A system model for lifecycle monitoring of bridges

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ABSTRACT: In current bridge maintenance practice, condition grades are assigned to individual bridges, based on regularly performed inspections. The main limitations to this approach are the time-discrete and also subjective nature of grade assignment. To overcome this issue, major bridge authorities are developing new methods for condition assessment, based on collecting and evaluating sensor data in real time. In this research, a system model-based approach has been developed to accurately model the correlations between the deterioration mechanisms and the measurement values indicating the progress of the deterioration. A major challenge in this context is to correctly model the impact of local deterioration on the condition of the bridge as a whole. The actual state propagation mechanism is achieved by means of logical connection elements. The resulting impact tree can be used for propagating the condition assignments from the leaf nodes (the sensors) to the top (the entire bridge).

1 INTRODUCTION

In most industrialized countries, large parts of the infrastructure were erected during the 1960’s and 1970’s. As a result they are now facing an increasing aging stock of infrastructure buildings. To maintain the infrastructure safe and at the same time to keep the impact on public budget at a tolerable level, an elaborate management scheme for these buildings, including inspections, maintenance and repairs is necessary.

In current bridge maintenance practice, condition grades are assigned to individual bridges, based on regularly performed inspections. Some of the main limitations of this approach are the time-discrete and also subjective nature of grade assignment, resulting in significantly diverging grades for bridges in the same condition. To address this issue, major bridge authorities are developing new methods for condition assessment, based on collecting and evaluating sensor data in real time. In this context it is essential to correctly model the impact of local deterioration on the state of the entire bridge.

In this paper we introduce a system-model based approach which is used to precisely model (1) the correlations between the deterioration mechanisms and the measurement values indicating the progress of the deterioration and (2) the impact of the condition of individual bridge components on the condition of the overall bridge system. The resulting impact tree can be used for simulating deterioration mechanisms as well as for determining the actual condition of bridge, based on sensor measurements. To this end, condition assignments are propagated from the leaf nodes (the sensor measurements) to the top node (the entire bridge). A major function of this propagation mechanism is provided by the logical connection elements which are located between the different layers of the impact tree and model rules for state propagation. These rules can either be based on empirical models or probabilistic or deterministic approaches.

2 COMMON MODELING APPROACHES

Some system modeling methods are already used to describe real bridge structures (Sianipar & Adams 1997, LeBeau & Wadia-Fascetti 2000). These approaches have in common that the investigated bridge is subdivided into single structural components, which are linked by logical conjunctions to obtain the entire bridge system model. The level of detail for a structural component depends on the relevance of the element for the structure. Commonly used modeling approaches in the context of reliability analyses are reliability block diagrams, fault tree analysis and event tree analysis (Klinzmann 2008).

In the abovementioned modeling approaches, structural elements can be set to the states “in service” or “default”. This binary description is based on Boolean operators. The relevance of each element depends on the particular problem (stability, durability etc.) and the system structure. The individual elements have to be placed in their position in the system model and linked to each other, according to their task in the real bridge system. Complex systems can be modeled in this way as serial or parallel system or as combination of the two. The systems structure function can be set up using state variables of individual elements and, based on this function, the failure probability of the system can be evaluated.

The reduction of complex interrelationships to a binary notation leads to a significant limitation in system modeling of bridge structures. It is not possible to capture partially deteriorated or damaged structural elements in this model. In addition, time dependent modeling of damage processes (e.g. corrosion of reinforcement) are not taken into consideration by the abovementioned approaches.

3 IMPACT TREE

3.1 *The system model approach*

The key idea of the new approach is to generate a system model which takes into account dependencies of structural components as well as interactions between damage mechanisms. It is important to avoid “black-box” systems in order to obtain a better understanding of deterioration processes and their interactions (Neumann & Haardt 2012). The developed system model is able to identify causes of damage and to determine the criticality of damage as well as their impact on individual bridge components and on the bridge itself.

The newly introduced impact tree model enables the analysis of condition and damage potential for both single structural components and complete systems. Implemented in software the impact tree can be used for condition assessment of structures in real time. Also it is possible to simulate certain deterioration processes by variation of input parameters to identify critical damage hot-spots at the planning stage of a bridge.

