General methodology for probabilistic assessment of industrial heritage structures

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1 INTRODUCTION

A number of factories, warehouses, power plants and other industrial buildings has been worldwide registered as industrial cultural heritage. According to the International Committee on the Conservation of the Industrial Heritage TICCIH (2003), such structures are mostly of significant architectural, historic, technological or social value. It is indicated that protection (including adaptations and re-use) of the industrial heritage structures is an important issue since it may positively contribute to the sustainable development of urban areas by:

- Preservation of cultural values (the industrial heritage often forms a part of the urban landscape and provide the cityscape with a visual historical landmark),
- Recycling of potential resources and avoiding wasting energy,
- Facilitating the economic regeneration of regions in decline.

However, insufficient attention seems to be paid to systematic recognizing, declaring and protecting the industrial heritage in most countries. This is an alarming situation as the lack of attention and awareness of the industrial structures may gradually lead to their extinction.

When out of use, the industrial heritage structures are degrading and often turning into ruins. Re-use and adaptation of such structures allow for integration of the industrial heritage into a modern urban lifestyle and help protect cities' cultural heritage, Läuferts & Mavunganidze (2009). These structures are often adapted to become hotels, museums, residential parks, commercial centres etc.

Decisions about adequate construction interventions should be based on the complex assessment of a structure. It has been recognised that many heritage structures do not fulfil requirements of present codes of practice. Minimisation of construction interventions is required in rehabilitation and upgrades, but sufficient reliability should also be guaranteed. Application of simplified procedures used for design of new structures may lead to expensive repairs and losses of the cultural and heritage value. A general probabilistic procedure is thus proposed to:

- Improve the reliability assessment of industrial heritage structures,
- Describe better uncertainties related to the assessment and
- Allow for inclusion of results of inspections and tests and the satisfactory past performance of a structure.

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Since construction interventions may be excessively expensive and may lead to losses of the cultural and heritage value, a general framework based on probabilistic optimisation is proposed to indicate optimum target reliability levels for the industrial heritage structures. Obtained results are compared with the target reliability levels indicated in ISO 2394 (1998) and those based on the empirical relationship proposed by Schueremans & Van Gemert (2004). Application of the probabilistic techniques is illustrated by a numerical example.

2 INITIATIVES CONCERNING THE INDUSTRIAL HERITAGE

The protection of the industrial heritage is a multidisciplinary topic including historical, architectonic, civil engineering and ecological aspects. In 1978 the International Committee on the Conservation of the Industrial Heritage (TICCIH) was founded to study, protect, conserve and explain remains of industrialisation. Its recent efforts have resulted in registration of more than 40 industrial sites in the World Heritage List, Zhang (2007).

In the Czech Republic numerous industrial heritage structures were built from 1870 to 1930. Fragner (2010) indicates that views of Czech architects and civil engineers on protection of the industrial heritage are often considerably different and an important issue may be to achieve consensus on significance of the heritage value. Desired coordinating platform is provided by the Research Centre for Industrial Heritage that maintains a database of the Czech industrial monuments (containing more then 10 000 monuments) and seeks for new uses of the industrial heritage structures.

In addition the Czech Technical University in Prague and the University of Applied Sciences in Ås (Norway) have launched the research project Assessment of historical immovables, mainly focused on assessment of the industrial heritage structures.

3 GENERAL ASPECTS OF THE ASSESSMENT

As a rule re-use and adaptation of the industrial structures require assessment of structural reliability. However, it appears that insufficient attention has been paid by experts to specific issues of the reliability assessment of such structures so far. The following differences between the assessment and design of new structures should be carefully considered:

- Social and cultural aspects - loss of cultural and heritage values,
- Economic aspects - additional costs of measures to increase reliability of a heritage structure in comparison with a new structure (at a design stage cost of such measures is normally minor while cost of strengthening is much higher),
- Principles of the sustainable development - waste reduction and recycling of materials (these aspects may be more significant in case of the assessment),
- Lack of information for the assessment - commonly, testing of the mechanical properties of materials is difficult, expensive, but also very important due to variability of mechanical properties and changes that may have occurred during the working life of a structure (influence of deterioration and damage).

