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Re-evaluation of Structural Load Carrying Capacities

Détermination de la capacité portante actuelle

Ermittlung des vorhandenen Tragwiderstandes

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SUMMARY

Inclusion of information on measured structural characteristics in probabilistic reliability analyses for re-evaluation purposes are briefly described. Application of the methods are illustrated by a case with re-evaluation of the reliability of a road bridge. Actual material strengths and test load results are used. The formal failure probabilities are further used for risk analyses where the total costs associated with various rehabilitation strategies are assessed, in order to select the best solution.

RÉSUMÉ

Les données sur les grandeurs caractéristiques mesurées sont inclues dans une évaluation probabiliste de l'état de la structure. L'application de cette méthode à un pont routier est illustrée à l'aide des résistances effectives des matériaux et des résultats d'essais de charge. Les probabilités de rupture sont employées avec les coûts globaux de différentes stratégies de maintenance, dans une analyse de risques pour le choix de la meilleure solution.

ZUSAMMENFASSUNG

Informationen über die gemessenen charakteristischen Grössen werden in einer probabilistischen Ermittlung des Bauwerkszustandes berücksichtigt. Die Anwendung der Methode wird anhand einer Strassenbrücke gezeigt, wobei wirkliche Baustoffestigkeiten und Resultate von Belastungsversuchen verwendet werden. Die Versagenswahrscheinlichkeiten werden für eine Risikoanalyse zusammen mit den Gesamtkosten verschiedener Instandstellungsstrategien zur Wahl der besten Lösung weiterverwendet.

1. INTRODUCTION

Increasing demands or progressing deterioration have resulted in a number of existing structures being found structurally insufficient when their load carrying capacity is assessed by current design methods.

As test loading of structures have often revealed that the load carrying capacities can be considerably larger than calculated, a wish for supplementary investigations arises in the aforementioned situation in order to utilize an existing structure best possible.

Load and resistance factor design methods are often inadequate for the inclusion of such supplementary information in the re-evaluation procedures mainly because no measure is given for the importance of deviations from the stated rules.

Probability based limit state analyses offers such possibilities primarily because a probability of limit state exceedance is calculated. The methods allows additional informations on the structures or structural parameters to be included (updating), whereby posterior evaluations are obtained.

The probability of failure in combination with the estimated costs of failure can be used to evaluate the risk associated with various maintenance strategies. The risk may be used as a decision parameter when priority must be given between various strategies.

2. PROBABILISTIC RELIABILITY ANALYSIS

Reliability models with distribution functions and parameters describing the random variation of the physical characteristics and the uncertainty of the calculation models are used to establish a reliability index - β.

The reliability index β is defined as $\beta = -\Phi^{-1}(p_f)$, where Φ is the inverse normal distribution function and p_f the probability of limit state exceedance (failure). It is calculated by the First Order Reliability Method (FORM) [3].

The probability of limit state exceedance or failure, p_f, may be expressed as

$$p_f = P\ (\ M(\underline{x}) < 0\ )$$

where the limit state function $M(\underline{x})$ of the basic variables, $\underline{x}$, is positive for all acceptable states of the structure (safe or intact), and negative for all unacceptable states (**failure** or unsafe).

The reliability depends upon the available information on basic parameters and upon the calculation model applied. The reliability is consequently not a physical property of the structure, but an evaluation variable applicable for decisions concerning the structure.

2.1 Improved basis for evaluation (UPDATING)

2.1.1 Updated basic variables and improved calculation models.

An improved evaluation of the reliability can be achieved by use of improved calculation models or by use of observed values of basic parameters, obtained either during construction or at a later stage. The observations are combined with the originally available information (prior), from which an updated probability distribution function is obtained by use of Bayesian statistical models [2],[5].

2.1.2 Updating of system reliability

When a structure has resisted external loads either through normal operation or during test loading, this is information on the load carrying capacity not available at the design stage. It may be used for updating of the reliability. However, the information relates not to a single basic parameter but to the entire structural system.

The failure probability for ordinary loads to be carried in the future can thus be expressed as

$$p_f = P(\text{ failure for L given safe for Q }) = P(L > R \mid R > Q)$$

$$= \frac{P(\text{ failure for L and safe for Q })}{P(\text{ safe for Q })} = \frac{P(L > R \cap R > Q)}{P(R > Q)}$$

where

- L is Ordinary loads
- Q is load(s) resisted by the structure (load history or test loading)
- R is the resistance of the structure

The last formulation is made in order to facilitate calculations.