The impact tree is an improvement of the above mentioned fault tree. It uses a new rating system and more flexible connection elements than those used in the binary description of the fault tree (Reay & Andrews 2002).

The impact tree is composed of three hierarchical ordered levels: (1) the structure level, (2) the damage level and (3) the parameter level (Fig. 1). The elements can be grouped to modules to simplify the process of modeling an impact tree. All elements of each level can show their actual condition as output value. So the cause of a condition change of the whole bridge can be determined exactly.

3.2 *Structure level*

The structure level of the new modeling approach comprises all aspects of the bridge regarding the static system, relevant structural components and, at the lowest level, the building materials.

In the course of structure level preparation the bridge is fragmented into functionally smaller and smaller structural elements and ordered into a hierarchical way according to their role in the system of the bridge. These components are named structure elements of the system model. The bridge itself is represented by the top element of the impact tree.

As shown in the example below structure elements of particular interest, e.g. the bridge superstructure can be subdivided in several uniform elements. This will facilitate the allocation of condition changes in significant parts of the system model.

3.3 *Damage level*

The next level, which extends the structure level, is the damage level. Here, possible damage mechanisms which could occur on a structural component are allocated as damage elements to the corresponding (lowest) elements of the structure level. A damage element could be e.g. failure of reinforcement. The connection of a damage element to a structural element defines the exact allocation of the specific damage. This enables a functional system analysis. Using sophisticated building information modeling approaches the connection of damage elements to structure elements could be done by using a 3D model of the structure (Borrmann et al. 2012 & Lukas et al. 2012).

Damage elements which may have more than one cause will be hierarchically divided into sub-elements. As an example corrosion of reinforcement can be subdivided into elements regarding to the cause of corrosion: chloride respectively carbonation inducement. Damage elements are visualized by dash-dotted boxes within the impact tree model.

3.4 *Paramter level*

A further subdivision of the damage elements leads to the finest level of the impact tree: the parameter level. Parameters, which constitute an indication of beginning or further propagation of damage, will be allocated to the corresponding lowest element of the damage level. They can be a precondition or a cause of damage. Also parameters which indicate the propagation of damage are located in the parameter level. For reinforcement corrosion one precondition parameter is humidity. In contrast, the spalling of the concrete surface can already indicate onset or progression of reinforcement corrosion. All these parameters provide input values for the system analysis.

Wherever possible, all necessary parameters should be a part of a suitable monitoring concept that can feed the system model real time data to determine the condition of the bridge. Another approach to fill the system model with input data is to manually define the necessary or missing parameters. Although the parameters within the system model are linked to a damage element and thus bounded to a structure element, there is no need to locate them on the corresponding component of the bridge. For example the settlement of a pier can provide information about the condition of superstructure elements. Therefore, the measuring process actually takes place on the pier, but the impact is considered at the superstructure element. Parameter elements are depicted as dotted boxes within the impact tree model.

3.5 *Connection elements*

A difficulty in creating an impact tree is the limited number of reliable described damage mechanisms. There are some damage mechanisms and correlations which have been investigated in detail (e.g. Sudret 2008), but the broad scope cannot be described by available realistic models.

For the newly introduced system model, interconnections between elements can be described by freely definable calculation rules. The main difference between the impact tree and the fault tree are these interconnections called logical connection elements (logic). In contrast to connections by Boolean operators of a fault tree, the logic element of the impact tree can describe different relationships between elements in a very flexible manner. These relationships are defined as a combination of equations and rules that describe the propagation of damage from one element to another.

There is the possibility to apply the following models and approaches:

- physical models with deterministic approaches
- chemical models with deterministic approaches
- probabilistic approaches
- empirical approaches
- etc.

As an example for a physical model, the description of fatigue behavior of reinforcing steel by a Wöhler curve can be mentioned. In this case parameter elements contain stress range and number of load cycles. This input values enable us to draw conclusions on the condition of the structure element (reinforcing steel) by the use of the hypothesis of damage accumulation according to (Palmgren 1924 & Miner 1945). The calculation rule is implemented in the connection element.

