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Proportionality of interventions to restore structural safety of existing bridges

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ABSTRACT: The proportionality of interventions on existing structures comprises a comparison between effort (cost) and benefit of interventions with the objective of an efficient use of means. This contribution discusses the evaluation of interventions to restore sufficient structural safety of existing bridges as encountered in real case applications. The considered hazard scenarios include accidental actions and one extreme live load event. For all hazard scenarios, structural safety check could not be fulfilled. Consequently interventions to restore structural safety were developed and their efficiency was analysed by a comparison of risk reduction with respect to safety costs. In addition, safety requirements, operational availability of the structure, magnitude of damage as well as the preservation of material and cultural values were considered. In three of the four cases the safety interventions turned out to be disproportionate. This paper presents a review of the chosen approach and assumed values and numbers used to estimate risk reduction and corresponding safety costs. Finally, issues are raised regarding the decision to implement or not the intervention to restore structural safety.

1 INTRODUCTION

For the examination (often referred to as "assessment") of existing bridges, most structural engineers apply the codes and in particular load models valid for the design of new bridges. This is a problematic approach since the codes for design and construction of new structures are in principle not or only analogously applicable to existing structures; also, they do not provide a risk-based safety approach.

The professional approach to existing structures is based on an inherent methodology [SIA 269] that essentially includes collecting actual information since the structure exists. The controlling parameters are determined more precisely, and for example, the structural safety of an existing structure is proven using so-called updated values for actions and resistance. Also, a risk-based safety approach is applied.

In this way, it can often be shown that an existing structure may be subjected to higher solicitation while meeting the safety requirements. Such an approach is needed to avoid rather cost-intensive or even unnecessary maintenance interventions (which are often the result of insufficient knowledge and information about the existing structure).

In cases where the structural safety cannot be verified interventions to restore structural safety need in principle be implemented. However not all safety measures are proportionate, i.e. balanced in terms of invested means for achieved safety. As a matter of fact, the objective is the efficient use of means, in particular financial means. Infrastructure managers have to allocate their means to the most relevant safety problems of a system. They need a systematic approach to be able to objectively evaluate the proportionality of safety measures in situations of insufficient structural safety.

The proportionality of safety interventions on existing structures comprises a comparison between (safety) cost and benefit of interventions in terms of risk reduction.

This paper presents a methodology to evaluate proportionality of safety measures, discusses assumed values and numbers that are used to estimate risk reduction and corresponding safety costs. Application examples will be outlined to illustrate the methodology. Finally, issues are raised regarding the decision to implement or not the intervention to restore structural safety.

2 METHODOLOGY

2.1 *Updating and deterministic verification*

Structural engineering in the domain of existing structures relies on an inherent methodology since the structure exists already for some time and has its history of performance. It is thus possible to obtain and gain more or less detailed information on a specific existing structure. In this way, uncertainties in structural parameters are reduced through updating. (This is a fundamental difference with respect to the methodology used for the design of new structures where uncertainties are dealt with by relying on information gained from experience).

Consequently, variables describing actions and action effects as well as material and structural behaviour are updated based on information gained from the existing structures. Updating takes into account the experience gained from the surveying and monitoring of a structure, the results of condition surveys and the foreseen modifications during the remaining service life.

In this way, the influencing parameters for the structural analysis are obtained through the updating process.

The structural safety verification is then performed using updated values. In general, deterministic verification will be conducted; probabilistic verifications are in particular appropriate in cases where either very little or a lot of information on the structure is available as well as in cases of large consequences of structural failure.

The notion of degree of compliance n is introduced in the deterministic verification of the structural safety [SIA 269]:

$$n = \frac{R_{d,updated}}{E_{d,updated}} \tag{1}$$

where $R_{d,updated}$ and $E_{d,updated}$ are the examination values of resistance and action effect, respectively. This formulation not only gives the information whether the structural safety is fulfilled, i.e. $n \geq 1.0$, it also indicates by how much the verification is fulfilled (or not). The latter is necessary for the evaluation of results and in view of the planning of interventions.

2.2 *Risk-based safety and probabilistic verification*

In detailed examination safety verification should be performed based on a risk-based approach [SIA 269]. In this way specific data of a given structure are considered in a systematic way.

The risk-based safety approach may be adopted from the Probabilistic Model Code of the Joint Committee on Structural Safety [JCSS 2001]. The target value of the failure rate depends on the consequences of a failure and the efficiency of interventions (Table 1).

