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Safety equivalent assessment of bridges considering structural monitoring

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ABSTRACT: Due to the large number of old bridges as well as the increase of traffic loads the realistic assessment of existing structures becomes more important. Therefore, structural monitoring is being used increasingly to assess the condition of existing bridges in a more realistic way. Meanwhile, the options of using monitoring are versatile and the technical conditions for a safe implementation are given. However, it still must be clarified, to which extent the additional information obtained by structural monitoring are considered within the structural safety concept.

This paper describes how measurement-based information about actual stresses can be integrated into the safety concept for the assessment of existing bridges. In the ultimate limit state, this is done by measured and evaluated extreme values. In the fatigue limit state, the entire loading spectrum is relevant.

1 INTRODUCTION

In Germany exist about 39.500 road bridges in the federal highway network and about 85.500 road bridges in the subordinated road network. Along with about 25.000 railway bridges there are nearly 150.000 bridges in Germany. Most of the existing road bridges were built in the 1960s and 1970s. The increase of traffic loads was not expected to that extend as it has come today. The long working life – especially on railway bridges – intensifies the problem additionally. Apart from that the design codes as well as the load models in the design codes were developed during recent decades. For new constructions it is necessary to consider increasing traffic loads for the whole working life. But for many existing structures, particularly this calculative safety analysis, results in calculative deficits. Existing structures are characterized by the possibility of obtaining additional information about the resistance, actual stresses and their real loads. Fischer (2010) developed a method with which the resistance-side partial safety factors can be modified on the basis of building material tests. Liebig (2011) examined and developed impact-side traffic load models based on structural measurements. Krohn (2014) has shown possibilities to consider measured load collectives in the fatigue check by means of a modified damage equivalence factor. When assessing structures, the traffic loads are the significant part on the load side. It's worth to describe these parts in a more realistic and systematical way. The aim of this paper is to integrate measurement data about the real traffic into the safety concept.

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2 FUNDAMENTALS OF RELIABILITY THEORY

2.1 Limit state and failure probability

Effect E and resistance R are random variables, the basis variables. There is an overlapping area, where effect E is greater than the resistance R. The density function $f_x(x_i)$ that describes all possible states is given by the convolution of the density functions of the basis variables. The limit state function splits the density function $f_x(x_i)$ in a safe and an unsafe area. The limit state is every state where E = R. The point on the limit state function with its shortest distance to the mean of the density function is the design point. The failure probability is given by the convolution integral in the unsafe area. An equivalent measure for the failure probability is the reliability index β, see e. g. Spaethe (1992).

2.2 Target values for the reliability index

In the DIN EN 1990: Eurocode 0 (2005), Annex C a distinction for the target reliability index depending on the limit state is given for middle consequence class CC2, see Table 1.

Table 1. Target values for the reliability index according to DIN EN 1990: Eurocode 0 (2005)

Limit state	Target values for the reliability index	
	1 year	50 years
Ultimate	4.7	3.8
Fatigue		1.5 to 3.8 [a]
Service	2.9	1.5

[a] Depending on access, repairability, consequence tolerance

Further distinctions can be done by economical consideration (JCSS (2001-2015)) or human safety consideration, e. g. Steenbergen, R. D. J. M. et al. (2015). Both gives reduced reliability indices in the range of $\Delta\beta = 4{,}7 - 4{,}2 = 0{,}5$ (related to one year). In Germany such deliberations are not intended by the codes.

3 FUNDAMENTALS OF NORMATIVE RULES

To maintain the required safety level and for the sake of simplifying, for each basis variable there is a safety element defined in the semi probabilistic safety concept. The following Table 2 gives the safety elements on the load side in the ultimate limit state (ULS) and the fatigue limit state (FLS).

