BRIDGE OWNER'S BENEFITS FROM PROBABILITY-BASED MANAGEMENT OF OLD BRIDGES

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ABSTRACT:

The growth of national economies in the later half of the 20th century has resulted in steadily increasing traffic volumes on trading routes and in an increase in the demands placed on an aging bridge stock. Ironically, economic growth has not resulted in an increase in the budgets available to bridge owners for maintenance of their aging resource. The approach adopted by the Danish Road Directorate with Ramboll as consultant in addressing this challenge has been to exploit advances in scientific methods in the management of its bridges. The use of probabilistic approaches within the areas of safety assessment of bridges, safety-based bridge management and ship impact assessments have resulted in substantial cost savings and the future maintenance and repair needs have been decreased. The various areas where the probabilistic approaches have been applied are exemplified presenting both the technical approach and administrative and financial benefits.

Keywords:
Bridge; Probability; Engineering decisions; Maintenance; Cost benefit

1. INTRODUCTION

The Danish Road Directorate (DRD), Ministry of Transport uses modern technology to construct roads and bridges that meet Denmark's transportation needs and provide a well-functioning infrastructure, adapted to the requirement of citizens and road-users. The DRD is responsible for the 3600 km national road network and approximately 2100 smaller bridges and 50 special bridges and tunnels on this road network. Special bridges are defined as large bridges either on land or over water. 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 main focuses of attention for the DRD are on safety, preservation of invested capital and availability of an uninterrupted traffic flow, closely followed by provision of high-quality service, environmental considerations in all decisions and aesthetic design.

The current and future challenges for the DRD in order to live up to its own values and the users requirements are numerous. An ageing bridge stock, steady increase in traffic, Figures 1 and 2, increased focus on road-user inconveniences and costs and demands for increased load-bearing capacity are just some of the challenges the DRD faces now, with even more predicted in the future.

The majority (60%) of the bridges administered by the DRD were built more than 30 years ago and 50% are between 25 and 40 years old. Today the DRD faces the combination of an old deteriorating bridge stock and limited budgets. Significantly, many of these ageing bridges are vital for the infrastructure system. In addition the DRD must meet an annual 2% reduction in its budget for total costs.

In order to deal with this situation, the DRD is always interested in new approaches, which can provide cost savings or give a better basis for decision or postponement of costly rehabilitation and strengthening projects.

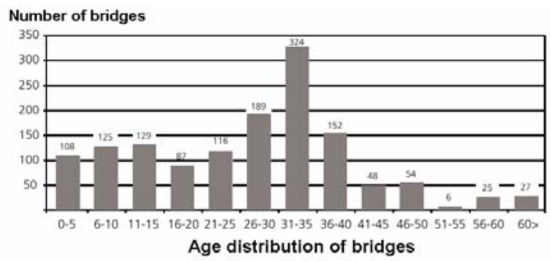


Figure 1 - Age distribution of DRD bridges. About 50% of the bridges are 25-40 years old.

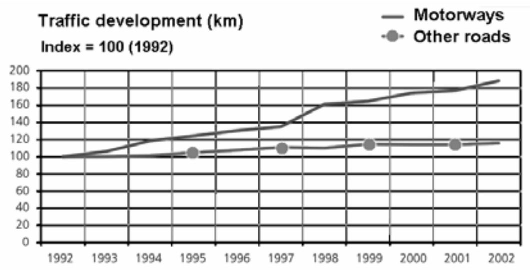


Figure 2 - Motorway traffic (in kilometres driven) has doubled from year 1992 – 2002.

One of the approaches adopted by the Danish Road Directorate in addressing this conundrum has been to attempt to exploit advances in scientific methods especially probabilistic approaches within the management of existing bridges. A complete set of management tasks is employed at the level of the specific bridge and for the network as a whole. These tasks range from classification to lifetime safety assessment and management

2. BENEFITS FROM USING PROBABILISTIC APPROACHES

As outlined in the previous section the DRD has used probabilistic approaches for a number of technical and a variety of management and administrative purposes. These may be divided into applications for

- non-deteriorated bridges
- deteriorated bridges.

For non deteriorated bridges the main benefit from using a probabilistic approach is the ability to adopt an individual approach. In the individual bridge approach, an assessment of bridge safety is determined which directly and consistently takes the bridge specific uncertainties and local traffic situation into account. The result is an individual classification often permitting higher traffic loading following the principle that a bridge does not necessarily have to fulfil the specific requirements of the general deterministic code as long as the overall level of safety defined by the code is satisfied. A clear advantage of the individual approach lies in its ability to incorporate bridge specific information and bridge specific safety modeling. For the cases considered within the DRD during the last 5 years, the use of a probability-based approach has demonstrated a higher capacity than the deterministic approach. It is clear that applying the probability-based approaches can result in considerable monetary savings by avoiding the need for costly strengthening and replacement of existing serviceable bridges. Specifically for this purpose, the DRD has developed a guideline for Reliability-Based Classification of the Load Carrying Capacity of Existing Bridges; see Enevoldsen (2001), Enevoldsen et al (2004).

