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A STUDY ON THE EFFECT OF IMPROVED LOAD MODELS ON STRUCTURAL SAFETY

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In modern structural design standards, reliability requirements are verified by a semi-probabilistic approach, in which the safety of a structure is controlled by partial safety factors. These standards are typically based on simplified models of load and structural performance, where approximations and assumptions are selected conservatively, which leads to additional “hidden” safety. If these models are replaced by more sophisticated and potentially more accurate models, some of this hidden safety might be lost. Overall, increased accuracy is preferable, as it leads to a more economical and sustainable use of resources, but the question is if lost hidden safety leads to an overall reduction in structural reliability, and by how much.

This study investigates the hidden safety associated with the traffic load model of road bridges defined in the Eurocode. The Eurocode model is compared to a direct simulation of the traffic load. The hidden safety is determined within the domain of reinforced concrete T-beam bridges. It is estimated via a comparison of the nominal probabilities of failure of two designs of the bridges within the considered domain: One design using the Eurocode traffic load model and another design using the simulated traffic. The nominal probability of failure of the two design variations differs by a factor of 10^4 to 10^9, depending on the number of spans, the length of the spans and the traffic data used within the simulation.

Keywords: Structural design standards, hidden safety, road bridges, traffic load model.

1 Introduction

In modern structural design standards, such as the Eurocode, reliability requirements are verified by a semi-probabilistic approach: On the action side, loads are applied to a static model and characteristic load effects S_k at critical cross sections are calculated. On the resistance side, values of material properties are used as input values to resistance models and the characteristic resistances R_k are calculated. The safety of a structure is controlled by partial safety factors, which increase S_k and decrease R_k, resulting in the design actions S_d and design resistances R_d. The verification of the structure against failure is then performed by ensuring the following inequality:

$$S_d \leq R_d \tag{1}$$

However, not only the partial safety factors influence the safety of the structure. In addition, assumptions and approximations in load models, the static model, the material properties and the resistance models are typically selected on the safe side. If the calibration of partial safety factors does not take this into account, these model choices lead to additional "hidden" safety.

Erasing hidden safety is desirable since it leads to a more resource efficient design. However, it may simultaneously effect the structural reliability. In this study, the hidden safety arising from the traffic load model *LM1* of the Eurocode 1 part 2 (2010) and its national annex (2012) is investigated by means of the domain of T-beam road bridges.

2 General problem description and definition of a measure of hidden safety

Structures are – or are planned to be – parts of reality. Structural design methods try to translate aspects of the reality of a structure into the language of mathematics. This is an epistemological problem of the interaction of reality, models of the reality and theories applied to these models (Cartwright and McMullin 1984, Cartwright 1994 and Bailer-Jones 2009).

Models and theories are not perfect representations of reality. Hence an approximation error exists in the calculated values of the considered aspect. This adds uncertainty to the structural design process. If parts of a structural design method are replaced with a more realistic method and the partial safety factors are not adapted to the new method, this affects the design of the structure in two ways: On the one hand, the reduced uncertainty leads to an oversizing of the bridge resistances. On the other hand, the elimination of assumptions on the safe side leads to a reduction of the design resistances. If the latter dominates, buildings become less safe. The amount of lost safety is the hidden safety associated with the simpler model.

To be able to measure the amount of hidden safety introduced by a part of a design methodology P, the following measure is used:

$$h_{log}(P, P_r, D, R) = \log_{10}(\Pr(F|P_r, D, R)) - \log_{10}(\Pr(F|P, D, R)) \quad (2)$$

where P_r is a reference method to calculate the same aspect as P in a presumably more realistic way. D is the design methodology of which P and P_r are part. R is the performed reliability analysis and F the definition of failure defined within R.

This measure of hidden safety is only defined in a relative sense and is dependent on the design methodology and the utilized reliability analysis. Calculation of an absolute measure is not feasible, since it would require "perfect information" of "reality".

3 Hidden safety in the traffic load model of the Eurocode

This study focusses on the hidden safety in the load model *LM1* of the Eurocode for traffic applied to the domain of reinforced concrete T-beam road bridges. To investigate the hidden safety resulting from this model, it is compared to a reference model based on a simulation *Sim* of the traffic load. In all other aspects, the design methodology follows the Eurocode and uses the following models and theories. Thus two different design variations of the bridge are compared - one using $LM1$ and one using Sim – and the logarithmic measure of hidden safety $h_{log}(LM1, Sim, Eurocode, R_{FORM})$ is calculated. R_{FORM} is a reliability analysis based on the First Order Reliability Method (FORM) (Rackwitz and Fessler 1978).