It has been recognised that many heritage structures do not fulfil requirements of present codes of practice. Minimisation of construction interventions is required in rehabilitation and upgrades, but sufficient reliability should also be guaranteed. Decisions about adequate construction interventions should be based on the complex assessment of a structure considering actual material properties, use and environmental conditions.

Significant uncertainties related to actual material properties and structural conditions usually need to be considered in the reliability assessment of the industrial heritage structures. In design codes a limited number of safety factors is intended to cover all possible design situations. Therefore, verifications based on deterministic design procedures may be

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too conservative, Stewart et al. (2001). Application of commonly used design procedures may thus lead to expensive repairs and losses of the cultural and heritage value. It follows that use of deterministic design procedures may not be an appropriate approach.

It has been recognised that assessment of existing structures is a structure-specific task that is difficult to codify. In accordance with EN 1990 (2002) and ISO 13822 (2003), a general probabilistic procedure is thus proposed to improve the reliability assessment of the industrial heritage structures and allow for inclusion of results of inspections, testing and consideration of the satisfactory past performance of a structure.

4 PRINCIPLES OF PROBABILISTIC ANALYSIS

Matthews (2009) indicates that probabilistic methods may be useful for the assessment of existing structures where appropriate data can be obtained. According to Ellingwood (1996) uncertainties that can be greater than in structural design (such as uncertainties related to inaccessible members and connections where construction details cannot be inspected and verified) may be adequately described by such methods. On the contrary, some of the uncertainties reflected (often implicitly) in the load and resistance factors (modelling approximations, deviations from specified dimensions and strengths) may be less than in new construction, particularly when in-situ measurements are taken.

4.1 *Specification of models for basic variables*

Models for 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 considered according to the actual state of a structure verified by destructive or non-destructive testing. It may often be appropriate to combine limited new information with prior information. Bayesian techniques, described e.g. in ISO 12491 (1997), Diamantidis (2001) or JCSS (2006), provide a consistent basis for this updating.
- When significant deterioration is observed, an appropriate deterioration model should be used to predict changes in structural parameters due to foreseen environmental conditions, structural loading, maintenance practices and past exposures, based on theoretical or experimental investigation, inspection and experience.
- Dimensions of structural members should be determined by 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 considering the values corresponding to 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.
- 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 established from measurements.

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

4.2 *Probabilistic updating*

The failure probability, related to the period from the assessment to the end of a working life t_D, can be obtained from a general probabilistic relationship:

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$$p_f(t_D) = P\{\min Z[\mathbf{X}(\tau)] < 0 \text{ for } 0 < \tau < t_D\} = P\{F(t_D)\} \tag{1}$$

where $Z(\cdot)$ = limit state function; $\mathbf{X}(\cdot)$ = vector of basic variables including model uncertainties, resistance, permanent and variable actions; and $F(t_D)$ = failure in the interval $(0,t_D)$.

When additional new information I related to structural conditions is available, the failure probability may be updated according to ISO 13822 (2003) as follows:

$$p_f''(t_D|I) = P\{F(t_D) \cap I\} \,/\, P(I) \tag{2}$$

The information should be selected to maximise correlation between the events $\{F\}$ and $\{I\}$. Strong correlation improves the posterior estimate of failure probability while weak correlation yields nearly the same estimates as based on Equation 1, Ellingwood (1996). The new information may be based on:

1 Inspections that can for instance provide data for updating of a deterioration model,
2 Material tests and in-situ measurements that can be taken to improve models of concrete compressive strength, steel yield strength, geometry etc.,
3 Consideration of the satisfactory past performance.

In the first two cases the new information is usually applied in the direct updating of (prior) distributions of relevant basic variables that are commonly based on experience from assessments of similar structures, long-term material production, findings reported in literature or engineering judgement. The last case may be very important for the industrial heritage structures. For instance a structure, originally used as a factory, might have likely survived loads much greater than those expected for future use as e.g. a museum or gallery.