For old bridges the use of systematic probability-based maintenance management plans for special bridges makes is possible to postpone costly major repair and rehabilitation projects until the required budget for repair is available or until uncertainties regarding the future use of the bridge in question have been established, see Jensen et al (2004a)

The current condition of bridges owned by the Danish Road Directorate is very good. However, for a few special bridges the current condition or the uncertainty regarding the future of the bridge may make it optimal to postpone major repair or replacement. In these cases the lifetime criteria becomes the safety of the bridge. The core idea in safety-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. The principal motivation is cost savings and the assessment of all available options for extending the service lifetime of the structure.

A safety-based Bridge Maintenance Management plan can be based on a deterministic or a probabilistic approach. In many cases for critical bridges a general deterministic approach has been shown to suggest “repair and rehabilitation now” as the only possible option if the (deterministic) safety of the bridge is not to be jeopardized. The probabilistic approach in addition to reducing the conservatism inherent in an assessment performed using a general approach provides a rational means of including estimates of the deterioration and deterioration rate with related uncertainties of e.g. concrete and reinforcement see Enevoldsen (2001), Jensen et al (2004a), O’Connor et al (2004b).

A number of applications for non deteriorated bridges are presented in section 4.1 while applications for deteriorated bridges are presented in section 4.2.

3. BASIS FOR APPLICATION OF PROBABILISTIC APPROACHES

The Danish Road Directorate has used probabilistic approaches for a number of technical and a variety of management and administrative purposes. A fundamental requirement for the application of probabilistic-based assessment, is that the authorities in the countries where the methods are used, establish the legal basis – and that the authorities develop guidelines for correct and systematic use of the methods.

Bridge specific probability-based safety assessment is now common practice within the Danish Road Directorate having been fully integrated into ordinary practice over the last five years. A guideline for probability-based assessment of bridges has been made by the DRD and is in use today; see Enevoldsen et al (2004).

It is obvious that it is a fundamental requirement for a bridge owner such as the DRD, in order to be able to use probability-based management, that the legal justification for the methods is 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 who are going to approve the assessment results. To provide this legal justification the DRD decided to commission the preparation of a guideline to be used in conjunction with the relevant codes of practice for bridge assessment; DRD (2004). The background documentation for the Nordic countries describe in detail how a probabilistic-based assessment can be performed in accordance with the requirements for the safety level in the Nordic countries (NKB 1978). It also specifies the principles of modelling of uncertainties including incorporation of model uncertainty.

The guideline; DRD (2004), is believed to be the first in the world of its kind and describes in detail how a probability-based assessment of the load bearing capacity can be performed in accordance with the requirements for the safety level prescribed by the Danish Road Directorate.

The procedure for the probability-based safety assessment of an existing bridge according to the new DRD guideline is illustrated graphically in Figure 3. First specific problems are identified using the general approach, i.e. traditional deterministic code. This is cost-efficient because the subsequent probabilistic modelling of the problems with related limit states requiring more careful consideration, in a so-called individual approach, 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.

The requirements at the ultimate limit state for the structural safety are specified with reference to failure types and failure consequences, i.e. safety class with requirements for the formal annual probability of failure p_f. The definition of the safety index, □, in this regard is taken from the existing Nordic recommendation for loading- and safety regulations for structural design. The safety index, □, is formally defined in terms of the probability of failure:

$$\beta = -\Phi^{-1}\left(p_f\right) \qquad (1)$$

for which $\Phi^{-1}(\cdot)$ is the inverse function of the standardised normal distribution.

Table 1 outlines the requirements of the new Danish guideline in this regard.

Table 1 - Guideline Requirements (DRD 2004).

Failure Consequences (Safety Class)	**Failure Type I:** Ductile failure *with* remaining capacity	**Failure Type II:** Ductile failure *without* remaining capacity	**Failure Type III:** Brittle failure
Very Serious: High safety class	$P_f \leq 10^{-5}$ $\beta_t \geq 4.26$	$P_f \leq 10^{-6}$ $\beta_t \geq 4.75$	$P_f \leq 10^{-7}$ $\beta_t \geq 5.20$

