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Sustainable Upgrading of Existing Bridges by Reliability-Based Assessment

Silja T. Nielsen
Specialist, Monitoring and Analyses of Existing Structures, Ramboll, Copenhagen, Denmark

Joan H. Roldsgaard
Chief Consultant, Monitoring and Analyses of Existing Structures, Ramboll, Copenhagen, Denmark

Dániel Honfi
Senior Specialist, Monitoring and Analyses of Existing Structures, Ramboll, Copenhagen, Denmark (Currently: Strategic Planner, Transport Department, City of Stockholm)

ABSTRACT: This paper presents recent applications of the Danish guideline for reliability-based assessment for existing bridges, resulting in a traffic load upgrade of up to 60%. The guideline reflects a commitment to consider reliability-based assessment for all bridge structures that have failed a deterministic assessment. This commitment is in-line with the general sustainability agenda imposed by the society by reducing costs, CO_2 emissions, and societal disruptions caused by strengthening or replacing of existing infrastructure.

1. INTRODUCTION

Verification of adequate reliability level of existing bridges is often a necessity due to e.g. increased traffic volume, changes in locations of lanes, signs of deterioration, lifetime extension, increased needs for heavy transports. The consequences in terms of sustainability footprint can be very negative for bridges which fails to meet the needs from the users and/or owner, as strengthening or replacement of the bridge often is the solution for meeting todays requirements. Nonetheless, application of reliability-based assessments can often mitigate the need for replacement or strengthening, by demonstrating that the bridge already possesses the required reliability level.

The UN established a set of Sustainable Development Goals (UN, 2015), which also focus on reduction of our ecological footprint by changing the way we use our resources. For existing bridges this goal can be met with postpone strengthening or replacement as long as possible even beyond the initially expected lifetime of the bridge. One way to help this sustainability agenda along is by assessing the capacity of a structure through reliability-based assessment. By this approach the costs and the environmental impact can be reduced by minimizing demolition and related carbon emissions. In addition, it can facilitate preservation of cultural heritage and prevent traffic disruption. These benefits make reliability-based assessment an attractive option for infrastructure owners seeking to balance the multiple dimensions of sustainability, which are shown in Figure 1.

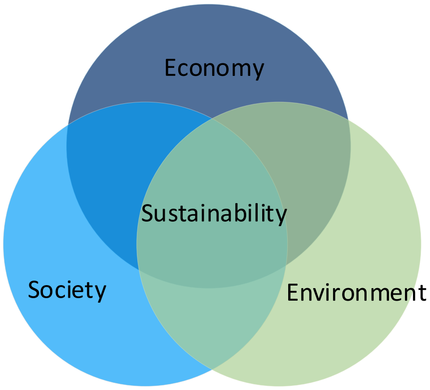

Figure 1: Concept of sustainability (Barbier, 1987).

This paper presents four recent examples of application of reliability-based assessment of existing bridges in Denmark. In all four cases, the bearing capacity of the bridge was improved compared to the deterministic assessment. As a result, it was possible to avoid weight restrictions, diversions of heavy transports, strengthening or reconstruction. Given Denmark's climate policy mandating 70% reduction of greenhouse gas emissions by 2030 relative to 1990 (Danish Ministry of Climate Energy and Utilities, 2020), it is essential to adopt sustainable practices for structures such as bridges.

Therefore, this paper recommends a widespread adoption of reliability-based assessment as the preferred approach for all bridge structures that have failed a deterministic assessment, ensuring the safety of the public in an environmentally responsible and sustainable and manner.

2. RELIABILITY-BASED ASSESEMENT OF EXISTING BRIDGES

Given that critical failure mechanisms of a structure have been identified but traditional deterministic assessment has failed to prove adequate safety, reliability-based assessment may be considered to reduce conservativeness of the traditional partial safety factor method as this has to cover all types of bridges in all types of loading situations. With reliability-based assessment, the failure event is described by the limit state function, $g(\mathbf{x})$:

$$F = \{g(\mathbf{x}) \leq 0\} \tag{1}$$

where $\mathbf{x}$ is a vector with realizations of the basic random variables $\mathbf{X}$ representing the relevant uncertainties influencing the probability of failure, p_f.