The satisfactory past performance of a structure during a period t_A till the time of assessment may be included in the reliability analysis considering the conditional failure probability $p_f''(t_D|t_A)$ that a structure will fail during a working life t_D given that it has survived the period t_A. This probability may be estimated in several ways. When the load to which the structure has been exposed during the period t_A is known with negligible uncertainties, the resistance or a joint distribution of time-invariant variables may be truncated (a lower bound is set to the value of load). Using the bounded distribution, the conditional (updated) probability $p_f''(t_D|t_A)$ can be estimated. This approach, similar to the updating for proof load testing described by Diamantidis (2001), is illustrated elsewhere, Sykora et al. (2010). More generally, the updated failure probability may be determined using the following relationship:

$$p_f''(t_D|t_A) = \frac{P\{F(t_D) \cap \bar{F}(t_A)\}}{P\{\bar{F}(t_A)\}} = \frac{P\{F(t_D)\} - P\{F(t_D) \cap F(t_A)\}}{1 - P\{F(t_A)\}} \tag{3}$$

where $\bar{F}$ = complementary event to the failure. The updated probability can be determined by standard techniques for reliability analysis such as the FORM/SORM methods or importance sampling. Updating based on Equation 3 is applied in a numerical example.

5 TARGET RELIABILITY LEVELS

Reliability verification may be based on the following (equivalent) relationships:

$$p_f''(t_D|I) < p_t, \quad \beta''(t_D|I) = -\Phi^{-1}[p_f''(t_D|I)] \geq \beta_t \tag{4}$$

where p_t = target failure probability; Φ^{-1} = inverse cumulative distribution function of the standardised normal variable; and β_t = target reliability index.

The target reliability level can be taken as the level of reliability implied by acceptance criteria defined in proved and accepted design codes. The target level should be stated together with clearly defined limit state functions and specific models of basic variables. For the industrial heritage buildings, moderate consequences of failure and moderate costs of safety measures can often be assumed. In this case ISO 2394 (1998) indicates $\beta_t = 3.1$.

The target reliability level can also be established taking into account the required performance level of the structure, reference period, cost of upgrades (including potential losses of the cultural and heritage value) and possible consequences of failure or malfunction. Lower target levels can be used if they are justified on the basis of social, cultural, economical, and sustainable considerations, ISO 13822 (2003). A simple model for estimation of the target reliability level was proposed by Schueremans & Van Gemert (2004):

$$p_t = S_c\, t_D\, A_c\, C_f / (n_p\, W) \times 10^{-4} \qquad (5)$$

where S_c = social criterion factor (recommended value for listed historical buildings 0.05); t_D = remaining working life (considered as 50 years); A_c = activity factor (recommended value for buildings 3); C_f = economical factor (5 for a moderate consequences, recommended values: 10 - not serious, 1 - serious consequences of failure); n_p = number of endangered persons (in accordance with Trbojevic (2009) the most favourable and unfavourable estimates $n_{p,min} = 1$ and $n_{p,max} = 10$, respectively, are considered for significant risk of injury or fatalities - a middle class of consequences); and W = warning factor (1 - sudden failure without previous warning). Considering these indicative data, lower and upper estimates of the target reliability level are obtained from Equation 5 as follows:

$$p_{t,max} = 0.05\times50\times3\times5/(1\times0.3) \times 10^{-4} \approx 3.8 \times 10^{-3};\ \beta_{t,min} = 2.7 \qquad (6)$$
$$p_{t,min} = 0.05\times50\times3\times5/(10\times0.3) \times 10^{-4} \approx 3.8 \times 10^{-4};\ \beta_{t,max} = 3.4$$

It appears that the target reliability is within the broad range from 2.7 to 3.4. The value recommended in ISO 2394 (1998) is approximately in the middle of this range.

6 PRINCIPLES OF THE TOTAL COST MINIMISATION

According to Ang & De Leon (1997) the underlying economics is of concern and importance in the upgrading of existing structures. ISO 2394 (1998) indicates that 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 may be to minimize the total working-life cost. Based on studies concerning existing structures by Ang & De Leon (1997) and Onoufriou & Frangopol (2002), the objective function for the total cost C_{tot} of the industrial heritage structures is proposed as follows:

$$\text{minimise}_{\mathbf{p}}\ \mathrm{E}[C_{tot}(t_D;\mathbf{p}|I)] = \mathrm{E}[C_{IM}(t_D;\mathbf{p}|I)] + \mathrm{E}[C_R(t_D;\mathbf{p}|I)] + \Sigma_i \mathrm{E}[C_{f,i}(t_D;\mathbf{p}|I)] \qquad (7)$$