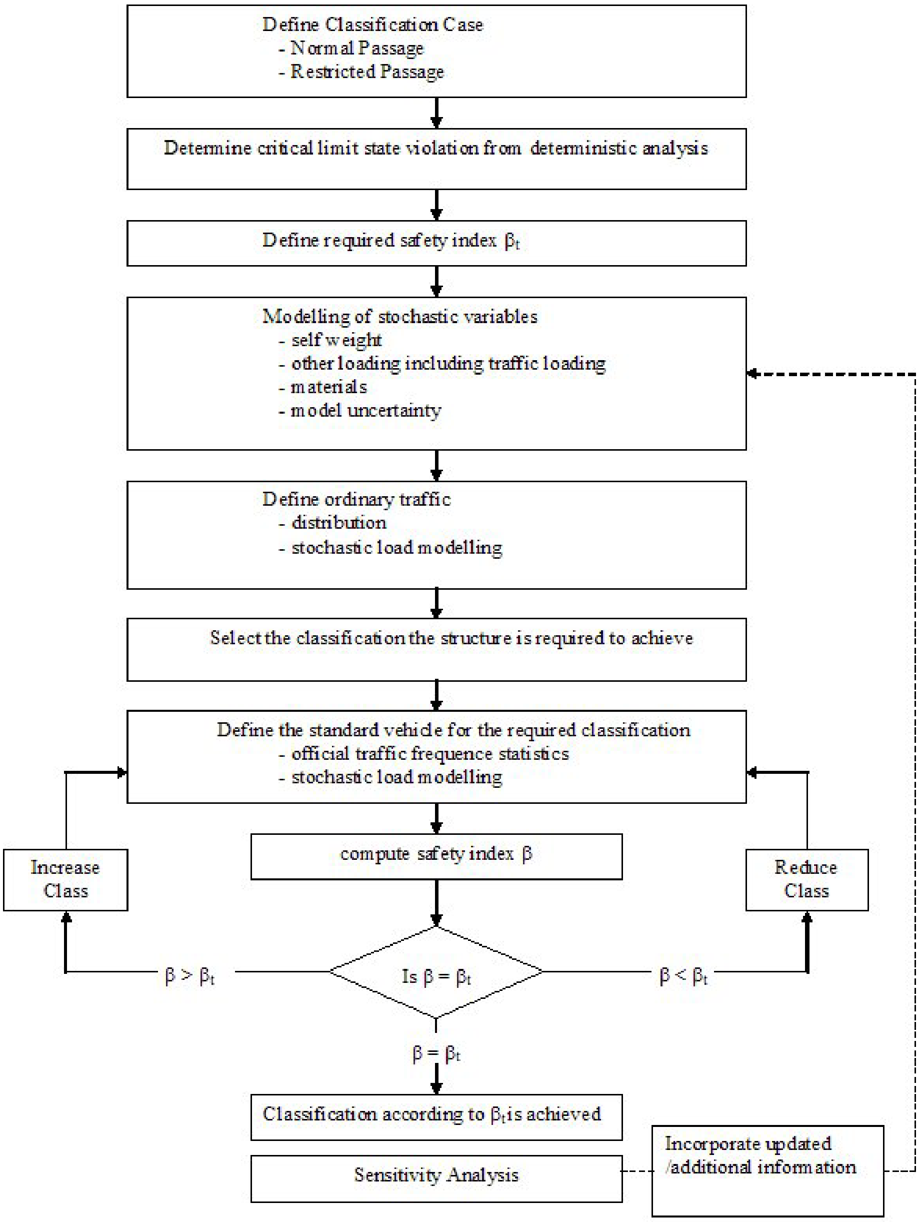


Figure 3 - Flowchart of probability-based classification according to the new DRD guideline; Enevoldsen et al (2004)

At the serviceability limit state the guideline distinguishes between reversible and irreversible conditions. In selection of the appropriate safety index, β_t, it is suggested that consideration be given to the cost of loss of serviceability and repair and of the cost of reducing the risk of attaining such a limit state. Reference is made to suggested values in other codes/guidelines indicated in Table 2.

Table 2 - β_t, Serviceability limit state

Code	Limit State	β_t
NKB (1978)	Reversible and Irreversible	1.0 – 2.0
ISO (1999)	Irreversible	2.9
	Reversible	2.2
EN 1990-2002	Irreversible	2.9

The guideline also provides detailed information on load and resistance modelling including the incorporation of uncertainties. The model uncertainty takes account of: the accuracy of the calculation model, possible deviations from the strength of material properties in the structure involved as compared with that derived from control specimens and material identity.

The DRD now employs probability-based assessment as a matter of course for any structure, which fails an initial deterministic assessment. The guideline is central to this process, as it ensures that at no stage in the process is the safety of the structure compromised. The result of this policy has been the ability to avoid unnecessary rehabilitation or replacement of existing structures with considerable cost savings. Table 3 presents the results of some selected case studies in which probability-based assessment has been performed. In Table 3 *W* is the weight of the permitted vehicle load. For the bridges Skovdiget and Storstroem the methods was used to extend the lifetime of the structures by documentation of adequate safety in the extended lifetime; Enevoldsen (2001), Enevoldsen et al (2002), Jensen at al (2000). It is evident that the cost saving to the DRD in these cases alone is in excess of $30 million USD.

Table 3 – Examples of DRD savings from probability-based assessment.

Bridge	Result of Deterministic Analysis	Probability-based assessment	Cost Saving $US
Vilsund	Max W = 40 t	Max W = 100 t	4,000,000
Skovdiget	Lifetime ~ 0 years	Lifetime > 15 years	12,500,000
Storstroem	Lifetime ~ 0 years	Lifetime > 10 years	2,500,000
Klovtofte	Max W = 50 t	Max W = 100 t	2,000,000
407-0028	Max W = 60 t	Max W = 150 t	1,500,000
30-0124	Max W = 45 t	Max W = 100 t	500,000
Norreso	Max W = 50 t	Max W = 100 t	500,000
Rødbyhavn	Max W = 70 t	Max W = 100 t	500,000
Åkalve Bro	Max W = 80 t	Max W = 100 t	1,500,000
Nystedvej Bro	Max W = 80 t	Max W = 100 t	2,000,000
Avdebo Bro	Max W = 80 t	Max W = 100 t	3,000,000
		TOTAL	30,000,000

While the purpose of the guideline is to serve as a basis for the probability-based assessment of Danish bridges it can also easily be applied in other countries. With the available probability-based techniques, the guideline and the obtained experience huge monetary savings has already been achieved and more are expected in the future.

