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Probabilistic methods for assessment of existing structures

Pravděpodobnostní metody hodnocení existujících konstrukcí

Summary

Rehabilitation of existing structures is a matter of great economic significance as more than 50 % of construction activities are presently related to existing structures. Many of these structures do not fulfil requirements of present standards. They have been designed and executed according to past standards and are often affected by severe environmental influences that may cause deterioration and gradual loss of reliability. Hence, assessment of existing structures and effective procedures of their upgrades are becoming important issues.

Assessment differs from design of new structures primarily in increased costs of safety measures, shorter remaining working life and additional information on real structural conditions. Therefore, this study proposes a procedure facilitating consideration of these differences in reliability verification.

Probabilistic reliability analysis is shown to provide a suitable tool for assessment of existing structures particularly due to adequate description of uncertainties and better reflection of actual structural conditions. It is demonstrated that updating of probabilistic distributions of basic variables can effectively combine prior knowledge based on long-term experience with new information obtained from tests, measurements and inspections. This approach can be well used in a number on practical cases.

It appears to be uneconomical to require the same reliability level for existing structures as for newly designed structures. Probabilistic optimisation then provides an effective tool for specifying appropriate target reliability for existing structures. Decisions of the assessment can result in the acceptance of an actual state or in the upgrade of a structure. Two reliability levels are thus needed - the minimum level below which the structure is unreliable and should be upgraded, and the target level indicating an optimum upgrade strategy.

Souhrn

Více než 50 % investic ve stavebnictví souvisí s modernizacemi existujících konstrukcí. Tyto konstrukce většinou nesplňují požadavky současných norem, poněvadž byly navrženy a provedeny podle dříve platných postupů a jsou často vystaveny degradačním procesům. Proto se rozvoj hodnocení existujících konstrukcí a efektivních postupů jejich zesilování stává důležitou úlohou ve stavebnictví.

Hodnocení existujících konstrukcí se liší od navrhování nových konstrukcí především ve vyšších nákladech na zajištění spolehlivosti, kratší životnosti a dodatečných informacích o skutečných podmínkách konstrukce. V této studii je navržen postup umožňující zohlednit tyto rozdíly při ověřování spolehlivosti.

Ukazuje se, že pravděpodobnostní metody jsou vhodným nástrojem pro hodnocení existujících konstrukcí – výstižně popisují nejistoty a umožňují přihlédnout ke skutečným podmínkám konstrukce. Prostřednictvím aktualizace pravděpodobnostních modelů základních veličin lze účelně kombinovat apriorní informace založené na dlouhodobých zkušenostech s novými informacemi získanými z testů, měření a prohlídek. Tato aktualizace se může uplatnit při praktických aplikacích.

Ze studie vyplývá, že je neekonomické požadovat stejnou směrnou úroveň spolehlivosti pro existující a nové konstrukce. Pravděpodobnostní optimalizace nákladů umožňuje odvození směrných úrovní spolehlivosti pro existující konstrukce. Při hodnocení je možné přijmout současný stav nebo rozhodnout o zesílení. Dvě směrné úrovně spolehlivosti jsou proto potřebné - úroveň, pod kterou je konstrukce považována za nespolehlivou a měla by být zesílena, a úroveň pro optimální způsob zesílení.

Key words:
economic optimisation, existing structures, probabilistic methods, probabilistic updating, target reliability, uncertainty

Klíčová slova:
ekonomická optimalizace, existující konstrukce, pravděpodobnostní metody, pravděpodobnostní aktualizace, směrná spolehlivost, nejistota

Contents

1. Introduction

1.1. Significance of assessment

Rehabilitation of existing structures is a matter of a great economic significance as more than 50 % of all construction activities apply to existing structures [1]. In particular rehabilitation of existing bridges is an urgent problem in many countries worldwide. Present expenditures on maintenance and rehabilitation of existing structures are limited and seem to be inadequate.

Competent decisions about various interventions should be always a part of the complex assessment of a structure, considering relevant input data including information on actual material properties. The assessment of existing structures differs from design of new structures primarily in the following aspects:

- Increased costs of upgrading in order to achieve the same reliability level;
- Remaining working life shorter than the standard design working life of 50-100 years depending on the type of structure (residential or industrial building, bridge etc.);
- Additional information on actual structural conditions that may be available for the assessment of an existing structure due to inspections, tests and measurements.

Obviously the differences between assessment of existing structures and structural design need to be adequately reflected in the reliability verification.

1.2. Motivation for application of probabilistic methods

It has been recognised that many existing structures do not fulfil requirements of present codes of practice. One of the reasons is the fact that existing structures are often affected by severe environmental influences and other adverse actions that may cause deterioration and gradual loss of their reliability. Hence upgrades of such structures including design of adequate interventions are becoming an important issue.