A probabilistic deterioration model for the description of reinforcement corrosion applied for life cycle management can be seen in (Gehlen 2000).

On basis of empirical values or statistical analysis decision-matrices can be set up without any detailed background knowledge about the damage process itself. In this type of matrix input parameters were correlated to each other in consideration of their consequences on the condition of the connected structure element. The defined relationships determine the output values of the logic elements - the grade of damage of a structure element.

When no calculation models or applicable descriptions of damage propagation are available, logic elements can be defined according to the currently used - inspection based - grade assignment methodology. Thus, a stepwise transition from the current approach to a full reliability based procedure can be realized in practice.

4 CONDITION EVALUATION BY THE IMPACT TREE

4.1 *Evaluation process*

The condition of individual elements can be represented on a rating scale. For example a ten-stage scale or a scale of warning colors similar to traffic lights (green: insignificant, yellow: warning, red: critical) can be implemented to elements of an impact tree. The condition, indicated by the scale, depends on stepwise predefined lower or upper limit values, e.g. maximum chloride content. The classification of the condition on a scale is independent of the calculation rule implemented in the logic element. Thus a consistent format can be used to show the condition of all elements.

The process using an impact tree for condition evaluation goes from bottom to top. The input values of parameter elements are checked and updated constantly during the evaluation. In the connected superordinate logic operation, these values are evaluated by predefined calculation rules. The easiest calculation rule is a comparison to limit values. If the values are below the limit, the rating scale shows an insignificant state (green light). Exceeding predetermined limit values leads to a warning or critical state based on the exaggeration of the limit by measuring values. The damage element will be activated if a signal of the subordinate parametric element shows a warning or critical value. The rating scale of the structure element gives notice of its condition which is calculated by the connected logical element. The condition evaluation process continues in loops until the parameter values change and an uncritical state is reached or until the top element in the structure level (which symbolizes the bridge itself) is reached.