4. EXAMPLES - USE OF PROBABILISTIC APPROACHES

In terms of bridge assessment, one of the most promising and most beneficial scientific advances in the last three decades has been the development of a catalogue of probabilistic approaches. Recognizing this, the Danish Road Directorate have employed probabilistic techniques for bridge assessment for the last 15 years. In the following a number of examples for both non deteriorated and deteriorated older bridges are presented.

4.1 Non deteriorated bridges - Load carrying capacity assessment

In the past years large effort has been put into the assessment of the load carrying capacity of the bridges managed by the Danish Road Directorate (DRD). The assessments are mostly dealing with the passing of heavy vehicles, where a heavy vehicle is defined as a vehicle with a weight larger than 48 t which needs special permission from the police.

A classification system has been developed for administration of heavy vehicles. The system is based on the idea that both the bridges and the heavy vehicles should be classified in a way such that the classes are comparable. In this way the assessment of bridges regarding heavy vehicles should only be carried out once. Once the bridges are classified it is easy for the police and road/bridge administrators to decide if a specific heavy vehicle with a certain vehicle class can pass the bridge with a certain bridge class. The classification system; DRD (1996), is based on a set of standard vehicles representing vehicles with a total weight ranging from 20 t to 200 t. In a regular deterministic assessment of the bridge class a relatively conservative traffic load combination is applied comprising the standard vehicle of 50 t with a second standard heavy vehicle (weight 50 t – 200 t). The resulting bridge class is equal to the weight in tons of the heaviest standard vehicle in the load combination. Furthermore, bridge classes are determined for passages of heavy vehicles with imposed restrictions such as speed limits and exclusion of other traffic.

In line with this classification system, a relatively detailed so-called *Blue Road Network* has been established comprising roads with no bridges having a class less than 100. As the blue road network includes all motorways and many other major roads it ties together transport routes throughout all of Denmark. The police and road/bridge administrators use a map of the blue road network when preparing special weight permits while haulage contractors use it when planning transports and selecting routes. All roads administered by the DRD are part of the road network provided for heavy vehicles, which includes all motorways and many other major roads. This network ties together the whole country as illustrated in Figure 4.

It has been the aim of the DRD for some time that all state roads and, as many other main roads as possible should be included in the blue road network. As about 98 % of all heavy vehicles are classified below 100 t, and hence need no special investigation when passing on blue roads, an easy and efficient administration for the police and bridge administrators has been hereby established together with the provision of satisfactory service to the industry.

Inclusion on the blue road network requires initially that bridges have been assessed by applying general deterministic methods with elastic or plastic limit state analysis according to the Danish guideline for classification of bridges; DRD (1996). Where the obtained bridge class is insufficient (< class 100) traditionally the alternatives of expensive rehabilitation or replacement have been considered. In recent years the DRD have consistently considered a third alternative, probability-based approaches, before an expensive strengthening or rehabilitation project is implemented. The probability-based approach is often combined with advanced response models. The results of the probability-based assessment have often been found to considerably raise the bridge class achieved in deterministic assessment; Enevoldsen (2001), Enevoldsen et al (2002), Jensen et al (2000), O'Connor et al (2004a). In many cases these analyses have resulted in a satisfactory bridge class (i.e. >100) thereby minimizing or avoiding strengthening projects. It is important to stress that at no stage is the safety of the structure compromised rather the bridge specific safety is calculated. Therefore these methods have proven to be very beneficial for bridge managers with large cost savings as results.

In the following, examples from Denmark are presented.

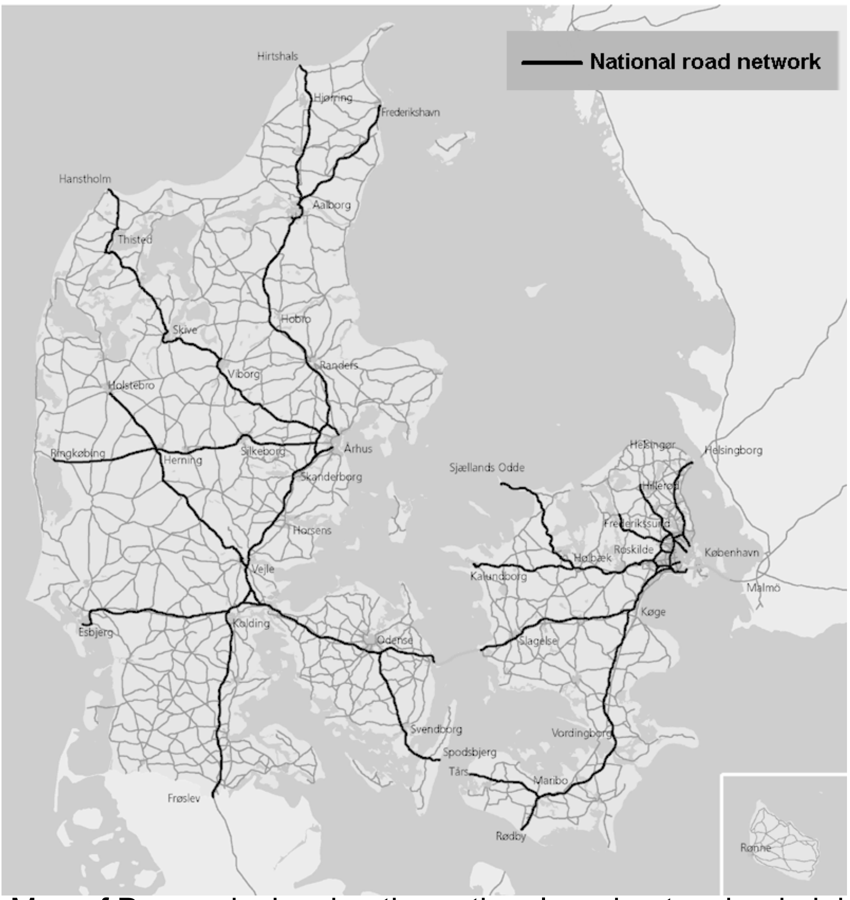


Figure 4 - Map of Denmark showing the national road network administered by the Danish Road Directorate (national road network is shown using a darker colour).

