

Probabilistic Building Inspection and Life Assessment – a computer program for reliability based system assessment

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ABSTRACT: The collaborative research centre (CRC) 477 explores innovative methods for structural health monitoring. In project field A1, methods and strategies, the modular knowledge-based computer program PROBILAS (Probabilistic Building Inspection and Life ASsessment) is developed. Its main focus lies on the optimization of structural health monitoring measures. One opportunity to optimize the monitoring process is to concentrate the monitoring measures on a few critical weak points of a structure. These critical weak points are identified by using methods of the system and reliability theory. Additionally these methods provide the opportunity to evaluate and to assess the probability of failure of a system. This paper concentrates on the implementation of the described methods into PROBILAS. Especially the database model, its integration into the program modules and the calculation procedure used for reliability analysis are discussed further.

1 INTRODUCTION

The construction of new civil infrastructure used to be the typical business of the construction industry. Nowadays this has changed, because the preservation or renewal of structures has become more and more important. These changes result from the fact that the structures erected in the early 1960's are now reaching the end of their predicted lifespan of service or show at least serious signs of deterioration. This happens at a time when the need for the reduction of costs in public budgets is always present, which leads to the problem that not every necessary measure of rehabilitation can be carried out. In most cases this does not mean that the overall safety of the structure is endangered, because especially structures erected in former times have been designed with high margins of safety. Until the damage of the structure increases, it can be safely utilized. In these cases, structural monitoring can be used to ensure the required load bearing capability. The structural monitoring process as well as construction and rehabilitation measures have to be cost effective. Finding the optimal and cost-effective maintenance strategy is a field of research, which came up in many recently published papers, e.g. in Frangopol & Liu (2004).

One of the main focuses of the collaborative research center (CRC) "Life cycle assessment of structures via innovative monitoring", funded by the DFG at Braunschweig University of Technology is to optimise methods of structural monitoring. This

paper describes the approach of project field "A1" to develop methods for reliability-based system assessment and their integration into PROBILAS. With the help of PROBILAS, the weak points of the modelled structures can be identified and the further developments of the probability of failure of the structure can be predicted.

2 METHODOLOGY

2.1 *Reliability-based system assessment*

The idea of reliability-based system assessment is the combination of methods of system and reliability theory. Before these methods can be used to create a describing probabilistic system model of a structure, all necessary information about the structure has to be acquired. This includes material models and properties of the structure, loads imposed on the structure and resulting failure mechanisms. With the help of event tree analyses, the behaviour of the structure is studied when all the important parts of the structure are subjected to failure one after the other. With the results from these analyses, the most important elements for system reliability are known and a fault tree can be constructed. The fault tree describes how dependencies and relations of subsystems and components can lead to an overall system failure. The interaction between components in a fault tree is described via logical knots known from the system theory. Components can interact in serial



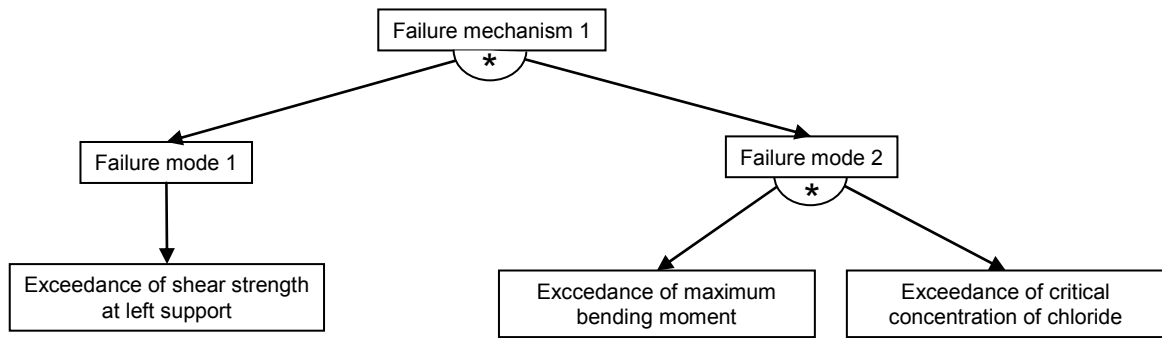


Figure 1. Example for failure mechanism and failure modes for a simple beam on two supports

systems (disjunction), where the failure of one component leads directly to the failure of the system or in a parallel system (conjunction) where the failure of the system occurs only after the collapse of all components. In reality structures normally consist of a combination of both types. The computation of the probability of failure of a structure represented by a fault tree is enabled by the use of limit-state equations. A limit-state equation compares the actions imposed on a structure (e.g. live load) and the resistance of the structure (e.g. material strength). Formula 1 shows its general form.

