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Guideline for Reliability-Based Classification of Existing Bridges

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ABSTRACT: This paper presents the forthcoming update of the Danish guideline for reliability-based classification of existing bridges to published by the Danish Road Directorate (DRD) in 2023. The update of the guideline reflects the commitment of the DRD to consider reliability-based assessment for all bridge structures that have failed a deterministic assessment. This is very much in-line with the high focus from the society to become more sustainable. The Danish guideline for reliability-based classification of existing bridges is unique in the sense that it gives structured guidance for practicing engineers on how to perform a reliability-based classification of an existing bridge. The newest update of the guideline is based on decades of experience of reliability-based assessment of existing bridges in Scandinavian countries. A significant contribution to the updated guideline has been to guide the users in how model uncertainties can be quantified, assessed, and modelled in a consistent way to reflect the calibration of the Danish partial safety factors. The guidance on the formulation of critical limit states and how the critical limit state and failure mechanism is related to the target safety level has also been elaborated. Furthermore, an illustrative example of a generic bridge has been included to guide the users through the most common limit states (i.e. bending moment and shear with stirrups) for existing concrete bridges in Denmark.

1. INTRODUCTION

This paper presents the recent update of the Danish Road Directorate's Guideline of Reliability-Based Classification of Existing Bridges. The guideline is believed to be the first of its kind (O'Connor & Enevoldsen (2009)), and also the only one focusing specifically on bridges with detailed advice on how to model the uncertainties associated with both the load and resistance variables. The recent update of the guideline is motivated by an increased focus on enabling a more sustainable infrastructure sector whereby unnecessary repairs/interventions are avoided.

The new guideline features an example of a concrete beam bridge where the modelling of the critical limit states, the associated stochastic variables and the assumptions are described in detail and can serve as training material for consulting engineers.

The new version of the Eurocodes will have a much greater focus on reliability-based assessment with extensive background material available of the assumed uncertainties for the calibration of the safety factors. The increased focus on reliability-based assessment of structures and geotechnical structures might be seen in-line with the general trend in society to provide for more sustainable infrastructure management practices, including those related to bridge structures. This translates directly to life-time extension, minimizing replacement and new build, minimizing repair, while still being operable and in many situations even increasing functionality.

The context for the use of the guideline can be further elaborated when one considers the aging stock of existing bridges subjected to capacity demands for which they were not initially designed, including those related to special transport movements.

2. CLASSIFICATION SYSTEM IN DENMARK FOR HEAVY TRANSPORTS

In Denmark a classification system is implemented for the administration of heavy vehicles (DS/EN 1991-2 DK NA:2017). The system is developed such that both the bridges and the heavy vehicles should be classified such that the classes are comparable. This ensures that for a given bridge the capacity assessment (classification) only needs to be carried out once and that once the bridge is classified it is easy for the administrators to decide whether a given heavy vehicle is allowed to pass the bridge with its given classification.

Figure 1 shows the Class 100 road network in Denmark for the roads that is administered by the Road Directorate. To have an effective traffic flow it is the goal that all bridges in this network can be classified as minimum Class 100. Where Class 100 implies that the structure is capable of carrying a 100 t vehicle without any restrictions on normal flow conditions (i.e. multi lane presence longitudinally and transversely).

For a normal deterministic classification of a road bridge the traffic load combination applied is comprising the standard vehicle of (weight 50 t – 200 t) with a secondary standard heavy vehicle of 50 t. The secondary standard vehicle is to present a “normal” truck which is loaded and has an axle configuration according to the Danish Traffic Act.