4.1.1 Vilsund Bridge, Denmark – Classification

The Vilsund Bridge, Illustrated in Figure 5, is a 381 m long steel bridge from 1939 consisting of 5 ordinary 67.8 m spans and a 34 m bascule span. The two lane road bridge has a width of 8.6 m with a concrete slab deck supported by a steel girder system with cross girders for every 5.58 m.

Figure 5 - Vilsund Bridge, Denmark. 5 ordinary spans and 1 bascule span.

The Danish Road Directorate decided that it would be desirable to allow trucks with a total weight of 100 metric tons to pass the Vilsund Bridge instead of a maximum truck weight of 50 metric tons. (Trucks with a weight above 50 metric tons must take a 150 km long detour if the Vilsund Bridge cannot be passed).

Analyses of the bridge were performed according to the general approach for classification of existing bridges in Denmark with Class 50 as a result, which corresponds to a situation where two Class 50 trucks with an approximate weight of 50 metric tons, are passing each other on the bridge in the most critical situation for the considered structural element.

The results of the analyses showed that the critical structural members are the main cross girders supporting the concrete deck and some of the steel truss members in the ordinary spans. A rough estimate of strengthening cost of the Vilsund Bridge to Class 100 was found to be $4 million.

Instead of performing the strengthening project, it was suggested to perform a bridge specific reliability analysis of the critical elements in order to reduce or eliminate the costs of the strengthening project. The reliability evaluations were split into probabilistic-based evaluation of a) the main cross girders and b) of the critical steel truss members in the main structure.

The objective of the probabilistic-based reliability evaluation of the main cross girders is to decide whether the girders could be assigned a higher Class than 50 based on the bridge specific conditions. The failure of the main cross girders is assigned to the failure consequence class denoted "very serious" and failure type II, including ductile failure without any extra load carrying capacity according to Table 1 from which it is possible to obtain the requirement for the reliability index as $\beta \geq 4.75$.

The reliability evaluation of the main cross girder is based on the meeting event of two heavy trucks. The yearly probability of failure will then depend not only on the weight of the trucks but also on the yearly number of trucks passing the bridge. It is obvious that the probability that one heavy truck meets another heavy truck is lower for a bridge with a relatively low heavy truck frequency and vice versa. The largest load effect within a given time interval is in the reliability evaluation modelled as a so-called thinned Poisson load-pulse process. The reliability model includes a model for determination of the cross-sectional forces in a cross girder and a modelling of the uncertain variables as stochastic variables based on the available information concerning the bridge from material characteristics and as-built data from the thirties and later. This information is obtained from the maintenance program of the bridge and traffic counting on the bridge. The variables modelled as stochastic were: the weight of the trucks with the related total weight of the two meeting trucks, the yield stress, the dynamic amplification factors, the position of the trucks, the dead load of the bridge deck and a number of model uncertainties.

The results show that the main cross girders can be classified in Class 100, i.e. a \$2 million strengthening project was avoided without compromising on the safety of the bridge deck.

Encouraged by the above results it was decided to proceed with a probabilistic-based reliability evaluation of the critical truss members in the ordinary span. A deterministic analysis performed according to the general approach showed that the problem was a two-fold. The critical members are the first 3 beam trusses in the head of the span. This interferes with another problem in the structure. Figure 6 shows a bracing, which was requested removed because the clearance profile is too small for high trucks.

It was decided to perform a probabilistic-based evaluation with the purpose of evaluating if it was possible to remove the bracing or strengthen the structure in the area connected to the bracing and classify the beams in Class 100.

The failure of the members is assigned to failure consequence class “very serious” and failure type I for ductile failure with extra load carrying capacity (elastic limit state) resulting in the safety requirement $\beta \geq 4.26$ corresponding to a formal yearly probability of failure $P_f \leq 10^{-5}$, Table 1.

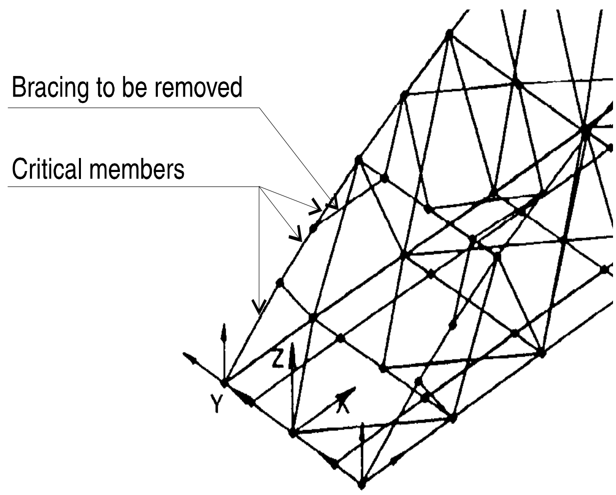


Figure 6 - Vilsund Bridge, Denmark. Critical members and bracing to be removed.

