THE OWNER’S PERSPECTIVE IN PROBABILITY-BASED BRIDGE MANAGEMENT

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Abstract. This paper describes how the Danish Road Directorate is applying probability-based bridge management as a part of the maintenance management of older or deteriorated bridges. The core idea is to maintain the safety of the bridges and the motivation is cost savings. The approach is briefly described. It is shown that there is a legal justification for applying probabilistic techniques in the safety evaluation. Practical experience from the two bridges in Figure 1 is presented. Finally, the future perspectives and policy of the Danish Road Directorate are presented with a clear recommendation for other bridge owners and some indications of the expected level of cost savings.

Figure 1 Skovdigt West Bridge from 1966 (left) and the Storstroem Bridge from 1937 (right)
1 INTRODUCTION

The Danish Road Directorate (DRD), Ministry of Transport is responsible for the 1600 km national road network and the approximately 1350 smaller bridges and 35 special bridges and tunnels on this road network. The special bridges are larger bridges either on land or over water.

The majority of the bridges were built more than 30 years ago – and the DRD today faces the combination of an old deteriorating bridge stock and limited budgets. Additionally, many of these ageing bridges are vital for the infrastructure system and consequently rehabilitation projects are associated with large road-user inconvenience costs. In addition there is a rising demand for increased load carrying capacity combined with low budgets for rehabilitation and strengthening of older bridges. Finding the optimum balance between cost and bridge safety is becoming an important issue for the DRD – and a common problem throughout the world for all bridge managers.

The paper will describe how the Danish Road Directorate has taken up a safety-based approach for some critical bridges. The conceptual approaches will be described from an administrative perspective. It will further be described how the Danish Road Directorate plans to apply the approaches in the future as part of daily bridge management.

2 CHALLENGES IN MANAGEMENT OF EXISTING BRIDGES

The national road network in Denmark carries almost 25% of the total road transport volume, i.e. general traffic between regions, major ports and border crossings.

The DRD core values are: New thinking, Responsibility, Cooperation across the organisation, Result orientation and Professionalism. The DRD is a modern enterprise using modern technology to construct roads and bridges that meet Denmark’s transportation needs and provide a well-functioning infrastructure, adapted to citizens’ and road-users’ requirements for reliability, safety, service, the environment, aesthetics and cost.

The future challenges for the DRD in order to live up to our own values and the users’ requirements are numerous. An ageing bridge stock, steady increase in traffic, increased focus on road-user inconveniences and costs, demands for increasing load-bearing capacity are just some of the challenges the DRD faces now – and even more in the future. As a consequence the DRD is always interested in new approaches, which can give cost savings or give a better basis for decision or postponement of costly rehabilitation and strengthening projects.

In order to deal with this situation, a new paradigm has been introduced in Denmark, which includes safety-based bridge maintenance management. The basic idea is that when it becomes impossible (for technical or political reasons) or too costly to maintain bridges to as-built standard, the DRD must at least ensure that the structural safety of the bridges is adequate. In addition, safety-based bridge management may be used to increase the load carrying capacity of existing older bridges without costly rehabilitation and strengthening projects.
3 PROBABILITY-BASED BRIDGE MANAGEMENT

3.1 Idea and motivation

Basically the core idea in probability-based bridge management is to maintain the structural safety of the bridge, i.e. all actions must be evaluated in relation to safety with the corresponding value and cost. This is a new trend for the DRD and considered as a step forward compared to the general condition-based approach in which the maintenance management is only based on inspections on the bridge, assuming that if the condition is satisfactory then the requirement for the safety level is also satisfied. This condition-based approach can be impossible for highly deteriorated bridges. One could say that when it becomes too costly to maintain the condition or the appearance of the bridge the safety should at least be maintained.

The use of safety-based bridge management gives the DRD more degrees of freedom when managing the entire bridge stock. In many cases for critical bridges a general deterministic approach may yield “repair and rehabilitation now” as the only possible option if the (deterministic) safety of the bridge is not to be jeopardized.

Problems in safety administration often require a high degree of engineering expertise, which is needed when a bridge has to be rehabilitated due to deterioration and/or has to be strengthened to increase its load-carrying capacity. In many cases the DRD would like the bridge to be able to carry the desired load with sufficient safety at the lowest rehabilitation or strengthening cost. In all cases this requires an evaluation of the bridge load-carrying capacity.