This means reliability-based assessment determines the reliability level by considering the uncertainties of the load and resistance parameters, that is specific to the failure mechanism of the bridge in question. Thus reliability-based assessment is a powerful tool for assessing a more realistic reliability level of a structure and thereby avoid overstated conservatism often obtained when applying deterministic partial factors calibrated to be broadly applicable.

In a reliability-based assessment the reliability index, β, is calculated, which is defined in terms of the probability of failure:

$$\beta = -\Phi^{-1}(-p_f) \tag{2}$$

for which $\Phi^{-1}(\cdot)$ represents the inverse function of the standardized normal distribution. In addition, sensitivity analysis is performed to evaluate which stochastic variables that have large influence on the reliability level and to determine the sensitivity of β to the variations describing the stochastic models in the analysis.

For road bridges in Denmark both requirements for the reliability index and the uncertainties are described in the Danish Road Directorate's (DRD) guideline for reliability-based classification of existing bridges (Road Directorate (2004)). The guideline is to be updated in 2023 to ensure that experience from the past 20 years are reflected in the new edition and to increase the use of reliability-based assessments (Roldsgaard et al. (2023)), thus enabling bridge owners to make more sustainable decisions.

2.1. Safety requirements

The requirements for the reliability index given in the DRD guideline are in accordance with the Danish National Annex to Eurocode 0 (DS/EN 1990 DK NA:2021) and depends on the failure mechanism in the modelled limit state, see Table 1. This way the requirements for the target reliability index, β_t, differentiates between brittle and ductile failure modes.

Table 1: Target reliability index for the ultimate limit state.

Failure type	*Failure with warning and bearing capacity reserve*	*Failure with warning but without capacity reserve*	*Failure without warning*
$\beta_t \geq$	4.26	4.75	5.2
$p_f \leq$	10^{-5}	10^{-6}	10^{-7}

2.2. Modelling of stochastic variables

In the DRD guideline, recommendations are given for modelling the most relevant stochastic variables for existing road bridges. These recommendations cover e.g. distribution type, distribution parameters as well as model uncertainties of both resistance and load parameters. E.g. it is recommended to model material strength parameters by log-normal distributions, while structural dead load, superimposed dead load and weight of traffic is modelled by a normal distribution. The model uncertainties of the resistance variables are included in the stochastic modelling of the material parameters in accordance with the method outlined in in NKB (1978).

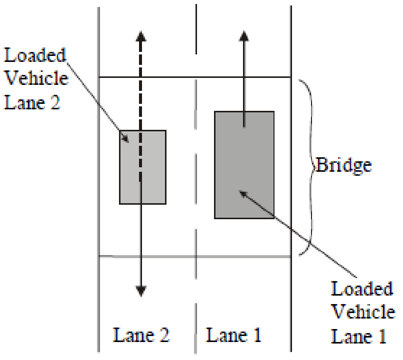

Figure 2: Normal passage situation with a Heavy transport and standard vehicle (Road Directorate (2004)).

For short and medium span bridges located on a highway or a main road, traffic loads are the most important variable loads. Variations in the loading resulting from e.g. the weight, speed and relative positions of vehicles on the bridge. Figure 2 illustrates a typical meeting event for a small or medium span bridge. The extreme value distribution of such meeting events can be modeled by a thinned Poisson process, where the vehicle speed, vehicle length, bridge influence length, traffic intensity (annual frequency), relative importance of lances and model uncertainty is taken into account (Road Directorate (2004)).