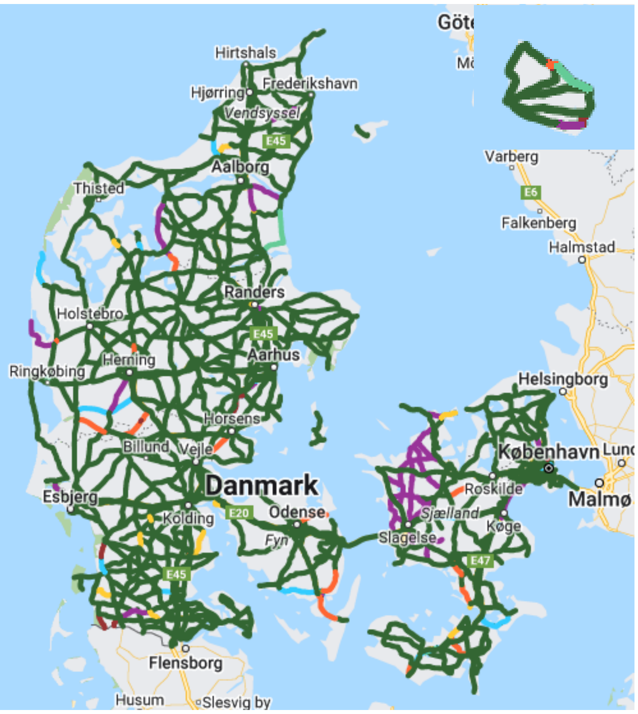

Figure 1: Class 100 Road Network in Denmark.

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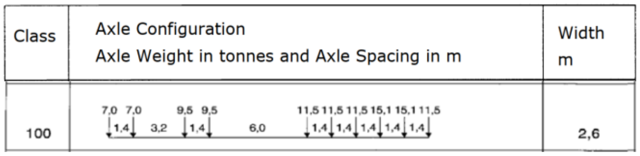
The classification system (DS/EN 1991-2 DK NA:2017) is based on a set of standard vehicles representing vehicles with a total weight ranging from 20 t to 200 t an example of standard vehicles is shown in Figure 2.



Class	Axle Configuration Axle Weight in tonnes and Axle Spacing in m	Width m
100	7,0 7,0 9,5 9,5 11,5 11,5 11,5 15,1 15,1 11,5 1,4 3,2 1,4 6,0 1,4 1,4 1,4 1,4 1,4	2,6

Figure 2: Example of a standard vehicle – Class 100.

3. SAFETY LEVEL AND CODE COMPLIANCE

The guideline has over the past 20 years served as the justification for bridge owners like DRD in Denmark for applying reliability-based assessment of bridges. The current update of the guideline ensures that the learnings from the past 20 years in the application of this guideline (Road Directorate (2004)) are reflected. This taken together with the examples is considered to make the guideline operative for both code users but also for bridge owners like DRD who will approve the reliability-based classification of their bridges.

To provide legal justification for reliability-based assessment of bridges the guideline should not only be operative but the requirement for the reliability-index or failure probability shall be as for the deterministic assessment and the requirement for bridge in Denmark.

The reliability index, β, 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 standardized normal distribution.

The requirement for the reliability index in Denmark was lowered from 5.2 (new bridges) to 4.75 for existing bridges in 2017 (Vejregler (2017)). This was also reflected in the deterministic assessment, where the safety factor applied to the heavy vehicle (giving the classification) was lowered from 1.40 to 1.25 for new and existing bridges respectively.

The requirement for the reliability index depends on the failure mechanism in the modelled limit state, see Table 1. The target reliability index reflects the value of γ_1 in the Danish National Annex (DS/EN 1990 DK NA:2021).

The requirement for the target reliability index shown in Table 1 differentiate between brittle and ductile failure modes, where ductile failure modes can be e.g. the bending moment failure or shear with stirrups, where cracking of the concrete will give warning before a failure will occur. Whereas for the brittle failure mode the failure can be seen as sudden without any previously warning e.g. shear without shear reinforcement for a concrete beam.

Table 1: Target reliability index for the ultimate limit state DRAFT - Road Directorate (2023).

Failure type	*Failure with warning and bearing capacity reserve*	*Failure with warning but without capacity reserve*	*Failure without warning*
β_t	*4.26*	*4.75*	*5.2*
p_f	10^{-5}	10^{-6}	10^{-7}

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4. MODEL UNCERTAINTIES

The model uncertainties are split into three different approaches which allows for more detailed information to be taken into account as/where available. The three methods are respectively termed:

1) General
2) Quantified with tests
3) National calibration

4.1. General

The first method 1) general refers to the method outlined in NKB (1978) which is directly applicable for all failure mechanism in all limit states. This general applicability is powerful if the interpretation across the users is aligned. Hence, more concrete examples of how the model uncertainties can be interpreted is given in the update of the guideline.