$$G = R - S \quad (1)$$

The component fails, when the resistance quantity (R) is smaller than the action quantity (S). Both quantities are functions of parameters, which are stochastic and/or uncertain and are generally described with statistical distributions. These equations are often formulated analytically by adapting classic dimensioning equations. The probability of failure of the fault tree is carried out using the first and second order reliability method (FORM/SORM), a method of approximation which has been described by Ditlevsen & Madsen (2003), amongst others. This method has the advantage that apart from the probability of failure p_f and the safety index β respectively, a sensitivity factor α_i is computed for each parameter in the limit state equation. This sensitivity factor indicates the influence of the parameter on the probability of failure. One of the main ideas of reliability-based system assessment is to monitor only the most significant parameters of the structure indicated by the sensitivity factors in order to optimize the whole monitoring process.

2.2 Probabilistic system model

The creation of the probabilistic system model with the fault tree and the limit state equations is the most sensitive part in reliability analysis. Especially the complexity of the fault tree increases severely when structures with numerous components and subsystems are analysed. In this paper an approach for schematising the construction of a fault tree is proposed, which enables the computer able to help users with this difficult task.

2.3 Failure mode

Normally structures do not fail completely, when one of their components fails. Most systems are redundant and therefore have the ability to transfer loads to other parts of the structure in case of a local damage. In the schematised fault tree a local damage is called failure mode. A failure mode can be described by rather simple mechanical models (e.g. shear failure) or have to be modelled considering quite complex relations (e.g. bending failure due to chloride intrusion). Examples can be seen in Figure 1. When modelling failure modes serial and parallel systems can be used.

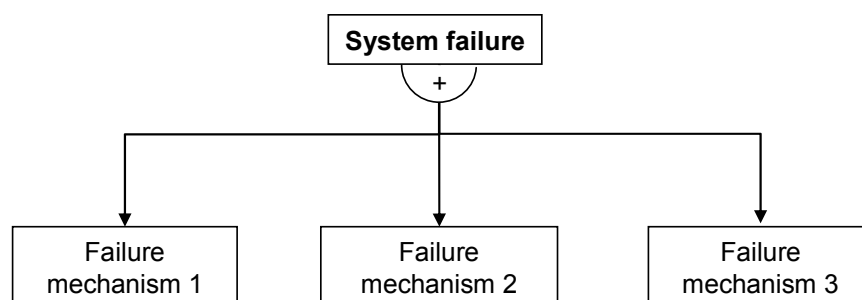


Figure 2. Serial system of failure mechanisms



2.4 Failure mechanisms

A combination of failure modes which leads to an overall system failure can be called failure mechanism. In most cases a structure has several possibilities how local damages together lead to system failure. If all combinations are identified by an event tree analysis, the global system failure can be represented by a serial system of failure mechanisms (Figure 2).

3 THE PROGRAM SYSTEM PROBILAS

The main focus of the computer code PROBILAS is to optimize structural health monitoring measures by identifying the weak points of probabilistic modelled structures and to make lifespan predictions using reliability analysis. The computer code is designed as object-orientated Client/Server application and is written in Borland C++. The application flow of PROBILAS is illustrated in Figure 3.

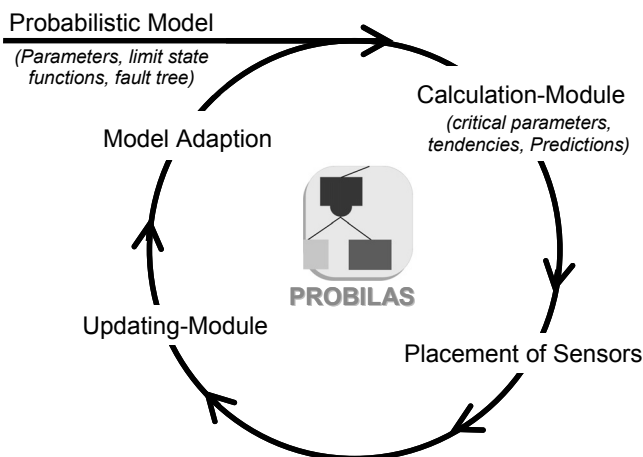


Figure 3. Structural evaluation process of PROBILAS

The primary input data in the program system is the probabilistic model already discussed. The construction of this model is simplified by an intelligent assistant provided by PROBILAS. The architecture of the assistant is one subject of this paper. When the probabilistic system model with fault tree, limit state equations and stochastic model is completed, the calculation module carries out the reliability analysis. In PROBILAS two analysis modes are implemented.