European standards – Eurocodes - are primarily focused on design of new structures. Additional operational rules for existing structures are still missing. The international standard ISO 13822 [2] (together with the Czech version CSN ISO 13822 and its National Annexes issued as CSN 73 0038) provides only general principles for assessment of existing structures which should be further developed for their effective operational use in practice. Three approaches to verification are distinguished in ISO 13822 [2]:

- Assessment based on satisfactory past performance;
- Assessment using the partial factor method and
- Probabilistic assessment.

The first approach is applicable for a limited number of existing structures only. At present, the existing structures are mostly verified using the partial factor method accepted for structural design. However, such assessments are often conservative and may lead to expensive upgrades since the assessment of an existing structure is a situation-specific task.

The explicit consideration of the uncertainty related to the most significant parameters and reflection of new information may be of great importance and may lead to significant economic benefits [3]. In general probabilistic reliability analysis provides an effective tool of the assessment of existing structures [3-6]. Such an analysis improves reliability assessment particularly with respect to:

- Better description of uncertainties;
- Identifying importance of basic variables and
- Facilitating inclusion of inspection and test results, and information about the satisfactory past performance of a structure.

That is why this study is focused on probabilistic assessment of existing structures with special emphasis on probabilistic updating.

2. Basis of probabilistic assessment

2.1. Principles

The approach to assessment of existing structures is in many aspects different from that taken in designing the structure of a newly proposed building. The effects of the construction process and subsequent life of the structure, during which it may have undergone alteration, deterioration, misuse, and other changes to its as-built (as-designed) state, must be taken into account. However, even though the existing building may be investigated several times, some uncertainty in behaviour of the basic variables shall always remain. Therefore, similarly as in the design of new structures, actual variation in the basic variables describing actions, material properties, geometric data and model uncertainties is taken into account by appropriate probabilistic models.

The main general principles of the assessment can be summarized as follows:

1. Available scientific knowledge and know-how including currently valid codes should be applied; historical practice and provisions valid in the time when the structure was built (designed) should be used as guidance information only;
2. Actual characteristics of structural material, action, geometric data and structural behaviour should be considered; original documentation including drawings should be used as guidance material only.

The first principle should be applied in order to achieve similar reliability level as in case of newly designed structures. The second principle should avoid negligence of any structural condition that may affect actual reliability (in a favourable or unfavourable way) of a given structure.

It follows from the second principle that a visual inspection and measurements of the assessed structure should be made whenever possible. Practical experience shows that inspection of the site is also useful to obtain a good feel for actual situation and state of the structure.

Generally, actual properties of basic variables describing actions, material properties, and geometric data are to be considered. In addition, expected societal and economic consequences of a required intervention and possible structural failure should be taken into account. That is why the assessment of existing structures often requires application of sophisticated tools including probabilistic methods, as a rule beyond the scope of traditional design practice.

The most important steps of the probabilistic assessment include specification of the target reliability level, evaluation of inspection data and updating of prior information concerning all the basic variables. Typically the assessment of existing structures is a cyclic process in which the first preliminary assessment must be often supplemented by subsequent detailed investigations and assessment.

2.2. Treatment of uncertainties

Probabilistic methods are useful for assessment of existing structures where appropriate data can be obtained [3,7]. Uncertainties that can be greater than in structural design (such as the statistical uncertainty due to a limited amount of test data or uncertainties related to inaccessible members and connections where construction details cannot be inspected and verified) can be adequately described by such methods. On the contrary, some of the uncertainties reflected (often implicitly) in the load and resistance variables (modelling approximations, deviations from specified dimensions and strengths) may be lower than those in new construction, particularly when in-situ measurements are taken. Figure 1 indicates uncertainties affecting reliability of existing structures.

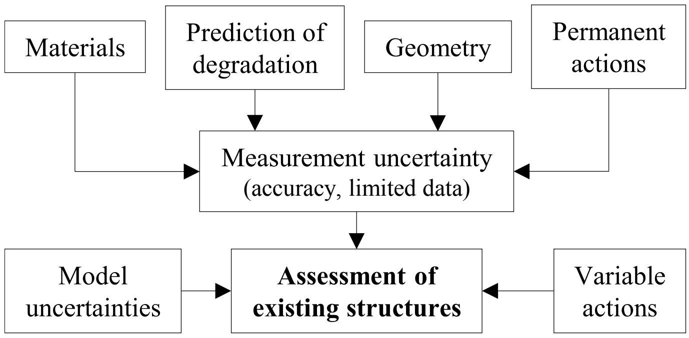

Figure 1 Uncertainties in assessment

Theoretical models describing basic variables should be adjusted to the actual situation and state of a structure and verified by inspection and testing. The following principles should be taken into account:

- Material properties should be described by models reflecting the actual state of a structure as verified by destructive or non-destructive testing. It may often be appropriate to combine limited new information with prior information. Bayesian techniques provide a consistent basis for this updating. Prior information may be found in normative documents, scientific literature, reports of producers and other technical reports etc.
- When significant deterioration is observed, an appropriate deterioration model should be used to predict changes in structural properties due to expected environmental conditions, structural loading, maintenance practices and past exposures, based on theoretical or experimental investigation, inspection and experience.
- Dimensions of structural members should be described by models based on measurements. When the original design documentation is available and no changes in dimensions exist, nominal dimensions given in the documentation may be used.
- Load characteristics should be introduced by models representing well the actual situation. For structures with significant permanent

actions, the actual geometry should be verified by measurements and weight densities should be obtained from tests.