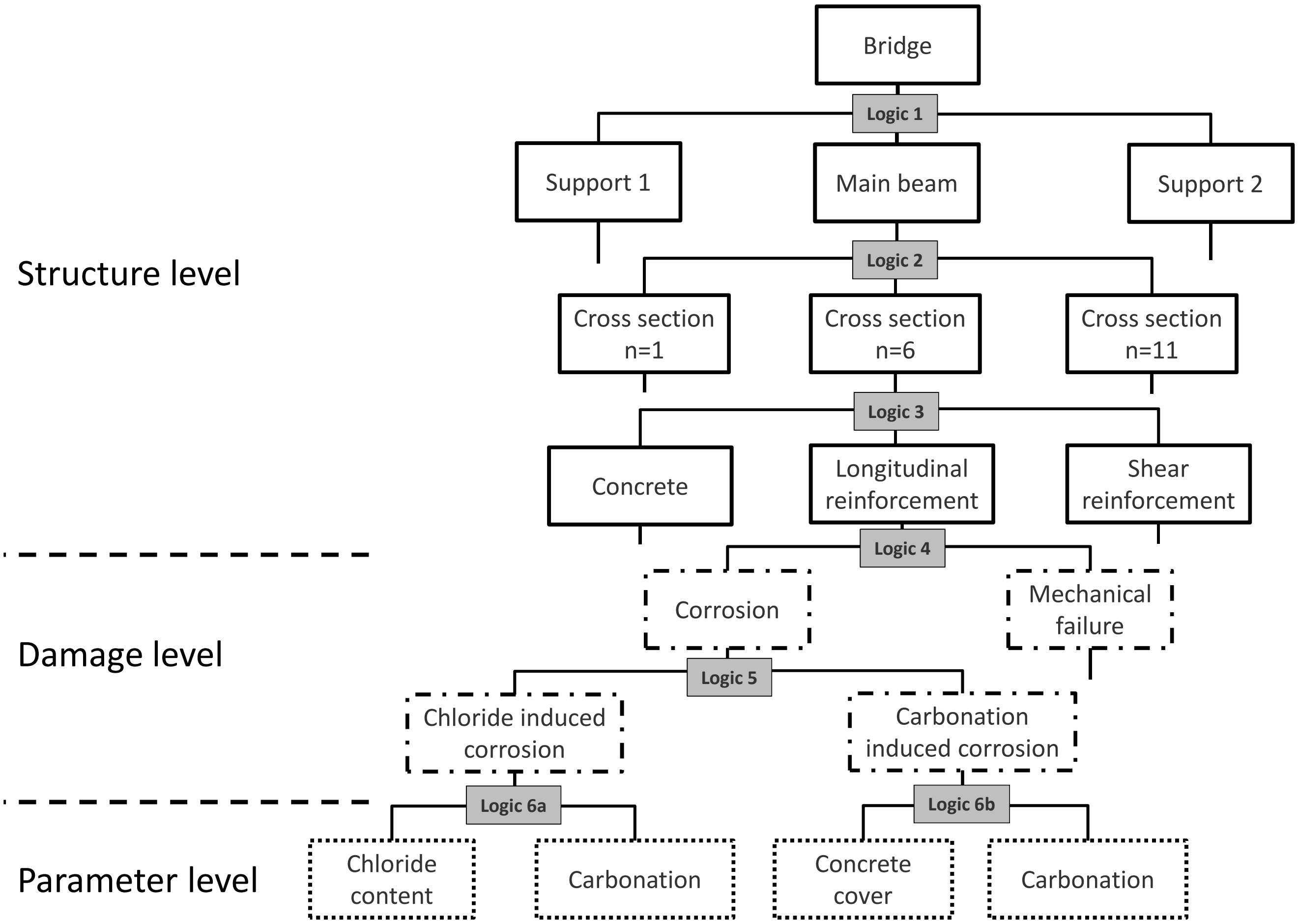

Figure 1. Example: condition evaluation by the impact tree

4.2 *Sample application of the impact tree*

Using the example of a single span reinforced concrete bridge the application of the impact tree approach is explained in the following.

4.2.1 *Deterioration mechanisms*

As a representative deterioration mechanism corrosion of longitudinal reinforcement is chosen in this example. In the damage level of the impact tree (Fig. 1) are shown the subelements “chloride induced corrosion” and “carbonation induced corrosion” according to the cause of damage.

In this example an approach by (Novak et al. 2002) was selected to model the deterioration mechanisms. This approach is implemented in the connection elements “logic 6a” and “logic 6b” of the impact tree in form of a decision matrix. The incorporated input values are carbonation, concrete cover and chloride content (Tab. 1 & 2).

Table 1. Corrosion rate due chloride induced corrosion (Novak et al. 2002)

Carbonation	Chloride content M%	Corrosion rate µm/a
yes	0,5	100
	2,0	150
no	0,5	10
	2,0	50

Table 2. Corrosion rate due carbonation induced corrosion (Novak et al. 2002)

Carbonation	Concrete cover d cm	Corrosion rate µm/a
yes	d ≤ 2	60
	2 < d ≤ 4	20
	d > 4	30
no	-	0

4.2.2 *Structure of the impact tree*

The top element of an impact tree is always the structure as a whole – in our example the bridge. In the next division the bridge is subdivided according to its static system in the supports and the main beam. In this example the focus is on the main beam. Hence the beam is modeled as combination of several cross sections. At each of them the lowest partition of structure level is built of the used materials.

By the element “logic 4” structure and damage level are connected. In this case study corrosion processes of longitudinal reinforcement are discussed. The remaining branches of the impact tree are neglected. According to the used approach of the corrosion process, subordinated damage elements with their appropriate parameter elements are modeled.