The consequences of structural failure are expressed in terms of the ratio ρ of direct costs C_F at failure to the costs C_W necessary to restore the structure:

$$\rho = \frac{C_F}{C_W} \tag{2}$$

The *probabilistic verification of structural safety* is conducted according to the following format:

$$p_f \leq p_{f,0} \tag{3}$$

where p_f is the failure rate (or probability of failure) of a structure or a structural element; $p_{f,0}$ is the target value of the failure rate.

Intervention to restore structural safety is necessary if the failure rate is larger than the target value and the intervention is proportionate.

2.3 *Proportionality of intervention*

The proportionality of safety interventions may be verified by expressing the efficiency of intervention, i.e., confrontation of cost and benefit, considering safety requirements, availability of the structure, magnitude of damage and in some cases also the preservation of material and cultural values.

The *efficiency of intervention* EF_I is evaluated by a comparison of risk reduction ΔR_I with respect to safety costs SC_I, as expressed by the following ratio:

$$EF_I = \frac{\Delta R_I}{SC_I} \tag{4}$$

A safety intervention is proportionate when $EF_I \geq 1.0$ and shall be implemented. On the contrary, a safety intervention is in principle not conducted

Table 1. Target values of the failure rate $p_{f,0}$ for structural safety according to [SIA 269].

	Consequences of structural failure		
Efficiency of intervention EF_I	Low $\rho < 2$	Moderate $2 < \rho < 5$	High $5 < \rho < 10$
Small: $EF_I < 0,5$	$p_{f,0} = 10^{-3}$/year	$3 \cdot 10^{-4}$/year	10^{-4}/year
Medium: $0,5 \leq EF_I \leq 2,0$	10^{-4}/year	10^{-5}/year	$5 \cdot 10^{-6}$/year
Large: $EF_I > 2,0$	10^{-5}/year	$5 \cdot 10^{-6}$/year	10^{-6}/year

when $EF_I \geq 1.0$ but additional considerations such as the availability or the preservation of values could lead to a different result.

3 CASE STUDY 1—VEHICLE IMPACT ON PARAPETS OF A HISTORICAL BRIDGE

3.1 *Problem description*

In the context of a rehabilitation project, the parapets made in reinforced concrete of a 100 year old bridge of high cultural value (Fig. 1) was evaluated in terms of structural safety and eventually necessary safety interventions. As these parapets obviously were initially not designed for vehicle impact an intervention solution consisted in replacing them by new ones. The question whether this intervention is proportionate needs to be answered.

3.2 *Updating and deterministic safety verification*

In the past, the bridge was in use for low speed unlimited inner city road and pedestrian traffic. For some years and in the future, trucks are no longer allowed and the heaviest vehicles are public transportation buses (Fig. 2) and emergency vehicles (fire workers trucks) with a mass of maximum 30 tons. The frequency of occurrence of heavy vehicles is thus rather small and the regular speed of vehicles is around 50 km/h.

The hazard scenario is the lateral impact of a heavy public transportation vehicle of about 25 tons to rupture of the parapets. As the vehicle would penetrate the parapet and fall into the river, such an event could lead to several casualties in addition to material damage.

Lateral impact of a vehicle leads to a force acting perpendicular to the parapet according to Figure 3.

Figure 1. Historical concrete bridge over the Rhine river at Rheinfelden, designed and built by Robert Maillart in 1912.

Figure 2. View of today's road lanes and pedestrian sidewalks.

Specialized literature provides an estimated value for such an impact force of Q_{yd} = 200 kN in the case of unlimited road traffic, i.e. including heavy vehicles with an allowed maximum mass of 40 tons and maximum speed of 60 km/h.

The impact force depends linearly on vehicle mass and squared on vehicle speed. The given traffic conditions allow for updating and an estimated force value of $Q_{yd,updated} = 110\ kN$ is obtained. (Remark: In addition, it may also be considered that depending on how the impacting vehicle is constructed, not all the vehicle mass is acting instantly, leading to a smaller impact force.)

Consequently, the maximum bending moment acting on the parapet due to the impact force which occurs at 0.70 m above the fixed section of the parapet is thus $M_{d,updated} = 77\ kNm$ (Fig. 4).

The parapets in reinforced concrete comprise only a low reinforcement content (as these elements were not designed to resist significant impact forces) (Fig. 4). A plastic bending moment resistance of $M_{Rd,\,updated} = 58\ kNm/m'$ was determined using updated values for material properties and considering a certain contributing width of parapet resistance.