4.2. Quantified with tests

The model uncertainties quantified with tests shall directly follow the approach described in DS/EN 1990: 2007 Annex D for calculation of the bias and uncertainty of the capacity formula used to model the failure mechanism. These can then be used directly in the reliability-based assessment as stochastic models for the model uncertainty. It should always be ensured that the used tests are representative and are sufficiently numerous with regard to different testing facilities to avoid any unintentional bias, which would not then be representative of the test population.

4.3. National calibration

DS/INF 172 (2009) represents the background information about the Danish partial safety factors. The applicability for this is limited to use of Danish partial safety factors, hence it is chosen not to elaborate in detail. In brief, the model uncertainties are directly linked to the material parameters, hence, no differentiation between the failure mechanism is made.

5. MATERIAL STRENGTH

It is important to realize that the definition of material strength might have changed over time for different versions or generation of a given standard.

5.1. Concrete structures

The tables for the stochastic models for the concrete compressive strength in the updated guideline have been adjusted to reflect the use of the 5%-fractile instead of the 10%-fractile, which has been used in earlier versions of the Danish standards. In general, it is recommended that concrete cores are taken from the actual structure and tested if the concrete compressive strength is found critical for the capacity assessment. The underlying stochastic models are as presented in the original version of the guideline.

The table presenting the stochastic models for the non-prestressed steel reinforcement has been adjusted to represent the 5%-fractile instead of the 0.1%-fractile, which has been used in earlier versions of the Danish standards. The standard deviation is kept constant with 25 MPa, hence, the uncertainty of older steel types such as St 37 has larger uncertainty than for example tentor steel, which is in-line with test results of reinforcement steel from older bridges.

5.2. Steel structures

An extension of the table presenting the stochastic models for structural steel has been included, as newer types of steel such as S235, S355 etc. have been introduced. The stochastic models for these types of steel suggest that the yield stress f_{yk} is the 5%-fractile, however, the new version of the Eurocodes might specify another fractile such as the characteristic yield stress. For the assessment of existing structures, it is recommended to perform tests of the steel if the strength is found critical for the capacity assessment.

5.3. Other types of structures

The general principles presented in the guideline is intended to be applicable for a wide range of structures and limit states.

6. TRAFFIC LOAD

The Danish Road Directorate has several WIM stations throughout Denmark and significantly many traffic counters, which can only measure the length of the vehicles passing. The WIM measuring stations are all placed at roads which are Class 100, meaning it is difficult to separate the Class 60 vehicles (special transport with a special permit) with a truck according to the Road Traffic Act (RTA) with overweight. However, from the WIM measuring stations it is clear, that the number of heavy vehicles has increased significantly during the past two decades.

6.1. Associated vehicle

In the deterministic assessment the heavy vehicle (50 t – 200 t) is placed next to the standard vehicle of weight 50 t, whose statistical characteristics have been modelled with a mean as the characteristic value and standard deviation of 5 t. The WIM data suggests that the mean value is lowered, and the standard deviation is increased. The standard deviation of 5 t comes from the assumption that there is more control with special heavy vehicles, which is still considered to hold, however, not for the RTA truck as this truck can pass all normal bridges without any special permit or control. Hence, the mean value and the coefficient of variation have also been adjusted to give a better representation of the actual traffic. The values can be seen in Table 2, where a selection of vehicles have been included.

Table 2: Selection of standard vehicles – weight and distribution parameters DRAFT - Road Directorate (2023).

Standard vehicle Weight Wi	*Mean weight [tons]*	*Standard Deviation [tons]*	*Coefficient of variation*
Secondary vehicle B	*47.7*	*7.2*	*0.15*
The Road Traffic Act (RTA)	*53.1*	*6.9*	*0.13*
Class 60	*63.4*	*5.1*	*0.08*
Class 100	*109.2*	*6.6*	*0.06*
Class 125	*131.4*	*7.0*	*0.053*

6.2. Dynamic amplification

The dynamic amplification factor is only modelled as function of the influence length in the deterministic classification of bridges. For the stochastic modelling it is also modelled to be a function of weight, where the dynamic amplification decreases with both increasing influence length and the weight of the vehicles, see Figure 3.