2.2 Risk analysis

Economic considerations incorporating the probability of failure may indicate whether it is reasonable to continue the use of the unaltered structure or precautions should be taken to improve the reliability [2],[4].

The formal failure probability p_f is used for the expected average frequency of failure for the structure, and the total expected cost, G, associated with a specific decision for the bridge is thus

$$G = c(p_f) + (d + c_{new}) \cdot p_f$$

- $c(p_f)$ is construction costs for a new structure or costs of strengthening works and a decreasing function of the failure probability ($c(p_f)=0$ for an unaltered bridge).
- d covers user losses, personal injuries, material damage at failure, the cost of demolition and any additional costs due to the aversion against larger catastrophic events.
- c_{new} cost of a new structure as a substitute for the failed.

The optimal reliability level corresponds to the value p_f^*, which gives the minimum total expected cost G^*. The total cost G^* may be used as a decision parameter.

Only failures due to stochastic variations in the basic parameters for the bridge are considered, whereas gross errors are omitted [2]. It will lead to a conservative evaluation of the optimal failure probability p_f^*.

A considerable problem in the above mentioned calculations is the determination of the failure cost, d, mainly due to the difficulty of evaluating the capital costs of personal injuries and fatalities and aversions due to large catastrophic events [1],[4].

3. CASE STUDY: SMALL ROAD BRIDGE

The application of the principles outlined in the preceding chapter have been illustrated by an example covering a former road bridge Figure 1.

The bridge was test loaded before demolition and concrete cores and samples of the main reinforcement were taken for strength tests.

The variable load was considered to be a fixed parameter without any uncertainty due to insufficient stochastic informations on extreme traffic load effects in short to medium span bridges.

3.1 Structural calculational model

A grid of beam elements was used for the calculations. Bending and torsional effects were considered, but not shear. Elastic and plastic models are used and with and without of torsional stiffness of the beam elements.

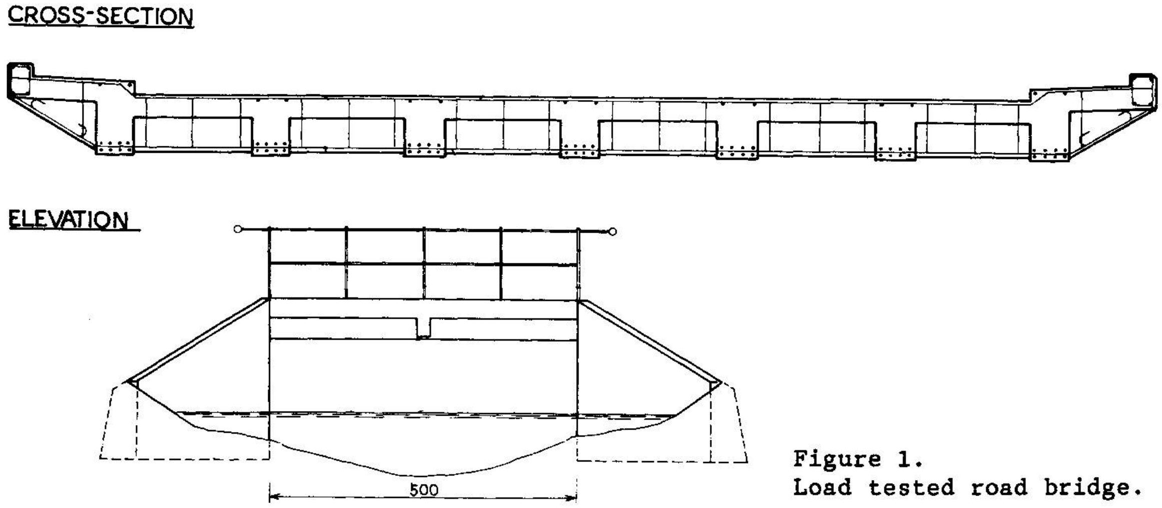


Figure 1.
Load tested road bridge.

One position of the traffic load and the corresponding internal forces were investigated.

The influence of the calculation model on the reliability is shown in Figure 3.