The procedure for the safety assessment of an existing bridge is first to identify specific problems using the general approach, i.e. the traditional deterministic code. This is cost-efficient because the subsequent probabilistic problems with related limit states requiring more careful consideration are narrowed down to a minimum. The condition of bridges in Denmark is in general very good – so the majority of bridges can still be assessed using a deterministic approach. However, in recent years a number of special bridges have shown that a continuation of deterministic management would either require expensive strengthening or replacement projects.

In these special cases, probability-based management should be considered before an expensive rehabilitation project is initiated. Probabilistic-based management will in many cases be fruitful, especially if the bridge has problems with limit states that are believed to be conservatively modelled according to the deterministic code. Further, it can be necessary to introduce probabilistic models in order to model the deterioration and the uncertainties related to the deterioration. A topic which is never a part of a traditional deterministic code.

Benefits are obtained from the difference between a general approach and a more thorough individual approach. The general approach for safety evaluation of an existing bridge is based on codes and regulations for evaluation of bridges. The codes are based on a partial safety factor format and often include a high degree of generalisation both in terms of safety and load specification. The fact that the codes generalise, and therefore can be used for the design of many types of new bridges, is efficient because the load and safety calculations become easy.
and because the extra cost due to the generalisation is marginal in the budget for a new bridge. But in the case of rehabilitation or strengthening of an existing bridge, the required safety or load-carrying capacity can often not be obtained from the general approach and the result may be an expensive strengthening or replacement project.

The individual approach is based on the concept that a bridge does not necessarily have to fulfil the specific requirements of a general code, as long as the overall level of safety defined by the code is satisfied. In other words, the purpose of the individual approach is to cut or reduce rehabilitation cost without compromising on the level of safety. In this method, safety evaluations are based on probabilistic methods. In a probabilistic-based safety evaluation, the uncertainties of the specific bridge condition including deterioration and the local traffic situation can be taken into account consistently. It could be said that this approach establishes a ‘code’ for the deteriorated individual bridge.

The probabilistic-based approach also provides an efficient tool for inclusion of information from bridge inspection and test results, for example inspection of the degree of deterioration. The main purpose of such inspections and tests is usually to obtain further knowledge of the structure in order to be able to model the uncertain variables better. These can then be taken directly into account in the probability-based safety evaluations. In comparison, it is often impossible in a rational way to combine better knowledge from the test results (e.g. stochastic modelling of deterioration) with a code based on a general partial safety factor format. Hence, probabilistic-based tools become a strong safety management tool.

This is precisely what is needed for the DRD – or any other safety administration – since it allows selection of the most economic (optimum) plan of action including for example inspection, test loading, repair, strengthening or simply no action in the future. These actions are typically amortised and compared with gained safety and development of safety in time. This also makes it easy to choose between different alternatives for various bridges and hence to perform an optimum economic safety administration of an entire bridge stock.

Even though the individual approach is more expensive than the general approach, the difference is marginal compared with the possible cost savings.

4 LEGAL JUSTIFICATION

It is obvious that it is a fundamental requirement for a bridge owner as DRD, in order to be able to use probability-based management, that the legal justification for the methods are present. Some codes simply state that it is legal to use alternative assessment methods if it can be shown that the safety level is maintained. However, this statement is not operative for the code users or for the DRD that are going to approve the assessment results.

Better and more operative methods can be found in the background documentation for the Nordic countries1, in which it is described in detail how a probabilistic-based assessment can be performed in accordance with the requirements for the safety level in the Nordic countries. It also specifies the principles of modelling of uncertainties including model uncertainties. The requirement in the ultimate limit state for the structural safety is specified with reference to failure types and failure consequences, i.e. safety class with requirements for the formal
yearly probability of failure $P_f$. The formal yearly probability of failure $P_f$ or the corresponding reliability index $\beta$ and using the “safety class” and “failure type” as input makes it possible to determine whether the requirements for the structural safety are fulfilled or not. It can therefore be concluded that the legal justification for application of probabilistic-based approaches in the Nordic countries is present. Similar principles can be found in Eurocode 1 and ISO\textsuperscript{1,2}.

