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HUMAN SAFETY CRITERIA FOR EXISTING BRIDGES CONSIDERING EMERGENCY AND CRISIS SITUATIONS

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Abstract: *Specification of the target reliability levels is a key issue of the assessment of existing bridges in emergency and crisis situations. ISO 2394 indicates procedures for specification of the target reliability by the total cost optimisation in conjunction with human safety criteria. Since the latter criteria often dominate the target reliability for existing structures, their application is discussed in detail focusing on conditions specific to emergency and crisis situations. For a reference period of one week the target reliability indices range mostly from 3.1 to 3.6, thus significantly lower than those applied in the design of new structures.*

Keywords: Target Reliability, Human Safety, Existing Bridges, Emergency Situations.

1. Introduction

The target reliability levels in national and international documents for new and existing structures are inconsistent in terms of the recommended values and the criteria according to which appropriate values are to be selected. Almost no recommendations are available for temporary structures (Holicky, 2013) and for structures under temporary conditions including emergency and crisis situations.

In this study a general procedure for the assessment of target reliabilities of structures during emergency or crisis situations is developed. An emergency or crisis situation is assumed to last only few days or weeks. Target reliabilities discussed in the study are to be applied in the assessment of existing bridges in ultimate limit states when immediate decisions on permissions for crossing of heavy freights due to military and civilian traffic are needed and a bridge resistance cannot be readily increased.

Specification of the target reliability levels is required for the probabilistic assessment of existing bridges as well as modifications of partial factors used in a deterministic assessment. The reliability assessment in emergency or crisis situations is generally associated with a short duration and it should be considered that it may be difficult or even impossible to strengthen a bride during such a limited period.

The target reliability levels recommended in *EN 1990:2002* for the basis of structural design are primarily intended for new structures; different reliability classes are associated with different consequences of failure. More detailed classification is given in *ISO 2394:1998* for the general principles on structural reliability where relative costs of safety measures are also taken into account. *ISO 13822:2010* for the assessment of existing structures indicates four target reliability levels for different consequences of failure. For instance moderate consequences are associated with the target reliability index (see *EN 1990*) $\beta = 3.8$, high consequences with $\beta = 4.3$. These values are related to "a minimum standard period for safety (e.g. 50 years)". In addition *ISO 13822* indicates a possibility to specify the target reliability levels for existing structures by optimisation of the total cost in conjunction with the criteria for safety of people. Sykora and Holicky (2012) recognised that upgrades of existing structures are expensive and economic criteria yield lower optimum reliabilities than those required for human safety. Therefore, the present study is focused entirely on human safety criteria; cost optimisation for existing bridges in emergency and crisis situations is discussed by Sykora et al. (2014).

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2. Requirements on Individual Human Risk

General guidelines for the assessment of target reliabilities with respect to human safety are provided in *ISO 2394*. In principle, structural design and assessment of existing bridges are not distinguished. It is noted that a recent draft of this standard introduces new procedures to establish appropriate target reliabilities considering human safety on the basis of the Life Quality Index, Nathwani et al. (2009). Since further developments seem to be needed to facilitate practical applications of this approach, the present study deals with the principles provided in *ISO 2394:1998*.

ISO 2394 states that structural reliability is important first and foremost if people may be killed or sustain injuries as a result of the collapse. An acceptable maximum value for the failure probability might be found from a comparison of risks resulting from other activities. Individual lethal accident rates ranging between 10^{-6} and 10^{-5} per year (as accepted by Steenbergen and Vrouwenvelder (2010) and Sykora and Holicky (2012)), seem to be reasonable for structures in persistent design situations, when compared to the typical rates in industries, e.g.:

- 10^{-4} per year for work in all industries (2×10^{-4} for users of motor vehicles),
- 10^{-5} per year for third parties in ship industry (passengers or public ashore).