3. EXAMPLES OF APPLICATION OF RELIABILITY-BASED ASSESMENT

Examples of recent applications of reliability-based assessments in the ultimate limit state are presented here for various concrete bridges where upgrading of the load-bearing capacity was possible with a probabilistic approach compared to the deterministic assessment. For all cases the result of the reliability index is presented together with sensitivities of the stochastic parameters on the reliability level. All represented bridges are more than 50 years old but are all found to be in good condition.

The distribution type and distribution parameters for each stochastic variable in the limit state function is not presented in each example due to a lack of space. However, the assessments and thereby the stochastic variables and model uncertainties were carried out in compliance with the DRD guideline. The probabilistic calculations were carried out using the structural reliability software Comrel (STRUREL (2021)).

3.1. Heager Å

The bridge passing *Heager Å* is reinforced concrete bridge with a span length of 7.1 m. The bridge is built in 1925 and was expanded to both sides in 1979, see Figure 3. The bridge is located on a main road in the Western part of Denmark and is one of the main connections between two larger cities, thus required to have a load bearing capacity of Class 100 i.e. simultaneously carrying a heavy vehicle of 100 t and a standard vehicle of 50 t. In deterministic assessment the bending moment capacity of the original part of the bridge, both of the main girders and cross beams, was found to be the critical failure mechanism, limiting the bearing capacity to Class 70 (a heavy vehicle of 70 t).

To upgrade the bending moment capacity of this bridge without its replacement would require difficult repairs above the water. Instead of physical interventions, that impact both environment and traffic, a reliability-based structural assessment of the bridge was carried out.

Figure 3: Bridge passing Heager Å. Photo taken from (Generaleftersynsrapport, (2006)).

The critical limit state is formulated by:

$$g(\mathbf{x}) = M_{Cap}\left(f_c, f_{y,L}, f_{y,T}\right) - M_{Load}(G, G1, WA, MUncA, DAF, DAF_{unc}) \qquad (3)$$

where $g(\mathbf{x}) \leq 0$ indicates failure of the limit state. M_{Cap} describes the capacity model and M_{Load} is the model describing the bending moment. both are functions of stochastic parameters. The capacity model consists of following stochastic parameters:

- f_c , concrete compressive strength
- $f_{y,L}$, yield stress of reinforcement the main girders
- $f_{y,T}$, yield stress of the reinforcement in cross girders

while following stochastic variables is included in the load model:

- G, structural dead load
- $G1$, superimposed dead load
- WA, weight of the heavy vehicle
- $MUncA$, model uncertainty of traffic load
- DAF, dynamic amplification
- $\mathrm{DAF}_{\mathrm{unc}}$, model uncertainty of dynamic amplification.

The load model consists of passage of 1 vehicle solely, as no meeting of vehicles is possible on the original bridge from 1925 and no interaction with the new parts of the bridge is considered.

The target reliability index considered appropriate for the bending moment failure mechanism and bridge is β_t = 4.75 (ductile failure without capacity reserve) as the bridge is a simply supported structure.

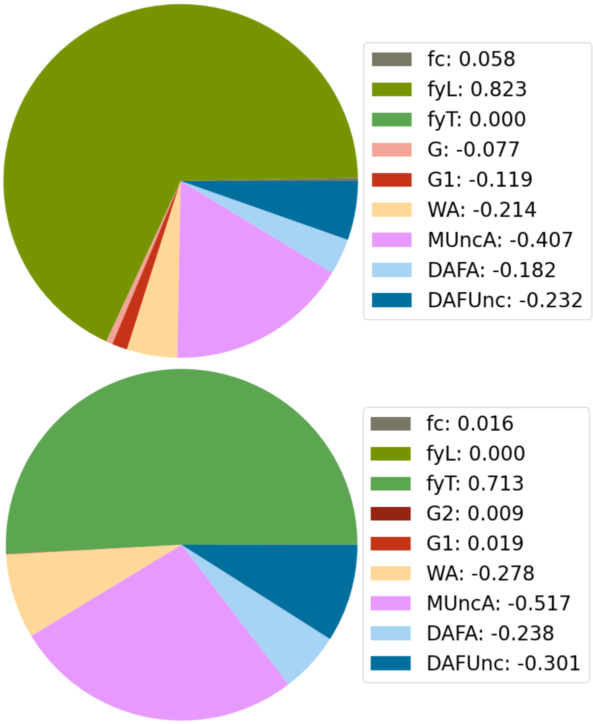

Figure 4: Sensitivities – relative influence given as α-values on the reliability level of the main direction (top) and of the cross direction (bottom) for Heager Å.