<table>
<thead>
<tr>
<th>Failure consequence (Safety class)</th>
<th>Failure type I, Ductile failure with remaining capacity</th>
<th>Failure type II, Ductile failure without remaining capacity</th>
<th>Failure type III, Brittle failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less Serious (Low safety class)</td>
<td>$P_f \leq 10^{-3}$</td>
<td>$P_f \leq 10^{-4}$</td>
<td>$P_f \leq 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$\beta \geq 3.09$</td>
<td>$\beta \geq 3.71$</td>
<td>$\beta \geq 4.26$</td>
</tr>
<tr>
<td>Serious (Normal safety class)</td>
<td>$P_f \leq 10^{-4}$</td>
<td>$P_f \leq 10^{-5}$</td>
<td>$P_f \leq 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$\beta \geq 3.71$</td>
<td>$\beta \geq 4.26$</td>
<td>$\beta \geq 4.75$</td>
</tr>
<tr>
<td>Very Serious (High safety class)</td>
<td>$P_f \leq 10^{-5}$</td>
<td>$P_f \leq 10^{-6}$</td>
<td>$P_f \leq 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$\beta \geq 4.26$</td>
<td>$\beta \geq 4.75$</td>
<td>$\beta \geq 5.20$</td>
</tr>
</tbody>
</table>

Table 1 Safety requirements for the Ultimate Limit State specified as formal yearly probability of failure $P_f$ and the corresponding reliability index\textsuperscript{1}.

5 PRACTICAL EXPERIENCE

In the following the practical experience with using the new safety based management approach is presented using two examples from recent years. The DRD has also been using probability-based methods in a number of years for assessment of bridges for heavy special vehicles\textsuperscript{4}.

5.1 Skovdigt West Bridge (1998-1999)\textsuperscript{5}

The Skovdigt twin bridges are located NW of Copenhagen and were constructed in 1965-67, see Figure 1. Each carries a 3-lane motorway with average daily traffic of 55,000 vehicles. The bridges are concrete post-tensioned, combined box-girder and beam-slab bridges.

Due to poor workmanship and unfortunate design, both bridges started to deteriorate shortly after construction. In the late 70’ies substantial damage was registered on both bridges. Major repair was done on the East Bridge in 1978. The cost of rehabilitation of the East Bridge was EUR 3 million in 1978. Since the repair on the East Bridge proved so costly, it was decided to leave the West Bridge without repair and replace the bridge when required safety could no longer be documented. Instead it was decided to monitor the West Bridge closely. In addition to the frequent visual inspection, a test loading of the West Bridge was carried out in 1984, 1988 and 1993. A test loading for Skovdigt West was due in 1998. A test loading is costly and does not give sufficient information to be used for lifetime predictions, evaluation of the present and future load carrying capacity or information to decide between various rehabilitation options. Based on this fact combined with the results from the last special inspection in 1995, which locally showed severe deterioration, it was decided to implement a management plan based on probabilistic methods.
A 10-phase procedure for safety-based bridge management was applied in 1998. By use of deterministic load carrying calculations combined with traditional lifetime estimates, the bridge would either require major rehabilitation or replacement. A probabilistic-based assessment was made (see Figure 2, left) which showed a remaining lifetime of 5-8 years. In order to choose the correct rehabilitation plan for extending the lifetime, a number of possible options were analysed (see Figure 2, right). This meant a number of safety-updating inspections and a “survival” wearing course carried out in 1999. This resulted in an extended lifetime of 10-12 years. Thus, the application of a probabilistic-based management plan postponed major rehabilitation, repair and replacement, and gave a saving of more than EUR 10 million compared to use of a traditional deterministic analysis and lifetime estimation.

5.2 Storstroem Bridge, Cantilevered Sidewalk (2000-2001)

The cantilevered sidewalk on the 3.2 km long Storstroem Bridge from 1937, see Figure 1, has serious deterioration on both the concrete and the reinforcement. Any form of repair will be costly due to the length of the bridge.
bridge connecting Denmark and Germany. If the Femern Bridge is constructed, then the Storstroem Bridge may need to be extended from one to two train tracks. Therefore, the DRD would like to postpone major repairs of the Storstroem Bridge until a decision has been taken regarding the future of the bridge. However, at the same time the DRD must ensure that the bridge is safe for both cars and pedestrians at all times.