6.3. Number of trucks

From the WIM data and the traffic count stations it is apparent that the number of trucks which has a total weight around the limitations of the RTA has significantly increased, hence the number of suggested vehicles for a motorway has increased from 200 per year to 640,000 per year, this includes some conservatism to allow for traffic growth and represent one of the most heavily trafficked motorways in Denmark. The annual number of administratively determined standard vehicles are given in Table 3 DRAFT - Road Directorate (2023).

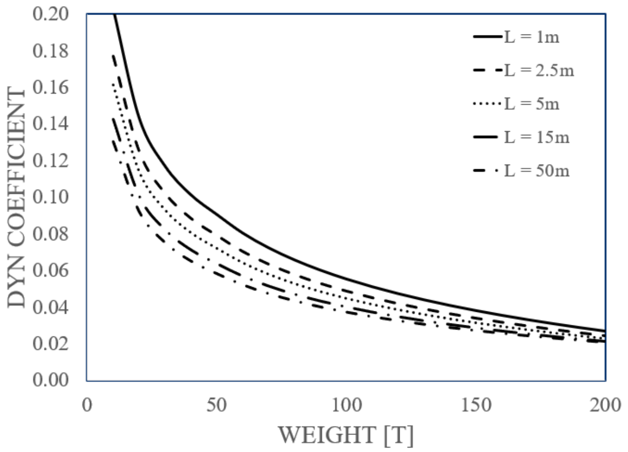

Figure 3: Example of the dynamic coefficient as function of the weight – DRAFT - Road Directorate (2023).

6.4. Number of trucks

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Table 3: Administratively determined annual number of standard vehicles – N_i, DRAFT - Road Directorate (2023).

Class/Road Type	*RTA (Road Traffic Act)*	*80*	*100*	*150*
Motorways	*640 000*	*1800*	*750*	*200*
Main roads	*370 000*	*1000*	*200*	*100*
Other	*240 000*	*500*	*100*	*50*

7. DOCUMENTATION

To assess whether the results of the reliability-based classification and the modelling of the stochastic variables meet the expectations of the bridge owners a need for more concrete recommendation of appropriate documentation is found. A proposal for an outline of the documentation has been included with a focus around detailing the assumptions made for the stochastic models and the results of a sensitivity analysis to assess the robustness of the results and computed reliability level.

8. PRACTICAL EXAMPLES

The objective with the update of the guideline is also to increase the use of reliability-based classification of bridges not just in number of bridges assessed but also to train more consultants in the use of reliability methods. Therefore, a practical example of typical concrete beam bridge has been included in the Appendix of the DRAFT guideline DRAFT - Road Directorate (2023). The concrete beam bridge example is presented here in compressed format. The interested reader is referred to the guideline for more comprehensive treatment.

8.1. Concrete beam bridge

A concrete beam bridge with a span width of 12 m, simple supported with a cross-section as shown in Figure 4 is considered in the example. The bridge is designed to be a Class 100 bridge, meaning that a 100 t truck can pass bridge without any restrictions. All bridges in Denmark are RC3/CC3 structures.

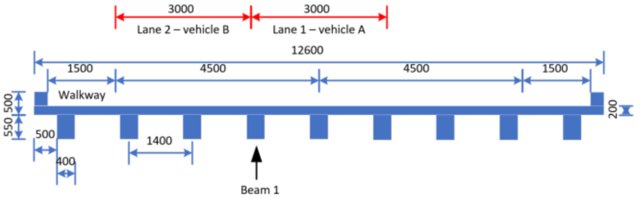

Figure 4: Cross-section of the concrete beam bridge. Measurements are given in mm.

