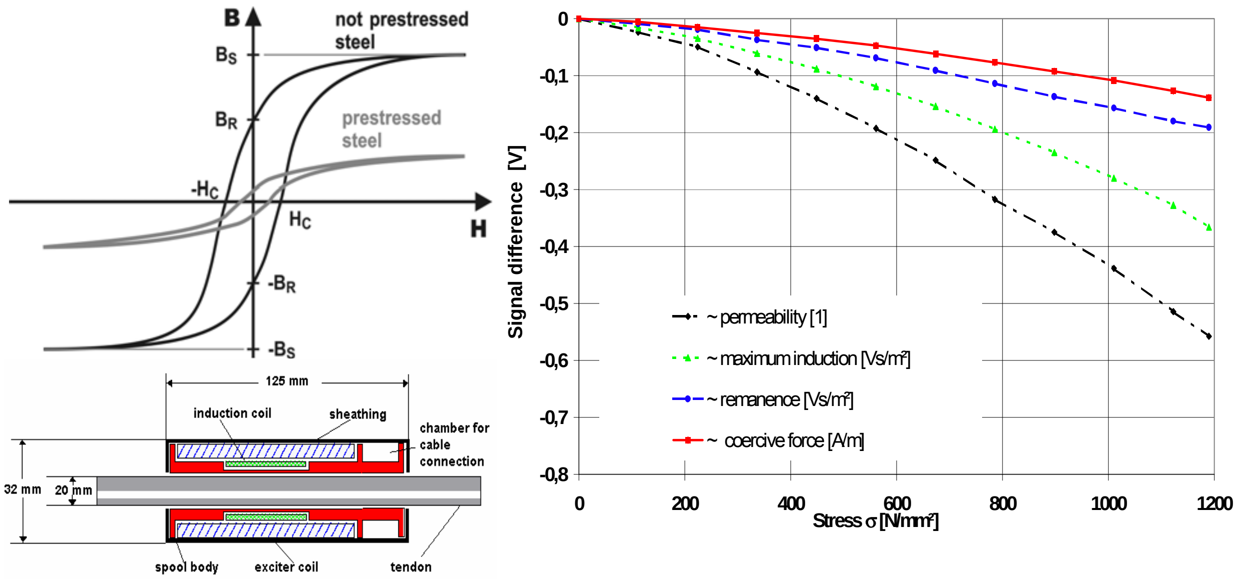


Fig. 1: Magnetostrictive prestressing force measurement. Left: measuring principle, magnetic hysteresis coil (B: magnetic induction, H: magnetic field strength) and design of the magnetoelastic coil sensor. Right: Magnetic properties under prestressing of a tendon.

2. Corrosion Monitoring

For monitoring of tensile members regarding corrosion activity, a distinction is made into two monitoring steps: the application phase (incubation phase, 1st monitoring step) and the damage phase (destruction phase, 2nd monitoring step). For the first monitoring step, suitable measuring sensors ("watch-dog" sensors) are used in the neighborhood of the prestressing steel for in-situ monitoring of parameters having a corrosion influencing effect. These may be the moisture content, the salt content (chlorides, sulphates, etc.) or the content of other aggressive substances, the pH value (carbonation) and the temperature. The measuring procedure involves conventional checks of the materials used, conventional temperature sensors, novel electrode sensors, and the fiber optics and microwave sensors developed by the Institute for High-Frequency Engineering (IHF). More details regarding the last type of sensors are to be found in the partial project C1a.

For the second monitoring step, a novel high-frequency reflection method, which is still in its trial phase, promises to yield good results. The surface of the prestressing steel proves to be a particularly good conductor of alternating currents of a high frequency (skin effect, Figure 2). Progressing corrosion results in local notch-like necking, which in its turn produces local frequency-related changes in impedance.

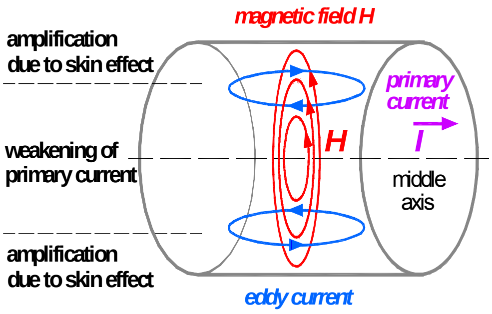


Fig. 2: Skin-Effect

After feeding an electromagnetic wide-band signal at the end of the prestressing steel, the local change of the reflection parameter can be detected in the frequency spectrum in the form of a response of the tendon. Figure 3 shows the results recorded in the laboratory for "naked" steel bars in a corrosion bath.

The measuring installation and procedure is similar to the electromagnetic resonance measurements used for fracture detection and localization (see below).