- Measurement uncertainty associated with accuracy of a test method and with statistical uncertainties due to limited data should be taken into account. This uncertainty is of great importance particularly for visual inspections, non-destructive and semi-destructive techniques whilst it may be negligible when destructive tests are conducted.
- Model uncertainties should be considered in the same way as at a design stage unless previous structural behaviour (especially damage) indicates otherwise. In some cases model factors, coefficients and other design assumptions may be estimated on the basis of measurements.

It follows that reliability verification of an existing building should be backed up by inspection including collection of appropriate data. Evaluation of prior information and its updating using newly obtained measurements is often a crucial step of the assessment.

3. Probabilistic updating

3.1. Sources of information

In assessment of existing structures vague prior information is commonly available and needs to be supplemented by experimental data and/or by other additional information such as a qualitative assessment on the basis of inspection. It has been recognised that the probabilistic updating based on Bayesian methods provide a rational and consistent basis for the inclusion of the new information.

When assessing existing structures various types of information may be available. Examples of such information include:

- Survival of a significant overloading,
- Material characteristics from different sources such as destructive and non-destructive tests,
- Known geometry, damage and deterioration,
- Outcome of visual inspections,
- Capacity by proof loading,
- Static and dynamic response to controlled loading.

In the assessment of existing structures new information can be considered and combined with the *prior* probabilistic models by updating techniques. This results in the so-called *posterior* probabilistic models that are used for an enhanced assessment of the structure. Prior information is commonly based on experience from assessments of similar structures, long-term material production, findings reported in literature and/ or engineering judgement.

Two fundamental types of the probabilistic updating can be distinguished:

- Updating of the (multivariate) probability distribution of basic variables,
- Direct updating of the structural failure probability.

A common approach is to update firstly distributions of basic variables and then to analyse reliability considering updated distributions and additional information. Applications of direct updating are mostly limited to research studies. That is why updating of probability distributions of basic variables is discussed hereafter only.

3.2. Updating by material tests

Figure 2 shows three examples of prior and posterior probability density functions together with likelihood functions. In case a) the prior information is strong and the likelihood is weak (small sample size or significant measurement error). In case b) the prior information is weak and the likelihood is strong. Finally in case c) the prior information and the likelihood are of comparable strength. It is seen from Figure 2 that the modelling of both the prior and likelihood probabilistic models is of utmost importance.

In Bayesian updating characteristics $\mathbf{\Theta}$ of a probabilistic distribution of a random variable X (e.g. mean, standard deviation, skewness, lower bound etc.) are considered as random variables. Prior distributions of these characteristics are then updated using n test results x_1, x_2,…, x_n. The variable has the prior probability density function f‘(x|$\mathbf{\Theta}$) dependent on the random parameters $\mathbf{\Theta}$ and Π‘($\mathbf{\Theta}$) is the prior joint probability density function of the parameters $\mathbf{\Theta}$. Note that the symbol ‘denotes the prior characteristics, symbol “ the posterior characteristics and test results are indicated without the quotation marks. Joint probability density function Π“ of the uncertain mean and standard deviation, $\mathbf{\Theta} = \{\mu,\sigma\}^{\mathrm{T}}$, can be updated considering the test results as follows:

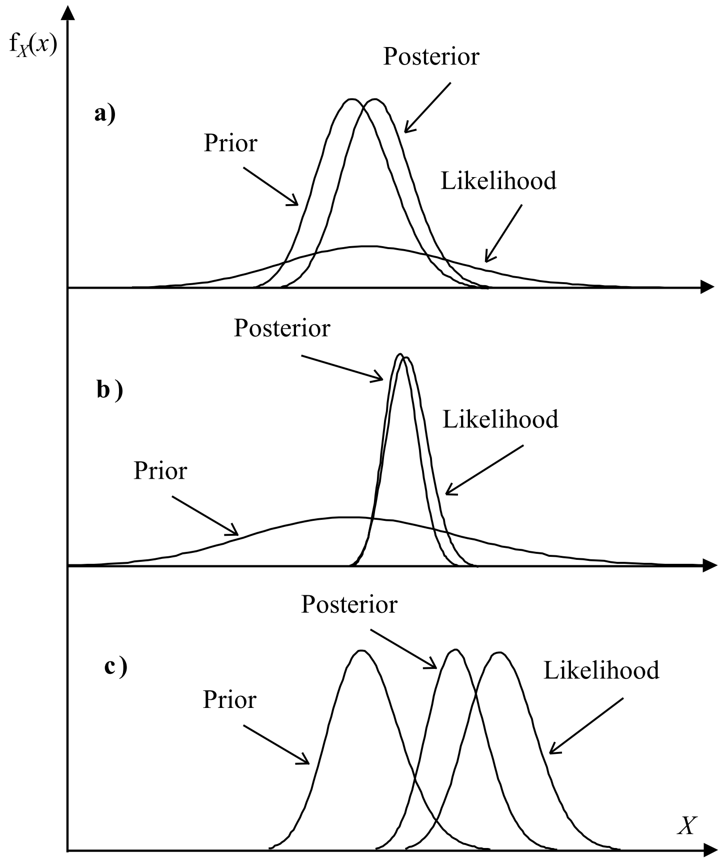

Figure 2 Updating of probabilistic models

$$\Pi''(\mu,\sigma|x_1,x_2,..,x_n)=\frac{\Pi'(\mu,\sigma)\prod_{i=1}^{n}f'(x_i|\mu,\sigma)}{\int_{\Theta}\Pi'(\xi)\prod_{j=1}^{n}f'(x_j|\xi)d\xi}= \qquad (1)$$

$$=C(x_1,x_2,..,x_n)\Pi'(\mu,\sigma)\prod_{i=1}^{n}f'(x_i|\mu,\sigma)$$

where C denotes a normalizing constant. Posterior probability density function of the random variable is obtained by integration:

$$\mathrm{f}''\left(x \middle| x_1, x_2, .., x_n\right) = \int_{\boldsymbol{\Theta}} \mathrm{f}'\left(x \middle| \xi\right) \Pi''\left(\xi \middle| x_1, x_2, .., x_n\right) \mathrm{d}\xi \tag{2}$$

A number of closed form solutions of Equations (1) and (2) can be found for special types of probability distribution functions known as the natural conjugate distributions [3,8]. These solutions are useful in the updating of random variables and cover a number of distribution types of practical relevance. When no analytical solution is available, FORM/SORM techniques can be used to assess the posterior distribution.

3.3. Updating by proof loading

In addition to test results, the updating of a model for resistance X can be based on information about the action effect E to which the structure or its member has been exposed and that has caused no damage or failure. Such information can be inferred from a proof test or from records about performance of the structure.

It is assumed that:

- The prior probability density function f'(x|**Θ**) is known.
- Action effect E can be determined without significant uncertainties and thus can be described by a deterministic value.
- Resistance X and action effect E correspond to each other; for instance they can represent flexural resistance of a critical cross section and bending moment due to the proof load in this cross section, respectively.

In this case it can be assumed that P($X < E$) = 0 and the posterior probability density function of X becomes:

$$\mathrm{f}''\left(x \middle| E\right) = \begin{cases} 0 & \dots \quad x < e \\ \dfrac{\mathrm{f}'(x)}{1 - \mathrm{F}'(E)} & \dots \quad x \geq e \end{cases} \tag{3}$$

where F'(·) denotes the prior cumulative distribution function of X. Effect of updating by the action effect is illustrated in Figure 3.

However, uncertainty in estimate of E needs to be taken into account in most practical cases and the effect of updating on structural reliability often vanishes. Sources of this uncertainty include model uncertainty in assessment of E and measurement uncertainty.

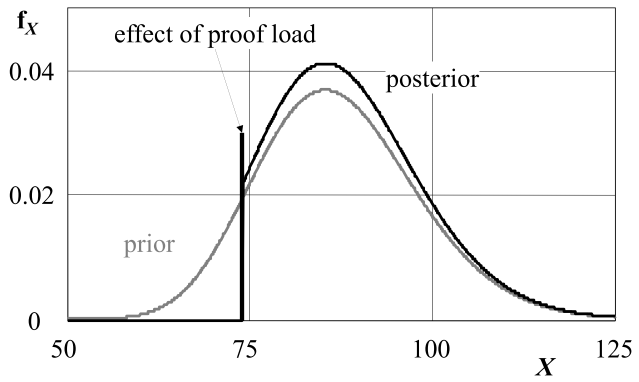

Figure 3 Posterior probability density function updated by known action effect

4. Target reliability

4.1. Target reliability in standards

Specification of the target reliability levels is required for the probabilistic assessment of existing structures. In addition the target reliabilities can be used to modify the partial factors for a deterministic assessment. It has been recognised that it would be uneconomical to specify for all existing buildings and bridges the same reliability levels as for new structures [9-11].

The target reliability levels recommended in EN 1990 [12] related to consequences of failure are primarily intended for new structures. More detailed classification is given in ISO 2394 [13] where relative costs of safety measures are also taken into account. The target reliability levels provided in both documents are partly based on calibrations to previous practice and should be considered as indicative only. ISO 13822 [2] indicates a possibility to specify the target reliability levels for existing structures by optimisation of the total cost related to an assumed remaining working life. This approach is further developed in this chapter.

4.2. Optimum upgrade strategy

ISO 13822 [2] indicates that lower target reliability levels can be used if justified on the basis of societal, cultural, economical, and sustainable considerations. In accordance with ISO 2394 [13] the target level of reliability should depend on a balance between the consequences of failure and the costs of safety measures. From an economic point of view the objective is to minimize the total working-life cost.