LM1 consists of uniformly distributed loads on each traffic lane and the remaining area of the bridge. Moreover, double-axle loads are added to each lane (Eurocode 2010). The load model was calibrated such that the resulting characteristic cross-section forces are equivalent to the 1000 year return period of the cross-section forces derived from measurements of multiple European bridges with extreme traffic conditions (Merzenich 1993, Merzenich and Sedlacek 1994).

Sim was performed following the approach of Nowak and Fischer (2017): Based on local traffic data from specific sites, traffic streams (sequences of vehicles) are generated applying numerical traffic simulation. Random sampling is performed based on stochastic models for various traffic parameters derived from the local traffic data. A structural analysis is carried out and the resulting load effect time histories for certain response parameters at decisive locations on the structure are evaluated. The simulations in this study are performed for a 100-year time period. Based on the time histories, stochastic descriptions are obtained describing the internal forces resulting from road traffic. The annual block maxima are taken to fit generalized extreme values distributions via the Maximum-Likelihood-Method. The 99.9 [%] quantiles of the fitted distributions are then taken as characteristic load effects to design the bridge (corresponding to the 1000 year return period used in *LM1)*.

On the load side, in addition to the traffic load only the permanent load induced by self-weight is considered and modeled according to the Eurocode 1 (2010). The loads are applied to a simple one-dimensional beam model of the bridge and the cross-section forces at the critical points are calculated using Euler-Bernoulli-beam-theory. In case of *LM1* this is done following the load combination rules of Eurocode 0 (2010). In case of *Sim* the load combination rules are circumvented, since the model directly generates the cross-section forces. Hence the subsequently derived measures not only estimate the hidden safety in *LM1* but also in the load combination rules.

On the resistance side, the material models follow Eurocode 6 (2010) and Eurocode 2 (2010). The bending and the shear resistance model both follow the Eurocode 2 (2010). The bending resistance model is derived via the equilibrium of the cross-section forces, whereby the concrete is assumed to be cracked and the compression zone is approximated via a parabolic-rectangular shape. The shear resistance model is derived from a truss model representing the tensile and compression stresses and their respective directions.

To obtain more general statements about the hidden safety in *LM1*, a generic bridge is examined, with varying number of spans from 1 to 3 and varying span length among 15, 20 and 25 meters. Moreover, the traffic-measurements of *Sim* are taken from different highways, representing a *low*, *middle* and *high* traffic density. All other parameters of the bridge are kept constant. Figure 1 shows the cross section of all bridges.

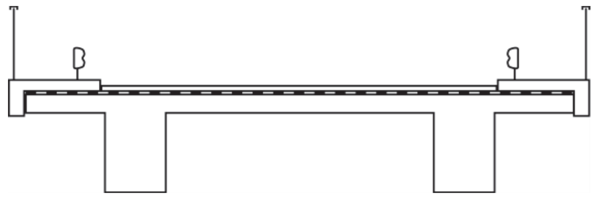

Figure 1. Cross-section of bridges within the considered domain.

To calculate the hidden safety for each of the bridge designs, a reliability analysis R_{FORM} was performed to derive the probabilities of failure. Failure was specified as system failure: For each bridge, multiple failure modes are defined as combinations of shear and moment cross-section failures, so that the bridge becomes kinematic. Cross-section is thereby defined as the cross-section of the whole bridge as in figure 1.

To perform the reliability analysis a probabilistic description of the loads and the resistances is necessary. The derivation of this probabilistic description closely follows the approach of the Eurocode. That is, it uses the same models but defines some of its parameters as random variables. Previous work on the sensitivity of the probability of failure has shown that most of the model-parameters can be chosen deterministically. Following Vrouwenvelder (1997), Spaethe (1992) and Wisniewski (2007), the following parameters are defined as random variables:

- Loads: The permanent load of the asphalt, the caps and the barriers, the self-weight of the bearing structure and the traffic load.
- Resistances: The steel cross section areas, the steel strength of each cross section and the concrete strength.