Table 2. Normative safety elements on load side

		ULS	FLS
Normative defined loadmodel (characteristic value)		E_k	E_k
Safety elements	Reference to real load level	α	λ
	Uncertainties of representive (characteristic) values of loads	γ_f	
	Uncertainties in modelling the loads and their effects	γ_{Sd}	
	(Normative defined) partial safety factor	$\gamma_f \cdot \gamma_{Sd} = \gamma_F$	
	(Normative defined) combination factor	ψ_0	$\psi_{1/2}$

3.1 Specifics concerning existing structures

Uncertainties of the loads as well as of the model are different for existing structures and new structures. Uncertainties of new structures at planning time are not present to the same extend as of existing structures. The model of load-bearing system can be validated by system identification measurements. Dead loads as well as traffic loads can be measured more precise and thus uncertainties concerning the loads can be reduced. According to the safety concept these lower uncertainties should be reflected in the partial safety factors. In Germany there is at least the possibility to use reduced partial safety factors for the dead loads on concrete or prestressed bridges, regulated in the guidelines for existing structures. Structural reanalyzes of existing structures with load models for new structures often result in calculative deficits, though the structure is still in good condition and the actual traffic loads are less then assumed by the codes. For existing structures, the load models must be defined more precisely in consideration of actual traffic.

3.2 Guidelines for existing structures

Assessing existing road bridges in Germany the "Richtlinie zur Nachrechnung von Straßenbrücken im Bestand" (Nachrechnungsrichtlinie, NRR), BMVBS (2011) has to be applied. For assessing existing railway bridges there is the "Richtlinie 805 - Tragsicherheit bestehender Eisenbahnbrücken" (Ril 805), DB Netz AG (2010), with its first edition from 1991. Both guidelines include four rating levels, with the effort and accuracy increasing from level to level. In both guidelines measurements are generally permitted in a higher grade.

4 STRUCTURAL MEASUREMENTS ON BRIDGES

4.1 System identification measurements

System identification measurements are performed over a period of a few days. They are used to validate the model of load-bearing system concerning a specific behavior, see e. g. Geißler et al. (2014). Common targets can be measuring deformations or elongations or calibrating the FE-model. In this case often proof loads are used to compare measured and calculated reactions. Also, modal analyses can be done with system identification measurements to identify natural frequencies and damping ratio. System identification measurement should always be done initially for the further introduced safety equivalent assessment.

4.2 Structural health monitoring

Using structural health monitoring a structure is monitored concerning a specific target over a longer period of several month to years. The measurement data acquisition can be permanent or periodic. Using structural health monitoring more detailed information, e. g. about the actual loads can be obtained.

4.2.1 Measurement of traffic stresses or traffic loads

In Figure 1, the measured elongation-time-course is shown at the lower flange of a two-field girder due to a crossing.

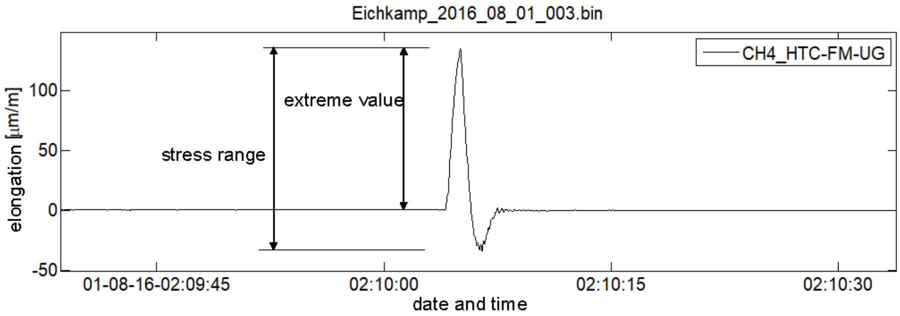

Figure 1. Measured elongation-time-course at the lower flange of a two-field girder due to a crossing.

The measured data can be processed directly statistically, see e. g. Figure 5. In addition, a combined evaluation of local and global measuring points can be used to identify the vehicles crossing over. As a result, a list of all crossing vehicles with their relevant information, e. g. time stamp, lane, vehicle type, speed, weight, axle loads, length and axle distance, is given. The principle measurement concept to identify traffic loads is shown in Figure 2, see Steffens (2019).