The fact that the main spans of the Vilsund Bridge are 67.8 m long made the probabilistic-based reliability evaluations more complicated, because when the load effects are evaluated in a beam truss member in the ordinary span it became necessary to examine the traffic mix of trucks and cars over the entire 67.8 m long span. Further, the bascule made the probabilistic-based reliability evaluations even more complicated because the queue release after closure of the bascule had to be modelled individually. The considered load situations were: 1) Maximum yearly load effect from freely moving traffic, 2) Maximum yearly load effect from queue release after closure of the bascule and 3) Maximum yearly load effect from a number of Class 100 trucks which meets the load effect from the instantaneous traffic (here defined as the maximum distribution for an 8 hour interval). The instantaneous traffic includes the probability of the meeting of a queue release after closure of the bascule.

Further, the wind load was introduced in the probabilistic modelling by application of a relatively crude model, because it turned out that the stress level in the critical members due to wind load were significantly smaller than the stress levels due to traffic load.

The theory behind the used probabilistic-based reliability models can be found in Ditlevsen and Madsen 1996 etc. The main idea is that based on the influence functions, statistical distributions of the load effects in the structural member can be found, based on the traffic intensity and mix between cars and heavy vehicles. The model takes among others the following parameters as input: a) daily number of vehicles, b) yearly number of Class 100 trucks, c) daily distribution of traffic, d) the traffic speed, e) distribution of the weight of the traffic and f) probability of queue release. Further, the relative part of the time the traffic was congested in a queue release after closure of the bascule and other parameters for description of the traffic were included in the models.

After the statistical distribution of the load effect was found it was possible to perform a more ordinary probabilistic-based reliability evaluation. The modelled stochastic variables were: stresses due to traffic loads, stress due to dead load, dynamic amplification factors, yield stress and a number of model uncertainties. The result of the reliability analysis can be seen in Table 4 for the critical truss element. It turned out that the reliability in the situation with removed bracing is slightly higher in the traffic load situations (the reliability is lower in the extreme wind situation but this is not critical for the structure).

Table 4 – Results of reliability analysis of the critical steel truss members

Load situation	1	2	3
β	5.86	4.65	4.54

It is seen that the reliability of the individual cases is higher than the required 4.26 with the conservative number of 100 yearly class 100 trucks. The 3 situations should in principle be combined in a series system that, however, cannot reduce the reliability level below the requirement. The results of the analyses further showed that the load effects due the traffic load were reduced by 35 % compared to the worst case model in the general approach. The sensitivity analysis shows that the results are in general relatively insensitive to large model changes.

Therefore the Vilsund Bridge was classified as a Class 100 bridge even with removed bracing. The use of bridge specific probabilistic-based methods has in this case saved approximately $4 million (excluding road users inconvenience costs).

4.1.2 Klovtofte Bridges, Denmark – Classification

Klovtoftebroerne are two sister motorway over-bridges situated just outside Copenhagen. Constructed in the early 1970's the bridges, illustrated in Figure 7, are composed of precast prestressed beams with an in-situ slab. The bridges have 4 span with two short side spans and two longer central spans.

Normal Passage Class 100:

$\beta = 5.70 > 5.20$

Restricted Passage Class 100:

$\beta = 6.45 > 5.20$

Figure 7 - Klovtofte Bridges, Denmark (left). Safety indices computed by PROBAN for the normal and restricted passage cases respectively (right).

Deterministic assessment of Klovtoftebroerne assigned Class 50 in accordance with the Danish Road Directorate Assessment (DRD) Code. Consequently, the load carrying capacity of the structures was limited to 2 x 50 tonne (class 50) vehicles. The implication of this deterministic classification was that the structures had insufficient carrying capacity to receive the rating necessary for inclusion on the Danish *Blue Motorway Network*. As it is the aim of the DRD to achieve this rating for all motorway structures the alternatives presented for a structure failing to achieve a KL100 rating are costly rehabilitation or replacement.

The critical limit state in the deterministic assessment was in shear in the prestressed concrete beams in the main spans. Significantly, available information on the shear design was minimal. The shear capacity of the OT-beams was assessed in two ways: (a) using a first principles approach and (b) using the equation provided by DS 411 which are equivalent expression 4.18 in the draft of Eurocode 2.

The requirements at the ultimate limit state for the structural safety are specified with reference to failure types and failure consequences, for shear failure in the prestressed beams of Klovtoftebroerne a p_f corresponding to *Failure Type III – Brittle failure* was selected.

The result of probabilistic assessment performed demonstrated that the structures did indeed have sufficient safety to receive a Class 100 rating and to be included on the Blue Motorway Network. The result represented a significant saving for the bridge owner both in terms of the direct replacement cost and of the indirect costs, which would have been incurred in replacing the structures.

4.2 Deteriorated bridges - Management of bridges

Within the overall management of bridges the key issues are whole life cost and whole life cost prioritisation, i.e. determine how the allocated budgets must be used for the whole bridge stock over a longer period of time and determine how the annual budget must be used.