The following degree of conformity is finally obtained:

$$n = \frac{M_{Rd,updated}}{M_{d,updated}} = \frac{58kNm}{77kNm} = 0.75$$

As the degree of conformity is smaller than 1, this means that the structural safety is not fulfilled in case of an extreme vehicle impact and an intervention to restore structural safety needs in principle to be implemented. Yet, this result also indicates that the parapets would resist with high likelihood against the impact of most vehicles that operate on the bridge.

3.3 *Evaluation of the proportionality of intervention*

In a first step, the probability of occurrence of an impact is estimated. For almost 100 year during which the bridge is in service no significant case

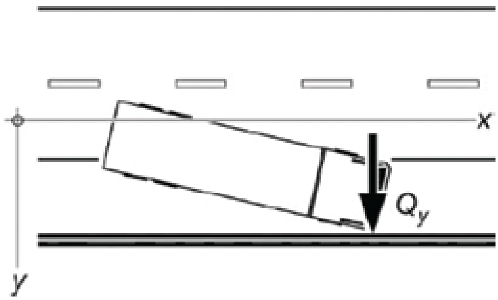


Figure 3. Lateral vehicle impact on a parapet.

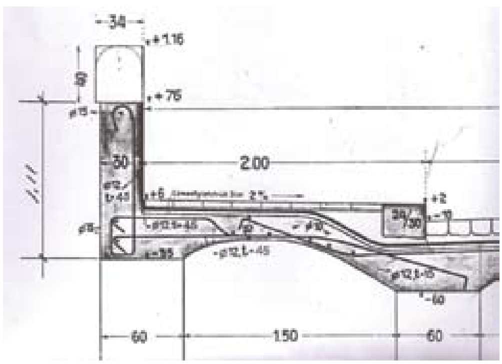


Figure 4. Steel reinforcement in the parapet.

of vehicle impact on the parapets is known. An important traffic volume of about 4'000 vehicles daily was observed since 1960 which corresponds to about 1.5 million vehicles per year that crossed the bridge without producing any impact.

Consequently, the probability of occurrence of vehicle impact was smaller than $7 \cdot 10^{-7}$ per year. Also, the highest impact forces would have been produced by trucks which had a part of about 10% of the whole traffic volume. Thus, the probability of occurrence of truck impact was smaller than $7 \cdot 10^{-6}$ per year. This value may be seen as a reference for evaluating future impact events.

Future utilization of the bridge excludes private trucks and only public transportation and emergency vehicles will cross the bridge. Thus, the probability of occurrence of an impact by a heavy vehicle must be significantly smaller than in the past. It must be in the domain where the hazard scenario can be considered as an "accepted risk", i.e. the failure rate is smaller than the smallest target failure rate given in Table 1. Nevertheless, the proportionality of safety intervention shall be evaluated in the following.

Replacement of the parapets turned out to be a more cost effective safety measure than strengthening of the existing parapet for increasing the resistance of the parapet against vehicle impact. The proportionality of this intervention is evaluated following the above described approach applying equation (4).

Risk reduction due to the safety relevant intervention is expressed as follows:

$$\Delta R_I = \Delta p_f \cdot D \qquad (5)$$

and considers a yearly discounted monetary values valid over a considered time period, usually the remaining service life of the structure,

with:

D: damage in Swiss Francs (1CHF ≅ 0.75EURO). It may be assumed that a largest damage event due to a bus accident would imply 15 to 20 casualties. Assuming compensation costs of 3 to 10 million CHF per casualty [SIA 269], this leads to a damage totaling about 100 million CHF.

Δp_f: is the reduction of the failure probability due to the safety measure, i.e. the difference between the failure probabilities before and after intervention. New parapets imply a failure probability smaller than 10^{-6} per year. The difference between the failure probabilities before and after the intervention is thus roughly:

$$\Delta p_f = p_{f,before} - p_{f,after} = 10^{-5} - 10^{-6} \cong 10^{-5}/Jahr$$

Consequently, the risk reduction amounts to:

$$\Delta R_I = 10^{-5}/year \cdot 100 \cdot 10^6\, CHF = 1'000\, CHF/year$$

The safety costs:

$$SC_I = DF \cdot C_I \qquad (6)$$

are the costs C_I that are directly linked to the safety measure, and consider a yearly discounted monetary value (by means of a discounting factor DF) valid over a considered time period, usually the remaining service life of the structure.