The elements of the impact tree are linked by connection elements (logic 1-6) as shown in Figure 1. The resulting impact tree can be used for propagating the condition from the parameter level to the top element. In the following the main logical connection elements are specified. The logic elements 6a and 6b have two input parameters each. Based on the decision matrices of Table 1 & 2 the appropriate corrosion rate is defined as output value for further considerations. Also the logic calculates the criticality of the damage element. In the next step, in "logic 5", the interaction of both damage mechanisms is determined. In the current example the processes are assumed as accumulative. The remaining cross section of reinforcement is calculated in "logic 4" in consideration of the determined corrosion rate and a certain time period. In "logic 3" the statically required reinforcement is calculated and compared to the remaining cross section of reinforcement. Depending on this comparison the condition of the structure element (cross section *n*) is shown on the connected rating scale. Due to the fact that the system is statically determined, the condition of the cross section is identical to the condition of the main beam and the entire structure.

4.2.3 *Analysis by the impact tree*

The impact tree system model facilitates the analysis of deterioration processes and causes in the examined structure. There are different aspects on which we will focus further on. The first step of an impact tree analysis in the given example is to determine structural hot-spots. For this parameter elements are kept constant at a certain default value, while the structural element under investigation (main beam) is subdivided in a certain number of cross sections. To get a continuous significant curve in the result diagram, we introduce a variable longitudinal coordinate *x*. The corrosion rate is independent of the longitudinal coordinate *x*, because the input values of all connection elements of parameter and damage level are equal. So the critical cross section depends only on the load applied on the main beam. Assuming a uniformly distributed load, the bending moment in the middle is at its maximum. A comparison of the required to the remaining reinforcement by the implemented calculation rule leads to the result that the middle part of the beam is identified as most critical. This method easily can be transferred to more complex structures.

The prediction of future condition states is another possible application of an impact tree. A precondition is here a time dependent definition of deterioration processes. In the example the corrosion process is time dependent due to the corrosion rate in micrometer per year. The variation of the input parameter time leads as a result to time-condition diagrams of all elements. By means of this result the critical moment of structure elements or the bridge as a whole can be determined.

The influence of different damage mechanisms or some measuring values can also be investigated by the impact tree. For this application parameter elements of interest can be varied. The consequences of parameter variation can be seen on the rating scale of the appropriate element. In the given example variation of chloride content with or without present carbonation is a suitable parameter to determine the influence of measuring values (parameter level) on the deterioration process.

The determination of the actual condition of the structure is one of the most important applications of the impact tree. In combination with an appropriate monitoring system condition assessment can be executed in real time. Measuring devices applied at identified hot-spot areas deliver the input values for the system analysis by the impact tree. But also further locations have to be taken into account by planning a monitoring concept. Due to the fact that each element of the impact tree, whether structure element, damage element or parameter element, is connected to a rating scale which is representing its condition, it is not only possible to determine the condition of the bridge itself; moreover causes of damage (parameter level) and the propagation of damage can be recognized.

5 CONCLUSION

In this paper is introduced a system model based approach for determining the condition of bridges, based on sensor measurements. The impact tree model consists of three different levels (structure level, damage level and parameter level). The modeling approach considers correlations between the deterioration mechanisms and the measurement values indicating the progress of the deterioration and also the impact of the condition of individual bridge components on the condition of the overall bridge system.

There are different possible applications of the impact tree. It can be used to simulate deterioration mechanisms by variation of parameter elements as input values during the planning phase of a bridge to detect critical damage mechanisms or structural components – so called hot-spots. Also it is possible to determine the actual condition of a bridge, based on sensor measurements in real time. On the basis of this information the impact tree model can be used as well to propagate future condition states by varying significant input values. For all applications, condition assignments are propagated from the leaf nodes (the sensor measurements) to the top node (the entire bridge). The most important function in this propagation mechanism is provided by the logical connection elements which are introduced between the different layers of the impact tree and model rules for state propagation. These logic elements are able, in contrast to Boolean interconnections of the fault tree, to describe different and flexible relationships between elements using a combination of equations and rules that describe the propagation of damage from one element to another. Thus, the impact tree can represent the next generation of modeling approaches for bridge maintenance problems.

New investigations of damage mechanisms can be implemented easily in the logic connection elements of an impact tree. Future work will concentrate on developing logical connection elements for a broad range of deterioration mechanisms and different approaches to condition assessment (deterministic / probabilistic).

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