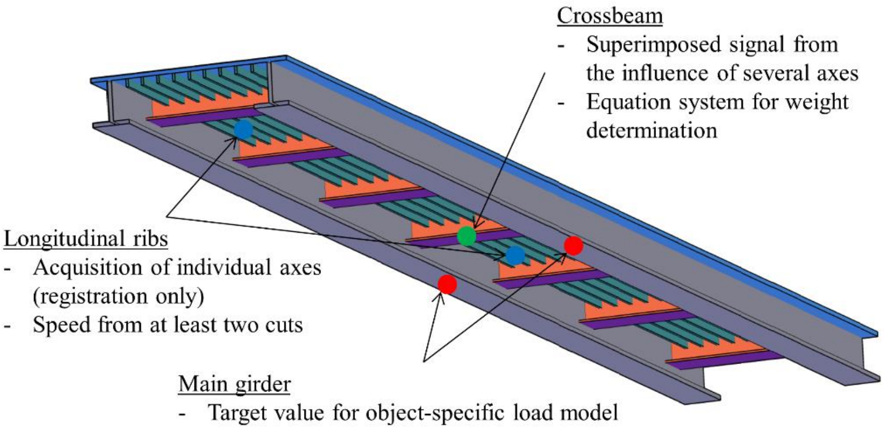

Figure 2. Measurement concept to identify traffic loads.

4.3 Common targets of bridge monitoring

The introduced method of safety equivalent assessment includes several levels, see Figure 3. At the highest level, the evaluation of existing structures can be done by solving the limit state function taking into account measured stresses. On the lower level simplified methods can be used to determine measurement-based safety factors as well as load models for time-dependent loads for ultimate limit state as well as fatigue limit state. On a further level additional issues can be handled, such as combination factors of temperature.

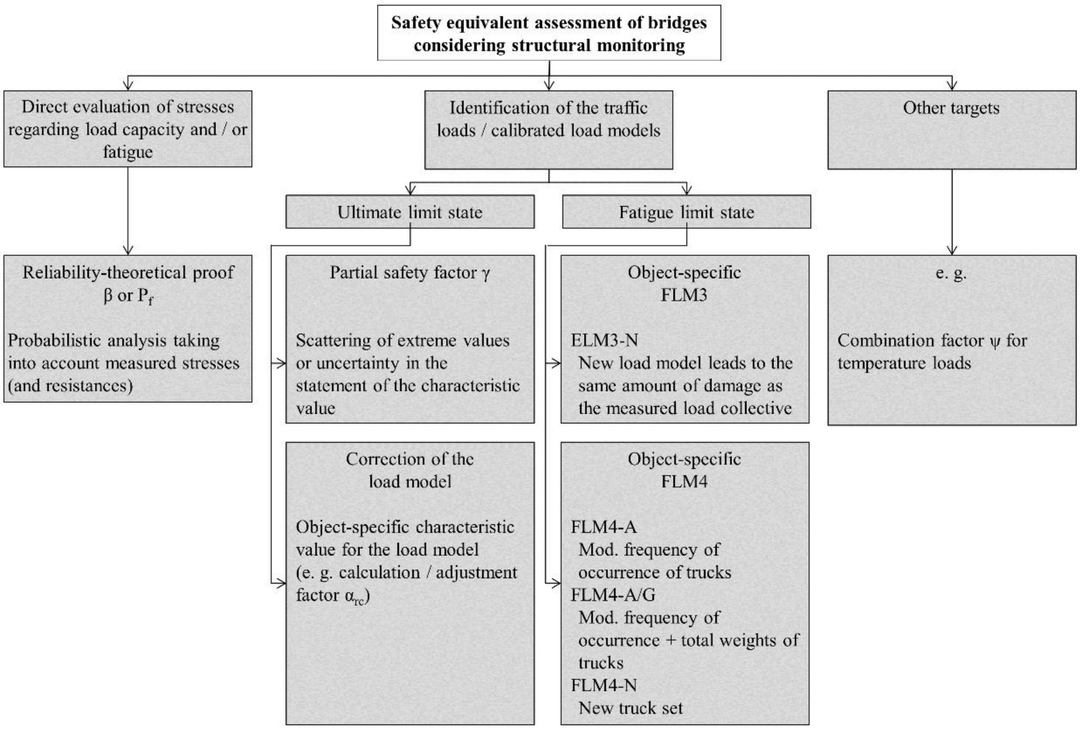

Figure 3. Common targets of bridge monitoring.