where C_{tot} = total cost over the working life; $\mathbf{p}$ = decision parameters specified in the assessment that may influence resistance, durability, maintenance, inspection, repair strategies etc.; C_{IM} = preventative inspection and maintenance cost over t_D; C_R = repair cost over t_D; and $C_{f,i}$ = failure cost over t_D, dependent on the failure probability for a failure mode i. The summation is made over all (independent) failure modes and load combinations. Principles of cost optimization techniques are described in more details e.g. by Ang & De Leon (1997), Rackwitz et al. (2005), Rackwitz (2002) and Holicky (2009).

The repair cost may include the cost of repair immediately taken after the assessment as well as costs of future repairs. These costs may cover:

- Direct cost related to surveys, design and construction, and loss of the cultural heritage value,
- Indirect cost associated with economic losses due to business interruption or replacement of users.

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The failure cost represents the cost related to consequences of structural failure (malfunction), including:

- Direct cost related to structural damage (cost of repair or replacement) and loss of the cultural heritage value,
- Indirect cost associated with economic losses, societal consequences (cost of injuries and fatalities), unfavourable environmental and psychological effects (release of dangerous substances, loss of reputation).

Decision in the assessment can result in the complete repair of a structure (to achieve a target reliability), minor repair to postpone the complete repair, or in acceptance of an actual state and postponement of the decision about repair. The target reliability is the reliability level corresponding to the optimum decision (optimum structural parameters $\mathbf{p}_{\mathrm{opt}}$):

$$p_{\mathrm{t}} = p_{\mathrm{f}}''(t_{\mathrm{D}},\mathbf{p}_{\mathrm{opt}}|I), \quad \beta_{\mathrm{t}} = \beta''(t_{\mathrm{D}},\mathbf{p}_{\mathrm{opt}}|I) \tag{8}$$

It is hereafter assumed that the decision concerns the immediate repair while inspection, maintenance and future repair strategies are influenced marginally. This may be a reasonable assumption in many practical cases. The optimum decision can then be found by minimisation of the modified total cost $C_{\mathrm{tot}}'(t_{\mathrm{D}};\mathbf{p}|I)$:

$$\min\nolimits_{\mathbf{p}} \mathrm{E}[C_{\mathrm{tot}}'(t_{\mathrm{D}};\mathbf{p}|I)] = \mathrm{E}[C_{\mathrm{tot}}(t_{\mathrm{D}};\mathbf{p}|I) - C_{\mathrm{IM}}(t_{\mathrm{D}}|I)] = C_{\mathrm{R}}(\mathbf{p}|I) + \Sigma_i \mathrm{E}[C_{\mathrm{f},i}(t_{\mathrm{D}};\mathbf{p}|I)] \tag{9}$$

For industrial heritage structures that are not in use, the immediate repair cost consists of the direct cost only. It is further assumed that the cost corresponding to an immediate repair strategy (decision on parameters **p**) can be reasonably well estimated using previous experience with repairs of similar structures.

7 SIMPLIFIED ESTIMATION OF FAILURE COST

Estimation of the failure cost is a very important, but likely the most difficult step in the cost optimisation. For consistency, the repair and failure costs need to be expressed on a common basis. The repair cost is normally specified in a present value. All the expected failure costs that may occur within a working life should thus be likewise estimated in the present worth, Ang & De Leon (1997). This leads to the expected failure cost as follows:

$$\sum_i \mathrm{E}\left[C_{\mathrm{f},i}\left(t_{\mathrm{D}},\mathbf{p}|I\right)\right] = \sum_i \int_{t_{\mathrm{D}}} \frac{C_{\mathrm{f},i}(t)}{(1+q)^t} r_i\left(t,\mathbf{p}|I\right)\mathrm{d}t \approx \sum_i C_{\mathrm{f},i} \int_{t_{\mathrm{D}}} \frac{r_i\left(t,\mathbf{p}|I\right)}{(1+q)^t}\mathrm{d}t \tag{10}$$

where $C_{\mathrm{f},i}$ = failure cost that can often be considered as time-independent; q = annual discount rate; and $r_i(\cdot)$ = conditional failure rate given by the relationship:

$$r_i(t,\mathbf{p}) = \mathrm{P}\{\mathrm{F}_i(t,t+\Delta t,\mathbf{p}|I)|\,\overline{F}_i\,(0,t,\mathbf{p}|I)\} \,/\, \Delta t = [p_{\mathrm{f},i}''(t,\mathbf{p}|I)]' \,/\, [1 - p_{\mathrm{f},i}''(t,\mathbf{p}|I)] \tag{11}$$

where (·)’ = time derivative.