Consideration of the correlation of material strengths between different cross sections has a significant influence, just like the distribution type for the basic parameters [2].

The possibilities for improving the evaluation of the structural reliability by improved calculation models are good, but it is not possible to require specific reliability levels for structures without specification of basic assumptions.

3.2 Updating material strengths

Results from laboratory tests with concrete and steel samples have been used to update the probability density functions for concrete and reinforcement respectively as shown in Figure 2.

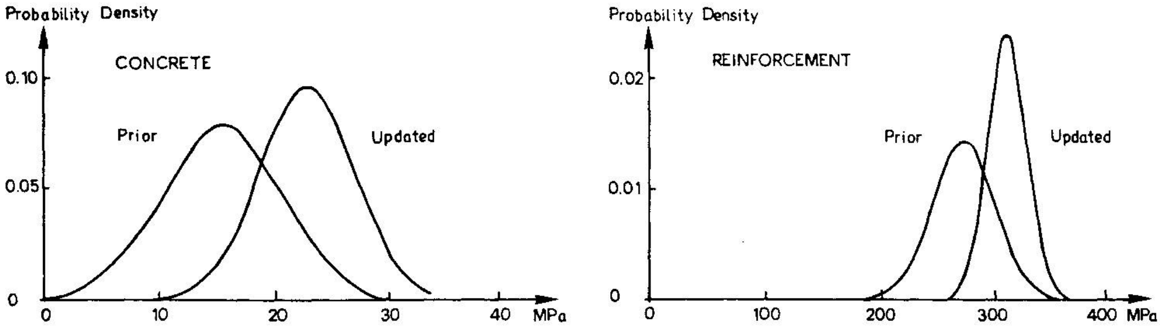


Figure 2: Probability density functions before (prior) and after (updated/posterior) observed material strengths are included.

The reliability index β is shown in Figure 4 for prior and updated strengths applied separately and in combination.

The reliability is increased considerably when both concrete and reinforcement strengths are updated. When only one material strength is updated the effect depends upon the load level. The reason is that both normal and overreinforced cross sections are considered to be possible failure modes for identical load levels and cross sections. This phenomenon requires special attention [2].

A possible way to utilize the results is to allow permissible loads to be increased to a level for which the prior and updated reliability are the same.

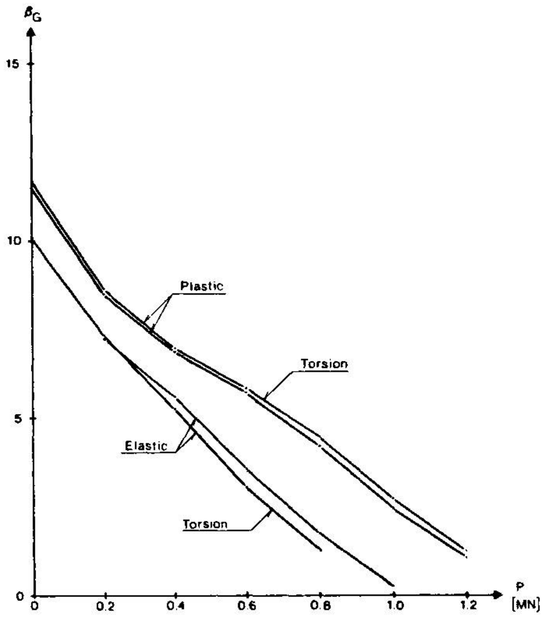


Figure 3: Reliability index β plotted against the variable load P
- 4 structural calculation models
- prior material strengths
- P deterministic