The overall individual lethal accident rate of 10^{-4} per year is a common value of reference; rates over 10^{-3} are deemed unacceptably high, Stewart (2011). For military situations Goldberg (2010) derived an individual lethal rate of 4×10^{-3} per year. Hostile actions, accidents, illnesses or self-inflicted actions for the Operation Iraqi Freedom in 2003-2006 were considered. In emergency and crisis situations higher risks may be acceptable since they may be compensated by a mitigation of consequences in endangered areas. Therefore, a tentative value of 10^{-3} per year is considered hereafter as associated with uncommon accidents, Melchers (2001). It is tacitly assumed that the safety of rescue corps members is endangered.

The concept of individual risk provided in *ISO 2394* then yields the following relationship between the target failure probability p_f and the conditional probability of occupant fatality p_1, given the structural failure in emergency or crisis situation:

$$p_f \text{ (per year)} \leq 10^{-3} \text{ per year} / p_1 \quad (1)$$

With respect to the loss of human life, *EN 1990* distinguishes among low, medium, or high consequences (CC1-CC3, respectively). The conditional probabilities p_1 indicated in Fig. 1 for assessment of bridges classified in various CCs are based on a literature review and recommendations by Steenbergen and Vrouwenvelder (2010). For emergency and crisis situations, the target failure probabilities of a structural member, related to a reference period t_{ref} in years become:

$$p_f \leq 10^{-3} \text{ per year} / p_1 \times t_{ref} \quad (2)$$

Corresponding target reliability index is derived using the cumulative distribution function of the standardized normal distribution, $\beta = -\Phi(p_f)$. Fig. 1 shows the variation of target reliability index β with the conditional probability p_1 for different reference periods. It appears that the target reliabilities are affected by the conditional probability p_1 and more significantly by the reference period. Considering middle values of p_1, the following target reliability indices may be considered:

- CC2 ($p_1 = 0.02$): $\beta = 3.1\text{-}2.6$,
- CC3 ($p_1 = 0.1$): $\beta = 3.6\text{-}3.1$

for reference periods from one week to one month, respectively. CC1 is not discussed hereafter as it is deemed irrelevant for most bridges. Regarding selection of an appropriate consequence class, background document to EN 1990 by CEN/TC250 (1996) indicates that a higher reliability level should be required for:

- a structure which is likely to collapse suddenly without a warning that would allow implementation of measures to avoid severe consequences,
- non-robust structural systems where a local failure may lead to a rapid progressive collapse.

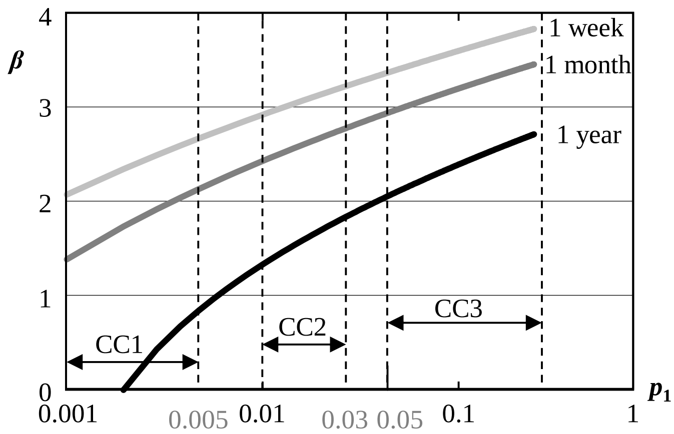

Fig. 1: Variation of β with the conditional probability p_1 for different reference periods.

3. Limitations of the Concept of Individual Risk

The aforementioned concept should be applied with uttermost caution. The target levels in Fig. 1 regard only safety of users of a bridge and fail to consider additional costs including life losses related to temporary bridge closure if the criterion is not fulfilled. The decision regarding the permission of heavy freight crossing depends on the case-specific conditions. In general, it should aim at balancing risks of users and risks of individuals endangered when the crossing is not permitted (see the example below).