It is found that the target reliability index is met for a Class 100 (heavy vehicle of 100 t) as the calculated reliability indices was β = 4.97 for the bending moment limit state of the main girder and β = 4.80 for the bending moment limit state of the cross girder. Figure 4 shows the relative influence (α^2-values) of the different stochastic variables by pie chart. For both bending moment failure in the two directions yield stress of the reinforcement $(f_{y,L}, f_{y,T})$ has the largest influence on the reliability index as expected for a bending moment failure. The variable with second largest influence is the model uncertainty of the heavy vehicle in both cases.

3.2. *Ribe Vester Å*

The bridge passing *Ribe Vester Å*, built in 1953, is a post-tensioned concrete bridge with a span length of approximately 36 m. The cross section of the superstructure consists of a top and bottom plate and girders both in the cross and main direction. The bridge is located on a main road, where the required load bearing capacity is Class 150 i.e. it must be able of simultaneously carrying a heavy vehicle of 150 t and a standard vehicle of 50 t.

Figure 5: Bridge passing Ribe Vester Å Photo taken from (Generaleftersynsrapport, (2014)).

In the deterministic assessment it was found that the capacity of the bridge is limited by the shear failure of the main girders. To upgrade the shear capacity of a concrete bridge drilled shear struts is an option, however, this would disturb the traffic flow and work would need to be carried out both above and below the bridge deck. Replacement of the bridge was considered an option, however, for now found too economical expensive. Instead, a reliability assessment was carried out, with the critical limit state is formulated by:

$$g(\mathbf{x}) = V_{Cap}\left(f_{yw}, f_p\right) - V_{Load}\begin{pmatrix} G, G1, WA, WB, MUncA, \\ MUncB, DAFA, DAFB \end{pmatrix} \tag{4}$$

where V_{Cap} is the shear capacity model and V_{Load} is the load model. For this limit state 2 stochastic parameters of two vehicles (vehicle A is the heavy vehicle and vehicle B is the standard vehicle). The extreme value distribution of meeting event between the heavy vehicle and standard vehicle is modelled by a thinned Poisson process, as mentioned in Section 2.2.

The target reliability index found suitable for the limit state is β_t = 4.75 (ductile failure without capacity reserve). This requirement was found to be met for class 150 corresponding to a heavy vehicle of 150 t (β = 5.23), which in the deterministic assessment gave a utilization ratio of 115%. From Figure 6, showing sensitivities, it can be seen that the yield stress of the shear reinforcement has the largest influence on the reliability level as expected.

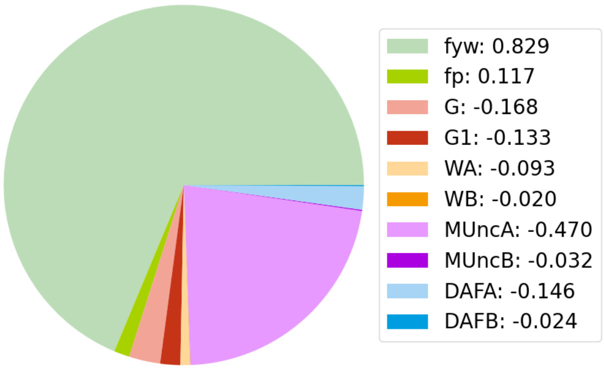

Figure 6: Sensitivities – relative influence given as α-values on the reliability level of Ribe Vester Å.