5 METHOD FOR SAFETY EQUIVALENT ASSESSMENT

The information about vehicle loads as well as statistical parameters from extreme values obtained via monitoring can be integrated into the safety concept. In the following, a brief methodical presentation is given of how traffic load measurement data can be used to derive modified safety elements and object-specific load models (Figure 3). Detailed explanations are given in Steffens (2019).

5.1 Ultimate limit state

First the differentiation between the adjustment factor and the partial safety factor must be emphasized. While the adjustment factor depends on how heavy the traffic is the partial safety factor describes the scatter of the traffic. For both – the object-specific load model and the modified partial safety factor – first, extreme values of the week are evaluated statistically and approximated by an extreme value distribution type I, see Figure 5.

5.1.1 Object-specific load model

The measurement-based adjustment factor for the recalculation of an existing bridge $\alpha_{rc,meas}$ is the result of the measurement-based characteristic value divided by a normative characteristic value depending on a chosen design code. The implementation of an extreme value distribution type I for the measured extreme week values leads to eq. (1) for the measurement-based adjustment factor.

$$\alpha_{rc,meas,i} = \frac{m_{1,meas} \cdot [1 - 0{,}7797 \cdot v_{1,meas} \cdot (0{,}5772 + ln\{-ln\, q\})]}{E_{c,code}} \tag{1}$$

with

$E_{c,code,i}$	normative characteristic value from calibrated FE model
$m_{1,meas}$	mean value of annual extreme value distribution (extrapolated from monitoring)
$v_{1,meas}$	variation coefficient of annual extreme value distribution (extrapolated from monitoring)
q	underrange probability of characteristic value depending on recalculation period

To calculate the adjustment factor, the main lane of the load model and the real truck lane should be in the same arrangement in cross direction to obtain the largest global adjustment factor.

5.1.2 Modified partial safety factor

When applying an object-specific load model (through the adjustment factor), consequently, the partial safety factor for the traffic load should also be modified. The reference to a normative required reliability level is only achieved by the partial safety factor, which includs the reliability index. As shown in eq. (2) the partial safety factor results from the measurement-based design value divided by the measurement-based characteristic value with an implementation of an extreme value distribution type I.

$$\gamma_{meas} = \frac{m_{T,meas} \cdot [1 - 0{,}7797 \cdot v_{T,meas} \cdot (0{,}5772 + ln\{- ln\, \phi(-\alpha_E \cdot \beta_T)\})]}{m_{T,meas} \cdot [1 - 0{,}7797 \cdot v_{T,meas} \cdot (0{,}5772 + ln\{- ln\, q^T\})]} \qquad (2)$$

with

T	recalculation period
$m_{T,meas}$	mean value of extreme value distribution belonging to recalculation period (extrapolated from monitoring)
$v_{T,meas}$	variation coefficient of extreme value distribution belonging to recalculation period (extrapolated from monitoring)
Φ	standard normal distribution function
α_E	sensitivity factor on load side
β_T	reliability index belonging to period of reanalysis
q^T	setting annual probability of shortfall of the characteristic value depending on recalculation period, extrapolated to period of reanalysis

The partial safety factor by code includes both the uncertainty of the model and that of the load, see DIN EN 1990: Eurocode 0 (2005). The monitoring data corresponds to the stresses on the measurement points, i. e. the model uncertainties are included on that specific points. As a rule, the presented method should be applied at selected points so that the measured value-based safety elements are available for all critical points.