Based on previous studies concerning existing structures, the expected total costs C_{tot} may be generally considered as the sum of the expected costs of inspections, maintenance, upgrades and costs related to failure of a structure. The decision parameter(s) d to be optimised in the assessment may influence resistance, serviceability, durability, maintenance, inspection, upgrade strategies etc. Examples of d include shear or flexural resistances, stiffness of a girder to control deflections etc.

The decision parameter is hereafter assumed to concern the immediate upgrade only while inspection, maintenance and future repair or upgrade strategies are influenced marginally. Moreover, the benefits related to use of the structure that in general should be considered in the optimisation are not affected by the value of the decision parameter. These assumptions may be reasonable in many practical cases.

In general the immediate upgrade costs consist of:

- Cost C_0 independent of the decision parameter (costs related to surveys, design, economic losses due to business interruption, replacement of users etc.),
- Cost $C_m(d)$ dependent on the decision parameter.

It is assumed that the upgrade cost can be estimated based on previous experience.

Failure cost C_f - the cost related to consequences of structural failure may include (depending on a subject concerned):

- Cost of rehabilitation or replacement,
- Economic losses due to non-availability or malfunction of the structure,
- Societal consequences (costs of injuries and fatalities),
- Unfavourable environmental effects (CO_2 emissions, energy use, release of dangerous substances),
- Psychological effects (loss of reputation).

Estimation of the failure cost is a very important, but likely the most difficult step in the cost optimisation. It is essential to include not only direct consequences of failure (those resulting from failures of individual components), but also follow-up consequences (related to a loss of the functionality of a whole structure). Background information for consequence analysis can be found e.g. in [14-16].

For consistency, the upgrade and failure costs need to be expressed on a common basis. The upgrade cost is normally specified in a present value. All the expected failure costs that may occur within a reference period should thus be likewise estimated in the present worth. This leads to the expected failure cost as follows:

$$\mathrm{E}\left[C_\mathrm{f}\left(t_\mathrm{ref}, d\right)\right] = \int_{t_\mathrm{ref}} C_\mathrm{f}(t)\pi_\mathrm{f}(t,d)\mathrm{d}t \approx C_\mathrm{f}\int_{t_\mathrm{ref}} \pi_\mathrm{f}(t,d)\mathrm{d}t \tag{4}$$

where E denotes expectation; C_f the present value of the failure cost; and $\pi_\mathrm{f}(t,d)$ is the discounted conditional failure rate given by the relationship:

$$\pi_\mathrm{f}(t,d) = [P_\mathrm{f}(t,d)]' \,/\, \{(1 + q)^t \times [1 - P_\mathrm{f}(t,d)]\} \tag{5}$$

where $P_\mathrm{f}(\cdot)$ is the failure probability; $(\cdot)'$ time derivative; and q the annual discount rate. The symbol of expectation is hereafter omitted for convenience of notation.

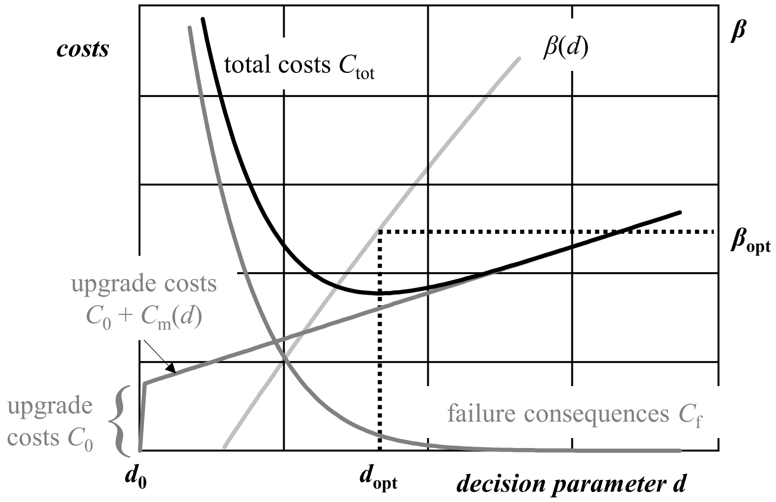

Figure 4 Optimal upgrade strategy based on minimisation of total costs

The expected total costs indicated in Figure 4 can now be expressed as follows:

In case of upgrade:

$$C_\mathrm{tot}(t_\mathrm{ref};d) = C_0 + C_\mathrm{m}(d) + C_\mathrm{f}\int_{t_\mathrm{ref}} \pi_\mathrm{f}(t,d)\mathrm{d}t \tag{6}$$

In case of no upgrade (accepting a present state):

$$C_{tot}(t_{ref}) = C_f \int_{t_{ref}} \pi_f(t, d_0)\mathrm{d}t \qquad (7)$$

where d_0 = value of the decision parameter before an upgrade. It is noted that the cost $C_m(d)$ can often be considered as linearly dependent on the decision parameter d.