Estimation of the failure cost requires analysis of cultural, economic, societal and environmental consequences. It is further assumed that the environmental consequences can be neglected. All the other components of the failure cost should be preferably assessed in monetary terms, which may, however, be difficult. To facilitate this task, JCSS (2006) proposes classification of the failure consequences. For three classes, the rate ρ between:

- Societal and economic consequences plus construction cost over
- Construction cost

is indicated. The rate ρ is primarily dependent on the purpose of a structure. For many industrial heritage structures typically adapted to serve as office, residential buildings, or museums, Class 2 may be considered (moderate consequences - risk to life given a failure

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moderate and economic consequences considerable; ρ between 2 and 5; examples: office, industrial, residential buildings).

The JCSS recommendations seem to be proposed primarily for new structures where construction cost may be assessed from previous experience. This technique may be adjusted for the industrial heritage structures as follows:

- Consider a new structure and adapted industrial heritage structure of similar configuration, intended for the same purpose,
- From the definition of the consequence classes, it follows that the rate ρ would be similar,
- The societal and economic consequences would also be similar since they logically depend primarily on purpose of a structure,
- This implies the societal and economic consequences of failure of the heritage structure be estimated using a relevant rate ρ and 'equivalent construction cost' C_0' that approximately equals to the construction cost of the new structure C_0, $(\rho - 1) \times C_0' \approx (\rho - 1) \times C_0$.

In addition the loss of a cultural heritage value needs to be quantified. In accordance with Annex I of ISO 13822 (2008), the cultural heritage value includes authenticity and integrity of a historic structure and its character-defining elements (historic materials, forms, locations, spatial configurations, morphology, concept and details, and structural design). It is indicated that judgments about the cultural heritage value may differ from culture to culture and it is thus difficult to establish any fixed criteria. Several methods have been proposed for the assessment of an environmental value of assets, which may be a similar issue to the estimation of the cultural heritage value as indicated by Sanz et al. (2003) and Bedate et al. (2004).

However, in most applications the loss of a cultural heritage value of a structure and possibly its content C_c is estimated by a qualitative expert judgement. In absence of any quantitative assessment of the cultural value, it is proposed to appropriately increase the rate ρ by $\Delta\rho_c = C_c / C_0'$. For instance, assuming the adaptation of a heritage structure to an office building, the middle rate $\rho = 3.5$ might be considered. Depending on an estimated cultural value, the rate may be increased by say $\Delta\rho_c \approx 1.5$ to cover the loss of the cultural value in case of failure.

Equation 10 can thus be rewritten as follows:

$$\sum_i \mathrm{E}\left[C_{\mathrm{f},i}\left(t_\mathrm{D},\mathbf{p}|I\right)\right] \approx C_0' \sum_i \left(\rho_i + \Delta\rho_{\mathrm{c},i} - 1\right) \int_{t_\mathrm{D}} \frac{r_i\left(t,\mathbf{p}|I\right)}{\left(1+q\right)^t} \mathrm{d}t \qquad (12)$$

8 DESIGN OF CONSTRUCTION INTERVENTIONS

If the structure does not satisfy reliability requirements, construction interventions may become necessary. When dealing with preservation of the industrial heritage structures, it may be difficult to propose construction interventions that respect all requirements for preservation of the cultural heritage value. According to Lourenco (2002) modern principles of interventions seem to include the following aspects:

- Removability,
- Unobtrusiveness and respect of the original conception,
- Safety of the construction,
- Durability and compatibility of materials,
- Balance between cost and available financial resources.