5.2 Fatigue limit state

An object-specific fatigue load model assumes that an arbitrarily compounded set of vehicles with respective frequency in a certain period of time leads to the same damage as the real stress collective. For reference of the measured stress collective to the normative fatigue load model, a measurement-based damage equivalent factor λ_{meas} can be justified by retroactive calculation on condition of damage equivalence. Alternatively, based on the vehicle identification, an object-specific truck composition can be derived, see 6.2.

6 EXAMPLES

The exemplarily selected two-span girder (26 m – 28 m) is a highyway bridge and was built in 1976. The superstructure is composed of three parallel steel main beams with open cross section and orthotropic slab (Figure 4).

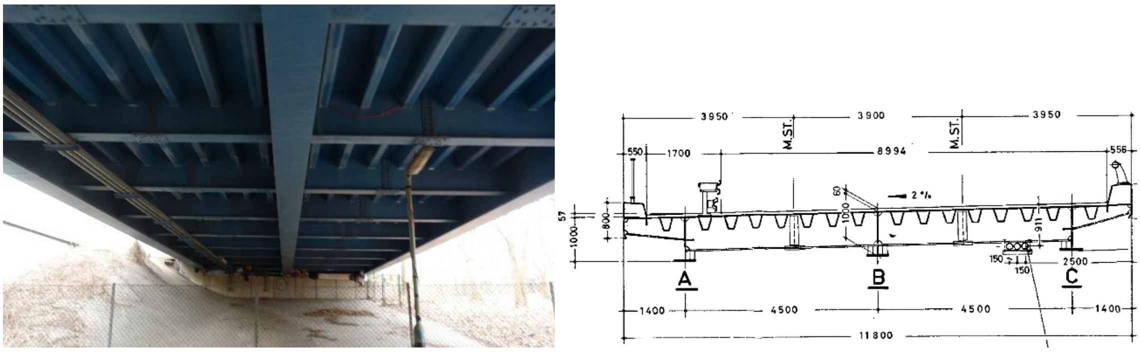

Figure 4. Bottom view and cross section of the steel bridge with orthotropic slab.

6.1 Load model

Figure 5 shows the histogram of the measured weekly extreme values of the lower flange of the main girder B (measuring point HTB-FM-UG). The extrapolation is based on the distribution of the annual and 50-year extreme values. The most common value in 50 years corresponds to the 98% quantile value of the annual extreme value distribution.

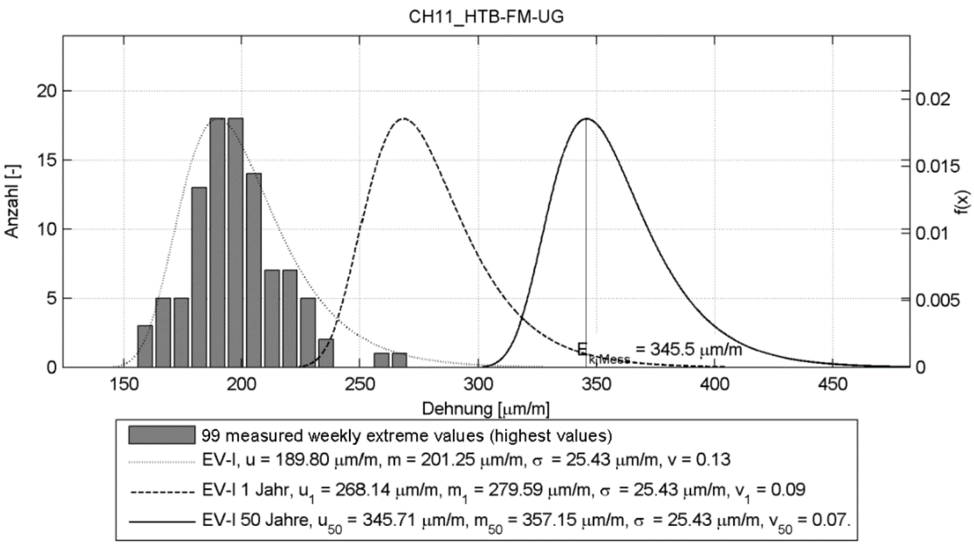

Figure 5. Measured and classified week extreme values due to traffic, approximation and extrapolation with extreme value distribution type I.