As most bridge managers throughout the world today, the DRD has a combination of an old deteriorating bridge stock and a limited budget for repair and maintenance. The consequence of these factors has been the necessity for the DRD to achieve a balance between sustainability, accessibility and cost in optimizing its maintenance budget. With this in mind the DRD began 5-10 years ago to introduce the concept of probability-based bridge maintenance management for a number of bridges where the use of traditional bridge maintenance techniques was requiring a considerable percentage of the annual maintenance budget to be concentrated on these structures.

The basic idea is that when it becomes impossible (for technical or political reasons) or too costly to use the traditional/deterministic approach for maintenance management it is often advantageous to make use of a more refined probability-based approach. The use of probability-based bridge management has given the DRD more freedom from a technical, strategic, political and most importantly from a financial viewpoint. In addition it has provided a valuable tool to ensure that the structural safety of the bridges is at all times adequate.

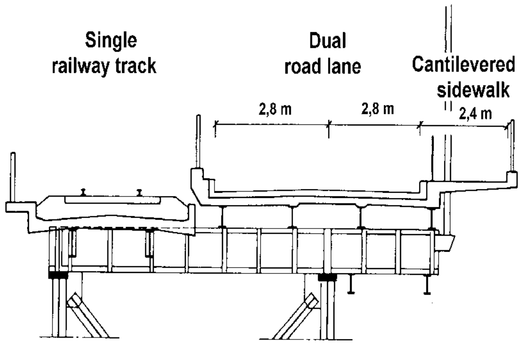
The core principle in probability-based bridge management is to make rational decisions on the maintenance management taking into account the inherent uncertainty. The use of probability-based bridge management gives the DRD more freedom when managing its entire bridge stock, by providing a justification to ignore the “repair and rehabilitation now” conclusion of a traditional deterministic analysis.

The condition of bridges in Denmark is in general very good. Consequently, the majority of bridges can still be assessed using a deterministic approach. However, in recent years a number of bridges have shown that a continuation of deterministic management would either require expensive strengthening or replacement projects. Probability-based management will in many cases be beneficial, especially if the bridge problem areas are believed to be modeled conservatively 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.

The probability-based approach also provides an efficient tool for inclusion of information from bridge monitoring, 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.

4.2.1 Storstroem, Denmark

The 3.2 km long Storstroem Bridge connects the Danish Island of Zealand (on which Copenhagen is located) with the southern Danish islands of Falster and Lolland. The contract for the building of the bridge was given to the British company Dormann, Long & Co., who also fabricated the main steel structure. The contract was awarded to a British company as a political move to offset the significant trade deficit which had developed between the UK and Denmark at his time due to Danish pork exports. The Danish contractor Christiani & Nielsen made the piers and the concrete deck. The contract was awarded in May 1933. The bridge opened in September 1937. The bridge carries dual road lanes and a single railway track and a cantilevered sidewalk for pedestrians as illustrated in Figure 8. Until 1985 when the Faroe Bridge opened, Storstroem Bridge was the only fixed connection between Zealand and the southern Danish Islands. The Faroe Bridge carries only cars. Today the Storstroem Bridge carries only local traffic with an average annual daily traffic (AADT) of about 8000 vehicles.



(a) Elevation (b) Deck Cross Section

Figure 8 – Storstroem Bridge

The main deck slab of the 3.2 km long Storstroem Bridge has suffered serious deterioration to both the concrete and reinforcement. Replacement of the bridge would be extremely costly especially when considered in connection with the possibility of the construction of the Femern Bridge at some point in the future. The bridge only carries local traffic, bicycles and pedestrians and trains. If the Femern Bridge is constructed, then the Storstroem Bridge may need to be extended from one to two train tracks. Thus, the DRD would like to postpone any decision on a strategy for the Storstroem Bridge until a decision about the Femern crossing is made. However, at the same time the DRD must ensure that the structure has sufficient structural safety for both vehicles and pedestrians at all times. In this regard a new paradigm has been introduced in Denmark, which includes safety based maintenance management. The basic idea is that when it becomes impossible (due to technical or political reasons) or too costly to maintain bridges to their as-built standard, the bridge owners must at least ensure that the bridges fulfill the requirements of structural safety. Thus, safety based bridge maintenance management becomes attractive as it enables bridge owners/managers to extend the service lifetime by reducing or postponing costly rehabilitation projects without compromising the required level of safety.

Continuing deterioration of the concrete and reinforcement in the cantilevered sidewalk meant that in the year 2000 the DRD decided to implement a safety-based management plan for the sidewalk. The plan was calibrated in a special inspection of critical points in 2001. It was shown that the remaining lifetime was at least 10 years. However, a weight limitation from 1500 kg payload to 500 kg was imposed when driving a forklift on the sidewalk.

Following successful implementation of the safety-based management plan for the cantilevered sidewalk it was next important to apply a similar plan to the concrete deck slab of the road lanes. A deterministic assessment of the deck slab using plastic response models produced a maximum load factor of 0.61 for combined dead and live load. This implies that the slab today was incapable of sustaining the applied load. The recommendation would therefore involve costly rehabilitation of the structure. The result of a probabilistic assessment was a reliability index of 7.2 (greater than the required 4.75 (NKB 1978)) without taking deterioration into account; O'Connor et al (2004b). Thereby verifying that the applied load could be sustained. To obtain an accurate measure of the current deterioration a number of inspections were made in 2002 at critical locations, previously determined as the area close to the transverse joints. From the inspections a conservative deterioration model was made. Analyses using this model gave a reliability index of 4.8 in 2002. The results of the assessment of the structure performed by RAMBØLL are listed in Table 5; O'Connor et al (2004b).