8.2. Critical Limit state

The critical ULS load combination using partial factors is given as shown in Eq. (2):

$$(1.25 \cdot VehA \cdot DAF_A + 1.05 \cdot VehB \cdot DAF_B + 1.0 \cdot G + 1.0 \cdot G_1) \cdot K_{FI} \tag{2}$$

where $VehA$ is the load effect from the heavy vehicle (here Class 100), DAF_A is the dynamic amplification factor for vehicle A, $VehB$ is the load effect from the secondary vehicle (Class 50), DAF_B is the dynamic amplification factor for vehicle B, G is the structural self-weight, G_1 is the super-imposed deadload and K_{FI} is the factor to differentiate between reliability/consequence class.

8.3. Load effects

The bending moment load effect is shown in Figure 5 and the characteristic section forces for Beam 1 are given in Table 4.

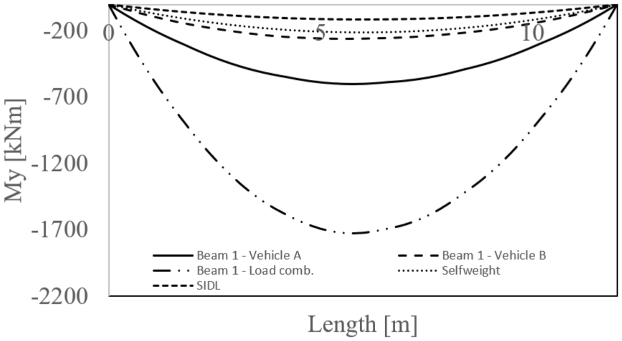

Figure 5: Bending moment curves for characteristic loads.

Table 4: Characteristic section forces for Beam 1 at x = 5.7 m.

Variable	*Bending moment [kNm]*
Self-weight	*211*
SIDL	*114*
Vehicle A	*600*
Vehicle B	*258*
Total incl. partial factors	*1726*

8.4. Deterministic capacity

The deterministic bending moment capacity of the cross-section can be found given in Eq. (3):

$$M_{Rd} = \left(d - \frac{1}{2} \cdot x \cdot 0.8\right) \cdot A_s \cdot f_{yd} \tag{3}$$

where

$$x = \frac{A_s \cdot f_{yd}}{f_{cd} \cdot 0.8 \cdot b_w} \tag{4}$$

It is assumed that there are 11.5 active bottom reinforcement bars with a diameter of 25 mm, the cover layer is 30 mm and the depth of the cross-section is d = 697.5 mm with a width of b_w = 1.4 m, which gives a height of the compression zone of x = 74 mm, which from Figure 4 is seen to be within the top flange. The characteristic concrete compressive strength is $f_{ck} = 45$ MPa and the material partial factor is according to DS/EN 1992-1-1 DK NA:2021 $\gamma_c = 1.4$. The reinforcement steel is assumed to be tentor steel will a yield strength of $f_{yk} = 550$ MPa and a material partial factor of $\gamma_s = 1.2$ according to DS/EN 1992-1-1 DK NA:2021.

With the assumptions above the bending moment utilization ratio is 1.0 for the capacity assessment with partial factors.

8.5. Target Reliability Level

The bending moment failure function for a reinforced concrete beam bridge is assessed to be a ductile failure mode, where severe cracking of the concrete and deflections will occur before an actual failure of the bridge is experienced. However, as the beam bridge is simply supported then there is no possibility to account for instance for plastic re-distribution of the forces, hence the target reliability level is found to be $\beta_t = 4.75$, see also Table 1.

8.6. Critical failure function

The critical failure function for the bending moment limit state is modelled as given in Eq. (5):

$$g(\mathbf{x}) = M_R - M_{Load} = \left(d - \frac{1}{2} \cdot \frac{f_y \cdot A_s}{f_c}\right) \cdot x \cdot b_w \cdot A_s \cdot f_y - M_{Load}\left(\begin{matrix} VehA, VehB, DynA, DynB, G, G_1, \\ MUncA, MUncB, MUncG \end{matrix}\right) \quad (5)$$

where the stochastic models are presented in Section 8.7.