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9 NUMERICAL EXAMPLE

The proposed procedure is applied in the example of reliability assessment of a steel member of a 100-year old building registered as the industrial heritage. The building, originally built as a part of a textile mill, will be used as an office building. The selected structural member is exposed to bending moment due to permanent and imposed loads. An anticipated working life is 50 years. Note that the reliability assessment is considerably simplified to illustrate general steps of the probabilistic verification and cost optimisation rather than to describe case-specific details.

Initially, reliability of the member is verified by the partial factor method. Characteristic values of the resistance and permanent action, given in Table 1, are specified considering results of on-site surveys and original design documentation. No significant degradation is observed. Characteristic value of the imposed load is determined in accordance with EN 1991-1-1 (2002).

The deterministic verification reveals that reliability of the member is insufficient as the actual resistance is approximately by 40 % lower than required by Eurocodes.

9.1 *Probabilistic reliability analysis*

The limit state function for the member exposed to bending can be written as follows:

$$Z(\mathbf{X},t) = K_R R - K_E\,[G + Q(t)] \tag{13}$$

where K_R = model uncertainty of resistance; R = flexural resistance; K_E = model uncertainty of load effects; G = permanent action; and Q = maxima of the imposed load related to a reference period t. The considered characteristic values and probabilistic models of the basic variables, based on recommendations of JCSS (2006) and findings published e.g. by Holicky & Sykora (2010), are given in Table 1. Note that for reference periods different from 50 years, the mean of the imposed load is modified as follows

$$\mu_{Q,t} = \mu_{Q,50} + 0.78\sigma_Q \ln(t / 50) \tag{14}$$

where t is in years. The standard deviation σ_Q is constant for any reference period and the coefficient of variation V_Q is adjusted accordingly. For convenience all the basic variables in Table 1 are normalised by $L^2 / 8$ (L is a span of the member).

The reliability verification is firstly based on Equation 1 (no new information). Using the FORM method, the reliability index is rather low, $\beta \approx 2.0$. Considering the target reliability levels indicated in Section 5, the reliability of the member seems to be insufficient.

Secondly, the reliability is updated considering the satisfactory past performance to improve this estimate. It is known from previous performance of the structure that the member has survived the load S equal to 1.2-times the characteristic value of the imposed load. Uncertainties in the survived load effect are described by the normal distribution with the mean equal to the observed value and coefficient of variation 0.05. Given the survival of the load S, the updated reliability index $\beta''(t_\mathrm{D}|S) \approx 2.6$ follows from the conditional failure probability based on Equation 3:

$$p_\mathrm{f}''(t_\mathrm{D}|S) = \langle \mathrm{P}\{K_R R - K_E(G + Q_{50}) < 0\} - \mathrm{P}\{K_R R - K_E(G + \min(Q_{50},S) < 0\}\rangle \, / \\ / \, \langle 1 - \mathrm{P}\{K_R R - K_E(G + S) < 0\}\rangle \tag{15}$$

It appears that the predicted reliability is still rather low.

Table 1. Models for basic variables.

Variable	Sym.	Unit	Dist.	x_k	μ_X / x_k	V_X
Bending resistance	R	kN/m	LN	5.21	1.19	0.08
Permanent load	G	kN/m	N	3.06	1	0.05
Imposed load (50 y.)	Q_{50}	kN/m	GU	3	0.6	0.35
Resistance uncertaint.	K_R	-	LN	1	1.15	0.05
Load effect uncert.	K_E	-	LN	1	1	0.1

x_k = characteristic value; μ_X = mean; V_X = coefficient of variation; LN = lognormal distribution; N = normal distribution; and GU = Gumbel distribution of maximum values.