3.1 Mode for life cycle monitoring

PROBILAS has the ability to assist the user when life cycle monitoring measures have to be performed. Based on the results of the reliability analysis, PROBILAS makes suggestions and these parameters have to be included in the future monitoring process. After the sensors have been placed, the monitoring process can be started. The

data obtained in the monitoring process is afterwards analysed by the updating-module of PROBILAS. The module compares the initial stochastic model of a certain parameter with the measured values and performs likelihood tests. If necessary, the stochastic model is updated using methods of Bayesian statistics. With this procedure, one pass of the structural evaluation procedure is finished. If a model update has been performed, a re-evaluation of the system becomes necessary. Especially changes of the standard deviation of parameters with high sensitivity values have a large impact on the probability of failure. In cases where the sensitivity value decreases significantly after a model update, the parameter may be excluded from the monitoring process. On the other hand it is also possible, that parameters which have not been monitored before become more important after the update. In this case PROBILAS indicates that the parameter should be included in the monitoring measures. Additionally the performance of the structure is assessed by evaluating the development of the probability of failure over the time. When the probability of failure descends below a predefined threshold, the user is informed.

3.2 Mode for service life prediction

Every structure is subjected to deterioration in the course of time. The simulation and the assessment of this fact are difficult and they are the objective of many publications (e.g. Gehlen 2000). For practical purposes the time variant problem can only be solved by simplification and approximation (Faber 2003). Examples are the use of Monte Carlo Simulation or of reliability index profiles formulated by Frangopol & Kong (2003). In this paper, a different approach is discussed which uses a time-step approximation procedure. This procedure is currently integrated into PROBILAS.

The purpose of this procedure is to estimate the development of the probability of failure and predict the lifespan of service of structures when they are subjected to deterioration. The process of deterioration has a direct influence on the probability of failure of a structure. Therefore deterioration functions are formulated for selected parameters of the probabilistic model. Assuming that the fault tree of the structure does not change significantly over time, a reliability analysis using the first and second order reliability method (FORM/SORM) at discrete time steps can be carried out. The result of these computations are time-dependent curves of the safety index β or the probability of failure p_f . Figure 4 shows exemplarily a time-dependent reliability curve for the collapse of the support of a clamped steel beam subjected to a bilinear corrosion function. Further examples can be found in Schnetgöke & Hosser (2005).

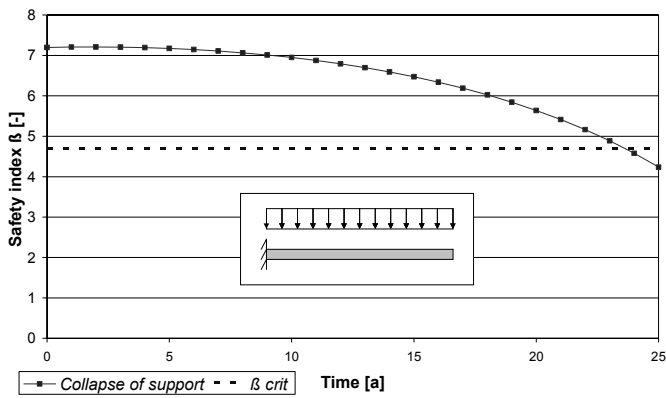


Figure 4. Example of a time-dependent reliability curve

It must be kept in mind that this procedure only leads to a rough estimation of the time-variant development of the safety of a structure. Additionally it must be stated that the model is highly dependent on the accuracy of the deterioration functions. With ongoing research in this area, the accuracy of the predictions can be improved. But even the information provided by the actual model can be helpful in the process of planning a structure or to estimate the ideal time for rehabilitation or maintenance.

In PROBILAS the time-variant deterioration functions are formulated depending on a reserved variable t_{pre} which is varied by the program between two calculation steps. Prior to every calculation, the amount of deterioration is evaluated for each parameter in the limit-state equation. As long as the deterioration function is of deterministic nature, the parameter is modified before the calculation for the next time step is carried out. Probabilistic deterioration functions will automatically be integrated into the probabilistic model of the structure.