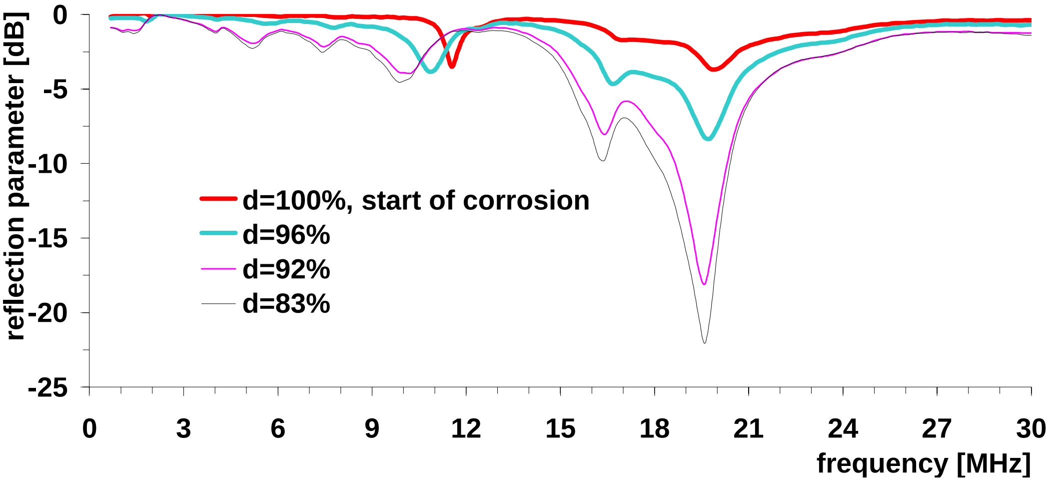


Fig. 3: Reflection response of the HF signal in the frequency spectrum for a stray-current corrosion test; initial rod diameter 7 mm, rod length 3.0 m, corrosion at 1.5 m, d - residual rod diameter

3. Fracture Detection and Localization

Some spectacular sudden damages of prestressed buildings like e.g. the congress hall in Berlin about 20 years ago led to enhanced efforts to find detection methods for steel fractures in tendons. In this project, a novel approach is presented. It exhibits the advantages of TDR-methods and avoids some of theirs drawbacks as well as the inherent disadvantages of magnetic procedures, e.g. that the tendons must be checked over their full length, their position must be accurately known, in case of overlapping tendons only the ones closest to the surface can be examined and the tendons should not be more than 20 to 25 cm below the surface. Another significant advantage of the presented method is that the required instrumentation is relatively simple.

The tendon is essentially considered as an unshielded resonator. It is excited at one (accessible) end by an electromagnetic wave. The other end or a fracture defines the length of the resonator. The associated reflected signal which defines the reflection coefficient $|S_{11}|$ is measured. Systematically varying the frequency allows to extract resonance frequencies f_{res} from the measured spectrum. The difference $\Delta f = |f_{res,i+1} - f_{res,i}|$ between two adjacent resonances of order i and i+1 is a characteristic of the resonator length.

In the easiest case, if no or only a very small electromagnetic coupling of the tendons is given, a fracture will significantly modify the spectrum: both the resonant frequencies and the respective differences will increase. For non-dispersive surrounding materials the distance Δf is constant.

Figure 4 shows the measured reflection coefficients obtained for single steel bars without any surrounding material. Their lengths were 430 cm, 630 cm, and 820 cm. Table 1 displays the Δf values extracted from the curves in Figure 4 and those calculated. Due to some idealizing assumptions made in the model, such as perfectly conducting bars and ground plane, open-circuit at the far end of the bars, ideal connection at the near end, the measured data Δf_{meas} systematically remain 3 to 5% below the calculated values Δf_{calc}.

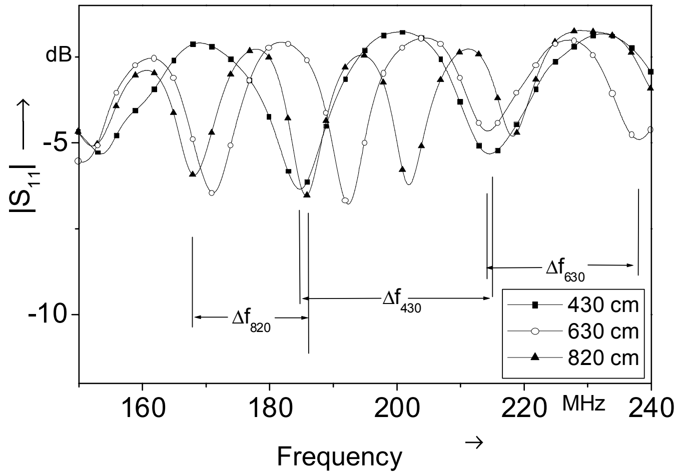


Fig. 4: Measured reflection coefficients of single steel bars of different length in air

Tab. 1: Comparison between experimental and calculated data

Length (cm)	Δfcalc (MHz)	Δfmeas (MHz)
430	34.9	33.0
630	23.8	22.5
820	18.3	16.5

Contact:
Prof. Dr.-Ing. H. Budelmann • Dr.-Ing. K. Hariri • Dipl.-Ing. A. Holst • Dipl.-Ing. H.-J. Wichmann • Institut für Baustoffe, Massivbau und Brandschutz • Beethovenstr. 52 • 38106 Braunschweig • Germany • Tel: +49(0)531-391-5405/-5487/-5587/-5905• Fax: +49(0)531-391-8179 • Email: H.Budelmann@tu-bs.de/K.Hariri@tu-bs.de/A.Holst@tu-bs.de/H.Wichmann@tu-bs.de