To ensure the safety of the sidewalk, test loadings had been made in 1987 and 1985, which showed that the sidewalk was capable of carrying the original design load of 500 kg/m². A cross-section of the bridge and sidewalk is shown in Figure 3. The DRD decided to implement a safety-based management plan in 2000 in order to assess the actual safety of the sidewalk and if possible postpone major rehabilitation projects.

A 10-phase procedure for safety-based bridge management was applied. Two load cases are relevant for the sidewalk: pedestrian loading and a forklift used for transport during repair and maintenance work on the bridge. The main difference in the probability-based assessment is that a stochastic modelling of the deterioration is introduced. Based on inspections models for the remaining efficient reinforcement areas and concrete strengths are introduced with distributions, expected values and standard deviations. This is very efficient because the uncertainties in the estimates directly influence the determined structural safety. (In a deterministic code this would correspond to partial safety factors at the efficient remaining reinforcement areas).

<table>
<thead>
<tr>
<th>Load combination</th>
<th>Pedestrian loading</th>
<th>Forklift loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic load carrying capacity</td>
<td>200%</td>
<td>84%</td>
</tr>
<tr>
<td>Original sidewalk (without taking deterioration into account)</td>
<td>( \beta = 8.2 ) ( p_f = 9.6 \cdot 10^{-17} )</td>
<td>( \beta = 5.2 ) ( p_f = 1.0 \cdot 10^{-7} )</td>
</tr>
<tr>
<td>2001 Using inspection results from 2001.</td>
<td>( \beta = 7.6 ) ( p_f = 1.1 \cdot 10^{-14} )</td>
<td>( \beta = 4.3 ) ( p_f = 7.1 \cdot 10^{-6} )</td>
</tr>
<tr>
<td>2010 Prediction based on 2001 results.</td>
<td>( \beta = 5.6 ) ( p_f = 1.3 \cdot 10^{-8} )</td>
<td>( \beta = 2.9 ) ( p_f = 1.8 \cdot 10^{-3} )</td>
</tr>
</tbody>
</table>

Table 2 Reliability index for pedestrian load case and forklift load case.

The safety-based management plans showed that the remaining lifetime is at least 10 years for pedestrian loading. The remaining lifetime is exhausted for forklift loading on the sidewalk. It was shown that local rehabilitation at the transverse expansion joints – either in the form of actual repairs or by bolting a continuous steel plate 1.5 m on each side of the expansion joint, would extent the lifetime of the sidewalk by 8-10 years allowing the forklift to drive on the sidewalk again. By using a safety-based management plan closure of the sidewalk was avoided and an expensive investment was postponed which saved large costs for the Danish Road Directorate.

6 FUTURE PERSPECTIVES FOR THE DANISH ROAD DIRECTORATE

The future challenges for the DRD – an ageing bridge stock, steady increase in traffic, increased focus on road-user inconveniences and costs, demands for increasing load-bearing
capacity – are many. In order to live up to the goals set by the DRD and live up the users’ requirements, it is essential to utilise new developments.

Sustainability and accessibility are major parts of the overall asset management principles of the DRD. However, the future challenges make it necessary to utilise all new developments to assist decisions on maintenance priorities. The DRD has as one of the first bridge management agencies utilised safety-based bridge management for increasing load capacity on bridges and for postponing costly repair and rehabilitation options. It can be given as a rule of thumb that the lifetime defined as the time until the structural safety can no longer be documented can be extended approximately 10 years compared to traditional deterministic techniques. This is, however, only a rule of thumb. Based on this the DRD expects that the continuing use of safety-based maintenance management will give substantial cost savings.

7 CONCLUSIONS

From the point-of-view of the DRD, applying safety-based bridge management is an important approach for extending the service lifetime, thereby giving the owner the possibility of reducing or postponing costly rehabilitation projects. The use of safety-based bridge management gives the DRD more degrees of freedom when managing the entire bridge stock.

In many cases for critical bridges a general deterministic approach may yield “repair and rehabilitation now” as the only possible option if the (deterministic) safety of the bridge is not to be jeopardized. Recently, for the 220 m long Skovdigt Bridge the application of a safety-based management plan postponed major rehabilitation, repair and replacement, and gave a saving of more than EUR 10 million compared to use of a traditional deterministic analysis and lifetime estimation. For the sidewalk on the 3.2 km Storstroem bridge using a safety-based management plan closure of the sidewalk was avoided and an expensive investment was postponed which resulted in large savings for the Danish Road Directorate.

REFERENCES