3.3 Database structure

PROBILAS is designed as knowledge based system, which means that the user is not only able to carry out the reliability calculations but he has access to a database structure which provides useful help when designing the probabilistic system model of his structure. Apart from simple material properties the database will also contain information about typical limit states and failure mechanisms for certain types of structures. Additionally, after completion of the calculation the user is able to include his failure modes and mechanisms in the example database for further use. The database consists of several parts, which are described in the following. The relations between the components are illustrated in Figure 5. Every probabilistic model is highly dependent of the type of structure and of the used building materials. Therefore all data in the databases is stored in relation to these two restrictions.

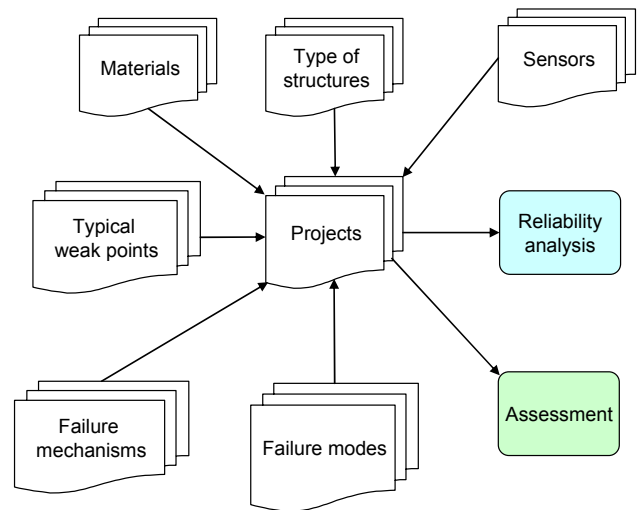


Figure 5. Relation of components of the database

3.3.1 Database with typical weak points and deterioration functions

Structures constructed out of different materials show different types of damage. Therefore PROBILAS will contain a database with typical weak points sorted by material and type of structure. The necessary data is entered into the database on the base of literature (e.g. Scheer 2000) or by importing already modelled structures. Additionally this database will contain some deterioration functions. This information can be improved based on ongoing research to ensure the maximum accuracy of the predictions and other calculation results.

The main intent for this database is to show the user which parts of his structure require a closer look when creating a probabilistic system model.

3.3.2 Database with failure modes

The smallest unit of a fault tree is the failure mode. The database stores samples of failure modes which can be reused when new models have to be created. These samples are called templates.

A template of a failure mode which is stored in the database can consist of a description, the corresponding fragment of a fault tree, the parameters for the components and a limit-state equation. The fault tree and the description are a required input value. Limit-state equations are normally closely linked to the specific mechanic model of the structure and therefore it is not necessary to include them in the template. In these cases, the description should provide the necessary information which is needed for the formulation of limit-state equations. Alternatively probabilities of occurrences can be entered as a component of the fault tree instead of a limit-state equation. Failure modes can be imported from existing projects.



3.3.3 Database with failure mechanisms

In this database templates for failure mechanisms are stored. Example datasets for failure mechanisms may also be quantitative if they describe only textually which failure modes result in a system collapse. In this case the user has to define the corresponding failure modes by himself. A failure mechanism can also be created from existing objects in the project database.

3.3.4 Project database

After the probabilistic system model of the structure is created via the assistant, all data is saved in the project database. If templates from the example databases are used, only copies are created in this database. In addition to this data, the project database contains all data related to former projects. This includes all calculation results and measured data from the structural monitoring process.

The calculation module only accesses the project database, which assures a great data security and flexibility in case of an extension of the template database.

3.3.5 Material database

In the material database typical values for different materials are provided. These values and the related distributions are derived from literature (e.g. JCSS 2002) and serve as knowledge base when formulating the limit-state equations. During the monitoring process the values of parameters are updated using the data from the measurements. To prevent the original material values in the database from being modified, a copy of the original material is created in the project database. After an analysis the updated material values can be imported into the material database to provide new material values for future projects.

3.3.6 Database with parameter categories / sensor database

One main aim of PROBILAS is to assist engineers to plan monitoring and rehabilitation measures. This includes the choice of sensors and their placement on the structure basing on the calculation results. Therefore a sensor database is needed which will be built in cooperation with the other subprojects of the collaborative research centre 477. In the sensor database, different properties of sensors for building monitoring are stored. This includes the selection of measurands which can be monitored by a sensor and the general requirements for the related measurements. Additionally the sensor database assigns parameter categories to sensors. When each parameter of the limit-state equations of the project are equally linked to these categories, the calculation module can recommend the appropriate sensor for every important parameter of the probabilistic model.