Analysis using a prediction of the future deterioration of the road slab identified that the safety of the road slab cannot be maintained for heavy trucks unless the transverse joints with the most severe deterioration are continuously repaired. If this is done the remaining lifetime of the road slab is at least 10 years. The repair of the transverse joints continues so that the most deteriorated joints are being repaired. The cost of these local repairs are insignificant to any major repair or indeed compared to replacement of the road slab.

Table 5 - Results of deterministic and probabilistic assessment; O'Connor et al (2004).

Load Combination	**Self Weight + KL10 Live Load**	
Deterministic plastic load carrying capacity	61 %	
Probabilistic Assessment: No deterioration	$p_f = 2.94 \times 10^{-13}$	$\beta = 7.20$
Probabilistic Assessment: Stochastic modelling of deterioration according to inspections results	$p_f = 6.92 \times 10^{-7}$	$\beta = 4.83$

By using a safety-based management plan, the closure of the sidewalk, further traffic restrictions on the road and expensive investments or repairs have been postponed, which resulted in major savings for the Danish Road Directorate; Jensen et al (2004a).

4.2.2 Skovdiget, Denmark

The 220 m long, 20 m wide Skovdiget West bridge, Figure 9, was constructed in 1967. The bridge carries a 3-lane motorway (60,000 daily vehicles) over local roads and a two track railway line. Due to poor workmanship and poor design, the bridge started to deteriorate shortly after construction. Major repair was performed on the identical East bridge in 1978. The cost of rehabilitation of the East bridge was $ 4 million in 1978 (a new bridge would cost $ 11 million). Since the repair of the East bridge proved so costly, it was decided to leave the West bridge without repair. Instead it was decided to monitor the West bridge closely by frequent inspections and test loadings and to replace the bridge when the safety could no longer be maintained.

A new test loading of Skovdiget West was due to be performed 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. Also, by use of deterministic load carrying calculations combined with traditional lifetime estimates, the bridge would either require major rehabilitation or replacement. Based on this fact combined with the results from the last special inspection in 1995, which showed very severe deterioration locally, it was decided that a management plan based on probabilistic methods should be implemented.

A 10-phase procedure for safety-based bridge management was applied in 1998-99; Jensen et al (2000). A probability-based assessment and corresponding management plan was implemented in 1999 with safety-updating inspections and a "survival" wearing course as initial results. This resulted in an extension of service lifetime until 2010-2014. In order to continuously verify the assumptions on the rate of deterioration, inspections have been ongoing from 1999. The rate of deterioration observed could reduce the service lifetime to the beginning of the estimated interval, i.e. to 2010. In 2003 it was therefore decided to install permanent monitoring at critical points. Measurements have shown that the deterioration rate is within the limits assumed in the probability-based management plan. At all times the remaining service life should at least be 8-12 years so that the safety is not jeopardized and preventive measures can be initiated in due time. The probability-based management plan is adaptive in nature and is able to include new information and thereby identify the cost-optimal solution – i.e. whether preventive measures, local strengthening or indeed replacement is the best administrative, technical and cost-optimal solution.

The result of the adoption of a probability based maintenance management plan by the DRD has been a cost saving > $12 million compared to traditional deterministic analysis where the bridge needed replacement now. The plan is continuously updated to ensure it's validity. The cost of maintaining the plan by doing inspections and monitoring is insignificant compared to the overall cost savings.

Figure 9 - Skovdiget twin bridges, Denmark.

5. CONCLUSIONS

Today the main focus of attention for the DRD is on safety, preservation of invested capital and availability of an uninterrupted traffic flow. Emphasis is placed on provision of high-quality service, environmental considerations in all decisions and aesthetic design. In addition today the DRD is required to meet an annual 2% reduction in its budget for total costs. It is expected that the requirement for annual reduction of budgets and a corresponding requirement for an annual increase of the productivity will be continued in the years ahead.

In order to face this challenge the DRD will continue its overall strategy based on the EFQM Excellence Model, which involves a continuous implementation of improvements and new methodologies so that all tasks within the DRD are solved more and more effectively.

This has involved the use of probabilistic approaches within the areas of: safety assessment of bridges, safety-based bridge management and ship impact assessments. The DRD will continue to take advantage of new methodologies and will start developing and applying probabilistic approaches within administrative and technical tasks such as uncertainty handling in project implementation, use of uncertainty modelling as a basis for further development and the use of probabilistic approaches within inspection planning.

In addition, the DRD in 2005 initiated work on a guideline for reliability based bridge maintenance management plans for deteriorated bridges to supplement the guideline for reliability-based classification of the load carrying capacity of existing bridges from 2004.

For the many examples presented in this article the cost savings have been substantial and the uncertainty on future maintenance and repair needs have been significantly decreased thereby making overall long-term budgets more accurate and it has facilitated the optimisation of available resources.

The DRD therefore fully recommended the use of these methods to other bridge administrations in order to better meet the universal requirements of increased efficiency, minimization of traffic inconvenience combined with reduction of available budgets.

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