From Equation (6), an optimum value of the decision parameter d_{opt} (optimum upgrade strategy, see Figure 4) can be assessed:

$$\text{minimum}_d\ C_{tot}(t_{ref};d) = C_{tot}(t_{ref};d_{opt}) \qquad (8)$$

The optimum upgrade strategy should aim at the target reliability corresponding to d_{opt}:

$$\beta_t = -\Phi^{-1}[P_f(t_{ref};d_{opt})] \qquad (9)$$

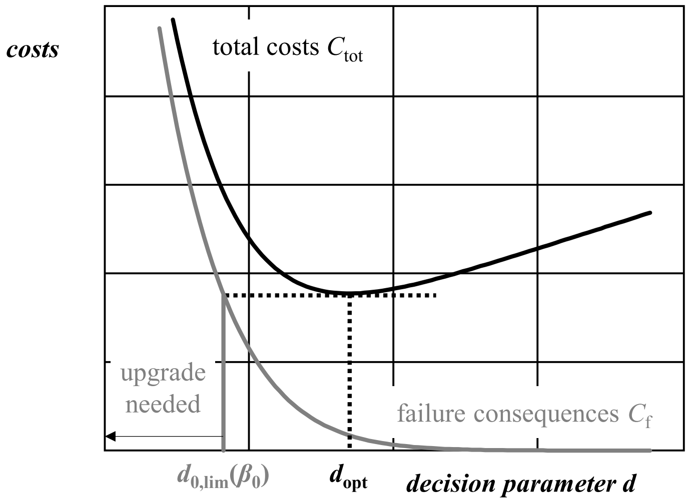

Figure 5 Decision on upgrade using economic optimisation

4.3. Decision on upgrade

From an economic point of view, no upgrade is undertaken when the total cost according to Equation (7) is less than the total cost of the optimum upgrade. The limiting value d_{0lim} of the decision parameter before the upgrade is then found as follows (see also Figure 5):

$$C_f \int_{t_{ref}} \pi_f(t, d_{0\,lim}) dt = C_0 + C_m(d_{opt}) + C_f \int_{t_{ref}} \pi_f(t, d_{opt}) dt \qquad (10)$$

For $d_0 < d_{0lim}$ the reliability level of an existing structure is too low, failure consequences become high and the decision is to upgrade the structure as the optimum upgrade strategy yields a lower total cost. For $d_0 > d_{0lim}$ the present state is accepted from an economic point of view since no upgrade strategy leads to a lower total cost than costs expected when no upgrade is taken.

The minimum reliability index β_0 below which the structure is assumed to be unreliable and should be upgraded is thus obtained as follows:

$$\beta_0 = -\Phi^{-1}[P_f(t_{ref};d_{0lim})] \qquad (11)$$

In addition to economic optimisation several other criteria are applied to establish target reliability levels of civil engineering structures. They include:

- Criterion for individual human safety provides a relatively simple approach in order to assure acceptable risks of occupants or users of the structure when compared to other daily-life activities.
- Group risk criteria are often used by governments and municipalities to avoid accidents with an excessive number of casualties.
- The LQI concept enables to balance investments of the society into health and life safety improvements amongst various industrial sectors.

Limits for human safety play an important role particularly for existing structures with a limited remaining lifetime [17]. However, detailed discussion of these approaches is beyond the scope of this study.

5. Concluding remarks

At present, the existing structures are mostly verified using the partial factor method accepted for structural design. However, such assessments are often conservative and may lead to expensive rehabilitations since the assessment of an existing structure is a situation-specific task.

Competent decisions concerning interventions should be always based on a complex reliability assessment of an existing structure. In such assessment it is essential to take into account actual structural conditions revealed by visual inspections, measurements and material tests. Currently valid codes should be applied and real characteristics of construction materials, actions, geometric data and structural behaviour should be considered.

It is indicted that reliability assessments of existing structures need to account for significant uncertainties related to actual structural conditions that can hardly be described by simplified design procedures. Probabilistic procedure is thus proposed in order to facilitate description of uncertainties and reflection of inspection results, tests and of satisfactory past performance.

It proves to be uneconomical to require the same reliability level for existing and new structures. Decisions of the assessment can result in the acceptance of an actual state or in the upgrade of a structure. Two reliability levels are thus needed - the minimum level below which the structure is unreliable and should be upgraded, and the target level indicating an optimum upgrade strategy. Procedure of probabilistic optimisation, developed by the author, can be effectively used to specify these target values.

6. References

1. *Diamantidis, D. and Bazzurro, P.*: Safety acceptance criteria for existing structures. In Special Workshop on Risk Acceptance and Risk Communication, 2007.

2. *ISO 13822*: Bases for design of structures - Assessment of existing structures, ISO TC98/SC2, Geneve, Switzerland, 2010.

3. *JCSS*: Probabilistic Assessment of Existing Structures, Joint Committee on Structural Safety, RILEM Publications S.A.R.L., 2001.

4. *Diamantidis, D. et al.*: Innovative Methods for the Assessment of Existing Structures, CTU in Prague, Prague, 2012.