In case the sensor database cannot be filled with enough data, every parameter is allocated to the information whether it is measurable or not.

3.4 Constructing the probabilistic system model

Probabilistic modelling of structures is not a common task for civil engineers. Helpful support for the construction of the probabilistic system model is provided by an assistant for the users of PROBILAS. The application flow of the assistant is shown in

Figure 6. The assistant uses the template data provided by the databases described above.

The first step when building a model is a thorough

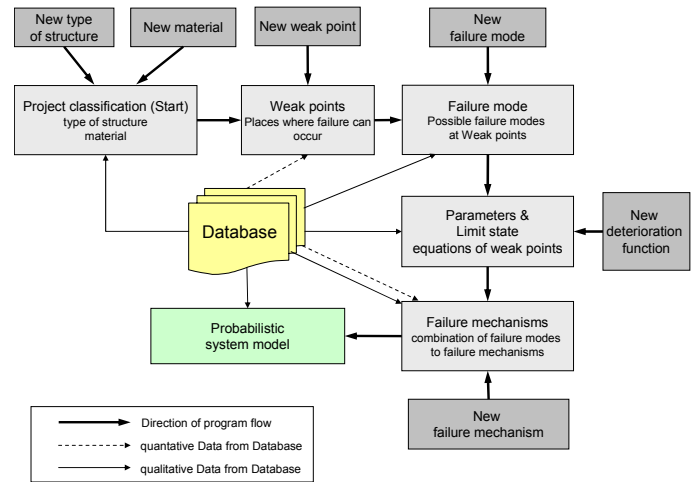


Figure 6. Program and data flow in the assistant

analysis of the static system. After the classification of the structure, PROBILAS can provide information on typical weak points depending on the specific material and the type of structure. After having selected or entered the weak points of the structure, the appropriate failure modes have to be defined. The assistant shows all templates of failure modes which are appropriate for the current structure. If required, the user can define new failure modes with a partial fault tree and description. Afterwards, he has to assign failure modes to the weak points. The example in Figure 6 shows the weak points and failure modes of a beam on two supports.

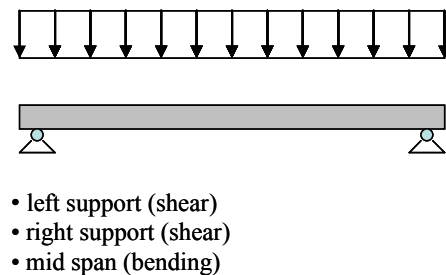


Figure 7. Weak points for a simple example

The simple illustration shows the necessity of a separation between weak point and failure mode. It



can be seen, that it in this case failure mode “shear” has to be used on two weak points, the supports on the left and right side of the beam. On the other hand it would be possible, that more than one failure mode has to be assigned to a weak point (e.g. shear and bending failure at the support of the beam in Figure 4).

After having selected or designed all failure modes, the limit-state equations and additional parameters of all components are defined. When the calculation mode for lifespan prediction will be used, a deterioration function has to be defined for the accordant parameter. After all input data has been entered, the user can combine the failure modes to failure mechanisms. With the help of event tree analysis he can decide, whether one failure mode alone or the combination of multiple failure modes would lead to the collapse of the whole system.

This knowledge is necessary for the automatic generation of the system fault tree, which is the last step of the assistant. With this step the probabilistic model of the structure is saved into the project database. Following this procedure the creation of complex system fault trees is schematized and simplified. In the calculation module a hierarchical view of the fault tree allows final checks of the probabilistic model.

3.5 *Future developments*

The main focus of future work lies in the development of decision guidance for the users of PROBILAS. This includes further help during the creation of the model and in the evaluation and assessment of the results of the reliability calculations. Further help will be provided in selection and placement of the sensors.

Another important field of work is the implementation of typical weak points, templates for failure modes and failure mechanisms of complex structures in the database of PROBILAS.

4 CONCLUSION

In this paper the methodology behind the modular computer code PROBILAS and its approach to the optimization of structural health monitoring is presented. This includes the concept for the schematisation of the fault tree, the database structure for the knowledge-based part of PROBILAS and the explanation of two possible calculation procedures. The application of the described methods is shown by Schnetgöke & Hosser (2005) in another article in this proceedings.

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