8.7. Stochastic modelling

The stochastic models are presented for the variables which are given in the failure function. The material parameters are modelled by use of the model uncertainties described in Section 4.1 by introducing the stochastic variable I_m for material capacities with the uncertainty given as given in Eq. (6):

$$V_{I_m} = \sqrt{{V_{I_1}}^2 + {V_{I_2}}^2 + {V_{I_3}}^2 + 2\left(\rho_1 V_{I_1} + \rho_2 V_{I_2} + \rho_3 V_{I_3}\right) V_m} \quad (6)$$

where I_1 is the accuracy of the computation model, I_2 is the accuracy of determining the material parameter, I_3 is the accuracy of the identity of the material.

Table 5: Characteristic section forces for Beam 1 at x = 5.7 m.

	fc	*fy*
Characteristic	*45 MPa*	*550 MPa*
V_m	*0.12*	*0.042*
I_1	*Good*	*Good*
I_2	*Medium*	*Low*
I_3	*Good*	*Good*
V_{tot}	*12.4*	*6.0*

For the concrete material with the failure mechanism being bending moment the accuracy of the computation model is assessed to be “Good”, the accuracy of the determining the material parameters “Medium” and the identity of the material by assuming as-built information as “Good”, the following uncertainties are then used according to DRAFT - Road Directorate (2023). For the yield stress of the reinforcement the same uncertainties are used except for the uncertainty of determining the material parameters is assessed to be “Low”. The stochastic models are presented in Table 6.

Table 6: Stochastic models.

		Distribution	*Mean*	*CoV*
Concrete incl. model unc.	*fc*	*Log-Normal*	*55.2 MPa*	*0.12*
Yield stress incl. model unc.	*fy*	*Log-Normal*	*590 MPa*	*0.06*

Self-weight	*G*	*Normal*	*1.0*	*0.05*
SIDL	*G1*	*Normal*	*1.0*	*0.1*
Weight of vehicle A	*VehA*	*Normal*	*131.4 t*	*0.053*
Weight of vehicle B	*VehB*	*Normal*	*53.1 t*	*0.13*
Model unc. self-weight and SIDL	*MUncG*	*Normal*	*0.0*	*0.05*
Model unc. VehA	*MUncA*	*Log-Normal*	*1.0*	*0.1*
Model unc. VehB	*MUncB*	*Log-Normal*	*1.0*	*0.1*

8.8. Results/Sensitivities

It is found that the target reliability level is met for a Class 125 vehicle as the heavy vehicle A in the classification scheme. The class of the heavy vehicle A is simply increased until the target reliability is met. The results are also given in Table 7. Here it can be seen that the classification is increased from Class 100 to Class 125, which means an increase in live load carrying capacity by 25% by performing reliability-based classification instead of using the normal partial factors.

Table 7: Results of the reliability-based classification.

Deterministic	*Reliability-based*
Class 100	*Class 125* $(\beta = 4.8)$

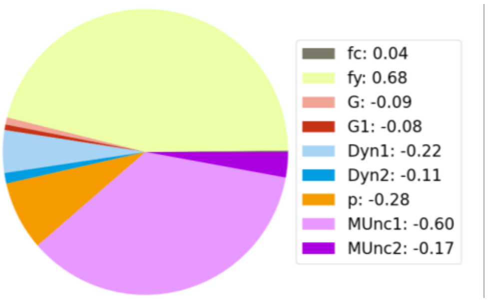

Figure 6: Sensitivities – relative influence given as α-values.

The relative influence of the different stochastic variables is shown in Figure 6 by the pie-chart and the table with the α-values.

Figure 6 shows the relative influence (α-values) of the modelled stochastic variables. The relative influence of the yield stress (f_y) of the reinforcement has the largest influence on the reliability index as expected for a bending moment failure function. The model uncertainty of the heavy vehicle A is the second largest influence. From the pie-chart is also apparent that the load effect in general has slightly more influence than the resistance side, where the yield stress of the reinforcement clearly is the dominant variable.

9. CONCLUSIONS

The main updates of the guideline for Reliability-Based Classification of Existing Bridges published by the Danish Road Directorate have been presented together with a practical training example. The main updates include specifically more guidance of the different assumptions and choices for how to perform the reliability-based classification such as the target reliability level, model uncertainties, traffic load modelling and the stochastic models for the material parameters.

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