The characteristic value from the code resulting from the LM 1 of DIN-Fachbericht 101 (2009) is $\sigma_{c,code}$ = 126,6 MPa. The statistical parameters from the extreme value analysis of the measured data can be converted in stress values. Then eq. (1) leads to the measurement-based adjustment factor $\alpha_{ra,meas}$ = 0.57 (instead of 0.8 for TS-load and 1.0 for UDL-load of LM 1 from DIN-Fachbericht 101 (2009)). The associated partial safety factor corresponding to eq. (2) is 1.31 (instead of 1.5).

6.2 Fatigue load model

All recorded vehicles are grouped in a vehicle collective (Figure 6 left). The load collective can be output for each vehicle type (Figure 6 right). The vehicle collective as well as the type-related load collectives lead to an object-specific fatigue load model (based on the FLM 4 by NRR, BMVBS (2011) (Table 3).

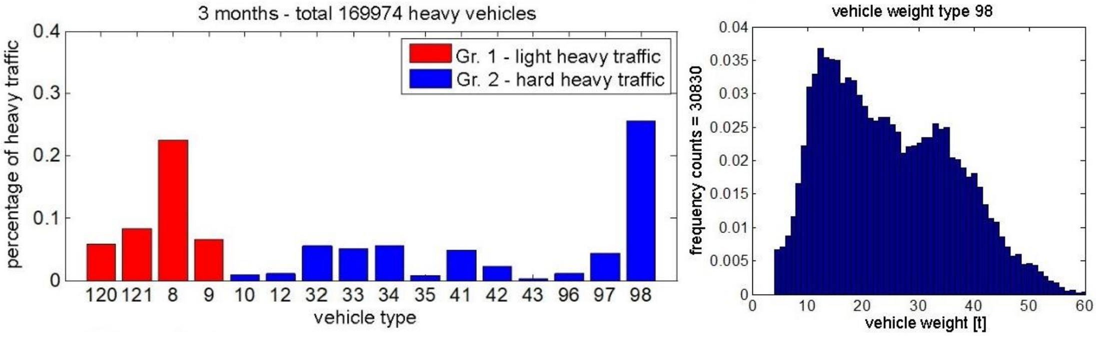

Figure 6. Distribution of truck types in measurement period (left) and vehicle loads per type (right).

Table 3. Comparison of FLM 4 according to NRR, BMVBS (2011) and object-related FLM 4-A/G

	Nachrechnungsrichtlinie – FLM4			Monitoring – FLM4-A/G		
N_{obs}	$0{,}6 \cdot 10^6$			$3{,}8 \cdot 10^5$		
truck type	total weight [t]	amount of N_{obs} lane 1 [%]	amount of N_{obs} lane 2 [%]	total weight [t]	amount of N_{obs} lane 1 [%]	amount of N_{obs} lane 2 [%]
8	20	40	4	16	34	37
9	31	10	1	20	11	9
98	49	30	3	36	46	33
97	39	15	1,5	29	7	6
35	45	5	0,5	34	2	1

N_{Obs}: Number of trucks per year on main lane 1 (truck lane)

7 CONCLUSIONS

For the assessment of existing bridges structural monitoring is increasingly used, when a recalculation with normative load models detects insufficient load-bearing capacity or insufficient fatigue resistance. Thereby object-related realistic information too actions, load-bearing system and resulting stresses can be obtained. In the guidelines for the recalculation of existing bridges structural measurements are generally approved. However, up to now it is normatively unclarified, to what extent this additional statistical information within the safety concept for recalculation must be considered. In this paper was shown, how by using measurement data, object-specific load models for proof of carrying capacity and fatigue can be justified and the associated normative partial safety factors can be modified. The normative required reliability level is maintained.

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