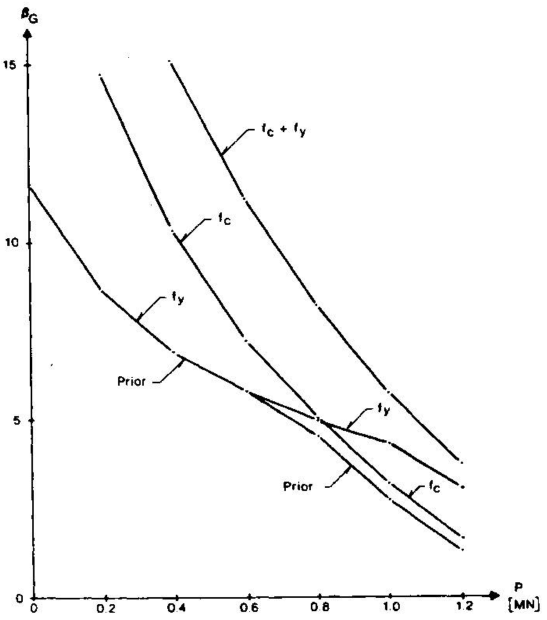


Figure 4: Reliability index β versus variable load P
- separate and combined updating of strengths f_c for concrete and f_y for reinforcement
- plastic model incl torsion
- deterministic load P, (D(P)=0)

3.3 Test loading

The effect on the reliability for test loading is shown in Figure 5. The test load Q is applied to the bridge in the same configuration as the variable load P. The test load Q is measured and thus considered deterministic. The variable load P has a constant mean value and six levels of the standard deviation for P, D(P).

A significant improvement of the reliability is obtained when the test load Q exceeds the mean value of the variable load P. For small standard deviations of the variable load, D(P), the benefit from a test loading is significant, but the effect is decreasing rapidly for increasing standard deviations, D(P). The required test load may be prohibitively high and it appears to be cheaper and more efficient to update the reliability through updating of material strengths and structural geometry in the present situation.

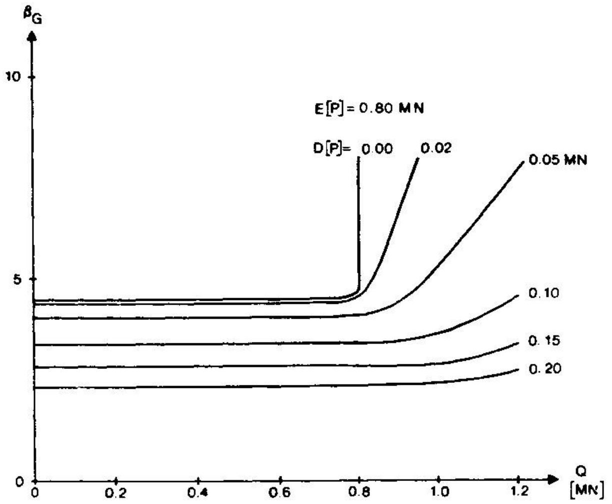
The reliability level is estimated on the basis of the random fluctuations in the basic parameters, but gross errors are not considered. As gross errors may be difficult or impossible to detect by other means than by test loadings they may still be relevant in certain cases.

3.4 Economic analysis

The principles of the risk analysis are used for analyzing three alternative decisions for the imagined future use of the bridge:

- continued use of the unaltered bridge (NTH)
- strengthening of the existing bridge (STR)
- demolition of the existing bridge and reconstruction (NEW)

For each load level the minimum total expected costs G_{NTH}, G^*_{STR} and G^*_{NEW} were determined. The minimum total costs are plotted in Figure 6.



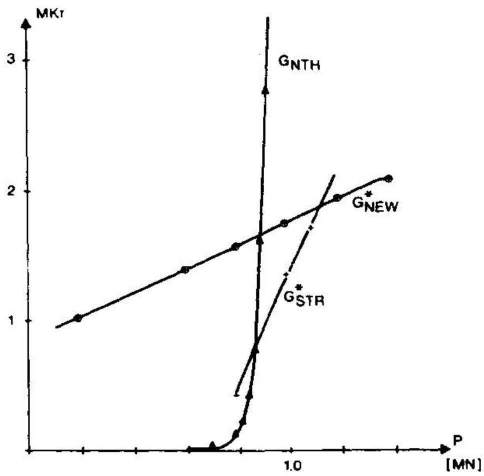


Figure 5: Reliability index β against the test load Q
- E(P) = 0.8 MN, Plastic model incl. torsion, prior strengths,
- six standard deviations D(P).

Figure 6: Minimum of expected total costs, G, for
- unaltered bridge : G_{NTH}
- strengthened bridge (FOR): G^*_{STH}
- new bridge (NY) : G^*_{NEW}

For the considered alternative decisions, the expected cost will be a minimum if the bridge is used unaltered for low load levels and is replaced by a new bridge for high load levels, whereas strengthening will be preferable for intermediate load levels.

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