5. *Caspeele, R., Sykora, M., Allaix, D.L. et al.*: The Design Value Method and Adjusted Partial Factor Approach for Existing Structures. Structural Engineering International, 2013, 23, No. 4, 386-393.

6. *Sykora, M., Holicky, M. and Markova, J.*: Verification of existing reinforced concrete bridges using the semi-probabilistic approach. Engineering Structures, 2013, 56, No. 0, 1419-1426.

7. *Holický, M. and Sýkora, M.*: Structural assessment of heritage buildings (invited lecture). In Proc. 1st Int. Conf. Defence Sites: Heritage and Future 2012 (eds. C. Clark and C.A. Brebbia), WIT Press, Arshurst Lodge (UK), 2012, pp. 69-80.

8. *Ang, A.H.S., Tang, W.H.*: Probabilistic Concepts in Engineering Emphasis on Applications to Civil and Environmental Engineering, 2nd edn., John Wiley & Sons, USA, 2007.

9. *Zwicky, D.*: SIA 269/2 – A New Swiss Code for the Conservation of Concrete Structures. In Proc. 3rd fib International Congress Precast/Prestressed Concrete Institute, Chicago, 2010, pp. 13.

10. *Vrouwenvelder, A.C.W.M. and Scholten, N.*: Assessment Criteria for Existing Structures. Structural Engineering International, 2010, 20, No. 1, 62-65.

11. *Sykora, M., Diamantidis, D., Holicky, M. et al.*: Target Reliability Levels for Assessment of Existing Structures Considering Economic and Societal Aspects. In Proc. IALCCE 2014 (eds. H. Furuta, D.M. Frangopol and M. Akiyama), CRC Press/Balkema, Leiden, 2014, pp. 838-845.

12. *EN 1990*: Eurocode - Basis of structural design, CEN, Brussels, 2002.

13. *ISO 2394*: General principles on reliability for structures, 2nd edn., ISO, Geneve, Switzerland, 1998.

14. *JCSS*: JCSS Probabilistic Model Code, Joint Committee on Structural Safety, 2001.

15. *Janssens, V., O'Dwyer, D.W. and Chryssanthopoulos, M.K.*: Assessing the Consequences of Building Failures. Structural Engineering International, 2012, 22, No. 1, 99-104.

16. *Imam, B.M. and Chryssanthopoulos, M.K.*: Causes and Consequences of Metallic Bridge Failures. Structural Engineering International, 2012, 22, No. 1, 93-98.

17. *Steenbergen, R.D.J.M., Sykora, M., Diamantidis, D. et al.*: Target reliability levels for assessment of existing structures based on economic optimisation and human safety criteria (invited contribution, submitted for review). Structural Concrete, 2015.

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- 1999-2000 bridge design and diagnostics, PONTEX Ltd.
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- 2002-present employed as a researcher at the Klokner Institute, active in a number of national and international research projects, forensic engineering assessments
- 2003 study stay at Technische Universiteit Delft (the Netherlands, supervised by Prof. A.C.W.M. Vrouwenvelder)

Research interests cover basis of structural design, structural reliability, probabilistic optimisation, load modelling, risk assessment of technical systems (including civil engineering structures and power plants) and applications of probabilistic methods in structural design. He is an author or co-author of several handbooks for practising engineers and a number of scientific publications (about 200, most of them in English, 25 of them registered at the Web of Science, 55 of them registered in SCOPUS). He is a member of the Editorial Boards of ACTA POLYTECHNICA (CTU Journal of Advanced Engineering) and of the Building Research Journal. He is a member of Scientific Committees of the conferences 'Defence Heritage' and 'STREMAH' (international) and 'Modelling in Mechanics' (national).

Teaching activities cover lectures on the basis of structural design and structural reliability at CTU in Prague. He is supervisor of two Ph.D. and one master student at the Klokner Institute. He was an external advisor of a successful Ph.D. candidate at the University of Bundeswehr, Neubiberg (Germany) and reviewer of a Ph.D. thesis at the Brest State Technical University. He is supervising a Ph.D. student from Budapest University of Technology and Economics during the stay in the Klokner Institute (September 2014 – July 2015). In 2013 and 2014 he gave lectures at the technical university of applied sciences OTH Regensburg (Germany). He is involved in the vocational training of practicing engineers and other experts active in construction industry within the life-long education (actions on structures, basis of structural design).