The estimated costs for the demolition of the existing and the construction of new parapets amount to C_I = 900'000 CHF. It is assumed that these investment costs are amortized in the present case over a service life of $n = 50$ years and that the discounting rate is $i = 2\%$ which is a value often applied in the domain of roads in Europe. From this follows the discounting factor DF to be:

$$DF = \frac{i(1+i)^n}{(1+i)^n - 1} = 0.032\ [1/year]$$

And the safety costs are thus:

$$SC_M = 900'000 \cdot 0.032 = 28'800\, CHF/year$$

Finally, the efficiency of intervention according to equation (4) is:

$$EF_I = \frac{\Delta R_I}{SC_I} = \frac{1'000}{28'800} = 0.035 << 1.0$$

The coefficient EF_I is significantly smaller than 1 and consequently the safety related intervention consisting in replacing the parapets is disproportionate.

3.4 *Discussion*

Despite the fact that the structural safety of the existing parapets against vehicle impact is not sufficient, the safety intervention consisting in replacing the parapets is disproportionate and shall not be implemented. From a socio-economic viewpoint the financial means shall more efficiently be invested into different safety related measures which prove to be proportionate.

The study also showed that the probability of occurrence of an impact of a heavy vehicle is in the present case very small such that this hazard scenario may be accepted as an "accepted risk".

Finally, keeping the existing parapets obviously is the best solution from the viewpoint of preservation of cultural values.

4 CASE STUDY 2 – THREE HAZARD SCENARIOS INVOLVING HIGHWAY BRIDGES

4.1 *Problem description*

Three hazard scenarios involving three different bridges on the same highway are analyzed and corresponding safety measures are evaluated in terms of their proportionality. All three hazard scenarios show insufficient structural safety since $p_f > p_{f0}$.

Hazard scenario A assumes failure of the deck slab of a narrow road underpass (Fig. 5) due to fire after a tank truck accident. Failure of the deck slab provokes a car accident on the highway leading to three casualties.

The probability of occurrence p_f of this accident as well as the target value of the failure rate for structural safety according to Table 1 are given in Table 2. They were estimated considering the given local conditions and relevant values were updated. The safety measure would consist in widening the underpass in width and height such as to improve road clearance as well as the visibility for vehicle drivers. This intervention would thus reduce the probability of occurrence of an accident. The estimated cost for this safety measure is also given in Table 2.

Figure 5. A: Underpass of a highway.

Hazard scenario B would be due to failure of a road overpass (Fig. 6) showing advanced corrosion damage of the posttensioning cables. Consequently, resistance of structural members is largely reduced and the occurrence of a high load event on the overpass would provoke failure of the midspan falling on the highway which would lead to a major accident on the highway involving an estimated number of five casualties.

The safety measure would consist in rehabilitation of the bridge to restore the necessary resistance of the structural members. The estimates failure probability and the target value as well as the safety cost are again given in Table 2.

Hazard scenario C describes steel railings of a viaduct with insufficient resistance against vehicle impact (Fig. 7). A bus would impact and penetrate the steel railing of this highway viaduct that is 25 m above ground.

The safety measure would consist in replacing the steel railings such as to restore the necessary impact resistance. The estimated failure probability and the target value as well as the safety cost are given in Table 2.

The interventions cost C_{int} given in Table 2 is the sum of the safety cost to restore structural safety and the cost to re-establish durability of the bridge.

4.2 *Estimating damage and safety costs*

It is assumed that such major accidents as described by the three hazard scenarios would occur only once during the service life of the structures. Only one major intervention would thus be necessary to reduce the corresponding risk. This means that

Table 2. Target and estimated failure rates and intervention costs (in million Swiss Francs) for the three hazard scenarios.

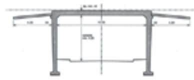
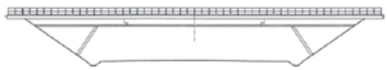
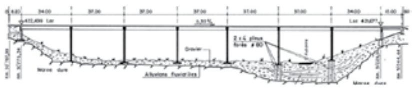
Hazard scenario	Bridge type	p_{f0}	p_f	C_{int} [mio CHF]
A. Underpass: Fire of a tank truck; 3 casualties.		10^{-5}	$5 \cdot 10^{-4}$	3.3
B. Overpass: Loss of load bearing resistance due to corrosion; 5 casualties.		$5 \cdot 10^{-5}$	$8 \cdot 10^{-3}$	2.7
C. Viaduct: Failure of railing after impact of a bus; 50 casualties.		$5 \cdot 10^{-6}$	10^{-2}	0.8

Figure 6. B: Overpass of a highway.