3.3. *Orehøjvej*

The bridge passing *Orehøjvej* is a post-tensioned bridge with a butterfly cross section. It spans a highway close to a larger city in Denmark and was built in 1972. The bridge consists of 4 spans and a total length of 76.5m cross section, see Figure 7.

The bridge is classified as Class 60 in the deterministic assessment, relatively low for a highway bridge. As torsion is found to be the critical limit state of the bridge and the concrete compressive strength has relatively large influence on the reliability level, strengthening of the bridge would be quite extensive. Meaning that disturbance of the traffic on the highway is inevitable and will cause delays and be of inconvenience of the road users. The highway has in 2022 a YDT of above 55,000 vehicles.

Figure 7: Bridge passing Orehøjvej.

The critical limit state is formulated by:

$$g(\mathbf{x}) = T_{Cap}(f_c, f_y) - T_{Load}\begin{pmatrix} G, G1, Ipar, WA, WB, MUncA, \\ MUncB, DAFA, DAFB \end{pmatrix} \tag{5}$$

where T_{Cap} and T_{Load} is describes the torsion capacity and torsion from permanent and traffic loading respectively.

A target reliability index of β_t = 4.26 was found appropriate (ductile failure with bearing capacity reserve). This target reliability level was meet by the performed reliability-based assessment resulting in a reliability of β = 4.48 for a heavy vehicle of 80 t. Figure 8 show the relative influence of the stochastic parameters on the reliability level, which indicates the three parameters with larges impact is the concrete compressive strength, the yield stress of the reinforcement and the model uncertainty of the heavy vehicle (vehicle A) while the influence of vehicle B is relatively small.

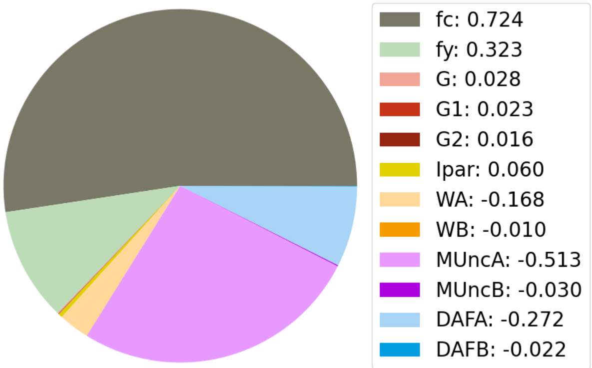

Figure 8: Sensitivities – relative influence given as α-values on the reliability level of Orehøjvej.

3.4. Vestmotorvejen

The bridge *Vestmotorvejen* carries a south going highway over a west going highway close to the capital in Denmark, see Figure 9. *Vestmotorvejen* was built in 1965 and is post-tensioned bridge with a butterfly cross section and 4 spans resulting in a total length of 98 m. The required load carrying capacity of the bridge is Class 100.

Figure 9: Bridge passing Vestmotorvejen.

In the deterministic assessment Class 70 (simultaneously presence of a heavy vehicle of 70 t and a standard vehicle of 50 t) was achieved and the torsion capacity was identified as the critical failure mechanism. Upgrade of the bridge is not a straight-forward strengthening project as it was the horizontal wall in the hollow box-girder cross-section which did not have enough capacity in the deterministic assessment. Strengthening would require comprehensive work from the underside of the bridge, if even possible. The passing of the bridge (above or underneath) has a YDT of 130,000 vehicles, which can cause severe inconvenience of the bridge users leading to socio-economic consequence by people being stuck in queues.