Moreover, model uncertainties were added to the load models (Braml 2010 and Voigt 2013), the static model (Vrouwenvelder 1997), the bending-resistance model (Bach 1992 and Bönig 2013) and the shear- resistance model (Braml 2010).

The only model of the probabilistic description, which is chosen differently to the Eurocode approach, is the traffic load model. The traffic is modeled using the same simulation approach *Sim* as described above. The time histories of the cross-section forces are superposed with respect to their contribution to the different failure modes. In doing so, the correlation of the inner forces is taken into account. On that basis a probabilistic description of the inner forces of the traffic load was derived, again with the help of extreme values statistics.

Overall the probabilistic description of the loads and the resistances includes 38 random variables. The probability of failure is calculated with FORM. The results are confirmed via a Subset Simulation (SuS) (Au and Beck 2001, Papaioanou et al. 2015). Table 1 summarizes the results.

Table 1. Measure of hidden safety h_{log} in the domain of loosely reinforced concrete T-beam bridges.

Number of spans	Length of each span [m]	Traffic load- model for reliability analysis	Traffic load-model for Design	Nominal probability of failure	Hidden safety h_{log}
1	15	Sim_{low}	LM1	10^{-17}	8
			Sim_{low}	10^{-9}	
		Sim_{mid}	*LM1*	10^{-17}	8
			Sim_{mid}	10^{-9}	
		Sim_{high}	*LM1*	10^{-17}	6
			Sim_{high}	10^{-11}	
	20	Sim_{low}	*LM1*	10^{-14}	6
			Sim_{low}	10^{-8}	
		Sim_{mid}	*LM1*	10^{-14}	5
			Sim_{mid}	10^{-9}	
		Sim_{high}	*LM1*	10^{-14}	4
			Sim_{high}	10^{-10}	
	25	Sim_{low}	*LM1*	10^{-15}	5
			Sim_{low}	10^{-10}	
		Sim_{mid}	*LM1*	10^{-15}	5
			Sim_{mid}	10^{-10}	
		Sim_{high}	*LM1*	10^{-15}	5
			Sim_{high}	10^{-10}	
2	15	Sim_{low}	LM1	10^{-17}	9
			Sim_{low}	10^{-8}	
		Sim_{mid}	*LM1*	10^{-16}	6
			Sim_{mid}	10^{-10}	
		Sim_{high}	*LM1*	10^{-16}	7
			Sim_{high}	10^{-9}	
	20	Sim_{low}	*LM1*	10^{-17}	8
			Sim_{low}	10^{-9}	
		Sim_{mid}	*LM1*	10^{-17}	8
			Sim_{mid}	10^{-9}	
		Sim_{high}	*LM1*	10^{-16}	6
			Sim_{high}	10^{-10}	
	25	Sim_{low}	*LM1*	10^{-16}	9
			Sim_{low}	10^{-7}	
		Sim_{mid}	*LM1*	10^{-16}	7
			Sim_{mid}	10^{-9}	
		Sim_{high}	*LM1*	10^{-15}	6
			Sim_{high}	10^{-9}	

Table 1 (continued). Measure of hidden safety h_{log} in the domain of loosely reinforced concrete T-beam bridges.

Number of spans	Length of each span [m]	Traffic load- model for reliability analysis	Traffic load-model for Design	Nominal probability of failure	Hidden safety h_{log}
3	15	Sim_{low}	*LM1*	10^{-17}	8
			Sim_{low}	10^{-9}	
		Sim_{mid}	*LM1*	10^{-17}	9
			Sim_{mid}	10^{-8}	
		Sim_{high}	*LM1*	10^{-16}	7
			Sim_{high}	10^{-9}	
	20	Sim_{low}	*LM1*	10^{-16}	8
			Sim_{low}	10^{-8}	
		Sim_{mid}	*LM1*	10^{-16}	8
			Sim_{mid}	10^{-8}	
		Sim_{high}	*LM1*	10^{-16}	7
			Sim_{high}	10^{-9}	
	25	Sim_{low}	*LM1*	10^{-16}	7
			Sim_{low}	10^{-9}	
		Sim_{mid}	*LM1*	10^{-16}	6
			Sim_{mid}	10^{-10}	
		Sim_{high}	*LM1*	10^{-15}	7
			Sim_{high}	10^{-8}	

h_{log} varies significantly between 4 and 9. Hence the nominal probability of failure of bridges designed according to *LM1* or *Sim* differs by a factor of 10^4 to 10^9.