Figure 7. C: Highway viaduct.

only the total implied costs must be considered (and there is no need to express costs in terms of annual monetary values (applying a discounting rate)).

The monetary value of the total damage D due to a hazard is expressed by the costs that would potentially be reduced after realizing the safety measures. This damage value D is composed of the estimated compensation costs for casualties, the cost for non-availability of highway operation after a hazard as well as the cost of restoring the bridge and highway after the accident.

The safety costs SC_I are the part of the intervention costs that are directly charged to restoring of structural safety and/or effective protection of the structure.

For three hazard scenarios, the estimated values for all categories of costs are given in Table 3. These values are based on a more or less crude estimation based on documents such as [Schubert & Faber 2009, Emch+Berger 2010]. Obviously, these cost values are overshadowed by some uncertainty since reliable data is not readily available.

While the cost for restoration may be estimated rather precisely within ±40%, costs of non-availability of operation as well as compensation costs for casualties are always topics to be subject to discussions of principles. They may vary largely, i.e. by a factor of 3, depending on the hypothesis.

The risk reduction is finally obtained by applying equation (5) with

$$\Delta p_f = p_f - p_{fO}$$

being the difference in probability of failure and the target failure rate valid after the safety related intervention.

The coefficient EF_I is then obtained according to equation (4) leading to the values given in Table 4.

The results in Table 4 may be discussed as follows:

Hazard scenario A: this intervention is clearly disproportionate and only complementary safety measures (like signaling reduced speed) may possibly be taken. This hazard scenario can be considered as an "accepted risk".

Hazard scenario B: the coefficient EF_I is larger than 1 and the safety related intervention must in principle be implemented. The values of SC_I and

Table 3. Estimation of costs involved in the three hazard scenarios, in million Swiss Francs.

Hazard scenario	Damage D (= reduction potential due to intervention): Compensation costs [mio CHF]	Cost of non-availability [mio CHF]	Cost of restoration [mio CHF]	Total [mio CHF]	Safety costs SC_I [mio CHF]
A. Underpass	9	1.4 (one lane closed during 14 days)	1.2	11.6	3.0
B. Overpass	15	1.0 (5 days of closure of the highway)	3.5	19.5	0.1
C. Viaduct	150	0.05 (traffic restriction during 1 day)	0.8	151	0.8

Table 4. Estimation of risk reduction, safety costs, in million Swiss Francs.

Hazard scenario	Risk reduction (monetary value): Δp_f	Degree of damage D [mio CHF]	ΔR_I [mio CHF]	Safety costs SC_I [mio CHF]	Coefficient $EF_I = \frac{\Delta R_I}{SC_I}$
A. Underpass	$4.9 \cdot 10^{-5}$	11.6	$57 \cdot 10^{-5}$	3.0	$19 \cdot 10^{-5} << 1$
B. Overpass	$\approx 8 \cdot 10^{-3}$	19.5	0.156	0.1	$1.56 > 1$
C. Viaduct	$\approx 10^{-2}$	151	1.51	0.8	$2.26 >> 1$

ΔR_I are however relatively small and the coefficient EF_I could also take a value smaller than 1 if certain cost estimations are determined in more detail. It is important to identify the values that influence most the result. Also, it is reasonable from the "sound engineering sense" to perform the rehabilitation (and thus the safety related measure) in any case because of the bad condition of the structure.

Hazard scenario C: the reduction in risk due to the safety measure is much higher than the safety cost. The safety related intervention is thus clearly proportionate and has to be implemented.

For all three hazard scenarios, the plausibility of the final result in terms of the coefficient EF_I needs to be checked by a sensitivity analysis of the various cost values. The compensation costs for casualties turn out to be the predominant aspect.

5 CONCLUSIONS

The proportionality of interventions to restore the structural safety of existing bridges was evaluated:

1. The proportionality of safety interventions may be evaluated by means of a comparison of risk reduction (as obtained from the safety interventions) with respect to corresponding safety costs. Relevant information and data have to be updated to consider the specific conditions of the existing structure.
2. The assumptions and available information and data to estimate cost parameters are of outmost importance. The compensation costs for casualties turn out to be the predominant aspect. Information and data related to cost parameters need to be improved.
3. Evaluation of proportionality of safety interventions may not be based on numerical results alone. Sound engineering judgment and non-monetary values needs to accompany the evaluation.

The case studies also show that application of modern engineering methods for professionally dealing with existing structures lead to more sustainable solutions.

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