Memberships in research and standardisation organisations:

- Joint Committee on Structural Safety (structural reliability, risk analysis, robustness of structures)
- *fib*, Special Activity Group 7 Assessment and Interventions upon Existing Structures (AIES)
- ESReDA PG on Critical Infrastructures Preparedness and Resilience – Modelling, Simulation & Analysis Data
- International Association for Life-Cycle Civil Engineering IALCCE
- Czech national contact for the Horizontal Group - Bridges of CEN
- Czech representative in CEN/ TC 250/ SC 1/ WG 3 Traffic loads on bridges
- Member of the sub-committee on concrete bridges under the Czech Technical Standardisation Committee TNK 36

Current and recent projects (project leader, co-leader or manager) include the international project:

- A/CZ0046/2/0013 Assessment of historical immovables (2009-2010)

and the national projects:

- VG20122015089 Safety Assessment of Transportation Structures Exposed to Accidental Actions (2012-2015)
- DF12P01OVV040 Assessment of Safety and Working Life of Industrial Heritage Buildings (2012-2015)
- P105/12/2051 Model Uncertainties in Resistance Assessment of Concrete Structures (2012-2014)
- OC08059 Assessment of structural robustness (2008-2011)

- GP103/06/P237 Probabilistic Analysis of Time-Variant Structural Reliability (2006-2008)

- EUFX CZ.04.3.07/4.2.01.1/0005 Innovations of Methods for Assessment of Existing Structures (2006-2007)

Current and recent projects (task leader, team member) include the international projects:

- COST Action TU1402 Quantifying the value of structural health monitoring (2014-2018)

- CZ/13/LLP-LdV/TOI/134014 Innovation Transfer in Risk Assessment and Management of Aging Infrastructures (2013-2015)

- CZ/11/LLP-LdV/TOI/134005 Vocational Training in Assessment of Existing Structures (2011-2013)

- LDVX CZ/08/LLP-LdV/TOI/134020 Transfer of Innovations Provided in Eurocodes (2008-2010)

- COST Action TU0601 Robustness of Structures (2007-2011)

and the national projects (selected):

- TE01020068 Centre of research and experimental development of reliable energy production (2012-2019)

- P105/12/G059 Centre of Excellence - Cumulative Time Dependent Processes in Building Materials and Structures (2012-2018)

- P105/12/0589 Probabilistic Optimization of the Target Structural Reliability (2012-2014)

- TA01031314 Optimisation of Safety and Working Life of Existing Bridges (2011-2013)

- GA103/09/0693 Assessment of Safety and Risks of Technical Systems (2009-2011)

- GA103/08/1527 Global safety format for design of reinforced concrete structures (2008-2010)

In addition he has been recently involved in the applied research project “Improved methodology for the assessment of reliability and working life of power plants using probabilistic methods” (2011-2012), fully supported by CEZ Group, a leading company on the electricity market in Central Europe.

Selected publications:

1. CASPEELE, R. – SYKORA, M. – TAERWE, L. Influence of quality control of concrete on structural reliability: assessment using a Bayesian approach; In: *Materials and Structures* 47(1-2): 105-116, 2014, Print ISSN 1359-5997, Online ISSN 1871-6873
2. ČEJKA, T. – HOLICKÝ, M. - SÝKORA, M. – WITZANY, J. Strength Assessment of Historic Brick Masonry (in press); In: *Journal of Civil Engineering and Management*, ISSN 1392-3730 (print), 1822-3605, 10.3846/13923730.2014.914087
3. HOLICKY, M. – MARKOVÁ, J. – SYKORA, M. Forensic assessment of a bridge downfall using Bayesian networks; In: *Engineering Failure Analysis* 30(June 2013): 1-9, ISSN 1350-6307
4. SADOVSKÝ Z.- SÝKORA M. Snow load models for probabilistic optimization of steel frames; In: *Cold Regions Science and Technology* 94(0): 13-20, ISSN 0165-232X
5. SYKORA M. – HOLICKY M. – MARKOVA J.. Verification of Existing Reinforced Concrete Bridges using a Semi-Probabilistic Approach; In: *Engineering Structures* 56(November 2013): 1419-1426, ISSN 0141-0296
6. CASPEELE, R. - SYKORA, M. - ALLAIX, D. - STEENBERGEN, R. The Design Value Method and Adjusted Partial Factor Approach for Existing Structures; In: *Structural Engineering International* 23/4, 2013, pp. 386-393, ISSN 1016-8664
7. VROUWENVELDER, T. – LEIRA, BJ. – SYKORA, M. Modelling of Hazards; In: *Structural Engineering International* 1/2012, pp. 73-78, ISSN 1016-8664
8. DIAMANTIDIS D., HOLICKÝ M., MARKOVÁ J., SÝKORA M., VROUWENVELDER T., ARTEAGA A., CROCE P., TANNER P., LARA C., TOPRAK S., INEL M., SENEL S. *Innovative Methods for the Assessment of Existing Structures*. Prague: CTU in Prague, Klokner Institute, 2012. 148 p. ISBN 978-80-01-05115-3
9. HOLICKÝ M., MARKOVÁ J., SÝKORA M. *Zatížení stavebních konstrukcí*. Informační centrum ČKAIT, 2010, 131 s. ISBN 9788087093894
10. HOLICKÝ M., MARKOVÁ J., SÝKORA M., KUKAŇ V., DRAHORÁD M. Ověřování existujících betonových mostů pozemních komunikací. *Technické podmínky TP 224*. Praha: Ministerstvo dopravy ČR, odbor silniční infrastruktury, 2010, p. 53.

In Prague, 16 March 2015 Miroslav Sýkora