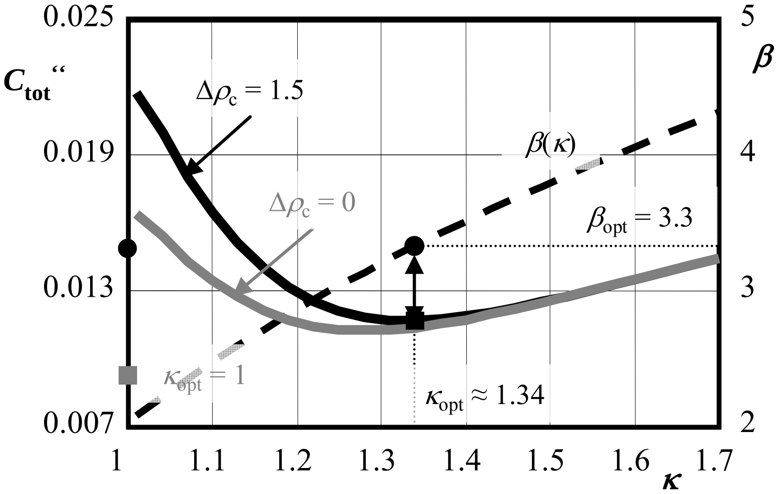

Figure 1. Variation of the standardised cost and reliability index with the decision parameter.

9.2 *Cost optimisation*

The total cost is further minimised to find the optimum decision on an immediate repair. The optimisation is based on the following assumptions:

- The decision does not concern inspection, maintenance and future repair strategies and related costs are not included in the optimisation,
- The immediate repair does not lead to the loss of cultural heritage value,
- The repair cost can be approximated by $C_R(\kappa) \approx [0.01(\kappa - 1) + 0.0075]C_0'$ where $1 < \kappa \leq 1.5$ is the ratio of the resistance after the repair over the actual resistance; if the actual state is accepted, the repair cost is $C_R(\kappa = 1) = 0$,
- The discount rate is $q = 3$ %,
- The moderate societal and economic consequences are considered (the rate $\rho = 3.5$).

Based on Equations 9 and 12, the objective function for $\kappa > 1$ reads:

$$\min\nolimits_{\kappa} \mathrm{E}[C_{tot}''(\kappa|S)] = \mathrm{E}[C_{tot}'(\kappa|S) / C_0'] = 0.01(\kappa - 1) + 0.0075 +$$

$$+ (2.5 + \Delta\rho_c) \int_{t_D} \frac{p_f''(\kappa, t|S)'}{1.03^t \left[1 - p_f''(\kappa, t|S)\right]} \mathrm{d}t \tag{16}$$

where $C_{tot}''(\cdot)$ = standardised cost. The updated failure probability, dependent on the decision parameter κ, and its time derivative are obtained from Equation 15.

Figure 1 shows variation of the standardised cost (left-hand vertical axis) with the decision parameter for two alternatives:

1 The loss of the cultural heritage value is taken into account ($\Delta\rho_c = 1.5$),
2 The loss of the cultural heritage value is neglected ($\Delta\rho_c = 0$).

In addition the reliability index as a function of the ratio κ is plotted in Figure 1 (right-hand vertical axis). It follows that the decision would be to accept the actual state when the loss of cultural heritage value is neglected. However, when considering the heritage value, the optimum decision is to repair the structure in order to achieve the optimum ratio $\kappa_{\mathrm{opt}} \approx 1.34$. Note that the corresponding reliability index is about 3.3.

It appears that the target reliability level depends on the cost of repair and consequences of failure including loss of the cultural heritage value. The target reliability index and the optimum ratio increase with the failure consequences. Complementary studies also indicate that the optimum reliability may also be dependent on a reference period and the discount rate.

10 CONCLUSIONS

Protection of the industrial heritage structures helps preserve cultural values, avoids wasting energy and facilitates economic regeneration of regions in decline. Present insufficient attention to systematic recognizing, declaring and protecting the industrial heritage may, however, lead to their extinction.

Reliability verifications of the industrial heritage structures should be backed up by inspection including collection of appropriate data. Assessments based on simplified conservative procedures used for structural design may lead to expensive repairs and losses of the cultural and heritage value.

Probabilistic methods can thus be applied to better describe uncertainties and take into account results of inspections and tests and the satisfactory past performance. Target reliability levels are primarily dependent on costs of safety measures and consequences of failure including loss of the cultural heritage value, and may be specified on the basis of the total working-life cost optimisation. Numerical example indicates that the decision about the immediate repair may be considerably influenced by estimation of the cultural heritage value of a structure. The target reliability index is approximately 3.3.

It is emphasised that applications of the cost optimisation in practice should be based on carefully formulated objective functions, well assessed costs, specified reference period and the discount rate.

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