The investigated domain of bridges was spanned by three dimensions: The number of spans, the length of each span and traffic density used in *Sim* or rather *LM1*. Keeping one dimension constant and averaging over the other two dimensions, the means $\bar{h}_{log}$ of table 2, 3 and 4 can be calculated.

Table 2. Mean measure of hidden safety $\bar{h}_{log}$ for various number of spans.

Number of spans	1	2	3
$\bar{h}_{log}$	5.8	7.3	7.4

Table 3. Mean measure of hidden safety $\bar{h}_{log}$ for various length of spans.

Length of spans	15	20	25
$\bar{h}_{log}$	7.6	6.7	6.3

Table 4. Mean measure of hidden safety $\bar{h}_{log}$ for various traffic load models.

Traffic load model	Sim_{low}	Sim_{mid}	Sim_{high}
$\bar{h}_{log}$	7.3	6.9	6.1

The lower hidden safety of one-span bridges compared to two- and three-span bridges can be explained with the hidden safety arising from the load combination rules, which are redundant in the one-span case. In other respects, the mean measure of hidden safety decreases with longer span lengths as well as with higher traffic density used within *Sim*.

4 Concluding remarks

This study investigates the effect of improved load models on structural safety. In particular, we measured the change in safety of concrete T-beam bridges, if the Eurocode traffic load model *LM1* is replaced by a simulation of the traffic *Sim*.

The two different traffic load models result in two different bridge designs for each bridge in the considered domain. In average, the design based on *Sim* decreases the volume of bending reinforcements by 26 % and the volume of shear reinforcements by 19 % in comparison to a design based on *LM1*. Hence a much more economical and sustainable use of resources could be achieved. The downside is a reduction of the safety.

To measure the change in safety probabilities of failure are calculated for each bridge design. They vary significantly between 10^{-8} and 10^{-16}. According to the Eurocode a reliability index of $\beta = 4.7$ is required. This corresponds to a failure probability of 10^{-6}. Hence the requirements are fulfilled in all cases. However, the Eurocode is inconsistent weather the required values correspond to a failure at system level or at cross-section level. In case of a failure definition on cross-section level, we expect much higher nominal probabilities of failure. This is confirmed by a more detailed study on a three span bridge (each span 25 [m]). The above definition of failure at system level resulted in the nominal probabilities of failure of 10^{-16} and 10^{-9} referring to the design with *LM1* and *Sim*. A failure definition at cross-section level results in 10^{-8} and 10^{-4} respectively.

It should be emphasized that the calculated nominal probabilities of failure are not the effective probabilities of failure, but only approximations. An approximation error, for instance, arises from the failure definition which implicitly assumes an infinitely rigid bridge plate. This is an unrealistic assumption which adds a bias. Moreover, the calculations neglect torsion failure modes or failure of the bearing and the influence of the temperature.

From the nominal probabilities of failure, the hidden safety is measured. Hidden safety arises from approximations in the models and theories used in the design process. It can only be measured in a relative sense to more realistic models or theories. For this purpose a measure h_{log} is introduced. In the domain of concrete T-beam bridges the mean measure of hidden safety in the traffic load model *LM1* of the Eurocode is estimated at $\bar{h}_{log} = 6.8$. Hence *LM1* is a very conservative traffic load model.

We identified three reason why *LM1* is conservative: First of all, the measurements used to calibrate *LM1* were taken from extreme traffic situations of European bridges. This overestimates the traffic of the average bridge. Instead the measurements should be taken from all traffic situations equally. Second of all, the characteristic value of the traffic load is defined as the 99.9 % quantile. Compared to other load models this is a rather high choice (e.g. the characteristic wind load corresponds to the 98 % quantile). However, the measure of hidden safety h_{log} in this study excludes the hidden safety related to this, since both design variation – one based on *LM1* and one based on *Sim* – choose the 99.9 % quantile as characteristic value. Third of all, *LM1* transforms the measured traffic into a combination of uniformly distributed loads and point loads. This transformation was done such that the resulting load effect were never underestimated for a wide range of bridges. This again overestimates the traffic load of the average bridge.

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