Besides the individual risk concept, *ISO 2394* indicates that in many cases authorities explicitly intend to avoid accidents with a large number of fatalities and proposes an additional societal risk criterion based on an *F-N* curve. However, application of this criterion requires a case-specific approach and it is out of the scope of this paper to provide a general guidance in this regard. Moreover, Sykora and Holicky (2012) showed that the individual risk criterion is dominating over the societal criterion except for failures with vast collapsed areas.

4. Examples

4.1. Human safety not endangered when transport is not permitted

The application of the derived target reliabilities in conjunction with the partial factor method (*EN 1990*) is illustrated by a simple example. An excessively heavy freight is to be transported over a reinforced concrete bridge. It is assumed that the duration of an emergency situation is two weeks and the crossing is to be allowed at any time during this period, $t_{ref} = 0.038$ y. The bridge is classified in CC3 (high consequence for the loss of human life in the case of failure, failure occurring without previous warning as may be relevant for shear failure of reinforced concrete beam or buckling of bridge piers) and thus $p_1 \approx 0.1$. Human safety is not endangered when the transport is not permitted. However, the driver's safety is to be considered.

Equation (2) then leads to $p_f \leq 3.8 \times 10^{-4}$ and $\beta = 3.4$. Adjustment of partial factors using the β-value is straightforward; see Caspeele et al. (2013) and Sykora et al. (2013). For instance the partial factor for concrete compressive strength reduces from $\gamma_C = 1.5$ for structural design to about 1.3 in this case.

4.2. Human safety endangered when the transport is not permitted

Now it is assumed that the human safety is endangered when the transport is not allowed. This can be represented by the transportation of decontamination units in immediate response to an industrial or chemical explosion, or the transport of portable flood barriers. Two hazard scenarios are considered in the case when the transport is not permitted - an expert judgement suggests that:

- Scenario 1: it is "impossible" that there are ten fatalities in the endangered area (associated with probability of about 0.02, Budescu and Wallsten (1985)), related risk in terms of the expected number of fatalities is a product of the consequences and probability of unfavourable event, R(scenario 1) = 10 × 0.02 = 0.2 (fatalities).

- Scenario 2: Provided that the event Scenario 1 does not occur (probability 1-0.02), it is "very unlikely" that there is a single fatality in the endangered area; the qualitative term "very unlikely" may be associated with probability of having a single fatality of about 0.15, Budescu and Wallsten (1985). The related risk is R(scenario 2) = 1 × 0.15 (1 - 0.02) = 0.15 (fatalities).

The decision "not to permit the transport" thus relates to the total risk $R = R$(scenario 1) + R(scenario 2) = 0.35 (fatalities). When the transport is permitted, related risk should be lower than in the previous case:

$$p_f(1 \times p_1 + R) \leq R \quad (3)$$

where p_f = failure probability given the crossing. The term in brackets in equation (3) represents risks given failure of the bridge. Only a driver is assumed to be present on the bridge during the crossing. For $p_1 = 0.1$ (CC3) and $R = 0.35$, equation (3) yields an excessively high failure probability, $p_f \leq 0.78$ ($\beta < 0$). In this case the target reliability should be established on the basis of risk optimisation considering both economic and societal consequences of the bridge closure and potential bridge failure due to the transport.

5. Concluding Remarks

The target reliability levels recommended in various standards for new and existing structures are inconsistent; almost no recommendations are available for structures under temporary conditions including emergency and crisis situations. Target reliabilities related to these situations can be required for the assessment of existing bridges when immediate decisions on permissions for the crossings of heavy freights are needed. It may be appropriate to require lower target reliabilities for existing bridges than for new structures. In particular situations it needs to be clarified whether and what minimum levels of human safety should be considered. Human safety criterion leads to target reliability indices within the range from 3.1 to 3.6 for a reference period of one week.

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