It was found beneficial to carry out reliability-based assessment of the critical failure mode with a limit state described by eq. (5) as for *Orehøjvej*. It was found appropriate to select a target reliability index of β_t = 4.75 for the ductile failure mode. The result of the probabilistic assessment was an upgrade of the bridge class to Class 115 (simultaneously presence of a heavy vehicle of 115 t and a standard vehicle of 50 t) with a reliability index of β = 4.79. Figure 10 show that the three parameters with highest influence on the reliability level is concrete compressive strength, the yield stress of the reinforcement and the model uncertainty of the heavy vehicle as found for *Orehøjvej*. However, the influence of the model uncertainty on the safety is in this case larger the concrete compressive strength. A more in-depth sensitivity of this limit state is presented in (O'Connor, (2018))

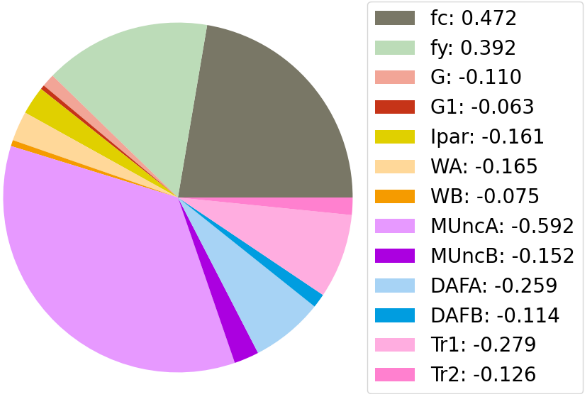

Figure 10: Sensitivities – relative influence given as α-values on the reliability level of Vestmotorvejen.

4. RESULTS

The experience with reliability-based assessment for various bridges suggests, also illustrated with current examples, that in most cases the load-bearing capacity can be upgraded. This is achieved by applying bridge-specific stochastic models instead of utilizing the conventional deterministic method with general partial safety factors.

The results show an upgrade in the bridge class, allowing for an increase in the weight of heavy vehicles by 25-60% compared to the deterministic analysis, as shown in Table 2. The upgrade of the capacity varies from bridge to bridge even in case of the same failure mechanism, which e.g. is the case for *Orehøjvej* and *Vestmotervejen*, as the stochastic parameters and their influence on the reliability level are specific to each bridge and failure mechanism.

Table 2: Results of deterministic and probabilistic assessment of 4 concrete bridges given by the achieved weight of the heavy vehicle.

Bridge	Deterministic	Probabilistic
Heager Å	70 t	100 t
Ribe Vester Å	150 t (UR = 115%)	150 t (UR < 100%)
Orehøjvej	60 t	80 t
Vestmotervejen	70 t	115 t

Table 3 presents a rough approximation of the financial outlay, expressed in Euros (EUR), and the additional CO_2 footprint that would have arisen, if the existing bridge had been replaced by a new bridge instead of conducting a reliability-based assessment to upgrade the bearing capacity of existing structure. A strengthening approach would likely entail lower costs and CO_2 emissions relative to the estimates outlined in Table 3 for a replacement solution.

It should be noticed that the approximated savings in Table 3 solely include expenses minimized CO_2 emission related to materials and do not account for any other costs such as traffic congestion, delays, additional construction work and consequential environmental impact.

Table 3: Estimated cost and CO_2 footprint connected to replacing the existing bridge with a new or conduct a comprehensive strengthening project.

Bridge	EUR	CO_2
Heager Å	> 250K	60 tons
Ribe Vester Å	> 5.5m	2300 tons
Orehøjvej	> 1.5m	100 tons
Vestmotervejen	> 2.5m	200 tons

5. CONCLUSIONS

Reliability-based assessment provides a means of achieving a more realistic evaluation of the reliability level of existing bridges, in contrast to the general deterministic approach that often yields a conservative assessment of individual structures, as the partial factors are calibrated to be broadly applicable.

The probabilistic approach offers the potential for upgrading the load bearing capacity of bridges, without unnecessary strengthening. Thus, it helps reduce maintenance costs, waste of materials and natural resources, and avoiding needless pollution and disruptions of peoples live. In this way, reliability-based assessment can contribute to the development of a sustainable society with respect economy, society and environment.

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